A longitudinal study of 16 - 18 year old students' understanding of basic chemical ideas

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Abstract

The understanding 16 - 18 year old chemistry students have of basic chemical ideas was probed in a longitudinal study using a test paper comprising twenty-three diagnostic questions. The students were attending schools and colleges in the UK and had chosen to study chemistry beyond the age of 16. They responded to questions investigating their ideas about the differences between elements, compounds and mixtures, the conservation of mass in chemical reactions, chemical changes and chemical bonding. Aspects of stoichiometry, thermodynamics, equilibria and rates of reaction were also featured. Students' responses were collected three times: at the beginning, in the middle and towards the end of their Advanced ('A') level courses. The written data was supported by interviews with selected students carried out after the first and second surveys.

The first survey (of 399 students) established a baseline against which students' progress could be gauged. Some had poorly developed particle ideas. Others did not conserve mass in chemical reactions, or confused mass and density. Many showed poor understanding about acids, combustion and dissolving. Although respondents knew about single and double bonds, many seemed unaware that covalent bonds involve electrons being shared. They found ionic bonds difficult to describe. Students did not know that energy is released when bonds form.

Two further surveys of 320 students were carried out. 250 students followed the Salters' Advanced Chemistry (SAC) course which adopts a context-led approach. Their understanding of most chemical ideas probed changed by the third stage, although some weaknesses were still apparent. The changes in responses observed in 70 non-Salters and a sub-sample of 70 SAC students suggest that different approaches produce some similar effects. The findings indicate that A level courses should include strategies for teaching basic chemical ideas and highlights areas for further development of SAC.

Whenever you set out to accomplish anything make up your mind at the outset about your ultimate objective. Once you have decided on it, take care never to lose sight of it.

Admiral Mahon

Chapter 1

Introduction

The research project which is the subject of this thesis had its origins in a talk given at the Annual Meeting of the Association for Science Education held at Lancaster University in January, 1990. The talk was about the Salters Advanced Chemistry (SAC) course[1], then under development. The project director explained that SAC was different to other A level chemistry courses because it used chemical contexts, called "Storylines", as a basis for introducing chemical ideas. Students would learn the chemical ideas relevant to a particular storyline. As students progressed through the course, the chemical ideas would be revisited, allowing students' knowledge about a specific area to accumulate. Two main claims were made about SAC: first, it would assist students' learning because they would be able to see how a chemical idea related to a given situation; and second, students' motivation towards chemistry would be improved by the SAC approach and so more would be encouraged to study the subject at university level. SAC students would learn their chemistry in context (see Holman, 1991), developing an authentic picture of the role of chemistry in a modern society. During the talk the idea for this project took shape. I wanted to know if the context-based situation genuinely would affect students' learning of chemistry and if their learning was different from that of students following Traditional[2] A level chemistry courses. A brief discussion with the project director indicated that this idea was worth investigating further.

1.1 Background to the research study

My interest in students' learning developed from my previous work on an MA course. A few months prior to hearing about SAC, I completed a dissertation (Barker, 1990) which examined children's understanding of the kinetic particle theory. This small-scale research study revealed that children aged 11 and 12 explained a simple

[1] The units comprising SAC are listed in full in the references. I will refer to the units by name and number throughout. SAC was published by Heinemann in textbook format in 1994.

[2] By "Traditional" courses I mean those which do not emphasise contexts for learning chemical ideas. In these courses, contexts are frequently "added on" after the chemical ideas are taught.

chemical reaction (the burning of magnesium in air) in a variety of ways, none of which was chemically correct. I had taught these children about reactions with oxygen, and we had discussed the formation of oxides. Nevertheless, when asked to explain "Where the white stuff came from" a few months later, almost all had misconceptions about the event. For example, some suggested that "it's the ash left over", a response apparently based on the everyday experience of burning coal or wood. Others thought it was "inside the magnesium", implying that the outer surface of the metal had been burned away, while some thought that the white stuff was "carbon". These and other explanations indicated that what I thought I had taught and what the class had learned were completely different. West et al (1985) explain this result as follows:-

> "We assume that the intention of teaching is to develop certain new knowledge bits in the learners' cognitive structures, that are inter-related in certain ways... In practice, different learners will internalise this intended knowledge structure with different degrees of completeness, different degrees of accord with the intended meanings and with different nature and degree of relationship with other aspects of their cognitive structure." (p 36)

Therefore, I should not have been surprised by the variation in responses. What had happened was simply that the children had assimilated their learning about oxide formation in different ways. Despite my efforts to transfer my expertise about the reaction to them, the class had not "learned" in the way I intended. Vosniadou and Brewer (1987) explain:-

> "Unlike the scientist, the problem for the developing child is not to independently discover a new paradigm, but to integrate current scientific views (coming from the adult world) with theories derived from his/her phenomenal experience. Children's misconceptions often reflect quite clearly these attempts to integrate conflicting pieces of evidence." (p 55)

The children were trying to answer the question, but did so with a mixture of ideas based on their own experiences of burning and the ones they had learned. If lower secondary age children used misconceptions in their answers, then it seemed equally possible that older children would do so too. Older students' experience of chemistry would be more extensive, and therefore liable to more mis-integration of the chemist's view with their own. Further, students studying A level chemistry may have misconceptions about chemical ideas learned previously, and also develop new ones about aspects of chemistry which feature only at A level. I wanted to discover more about students' learning of chemistry and factors which influence their progress. This project would allow me to probe students' learning in the 16 - 18 year old age range and determine how a context-led approach affected their progress.

1.2 The Alternative Conceptions Movement: this project in context

The project is firmly rooted in the traditions of the Alternative Conceptions Movement (ACM) (Gilbert and Swift, 1985), which has contributed significantly to science educators' understanding of the learning process over the last fifteen years. The ACM has probed students' understanding of specific concepts in science, yielding several hundred research papers; some are reviewed in the next chapter; many are listed in bibliographies such as those by Pfundt and Duit (1991) and Carmichael et al (1990). A wide range of research methods has been employed by those working in the ACM, including interviews about instances or events, concept maps, word association tests and written diagnostic tests. Millar (1989) notes that the research has built on the "established research style and methodology of the Piagetian school" (p 587), while the use of written tests has links with the move towards criterion-referenced testing and graded schemes of assessment. He states:-

> "[The ACM] has taken science education research into the classroom and the school laboratory, into contact with teachers' realities; by making the specific details of learning of subject matter the focus of attention, it is challenging the once-dominant paradigms of science education research that treated the learning process as a 'black box' and looked only at inputs and outputs." (p 587)

The ACM has placed students' prior knowledge at the forefront of many teachers' minds and has encouraged them to consider this in planning what they will say and do to encourage their students to develop scientific viewpoints. However, White (1987) points out that although much work has been done on probing the nature of alternative conceptions, relatively little has explored the formation of these ideas and how they change. He states:-

> "Although there has been speculation about their formation few, if any, researchers have asked students where they got their ideas from, nor have there been longitudinal studies tracing the emergence and development of a conception." (p 166)

He continues:-

> "... where a person's conceptions differ from those of established science we should try to discover whether they arose from incorrect observation, different interpretations of correct observations, erroneous teaching, misinterpretation of correct information, inconsistent logic, or a different but internally consistent system of logic." (p 166).

The proposed study would be longitudinal. I would establish a base-line of students' understanding at the start of their A level course, then trace changes as they progress. A diagnostic written test could be devised to probe students' ideas, supported by interviews along the lines suggested by White, above. The study would therefore contribute to the work of the ACM by adding the misconceptions of 16 - 18 year olds studying chemistry to the body of knowledge already accumulated, and would help to move the field in a new direction by investigating changes in students' understanding.

1.3 Why use SAC?

One reason for focusing on SAC has already been described; the project was stimulated by hearing a talk on SAC. There are, however, several further reasons why SAC provides a particularly interesting and useful context for research on students' learning.

1.3.1 SAC provides a structure

SAC comprises fifteen units each of which is made up of a "Storyline", "Chemical ideas" and "Activities". At the time of the study, the units were produced in an A4 tear-off pad format, which allowed students to interweave the storyline, chemical ideas, notes and activities sheets as they wished. Each unit is designed to require approximately three or four weeks of teaching time, that is, about twenty hours of work. Thirteen of the units supply the theoretical content determined by the agreed subject core (the most recent core was published in 1993, by the Royal Society of Chemistry). One unit is entitled "Visiting the Chemical Industry" and the other is a practical project carried out in the students' school or college.

The unit-based structure and the contextual settings of SAC provide a novel way of teaching the traditional content of an A level chemistry course. For example, the storyline of unit 2 "Developing Fuels" describes the development of petrol as the major world fuel and discusses the implications arising from this. The theory needed to understand the storyline is supplied by the chemical ideas section, which includes balancing equations, some thermodynamics, simple organic chemistry, isomerism, entropy and catalysis. These aspects of chemistry are developed in later units which are taught in a prescribed order. Therefore, a population of SAC students is likely to be at the same point in the course roughly at the same time. So, SAC is suitable for monitoring students' progress longitudinally, because a researcher can be reasonably confident that most of the sample will be at similar stages and will have been exposed to identical course materials. Students following traditional A level courses would show greater variation in the chemistry taught at specific points and almost certainly will not have used identical materials.

1.3.2 SAC 'drip-feeds' aspects of chemistry

Students following SAC learn parts of several aspects of chemistry simultaneously. This has two main implications. First, SAC effectively breaks down the traditional "physical", "inorganic" and "organic" divisions of chemistry, instead encouraging students to draw aspects of chemistry together. Second, students will only learn what they need in order to understand each storyline. This permits the learning of any one aspect of chemistry to be spread throughout the course. For example, equilibria receives qualitative treatment in unit 4, *The Atmosphere*, and is re-visited in several other units before receiving quantitative treatment in units 12, *Aspects of Agriculture* and 13, *The Oceans*. This permits students to assimilate earlier information before being faced with the more difficult parts. Traditionally, students would study all parts of equilibria at a sitting.

The SAC approach was the source of my original questions. What is the effect on students' learning of this "drip-feed" approach? Are there discernible differences in the understanding of students who learn chemistry in this way and those who do not? These questions could be answered by carrying out a longitudinal study, monitoring SAC students' understanding and looking in addition at the understanding of students following traditional A level courses to provide a baseline against which to evaluate the learning of the SAC students.

1.3.3 SAC is stimulating for students

One intention of SAC is to develop a wide range of teaching and learning styles. Thus, the units encourage development of information technology skills, and use directed activities related to texts (DARTs), oral presentations and group work alongside laboratory based activities to provide an interesting environment in which to learn chemistry. Holman (1991) writes about the course trial stage of SAC that:-

> "students and teachers are stimulated by the fresh approach and find that it makes the learning of chemistry more enjoyable. Significantly, schools are reporting that fewer of the students following the Salters course are dropping out in the early stages ..." (p 814)

The wide variety of learning experiences and the placing of chemistry in contextual settings may help students learn the chemical ideas. Millar (1989) concludes that "the process of eliciting, clarification and construction of new ideas takes place *internally*, within the learner's own head." (p 589) and that to encourage this

> "... science should be taught in whatever way is most likely to engage the active involvement of learners, as this is most likely to make them feel willing to take on the serious intellectual work of reconstructing meaning." (p 589)

SAC attempts to engage learners actively. If this approach helps students to reconstruct meaning, that is, change misconceptions they may have at the start for a chemist's viewpoint, this should be apparent towards the end of their course. However, White (1987) points out that:-

> "It will take a powerful new experience to overthrow all the earlier positive experience of the usefulness of the old notion." (p 167)

SAC must provide such "powerful" experiences if it is to challenge students to change their thinking. Thus, to undertake the type of study proposed amounts to an evaluation of the SAC method of teaching basic chemical ideas.

1.4 The research questions

1.4.1 Establishing the baseline

The preceding section in one respect leaps ahead a little, since the assumption behind it is that students will have misconceptions which need to be changed. Thus, my first research question must be:-

> What level of understanding do beginning A level students have about basic chemical ideas[3]?

Science education research has been dominated by studies of the 11 - 15 year old age group. While some work has been carried out on students' understanding of some aspects of chemistry, such as particle theory, conservation of mass and mole calculations, other areas are relatively poorly studied. Also, the level of understanding which students bring to an A level chemistry course has not been investigated, so this study will provide useful information in this regard. Data relevant to this research question are presented in chapter 4.

1.4.2 Changes in the SAC students

Having established a baseline, I must then investigate changes in students' understanding. Therefore, my second research question is:-

> In what ways is student learning influenced by the context-theory approach?

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[3] It would be impractical to investigate the full A level syllabus. I focused the study on what I call "basic chemical ideas" which are justified in full in section 3.2. Briefly, they include differences between elements, compounds and mixtures, conservation of mass in closed and open system chemical events, use of reacting mass reasoning, and aspects of chemical bonding, thermodynamics, equilibria and rates of reaction.

It may be that some of the chemical ideas are better developed by the context-theory approach than others. Data answering this research question are presented in chapter 5.

1.4.3 Changes in SAC students relative to Traditional students

Changes in SAC students cannot really be evaluated without some baseline against which to judge them. So, I intend to establish if the changes observed in the SAC sample are better, worse or equivalent to those observed in students following Traditional courses. Therefore, my third question is:-

> How does the development of SAC students' chemical reasoning compare with that of students following Traditional courses?

If more SAC than Traditional students adopt reasoning closer to a chemist's viewpoint, then the context-theory approach seems to offer advantages over a traditional one, and vice versa. If there is no significant difference, then the SAC approach may represent "value-added", given that the students are likely to experience a wider range of activities than Traditional students. Data relevant to this question are presented in chapter 6.

1.5 And finally ...

Herron (1978) writes that chemistry is the study of matter -

> "...what it is, why it exists in its various forms, how it can be changed from one form to another, how it *cannot* be changed from one form to another, the conditions necessary for those changes to take place. The more we know about matter the better able we will be to shape the world for our comfort and pleasure." (p 190)

This project is, essentially, a study of students' learning of chemistry. My understanding of their learning has been both challenged and changed as a result of carrying it out. I hope the reader will be as challenged by the findings as the writer has been.

Chapter 2

Students' misconceptions of basic chemical ideas: A review of the literature

The literature review provides support for this study in two ways. First, the study will focus on the learning of basic chemical ideas among A level chemistry students. So, it is important to ascertain what is already known about students' understanding at this level. Much work to date has explored students' ideas about matter. The review takes this as a starting point and progresses to discuss their understanding of changes of state, since these are central to the development of ideas about chemical phenomena. In subsequent sections I review research on students' ideas about chemical reactions, acids and bases, thermodynamics and equilibria. These sections establish the aspects of chemistry which seem to be widely accepted as "basic ideas" and so help to focus the study towards the areas suitable for investigation.

Second, the review provides an insight into the approaches used to ellicit information about students' understanding. A variety of methods has been employed. Although these are not reviewed explicitly, the relative merits of the approaches used by other workers will be assessed and will inform the strategy for the proposed study. So, this chapter is essential to developing the practicalities of carrying out the proposed research as well as providing information about the aspects of chemistry the study should include.

The chapter will begin by discussing students' ideas about the nature of matter.

2.1 A naive view of matter

"There are more than three kinds of 'stuff'... "

Children receive sensory information about matter from the moment they become aware of their surroundings. Collection of this data continues throughout childhood, becoming increasingly complex and requiring constant revision. Through mental processing of the information the child builds up a picture of matter, of which all his or her environment is made. Hayes (1979) suggests that this direct sensory experience results in a view about matter which is something like this:-

> "There are different kinds of stuff: iron, water, wood, meat, stone, sand etc. And these exist in different kinds of physical state: solid, liquid, powder, paste, jelly, slime; paper-like etc. Each kind of stuff has a usual state: iron, solid, water, liquid, sand is powder, etc., but this can sometimes be changed. For example, many stuffs will melt if you make them hot enough...and others will burn. Any liquid will freeze if you make it cold enough. Any solid can be powdered... There is no obvious standard way of changing a powder to a solid...
>
> Some solids decompose, i.e. change slowly into some other (useless) substance; or mature, i.e. change slowly into some other (useful) substance..." (p 242-70).

Evidence supporting Hayes' view of common sense thought about matter is found in the work of Stavy and Stachel (1985) who examined the conceptions children aged between 5 and 12 have of 'solid' and 'liquid'. Children experience difficulty in classifying substances which do not "fit" with their idea of solid or liquid. She found that 50% of 12 and 13 year olds classify non-rigid solids, like dough and sponge, and powders like sand and sugar separately from coins, glass or chalk. Stavy and Stachel suggest that:-

> "The easier it is to change the shape or the state of the solid, the less likely it is to be included in the group of solids." (p 418)

Metals and wood are perceived as typical solids, so substances with properties which do not meet criteria of being hard and rigid cannot be solids. Water is the standard against which other possible liquids are "measured" - hence, powders which can be poured have liquid properties but are known not to produce a sensation of wetness, so are classified independently. So, children identify more than three states of matter, grouping substances according to a set of standards based on sensory experience.

Stavy and Stachel found that in general children are able to classify "new" liquids more easily than solids. This could be because liquids tend to vary less in their physical characteristics than solids. So, overall, their work supports Hayes' suggestion that children spontaneously classify matter in what seems to them to be a "common sense" way.

Gases cause special difficulties for children since those commonly experienced by young children, like air for example, are invisible. In her more recent work, Stavy (1988) suggests that this invisibility prevents children from forming a concept of gas spontaneously. She finds that instruction is necessary if children are to acquire knowledge about gas properties, whereas her earlier work suggests that children learn intuitively about solids and liquids. Gases are also conspicuously absent from

Hayes' characterisation.

Séré (1986) investigated the ideas 11 year olds have about gases prior to teaching. She found that children associate gases with the use and function of objects, like footballs, tyres and suction pads. Stereotyped views about air were discovered to be commonplace, expressed in notions like "hot air rises" (but not "cold air sinks") and "air is everywhere". Also, air was frequently described as though it were alive, for example, "air always wants to expand everywhere". Séré notes that these ideas may arise through experience of air forming draughts and wind as well as by using air in various ways around the home.

Therefore, students do not perceive instinctively that gases are a form of matter in the way that they discover "solid" or "liquid" types of "stuff". Rather, students describe gases only in terms of physical characteristics. Children appear to rely solely on sensory information when reasoning about matter up to the age of around 14 years. Even if they have received teaching about the particle theory, such abstract ideas are not readily used to answer questions about the properties of matter. This supports Hayes' suggestions and indicates that young students tend instead to think of substances as continuous. Stavy and Stachel (1985) concluded,

> "The definitions ... used by children for 'solid' and 'liquid' related only to the physical behaviour of the materials. There were no definitions or explanations using terms from the particulate theory." (p 419)

Millar (1989) suggests that a possible reason for this is that children do not need to use particle ideas, since their own theory of matter has worked perfectly well for them. Also, the particle ideas do not help children understand anything additional which interests them. This has implications for influencing change in students' ideas.

" 'Stuff' can disappear but its taste and smell stay behind..."

Children's ideas about the behaviour of matter were studied by Piaget and Inhelder (1974). They formulated children's naive view of matter as follows:-

> "a. Matter has no permanent aspect. When matter disappears from sight (e.g. when sugar dissolves in water) it ceases to exist.
>
> b. Matter has a materialistic core to which various random properties having independent existence are attached. Matter can "disappear," whereas its properties (such as sweetness) can continue to exist completely independently of it.
>
> c. Weight is not an intrinsic property of matter. The existence of weightless matter can be accepted.

> d. Simple physical transformations (such as dissolution) are not grasped as reversible." (quoted in Stavy, 1990a, p 247)

Piaget suggests (see Stavy, 1990a) that the naive view of matter "...disappears when logical thought takes over..." (p 248) usually as a result of receiving teaching. Evidence supporting these statements has been collected, of which a sample is given for the purposes of this discussion. The remainder is discussed under "The Behaviour of Matter".

Russell et al (1989 and 1990) studied the ideas children aged 5 - 11 have about evaporation prior to teaching by asking them to explain the decrease in water level in a large tank after sunny weather. About 45% focussed only on the remaining water, seeing no need to explain where the "missing" water had gone. For these children the matter had simply ceased to exist (statement 'a').

Similar ideas were found by Stavy (1990a) in her study of the ability of children aged 9 - 15 years to conserve weight and matter. Her students were shown acetone evaporating in a closed tube. Around 30% of 9 - 10 year olds in her sample thought the acetone disappeared altogether, using the same idea as the infants (statement b). Statement 'b' gains additional support from Stavy's (1990a) study, which indicates that 30% of the 10 - 12 age group (30%) think the smell of the acetone remains, although the matter itself vanishes.

Prieto et al (1989) studied ideas about dissolving and report that 44% of 14 year olds think a solute "disappears" when dissolved, while 23% label the event "it dissolves" with no explanation. A further 40% of this age group thought that acetone became weightless because it had become invisible (statement 'c').

By the age of 15, Stavy (1990a) finds that 65% view the evaporation of acetone as reversible, with a large jump in proportion from 25 to 60% at age 13 - 14 when formal teaching about particle ideas is received (statement d).

Features of the naive view of matter

The naive views of matter of Hayes and Piaget and Inhelder together point to three key features of children's reasoning about matter. These are:-

> (i) children do not reason consistently - they may use sensory reasoning on some occasions and logical reasoning on others;
>
> (ii) sensory experience dominates in cases where the matter is not visible, leading to the fact that

(iii) many students aged 15 and over still use sensory reasoning about matter, despite being well advanced in thinking logically in other areas, such as mathematics.

Evidence supporting these points now follows.

Stavy's study (1990a) reports that children reason differently when the substance studied remains visible. Children were asked to explain what they thought occurred when solid iodine was placed in a closed tube and heated such that the purple vapour was produced. Their responses indicated a change in their reasoning pattern. This time, 30 - 50% of children across the age range 9 - 15 years perceived that the weight of the material was unchanged, while 70 - 95% thought the matter itself was conserved. These are in marked contrast to the figures for the acetone demonstration reported earlier. Stavy's results indicate that sensory information informs children's thinking, influencing them towards applying different reasoning in cases when matter remains visible.

Piaget states that when logical thought develops in adolescence, the naive view of matter disappears. Stavy's work indicates that a significant proportion (30 - 40%) of 15 year olds who have received teaching on the particle theory still use naive ideas about matter in solving particle problems. The Children's Learning In Science (CLIS) project (Brook, Briggs and Driver, 1984) found similar results. Piaget's view therefore seems to be at odds with this evidence. However, it is clear that ideas developed through childhood prevent many children from answering problems about matter in a consistent way. That is, the naive view of matter is so strongly and powerfully held that it controls the way these children think about matter. So, children may not answer correctly questions about matter which require logical or abstract thought, although they may have the skills necessary to do so. Thus, although logical thought may well develop as Piaget suggests, the application of such thought to problems about matter is poor. This may affect beginning A level students' answers to questions involving changes of state and gases.

The implications of the persistence of a naive view of matter are wide-ranging, as discussion on the learning of the particulate theory will indicate.

2.2. Students' ideas about the particulate nature of matter

Aspects of students' understanding of the particulate nature of matter have received considerable attention from science education researchers. Here, misconceptions concerning children's ideas about three basic tenets of the particulate nature of matter are discussed. These are:-

- all matter is made of discrete particles;
- the space between particles is empty;
- particles are in constant random motion.

The particulate nature of matter is usually introduced to children in the lower years of secondary school, at the age of 12 - 14 years. As implied by the previous section, these ideas are not likely to be grasped easily and much evidence exists to indicate that a significant proportion of adolescents retain parts of their naive view of matter to adulthood. This section describes the common misconceptions students develop when their naive view of matter interacts with the particulate theory. The discussion will take each statement in turn.

2.2.1 All matter is made of discrete particles

Children have difficulty in understanding that matter is made of particles for two main reasons. First, their naive view of matter focuses on what can be sensed directly, on the principle that "seeing is believing". The particulate theory is usually introduced through practical demonstrations which require a particle model for their explanation. This leads to the second problem. Students have already constructed a view of matter which does not include particles and which they have found effective, so they have no need for a particulate model of matter. This means that the new ideas being put across by the teacher clash with the way the child thinks. As a result, although the child may use particle terms and ideas in a science lesson to explain the phenomena demonstrated, as demanded by the teacher, these ideas are not automatically used by students to explain the "real world". Novick and Nussbaum (1981) describe the basic learning problem as requiring that:-

> "...the learner must overcome immediate perceptions which lead him to a continuous, static view of the structure of matter. He must accommodate his previous naive view of the physical world so as to include a new model adopted by scientists. Internalising the model therefore requires overcoming basic cognitive difficulties of both a conceptual and a perceptual nature."
> (p 187)

Many children do achieve some understanding that matter is particulate in nature following teaching. In their 1978 study, the same authors used interviews to probe the understanding 13 - 14 year olds had about gases after teaching, finding that about 60% consistently used particle ideas. This figure increased to more than 90% at age 18+. The CLIS project studied 15 year olds (Brook, Briggs and Driver, 1984) and reported that over half the sample used particle ideas consistently in replying to a wide range of questions covering all three states of matter. If teaching on the particulate theory had been recent, as in the Novick and Nussbaum study, the proportion using these ideas was higher still.

Students who do not use particle ideas may respond to questions about matter only in terms of the bulk properties of substances. For example, in the CLIS study (Brook et al 1984), this response was found in answer to a question concerning the change in temperature of a block of ice:-

> "As the temperature rises to -1 ^{o}C the ice will melt causing the block of ice to get smaller" (p 57).

Or, in response to a question on car tyre pressure during a journey,

> "When a car goes on a journey, the tyres start to warm up and this causes pressure".
> (p 35)

This type of answer is described by Brook et al as "low-level macroscopic". Of the children who do appreciate that matter is made of particles, many are not, immediately at least, able to relinquish all of their own naive view of matter in favour of accepted scientific ideas. Many of this group explain phenomena in terms of bulk properties of particles themselves. Other respondents said that particles could "expand, melt, decrease in size" (p 55-56). Happs (1980) reports similar ideas, finding that some students say particles:-

> "change their form [solid to liquid]; explode, burn, expand, change shape and colour, or shrink" (p 9 - 14).

More recently, Griffiths and Preston (1992) report in their small-scale study that about 50% of 18-year olds think that water molecules in steam are larger than those in ice. Students using this type of explanation for the behaviour of matter seem to be in an "intermediate" stage between full appreciation of the particulate nature of matter and their naive ideas. Although some of these students may develop completely correct understanding, it may be that many people do not move out of the intermediate stage.

2.2.2 Space between particles is "empty"

Novick and Nussbaum (1978, 1981) showed that the notion of empty space existing between particles causes special difficulties for students. They carried out a Piagetian-type interview study on Israeli 13 - 14 year olds (1978) to ascertain their application of particle ideas after studying a unit entitled "The Structure of Matter". Their later (1981) paper gives details of a cross-age study of American students aged 10 - 20 years to ascertain how student views about particles change with age. They found that 25% of the younger group described empty space between particles. Students seemed to suggest that although the particles were themselves discrete entities, the space between them either had to be filled, for example, by:-

> "Dust and other particles; other gases such as oxygen and nitrogen; air, dirt, germs; maybe a liquid; unknown vapours.." (Novick and Nussbaum, 1978 p 276)

or was non-existent, for example:-

> "The particles are closely packed - there is no space between them" or "No place is completely empty". (p 276).

In the 1981 study, in which students were asked, "What is there between particles?", about 40% of students aged 16 and above responded "vapour or oxygen", while a further 10 - 15% decided "a pollutant" was present. The persistence of this "space-filling" model is shown by Benson et al (1993), who found that although about 70% of university science students have a particulate model of gases, about 33%

> "seriously underestimated the relative amount of space between the gas particles themselves." (p 596).

Students of all ages, therefore, find space difficult to imagine and want to "fill" it with something. Since students depended on visible, sensory information about solids and liquids to develop their naive view of matter, their difficulty with acceptance of a model which proposes there is "nothing" in the spaces between the particles is perhaps not altogether surprising.

2.2.3 Particles are in constant motion

The constant motion of gas particles causes them to be evenly distributed in any vessel and to exert pressure on the sides of the vessel. Evidence suggests that students do not seem to understand either of these ideas easily.

The distribution of particles

Novick and Nussbaum (1978) asked 13 - 14 year olds to draw a picture to represent air in a partially evacuated flask. A significant proportion drew air around the sides of the flask, or in a mass at the bottom. Others, who indicated that air was composed of tiny particles, showed the particles in clumps or occupying only part of the flask. Explanations offered for these pictures included, "They are held in place by attractive forces..." (Novick and Nussbaum, 1978 p 277).

Students aged 16 and above seem to accept that gas particles are uniformly distributed. Novick and Nussbaum (1981) showed that almost 100% of the 16+ age group spontaneously showed uniform distribution in their pictures. However, when students were shown a closed flask containing air and were asked, "Why don't the particles fall to the bottom?", their answers indicated that only around half thought that the particles were in constant motion. About 20% explained that there were "repulsive forces between the particles".

Both the attractive and repulsive force ideas imply that the particles are static, suggesting that the movement of particles in a gas is a most difficult notion to learn. The attractive forces idea supports the "clumped together" model, while the notion of repulsive forces is used to explain uniform distribution of particles. No evidence exists to indicate whether any individual student imagines that attractive forces exist between particles when aged 14, and changes to the repulsive forces idea two years later. However, it may be that once a student has accepted the idea that particles are uniformly distributed, the attractive forces notion becomes redundant and a new explanation, repulsive forces, is substituted. The ideas are not, therefore, necessarily exclusive.

The cause of gas pressure

Brook, Briggs and Driver (1984) found that a significant proportion of students aged 15 years used the idea of attractive forces between particles of a gas to help explain air pressure. Some went further in suggesting that the strength of the forces was temperature dependent. In contrast, some 15 year olds in the CLIS study did not think forces existed between particles in the solid state (Brook et al, 1984 p 74). The report does not indicate if these students also think forces exist between gas particles. However, Engel Clough and Driver (1986) and Stavy (1988) among others report that students do not apply ideas consistently to problems, so the same student could imagine forces to be present between gas particles and not between particles of a solid phase substance.

Students offering these explanations of forces between gas particles believe the particles to be static. This is likely to affect their reasoning about changes of state and chemical bonding, both of which involve interaction between particles.

2.2.4 A summary of students' ideas about the particulate nature of matter

Three points can be made to summarise this section. First, only a small proportion of all students aged 16 have developed a particle model likely to be useful for explaining physical and chemical phenomena. Stavy (1990a) stated that young children spontaneously form ideas about solids and liquids, but not gases. Misconceptions about gases, then, may arise because children extend their functional particle model for solids and liquids to this "new" state of matter. Benson et al (1993) provide evidence for this, noting that some children think of gases as behaving like liquids, and thus sharing similar properties. The effectiveness of the continuous model of matter is such that although students are taught about the existence of particles, the majority use only a primitive particle model, which retains aspects of this naive view. For example, some 16-year olds think that the space between gas particles is non-existent or filled. Others think that particles expand when they are heated. A further group, who accept that the particles of a gas are uniformly distributed, explain this using the idea that repulsive forces exist between particles and hence imply that the gas particles are static. A small proportion of students do not use taught particle ideas at all, offering only low-level macroscopic responses to questions involving particle behaviour. This group retain their naive view of matter in a more complete form.

Second, Novick and Nussbaum (1978) concluded that:-

> "The aspects of the particle model least assimilated by pupils in this study are those most in dissonance with their sensory perception of matter" (p 280).

Certainly, the notions which cause the most difficulty for students are those for which immediate sensory evidence is lacking. Students' explanations attempt to make sense of what they cannot otherwise account for. Stavy (1990a) and Benson et al (1993) suggest that students' ideas may change if they are presented with visual evidence, since only then may the inadequacy of their naive model be made apparent.

Third, evidence suggests that some students apply different ideas to the three states of matter and do not see contradictions in their reasoning. For example, students may reason that attractive forces are present between gas particles and that these explain why gas particles may clump together, but they do not use this idea about particles in solids. A student may modify this later to explain the uniform distribution of gas particles in terms of repulsive forces. These ideas may create difficulties for students in understanding chemical bonding, which depends on attraction between particles.

Next, we consider how students' ideas about the particulate nature of matter influence their thinking about changes of state.

2.3 Students' ideas about changes of state

This section begins by examining children's ideas about the motion of particles. These provide a foundation for the sections on evaporation, condensation, melting and freezing which follow.

2.3.1 Ideas about the motion of particles

The previous section implied that the continuous random motion of particles is not well understood by school students. Many students aged up to 18 years do not appreciate that particles are moving at all, visualising them as static. Not surprisingly, then, such students offer scientifically erroneous explanations for the effect increasing temperature has on particle motion. This can be seen most clearly when students' ideas about heating and cooling gases are considered.

The effect of heating a gas

Novick and Nussbaum (1981) report that in answer to the question "How does heating affect gas particles?", about 40% of 16 year old students thought increased particle motion was the main effect. Over 40% of students aged 16 explained that "particles are forced apart" while around 20% used the notion of repulsive forces. The CLIS study (Brook et al 1984) reports similar responses to a question about air pressure in a car tyre. About 12% of 15-year olds used ideas which suggested that increasing forces between particles were responsible for a change in pressure of a car tyre during a journey. Séré (1982) in her study of 11 - 13 year olds' ideas about air pressure, noted that children use mechanistic terms like "force" to describe visual effects. However, Brook et al (1984) also found replies which used ideas like particles "swelling", or simply occupying more space. The use of mechanistic notions appears to be an alternative way of using sensory perception to describe phenomena.

The effect of cooling a gas

The decrease in particle motion on cooling seems to be harder to understand than the notion of increased particle motion on heating. Recall that about 40% of 16+ students thought that increased particle motion was the main effect heat has on gas particles. The converse question, "How does cooling affect gas particles?" yielded correct responses from less than 30% of 16 - 18 year old students and only 20% of university students (Novick and Nussbaum, 1981). This difference could be because fewer practical examples of cooling gases are available to assist understanding. Approximately 50% of students of any age offered descriptive responses to the question on cooling of gases. These included ideas about particles being able to shrink, condense, sink or settle. These terms are also examples of macroscopic phenomena being used to describe microscopic particles.

Taken to an extreme, the cooling of a gas leads to liquefaction. Novick and Nussbaum found that students represented this pictorially by drawing particles of air accumulating around the sides of the vessel, or collecting together at the bottom. This is precisely the same sort of picture drawn by some students to represent air anyway (see section 2.2.3). Approximately 70% of students from age 13 to university level drew this sort of picture, suggesting that misconceptions about liquefaction are widespread. Novick and Nussbaum (1981) state that

> "...many high school students attribute the decrease in volume of a gas on cooling not to decreased particle motion but to increased attractive forces." (p 192)

Brook et al (1984) found similar ideas in response to a question about a football left to cool down.

The difficulties students have in explaining the heating and cooling of gases in terms of particle motion are reflected in studies which specifically investigate children's ideas about changes of state.

2.3.2 Ideas about evaporation

...among young children

Children gain experience of evaporation from a young age. Misconceptions about evaporation are well described by Russell and Watt (1990) and Russell et al (1989), who report that a variety of ideas about evaporation is held by children aged between 5 - 11 years. Thus, the information collected in their studies is from children who have not received formal teaching about particles. A summary of their findings will useful for subsequent discussion.

As described earlier (section 2.1.1), Russell et al (1989) note that infant children notice evaporation has taken place, for example, from a water butt, but focus entirely on the remaining water, saying some water has simply "disappeared". About 22% of children aged 7 - 9 years acknowledge that water has gone, but attribute the disappearance to the work of an outside agent, like another person or the sun. Children also express this change using ideas about change of place. Beveridge

(1985) gives an example of this; he notes that children aged 7 -8 frequently think that water has soaked into the pan when it is boiled in front of them. Cosgrove and Osborne (1981) found children thought that water "went into the plate" if just left to evaporate. Russell and Watt (1990) find similar ideas among children who explain drying clothes by suggesting that the water which drips off soaks into the ground. They note that other children in the junior age range think the water has been transformed into mist, steam or spray (28%) while a further group describe water as changing to an imperceptible form (17%), such as water vapour or a 'gas'. For example, one child gave the excellent answer,

> "I think the water has split up into millions of tiny micro bits and floated up.." (Russell and Watt, 1990 p 33).

The authors note that this is the closest children seem to get to using particle ideas without receiving formal teaching on the subject.

Older children produce the same explanations, but in different proportions. About 57% of the 9 - 11 age group use the idea of an outside agent. The increase in the prevalence of this idea indicates that the role of the sun (or in the case of Beveridge, the saucepan) is acknowledged, but that the child has not quite linked this correctly with the disappearance of the liquid.

These ideas are interesting not only in themselves, but also because they indicate that the notion of evaporation is linked to the understanding of conservation of matter. In suggesting that an outside agent has removed the water, children seem to be conserving the amount of material, but are offering a faulty explanation as to why the water should have disappeared. As discussed above, their reasoning is on a sensory basis, applying what are to them satisfying explanations for an invisible change.

...and among secondary school students

Let us now consider how older students who have received teaching on the particle theory understand evaporation. We might expect that they will be able to use particle ideas in their responses and to indicate clearly that all the matter is conserved. Stavy (1990b) studied the link between evaporation and conservation of matter in detail. She examined the ideas of 9 - 15 year olds on two tasks involving evaporation (also reported in Stavy 1990a). Her results suggest that as many as 50% of 15 year olds do not conserve the amount of matter in evaporation. Stavy suggests that confusion arises for students because of problems with the ideas they are taught about density and weight. Students apply the statement "gas weighs less than liquid" to evaporation, explaining the phenomenon in terms of weight change (incorrect) rather than density change (correct).

Bar and Galili (1994) draw together 5 and 14 year old students' ideas about evaporation in proposing that development of ideas occurs in a series of stages which are age related. They report that although the notion of disappearance is prevalent among younger children, most make the transition to thinking that evaporating water is absorbed into the ground by the age of eight. This absorption view implies an understanding that the amount of water in conserved. Bar and Galili note that the next significant change occurs around the age of 12, when students have acquired the understanding that air is a medium which surrounds us. They estimate that 80% of children aged 12 think that evaporated water has changed its location to "the sky" and that water is made of small particles. The final transition, realising that water is transformed into water vapour made of tiny water particles, becomes the majority view at age 14 - 15.

However, Osborne and Cosgrove (1983; also reported in Cosgrove and Osborne, 1981) studied New Zealand students aged 8 - 17 years and revealed further misconceptions which do not fit into the Bar and Galili (1994) stage theory. An electric kettle was boiled in front of respondents and they were asked "What are the bubbles made of?". The replies included that the bubbles were made of heat, air, oxygen or hydrogen and steam. The question was answered by over 700 students and the same responses were found. Proportionately, these varied from age 12 - 17 as follows:-

heat	30% to 10%
air	30% to 20%
oxygen / hydrogen	25% to 40%
steam	15% to 30%

These data show that while the number offering a correct response, steam, does increase between the ages of 12 and 17, the majority of students at 17 years persist with alternative responses, none of which were apparent in studies with younger children. These alternatives imply that the water can be split into its component elements by heating; that heat is a substance in its own right; and that air is contained in water. Osborne and Cosgrove attribute these to the influence of teaching, but Bar and Galili (1994) dismiss this. They suggest, for example, that students have acquired the general knowledge that hydrogen and oxygen are gases and merely use these as "candidates for some gaseous water phase" (p 171). However, given that by the age of 17 students will have learned that the formula of water is H_2O, I think it is more likely that students imagine the water molecules break up on heating. Their understanding about chemical bonds may support this. Further, Russell et al (1989) note that children:-

> "are susceptible to focusing on very particular attributes of any given stimulus material some of which might be unexpectedly powerful in drawing thinking along certain directions..." (p 575).

So, students could focus on the formula of water and link this with the fact that hydrogen and oxygen are gases to arrive at their erroneous explanation.

Kruger and Summers (1989) asked primary school teachers to respond to questions very similar to those used by Cosgrove and Osborne. They found that these adults did not often use particle ideas, explaining the phenomenon of evaporation in macroscopic terms. Thus, people do not seem readily to change their ideas about particles, retaining child-like ideas into adulthood. This supports the point made above (section 2.2.4) that the development of a particulate theory of matter often does not go beyond acquisition of the most basic principles and that wrong ideas are very difficult to change. However, this finding contrasts with that of Bar and Galili, whose work implies that accepted particle ideas relevant to evaporation are acquired by a majority of students by the age of 14.

2.3.3 Ideas about condensation

Osborne and Cosgrove (1981, 1983) also report children's ideas about condensation. They held a saucer above a kettle boiling and asked "What is this on the saucer?". Among the younger (10 - 13 year old) respondents the ideas that the plate had become "sweaty" or simply "wet" were popular. Others of the same age and older said, "The steam turns back into water", or "The oxygen and hydrogen recombine to from water." About one quarter of the 13 - 17 year olds interviewed gave a correct response.

In a separate probe, Osborne and Cosgrove asked students to explain the origin of the water condensing on the surface of a sealed jar containing ice. Four main types of alternative answers were found. These were that "water comes through the glass" (age 8 - 15); "coldness comes through the glass" (age 12 - 17); "the cold surface and dry air (oxygen and hydrogen) react to form water" (age 12 - 17); and "water in the air sticks to the glass" (age 14 - 17). The proportion of students thinking that coldness or water was coming through the glass was very small at age 16 - 17, although around 30% of this age group used the idea that gases recombine on the surface to give water.

The authors note that correct responses using particle ideas were exceptions, and that

"...more ideas to do with particles moving and colliding appeared to be understood by older pupils, but sustained probing of these ideas did not produce sound scientific explanations in terms of intermolecular forces or of loss of kinetic energy." (Osborne and Cosgrove, 1983, p 830)

Thus, despite the teaching these students would have received, we see that misconceptions are tenacious and that 16-year old students may find it difficult to apply basic particle ideas in practical situations. These data indicate that students tend to confuse taught ideas about the composition of water (which may have included the electrolysis of water) with the change occurring when water boils.

2.3.4 Ideas about melting

Several workers including Osborne and Cosgrove (1983; also reported in Cosgrove and Osborne, 1981) have investigated children's ideas about melting. In the Cosgrove and Osborne study, three major ideas were expressed at interview by students aged 8 - 17 who were shown ice melting on a teaspoon. Common to the 8 - 17 year old age range was the response that the ice "just melts and changes into water". 12 and 13 year olds frequently suggested that the ice is "above its melting temperature" while 14 - 17 year olds commonly thought that "The heat makes the particles move further apart". (Figures indicating the precise proportions offering these ideas are not given.) A small number of respondents aged 14 to 17 used particle ideas in their replies.

Brook, Briggs and Driver (1984) asked 15 year olds to explain what happens to ice when it is removed from a freezer at -10^{o}C and left to warm to -1^{o}C. Written answers were requested together with a diagram. About half of the replies used particle ideas but showed misconceptions in the way these ideas were used. Examples of these answers include:-

"The block of ice cools and the particles are beginning to break away from each (other) to form gases." (p 53)

"The particles start to break away from each other because of the rise in temperature. When they have broken away from each other, they turn from a crystal form to a solution form." (p 53)

Both these replies use particle ideas and show aspects of the correct response. However, some confusion with other taught ideas is apparent. The first reply confuses melting with evaporation whilst the second introduces the idea of dissolving.

Another group of respondents applied macroscopic ideas such as particles expanding and contracting to explain the change in the ice. For example,

> "As the temperature rises, the particles take in the heat and begin to expand." (p 56)

> "When a block of ice is taken out of a freezer the sudden change of temperature reacts on the particles making them decrease in size." (p 57)

Other pupils thought that the particles themselves melted, or died. However, the question asked in this case was not expressly testing ideas about change of state, since the temperatures used in the question were both below zero, the melting point of water. So, some of the ideas expressed by students responding to the question may well have resulted from confusion about what they were actually being asked; many students interpreted the question as though the ice would melt.

2.3.5 Ideas about freezing

Children's ideas about freezing have not been investigated as such. However, Stavy (1990b) found that some children between the ages of 6 and 14 years realise that melting is a reversible process, but notes that:-

> "It is possible that pupils of these ages do not have a general conception of the reversibility of the melting process but judge each case specifically." (p 509)

Thus students may think that water can be frozen and will melt back to water, but not realise that other substances may also freeze and melt. Stavy (1990b) cites how the words "melting" and "freezing" were applied to candle wax and water. Reversibility of the ice - water phase change was accepted by almost 100% of all respondents, but the notion of the candle melting and freezing was understood by 50% of 10 year olds, rising to 100% only at age 16.

2.3.6 Changes of state - a summary

The student ideas presented above mirror those discussed in sections 2.1 and 2.2. Misconceptions about changes of state can be divided into two broad categories; those which arise by applying a primitive particle model in which particles are perceived as static, or matter as continuous; and those which arise due to confusion with weight and chemical reactions.

On the basis of the previous research, therefore, we might expect some students beginning an A level chemistry course to have some accepted particle ideas, but to apply these inconsistently. Such students may confuse mass and weight (section 2.3.2) and therefore not conserve matter on evaporation. In addition, they may not understand that changes of state of all substances are reversible.

Next, we will examine students' ideas about the differences between elements, compounds and mixtures.

2.4 Students' ideas about the differences between elements, compounds and mixtures

The differences between elements, compounds and mixtures form the basis for understanding chemical reactions. Implicit in making the distinction between elements, compounds and mixtures is the notion that matter is made of particles and that particles known as "atoms" can combine together to form groups called "molecules". Students' ideas about this have been probed by several researchers, for example Briggs and Holding (1986) and Ben-Zvi et al (1986).

Most chemistry textbooks offer definitions of the term "element". For example, Freemantle (1987) defines an element as

> "A pure substance which cannot be split up into any other pure substance" (p 123)

while Atkins (1989) adopts the statement:-

> "An element is a substance that consists of only one kind of atom." (p 8)

Thus, the notion of a chemical "element" is closely tied with the particulate theory of matter. To understand the Atkins definition, students must first know what is meant by "atom". To understand the significance of Freemantle's phrase "cannot be split up", students must appreciate that matter is composed of tiny particles which combine together. Briggs and Holding (1986) explored students' ideas about the distinction between elements, compounds and mixtures at the particulate level. Students were asked to select diagrams representing a mixture of two elements, a compound and an element alone from a set of diagrams. (These form the basis for the question *Molecules*, discussed in section 3. 6.1.) About 30% of respondents correctly selected all three. Briggs and Holding report that a number of students could not "...discriminate between particulate representations of compounds and elements" (p 43) and so thought that the picture of the compound alone represented an element (7%) or a mixture (39%). They suggest that

> "..about half of the students regarded any diagram that contained different symbols for atoms, whatever their location, as a representation of a mixture." (p 48)

Briggs and Holding supported their written data with interviews which suggest that students seem to have an understanding of the nature of an element on a macroscopic level, but not at a particulate level. For example, students suggested that an element was:-

> "...a single substance...?"
>
> ".... a form of chemical..."
>
> "An element is one, just made up of one substance...well if it was copper it would be made up of just copper..." (p 50 - 51).

These responses imply that an element has defined chemical characteristics, that all parts are the same and that an element is "pure". Other responses showed considerable confusion about the particles present in an element, for example,

> "An element is a particular kind of chemical...and all·molecules er atoms er molecules of the same substance.." (p 50)
>
> "...[an element] it is part of an atom, something that makes up an atom...um they can be joined by many of them an element is just one part of an atom." (p 50)

These findings support those of Ben-Zvi et al (1986), who probed 15 year old students' ideas about copper atoms and found that nearly half of the students attributed the bulk physical properties of the substance to single atoms of the element itself. In this view, each atom will be a microscopic version of the element. Selley (1978) suggests that chemistry teachers may inadvertently contribute to the confusion because they imply that molecules and atoms "increase in size" or "melt". Briggs and Holding (1986) state

> "...the overall reluctance of students to use particulate ideas in talking about elements, compounds and mixtures may [arise from or result in] gaps in students' thinking. If bridges are not continuously made between the macroscopic and particulate levels then students do not readily cross freely from one to another unless strong cues are present." (p 57)

Loeffler (1989) proposes a way to help students bridge this gap. He advocates avoiding the term "element" in favour of the term "substance", which could be used to describe any chemical which we would normally name as an element, compound or mixture. The term chemical "species" would be used to describe the particles present. By encouraging use of separate terms Loeffler suggests that students will learn the difference between the macroscopic and microscopic worlds and only gradually learn to integrate them. Eventually, names of substances could be made more precise, for example,

> "Na, atomic sodium .. O_2 molecular oxygen ... S, elemental sulphur" (p 929)

By this stage it is hoped that students would have learned about the properties of the substance and not associate these with the particles present. Vogelezang (1987) also subscribes to the view that the notion of "substance" should be presented to students prior to their learning about atoms and molecules because this relates more closely to students' own experiences. As we saw earlier (sections 2.2 and 2.3), students' naive view of matter is that it is continuous, so the term "substance" is nearer to the notion "stuff" than are the particle-oriented words "atom" and "molecule". While this suggestion is a worthy one, the difficulty would still remain that students need to know about atoms and molecules. Vogelezang acknowledges this, advocating the teaching method of de Vos and Verdonk (1985a, b, 1986, 1987a, b) discussed later (section 2.5). Nevertheless, the proposal provides theoretical support for the views of Stavy (1990a, b) and Novick and Nussbaum (1981) who believe that a visual picture is needed to help students overcome the dissonance between their naive view of matter and the accepted scientific view presented in science lessons.

Briggs and Holding (1986) also included questions which explore the distinctions 15 year old students make between elements, compounds and mixtures. The students were asked to identify an element from a list of four substances, each described using basic chemical terminology. Only 21% gave reasons for their choice which incorporated accepted particle ideas. Other responses included the idea that an element could be split, for example,

> "I think it is a because elements can not be split into anything except by chromatography..." (p 19)
>
> "...an element can be split into two more substances..." (p 20).

These students seem to be attempting to recall something similar to the Atkins definition, but become confused. A smaller group of respondents suggested that an element burns to give off a gas, or "...most elements need oxygen to stay living" (p 21).

In a different question, Briggs and Holding (1986) asked students to use results of "tests" carried out on a substance to discern if it was an element. This yielded an additional group of responses incorporating physical characteristics into a definition of "element", for example,

> "...no element can have a melting point above 200 ^{o}C and dissolve in water to give a colourless solution." (p 31)

This student may be aware that elements have specific melting and boiling points. Some students confused "element" with chemical characteristics or chemical reactions. These responses suggest that misconceptions about the term "element" are widespread. Gabel and Samuel (1987) note with concern that

"Even after the study of chemistry students cannot distinguish between some of the fundamental concepts on which all of chemistry is based such as solids, liquids and gases or elements, mixtures and compounds in terms of the particle model." (p 697)

Thus, it is likely that some beginning A level chemistry students with relatively little experience of chemistry may be unable to distinguish between elements, compounds and mixtures. This weakness is, as the above account indicates, most likely to be because these students do not know how to interpret this distinction in terms of a particulate model.

2.5 Students' ideas about chemical change

A chemical change occurs when atoms (or ions) in reactants are rearranged to form new substances. Often, chemical changes are accompanied by alterations in physical appearance, colour and production of a gas. Chemical changes may also produce heat, such that the test tube in which the reaction is occurring gets hot.

2.5.1 It is a chemical or physical change?

Several workers have found that students experience difficulty in recognising when a chemical change has taken place. Many students cannot discriminate consistently between a chemical change and a change of state, which chemists traditionally call a "physical change". For example, Briggs and Holding (1986) report the responses of 15-year olds to a question about a "chemical" which loses mass, expands in volume and changes colour on heating. Students were asked if they support the explanation that a chemical change has occurred. About 18% gave responses agreeing with this, the expected response, for example:-

"The substance changes in colour, mass and state, so it would appear to be obvious that a chemical change has taken place." (p 63)

About 45% reported the observations alone, while 23% offered responses including:-

"..The mass has melted and has fild (sic) the tupe (sic) but the grams have decreased. The substance has melted so the mas (sic) has gone higher." (p 63)

"The colour has changed. It has dissolved." (p 64)

These explanations use the terms "melt" and "dissolve", and therefore indicate confusion with state changes.

Schollum (1981) also reports that some students confuse state changes with chemical ones. He found that over 50% of 16 year olds replying to a multiple choice question about diluting strong cordial thought adding water constituted a chemical change. At age 14, the proportion suggesting this was 68%. In addition, Schollum found that 55% of 16 year olds and 48% of 14 year olds thought sugar dissolving was a chemical change. (Dissolving is discussed more fully later in section 2.6.2.) When asked to define the terms "physical change" and "chemical change", three students described a physical change as:-

> "When something changes its form from what it was before."
>
> "One where a reaction doesn't break up the compounds."
>
> "Change of properties...Can be easily reversed back to its original form." (p 20)

The same students defined a chemical change as:-

> "... when the molecular form is changed by doing something, e.g. adding or removing water."
>
> "One where the compounds are broken to form new compounds."
>
> "Change to a different form or state. Is not easily reversed." (p 20).

Applying these definitions, the first student would classify dissolving as a chemical change on the grounds that it involves adding water. The second student distinguishes the changes on the basis of whether compounds are broken or not, while the third focusses on changes of "form". All three thought that dissolving sugar was a chemical change.

Gensler (1970) dismisses these difficulties as being entirely artificial and the fault of chemists. He does not accept that the traditional phase changes of water should be presented as standard "physical" changes on the grounds that the water "does not change", saying,

> "Through first hand experience, everybody knows that, in fact, ice is not water; to maintain otherwise smacks of double talk." (p 154)

He continues,

> A detailed description of the processes ...is surely best given in terms of changes in intermolecular "chemical" bonding." (p 155).

Another experiment, common to lower secondary science courses, involves dissolving a solute, usually sugar or salt, and recrystallising the solid from solution. Gensler suggests this cannot truly be termed a "physical change". The solute retrieved from solution requires an act of "blind faith" from the learner to be considered to be the starting material. The returned sugar will have different intermolecular bonds to the original, and will probably be hydrated. Gensler says that

> "...in a discipline where experiment is paramount, the novice is being asked to distrust and discard his own experimental results and to place his faith in authority." (p 154).

Thus, he suggests that the confusion students experience stems from sensory information conflicting with what their teacher would have them learn. Recrystallised sugar, to a student, is not the stuff which was added; therefore, by the teacher's own definition, a chemical change must have taken place.

Strong (1970) follows Gensler's ideas, suggesting that a chemical change be defined by these four characteristics:-

> "(1) Identity of product determined by identity of initial materials
> (2) Mixing of initial materials is essential when more than one reagent is involved
> (3) Discontinuity between properties of initial materials and final product
> (4) Invariance of product properties when temperature, pressure and initial composition are varied." (p 689).

Strong may well be making a good suggestion which should be adopted. He thinks that these ideas should underpin an elementary chemistry course so that they are a learning outcome for the students. These criteria could easily be related to sensory characteristics which may help students develop an understanding of the actual changes occurring on the microscopic scale.

Having shown the difficulties students experience in deciding what constitutes a chemical change, we will consider one approach for helping them.

2.5.2 Learning the features of a chemical change

In a series of papers, de Vos and Verdonk (1985a, b, 1986,1987a, b) describe a strategy for helping students learn about chemical reactions. Their first step is to encourage students to acknowledge that a chemical change (or reaction) involves production of a new substance. The authors propose use of a cognitive conflict-type strategy (1985a), in which students are asked to grind potassium iodide and lead nitrate separately with a pestle. On mixing, the powders produce the bright yellow solid lead iodide. Students are asked, "Who put that yellow solid in the mortar?". One student's explanation reported by de Vos and Verdonk is that the white powders are like tiny eggs and that the yellow powder was present already. Andersson (1990) suggests that this arises because:-

> "It seems that most children at the age of 14 still firmly adhere to an unspoken and unconscious idea that each individual substance is conserved, whatever happens to it." (p 4)

With persistent questioning, students are forced to admit that the substance is new and "just appeared". de Vos and Verdonk note:-

> "The role of the teacher is to make it harder not easier for the student to abandon his or her former idea. The new view on substances should be a personal victory of the student and something to be proud of..." (p 239)

In their next paper, de Vos and Verdonk (1985b) suggest a way of helping students to extend this to other reactions and begin to develop a particle model for the events they observe. A petri dish containing a thin layer of water is used initially to observe the formation of lead iodide by migration of ions. Students may explain this using the idea that "molecules" of the substances "attract" one another. This is dispelled when students repeat the experiment by adding one reactant to the dish a few minutes before the other, resulting in instant formation of the precipitate. Other combinations of substances including sugar and salt and salt and lead nitrate help students to realise that precipitates do not always form, even though "molecules" of the substances collide with each other.

Thirdly, de Vos and Verdonk (1986) propose experiments which allow students to realise that heat is involved in chemical reactions. Students are invited to feel the temperature rise occurring when steel wool is placed in copper sulphate solution. The authors point out:-

> "[Students] are not looking for a general statement [to explain events] and they have no reason to generalise about chemical reactions on the basis of one particular experiment." (p 973)

This is important, because if a teacher were to give a general explanation, students may well think that all reactions produce heat. Next, students measure the temperature change occurring when sodium hydroxide solution is added in small aliquots to hydrochloric acid. Students are asked to explain where the heat has come from. Of course, the answer to this lies in the formation of new chemical bonds. Hence, the fourth step in the strategy is to introduce students to the notion that chemical reactions occur because particles in substances are rearranged. In their fourth paper (1987a), de Vos and Verdonk note:-

> "..most students attribute a particular identity to a molecule and suppose the molecule keeps this identity throughout chemical reactions... According to this view ... a molecule can go through many radical changes and yet retain its identity and belong to the original species." (p 693)

Only at this stage, then, is the students' tendency to conserve identity of substances - noted earlier on - dealt with. Chemists believe that although an atom retains its identity during a chemical reaction, a molecule does not. The authors acknowledge that getting students to change their thinking is difficult. In their final paper, de Vos and Verdonk (1987b) propose using the decomposition of malachite to introduce the idea that a "molecule" of malachite can be "broken" into two other substances. After this, using a copper cycle, they introduce the idea that a chemical element, copper, cannot be decomposed into anything else. Only then is the term "atom" introduced.

This sequence of steps is important because it describes a way of providing visual images to help students form an accepted view of chemical changes. Students are assisted at the outset to make the physical/chemical change distinction and thereafter to realise that chemical changes occur on a microscopic scale between atoms.

Having examined general aspects of students' ideas about chemical change, we will examine their ideas about specific examples.

2.5.3 Students' ideas about specific chemical changes

The three examples which follow characterise the type of reaction students aged 14 - 16 may observe in their science or chemistry lessons. The selection is not exhaustive, and will be supplemented with other reactions discussed in later sections.

Ideas about a tablet dissolving in water

Students experience a number of reactions which produce gases. For example, they may react magnesium metal and sodium carbonate with hydrochloric acid and observe the brown gas produced when nitric acid is added to copper metal. Although these reactions have not (yet) received the attention of researchers, students' ideas about the more everyday occurrence of a gas being produced when a tablet is dropped in water have been investigated. Schollum (1981a and 1982) interviewed students aged 11 - 17 about the events occurring when a vitamin C tablet is dropped in water. Typically, students said that the tablet "dissolved", and that a gas was produced. Most students of all ages thought that the gas would be air, although a few in the older age range named it as carbon dioxide. However, students could not describe how the gas was formed. Some indicated that the gas already existed, for example:-

> "When they made the tablet they put little air bubbles in"

> "...it must have been some sort of airlock in it and the air that's in it forces itself out and up to the top" (1981, p 5)

In this view, adding the tablet to the water simply released the gas which was contained inside the tablet. Others suggested that the tablet had reacted with the water:-

"The tablet is reacting with the water, splitting up the hydrogen and the oxygen. That's turning them into their gas forms and the gas comes out the top." (1981, p 5)

Students did not explain that the gas was formed by rearrangement of atoms. Their difficulty may have been affected by the fact that the compounds in the tablet which react to form the gas were not named. Even so, many students described the event as a chemical reaction. Their explanations for the evolution of the gas suggest that they did not really know what the term "chemical reaction" meant. They did not understand the fourth point of de Vos and Verdonk's strategy (reported above) that a chemical reaction involves rearrangement of atoms to produce a new substance. This supports the finding of Hesse and Anderson (1992), who note that:-

"... the term "reaction" was regularly found in students' explanations, yet these students demonstrated little understanding that reactions involve the interaction of atoms and molecules. The misconception remained for most students that scientific explanations involved little more than the ability to 'talk fancy'." (p 294)

Thus, it appears that students learn a scientific vocabulary, but not the basic ideas which lie behind the words.

Andersson (1984) asked Swedish students aged 13 - 16 about the reaction occurring when an aspirin tablet is dropped in water. He adds to the Schollum data the finding that about 25% of the sample at all ages reasoned that the gas produced had mass. This suggests that although students may not be able to explain how the gas is formed, some are at least satisfied that gases are material.

Ideas about copper reacting with oxygen

Reactions involving atmospheric oxygen are common in secondary school chemistry courses. Students may investigate the change in mass occurring when metals such as copper and magnesium are heated in air. In lighting a bunsen burner, they are starting the reaction between methane and oxygen. Both types of reaction have been studied by science education researchers. The combustion of fuels will be discussed more fully in section 2.6.

Students' thinking about the reaction between copper and oxygen has been explored by Andersson (1984, 1986) and Hesse and Anderson (1992). In the earlier study, Andersson asked students aged 13 -15 to explain how a dark coating forms on hot copper pipes. About 10% explained that "This is the way all copper pipes change" (Andersson, 1986, p 552). These students simply accept the event as fact, seeing no reason to explain something which to them "just is like that". Other students suggested that water had got through the pipes and caused the coating, a type of explanation which Andersson describes as "displacement". A further group suggested that the copper was changed in some way by the heat. Andersson describes this as a "modification"-type explanation. All these ideas are misconceptions about the actual event, which is a reaction between copper and oxygen. About 20% of 15-year olds recognised this, explaining, for example, that:-

> "Copper and oxygen have reacted"
>
> "It is oxidation. Air = oxygen reacts with copper, copper oxide is formed and that is the dark coating." (p 556)

In Hesse and Anderson's (1992) case study, one student (there is no indication of his or her age in the report) explained that copper and oxygen were reacting with "heat as the catalyst" (p 287). Thus, it appears that although some students have well-developed, accepted views of the copper/oxygen reaction, a majority at age 15 do not.

Ideas about precipitation reactions

Precipitation reactions may occur when two aqueous solutions are mixed together. Students may have come across these in tests for substances such as reducing sugars and sulphate ions. Although de Vos and Verdonk made use of precipitation reactions (see above), they have attracted the attention of few other researchers. However, Happs (1980) and Schollum (1982) interviewed students aged 10 - 17 about the formation of a precipitate made when aqueous solutions of lead nitrate and sodium chloride were mixed together. They found that students of all ages tended to describe what they saw, rather than what they thought had happened, saying:-

> "It's gone all murky" (Happs, 1980, p 10)

Others used more scientific language, such as the word "solvent", but very few described the white solid in the tube as a "precipitate". A number of students thought the precipitate was a new substance, while the younger ones described the reaction as the substances simply joining together. To some older students there had been no reaction at all:-

> "If those two (sodium chloride and lead nitrate) had reacted, it would have gone clear." (Schollum, 1982, p 12)

Clearly, there appears to be a need to study students' ideas about precipitation reactions in more detail. In particular, it would be interesting to establish whether students associate the formation of a solid with a mass increase, given the earlier indications that students may confuse mass and density.

Ideas about acids and bases

Most students will meet acids and bases in science lessons at secondary school.

Typically, they may learn the characteristics of acids and bases, and find out that "neutralisation" occurs when an acid and a base are mixed. The term "alkali" may be introduced as a "base which is soluble in water". Students are likely to measure the pH of laboratory acids and alkalis and general household liquids, so they may learn that acids and bases can be of different "strengths". Several workers including Hand and Treagust (1988), Cros et al (1986, 1988) and Ross and Munby (1991) have probed students' ideas about these aspects of acid-base chemistry.

Hand and Treagust (1988) identified five key misconceptions among sixty 16 year old students. These were :-

> "(1) An acid is something which eats material away or which can burn you;
> (2) Testing for acids can only be done by trying to eat something away;
>
> (3) Neutralisation is the breakdown of an acid or something changing from an acid;
> (4) The difference between a strong and a weak acid is that strong acids eat material away faster than a weak acid; and
> (5) A base is something which makes up an acid." (p 55)

These emphasise a continuous, or non-particulate model of acids and bases. Particle ideas, even incorrect ones, are conspicuously absent. Nakhleh (1992) found that 20% of 17 year olds who had studied chemistry drew images consistent with a non-particulate model of an acid when asked how an acid or base would "appear under a very powerful magnifying glass" (p 192). This implies that although students may measure pH and know about the corrosive qualities of acids and bases, they do not always associate this with particles present in the liquids. In contrast, Ross and Munby's (1991) interviews with 17 year old students showed that the notion of an "acid containing hydrogen ions" was reasonably well-known. However, they report the responses of only a few students and it may be that these findings relate closely to the students' situation.

Hand and Treagust attempted to change students' ideas using a series of carefully designed worksheets, finding that this strategy was not successful in changing all of these misconceptions. They state:-

> "Students will only change their misconception when the scientifically acceptable concept makes sense to them.." (p 61).

Twenty-four of the students used in the 1988 study were followed up two years later. This is reported by Hand (1989). By this stage, some of the students had been taught much more sophisticated ideas in a pure chemistry course, while others were studying a broader based science course or biology. A test based on the five original misconceptions was administered to the group. The results indicated that only students studying chemistry could answer basic recall questions correctly, while those studying biology did best overall. The author concludes that the biologists did better because "they were not having any interference from new definitions" (p 142). Carr (1984) agrees with this, stating that students' difficulties with acids and bases are:-

> "more usefully perceived in terms of confusion about the models used in teaching the concept rather than as a conflict between preconceptions and the scientific view" (p 97).

In advanced chemistry courses, acids and bases are redefined under the Brönsted-Lowry theory as "donors" and "acceptors", moving away from the Arrhenius definitions of an acid being a "substance which yields hydrogen ions" and a base producing hydroxide ions in solution. Hand suggests that presenting students with this new theory confuses them. On this point he is supported by Hawkes (1992), who states:-

> "It is inherent in human nature that we accept what we are told first and relinquish or change it with difficulty." (p 543)

Thus, students studying sixth form chemistry may continue to use ideas they learned much earlier and may see no reason to change them.

The work of Cros et al (1986, 1988) focuses on French university science students' ideas about acids and bases. First year students were asked to define an acid. Most used ideas about proton transfer, while significant numbers gave the Brönsted-Lowry definition and few used the Arrhenius statement (the sum of the percentages offering these response types is greater than 100%, suggesting error is apparent in the data supplied). These figures contrast with the data generated by Hand and Treagust, suggesting that science students ultimately reject the Arrhenius definitions. This difference may arise because the French study reports on the ideas of university science students who are academically more select than the Australian sixth formers. Higher proportions of second year students (Cros et al, 1988) gave both the Brönsted-Lowry and the Arrhenius definitions, suggesting that some students move away from the more advanced idea.

Two other findings of the Cros et al studies are worth noting. First, these workers found that the concept of bases was far less developed than that of acids. Many students gave the Arrhenius definition of bases being OH^- donors. Students could not name bases as easily as acids, giving only ammonia and sodium or potassium hydroxide as responses. Second year students showed no improvement on the first years in these respects.

Second, few students knew that heat was produced in an acid/base reaction. The authors attribute this to the fact that students only use dilute acids or bases and so do not notice any heat change. de Vos and Verdonk (1986b) use the neutralisation reaction in their teaching sequence on chemical change (see section 2.5.2) and note that students using dilute hydrochloric acid and sodium hydroxide do notice the heat produced and find it surprising. It may be that French students are not encouraged to make these observations.

2.5.4 Students' ideas about chemical change - a summary

The preceding sections suggest that students beginning A level chemistry courses are likely to have experience of quite a wide range of chemical reactions. Some, however, will be unable to discriminate between the types of changes which chemists call "physical" and "chemical". Many will not be able to describe the evolution of a gas in terms of rearrangement of pre-existing atoms. Others may think that new compounds form as a result of modification of reactants. Precipitation reactions are likely to be described in vague terminology based on appearance. Acids and bases are likely to form part of 16 year-olds' experience of chemistry, but many will only be able to describe these in "lay" terms associated with "burning away".

Having established that beginning A level students are likely to have at best poorly developed ideas about chemical change, we will now explore their likely understanding of one fundamental point: if they at least know that mass is conserved when chemical changes occur.

2.6 Students' ideas about closed system chemical events

A number of studies have used closed system events to explore students' thinking. These have revealed that students have misconceptions about the conservation of mass as well the precise nature of the events taking place. These are reviewed in this section.

2.6.1 Phosphorus

Driver et al (1984, 1985) and Andersson (1984, 1990) report the responses of 15 year old students to a question about a piece of phosphorus placed in some water in a sealed flask which is heated by the sun. Students are told that the phosphorus catches fire, producing a white smoke which dissolves in water and they are asked to say if the mass will be the same, greater, or less than the starting value once all these changes are complete. Both researchers report that about one-third of the sample gave conservation-type answers, suggesting that the mass would be unchanged because "the flask is sealed", for example:-

> "Despite a change of form or state, the same weight is present"
> (Driver, 1985, p 165)
>
> "The flask is sealed. Nothing is added or leaves"
> (Andersson, 1984 p 40 - 42).

A further 16% thought the mass would decrease, suggesting that:-

> "Smoke weighs nothing / is light / is lighter than a solid"
>
> "The phosphorus/the smoke dissolves in the water [so becoming lighter]"
>
> "The phosphorus burns up or is destroyed"
>
> "Oxygen is used up when combustion takes place"
> (Andersson, 1984 p 40 - 42).

Only 6% thought the mass would increase, for example, because:-

> "The smoke is heavier than the phosphorus"
>
> "When the smoke dissolves in the water, the weight increases"
> (Andersson, 1984 p 40 - 42).

Thus, about one-third of students aged 15 do not conserve mass in this reaction. Andersson (1984) suggests that:-

> "If a pupil is to be able to decide whether an amount of matter, or more exactly, mass, is conserved or not, he/she must be able to distinguish between what is material and what is not." (p 45)

In this situation, if students do not focus immediately on the fact that the flask is sealed, their response depends almost entirely on their thoughts about the smoke. Students who consider that smoke is "material" may offer a conservation response, or suggest that the smoke is heavier than the phosphorus. Those who associate "smoke" with the term "gas" and do not think that gases are material will give non-conservation responses. Alternatively, students may also think that matter is used up when a reaction occurs, and hence suggest the mass decreases.

2.6.2 Dissolving

Piaget and Inhelder (1974) reported that young children think that sugar "disappears" when dissolved in water, and thus do not "conserve" the mass of material. They are content with the notion that the mass of water would not change, because the substance added to it simply no longer exists. A number of workers including Driver (1985) and Cosgrove and Osborne (1981) have explored the prevalence of this and other explanations among older children. Driver in her study (reported in Driver et al, 1984) found that about two-thirds of students of all ages between 9 and 14 thought that the mass of a sugar solution would be less than the mass of the sugar and water. When a similar problem was given to 15 year olds (Andersson, 1984), over half of the sample thought that the mass of the solution would be less. Students offered a variety of explanations, including:-

> "When the sugar dissolves into the water the sugar has no mass so it is just like the 1000 g of the water."
>
> "The sugar will decompose and form a liquid with the water and so will weigh less."
> (Andersson, quoted in Driver et al, 1985, p 154 - 155)

These students do not conserve mass, suggesting that their thinking about this process may not have changed from early childhood.

About 30% of the 15 year olds in the Andersson study predicted that the mass would be unchanged. This figure rose to about 50% of the students who had studied chemistry. Responses in this category clearly showed that students knew the sugar would still be present, for example:-

> "Not one of the two substances would have gone anywhere else except in the pan ... even though the sugar cannot be seem it is still present."
> (Andersson, quoted in Driver et al, 1985, p 154).

Although this response does not use particle ideas, the student certainly conserves mass. Others achieved the same result by adopting an algorithmic approach, adding the masses of solute and solvent given in the question.

In the Cosgrove and Osborne study, about one-quarter of respondents used the word "melt" to describe what happened to sugar, for example:-

> "The sugar is dissolving ... the water is sort of melting the sugar crystals"
> (Cosgrove and Osborne, 1981, p 18)

The terms "dissolve" and "melt" seem here to be used synonymously. The tendency to give this type of response appears to decrease with age.

2.6.3 Students' ideas about closed system chemical events - a summary

Evidence presented above suggests that some beginning A level students may have misconceptions about closed system events. A student may not realise that the mass of a solution equals the mass of solute and solvent. Some 16 year olds may confuse mass and density, and use state changes to explain events which are actually chemical reactions. Others may think that substances are destroyed when chemical reactions occur. These data suggest that a significant proportion of beginning A level students will not have well-developed accepted ideas about events occurring in closed systems.

Next, we will examine their thinking about open system events.

2.7 Students' ideas about open system chemical events

Open systems involve the atmosphere and usually involve a reaction with oxygen, which chemists call "oxidation" or "combustion". Students' ideas about combustion reactions have been probed by a number of workers including Andersson (1984, 1986 and 1990), Schollum (1981a and b, 1982), Driver (1985), BouJaoude (1991), and Ross (1987 and 1993). We will begin by examining work carried out on students' ideas about reactions between metals with oxygen.

2.7.1 The origin of rust

Several workers, for example, Andersson (1984), Driver (1984) and Schollum (1981a) probed 14 -15 year olds' ideas about the origin of rust on an iron nail. All these workers report that a minority of students thought the rust formed because a chemical reaction took place. Responses suggest this was not always seen as including oxygen, for example:-

> "Rust is the form of the chemical reaction after the nail has been taken apart by the rain."
>
> "caused by water and an impurity in the nail reacting" (Schollum, p 13).

These students seem to have learned the term "reaction" and think that the production of rust is a suitable opportunity to use it. Further, even when a reaction with oxygen was acknowledged, students did not necessarily associate this with an increase in mass, for example:-

> "The iron had only reacted with the oxygen of the air which does not weigh anything." (quoted in Driver et al, 1985 p 163).

Clearly, this student does not think that gases have mass. More commonly, students thought that the mass of a rusty nail would be lighter than the original nail because the rust "eats away" the metal, for example:-

> "As the nail rusts away it will get smaller.."
>
> "Rust rusts away" (Andersson, 1984 p 34)

This type of response was given by about one-third of the students in the Driver (1984) study, and is similar to the low-level macroscopic thinking reported earlier. Here, life-like properties are ascribed to the rust. About one-third of students in the Driver study thought that the mass of the nail would be unchanged, usually because the rust was simply "part of the nail" (p 162). Schollum (1981a) also reports this type of response, for example:-

"[The rust is] there all the time under the surface of the nail" (p 13).

Andersson (1990) describes this type of response as "modification"; the rust existed before the event, but became visible when the nail was left in water. A different type of modification response is reported by Driver, who found that about one-third of the 15-year olds thought the nail would be heavier after rusting, because the rust was an extra substance. Examples of this type of response were also found by Andersson (1984):-

"Rust makes the nails heavier"

"Water is added when rust forms"

"Oxygen is added when rust forms"

"Oxygen and water are added when rust forms" (p 34 - 35).

Given that most of these studies report the ideas of 15 year olds, it is likely that some students beginning A level chemistry courses at the age of 16 may share the views presented above. Next, we will see if the range and type of responses differ when iron reacts more rapidly with oxygen.

2.7.2 Burning steel (or iron) wool

The rate of the reaction between iron and oxygen can be increased by heating the iron in the atmosphere. Where external heat is applied, chemists say the iron is being "burned" or "combusted" in oxygen. Students' ideas about this reaction are reported by Driver et al (1985), Andersson (1986) and Donnelly and Welford (1988).

In the Assessment of Performance Unit (APU) study reported by Driver (1985) students were asked to predict how the mass of iron wool would change once burnt in oxygen. About 40% of 15-year olds who had studied chemistry for two years thought that the mass of iron would increase because of a reaction with oxygen. These students have an accepted view of the event, and realise that the mass of oxygen must be taken into account. A further 6% thought that the mass would increase, but explained that this was due to soot from the flame adding to the dish. These students may have been swayed by the black appearance of the iron wool after heating.

Around 40% of 15-year old chemists in the APU study thought that the mass of the iron would decrease. This group included 19% who suggested that gas or smoke would be driven off and 10% who thought that the "burning" would leave ash, which would be lighter than the iron. These students do not recognise the role of oxygen in the reaction, and are using the term "burn" in a "lay" rather than a chemical sense. To them, the word "burning" labels the event, and does not mean "reaction with oxygen".

This view may arise because students are likely to be familiar with the ash remaining after burning coal or wood, which certainly is less bulky than the starting material.

About 5% of this sample thought that the mass of the iron would be unchanged, for example:-

> "It would stay the same because the powder is in the wool but heated up so there is really no difference." (Driver et al, 1985, p 160)

This type of response does conserve the amount of starting material, recognising that all the iron present at the beginning would still remain at the end. This student, however, does not see a role for oxygen in the reaction.

Andersson (1986) reports one additional type of response among 15 year old chemists:-

> "The steel wool that has burnt has turned into carbon. Carbon weighs more."
>
> "It forms carbon after being red-hot, which makes it heavier." (p 555)

In a previous study, I found that some 11 and 12 year olds used this reasoning in explaining how "the white stuff" from burning magnesium was formed:-

> "[It] is from burnt carbon/is the soot left after burning" (Barker, 1990, p 69).

This type of response is perhaps based on students' experiences of burning fuels, which are widely known to contain carbon. In the cases of metals burning, students who lack an accepted view of the events utilise this information in giving their response. Andersson classifies this type of answer as "Transmutation". The student is happy to suggest that one substance can change into another.

Students' ideas about iron burning in oxygen are similar to those about rusting. In answer to both questions students may think that mass is or is not conserved, or that oxygen may or may not be involved. Next, we will examine students' thinking about the reaction between fuels and oxygen.

2.7.3 Burning a candle

Students' ideas about burning candles have been widely studied, for example by Meheut et al (1985), BouJaoude (1991), Schollum (1981a, b). All these studies point to the fact that students find the phenomenon of a candle burning difficult to explain. Perhaps as many as one-quarter of students aged 14 use a state change model to describe their observations of a candle burning. Meheut et al (1985) found that about 25% of 11 and 12 year old children describe the change as melting, while BouJaoude (1991) describes 14 year old students who think a candle decreases in size because the wax evaporates. In this reasoning, the flame is ignored completely, and students focus instead on the melted wax. As the oxygen cannot be seen, students' senses tell them that only state changes occur. BouJaoude (1991) reports that students think that the candle flame is caused by the "wick burning", not the wax. This may help to explain the state change response, because students could reason that the heat from the flame (which is the wick burning) causes the candle to melt.

The change of state ideas about burning may in part be due to students' poor particulate models of matter. Schollum (1981b) reports that a significant proportion of students aged 14 upwards do not perceive either the wax or the flame to be particulate. Those who do think that the flame is composed of particles describe these as

> "burnt little bits...pretty small bacteria...oxygen from the air ...hydrogen particles from the air." (p 12).

Only two students in thirty-six perceived the flame as particles of hydrocarbon. This finding supports the continuous view of matter discussed earlier.

Ideas about the role of oxygen in burning a candle are reported by Meheut et al (1985). They report that although most children aged 11 and 12 knew that oxygen was needed for burning, they could not explain exactly how the oxygen was used. A number thought of the oxygen as being "used up" or "burnt away". In the BouJaoude study (1991), students aged 14 were interviewed about the involvement of oxygen in a candle burning. One student said:-

> "Oxygen feeds the fire and keeps the candle burning" (p 695).

Thus, the role of oxygen in burning candle wax is not well known. Instead, students may think that a state change is occurring, in which case the mass of the candle will only decrease if the wax evaporates. This type of thinking conserves the amount of original material. The view that oxygen is "used up" also appears to be prevalent, and indicates that students think oxygen is expendable and is destroyed when burning takes place. Students' thinking about the burning of two other fuels, butane and petrol will be discussed next.

2.7.4 Burning butane

BouJaoude (1991) and Schollum (1981a, b) asked students to explain what they thought was happening when a gas burner was lit. Schollum (1981b) reports that students readily agreed that "burning" was taking place. Noticeably, students did not use the change of state model, perhaps because gas cannot melt! A common response in students aged 12 - 15 featured the idea that the gas was being destroyed, for example:-

> "The gas is eating up, no the flames are eating up the gas... It eats it up and then it goes up in little pieces." (1981b, p 7)

One student in the BouJaoude study used the same sort of reasoning to explain that oxygen was "burned up".

When students were asked what was being produced, Schollum reports that many students aged up to 17 years replied "heat", for example:-

> "It turns into heat or heat waves." (1981b p 7)

Some older students described the products as carbon dioxide and hydrogen, but clearly the role of oxygen in the production of carbon dioxide and water was not well known. The combustion of a gas does not yield change of state ideas. Since students may use this reaction at home in cooking or heating, the response that the gas becomes "heat" is perhaps not unexpected. However, these responses indicate that a high proportion of 14 - 15 year olds may think that gas or oxygen is destroyed when burning occurs.

2.7.5 Burning petrol

Andersson (1984) reports the ideas 15 year olds have about burning petrol in a car engine. Students were asked to predict the mass of exhaust gas formed when 50 kg of petrol was placed in a car which was then driven until the tank was empty. Their responses can be compared with those given to the conservation of mass in closed systems, reported in section 2.6.

Andersson found that only 3% of 15 year olds thought the mass of the fuel would increase. Although some gave the expected response, that the petrol had reacted with oxygen, others thought the mass would increase because:-

> "The petrol is mixed with the air and then it gets heavier." (p 38)

This student recognised that air was involved, but did not appear to think that a chemical reaction had occurred. However, the terms "mixed" and "reacted" may, to these students, be synonymous, so this could be their way of saying that a reaction had occurred.

More than half of the students in Andersson's study thought the mass of the petrol would be unchanged. Many of these used the state change model, for example,

> "Even if it doesn't come out in liquid form it must weigh just as much."
> (p 38)

This is an indirect way of saying that the petrol simply turned into a gas, and mirrors the response the candle wax "melts" given above. These students do not perceive that oxygen is involved, but conserve the amount of petrol.

About 27% of respondents thought that the mass of exhaust gas would be less than the mass of petrol. Students give several explanations for this. One idea is that gases do not weigh as much as liquids, so regardless of what happened to the petrol, the very fact that gases are emitted means the mass must be less, for example:-

> "Gas is lighter than petrol (water), so if you only have 50 kg of petrol and it's transformed into gas, it must be lighter..". (p 37)

Students thinking this way seem to confuse mass and density. They may conserve amount of stuff, but think that the measurable mass has changed.

Another explanation for mass decreasing is that petrol has changed into energy, for example:-

> "It's less than 50 kg because part of the petrol was been changed into heat and kinetic energy." (Andersson, 1986 p 555)

Andersson describes this as an example of transmutation. Similar responses were found in explanations about butane burning. These ideas suggest that although students are well aware that burning generates heat, they do not know how the heat is produced. This notion is discussed in more detail in section 2.9.

The petrol question does not mention that oxygen is involved, leaving students to think about this for themselves. Hence, as many may not know what occurs in a car engine, the question may invite more responses like "what goes in must come out" and "gases are lighter than liquids", as this is the only basis on which responses can be made from the information provided. Nevertheless, the range of responses to the earlier fuel questions was comparable, and there is certainly evidence to suggest that even where the fuel was burned in the students' presence many still did not realise that oxygen was involved. So, although the petrol question appears to be problematic, it is still a valid way of probing students' thinking about an everyday event.

2.7.6 Students' ideas about open system chemical events- a summary

The preceding discussion indicates that many beginning A level students are not likely to be able to explain open system events in an accepted way. BouJaoude (1991) provides a useful summary of the views 14 year olds hold about burning which includes the following statements:-

> "Wax, alcohol and oxygen are not actively involved in burning.
> Substances undergo no chemical change during burning." (p 701)

In addition, Driver et al (1985) note that children have a prototypic view of burning which includes the notion that:-

> "Oxygen or air is needed [but] it may be ... 'burnt away' ..
> things get lighter when they are burnt" (p 158).

The results presented above suggest that these views are incorporated by many students into a model of burning which is far from the chemist's accepted view. Students' everyday experiences of burning provide powerful sensory images of flames, heat, ashes and destruction. Oxygen is the invisible agent which makes burning possible, while carbon dioxide (and water vapour) are the unseen products. The accepted view, which may or may not be taught to students before they begin an A level chemistry course, can only be developed when these images are placed in the appropriate context.

2.8 Students' difficulties with stoichiometry

Chemists measure quantity of substance in moles. One mole of any substance has a mass equal to its relative atomic or molecular mass in grams; and one mole of any substance will contain the same number of particles, roughly 6×10^{23} (Avogadro's number). Substances react in fixed mole ratios by mass; chemists can calculate the expected mass of products for a given reaction by reasoning from the reacting masses. Moles provide the vital link between what is represented in a chemical equation and what masses should be measured out to make that reaction occur in practice. Students are taught about moles at the age of approximately 16, although many will have been taught about chemical equations before this. That students experience difficulty with "the mole concept" is well-known (Lazonby et al 1982). Given the preceding sections which highlight the poor level of development of particle ideas and inconsistency in applying conservation ideas prevalent among teenage chemists, this is perhaps unsurprising. In this section, we look briefly at students' difficulties with these stoichiometric aspects of chemistry.

2.8.1 The cause of the difficulties

Dierks (1981) notes that the mole has only been adopted as a unit in chemistry in relatively recent years. He says that discussion of "the mole problem" began in 1953 (p 146) and that thereafter chemists spent a number of years agreeing on a definition. In this time, the word "mole" acquired three meanings: an individual unit of mass; a portion of substance; and a number (p 150). However, there was no doubt that the mole proved useful as a way of quantifying substances and so was introduced into the school chemistry curriculum. Dierks suggests that difficulties arise when moles are introduced to students who are not being prepared to become professional chemists. He reports that early work on students' difficulties centred on the connection which must be made between chemical formulae and equations and mathematical expressions representing amounts of substance. He states:-

> "It is generally argued .. that pupils need a clear conception of what is meant by amount of substance if they are to work successfully with this concept. This concept can apparently only be developed when amount of substance is interpreted as a numerical quantity." (p 152)

Taking the Ausubelian line that "meaningful learning occurs when new information is linked with existing concepts" (p 153), Dierks advocates beginning to teach the mole as a "number". Hence, the source of students' difficulties may be their lack of mathematical expertise. A student who cannot manipulate numbers readily is unlikely to be successful in learning about moles.

Shayer (1970, cited in Rowell and Dawson, 1980) explains students' difficulties in terms of their lack of the cognitive skills "necessary to deal with the concept" (p 693). Specifically, Shayer thinks that students who have not reached Piaget's formal operational stage of thinking cannot learn about moles, because such students lack the requisite cognitive skills, in particular proportional and ratio reasoning. This appears to be in broad agreement with Dierks' suggestion, since formal operational thinking involves:-

> "the ability to ... see the need to control variables in making inferences from data and to impose quantitative models on observations, specifically that of proportionality." (Driver, 1983 p 61)

Rowell and Dawson take issue with this proposal, suggesting that all students require is an appropriate step-wise scheme which leads them towards using moles in an accepted way.

2.8.2 Learning about moles

Rowell and Dawson (1980) begin teaching moles to 16 year old students by using a model of a simple chemical reaction such as $2Na + S \rightarrow Na_2S$ represented in small coins. Next, the idea of proportionality is introduced by showing a reaction in which 2A's make 1C. Students are asked what would be produced if only 1A was available. Once the idea that reactions occur in proportion was developed, Rowell and Dawson introduce the idea that the number of particles involved might be very large. At this point, they return to their original reaction and ask students to imagine that these are atoms of chemical elements. The conservation of number of atoms and masses are emphasised at each point. The authors carried out a six-week teaching strategy using this stepwise approach and tested students before, immediately afterwards and two months later. They found that twenty-one out of the twenty-four students gave error-free responses in the final test. This refutes the Shayer suggestion, since the students were not pre-selected for their ability to think in a formal operational way. The authors conclude:-

> "Teaching the mole concept is not an easy task but it need not be the mountain that some have made it." (p 707)

Kean et al (1988) suggest an alternative approach to this, advocating the use of algorithms. They note that a useful algorithm "allows students to solve problems with meaning rather than by rote" (p 987). Their paper suggests an eight-step strategy for helping students devise an algorithm for converting mass into volume measurements and vice versa. In a similar way, students can be taught an algorithmic sequence for solving proportionality problems and, eventually, calculation of reacting masses. Such a strategy may well help to develop students' confidence in handling numerical data, but requires careful instruction to ensure students can apply the method appropriately. Finley et al (1992) sound a warning note:-

> "Recent research has indicated that the ability to solve numerical problems does not guarantee conceptual understanding of the molecular basis of the problem." (p 254)

Although Kean et al's proposals may provide a means to an end, the students may well just learn the algorithm and not its meaning in chemical terms. The Rowell and Dawson approach, however, has much to recommend it, being rooted firmly in the chemical principles of stoichiometry.

2.8.3 Students' difficulties with stoichiometry - a summary

This section has differed from earlier ones in this chapter in that it has discussed the source of students' misconceptions rather than the misconceptions themselves. Nevertheless, it can be said that although beginning A level students may have met stoichiometry, many will not have practical strategies at their disposal which enable them to calculate reacting masses. The extent to which A level courses develop this understanding is something which can usefully be investigated.

2.9 Students' ideas about chemical bonding

Chemists have made extensive studies on the ways in which particles combine to make the seemingly infinite range of substances at our disposal. Broadly speaking, atoms combine either by sharing electrons, forming "covalent" bonds, or electrons are transferred between them forming oppositely charged ions which attract one another, thus forming an ionic bond. Of course, most compounds have bonds which fall between these two extremes, although this is not known to the beginning A level student. Molecules are also affected by intermolecular bonds, which, if these are extensive, influence the boiling and melting points of the substance. Students are introduced to these, specifically to hydrogen bonds and van der Waals' forces, during an A level course. Relatively little work has been carried out on students' ideas about chemical bonding prior to the age of 16, so in this section we will also review how students' thinking may be expected to develop.

2.9.1 Covalent bonds

Progression in understanding

Taber (1993a and b) reports an extensive case study carried out with one student during her A level chemistry course. The student, "Annie", was interviewed on three occasions about her understanding of chemical bonding. In the first interview, she recognised that a covalent bond exists in diatomic molecules in which the two atoms are identical. However, she did not explain covalent bond formation in terms of sharing electrons. Instead, Annie said that the atoms "pull together". The criteria on which she decided if a bond was covalent was to look at the chemical elements involved and to establish if both were non-metals. If this was so, then a covalent bond would form between them. After several months on an A level chemistry course, Annie was able to describe covalent bonds in terms of electrons being shared and realised that one result of electron sharing was that atoms acquire "full shells" of electrons. Towards the end of her course Annie was interviewed for the third time. At this point, she could describe the electrostatic attractions between atomic nuclei and the electrons, which indicates she had moved towards an accepted view of a covalent bond. Annie's progress is reflected in the increasing sophistication of her ideas.

Associated difficulties

In learning about covalent bonds students find out about the shapes of molecules and learn that almost all covalent bonds are polarised. In addition, students are expected to learn about "rules" of combination, for example, the "Octet rule" which predicts, in a limited way, the maximum number of electrons permitted in any orbital. Thus, besides learning the basic chemical idea about electrons being shared, students are also expected to assimilate many other associated concepts. In their work with Australian 17 year olds, Peterson and Treagust (1989) found that students' ideas developed during an advanced chemistry course, but their progress was often accompanied by misconceptions about these associated areas. For example, they found that 23% of 17 year olds thought that electrons were equally shared in all covalent bonds, while about one-quarter attributed the shape of molecules to repulsion between the bonding pairs of electrons, or to bond polarity. In addition, only about 60% of students knew the correct position of the electron pair in a bond between hydrogen and fluorine. The same question asked of first year university students studying chemistry (Peterson, 1993) yielded a 55% correct response, implying that most students who learn about bond polarity retain their knowledge.

2.9.2 Ionic bonds

Progression in understanding

Taber (1993a) reports that Annie began her A level course by recognising a class of bonds which she called "ionic" and which were found between metals and non-metals. She could not, however, recognise the bond type present in a diagrammatic representation of a sodium chloride crystal, describing this as "just sodium and chlorine atoms" which are arranged "in rows" (p 18). Taber summarises her view of sodium chloride as follows:-

> "...the structure is held together, but without any bonding; there are charges on the neutral atoms; atoms are combining without overlapping; and the atoms are exchanging not just electrons but force pulls related to the electronic configuration." (p 19)

After studying chemical bonding, Annie was interviewed again. At this point, she could identify the ions in sodium chloride, but tended to use the term "molecule" to describe ionic substances, as though the elements combined to form discrete particles like, for example, the methane molecule. She knew, too, that when ions combine, the overall effect is to produce something which is neutral. In her final interview, Annie described electron transfer as being involved in ionic bonding. However, she remained confused about whether any sort of bonding existed in sodium chloride, explaining:-

> "... it's almost like they're mixed but they haven't combined. I think they're held together just by the attraction of their forces in effect." (p 23)

She knew that positive and negative charges implied attraction, but was not able to describe accurately the role of these in the sodium chloride structure. In my view, this represents a disappointing lack of progress. Since the study relates only to one student, it is impossible to generalise this to a population of A level students. Nevertheless, this work is useful, insofar as it is, to my knowledge, the only work to date which reports a student's ideas about bonding in detail.

Other difficulties

Butts and Smith (1987) report the results of 28 interviews with 17 year old Australian students who had studied chemical bonding. These students were asked to draw and explain the structure of sodium chloride. While most associated the compound with ionic bonding, many did not appreciate that ionic bonds are three-dimensional.

Butts and Smith also report that some students consider sodium chloride to be molecular, suggesting that covalent bonds were present between sodium and chlorine, but that ionic bonds between molecules produced the full structure. Taber (1993c, 1994) supports this, noting that:-

> "... students embarking on an A level chemistry course do not exclude ionic material from their use of the construct 'molecule'." (p 8)

Taber suggests that students acquire this idea because they do not "share the framework of electrostatics knowledge" of the teacher, and also because they are taught about the formation of ionic bonds in a way which promotes the molecular model.

Students in the Australian study were asked to describe what would happen when sodium chloride was dissolved in water. All students responded that the particles would be dispersed, although some thought that sodium and chloride ions would still attract one another so there would be a "residual" structure in the water. Two students suggested that the salt would react with the water, forming sodium, chloride, hydrogen and hydroxide ions.

2.9.3 Intermolecular bonds

Progression in understanding

In her first interview, reported in Taber 1993a, Annie was presented with a diagram representing a chain of hydrogen fluoride molecules. The molecules were shown with the appropriate distorted electron cloud, and were drawn touching one another. Annie did not think any bonding was present between the molecules. Taber suggests this may have been because the shapes did not overlap one another. In her second, post-teaching interview, Annie could describe the difference between the O-H bond within a water molecule and the bond between two water molecules:-

> "You've got the two hydrogens added to an oxygen. And then the hydrogen brings a small bonding between like another oxygen, to hold the structure together but it's not like, it is a bond, but it's not as strong, as like, the ionic bond would be" (p 42).

In her third interview, Annie talked about hydrogen bonds involving lone pairs of electrons and demonstrated much clearer understanding of the intermolecular role of hydrogen bonding.

At her first interview, Annie was also asked about the structure of iodine. She explained that the iodine molecules were held together by "forces of pressure", not chemical bonds. After teaching, she was aware of the existence of van der Waals' forces, and correctly placed these between iodine molecules. However, she thought that they would also be present in a variety of other compounds, like sodium chloride, as though she was applying them to any structure which she could not otherwise explain. Annie knew at this second stage that van der Waals' forces would be affected by heat, but could not explain this in an accepted way. In her final interview, Annie retained the idea that van der Waals' forces existed in sodium chloride, and realised that these bonds would break before covalent bonds when a substance was heated.

Associated difficulties

In learning about intermolecular bonds some students develop misconceptions. One common error reported by Peterson and Treagust (1987) is misunderstanding of the different locations of inter- and intramolecular bonds. About 23% of students thought that intermolecular bonds were within a covalent molecule. In his later study, Peterson (1993) found that 36% of first year university chemists thought that silicon carbide had a high melting point because of "strong intermolecular forces".

Students also misunderstand the relative strengths of inter- and intramolecular bonds. Peterson and Treagust report that one-third of their sample of Australian sixth formers thought that "strong intermolecular forces exist in a continuous covalent network" (p 460).

2.9.4 Students' ideas about chemical bonds - a summary

It is difficult to know if the low level of understanding shown by Annie at the start of her course is typical of beginning A level students. However, students are likely to know about two types of chemical bond - ionic and covalent - and they may also recall that these tend to form between non-metal and metal and two non-metals respectively. Apart from these ideas, many beginning A level students will have almost no knowledge about chemical bonding. Their development of understanding in this area will be investigated.

2.10 Students' ideas about thermodynamics

The basic chemical idea associated with thermodynamics is that energy is released when bonds form and is required to make bonds break. A level students also learn the First Law of Thermodynamics, which states that "The energy of an isolated system is constant" (Atkins, 1986, p 40) and are taught to apply this in calculations of enthalpy changes. Students' ideas about these aspects of chemistry have received relatively little attention from researchers. However, their thinking about the Second Law of thermodynamics has been relatively well-studied. We will begin by reviewing work on the basic chemical idea, that of energy associated with chemical bonds.

2.10.1 Energy is released when chemical bonds form

Ross (1993) notes that many students think energy is released when chemical bonds break. He suggests that this arises because of the strong association students develop between fuels and energy; they learn the phrase "fuels contain energy" almost by rote. This is a misconception which Ross believes is a barrier to learning the accepted chemists' view. Students may begin to associate the notion that a fuel is an "energy store" with chemical bonds when they find out that each methane molecule, for example, involves the formation of four covalent bonds between carbon and hydrogen. Students' ideas about burning were discussed earlier (sections 2.7.2 - 2.7.5). These reveal that many 15 year olds do not know where the heat produced in burning comes from. Chemical bonding provides them with an answer. Ross (1993) suggests that to assist students, teachers should present the reactions between fuels and oxygen as a "fuel - oxygen system" and help them to develop ideas about the relative strengths of covalent bonds in different molecules.

2.10.2 Energy is conserved in chemical reactions

Brook and Driver (1984) investigated 15 year-olds' ideas about the conservation of energy. They found that less than one student in twenty provided written answers which explicitly used ideas about conservation of energy. When asked more directly about this principle, two-thirds of the students gave the response, "energy is used up or lost". The authors concluded that

> "...including an explicit statement of the principle of conservation of energy in the question stem does not have much effect on the pattern of responses." (Brook and Driver, 1984, p 12).

Similar difficulties were found by Finegold and Trumper (1989) in their study of

14 - 17 year olds. They report that 80% of their sample of 14 and 15 year olds did not conserve energy in their responses to basic questions. The notion of energy being "used up" was a commonly-expressed idea. Ross (1993) notes that students acquire this idea from everyday experience of batteries going flat, petrol tanks needing refilling and electricity being "used up" in providing heat and light.

Finegold and Trumper found that some students described energy as being "caused" by something, for example, in this interview extract:-

> "Student: I think something is supplying, that causes energy...
> Teacher: I don't understand.
> Student: For all energies there is something that activates them, that gives the strength" (p 106).

This student seems to be suggesting that energy is made rather than just being stored or changed. The exact proportion of students holding this view at any of the ages tested is not given, but the type of response is described as being used "frequently" (p 103).

These findings support those of the studies described earlier (Stavy 1990a, b) and indicate the difficulties students have with conservation. It would be interesting to ascertain whether A level students experience similar difficulties and, if so, whether these relate to problems in learning how to apply the First Law to chemical reactions.

2.10.3 Entropy increases to a maximum in chemical reactions

The Second Law of thermodynamics can be stated in a number of ways, but the essential principle is that disorder, or entropy, increases when a chemical reaction occurs. Another way in which this can be stated is that "heat will not flow spontaneously from a colder to a warmer body" (Freemantle, 1987, p 177). Duit and Kesidou (1988) studied 13 - 16 year olds' understanding of this statement of the Second Law. They report interviews with fourteen German students aged 16 years. A significant finding was that:-

> "Most students have intuitively the correct idea that temperature differences tend to equalise and that the processes will not totally run back after equalisation." (p 193).

The principle embodied in the Second Law does not seem to run against students' everyday experiences, hence there is less problem with this idea. The First Law is more problematic because the energy transfers included in a system are frequently invisible; for example, a toy car when wound up will only run for a limited period of time and to a child it seems that the energy has simply "run out" or has been "used up". That the energy has done work in making the car move against the environment is not obvious. In contrast, students are more likely to think that heat can only go in one direction, since again this fits with their every day experience.

2.10.4 Students' ideas about thermodynamics - a summary

It is unlikely that many beginning A level students will have developed accepted views about any aspect of thermodynamics. A typical student is likely to suggest that energy is "stored" in a fuel and may not think of energy being transferred and conserved, rather as something which is used up and destroyed. A level chemistry courses feature the First Law and the idea about energy being released in bond formation, so students' progress in understanding these areas are worth investigating further.

2.11 Students' ideas about chemical equilibria

Chemists are concerned with finding out how far a reaction will proceed to completion. This is important, since a reaction which produces an industrially useful product will only be useful if a profitable yield can be generated. The extent to which reactions "go to completion" is measured by their equilibrium constants. A very large value implies a large ratio of products to reactants, while a relatively small one suggests the reaction does not go to completion but achieves a situation in which equilibrium lies towards the reactants. The quantitative aspects of equilibria are traditionally taught at A level, while pre-16 year olds may be introduced to a "two-way" reaction in the context of industrial chemistry for qualitative treatment only. A number of workers have explored the development of equilibrium ideas in chemistry students and their studies are reviewed here.

The rate at which an equilibrium position is achieved is also an important concern for chemists. Students meet the factors which control the rate of reaction, heat, surface area and the presence of a catalyst, in pre-16 courses, and therefore may be familiar with these at the start of their A level course. These may have an impact on students' ideas about chemical equilibria, although their understanding of kinetics has not been the subject of extensive investigation to date.

2.11.1 Students' difficulties

An understanding of dynamic equilibrium is the basis for further work on chemical equilibria. To understand dynamic equilibrium, students must apply particle ideas and comprehend the nature of a chemical reaction. Le Chatelier's Principle embodies the notion of a dynamic equilibrium:-

> "When a system in equilibrium is subjected to a change, the system will alter in such a way as to lessen the effect of that change." (Freemantle, 1987, p 254).

Students are usually taught about this in their sixth form courses. Their progress in understanding the principle has been investigated.

Students' understanding of this, post-teaching, was probed by Hackling and Garnett (1985), who interviewed thirty 17 year-olds using a series of "probing questions" about a novel chemical reaction. The novelty of the reaction meant that students could not use taught ideas about commonplace reactions in their answers. They found three major misconceptions:-

> "1. The rate of the forward reaction increases with time from the mixing of the reactants until equilibrium is established;
> 2. A simple arithmetic relationship exists between the concentrations of reactants and products at equilibrium; and
> 3. When a system is at equilibrium and a change is made in the conditions, the rate of the favoured reaction increases but the rate of the other reaction decreases." (p 205)

Approximately one-quarter of the students held misconception number 1. Reaction rate is fastest in the initial stages of a reaction. The misconception was revealed by discussion and by inviting the students to draw a graph to represent changes for the reaction in question. Hackling and Garnett suggest that the misconception arises because students' earlier experiences of chemical reactions fit this pattern. For example, when magnesium ribbon dissolves in hydrochloric acid, the reaction appears to speed up since the metal is coated with an oxide layer which must first be dissolved before the metal and acid can react. Students will not perceive the oxide layer, but will notice that the reaction becomes more vigorous with time.

About half of the students held misconception number 2. Most commonly, students thought that at equilibrium the concentrations of reactants and products would be equal. The authors suggest that:-

> "This misconception can probably be attributed to the considerable emphasis placed on reaction stoichiometry in introductory chemistry topics." (p 211)

Students will be aware that chemical equations must be "balanced" and transfer this idea when they consider an equilibrium position.

Over half of the students held misconception number 3. They thought that a rise in temperature would only increase the rate of the forward reaction and that the reverse reaction would be unaffected. Banerjee (1991) found similar reasoning in 35% of university chemistry students and 49% of chemistry teachers. Some students, 27%, extended this to the role of catalysts, suggesting that the rates of the forward and reverse reactions would be affected differently, finding which is corroborated by Gussarsky and Gorodetsky (1988).

2.11.2 The origins of students' difficulties

Hackling and Garnett's (1985) work revealed common misconceptions about chemical equilibrium. However, two of the three misconceptions discussed above are associated with rates of reaction and may arise from the "rate approach" used in teaching equilibrium. Banerjee (1991) states:-

> "It is to be emphasised that equilibrium law depends on thermodynamics and not on kinetics." (p 490)

She advocates replacement of Le Chatelier's Principle with the laws of van't Hoff, which are based on thermodynamics. So, students' difficulties post-teaching may arise because of the way in which chemical equilibria is presented to them.

Maskill and Cachapuz (1989) used a word association test (WAT) to elucidate misconceptions about equilibria held by 14 and 15 year old students prior to teaching. In one WAT students were asked to write down the words which came to mind in the first thirty seconds after seeing the sentence "The reactions were at equilibrium". The authors suggest that the results reveal "interfering concepts" which may block students' learning. These include the phrases "static balance" and "equilibrium when everything is equal" (p 57) and note that a majority of students could not link collision theory, chemical reactions and reversibility. Also students did not understand the term "reversibility" in the sense of chemical reactions, although at interview, individual students did show some understanding of the term "dynamic" in a molecular sense. Overall, the authors describe their results as indicating

> "...a predominance of everyday meanings in all tests" (p64).

Students' difficulties with chemical equilibria arise from their more every day experiences of chemistry. They see reactions which, to them, go to completion and are not encouraged to think that the reverse reaction may be taking place. This is perhaps unsurprising, since up to the age of 16 the preceding sections have indicated that students have poorly developed ideas about chemical change, and about conservation of both energy and mass, and may even use a continuous model of matter to explain some phenomena.

In addition to these problems, Wheeler and Kass (1978) note that:-

> "treatments of chemical equilibrium ... tend to call for considerable abstraction and propositional thinking by the student." (p 223)

Thus, they advocate analysing students' cognitive levels according to Piagetian theory prior to teaching chemical equilibria. Such a proposal was also made by Shayer (cited in Rowell and Dawson, 1980) concerning stoichiometric calculations. These authors are proposing that students' difficulties arise because they lack the necessary cognitive skills.

So, students' difficulties with chemical equilibria have been attributed to three sources: they are taught in an inappropriate way; their previous experience of chemistry does not help them; and they may lack the requisite cognitive skills.

2.11.3 Equilibria - a way forward

Despite the findings above, however, van Driel et al (1989) argue that with careful selection of experiments students can be encouraged to develop the idea that a reaction can be reversible. They distinguish between two types of learning:-

> "... one of these can occur when students are confronted with new situations, which are in accordance with their existing concepts. This process can be characterised as 'learning more about the same'. The other process may take place when students are confronted with a situation in which they cannot adequately use their present concepts. In such a 'conflict situation', a student may revise his or her concepts quite radically." (p 2)

van Driel et al seek to develop students' ideas about chemical equilibria by placing students in conflict situations. They note the need to revise chemical reactions and help students develop the idea that a chemical event can be incomplete and propose that this can be done without recourse to particle theory. If this approach and attitude is adopted, the number of students holding misconceptions like those described by Hackling and Garnett may be reduced.

2.11.4 Students' ideas about chemical equilibria - a summary

Many beginning A level students are unlikely to understand that chemical reactions are in a state of dynamic equilibrium. During their course they will be expected to not only develop and understanding of this basic chemical idea, but to calculate equilibrium constants and begin to appreciate the connections between equilibria, rates of reaction and thermodynamics. The success of A level courses in developing these ideas will be investigated.

2.12 Conclusions

The introduction to this chapter noted that the review would have two purposes: to ascertain the level of understanding a beginning A level student may have about basic chemical ideas and to inform the research strategy. These purposes are now discussed in conclusion.

2.12.1 What might beginning A level students understand?

This review of earlier research suggests that understanding beginning A level students have of the aspects of chemistry discussed above is unlikely to be well-developed. Their difficulties may be affected by their having a naive view of matter which provides them with a powerful and effective strategy for explaining the behaviour of substances. One aim of chemistry teaching is to move students towards a chemist's view of matter. This chapter has shown that the tenacity of the naive view of matter contributes towards students' developing misconceptions as they attempt to reconcile their own and their teacher's views about matter. Beginning A level students will almost certainly have studied science or chemistry in earlier years. They may have developed a model of matter which includes aspects of the chemist's view, but are more likely to be dependent on their own naive understanding if they are asked to explain what they observe in chemistry lessons. Extensive evidence for this has been presented above.

Some beginning A level students may use a non-particulate model of matter in some situations. This contributes to their being unable to appreciate that chemical reactions involve rearrangement of atoms or ions. Students' dependence on appearances leads them to explain events in terms of what they see. So, a student may not think of exhaust gases as heavier than petrol, or know that burning refers to a chemical reaction not a state change. Some students may confuse mass and weight, leading to non-conservation ideas about reactions involving gases. Although their knowledge of chemistry may extend to knowing about ionic and covalent bonds, many beginning students are unlikely to be aware of intermolecular forces. Most students beginning A level chemistry will not be able to calculate reacting masses and many will think of fuels simply as "energy stores".

Besides these misconceptions about chemical events, students may "misuse" chemical vocabulary learned in earlier courses. Technical sounding words such as "reaction" may be invoked where the student is unable to explain a chemical event. In addition, students may use words which have a specific chemical meaning such as "burning" in one or more "lay" senses, explaining, for example, that a fuel "burns" (but oxygen is not involved) and an acid "burns your skin".

Of course, many of the studies above, especially those examining particle ideas and conservation of mass, do not always distinguish between students who have studied chemistry and those who have not. Almost all students beginning A level chemistry courses will have achieved a minimum standard in their General Certificate of School Education (GCSE) science or chemistry course. So, the students used in the study may be expected to have some facility with basic chemical ideas and may show better understanding than the overall summary given above implies.

2.12.2 Which areas of chemistry could be included in the study?

The review has covered much of the earlier work done on students' understanding of chemical ideas. By common consent, conservation of mass in reactions, combustion, stoichiometry and mole calculations, chemical bonding, thermodynamics and equilibria comprise the "backbone" of chemistry, since these areas have received the most attention from researchers. In addition, research has focussed on students' ideas about changes of state and specific chemical reactions, such as those between acids and bases. This earlier work is taken into account when the aspects of chemistry to be included in the study are discussed (section 3.2).

2.12.3 Which research strategy should be adopted?

This chapter reports the findings of a number of studies which used a range of approaches for collecting data, including clinical interviews, interviews-about-instances, cross-age questionnaires, WATs and diagnostic tests. The sample sizes used by researchers has varied from one student (for example, Taber, 1993) to several hundred (for example, Briggs and Holding, 1986). The age range of the students involved also varied between children aged 6 to 8 years (Russell and Watt, 1990) up to students aged 17 (for example, Osborne and Cosgrove, 1983).

A full discussion of the relative merits of different research strategies will follow in the next chapter (section 3.1). However, as this study intends to explore the understanding of basic chemical ideas in a population of students aged 16 - 18, WATs and in depth clinical interviews with a small number of students are unlikely to yield sufficient data. These methods are therefore eliminated at this stage.

2.12.4 Concluding comments

In conclusion, this review indicates that students beginning A level chemistry courses are likely to have misconceptions about one or more basic chemical ideas. It is also apparent that the ideas of students aged 16 and over have received relatively little attention from science educators to date. In addition, few studies have monitored the progress of a group of students; most are cross-age studies taking a "snapshot" view of students' thinking. Therefore, the research study which is the subject of this thesis will provide useful information about the development of 16 - 18 year old students' understanding, as well as contributing a longitudinal study to the wealth of information already collected.

Chapter 3

Methodology:
Organisation and planning of the research study

This chapter describes the organisation and planning of the research study. The primary source of data is a set of scripts obtained from students who responded to a test paper comprising twenty-two diagnostic questions about various chemical ideas. The written data was supplemented by interviews carried out with selected students. This chapter explains the rationale behind this approach and discusses how the survey instrument was devised, including the content of the questions and the results of a pilot study. The chapter concludes by explaining how the student interviews were carried out, and provides information about the student sample used in the study. I begin by providing Table 3.1, which outlines the key events of research study.

Year	Month	Event
1991	Oct - Dec	Literature review carried out
1992	Jan - April	Development of questions for inclusion in the pilot study
	Mar - May	Pilot study carried out, including data analysis
	April	Schools invited to participate in the main study
	June	Prototype test paper administered as final stage of the pilot study
	July - August	Analysis of pilot study data and preparation of the test paper
	September	**First administration of the test paper**
	October	First test papers returned for analysis
	December	Post-first test interviews carried out
1993	Jan - March	Development of coding schemes
		Preparation for the second administration of the test paper
	April	**Second administration of the test paper**
	May - Sept	Second tests returned for analysis
		Continuation of data analysis and development of coding schemes
	November	Post-second test interviews carried out
	December	Preparation for third administration of the test paper
1994	**January**	**Third administration of the test paper**
	February	Third tests returned for analysis
	Mar - May	Final coding schemes devised
		Scripts coded according to the final coding schemes
	June - Sept	Data analysis and write-up of several chapters completed

Table 3.1: Timeline for the research study showing dates of key events

Next, I explain the rationale for adopting a large-scale survey approach.

3.1 Adoption of a large-scale survey technique

The factors which influenced selection of this method are discussed, including reasons for not choosing other techniques. Weaknesses of the large-scale survey are also considered.

3.1.1 Factors favouring a large-scale survey

This section identifies the factors which influenced the choice of a large scale survey as the main data collection method for the study.

In preparing the original proposal for the research study, I had in mind surveys carried out by for example, the APU (1985), Brook, Briggs and Driver (1984) and Briggs and Holding (1986) on students' understanding of science concepts. These invited written responses to diagnostic questions organised in a "test", distributed to schools for administration by teachers. The surveys provide a fascinating overview of students' thinking, as large numbers of students were involved and therefore a wide range of responses was obtained. My hope was that a similar approach in the more specific area of A level chemistry would help to build a picture of the ideas A level chemistry students have about key chemical ideas. Thus, the decision to use as the principal research method, a large-scale survey, inviting responses to a set of diagnostic questions, was in line with well-established practice in science education research.

Two other factors played a part in confirming that a survey approach of this nature would be appropriate. First, a potential pool of approximately 500 students would be available from September 1992. Following a short presentation about the proposed research given at a meeting of SAC teachers in April, 1992, I obtained the co-operation of staff from thirty-six schools and colleges across the country, who provided estimates of their A level intake. This large data source would best be utilised through a survey, which could be easily administered by staff and returned directly to me.

Second, once the first survey data had been collected, I could not predict what changes in students' responses would occur, if any. Opportunities for observing gross changes in understanding would be enhanced with a large group of students, while an alternative approach involving a relatively small number of students may show little or no change in response types over the study.

Third, students involved in the study took both SAC and Traditional courses. Use of a large number of students meant that the performance of SAC students could be measured against a baseline provided by a sample of Traditional students, as the sample would be large enough to make differences statistically significant.

Fourth, I anticipated that, for a variety of reasons, the number of students involved in the survey would reduce as the courses proceeded. Beginning with a large pool of students meant that a decrease in numbers would not be significant loss to the work.

3.1.2 Factors favouring a longitudinal study

In contrast to the earlier work listed above, which took "snapshots" of the performance of students at one instant in their science careers, my intention was to follow changes in students' ideas as they progressed through their A level courses. This has the advantage of using the same group of students, so changes in students' reasoning can be monitored. As I wanted to explore the effects of SAC on the development of basic chemical ideas, a longitudinal approach was certainly the most appropriate, as changes in answers of individual students to questions could be observed and related to material studied in between. Interviews could be used to ascertain reasons for changed ideas, and I could also ask students to comment on the effects of SAC materials.

This approach required a two-year commitment on the part of teachers and students, as the students' ideas would be probed at the beginning, in the middle and towards the end of their courses. A survey instrument such as that described above would be best suited to this, as it could be easily administered on several occasions with minimal interference. Further, A level groups are generally allotted between four and five hours of time per week, so to request that three hours (the time required to take a one-hour test three times) be allotted to the research study over two years seemed reasonable.

Before discussing the limitations of the longitudinal survey approach, it is worth considering why alternative approaches were not used.

3.1.3 Possible alternative approaches

The case study

The "case-study" method involves detailed observation of students in lessons, perhaps supplemented with in-depth interviews. For the purposes I had in mind, that of yielding a wide range of information about students' understanding, this would not be suitable for several reasons. First, the structure of SAC would make a case study approach difficult, because each chemical concept area is revisited at several points in the course. Observation visits would need to be timed to coincide with teaching on these specific occasions. Second, planning the range of ideas to be investigated would be restricted by the possibility that students in more than one school could be studying the same material at the same time. To avoid possible clashes, students in different schools would need to be observed learning about different chemical ideas. This leads to the third objection; local conditions may influence how a particular concept area was taught, so findings could not be said to be typical of A level students as a group. In turn, there is therefore a danger that although the case study would investigate the progress of individual students, this would be in the context of the way in which SAC was implemented in that particular school or college. Conclusions from this type of study could not be applied to a larger population because any movement in students' thinking could be attributed to "local" conditions, such as the availability of apparatus, the quality of teaching, and the balance between work carried out in lessons or as self-supported study. The case study therefore contrasts with my original intention which was to produce a more general overview of changes in understanding of a large student population. Use of a large sample and a written test means that the affects of differences in teaching methods or use of SAC materials across various institutions are minimised, because no single student or group of students contribute a large percentage of the data.

The interview-about-instances approach

A second possible alternative is the interview-about-instances method used by Gilbert and Osborne (1980), Gilbert, Watts and Osborne (1985), Osborne and Freyberg (1985), and described by White and Gunstone (1992) as:

> "...a deep probe of the student's understanding of a single concept, that checks whether the student can not only recognise whether the concept is present in specific instances but also whether the student can explain his or her decision. The explanation reveals the quality of the student's understanding." (p 65 - 66)

This technique reveals students' misconceptions, because he or she is asked to explain in a one-to-one interview what they think is happening in the "instance", usually a line diagram. Development of students' thinking could be shown by interviewing the same person about the same instance before and after teaching. The method could be used to follow changes in students' ideas as they progress through SAC by interviewing a small group at various stages.

There are two main problems with this technique for the research proposed. First, this method could, practically, only involve a small number of students, and therefore the same arguments applied to the case study approach also apply here. Any changes in students' thinking could be attributable to the circumstances surrounding the individual student, not the course they studied. Further, if several students left the course mid-way, this could represent loss of a relatively large percentage of data. Second, I intended to investigate a number of chemical ideas. This would present problems of organisation - should all students involved be interviewed about every instance? If so, this would mean very lengthy interviews, given White and Gunstone's (1992) recommendation of 15 to 30 minutes per instance (p 67); if not, then this would mean logistics of planning would become very complex. Third, the technique would depend on suitable instances being devised for each chemical idea. Some, for example, rates of reaction, are not well-studied, so extensive trialling would be required to find suitable examples. Fourth, although students could be invited to supply written answers to supporting questions on the same chemical ideas, the study would be based around lengthy transcripts of detailed interview data at each stage. Changes in understanding would be based on the progress of individuals rather than a group performance, so although a detailed picture of a few students would be obtained, a wider, overall view would not.

However, it was decided to include interviews with students as part of the data collection, as they provide an insight into students' thinking and illuminate written answers. Therefore, although the primary data source would be written responses, this would be supplemented by interviews with selected students.

Concept mapping

A third possible technique which could have been employed for part of the study is concept mapping (see, for example, White and Gunstone, 1992). This method encourages students to draw a map to illustrate how they see relations between ideas. Chemical ideas are closely inter-linked, such that it is difficult to separate individual chemical concepts from one another. Students' maps representing how they perceive links between chemical ideas would provide interesting additional information which would usefully supplement their written answers and interviews. As students progress through their courses, the web of links between chemical ideas may be expected to increase in complexity, approaching that of an "expert" chemist towards the end of the two year period. Further, the contrast in approaches between SAC and Traditional courses may be reflected in the concept maps and the way in which these develop.

Despite these apparent advantages, I decided not to include concept mapping in the research study for several reasons. First, concept maps are a rather specialised technique which would need to be taught to students before being used for research purposes. This would entail much closer co-operation with schools, which, while this in itself could have been arranged, would require the investment of significantly more student and staff time, particularly given the longitudinal nature of the study. A second problem arises from this. Since the use of concept mapping is rather more labour intensive, a question would arise as to how many maps would be needed to show a pattern in responses sufficient to be useful in the study. Visiting all thirty-six schools and colleges would be an unrealistic proposition, and using students from three or four leads back into the arguments expressed before (see above) regarding local conditions influencing outcome rather than observing a general pattern. A third disadvantage with concept mapping is the difficulty of analysing the maps. White and Gunstone (1992) advocate a "scoring" method involving marking on a number of criteria, such as the

> "number and meaningfulness of links between concepts; the extent to which the map shows appropriate hierarchy among the concepts; the existence of links between different parts of the concept hierarchy..." (p 38)

Even given that a concise scoring method based on these suggestions could be developed, any meaningful data would require considerable numbers of maps to be significant.

It could be argued that even about twenty concept maps taken at the same three stages would have been an added dimension to the data, particularly if these supported interviews with the same students. Schools local to the Department could have been invited to participate in this section, to facilitate easy training of respondents. However, I believe that although the extra information could be a valuable addition, the written responses and supporting interviews provide a sufficiently rich source of data.

Having considered alternative techniques and discussed reasons for not using them, I must now discuss weaknesses in the selected method, the survey strategy.

3.1.4 Limitations of the longitudinal survey strategy

This section discusses the limitations of the written, longitudinal survey strategy and describes how I attempted to minimise these in the research procedure.

First, in a written test, there is the possibility that students may have guessed their answer. A guess may arise in one of two ways. The student may have guessed the correct answer without understanding the chemical idea. Alternatively, the student may understand the chemical idea but guessed an incorrect answer because the question was unclear. Neither reason for the guess is apparent in analysis because the student is not there to explain what they meant. The response has to be taken at face value. I attempted to minimise the opportunity for guessing by discouraging this in a letter to each student (printed in the test paper, Appendix 2) and by ensuring as far as possible that questions were not ambiguous. Where multiple choice was included, students could guess one option then choose not to explain their selection. Responses of this type were coded separately, as will be seen later.

Second, there is the possibility in this type of study that students might remember questions from test to test and therefore have the opportunity of looking up a correct answer in between times. This would give them an advantage at subsequent tests, as they had learned the answers. Students took the test on three occasions - in September, 1992, in April 1993 and in January 1994. These intervals, I believe, were long enough to ensure that students had not recalled questions in between and worked on them. I took steps to ensure that the number of papers sent to each school matched the number of students, and asked schools to send any spares arising from students' absences back with completed scripts (see letter 4, Appendix 4). This meant that students were not able to obtain a copy of the paper in between surveys. I also think it unlikely that students were interested enough in the work to seriously study the questions. They were simply asked to complete the test papers and this is what they did.

Third, a more serious consideration, is that staff might discuss questions with students and assist them towards giving the correct answers. I tried to prevent this by explicitly asking teachers not to do so (see letter 6, Appendix 4). I attempted as far as possible to ensure that teachers understood the purpose of the study and therefore why their intervention was not required. I can only trust that teachers adhered to the instructions, but would add that, having met the teachers concerned and discussed the issues involved in the work with them, I am confident that any intervention, if it did occur, was minimal and did not seriously affect the outcome.

A way of resolving both the two preceding issues would be to provide a different test paper on each occasion. This would prevent students carrying over information, and also reduce intervention because staff would not be able to predict what questions would be in the next test. However, this was not practicable for several reasons. A bank of test questions was devised and piloted, but I quickly realised that only a relatively small selection yielded a range of responses (see section 3.4.2, below) suitable for analysis. This meant that if I were to produce three test papers each would be very limited in scope, as I could only include a small range in order to save questions for the other occasions. Also, there is no real guarantee that different questions would probe precisely the same idea, so if I used different test papers the study would not have been strictly longitudinal; rather, I would have carried out three different cross-age studies, albeit on the same group of students.

A fourth limitation of the proposed strategy is that staff may allow students to take the test as "homework" and therefore participants in different schools and colleges would be answering the questions under varying conditions. This, again, is potentially damaging to the data, as students working at home would be able to consult textbooks or take longer than was intended to produce higher quality answers than their co-respondents. I attempted to ensure that similar conditions in all thirty-six schools and colleges were adopted by providing instructions for administration to all participating staff (see letter 4, Appendix 4). These encouraged them to administer the test in lesson time and to operate examination conditions.

A fifth weakness of this strategy is the type of question used. I knew that as the study would use students' written answers as the primary data source the questions included had to be understood by a wide range of students. I needed to be confident that the students' responses reflected their understanding, that is, there was nothing in the question which prompted them to answer in a particular way. I therefore arranged a pilot study (section 3.4), in which questions were trialled carefully to develop clear probes.

In the next section I describe the steps involved in developing the survey instrument used through out the study.

3.2. Deciding which aspects of chemistry to investigate

Once the principal method of data collection was established, the next task was to devise the survey instrument, which I call the "test paper". Several stages were followed, beginning with deciding which areas of chemistry should be investigated. The starting point for this was the chemical content of an A level chemistry course, as detailed by the "common core" (Royal Society of Chemistry, 1993). Studying all aspects of the subject covered within the constraints of a two year study would be both unrealistic and impractical. Decisions had to be made as to which parts of the syllabus would best assist in meeting the research objectives outlined in chapter one. To aid the decision-making process, I divided the A level syllabus into five sections, which, although somewhat artificial, enabled me to group chemical ideas together in a useful way. These sections are discussed below. First, though, I explain two criteria which were used to "test" chemical ideas for their usefulness to the proposed study.

3.2.1 Two criteria were applied

To assess the value of each section to the proposed study I applied two criteria. Sections, or parts of sections, which satisfied both criteria proceeded to the next stage, that of devising prototype questions. The two criteria were:-

1. Have any of the chemical ideas in this section been researched for younger students?
2. Do chemical ideas in this section feature in GCSE science or chemistry courses?

The importance of these will be explained in more detail.

The literature on students' conceptions of chemical ideas reported in chapter two indicated the main areas of interest to researchers to date. These include the particulate theory of matter, equilibria, acid-base chemistry, the mole, the nature of a chemical change and the conservation of mass in reactions. Most studies involved 11 - 16 year olds. Work with students aged 16 - 18 years is infrequently reported, although data relating to this age group features in cross-age studies, for example, that by Osborne and Cosgrove (1983). Thus, two advantages arise from taking earlier work into account. First, the existing literature provides valuable indications as to beginning A level students' likely performance. Second, the proposed research would usefully extend findings in these areas of chemistry to the 16 - 18 year old age group.

Many of the chemical ideas taught at A level are completely new to students, while others build on areas met more simply at GCSE (pre-16) level. As the proposed study intended to observe changes in students' thinking, it seemed important to ask about chemical ideas the respondents would recognise. Therefore, probes featuring, for example, functional group chemistry, standard electrode potentials or the reactions of the halogens could not be included unless a way was found to ask a question in a form appropriate to a beginning A level student.

We will now examine A level course content in more detail, applying these criteria.

3.2.2 'A' level course content

In an attempt to make the course content manageable, the chemical ideas are placed under five broad headings. The headings are not intended to represent clearly defined barriers; they are simply one way of grouping the course content. While labelling parts of chemistry in this way seems to artificially isolate certain chemical ideas from others, the specific content under each is somewhat fluid, so overlaps or alternative placements for some chemical ideas are possible. The headings are:-

physical
inorganic
organic
stoichiometric
practical.

In the following discussion, I have not attempted to list every chemical idea which features in an A level syllabus. The content described in each heading is intended only to make distinctions between the sections clear.

Physical

This section covers the chemistry used to describe a chemical reaction. De Vos et al (1992) describe this as a "key concept" (p 2) in chemistry, since a chemical change distinguishes chemistry from other sciences.

The chemical reaction notion can conveniently be described in three parts. One is the distinction between a physical and a chemical change, which, as chapter two indicates, is not easily defined. The second is the distinction between an element, a compound and a mixture, a feature which de Vos et al (1992) call the "substance concept" (p 2 paraphrased). Learning about both these aspects of chemical reactions requires students to make decisions like, for example, whether a "reaction" is a physical or chemical change or whether a unknown substance is an element, a compound, or a mixture. Gagné (discussed in White, 1988), describes this as learning about "concrete classes" (p 36), as the student is expected to apply a set of learned criteria to decide if an instance could be a member of a named class. A pre-requisite to understanding these ideas is the notion that matter is made up of discrete particles capable of interacting with one another. Thus, atoms, atomic structure and chemical bonding are also placed in this section. All of these chemical ideas meet the two criteria as they feature in GCSE courses and in earlier research work.

The third part of the chemical reaction notion is the collection of factors which control various aspects of a chemical reaction. This large group includes kinetics, which describes how fast a reaction reaches completion; equilibria, which explains how close the reaction gets to completion; thermodynamics, which describes the energy changes involved in reactants becoming products, and chemical bonding, which explains the apparent changes in the substances involved. Within each of these factors lies a large group of interdependent chemical ideas some of which have been investigated in earlier work. All these areas are considered in GCSE courses, although the depth of treatment at this level may depend on whether the student follows a Science (double award) course or Chemistry as a single subject. So, chemical ideas placed in this section satisfy the criteria and could be included in the next stage.

Inorganic

Under this heading I place the chemistry of the elements in the Groups of the Periodic Table. This provides the repertoire of chemical reactions which physical chemistry seeks to explain. At GCSE level, students learn about simple reactions, such as those between acids and bases, acids and metals, elements and oxygen. They may also learn about the reactivity series of metals. Much of this information can be represented in phrases such as "an acid plus base makes a salt plus water", or "carbon plus oxygen makes carbon dioxide". White (1988) calls this type of information a "string" (p 23), that is, a unit of words which cannot be readily paraphrased. A string is learned as a self-contained unit and may be repeated with or without understanding of, in these cases, the chemical ideas embedded within them. As students study chemistry at GCSE, they will collect strings for various reactions. The set of strings will be considerably increased at A level, as the range of reactions studied becomes more extensive.

Students' learning about the repertoire of chemical reactions does not feature in the research literature. Such work, on the number and type of reactions recalled by students, would be both tedious and less interesting than that investigating the ideas contained within strings, such as the work reported on acid-base chemistry. The distinction between an acid and a base is similar to those discussed above, as it involves deciding to which class a substance belongs. This topic does meet the two criteria.

The notion of periodicity is included in this section, since this gives structure to the repertoire of reactions. Although some work on this is done at GCSE, there is no research base on which to build findings, so this chemical idea does not meet the criteria.

In order to probe the chemical ideas listed in the physical section, examples of chemical reactions are essential. In devising questions which can be answered by beginning A level students the set of strings learned at GCSE must be taken into account.

Organic

Here I place all the chemical reactions of gas and oil derivatives and any additional reactions of carbon and its compounds. To my knowledge, only van Keulen (1993) has studied chemical ideas which are exclusively part of this section. His work, with university chemists, is beyond A level so does not provide a foundation for this study. Understandably, as organic reactions can become very complex, few reactions of this type feature in GCSE courses. So, chemical ideas in this section meet neither of our two criteria. Also, like inorganic chemistry, organic reactions can be learned as strings, and as before, ascertaining changes in the range of strings would not be as valuable research as, for example, investigating whether students can distinguish between the classes of organic compounds. This latter is a potentially rich area for study, but as most types of organic compound are completely new to A level students, research in this area could not be included in this work.

However, in common with inorganic reactions, some chemical changes in this section are needed to probe some chemical ideas featuring in the physical section. For example, the combustion of fuels, used widely in teaching thermodynamics, is categorised here, as are the simple hydrocarbons, methane and ethene, which are frequently used as examples of single and double covalent bonding. Therefore, although there is no research base and limited coverage of this type of reaction at GCSE, the formulae of simple compounds and the reactions of carbon, methane and petrol with oxygen could supply contexts for questions to be used in the study.

Stoichiometric

The mole concept, balancing equations and volumetric calculations are placed in this section. These topics come into White's (1988) group of intellectual skills called "rules", since they involve

> "...procedures, algorithms, which are applicable to classes of tasks" (p 38).

Balanced equations and amounts of substances are used to explain the chemical ideas included in the other four sections. These "rules" are therefore the tools available to a chemist to represent and help explain chemical reactions. All these chemical ideas are rooted in the assumption that mass is conserved in chemical reactions, that is, the mass of the products will equal the mass of the reactants.

Although significant research has been undertaken about students' understanding of the mole, relatively little previous work on balancing equations and volumetric calculations exists. At GCSE level, students will learn to balance equations, but some may not use moles to express amounts of substance and therefore do not learn to carry out volumetric calculations at this stage. A level courses begin with the assumption that students' experience of stoichiometric chemistry is a somewhat hazy recall that "equations have to be balanced". Nevertheless, the ability to manipulate mole values, reason in terms of reacting masses and balance equations is vital to chemists, so these and the underpinning idea that mass is conserved in chemical reactions will be included in the study.

Practical

All A level syllabuses expect students to either take a practical examination, carry out assessed practicals or, in the case of SAC, undertake a small project. This requirement is based on the assumption that chemistry is a practical science, so its students should learn how to manipulate pieces of apparatus to provide suitable conditions in which chemical reactions from the prescribed repertoire can occur. White (1988) describes these as "motor skills", which, like rules, are applied to classes of tasks. At GCSE, students learn to handle very basic pieces of equipment, such as test-tubes, bunsens, splints and gas jars. In an A level course, the range is extended to include pipettes, burettes, colorimeters, pH meters and so on. The development of students' practical skills in chemistry has not, to my knowledge, received extensive attention from researchers, so does not satisfy both criteria. Further, assessment of students' progress in this area would require extensive lesson observation and is therefore more appropriate to a case study approach, which is not, as section 3.1.3 explains, being used for this work. Therefore, practical skills are not being investigated in this study.

Concluding the content analysis

The analysis of the chemical content of an A level course reveals that aspects of physical chemistry seem most appropriate for inclusion in this study. This section seems to most closely represent the essentials of chemistry, that is, reactions, changes to substances and why these changes happen. A professional chemist will acquire knowledge, "strings", for many chemical and physical changes, but controlling, predicting and analysing the characteristics of these will be at the centre of his or her work. For the novice, chemistry must, at a basic level, mean learning how controlling factors inter-relate to influence a reaction. Inorganic and organic reactions from the GCSE repertoire will be used to provide suitable settings for probing development of the physical chemistry ideas. The stoichiometric "rules" of chemistry will also be probed, using ideas about the conservation of mass in chemical reactions, balancing equations and calculation of mass of product.

I will end this section with a list of the areas of chemistry within which questions will be devised:-

characteristics of atoms;
differences between elements, compounds and mixtures;
chemical and physical changes;
chemical bonding;
thermodynamics;
conservation of mass in reactions;
calculation of reacting masses;
rates of reaction;
equilibria.

3.3 Devising questions

The next stage towards devising the test paper involved writing questions to probe students' thinking in the areas of chemistry listed above. The process of writing questions took place over several months, and involved several revisions of wording, layout, and content. Colleagues within the department assisted in this, suggesting modifications and improvements. The following discussion is, therefore, a summary of the key points in a complex series of events which led to the production of questions used in the final test paper.

To produce the questions in the first instance I applied some simple "ground rules". As this stage progressed, these guidelines became more firmly established as characteristics of questions likely to be useful to the study. This section therefore begins with these, as they will assist subsequent discussion.

3.3.1 The characteristics of diagnostic questions

Four characteristics can be identified. The first three were considered prior to students' answers being obtained. The fourth became apparent following the pilot study.

First, the questions had to be answerable by students who had completed GCSE science or chemistry several months earlier. The research study intended to probe beginning A level students' understanding of the selected chemical ideas to provide a base from which changes could be observed. Questions which students could not answer would not provide such a base of responses. So, any reactions or physical changes used to provide chemical settings for questions had to come from the repertoire common to GCSE courses, otherwise a strong possibility existed that students would not answer the questions because the content was unfamiliar.

Second, questions needed to be suitable for the context of the study. The survey instrument would be a one-hour test paper of probes on a wide range of chemical ideas, so any one question could only take about three minutes to answer. This meant that long preambles could not be allowed, nor questions requiring answers of more than one or two sentences.

Third, ideally the questions would probe one basic chemical idea each. That is, the answer to any one question could not depend on a student understanding another chemical idea in order to obtain the correct answer. As chemical reactions from the inorganic and organic sections were necessarily included to probe ideas classified as physical chemistry, questions could never be entirely free from contextual difficulties. I tried to minimise potential problems for students by ensuring that substances and reactions were as simple as possible and stood a good chance of being known by a majority of students.

The fourth characteristic is that questions had to generate a range of responses. This only became apparent after the first questions had been trialled. Technically, it was possible that beginning students would understand some of the chemical ideas under investigation, such that a range of answers would not result because everyone gave the correct response. However, I felt this to be unlikely, given the evidence of earlier research. So, questions which, in the trial, yielded many identical responses were probably not probing the variety of understandings of the chemical idea in an effective way. A second aspect of this was the need to produce questions challenging to students completing an A level course. At this early stage, I could not predict whether probes would generate different response patterns from more experienced students answering later in their A level courses. I reasoned that if questions did produce a range of answers among beginning A level students, then the range and types of response would be likely to change as they learned about the chemical ideas in their courses.

3.3.2 Themes and variations - prototype questions

An initial batch of questions was circulated to colleagues for comment, and after discussion, these questions were refined and organised into sets for use in the pilot study. At this stage, we will briefly examine the types of question written to probe the areas of chemistry listed above. For ease of reference, these questions are included in Appendix 1, which comprises the five sets of trial questions, lettered A - E, used in the pilot study, discussed in detail next. The questions themselves can be divided broadly into two categories:-

(i) questions adapted from earlier studies;
(ii) questions written for this study.

Examples of both types will be identified as the discussion proceeds.

Characteristics of atoms

Since knowledge about these particles is perhaps the most basic in chemistry, I attempted to find out what characteristics students attribute to atoms using question A4. Earlier versions used textbook diagrams of atoms to prompt responses, but I could not guarantee that all students would have seen atoms represented in these ways. Asking them to "imagine" they could see an atom of carbon allowed their own ideas to be expressed.

Differences between elements, compounds and mixtures

Two questions probing this were adapted from Briggs and Holding (1986). A1 was based on their diagram discrimination question (p 39) which probes students' ideas at the particulate level. A respondent who can distinguish correctly between the four gases is likely to have a good understanding of the distinctions between elements, compounds and mixtures, because they realise the meanings of the different arrangements of atoms. In my adaptation the symbols could represent the "real" elements hydrogen and chlorine, so the four gases would be a mixture of hydrogen (or chlorine) and hydrogen chloride (A); the compound hydrogen chloride alone (B); the element hydrogen or chlorine alone (C); and a mixture of the elements. This gives the question internal consistency.

Question A2 was based on the "element selection" question in Briggs and Holding (1986, p 14). Here, students are asked to use information in deciding to which class a substance belongs. This applies in a practical way the idea tested in A1.

Question A3 was written for this study. Its objective was to find out if students could recall definitions for "element" and "compound" and could apply these to practical tests.

Chemical and physical changes

A variety of chemical changes was used in trial questions. Here, I wanted to probe students' ideas about the rearrangements of atoms which occur in chemical reactions. Specifically, I intended to probe the idea that a product of a reaction is formed from atoms already present in the reagents. I also hoped they would be able to distinguish between physical and chemical changes in terms of the types of bonds involved, an area which overlaps chemical bonding. A8 and B8 use the same reaction, but the question "Where has the gas come from?" (A8) directs students back to the tablet and water, while "Where was the gas before the reaction?" places emphasis on the gaseous product. The same questions were asked about other reactions between hydrochloric acid and calcium carbonate or magnesium metal, in A9, B9 and C9. A different approach was tried in questions A10, B10(a) and C10(a), where a gas, oxygen, was included as a reactant, not a product.

Chemical bonding

At GCSE, students learn about covalent and ionic bonding, but not intermolecular bonds. I wanted to probe the development of students' ideas about chemical bonds, as this area of chemistry receives much more detailed attention at A level. So, questions about intra- and intermolecular bonds were devised.

Question A5/B5/C5 asks students to describe what they understand by conventional symbols for types of chemical bond and to explain any perceived differences between them. In A6/B6/C6, students were asked, indirectly, to describe the formation of an ionic bond between sodium and chlorine. A companion question to this, E12, asks why methane has the chemical formula CH_4, which invites responses in terms of covalent bond formation.

Number D9/E3 probes students' understanding of state changes in the context of two chlorides with very different properties and is based on a question set by the University of London Examinations and Assessment Council (ULEAC) in the June 1990 A level Chemistry paper 1. This question probes ideas about intermolecular forces, expecting students to explain that ionic bonds are stronger than the van der Waals' forces between molecules of the covalent chloride.

Thermodynamics

Fundamental to chemical thermodynamics is the idea that energy is required to break chemical bonds, but energy is released when chemical bonds form. I sought to probe students' developing understanding of this in questions A11/B11/C11, using the example of methane burning in oxygen. A related question, A12/B12/C12, indicates which bonds break and form in an esterification reaction, and asks students to explain why the overall energy change is 0 kJ/mol. This is based on a ULEAC A level chemistry question. In a third question, E13, the reaction between sodium and chlorine is used to probe students' understanding of energy change diagrams.

Conservation of mass in reactions

I wanted to know to what extent beginning A level students realise that mass is conserved in chemical reactions. As this notion underpins several other areas of chemistry, I probed this using a variety of situations. Several questions used in this area were adapted from earlier studies. Number D7/E9 was used by Andersson (1986) and Driver et al (1984) to find out if students conserve mass in the closed system chemical reaction between phosphorus and oxygen. It seemed valuable to use these questions, as they yielded a variety of responses with younger children and, if the same were true for beginning A level students, this would provide a yardstick against which changes in understanding could be identified. Slight modifications to improve clarity were made to the original questions. These included adopting "mass" consistently instead of "mass" in the stem and "weight" in the question; and altering the mass values to be more realistic. Question D5/E6, devised for this study, is very similar, as it tests the same idea in the context of a precipitation reaction. Number

D6 uses an open system chemical reaction and invites students to estimate the mass of exhaust gas is produced when petrol combusts in oxygen.

Calculation of reacting masses

Questions in this area attempted to find out if students could apply reacting mass reasoning to a simple two element / one product reaction. Implicit in this is the principle of conservation of mass. Respondents were expected in question D4/E7 to realise that 240 g of XY is produced with 10 g of Y left over, because the elements react in a fixed ratio. This question was adapted from Briggs and Holding (1986), by removing the multiple-choice option and making the compound iron sulphide rather than zinc sulphide. My reason for this change was that the reaction between iron and sulphur is frequently carried out in schools to illustrate the differences between elements, compounds and mixtures, so this was more likely to be familiar to students.

Questions D3 and D8 (also E3 and E15) formed a pair which probed this in the context of an open system chemical reaction. Numbers D3/E3 provide the data needed to answer D8/E15, which involves calculation of the number of moles of coal in 1000 tonnes. Both relate to the conservation of mass questions discussed above.

Rates of reaction

Questions about rates of reaction proved very difficult to write. At GCSE, kinetics receives very basic treatment; students learn that surface area, concentration and temperature may affect the rate of a chemical reaction, and may draw graphs to represent these effects for certain reactions. At A level, kinetics becomes more complex, involving rate equations and calculation of rate constants. The contrast between the two levels made it difficult to find an aspect of this area of chemistry which met the three pre-established guidelines. Eventually, one question, D2, was produced, which erred towards the GCSE level, attempting to probe students' interpretation of graphs for liquid/liquid and solid/liquid phase reactions.

Equilibria

At GCSE, students generally meet two reactions, in the Haber and Contact processes, which are labelled "equilibrium reactions". So, questions about this could, in meeting the guidelines, only include these reactions. However, I wanted to find out if students develop understanding of the basic principle that all reactions are equilibrium reactions, and that the value of equilibrium constants reflects the extent to which reactants remain at completion. Question D10/E16 is the trial version probing this.

Having devised some questions, I tested them in a pilot study.

3.4 The pilot study

The aim of the pilot study was to ascertain which questions best satisfied the characteristics described in section 3.3.1. Questions which proved to be unsatisfactory would either be modified or not included in the final test paper. This section describes how the pilot study was carried out and re-examines the questions in terms of the range and types of responses they generated.

3.4.1 Organisation

Preparing sets of questions

Draft questions were discussed at a departmental seminar on the project in March, 1992. Following this, possible questions for inclusion in the test paper were circulated to chemistry educators for comment. Specifically, colleagues were asked to comment on the wording, structure and the chemical sense of questions, and to assess how A level students may answer them. Modifications were made to some questions prior to testing in schools.

At this stage, March 1992, three prototype test papers lettered A - C were prepared (Appendix 1). Each comprised about twelve questions. Where variations in wording were being tested, care was taken to make sure each paper included one example only. In June 1992, a further two test papers, D and E, were prepared, which included questions on chemical ideas not used in the earlier papers. Set E was compiled from sets A - D. This was essentially the trial version of the complete test for use in the main study. Set E included the majority of the productive questions from sets A - D and others which had been devised in the intervening period.

On the front page of each test paper a few questions were included to provide information on students' science background.

Testing in schools

Lower sixth form students in three schools and one sixth form college were asked to respond to one set of questions each. One school was a mixed comprehensive; the other two were single sex grammar schools, one boys and one girls. A mixture of prototype tests was sent to each school or college, to ensure that no one group of students answered only one set. Sufficient copies were distributed to ensure that about twenty responses to each question were obtained. Staff were asked to allow students about forty-five minutes to complete the questions under examination conditions.

Lower sixth students (aged 16 and 17) were used, for two reasons. First, this age group are approaching the mid-point of their A level courses. So, their responses should indicate whether the chemical ideas were being probed at an appropriate level. If almost all of these students gave correct answers to a question after two terms (about six months) of A level study, this would suggest that the chemical idea being probed was well-understood and was not appropriate for inclusion in the main study.

As the aim of the pilot study was to assess the suitability of the questions, in terms of the types of response they generated, the syllabus the students were studying was unimportant. Further, I wanted to make sure that SAC teachers and students would meet the questions for the first time when the main study began. Using non-SAC schools helped to ensure that teachers were not tempted to teach to the questions prior to the large scale work.

Following administration of set E, five students were selected for interview on the basis of their having used unorthodox chemical reasoning in responding to the questions. Discussion with students centred on establishing whether the wording or style of the questions had prompted their responses. This resulted in additional modifications, clarifying wording or diagrams.

3.4.2 Results

In this section, I examine students' responses to the trial questions. The questions are considered in the order given in section 3.3.2. To keep this section to a practical length, only a few students' responses are quoted under each heading. Quoted responses are followed by a student reference number.

Every question included in the final survey was given a name. To assist in observing the changes made between trial and final versions, the names of the final test items are given as the discussion proceeds. The test paper used in the main survey is included in Appendix 2.

The number of student responses

The number of responses received for each set were:-

Set A	18	Set C	10	Set E	10
Set B	16	Set D	9		

Approximately twenty responses were received to each question.

Characteristics of atoms

This question, A4/B4/C4, produced many responses like:-

> "(a) A small nucleus surrounded by space and then an area of electrons (b) Black." (Student number 7)

These answers indicate that by the mid-point, most students know about the existence of sub-atomic particles and that much of the atom is space. It is likely that students described the colour as black because samples of carbon are black. This is not very revealing, as most only gave the colour and no other physical properties. As the range of responses is restricted, this question was excluded from the main survey.

The distinction between elements, compounds and mixtures

The multiple-choice part of question A1 was answered correctly by almost all respondents, but some students failed to describe the contents of the remaining box, gas A, correctly. Responses close to the expected answer included:-

> "A compound with excess of a certain element" (4)

> "An unfinished reaction, some molecules of a compound are formed, but one kind of element also left." (15)

Some students used inappropriate terms in their answers, for example:-

> "A compound of two gases (like chlorate)" (14)

> "A mixture of radioactive gas." (6)

These responses suggest that the particulate distinctions are less well-known than I expected, given the students' level of chemical experience. Similar findings applied to question A2. Some students mis-identified one or more of the substances, with substance D proving most difficult. Question A3 indicated that while students could give textbook-style definitions of "element" and "compound", relatively few could name tests to support these in part (c). Incorrect answers include:-

> "[water] heat it in oxygen - no product is formed except water vapour" (6)

> "Boil the water, testing for oxygen and hydrogen" (11).

On this basis, all three questions were included in the main study, as *Molecules*, *Substances* and *Element and Compound.*

Chemical and physical changes

No perceptible difference was found in the response types given to the two wordings. For example, student 15 answered, "Present in water" to question B8 and "Marble chip ($CaCO_3$), the gas is CO_2" to B9. The difference in wording did not seem to affect his idea that the gases must have come from reactants. The implication of these answers is that the gases existed before the reaction took place, and that it was simply "released" in the process. A number of students gave this type of answer. In the final test paper, question B8 was used to probe this idea. Items A9 and B9 involve "acid", a chemical idea tested elsewhere in the final paper. So, the final test paper includes the question *Tablet*, rather than one involving acid/carbonate, or acid/metal.

Question D9/E3 produced many answers explaining simply that

> "oxygen in the air has reacted along with the water on the iron..." (7)

A similar lack of variety was observed in responses to part (b), which attempted to probe students' ideas about the relative reactivities of magnesium and zinc. Therefore, this question was withdrawn. However, in the final test paper the question *Copper* was substituted. This question probes students' ideas about the formation of a solid metal oxide and, as Andersson (1984) showed, could yield answers indicative of misconceptions about the origin of the "black stuff".

Chemical bonding

Question A5/B5/C5 about types of bonding yielded answers which varied in the amount of detail included. Some students used sigma and pi-bonds in their answers, while others simply described the bonds as "single" and "double". As these students had studied intermolecular bonds, most were able to identify hydrogen bonds correctly. The variety of responses at this stage suggested that this question could show differences between beginning students. A slight modification was made to this question in set E, in that I decided to label the substance diagrams instead of asking students to do this, thus making a small saving on their use of time. The final version is called *Chemical bonds*.

Item A6/B6/C6 produced a variety of explanations about the reaction between sodium and chlorine. Some showed understanding of the chemical idea, for example:-

> "The two elements are very electronegative and so readily form a strong ionic compound." (1)

> "It is violent because the outer electron of the sodium atom is easy to remove..." (7)

Others were clearly incorrect, suggesting students misunderstood the event, for example:-

> "The sodium contains the energy to lose its electron.." (4)

These interesting variations could be repeated among beginning A level students if this question was included in the main study. In the final version, *Sodium and Chlorine*, a diagram of a gas jar was added to provide a visual image.

The companion question about the formation of methane, E12, also produced a range of answers including:-

> "The carbon needs to gain 4 more electrons and hydrogen needs to gain 1 electron..." (18)

> "Carbon is most stable when bonded to four other elements..." (12)

Other respondents used terms like "valency" (7), or mentioned electron configurations (19). These responses suggested the question would prove useful to the main study and the test paper version is called *Methane molecules.*

One other question, E3, probed students' ideas about intermolecular bonds between chlorides. Most students gave answers indicative of misunderstandings, for example:-

> "$MgCl_2$ will have broken down to form $2Cl^-$ and Mg^{2+} ions at such high temps" (12)

These suggest that ideas about intermolecular bonds are not well-developed. Changes in students' understanding about this chemical idea may change through a course. This question is therefore included in the main study as *Chlorides*. An additional question, *Boiling*, was added, to probe students' ideas about what happens when water boils.

Thermodynamics

Question E12, using an esterification reaction to probe bond-making and breaking, produced mainly correct answers. The item was not pursued for several reasons: first, it seemed to provide too many "clues" to the student, by labelling bonds in the molecules. Second, a long preamble is required to get to an answer which is very short, which means poor use of time in the test. Third, the reaction is too complex for beginning students, who would not be familiar with the formulae of reactants and products.

Probe A11/B11/C11 proved more useful. The most effective version, A11, generated several types of response, to the third part about the source of energy, including:-

> "Stored in the bonds of the methane which was released during combustion." (10)

> "In the methane gas the spark ignites gas releasing the energy within it." (12)

To help students think in terms of bond enthalpies, the question was modified to include the diagram used in C11. This combined version was used in the main study, and is called *Methane*.

Energy change diagrams feature in D1/E13. This question, to which the best answer is diagram A, produced a range of answers, including:

> "B. Because both 2Na and Cl_2 are quite stable but they are even more stable in compound." (5)

> "C. A reasonable amount of energy is needed to break the Cl-Cl bond, but forming the NaCl bond gives out much more energy." (14)

The range of responses suggested this probe should be included in the test paper, but modifications were made in producing the final version, *Energy change*. Diagram B was altered to look more like A and C by removing the line below the right-hand arrow. Rather than asking for a "reason", students were invited to explain "how they decided", as their responses indicated they put together several pieces of information in making a choice.

Conservation of mass in reactions

Although most students answered D7/E9 correctly, enough gave incorrect answers to suggest that inclusion in the main survey, as *Phosphorus*, may indicate a poor grasp of conservation in this closed system. Student number 18, for example, explained the mass would be less than 400 g, because:-

> "as the phosphorus burns it uses up some of the oxygen supply so it will weigh less." (18)

In contrast, number 11 explained the mass would increase, because:-

> "Energy is added using Einstein's $E = mc^2$..." (11)

Item D5/E6 produced similar responses about the precipitation reaction. For example, student 16 was one of several who suggested the mass would increase because:-

> "The precipitate may be heavier than the solution which it replaces." (16)

In interviews, I discussed examples of precipitation reactions, and this helped students to talk about their ideas. I therefore modified the question to include a specific example in preparing *Precipitation* for the main study.

Two untrialled questions, *Solution* and *Hydrogen chloride* were added to the test paper following discussions with colleagues about students' understanding of dissolving. *Solution* probes students' ideas about the dissolution of sodium chloride using a similar format to *Precipitation* and *Phosphorus*. Although dissolving is not strictly a chemical reaction, it seemed likely that, as a closed system, respondents might not conserve mass in this situation. *Hydrogen chloride* asks about dissolving hydrogen chloride gas to make hydrochloric acid, and about how hydrogen gas is evolved when magnesium metal is added, and thus uses dissolving to probe the idea that an acid contains hydrogen ions.

Question D6/E14 used an open system chemical reaction, asking for estimates of the mass of exhaust gas produced when petrol burns. Few students gave the correct answer. Most conserved the mass of petrol, explaining:-

> "The petrol cannot have just disappeared..." (12)

Many of these responses may have been caused by distracting information in the question stem, which fails to explain that oxygen is involved. Also, students may not have known what to give for "The approximate mass", so put down the mass of petrol. However, students' explanations and interviews suggested they really did not understand what happens in a car engine, even when the full equation was provided, so despite reservations over the wording, I included this probe, as *Petrol* in the main study.

Calculation of reacting masses

Item D4/E7 asked students to calculate the ratio between chemicals X and Y and work out the mass of the product XY. Most responses added the two mass values, obtaining 250 g. At interview, students asked about this did not realise that the elements reacted in a fixed ratio. This question therefore seemed important to include in the main study, as the extent of this lack of understanding in a large group would be interesting to know. To help students, I modified the question to include a specific example, the reaction between iron and sulphur, and altered the wording in the final version, *Iron sulphide*.

In answering the pair of questions, D3/D8 and E3/E15, students again produced a range of answers. Although most correctly gave "88 g" in answer to D3/E3, using moles to obtain this, many could not use moles to convert the mass of coal to moles and then find the mass of carbon dioxide. One student, number 13, assumed the mass of oxygen would equal the mass of coal, so the total would be 2000 tonnes; another gave 44 000 tonnes, on the basis of 44 x 1000 = 44 000. This suggested poor understanding of reacting mass reasoning was apparent, so should be probed further in the main study. These questions became *Carbon* and *Power Station*.

Rates of reaction

The one question probing this, D2/E11, yielded a very wide range of mostly incorrect responses, indicating that students have poor appreciation of how graph shapes relate to the rates of actual reactions. Student 14 explained her choice of C for the liquid X/Y reaction as follows:-

> "in a[n] acid alkali titration a solution is alkaline..." (14)

In interview, student 11 explained why he guessed graph B for both reactions:-

> "When you see an equation, eg Na + Cl -> NaCl you just think of the equation, not what's happening behind it." (11)

At time of the pilot study, students had not studied kinetics, so these explanations may change later in their courses. Hence, this question, as *Reaction rates*, was included in the main survey.

Equilibria

In their answers to D10/E16 some students referred to "energy" and the fact that more was needed to reverse the H_2/O_2 reaction than the H_2/N_2 reaction. Others suggested, for example, that:-

> "The second reaction is a chemical one which cannot be reversed" (8)

This indicates poor understanding at this stage, but shows that the question could be answered by students who had not yet studied equilibria in their courses. The question was modified to include the enthalpy change for reaction to assist students, and was called *Reactions*.

3.4.3 Conclusions

Several conclusions were drawn from the pilot study. First, all of the questions appeared to be at an appropriate level for the students. The examples of reactions chosen were known, and respondents in almost all cases clearly understood what they were being asked to do. This latter point was confirmed in the five interviews. Second, the trial sets could be answered in a time period which suited schools. Set E, the longest paper, required about one hour, although some students took considerably less time than this. Third, most questions produced a range of answers. Those which did not were discarded. The range of answers included correct, incorrect and those part-way, which hinted towards a coding scheme based on three tiers of response type.

That most questions did produce a range of responses from understanding to misconception indicated that this method would be suitable for probing development of students' chemical ideas. A large sample of beginning students might be expected to give an even broader spectrum of responses, subject to change with time.

The pilot study, as suggested above, hinted at a strategy for analysing the data produced from a larger group. Categories of response would arise from the sample, and could be grouped on the basis of degree of understanding of the chemical idea. The balance between categories may change as the participants progress through their courses, and may even differ between SAC and Traditional students. Also, common types of misunderstanding could be identified and described. Thus, the pilot study proved to be a valuable indication that the proposed strategy would yield data relevant to the research questions discussed in chapter 1.

3.5 Preparing and administering the test paper

Following the pilot study, the test paper (Appendix 2) was compiled. I modified questions as discussed above and made several general changes to improve consistency and layout. References to "X" and "Y" in some questions were dropped in favour of "real" chemicals from the GCSE repertoire to make questions appear chemical rather than mathematical. Diagrams were drawn using a computer-drawing package to ensure clarity and a professional appearance. As shown above, probes were given names to facilitate reference and make the test appear less like a formal examination. An informal letter was included to explain to students the purpose of the test paper. Questions probing the same chemical idea were separated from one another and less-demanding questions were placed on the first page, to encourage weaker students to complete these then turn over. The test was printed in an A4 booklet format in two forms, which I call "A" and "B", in which the questions were ordered differently. No outward sign of the difference was included. I did this to check that positioning questions in a particular order did not influence responses. It is possible that, for example, students may be influenced towards answering in a specific way if the preceding item related, however vaguely, to the content of the question being considered.

To help compile information about the student population answering the test, I constructed a student survey, also included in Appendix 2. This asked respondents to (anonymously) give their GCSE background, details of other A level courses and indicate what they hoped to do after completing sixth form studies. A companion survey was included in the third test paper to assess how the students perceived their progress. The data yielded from this will be the subject of a paper outside this thesis.

Printed papers were distributed to the volunteer schools and colleges for completion by students in the first week of their A level courses in September, 1992. A full list of participating establishments is included in Appendix 3. Equal numbers of both paper type were sent to all institutions, accompanied by a letter (Appendix 4, Letter 1) giving instructions for administering the test.

Similar arrangements were made for subsequent tests. Staff were encouraged to complete the test within a certain time period and return the scripts to the Department. At the second and third stages, a short survey was sent to schools to establish the progress being made through the A level courses. Information from this was used in data analysis. Dates on which the test was administered are shown in Table 3.1.

3.6 Content of the test paper

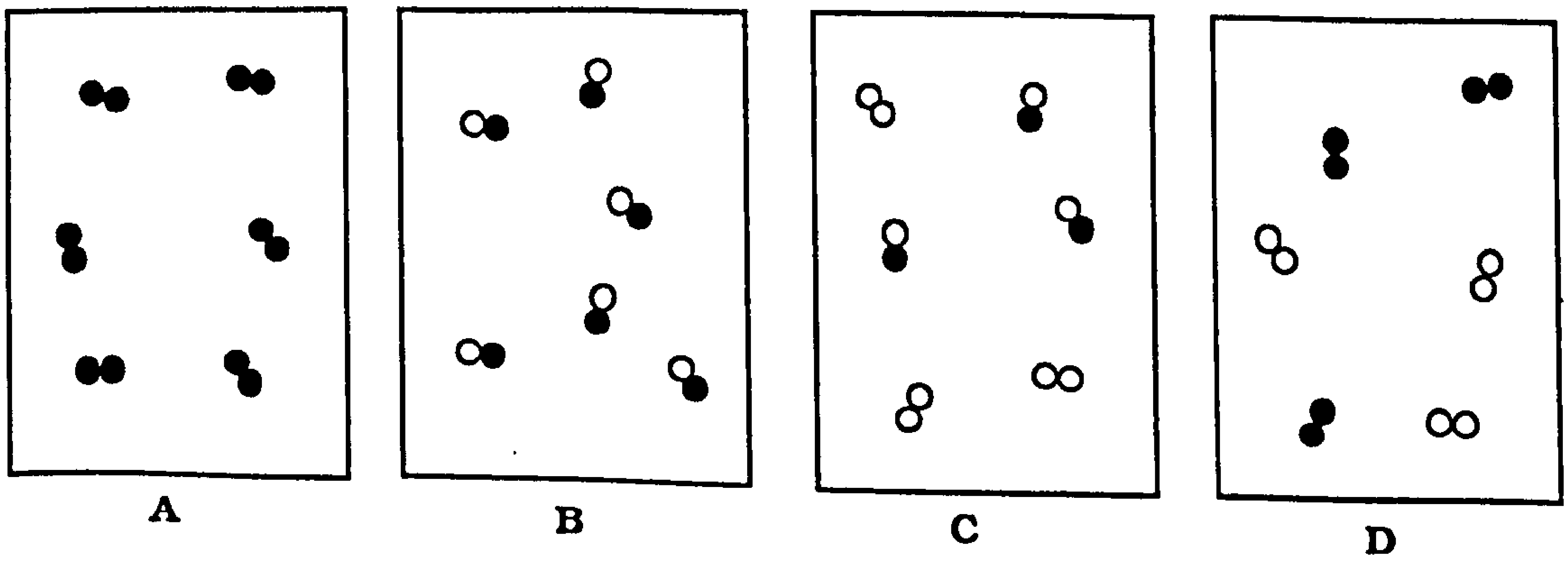
In this section, I examine each question in the test paper, describing the chemical ideas being tested and the correct, or intended, answer. Some questions also include a chemical event, the understanding of which may affect students' responses. The chemical events are discussed as they arise. Potential difficulties for students are also assessed. Probes are discussed in the order previously used in sections 3.3.1 and 3.4.2.

3.6.1 Differences between elements, compounds and mixtures

Three questions, *Molecules*, *Element and compound* and *Substances*, probe students' understanding of this area of chemistry. The ability to make this distinction underpins understanding the characteristics of a chemical change, as well as providing students with an introduction to the idea that all compounds and mixtures are composed of only about a hundred chemical elements.

<u>Molecules</u>

The diagrams lettered A - D represent four different gases. All four of the gases are made from two chemical elements. The atoms of the elements are given the symbols O and ●.



Identify which gas is:-

(a) a mixture of the two elements; ________

(b) a compound; ________

(c) one element alone. ________

There is one diagram which you haven't chosen. What do you think is represented by that diagram?

This question was placed first in the test paper as it probes a very basic idea which all students are likely to have met before starting A level and therefore would be a non-threatening start for students. *Molecules* uses pictorial representations of four gases to probe students' ability to distinguish between elements, compounds and mixtures. The elements are represented by different coloured circles. Atoms bonded as molecules are shown by circles placed adjacent to each other.

The chemical idea being tested is: The distinction between elements, compounds and mixtures arises because atoms are arranged differently in each. Elements comprise one type of atom, mixtures have two or more types of atom (or molecule) not bonded together, and compounds have two or more types of atoms bonded together.

The expected answers are:-

(a) D (b) B (c) A.
Diagram C represents a mixture of an element and a compound.

Element and compound

Iron (Fe) is a chemical element. Water (H_2O) is a compound.

Define the terms "element" and "compound".

What test (or tests) could a chemist do on a sample of iron to show that it is an element?

What test (or tests) could a chemist do on a sample of water to show that it is a compound?

Element and compound looks at the distinction from a third perspective. Students are asked for definitions of the two terms and are asked to support this by describing suitable tests. Of course, a beginning student will not know about mass spectrometers, but could use the type of information given in *Substances* as the basis of an answer. Thus, *Element and compound* turns the distinction upside down by inviting the student to play the part of the chemist instead of depending on a supply of information.

Identify which gas is:-

(a) a mixture of the two elements; ________

(b) a compound; ________

(c) one element alone. ________

There is one diagram which you haven't chosen. What do you think is represented by that diagram?

This question was placed first in the test paper as it probes a very basic idea which all students are likely to have met before starting A level and therefore would be a non-threatening start for students. *Molecules* uses pictorial representations of four gases to probe students' ability to distinguish between elements, compounds and mixtures. The elements are represented by different coloured circles. Atoms bonded as molecules are shown by circles placed adjacent to each other.

The chemical idea being tested is: The distinction between elements, compounds and mixtures arises because atoms are arranged differently in each. Elements comprise one type of atom, mixtures have two or more types of atom (or molecule) not bonded together, and compounds have two or more types of atoms bonded together.

The expected answers are:-

(a) D (b) B (c) A.
Diagram C represents a mixture of an element and a compound.

Element and compound

Iron (Fe) is a chemical element. Water (H_2O) is a compound.

Define the terms "element" and "compound".

What test (or tests) could a chemist do on a sample of iron to show that it is an element?

What test (or tests) could a chemist do on a sample of water to show that it is a compound?

Element and compound looks at the distinction from a third perspective. Students are asked for definitions of the two terms and are asked to support this by describing suitable tests. Of course, a beginning student will not know about mass spectrometers, but could use the type of information given in *Substances* as the basis of an answer. Thus, *Element and compound* turns the distinction upside down by inviting the student to play the part of the chemist instead of depending on a supply of information.

The chemical idea being tested is: (definitions) Elements are made up of atoms which have identical chemical and physical properties. Compounds are made up of two or more different types of atom chemically bonded together.

The chemical idea being tested is: (tests) A test must identify how many types of atoms are present in the substance. The atoms in a compound must be split apart to be counted. The mass spectrometer does this by breaking molecules up. Electrolysing water separates hydrogen from oxygen.

The expected answers are:-

1. An element is a pure substance which cannot be split up into any other pure substance (Freemantle, 1987)

OR An element is a substance that consists of only one type of atom. (Atkins, 1989)

OR An element is composed of atoms with identical numbers of protons.

2. A compound is a specific combination of elements with a fixed composition. (Atkins, 1989)

OR A compound is a pure substance composed of two or more elements combined in fixed and definite proportions. (Freemantle, 1987)

OR A compound is composed of atoms with different numbers of protons chemically bonded together.

3. A test for iron is to use a mass spectrometer which separates atoms with different proton numbers. Only one peak will be seen (excepting isotopes).

OR Iron will give one product (a mixed oxide) when burned in air.

4. A test for water is to use a mass spectrometer. More than one peak will be seen, due to the molecules of water breaking up into smaller parts. This shows that water is a compound.

OR The elements in water can be separated by electrolysis.

As students will not give the definitions precisely in the format of words given above, these can only be taken as examples of suitable answers. Students may use similar formats to express the same information.

Substances

For each of the substances described below, tick the box you think best fits the description of the substance. Also, explain how you decided which box to tick.

A is a yellow solid which does not conduct electricity, but burns in oxygen to give one product.

Substance A is :-

a compound ☐ a non-metal element ☐ a metal element ☐ a mixture ☐

Explanation

B is a silvery grey solid which conducts electricity and burns in oxygen to give one product.

Substance B is:-

a compound ☐ a non-metal element ☐ a metal element ☐ a mixture ☐

Explanation

C is a colourless liquid which burns when ignited to give carbon dioxide and water.

Substance C is:-

a compound ☐ a non-metal element ☐ a metal element ☐ a mixture ☐

Explanation

D is a dark blue liquid which produces several spots on a chromatogram.

Substance D is:-

a compound ☐ a non-metal element ☐ a metal element ☐ a mixture ☐

Explanation

Substances probes students' ability to recognise elements, compounds and mixtures using information about physical and chemical characteristics. The distinction between metal and non-metal elements is studied early in chemistry courses. The term "chromatogram" may not be well-known, so substance D may not be identified by beginning students as a mixture.

The chemical idea being tested is: Elements, compounds and mixtures can be distinguished by studying evidence from physical characteristics and chemical tests.

The expected answers are:-

A is a non-metal element, because it does not conduct electricity and burns in oxygen to give one product only.

B is a metal element, because it does conduct electricity and burns in oxygen to give one product only.

C is a compound, because it burns to give two products. It must contain carbon and hydrogen combined together. These elements are separated in the chemical reaction.

D is a mixture, because the components can be separated by physical means.

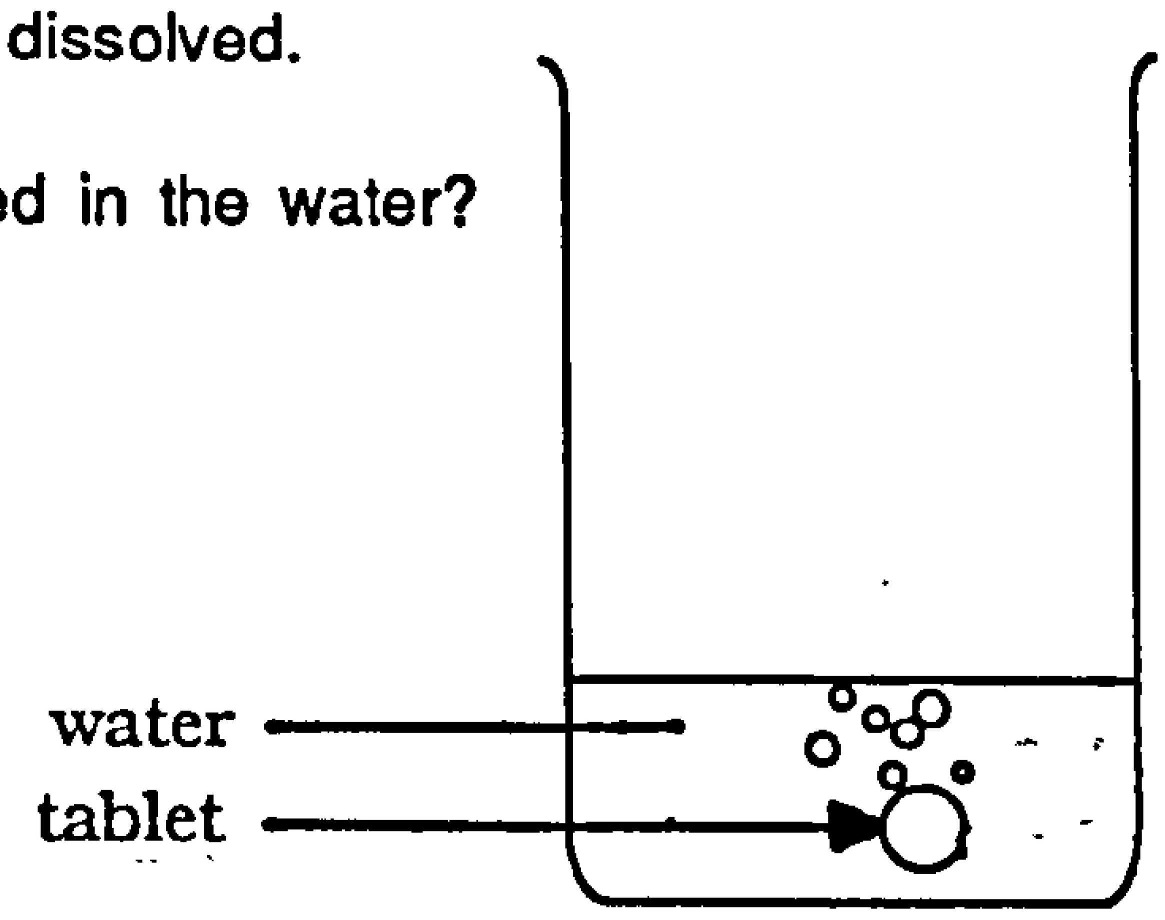
3.6.2 Chemical change

These questions probe students' understanding of different features of chemical changes. Questions involving physical changes are included in the chemical bonding section, as explanations for these involve intermolecular bonds.

<u>Tablet</u>

An Alka-Seltzer tablet is dropped into a beaker of water. Bubbles of gas are seen and after a while the tablet has completely dissolved.

Where was this gas before the tablet was dropped in the water?

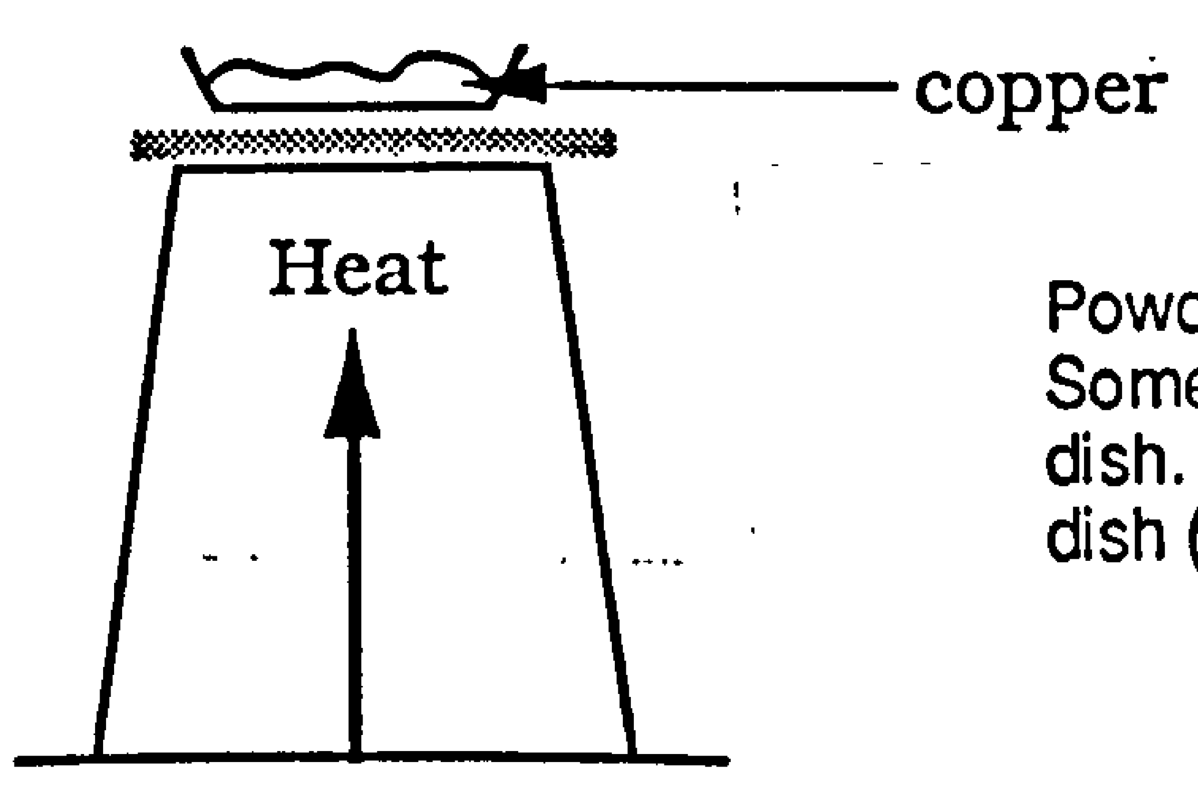


Tablet probes students' ideas about the evolution of gases in chemical reactions. I wanted to know if students recognise that gases form as a result of rearrangement of atoms of reactants, rather than thinking that the gas evolved pre-existed in, for example, tiny bubbles, waiting to be released.

The chemical idea being tested is: The gas is formed as a product of a chemical reaction and did not exist at the start. Atoms of the reactants rearranged to form the gas.

The expected answer is:-

The gas did not exist. The atoms it is made of were rearranged in a chemical reaction.



<u>Copper</u>

Powdered copper metal has an orange-red colour. Some powdered copper metal was placed in a small dish. The mass of the dish and copper was 40g. The dish (and metal) were heated in air.

After a few minutes, black stuff appeared in the dish. The mass of the dish and contents had gone up to 45g.

Where did the black stuff come from?

This question was not trialled, but was included as an alternative to A10/B10(a)/C10(a) at the final stage. An example of a reaction involving a gaseous reactant forming a solid product was used to contrast with *Tablet*, where a gas is produced. If students did not realise a chemical reaction had taken place in this instance, they may suggest that the "black stuff" came from another source, such as the air, or that the metal had "turned into" carbon.

The chemical idea being tested is: A chemical reaction has occurred between copper and oxygen which forms a solid, black product. The increased mass is the oxygen which has combined with the copper.

The expected answer is:-

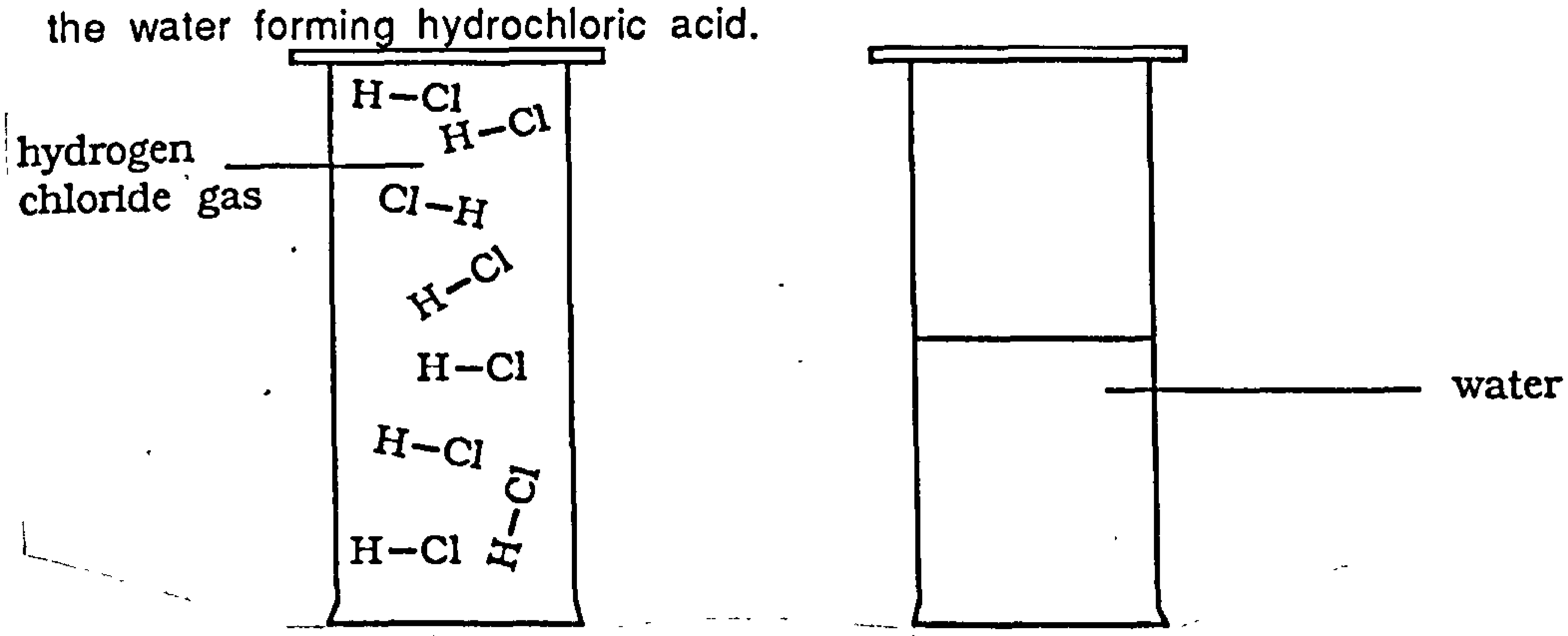
The increase in mass is due to the copper reacting with oxygen in the air:-

$$2Cu\ (s) + O_2\ (g) \rightarrow 2CuO\ (s).$$

The "black stuff" is copperII oxide.

Hydrogen chloride

Water is added to a gas jar of hydrogen chloride gas. The gas dissolves in the water forming hydrochloric acid.



(a) Use the second diagram to show how hydrochloric acid is formed from hydrogen chloride and water. You can show water particles too if you wish.

(b) A piece of magnesium is added to the hydrochloric acid. A reaction takes place producing hydrogen gas.

Explain how the hydrogen gas is formed.

Several chemical ideas are contained in this question. An acid/metal reaction probes students' ideas about the displacement of hydrogen. It also examines students' ideas about acids, specifically, that acids contain hydrogen ions. *Hydrogen chloride* supports the information gained from *Solution* by providing an example of a gas dissolving in water. In addition, the production of hydrochloric acid by this route includes an example of heterolytic fission. *Hydrogen chloride* was only devised shortly before completion of the test paper, so was not included in the pilot study.

The chemical ideas being tested are: Acids contain hydrogen ions. In hydrochloric acid, these form when hydrogen chloride molecules split into hydrogen ions and chloride ions (an example of heterolytic fission) when the gas is dissolved in water. The hydrogen ions are displaced as hydrogen gas when magnesium metal is added.

The expected answers are:-

> H^+ or H_3O^+ ions should be drawn in the second gas jar with Cl^- ions alongside them.
>
> The chemical event:-
>
> $$2H^+\ (aq) + Mg\ (s) \rightarrow H_2(g) + Mg^{2+}(aq)$$
>
> applies to the second part. Hydrogen ions are displaced when magnesium metal is added. Each one accepts an electron from a magnesium atom and forms a covalent bond with a second hydrogen atom. These pairs of atoms are displaced as gas.

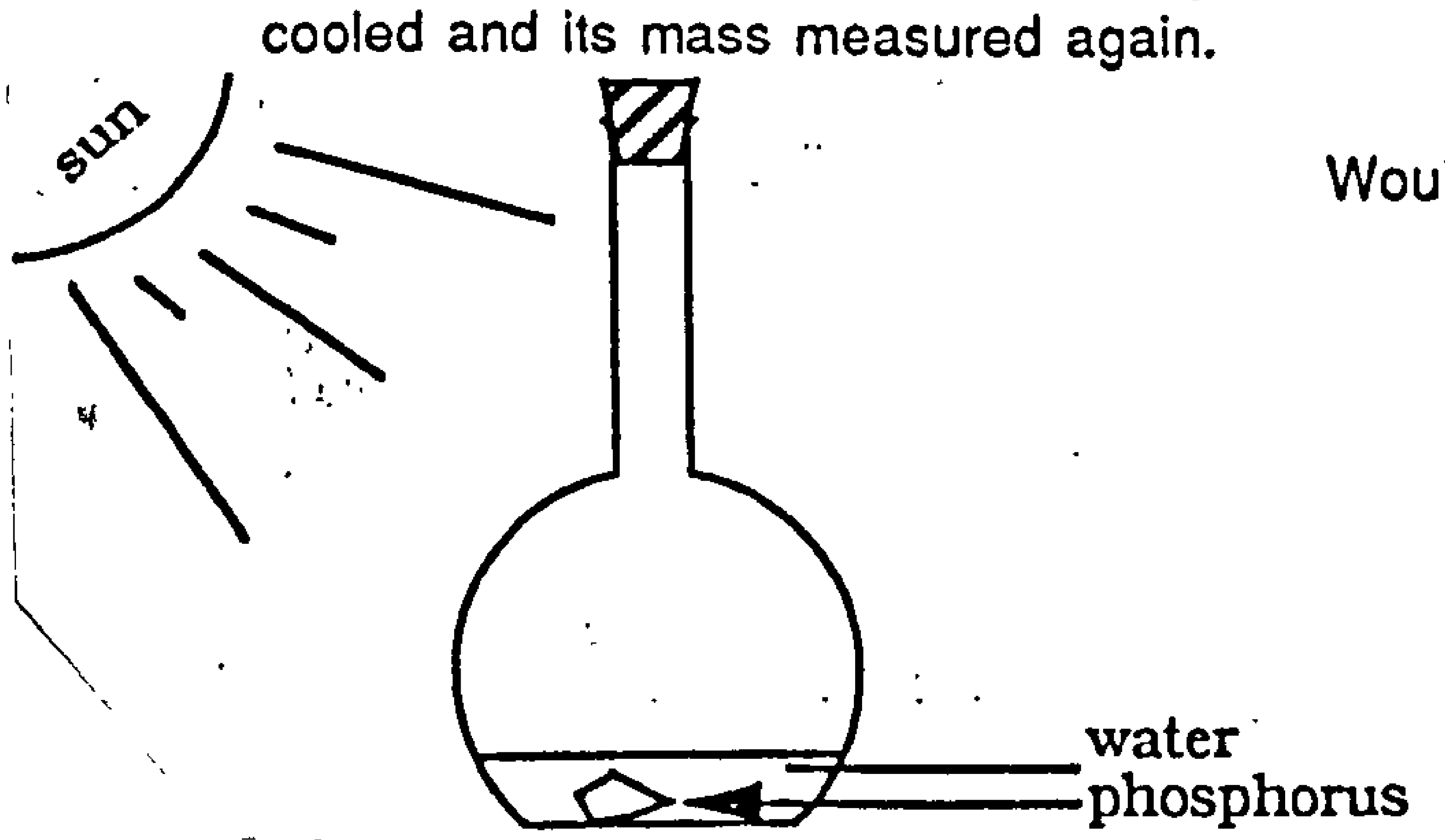
Care was needed in coding responses to *Hydrogen chloride*, as students could misunderstand the chemical event.

3.6.3 Conservation of mass in closed systems

Three questions, *Phosphorus*, *Precipitation* and *Solution*, probe ideas about conservation of mass in closed systems.

<u>Phosphorus</u>

A piece of phosphorus and some water were placed in a flask. The flask was sealed with a rubber stopper. The mass of the flask and contents was 400g. The sun's rays were focussed on the phosphorus which caught fire. White smoke was produced which slowly dissolved in the water. The flask was cooled and its mass measured again.



Would you expect the mass to be:

- ☐ more than 400g
- ☐ 400g
- ☐ less than 400g

Explain why you chose your answer.

Phosphorus uses the reaction between phosphorus and oxygen in a sealed chamber as a means of probing students' ideas. Although the question is straight-forward, the reactions involved are relatively complicated and are not explained. These could distract respondents to give incorrect answers.

The chemical idea being tested is: Mass is conserved when chemical reactions take place.

The chemical event is: Two reactions occur. The first happens after the water has evaporated:-

$$4P(s) + 5O_2 (g) \rightarrow 2P_2O_5 (s)$$

the "white smoke" is the P_2O_5. The second stage occurs on cooling:-

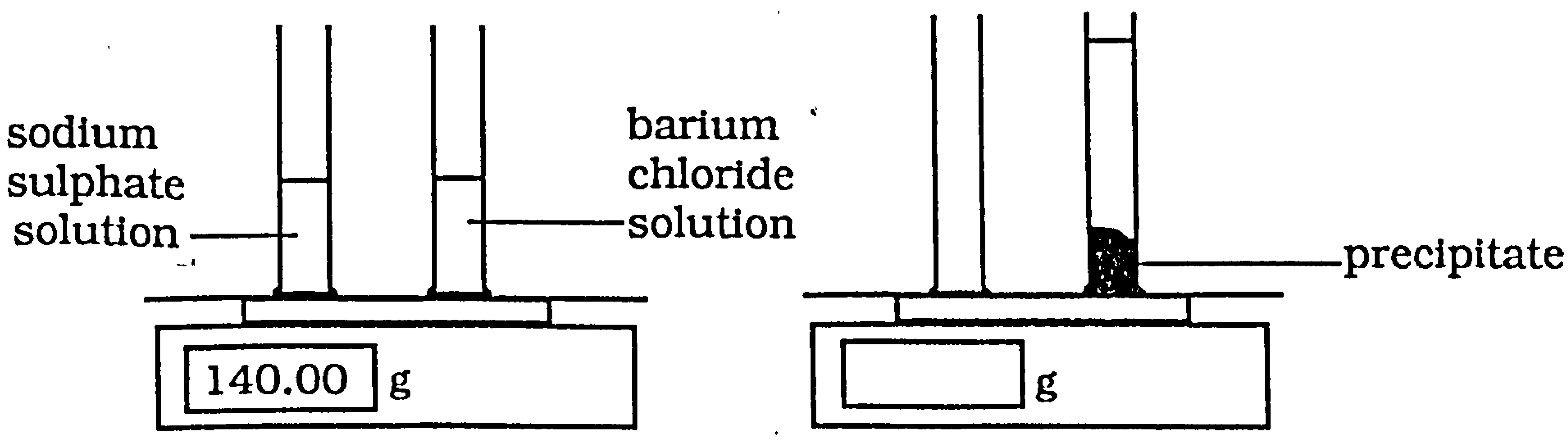
$$3H_2O(l) + P_2O_5 (s) \rightarrow 2H_3PO_4 (aq)$$

After the water recondenses the white smoke dissolves forming phosphoric acid.

The expected answer is: 400 g. The mass will be unchanged although a chemical reaction between oxygen and phosphorus takes place. Also, the flask is sealed so nothing can escape.

Precipitation

Aqueous solutions of two salts, sodium sulphate (Na_2SO_4 (aq)) and barium chloride ($BaCl_2$ (aq)), are placed in separate measuring cylinders on a top pan balance. The total mass is recorded as 140g.



The sodium sulphate solution is poured into the barium chloride solution. Both measuring cylinders stay on the balance. A precipitation reaction takes place.

What will the mass reading be after the reaction?

☐ Less than 140g

☐ 140g exactly

☐ More than 140g

Explain why you think this.

Precipitation uses a different closed system, the reaction between two aqueous solutions, to probe students ideas. Here, students cannot give a response equivalent to "the flask is sealed", as although the reaction is contained, both cylinders remain open. Beginning students may find this question difficult if they have not seen a "precipitation" reaction and do not know the meaning of the word. Also, students may not know the compounds used, so may be dissuaded from answering the question.

The chemical idea being tested is: Mass is conserved when a precipitation reaction takes place.

The chemical event is:-

$$BaCl_2\ (aq) + Na_2SO_4\ (aq) \rightarrow BaSO_4\ (s) + 2NaCl\ (aq).$$

The expected answer to *Precipitation* is 140 g. The explanation is that the mass is unchanged although a chemical reaction has occurred.

Solution

20g of sodium chloride is dissolved in water. The mass of the water and beaker before any sodium chloride is added is 200g.

(a) What is the total mass of the sodium chloride solution and beaker?

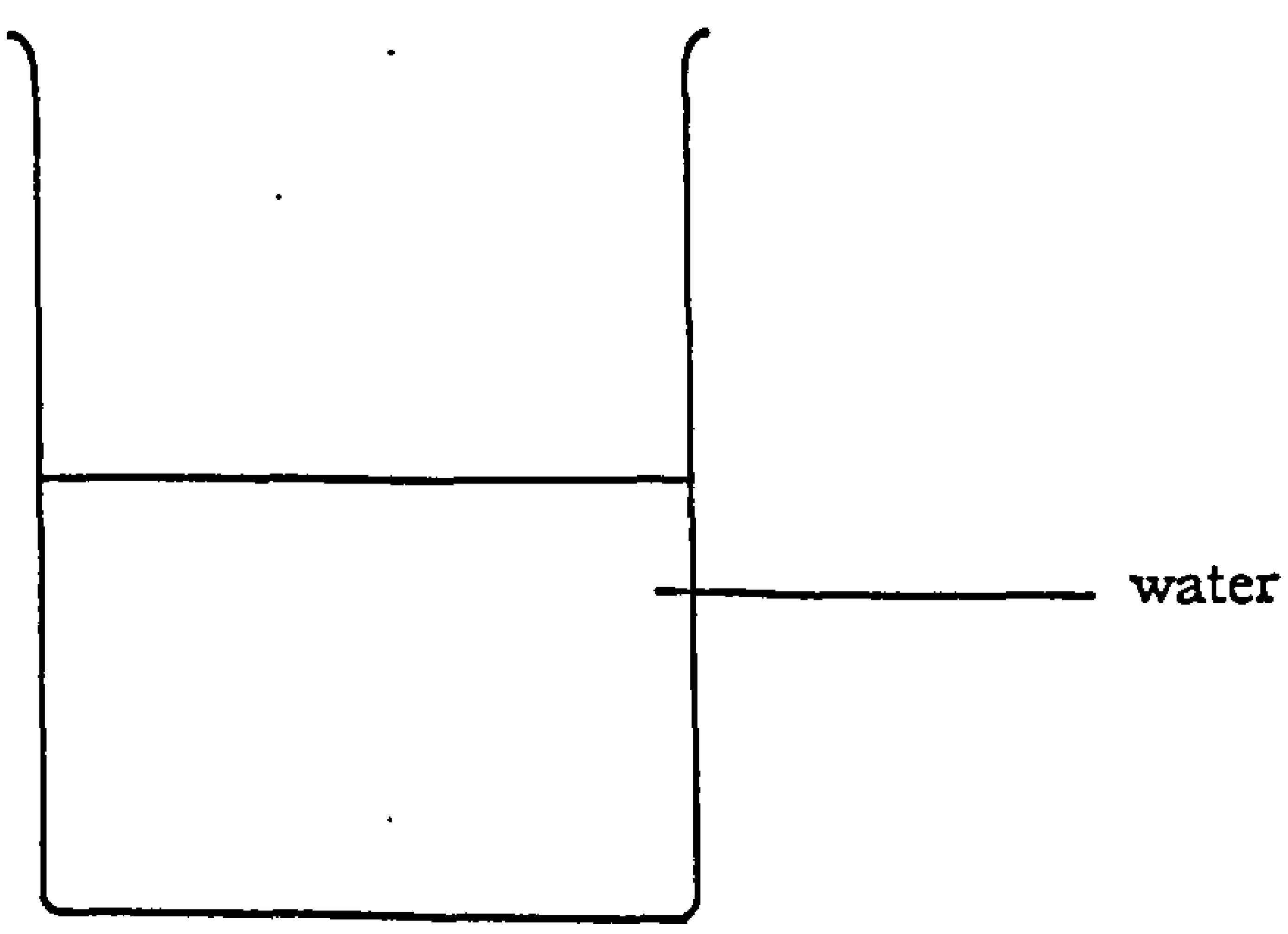
☐ Less than 220g

☐ More than 220g

☐ 220g exactly

Explain why you think this.

(b) Use the diagram of the beaker to show what you think happens when the sodium chloride is dissolved in water.
You can show water particles too if you like.



Although dissolving may not, as chapter 2 shows, be considered a chemical reaction, this question was included because students may not realise that mass is conserved when a substance dissolves in water. *Solution* was devised after the pilot study, so had not been trialled prior to inclusion in the test paper. Although only responses to the written part of the question were analysed in the data chapters, the diagrams gave useful indications as to the meanings of the written statements and therefore supported the coding scheme.

The chemical idea being tested is: The mass of a solution equals the mass of solute and the mass of solvent. Mass is conserved in dissolving.

The chemical event is: the dissolution of the ionic lattice of sodium chloride:-

$$NaCl(s) \rightarrow Na^{+}(aq) + Cl^{-}(aq)$$

The expected answer is: 220 g, because mass of solution equals the mass of solute plus the mass of solvent. Mass is conserved when a substance dissolves.

3.6.4 Reacting mass reasoning

Three questions probe students' ability to calculate reacting masses. *Carbon* and *Power Station* form a pair, using the open system carbon/oxygen reaction, so add to the information gained from answers to *Petrol. Iron sulphide* utilises the reaction between iron and sulphur.

<u>Iron sulphide</u>

Iron and sulphur react to form the compound iron sulphide. 56g of iron and 32g of sulphur produce 88g of iron sulphide.

$$\begin{array}{lclcl} Fe\ (s) & + & S\ (s) & \longrightarrow & FeS\ (s) \\ 56g & + & 32g & \longrightarrow & 88g \end{array}$$

What would you get when twice as much iron, 112g, and more than twice as much sulphur, 80g, are made to react?

This question probes directly understanding of the principle that elements only react in fixed proportions. Students who do not know this (or who miss the point, but do know it) will add 112 and 80 to give 192 g of iron sulphide. This reaction was chosen because it is used frequently at GCSE to demonstrate the formation of a compound, and so is likely to be familiar to most respondents.

The chemical idea being tested is: Elements react in fixed proportions by mass. I call this "reacting mass reasoning".

The expected answer is: 176 g FeS + 16 g S.

Carbon

Use the equation below to estimate the mass of carbon dioxide produced when 24g of carbon is burned in 64g of oxygen gas. The equation for the reaction is:-

$C (s) + O_2 (g) \longrightarrow CO_2 (g)$

Relative atomic mass values are :- C = 12, O = 16.

The question *Carbon* was included in the test paper in order to provide the information needed to answer the later question *Power Station*. The link, however, was not explicitly pointed out, so in practice, students may recall the data required quite independently of this question. The correct answer can be obtained by adding the two figures provided, a point considered when coding the responses.

The chemical idea being tested is: Carbon and oxygen react in fixed ratio by mass. Two moles of carbon react with two moles of oxygen gas producing two moles of carbon dioxide.

The expected answer is: 88 g CO_2.

3.6.5 Conservation of mass in open systems

Two questions probe students' ideas about open system chemical reactions.

Petrol

A car with a mass of 1000 kg has 50 kg of petrol put in its tank. The car is driven until the tank is completely empty. The car then has a mass of 1000 kg again. What is the approximate mass of the exhaust gases given off while the car is being driven?

The approximate mass of exhaust gases is ....kg

Explain your reasoning as fully as possible.

Petrol probes students' ideas about conservation of mass in reactions using an open system chemical reaction between petrol and oxygen. Students are expected to realise that the mass of exhaust gas would be greater than the mass of the petrol, because of the additional oxygen from the atmosphere. Although the question does ask for an "approximate mass", which may imply that a calculation is needed, the range of responses produced in the pilot study suggested that students' misunderstandings were caused by deeper difficulties than this. The chemical compound petrol provides the storyline for one of the early SAC units teaching basic thermodynamics and organic chemistry, so students' responses may change after studying this unit. Therefore, despite reservations about the wording of *Petrol*, the question was included in the test paper.

The chemical idea being tested is: Petrol combines with oxygen to give a mixture of exhaust gases which include carbon dioxide, carbon monoxide and oxygen.

The chemical event is: A useful summary of the complex series of reactions assuming complete combustion is:-

$$2C_8H_{18}\,(l) + 25O_2\,(g) \rightarrow 16CO_2(g) + 18\,H_2O\,(g)\,.$$

The expected answer is: The mass of exhaust gas is greater than the mass of petrol, because petrol reacts with atmospheric oxygen and produces a mixture of exhaust gases.

Power Station

> A coal-burning power station burns 1000 tonnes of high quality coal each day.
>
> Estimate the mass of carbon dioxide which will go up the flue chimney each day.

Power Station uses the same reaction as *Carbon*, but applies this on a much larger scale. To solve the problem, students have to convert the mass of coal to moles, then multiply this by the relative molecular mass of carbon dioxide to obtain the mass of product. Students may not answer this because the units, tonnes, are unfamiliar, or because they cannot carry out the first step in the calculation. Also, the reactants, carbon and oxygen, are not explicitly named, so respondents are expected to realise that "high quality coal" is basically carbon. The pilot study indicated that students approach this question in a variety of ways and that a proportion do not conserve mass in this situation. *Power Station* was included in the test paper to assess how students' ideas about this develop as they progress through an A level course.

The chemical idea being tested is: 1000 tonnes of carbon (coal) burn in oxygen to produce carbon dioxide. The mass of carbon dioxide is greater than the mass of coal.

The chemical event is:-

$$C(s) + O_2(g) \rightarrow CO_2\,(g)$$

The expected answer is: The mass of carbon dioxide is approximately 4000 tonnes. If the correct data is used, and coal is assumed to be 100% carbon, the more precise value, 3667 tonnes, is obtained.

3.6.6 Chemical bonding

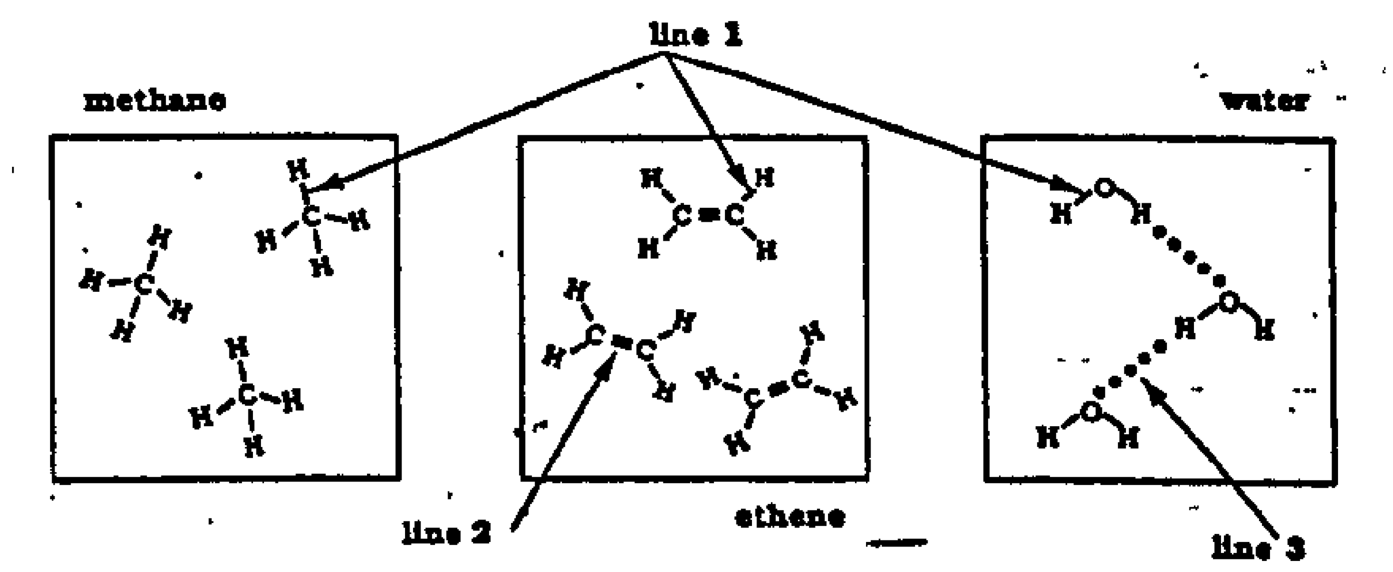
Questions probing ideas about intra- and intermolecular bonds are included. Care was taken that intermolecular bonds were probed as far as possible using chemical events likely to be familiar to beginning A level students.

Intramolecular bonds

The first question, *Chemical bonds,* probes ideas about covalent and hydrogen bonds, so although the complete question is given here, the chemical ideas being probed are considered separately.

<u>Chemical bonds</u>

The diagrams represent molecules of methane, ethene and water.



(a) Explain as fully as possible the meanings of the lines marked 1, 2 and 3.

Line 1

Line 2

Line 3

(b) What differences are there between:-

(i) line 1 and line 2;

(ii) line 1 and line 3? (I already know that line 3 is not a line but dots...)

This question probes students' ideas about covalent bonds. As these feature in both GCSE and A level courses in different degrees of detail, I anticipated that this would be reflected in the types of descriptions respondents give.

The chemical idea being tested is: A covalent bond comprises two electrons, one from each atom, sharing the same electron orbital. If two electrons are involved from each atom, a "double" bond is formed. Covalent bond formation confers stability on the atoms.

The expected answer is:-

> Line 1 represents a single covalent bond formed between carbon and hydrogen when each donates one electron to form a pair between the two nuclei; line 2 represents a double covalent bond in which two pairs of electrons are shared between two carbon atoms.
>
> A double covalent bond is stronger (requires more energy to break) and shorter than a single covalent bond.

As the pilot study responses indicate, students may give more detail than this. Also, information in the "Line 1 / Line 2" section above may be given in the part asking about differences between the bonds.

Methane molecules

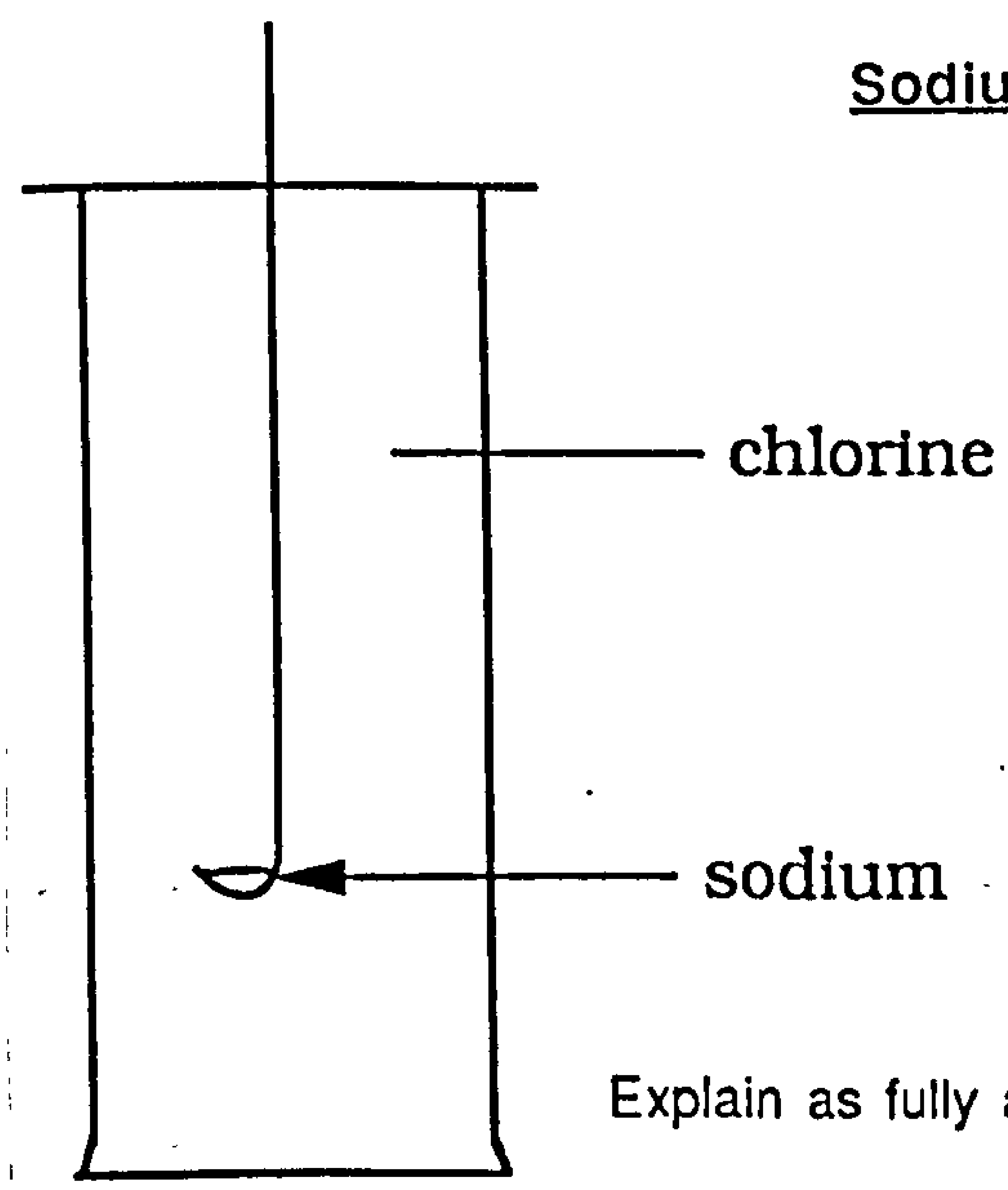
> Natural gas is mainly methane, CH_4.
>
> Explain as clearly as you can why carbon and hydrogen form molecules with the formula CH_4 rather than CH_3 CH_2 or CH.

This question probes students' association of covalent bond formation with electron configurations. Students meet electron configurations at A level, so may use this in the second and third surveys.

The chemical idea being tested is: Stability is associated with the formation of covalent bonds by which electron orbitals are filled by sharing a pair of electrons between two atoms.

The expected answer is: CH_4 is the most stable formula of those listed. This formula confers the greatest stability on both atoms as their outer electron shells are filled by sharing electrons with this combination.

Sodium and chlorine



> When a piece of hot sodium metal is placed in a gas jar of chlorine, a violent reaction takes place and spots of a white substance (sodium chloride) are spattered on the inside of the jar.
>
> Explain as fully as you can what is happening in the gas jar.

This question probes students' ideas about the formation of ionic bonds. Sodium chloride was selected as a compound likely to be familiar to all students.

The chemical idea being tested is: Elements may form bonds by ionic bond formation. In this process, one or more electrons are transferred between atoms, making charged particles called ions. The ions bond together by electrostatic attraction, forming an ionic lattice by releasing energy.

The chemical event is: $Na(s) + Cl_2(g) \rightarrow 2NaCl\ (s)$

The expected answer is: The violent reaction occurs because an ionic lattice is being formed between sodium and chlorine. This involves the transfer of an electron from a sodium atom to a chlorine atom, resulting in the formation of ions. The violence of the reaction is related to the large amount of energy released when the ions of opposite charge bond together.

Intermolecular bonds

The expected answers to three questions, *Hydrogen bonds*, *Chlorides* and *Boiling* depend on understanding that intermolecular bonds affect physical properties.

Hydrogen bonds

This question is part of *Chemical bonds*, given above. Water is the most well-known substance whose physical characteristics are affected by hydrogen bonds. Although GCSE students are not taught about hydrogen bonds, this question was included to establish how students' ideas about these bonds develop.

The chemical idea being tested is: Hydrogen bonds form between molecules in which hydrogen is covalently bonded to a highly electronegative atom, namely N, O or F. Hydrogen bonds increase the boiling and melting points of substances, giving higher values than expected from relative molecular mass values.

The expected answers are: Line 3 represents a hydrogen bond. The hydrogen bond arises because oxygen is very electronegative so water molecules are polar. The negative and positive regions of two water molecules bond together. Differences between line 1 and line 3 include: line 1 is an intramolecular bond and line 3 intermolecular; line 1 is longer and weaker than line 3.

Boiling

When water boils, bubbles appear in the liquid.

What is in the bubbles?

Boiling was adapted from Osborne and Cosgrove (1983) and was included in the test paper to probe more closely students' ideas about physical changes. The question was not included in the pilot study. To answer *Boiling* correctly, students need to understand that intermolecular bonds break, and therefore the bubbles contain steam, or gaseous water. If students respond "hydrogen" or "hydrogen and oxygen" this implies breaking of intramolecular bonds between hydrogen and oxygen.

The chemical idea being tested is: Boiling is a change of state. Water molecules change from the liquid state to the gaseous state. Hydrogen bonds between molecules are broken in the process. Gaseous water is called steam.

The chemical event is: $H_2O(l) \rightarrow H_2O\ (g)$

The expected answer is: The bubbles contain steam, since the hydrogen bonds between water molecules break when water boils so the molecules can separate further from one another.

Chlorides

The bonding in magnesium chloride ($MgCl_2$) is ionic. The bonding in titanium(IV) chloride ($TiCl_4$) is covalent.

A mixture of the two chlorides is heated to 1000 ^oC.

Explain why the vapour above the mixture consists only of titanium(IV) chloride.

This question probes ideas about intermolecular forces other than hydrogen bonds. Beginning A level students may not have heard of the compounds mentioned, although the pilot study suggested that by the mid-point of their courses, students were able to answer this question.

The chemical idea being tested is: Small dipole-dipole attractions (van der Waals' forces) between covalent molecules require much less energy to break than an ionic lattice.

The expected answer is: The vapour consists only of titanium(IV) chloride molecules because the intermolecular bonds between $TiCl_4$ molecules require relatively little energy to break them. Magnesium chloride has an ionic lattice structure which requires much more energy to break up.

3.6.7 Thermodynamics

Two questions, *Methane* and *Energy change*, probe students' ideas about basic ideas in thermodynamics.

Methane

Methane is natural gas. When methane burns, the equation for the reaction is:-

$$CH_4\,(g) + 2O_2\,(g) \longrightarrow CO_2\,(g) + 2H_2O\,(l)$$

This reaction can be represented on a diagram like this one from a chemistry textbook:-

Explain why

(a) a spark or match flame is needed to start methane burning;

(b) methane will continue to burn until it is all used up.

(c) The diagram shows that the burning of methane releases energy to the environment.
Explain as best you can where this energy comes from.

The chemical idea being tested is: energy is needed to break bonds between atoms but energy is released when bonds form. For any reaction, the difference between the energy required to break bonds and the energy released on bond making is the enthalpy change of reaction.

The expected answers are:

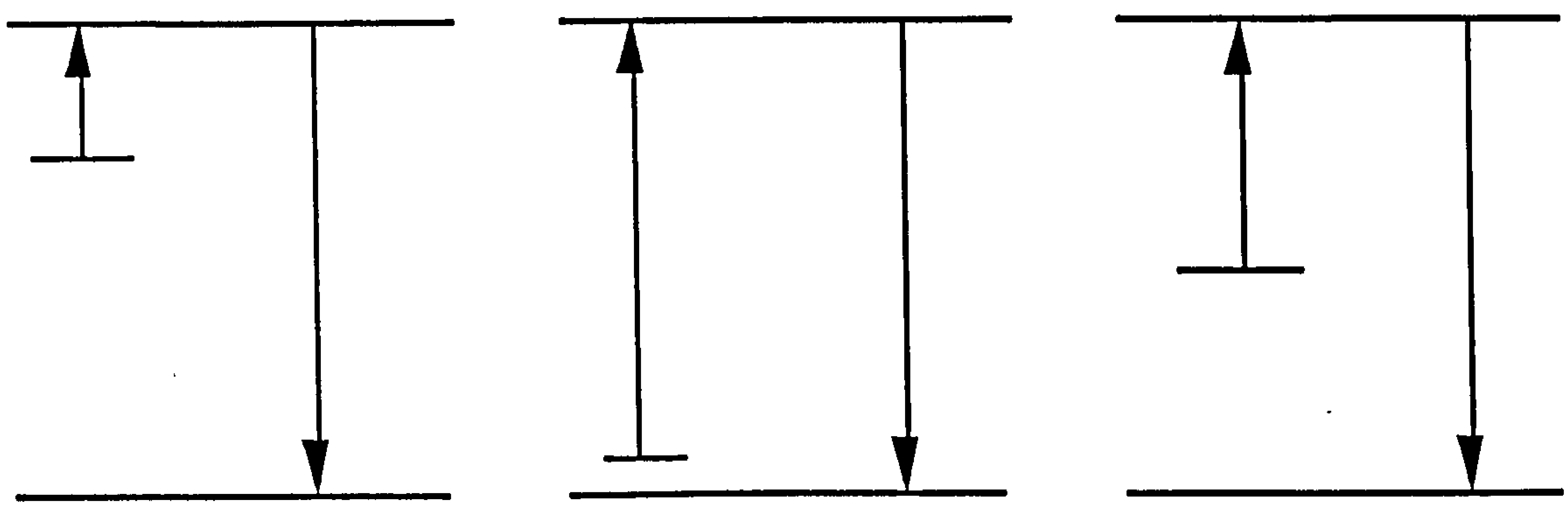
(a) methane and oxygen are stable as a mixture, but some molecules will break apart if energy is supplied. This starts a reaction between them.

(b) Energy is released when carbon dioxide and water form as products of combustion. Some of this energy is used to break up more molecules of reactants. This will continue until the supply of one reactant is exhausted.

(c) The energy comes from bonds forming between atoms of oxygen, carbon and hydrogen to make molecules of carbon dioxide and water.

Energy change

The three diagrams below represent the energy changes which take place during three chemical reactions.



A B C

Which of these energy diagrams do you think best represents the reaction between sodium and chlorine?

$2Na(s) + Cl_2(g) \longrightarrow 2NaCl(s)$ Energy diagram A / B / C

Please explain how you decided.

Energy change probes how students relate ideas about bond breaking and bond making to energy diagrams. The sodium/chlorine reaction is used as an example likely to be well-known. Two diagrams, A and C, could be correct, as no scale is included to assist students in discerning between them. This is taken into account in both the correct answer and the coding scheme.

The chemical idea being tested is: An upwards arrow on an enthalpy diagram represents energy absorbed when bonds are broken, a downwards one represents energy given out when bonds are made. The difference in lengths measures amount of energy released in a chemical reaction.

The chemical event is: The reaction between sodium and chlorine used in *Sodium and Chlorine*.

The expected answer is: Diagram A best represents the reaction. This shows the largest difference between the arrows suggesting a highly exothermic reaction. As no scale is given, diagram C could also represent this reaction.

3.6.8 Equilibria and Rates of reaction

One question, *Reactions*, probes students' ideas about equilibria. The pilot study suggested that students would give a range of responses, and that the range may be improved if more information to help the students was provided. Thus, energy change data was given to assist in determining the extent to which back reactions may be energetically feasible. Beginning students who have not seen this kind of information before may dismiss the question as "too difficult", but the extent of this type of response is expected to diminish as A level courses proceed.

<u>**Reactions**</u>

Hydrogen gas reacts with nitrogen and also with oxygen. The equations for the reactions are:-

$N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$ $\Delta H = -92\ kJmol^{-1}$

$O_2(g) + 2H_2(g) \longrightarrow 2H_2O(l)$ $\Delta H = -572\ kJmol^{-1}$

(a) Why is an equilibrium arrow ($\rightleftharpoons$) used in the nitrogen/hydrogen reaction but not in the oxygen/hydrogen reaction?

(b) Most reactions are written with an ordinary arrow ($\longrightarrow$) like in the oxygen/hydrogen reaction and are not called "equilibrium" reactions.

Explain as best you can why this is so.

The chemical idea being tested is: All reactions are equilibrium reactions, but where the equilibrium constant is very large (in practice, $>10^{10}$) a -> arrow is used. Even then, a tiny amount of material will be left unreacted at the end.

The expected answers are:-

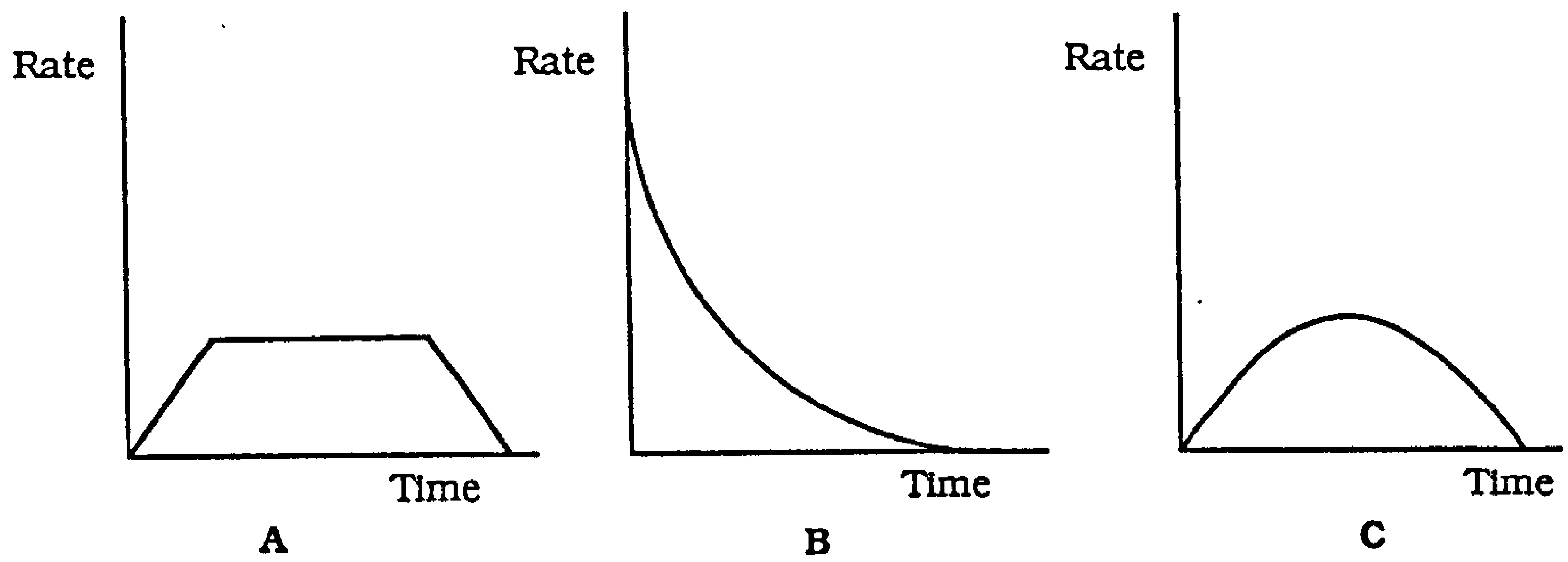
(a) The equilibrium arrow for the N_2/H_2 reaction indicates that the reverse reaction is thermodynamically feasible, but is not feasible for the O_2/H_2 reaction.

(b) All reactions are equilibrium reactions, but the equilibrium constants for some are very large, indicating that the amount of reactants remaining is very small. This is summarised by the -> symbol.

One question, *Reaction rates*, was trialled and included in the test paper to probe students' ideas about rates of reaction. Respondents were invited to explain what they thought the graphs represented, and to identify the most suitable graphs for two reactions. Reactions likely to be familiar from GCSE were selected. Students may find this question difficult because the graphs show rate against time, rather than, for example, "volume of gas produced", which they may have measured during rates of reaction experiments. In coding responses, only answers to parts (a) and (b) were considered, thus making the scheme much more manageable.

Reaction rates

Here are three graphs which show how the rate of a chemical reaction changes as time goes by.



Describe in words what each graph says about how the rate of a chemical reaction changes as the reaction goes on.

Graph A

Graph B

Graph C

Choose the graph you think best represents the reactions shown below.

(a) A solution of sodium carbonate is added to dilute hydrochloric acid.

$$Na_2CO_3(aq) + 2HCl\,(aq) \longrightarrow 2NaCl(aq) + H_2O(l) + CO_2(g)$$

Answer Graph .... represents this reaction best because..

(b) A piece of magnesium ribbon is added to dilute hydrochloric acid.

$$Mg\,(s) + 2HCl\,(aq) \longrightarrow MgCl_2(aq) + H_2\,(g)$$

Answer Graph .... represents this reaction best because..

The chemical idea being tested is: The initial rate of a liquid/liquid phase reaction is much greater than that of a solid/liquid phase reaction because surface to surface contact between reactants is much greater.

The expected answers are:-

(a) Graph B, because in a liquid/liquid phase reaction, the surface area is infinite, so the initial rate of reaction is very high.

(b) Graph C, because in a solid/liquid phase reaction, the rate depends on surface area. In this case, the acid first dissolves the oxide layer present on the metal surface, hence the rate increases slowly to a maximum.

Graph A implies that the rate of a reaction is constant for a period of time. This occurs in catalysed reactions where the maximum rate is limited by the availability of catalyst. Neither reaction is catalysed, so this graph is incorrect.

3.7 Student Interviews

To support the data obtained from the written survey, interviews with students were carried out after the first and second surveys. The post-first survey interviews sought to verify students' responses for coding purposes. Those carried out post-second survey were more extensive, aiming to find out if students could account for changes in their responses. In total, thirty-five respondents were selected for interview by arrangement with the school or college they attended. This section discusses the purpose of both sets of interviews, describes how students were selected and explains the interview strategy employed in both cases. The post-first survey interviews are considered first.

3.7.1 Post-first survey interviews

The post-first survey interviews with twelve students took place in December 1992. Their purpose was to verify answers given to the questions about conservation of mass in reactions and calculation of reacting mass. At this stage, coding schemes were available for these questions, so I focussed the interviews on these basic chemical ideas. I aimed to ascertain that the written answers were genuine statements of the students' thinking. This was important for two reasons. First, in coding responses I found, in some cases, that interpretation of a student's response was needed in order to place it in a category or code group. The student had not quite expressed him or herself sufficiently clearly for the answer to be coded instantly in one code group. If the response was interpreted in another way, it could be coded in a different way. Such responses could not be coded reliably on the basis of the written response alone. An interview might indicate the student's intended meaning. Second, an interview would indicate if the questions were indeed clear and unambiguous. I tried to be sure that nothing in the question had prompted the student towards giving an answer which an alternative wording, or inclusion of other information may have prevented.

Students gave their first responses to the test paper in September 1992. By the beginning of December, early coding schemes were devised for the questions on conservation of mass in reactions and the calculation of reacting mass. Interviews with twelve students from two colleges in different parts of the country were carried out. The students were selected from the sample on two criteria. First, the responses the students gave to some of these questions indicated they had misconceptions about some of the chemical ideas being probed. I asked about these answers because I needed to be sure they were what the students had intended to say. Second, the colleges they attended had to be accessible; although many students' responses were interesting and met the first criteria, some schools and colleges were a considerable distance from the Department.

The interview strategy

Appointments were made with individual students through their teaching staff. Teachers were not briefed beforehand about the content of the interviews and I did not ask for information about the extent of students' likely co-operation. I had not met any of the students prior to talking to them in the interview situation. I talked to each on a one-to-one basis, making a recording of the conversation with the student's agreement.

I attempted to put students at their ease by adopting a relaxed approach. Most were willing to talk and did so freely; others needed encouragement and gentle prompting. My aim was not to teach, but to encourage the student to talk about his or her answers in a non-confrontational way. I did not use a prepared set of questions; rather I allowed each student to talk at their own pace and based my next question on their preceding answer. Use of a pre-defined interview for all students was inappropriate because the wide variation in their written responses meant that no one set of questions would apply to all students selected for interview.

3.7.2 Post-second survey interviews

A second set of interviews was carried out in November, 1993 following the second survey in April that year. These aimed to find out what prompted changes in students' responses between the first and second surveys. Twenty-four students (one student was interviewed on both occasions) from six schools and colleges were interviewed about their answers to between six and ten questions. Students were selected so that about six responses to each question were included.

Selecting students

Students selected for interview at this stage demonstrated significant changes in their responses at the second survey. Obviously, not all students had given different answers, and some only changed their responses to certain questions. The twenty-four students were selected using a system based on scoring the number of changed answers found in the whole sample. This produced a subset of the large sample whose responses were examined closely to produce a "master-sheet" on which between six and ten changed answers to each question were recorded. A more detailed account of the selection procedure follows.

The codes given to first and second survey responses were recorded. The extent of change was determined using a scoring system which credited +1 for movement towards a correct answer and -1 for change away from the correct answer. Students whose answers to about ten questions had changed were noted. These formed a subset of the sample whose reasoning appeared to have altered significantly between surveys. A grid was drawn up showing student code number against question name. The grid was completed using students from the subset such that each question was included between six and ten times. This ensured that each question was adequately covered and that interviews for some students would involve approximately the same number of questions.

Organising the interviews

Appointments for the interviews were made through teaching staff. Interviews took place one-to-one, usually in a private tutorial room or office, occasionally in an otherwise empty laboratory. Students' permission to record the interview was sought in every case. About thirty minutes were allocated to each interview.

Interview strategy

Questions were prepared for every student which provided a basis for each interview, although discussion often ranged more widely. Students were always asked which answer they agreed with "now" and to identify, if possible, why their answer had changed. I was conscious that students had not been asked this type of question before, and so attempted to put them at their ease and to explain clearly what I required. Nevertheless, several students were extremely shy and needed a great deal of encouragement to give answers longer than one word. On these occasions I had to prompt answers by asking rather more "leading" questions than I would have liked. Most, however, were confident young people who were keen and interested in their work and this enthusiasm was apparent in the way they participated in the interview process.

Students who used incorrect reasoning were allowed to do so for a time, but I always sought to lead the discussion towards the correct reasoning where possible. With more confident students I adopted a "cognitive conflict" strategy (Nussbaum & Novick, 1981) to assist with this. On other occasions, I simply told the student the correct answer, in order to see if this was recognised by the student.

Interview outcomes

The interviews provided a rich source of data which supplemented the students' written answers. Despite the fact that the interviews took place several months after completion of the test paper, most students were able to provide helpful information about changes in their reasoning. Recalling their responses and thinking seemed not to be a problem. However, as chapter 5 will show, some questions proved easier to discuss than others.

A possible improvement may have been to interview the same students on both occasions. This could have provided continuity, enabling changes in students' thinking to be more closely identified. This was not considered when the first interviews were arranged, because at that stage I could not predict how many students (and schools or colleges) would be able to maintain their involvement in the study through to its conclusion. Indeed, several students included in the first group of interviews left their courses before the second survey, or did not complete the three papers.

3.8 Conclusion

This chapter has set out how the test paper used as the main data collecting instrument was devised. The pilot study, which formed part of the development process, has been described. I have explained how the written data, collected three times, was supported by interviews with selected students to verify responses and to aid ascertaining reasons for changes. In the next three chapters, we will examine the types of responses generated by the test paper and see how these change as students proceed through their courses.

Chapter 4

An Overview of the First Survey: What do beginning A level students understand?

Having described the methodological aspects of the study, we are now in a position to look at the results. This chapter is the first of three presenting data obtained in the research study. Here, I discuss the responses of 399 beginning A level students to the twenty-two questions presented in the test paper described in section 3.6. We will find out what difficulties the students had and, for some questions, see how their written responses were verified through interviews. First, however, I will explain how the coding schemes which follow in Tables 4.4 - 4.26 were devised.

4.1 Development of the coding schemes

Students' responses needed to be analysed in a systematic way using a common structure which could be applied to all twenty-two questions. I wanted to see clearly the levels of expected answers and those indicative of misconceptions, and be able to monitor changes in these as the study progressed. I began by looking at the responses of about twenty students to the questions probing aspects of mass conservation in reactions and gradually extended this to the full range of both scripts and questions. It quickly became apparent that I needed a system which would be flexible enough to accommodate a wide range of response types and permit rapid analysis of the final set of data.

The final structure upon which the data analysis is based uses six categories of response, lettered P - U, not all of which apply to every question. This was developed from early schemes which used a three-tier approach. In order to help understand reasons for using this seemingly complex system, I will describe how and why it evolved, beginning with the original coding scheme proposed for the first question I attempted to analyse, *Phosphorus.*

4.1.1 The first coding scheme

After the first survey scripts were returned, I began to devise a system for coding students' responses to *Phosphorus*. One reason for starting with *Phosphorus* was that this question was used (albeit with slightly different wording) in earlier studies (Andersson, 1984; Driver et al 1985), so a range of responses could be anticipated. Also, this question (see section 3.6.3) uses a multiple-choice format which made devising categories simple, as I could place answers in one of three groups depending on the box selected.

Table 4.1 gives my first attempt at coding responses to *Phosphorus.* Each response was given an individual code, comprising a letter and a number, for example, "A1". The letter corresponds to the box selected and the number(s) corresponds to the type of explanation offered.

Code	Description	No.	%
A0	< 400 g - no explanation	11	2.1
A1	< 400 g - uncodeable	8	1.5
A2.1	< 400 g - non-conservation - phosphorus used up	22	4.2
A2.2	< 400 g - mass decreases because P dissolves	18	3.4
A3.1	< 400 g - gas (or liquid) weighs less than solid	49	9.3
A3.2	< 400 g - non-conservation - energy lost from flask	13	2.5
A4	< 400 g - insufficient information	4	0.8
A	Total	125	23.8
B0	400 g - no explanation	16	3.0
B1	400 g - uncodeable	8	1.5
B2.1	400 g - common sense conservation	250	47.5
B2.2	400 g - common sense conservation - particle ideas	19	3.6
B3.1	400 g - elaborate accurate reasoning	21	4.0
B3.2	400 g - elaborate incorrect reasoning	47	8.9
B4	400 g - insufficient information	12	2.3
B	Total	373	70.9
C0	> 400 g - no explanation	8	1.5
C1	> 400 g - uncodeable	3	0.6
C2.1	> 400 g - more reactant made	3	0.6
C2.2	> 400 g - mass increases on dissolving	4	0.8
C3.1	> 400 g - solid weighs more than gas (or liquid)	1	0.2
C3.2	> 400 g - energy absorbed from the sun	3	0.6
C3.3	> 400 g - smoke is heavy	3	0.6
C4	> 400 g - insufficient information	3	0.6
C	Total	28	5.5

Number of responses = 526 Response rate = 96. 0%
No response = 22

Table 4.1: First coding scheme for responses to *Phosphorus*

Although this scheme does show the full range of responses in a systematic way, a number of problems became apparent as the coding progressed to other questions.

First, codes A1 and A4, B1 and B4, and C1 and C4 within each category seemed to represent the same type of response. If a student has not given sufficient information this response is effectively uncodeable, so the distinction between the two is unnecessary. In addition, I realised that similar explanations had been placed in the two different categories. For example, this response[3] was coded A1:-

"Some of the water would have been evaporated by the sun."

[3] Students' responses given in this section are deliberately not numbered. In subsequent sections, students are referenced using numbers 001 to 399.

while another, almost identical explanation was coded A4:-

> "Some of the water evaporated in the heat."

In subsequent versions, the two codes were combined under the label "uncodeable".

Second, the meanings of some response code descriptions were unclear. For example, by "elaborate accurate reasoning" (code B3.1) I meant responses such as:-

> "The sun produced the white smoke which then dissolved back into the water. The water will evapourate (sic) and thus condense = same mass."

which seem to arrive at the expected answer by giving a full explanation of events taking place in the flask. This type of response is discussed more fully in section 4.1.3.

Third, while this structure proved satisfactory for a multiple-choice format, it had to be borne in mind that there was no guarantee responses to other questions would fall neatly into three clearly defined categories.

Finally, and most importantly, it became clear that a coding scheme arranged purely on the "less than 400 g", "400 g", "more than 400 g" model did not fully distinguish between the expected and misconception-type answers. For example, responses such as:-

> "The oxygen would be burnt up reducing the mass." (coded A2.1)

and

> "...phosphorus produced a reaction with oxygen so some of the pho[s]phorus combined with the oxygen increasing the mass..."
> (coded C2.1)

clearly express a non-conservation idea, that mass changes when a chemical reaction takes place, yet they are coded differently. Other examples include ideas about energy, such as:-

> "Because energy had disappeared." (coded A3.2)

> "The energy from the sun was absorbed." (coded C3.2).

In addition, the responses coded B are placed in the centre of the table, which makes it difficult to assess quickly the proportion giving the expected answer. The coding scheme was therefore revised. So, let us look at the second version.

4.1.2 The second coding scheme

Table 4.2 gives the second coding scheme for responses to *Phosphorus.* It is similar in structure to the first, being based on three main categories lettered L, M and N.

RC	Description	No.	%
L1	400 g the flask is sealed/nothing can escape	213	53.4
L2	400 g formal conservation statement	1	0.2
L3	400 g the number of particles is unchanged	14	3.5
L4	400 g elaborate accurate reasoning	17	4.3
L	**Total**	**245**	**61.4**
M1	400 g elaborate incorrect reasoning	27	6.8
M2	400 g uncodeable or no explanation	12	3.0
M	**Total**	**39**	**9.8**
N1	< 400 g because energy is lost from flask	8	2.0
N2	> 400 g because energy is absorbed from the sun	3	0.8
N3	< 400 g mass decreases because P dissolves	15	3.8
N4	> 400 g because mass increases on dissolving	3	0.8
N5	< 400 g because gas / liquid weighs less than solid	30	7.5
N6	< 400 g because water evaporates	1	0.2
N7	> 400 g solid weighs more than gas / liquid	2	0.5
N8	< 400 g because phosphorus is used up	17	4.3
N9	> 400 g because more reactant made	6	1.5
N10	> / < 400 g uncodeable or no explanation	17	4.2
N	**Total**	**102**	**25.6**
NR	**No response**	**13**	**3.2**
	Overall total	**399**	**100.0**

Number of scripts	= 399[4]	No response	= 13
Number of responses	= 386	Response rate	= 96.7%

Key: RC = response code; the symbol / indicates equally acceptable answers.

Table 4.2: Second coding scheme for responses to *Phosphorus*

This scheme addresses many of the difficulties associated with the first one. Response codes L1 - 4 cover explanations which are in line with the expected answer. Answers coded N1 - 10 include responses indicative of misconceptions about the conservation of mass in this closed system reaction. Explanations such as those about energy are placed together, regardless of the original box selected by the student, so the proportions expressing these ideas can be estimated. In many respects, therefore, this coding scheme is an improvement on its predecessor.

However, there are still issues to be resolved. First, the characteristics of the "M" category are unclear. I placed responses such as:-

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4 The total number of students differs from the figure given in table 4.1. The 399 students were selected at random from the 526 to give a manageable number for the remainder of the study.

> "The water and phosphorus measures at 400 g, all that has changed is the phosphorus has gone from a solid to liquid and it's mass stays the same." (originally coded B3.2)

in the "M" category because although such students have selected the expected box, they do so for an incorrect reason. In this example, the student assumes that the phosphorus has changed state rather than reacted with oxygen. Also, responses where the expected box is chosen without explanation or with an uncodeable explanation are difficult to place. It would be unfair to code these "N", since no misconception is expressed, although an "L" code seems too generous, as many could be guesswork. So, these were coded "M" by default. Similarly, students who selected "less than 400 g" and "more than 400 g" but offered no explanation were not clearly expressing a misconception; they may have simply guessed incorrectly, or were not taking the question seriously.

Therefore, further modification was needed. In particular, the middle category required clearer definition. Also, an extra category could be created for responses like those coded N10, which would prevent their inclusion in the misconceptions section. I also needed to be sure that the basic structure of the scheme would be applicable to all questions. So, although the second coding scheme has some advantages over the first version, more work was needed to develop the clearest possible scheme of analysis. Development of the structure of the third and final coding scheme is discussed in the next section.

4.2 The final coding scheme structure

My first task in modifying the second coding scheme was to find a way of clarifying the "middle ground" responses which seemed to be neither in line with the expected answers nor expressing a misconception. This is discussed first. Next, I explain how resolving this provided the basis for the structure of the schemes used to code responses to the questions used in the study.

4.2.1 Understanding the chemical idea and the chemical event

Responses such as the B3.2 example given above provided the key to developing the final coding scheme structure. This student appears to understand the principle of mass conservation, but not that phosphorus reacts with oxygen. He (or she) misunderstands the chemical event. Similar types of response were found in answers to other questions. For example, some students explained that the gas produced in *Tablet* :-

"...did not exist, but was formed by elements in the water and tablet combining..."

This response type demonstrates understanding of the chemical idea being probed - the gas "did not exist"- but the accompanying statement represents misunderstanding of the reaction, which is between compounds in the tablet, not the tablet and water. In answer to *Hydrogen chloride*, some students knew that hydrogen ions were present, but explained that magnesium would react with the chloride ions. This again shows understanding of the chemical idea being probed, but misunderstanding of the chemical event.

A useful way of redefining the "M" category, therefore, would be to acknowledge in the coding scheme that students could show understanding of the chemical idea, but also misunderstand the chemical event implicit in the question. Codes could therefore be given on the basis of evidence of understanding one of two aspects:-

Aspect 1 The chemical idea probed by the question;
Aspect 2 The chemical event implicit in the question.

Of course, aspect 2 would only apply to questions in which a chemical event "took place", but was not explained in the preamble. These are: *Tablet, Copper, Hydrogen chloride, Phosphorus, Precipitation, Solution, Sodium and chlorine, Petrol, Energy change* and *Reactions.*

This meant I could place responses which gave evidence of understanding the chemical event alone, but no misunderstanding of the chemical idea into a separate category. Evidence of understanding these aspects could be used to define all categories and would apply to all questions because each involves a chemical idea. Let us look next at the application of these two aspects to the full range of categories.

4.2.2 Descriptions of the categories

Evidence for understanding aspect 1, no evidence for misunderstanding aspect 2

One objective of the research is to chart the development of students' understanding of basic chemical ideas. So, the first category must be for responses which give evidence of understanding the chemical ideas being probed. For example, these responses to *Solution* and *Phosphorus* respectively:-

"The mass doesn't change. By dissolving no atoms are lost." (220 g, *Solution*)

"Everything that was there originally is still there and will have the same mass." (400 g, *Phosphorus*) demonstrate understanding of the chemical idea that mass is conserved, since the box selected is consistent with the explanation. These students may demonstrate understanding of aspect 1, the chemical idea being probed, but give no indication of their thinking about aspect 2. Since, in practice, responses were either in terms of the chemical idea or chemical event, it proved impossible to devise a further category of evidence of understanding both, although students' ideas were probed more fully about both aspects in post-survey interviews.

Let us look at evidence of understanding aspect 1 required by other questions, where the chemical event is explicit in the question. For example, *Methane*, evidence is provided by an explanation alone, such as:-

> "Energy is needed to break the bonds in methane. A chain reaction has been started... Energy is released when bonds are made."

The chemical event relevant to the *Methane* question is clearly explained in the text, so students are placed in this category on the basis of evidence for understanding the chemical idea alone. For *Iron sulphide*, which probes students' ability to use reacting mass reasoning, evidence of understanding aspect 1 is given by "176 g" or "176 + 16 g sulphur", or the equivalent in words. Similarly, for *Power Station*, the response "3667 tonnes" is sufficient evidence.

Partial evidence for understanding aspect 1, no evidence for misunderstanding aspect 2

Several types of responses provide insufficient evidence of understanding aspect 1 for one of several reasons, illustrated by three examples. First, some questions, for example, *Precipitation*, can be answered by selecting the correct multiple-choice option alone, in this case 140 g. The student answering this way may have guessed, or he (or she) knew the explanation but for whatever reason did not say so. Second, the response "88 g" to *Carbon* is correct, but the numbers given in the question add up to 88, so it is possible the student may have obtained the correct figure by addition, not using reacting mass reasoning. So, this response alone amounts only to partial evidence. *Substances* provides the third example. A student may answer only some parts of the question correctly, leaving others blank, because although he or she is unable to distinguish between a mixture and a compound. Students who simply tick all the boxes may have guessed, or reasoned logically ("I'm sure there's one of each") being unsure of the explanations. Both these responses provide partial evidence of understanding the chemical ideas.

Evidence for understanding aspect 2, no evidence for misunderstanding aspect 1

Responses placed in this category are expressed in terms of aspect 2, the chemical event. For example, students may select the expected option, 220 g, in answer to *Solution*, but explain this as follows:-

> "I don't think that any gas would be given off to lose weight and nothing would increase it."

This student knows that sodium chloride does not react with water. These answers give no evidence for misunderstanding of aspect 1, but relate to the chemical event rather than the chemical idea. Other examples include answers to *Precipitation* in which 140 g is selected supported by an equation for the reaction.

Evidence for misunderstanding aspect 2, evidence for understanding aspect 1

Responses may imply understanding of aspect 1, the chemical idea, but demonstrate misunderstanding of the chemical event. *Solution* provides examples of this, such as:-

> "Sodium chloride reacts and gives off a gas" (less than 220 g)

This student in effect conserves mass, because the implication in selecting "less than 220 g" is that the gas given off will have mass, but he (or she) does not realise that no such reaction occurs. Similar examples are found in answers to *Phosphorus*, such as that given above (section 4.1) and *Precipitation*, where the notion that a gas is given off when the reaction occurs is also found. Responses to *Copper*, which suggest that the black stuff is a "mixture of copper and oxygen", imply that no reaction has occurred, so are also placed in this category.

Evidence of misunderstanding aspect 1

Responses demonstrating misunderstanding of aspect 1, such as most of those coded N in Table 4.2, form the fourth category. These indicate the student has a misconception about the chemical ideas being probed. Examples of evidence for misunderstanding of aspect 1 include the answers "<50 kg" or "less than 400 g" to *Petrol* and *Phosphorus*, accompanied by the explanations that patroller phosphorus is "used up". This response contradicts the chemical idea that mass is conserved in chemical reactions. The explanation to the third part of *Methane* that "bond-breaking releases energy" is also a misconception. In *Methane* the chemical event is explicit, so a student either understands the chemical idea that bond making releases energy, or he (or she) does not.

Uncodeable responses

Responses which cannot be placed in any of the other categories are coded U. These include responses which are incorrect with no explanation or which are incorrect and incomplete. Nonsense answers, of which there are a few, are also placed in this category. Examples include the N10 responses (Table 4.2), which do not provide any evidence for understanding or misunderstanding either aspect.

4.2.3 A summary of the six categories

The six categories of response are lettered P - U. A summary of the types of evidence placed in each follows:-

P Evidence for understanding aspect 1, no evidence for misunderstanding of aspect 2

Q Partial evidence for understanding of aspect 1, no evidence for misunderstanding of aspect 2

R Evidence for understanding aspect 2, no evidence for misunderstanding of aspect 1

S Evidence for misunderstanding aspect 2, evidence for understanding of aspect 1

T Evidence for misunderstanding aspect 1

U Uncodeable responses.

Thus, in the data tables each response code comprises a letter, P - U, and are numbered sequentially within each category. Two closely related responses, such as those describing the role of energy in answer to the *Phosphorus* question, are given the same letter and number, followed by a lower case letter. Thus, these responses about energy are coded "T1a" and "T1b" (Table 4.10).

The adoption of a six-category system allows the maximum flexibility while enabling every response to be placed into a specific section on the basis of extant written evidence. The use of the two aspects means that the poorly defined "middle ground" has structure and that descriptions for each response code are clearly expressed in terms of the chemical ideas and chemical events.

4.2.4 Verification of the coding scheme structure

Chemical educators were invited to comment on the coding schemes during the development of the final version. The distinction between chemical idea and chemical event was thought to be useful and clear. It was noted that the structure did indeed apply to all questions in the test paper. Comments on the placing of responses in specific categories were noted and alterations made. The final coding schemes were organised following this consultation period and are presented in Tables 4.4 - 4.26.

Next, prior to presenting the data, I discuss factors which influence the placing of responses in specific categories.

4.3 Factors affecting the coding of responses

In the case of some questions, one or more factors may contribute to placing a response in the appropriate category. It is important that these are understood before the data tables are examined.

The chemical event

Understanding of aspect 2 comes into play only where questions do not explicitly state the chemical event. Therefore, some coding schemes, for example for *Phosphorus* and *Petrol* use the full range of categories lettered P - U, because students' thinking about the chemical event may affect their answer. The coding schemes for most questions use four categories, P, Q, T and U, since the chemical events are explained in the question so students respond only in terms of aspect 1.

The expected answer

Placing a response in the most appropriate category depends on the nature of the expected answer. Some expected answers will not be coded P, because allocation of responses to categories is based on the accompanying explanation, or the working used to generate the answer. For example, as stated above, the expected answer to *Carbon* can be obtained by adding the numbers given in the question. So, the answer "88 g" alone is considered insufficient evidence for a P code. However, the response "3667" to *Power Station* would be coded P, as even though no working is given the student can only produce this answer by understanding the chemical idea being probed.

The effect of negative and implicit evidence

The absence of negative evidence may play a part in selecting the appropriate category for a response. For example, the response to *Phosphorus* 400 g "because the flask is sealed" is coded P, on the grounds that the student has shown evidence of understanding aspect 1, although it is possible the student does not understand that a chemical reaction has occurred in the flask. His or her understanding about the chemical event can, in this case, have no bearing on the category, because the respondent has said nothing about it, so evidence of misunderstanding the chemical event is absent. Secondly, implicit evidence of understanding one of the aspects has to be considered for some responses. For example the response to *Precipitation* "<140 g, because a gas is given off" is coded S. The student clearly misunderstands the chemical event - no gas is given off in the reaction - but implies that the gas has mass, so is conserving mass in his or her version of the chemical reaction and hence implicit in their answer is understanding of aspect 1.

The effect of the wording of the question

The wording of the question also has to be considered in placing a response in a category. For example, the question *Power Station* requests an "estimate" of the mass of carbon dioxide, implying that an accurate calculation is unnecessary. Sensible methods along the lines of the methods suggested below (section 4.9) which arrive at an estimate of say, 3800 or 4000 tonnes must therefore be coded P, as well as those stating 3667 tonnes.

4.4 The pre-16 background of the sample

In considering the responses of beginning A level students, their pre-16 background may be of interest. Table 4.3 presents the pre-16 background of the students responding to the first survey. The data indicate that more students had studied double award science courses than single subject chemistry.

	Grade	Single subject chemists		Double award scientists		Total %
		No.	%	No.	%	
Female	A	42	10.5	33	8.3	18.8
	B	25	6.3	31	7.8	14.1
	C	13	3.3	16	4.0	7.3
	BC	N/A	-	2	0.5	0.5
	D	3	0.8	1	0.2	1.0
	NR	1	0.2	-	-	0.2
		84	21.1	83	20.8	41.9
Male	A	37	9.3	63	15.8	25.1
	B	42	10.5	33	8.3	18.8
	C	17	4.3	23	5.3	10.1
	D	1	0.2	2	0.5	0.7
	E	-	-	1	0.2	0.2
	NR	-	-	-		
		97	24.3	122	30.6	54.9
Unknown	A	-	-	1	0.2	0.2
	B	1	0.2	1	0.2	0.4
	C	-	-	1	0.3	0.3
		1	0.2	3	0.7	0.9
Totals		182	45.6	208	52.1	97.7

In addition, nine students (2.3%, 3 female, 6 male) provided no information about the GCSE background. These may include students with overseas qualifications.

Table 4.3: Pre-16 background and gender distribution of the sample responding to the first survey.

Table 4.3 shows about 12% more boys than girls made up the sample. High proportions of both girls and boys had obtained A or B grades at GCSE, suggesting that many students had selected to study A level chemistry in the light of their examination success. Appendix 3 lists the schools and colleges from which the students were drawn.

At this stage, the type of A level course the students would follow is not important, as this chapter reports their responses to the test paper at the start. These provide a starting point against which progress can be monitored. Suffice it to say, therefore, that the 399 students comprised seventy-nine students who would follow "Traditional"-type A level courses, and 320 who would take the Salters' Advanced Chemistry course (SAC).

Let us now examine the data obtained in the first survey and the coding schemes for the questions in detail.

4.5 Differences between elements, compounds and mixtures

Three questions, *Molecules*, *Element and compound* and *Substances* probe students' ideas about the differences between elements, compounds and mixtures. The coding schemes and fundamental ideas are given in figures 1 - 3. The distinction between elements, compounds and mixtures is made very early on in students' experience of chemistry. These questions therefore probe a basic chemical idea which all students are likely to have met during their GCSE studies.

4.5.1 Molecules

Molecules probes students' ideas about elements, compounds and mixtures at the particulate level. The four "pictures" represent four gases. The preamble suggests that the gases could be "real". A possible quartet of real gases is the $H_2/Cl_2/HCl$ system, in which A would represent hydrogen or chlorine gas, B would be hydrogen chloride, C a mixture of hydrogen chloride and an element and D a mixture of hydrogen and chlorine.

Responses given to *Molecules* at the first survey are shown in Table 4.4.

RC	Description	%
P1	DBA A mixture of a compound and an element	73.4
P	Total	73.4
Q1	DBA No response	7.5
Q	Total	7.5
T1	DBA Incorrect explanation	14.1
T2	Multi-choice and explanation incorrect	4.0
T	Total	18.1
U1	Uncodeable	-
U2	No response	1.0
U	Total	1.0
	Overall total	100.0

n= 399

Table 4.4: First survey responses to *Molecules*

Table 4.4 shows that about 73% of the sample selected the correct gases and identified the components of gas C. This is one of the highest figures for P-coded responses in the first survey. Those placed in category Q amounted to a further 8%. These students only provided partial evidence of understanding, as although the multiple-choice parts were answered correctly, no response was given to the second part. Their answers are incomplete.

About 14%, coded T1, selected the correct multiple choice answers, but could not give a correct explanation for gas C. Examples of incorrect explanations include:-

> "An unstable compound as it has different amounts of elements in it."
> (Student number 035, response code T1)
>
> "A mixture of three elements?" (T1, 050)
>
> "It has its own element as impurity." (T1, 092)

These responses are evidence of misunderstanding the chemical idea, as they do not distinguish between elements, compounds and mixtures. Their responses also suggest that explaining the particulate nature of mixtures is harder than identifying elements and compounds alone. About 4% did not answer either the multiple choice or the second part correctly. These students may not have had a working particulate model of matter and were unable to visualise elements, compounds and mixtures in particle terms.

4.5.2 Element and compound

Element and compound probes students' application of the differences between substances to practical tests after first giving definitions for "element" and "compound". The responses of the 399 students to *Element and compound* are given in Table 4.5.

RC	Description	%
P1	E & C defined, two feasible tests suggested	11.3
P2	E & C defined, one feasible test suggested	28.8
P3	One correct definition, two feasible tests	0.3
P	**Total**	**40.4**
Q1	E & C defined, no feasible tests suggested	30.1
Q2	One correct definition, one feasible test	6.5
Q3	No correct definitions, two feasible tests	0.5
Q	**Total**	**37.1**
T1	One correct definition, no feasible tests	12.0
T2	No correct definitions, one feasible test	2.3
T3	No correct definitions, no feasible tests	8.0
T	**Total**	**22.3**
U1	Uncodeable	-
U2	No response	0.2
U	**Total**	**0.2**
	Overall total	**100.0**

n = 399

Table 4.5: First survey responses to *Element and Compound*

Addition of the figures for groups P1, P2 and Q1 shows that about 70% of the sample gave acceptable definitions for these terms, for example:-

> "Two or more elements which have formed bonds to each other." (Compound, 0223, P1)
>
> "When a particle is made up of only one sort of atom." (Element, 0306, P1)

The high level of correct responses to *Molecules* suggests that many students were able to visualise differences between elements, compounds and mixtures in terms of particles. Answers to *Element and Compound* confirm that standard textbook definitions were well-known by a majority of beginning A level students. Some gave a correct definition of element, but explained that a compound is :-

> "..a mixture of two or more elements." (057, T1)

These students seem to mean that a mixture is "bonded". This is significant, because it implies that this group did not distinguish between a mixture and a compound, but used the words interchangeably.

The coding scheme for *Element and Compound* is based on the proportions offering feasible tests to support definitions given in the first parts of the question. Table 4.5 shows that only 40%, a much lower figure, apply these definitions to a practical situation and that most of these (29%, P2) gave only one feasible test. Examples include:-

> "Burn it with oxygen and if only one kind of compound is formed, it is an element." (Iron, 003, P1)

> "..pass electricity through it using the process electrolysis to decompose it into hydrogen and oxygen." (Water, 003, P1)

Although iron would probably form more than one oxide, this answer must considered feasible as students were not likely to know about the complication of multiple oxidation states. Similarly, the experiment to electrolyse "water" is actually electrolysis of dilute sulphuric acid; again students were given the benefit of the doubt.

Responses coded Q totalled 37% and mainly comprised answers to the first part only (Q1). The remaining 22% were coded T, as the tests suggested were not feasible, for example:-

> "See if it conducts electricity." (Iron, 013)

> "Add sulphuric acid and if a green or brown gelatinous precipitate is formed, it shows that there are iron elements." (Iron, 000)

> "See if it is magnetic." (Iron, 021)

> "It could be melted and fractionally distilled." (Iron, 048)

> "Water turns copper cobalt paper blue to pink." (Water, 021)

These describe a test to identify the iron as iron or water as water, and cannot be generally applied to all elements or compounds. The respondents either misunderstood the intention of the question, or understood the question but could only think in terms of these identification tests. Thus, although many students offered the expected definitions, these appear to be rote-learned. Students did not know how these definitions applied in practice. This is perhaps to be expected, given that a principal identification technique, mass spectrometry, is only taught at A level. We will see in the next chapter if the proportion able to offer feasible tests changes in subsequent surveys.

4.5.3 Substances

Substances describes basic characteristics (conductance of electricity, colour and physical state, reaction with oxygen or separation by chromatography) of four substances. The intention was that all the information provided in the description be used by the student in deciding if the substance is a non-metal element, a metal element, a compound or a mixture. Substance C could be a mixture of hydrocarbons, a factor which is considered in coding responses, although in practice very few suggested this. Table 4.6 gives the first survey responses to *Substances.*

RC	Description	%
P1	Correct responses All information used	36.3
P2	Correct responses Most information used	18.8
P	**Total**	**55.1**
Q1	Correct responses Incomplete explanations	9.3
Q2	Incomplete responses Incomplete explanations	7.3
Q	**Total**	**16.6**
T1	Incorrect response pattern	28.1
T	**Total**	**28.1**
U1	Uncodeable	-
U2	No response	0.2
U	**Total**	**0.2**
	Overall total	**100.0**

n = 399

Table 4.6: First survey responses to *Substances*

Table 4.6 shows that 55% of the sample gave answers coded P. These students selected the correct choices to all four substances and gave explanations in terms of the information provided in the question. This figure falls between those for *Molecules* and *Element and Compound.*

Responses coded Q (17%) were incomplete. These students answered parts of the question correctly, but left others blank. Most frequently in this group substance D was not answered, possibly because students were unfamiliar with the word "chromatogram" and so did not understand the significance of the information provided.

Around 28% gave evidence for misunderstanding the chemical idea and were coded T, making the wrong choice for one or more substances, for example:-

> "A = compound. If it does not conduct ... it cannot be a metal, when burned it combines with oxygen so it cannot be a mixture, also as it gives one product it must be a compound.
> B = compound. If it burns in oxygen to give one product it must be a compound." (024, T1)

These students could not correctly apply the information to the substances given.

This group of questions reveals that while three-quarters of the students were able to distinguish between elements, compounds and mixtures at the particulate level, only about half could apply practical tests to support this knowledge. Two factors may contribute to this. First, students seemed to know definitions for elements and compounds which could be readily recalled. Even if they did know tests to confirm the identity of a substance as an element or compound, they were unable to recall them, leaving only the definition as the relevant piece of information. Second, *Element and Compound* asks students to think up tests for themselves, which is more difficult than starting with information and working out an answer. The first response of many was to recall the actual tests for the substances named, rather than give general tests to confirm the number of types of atom present.

4.6 Chemical change

Three questions, *Tablet*, *Copper* and *Hydrogen chloride* probe students' ideas about chemical changes. These questions provide an indication of students' understanding of a basic principle in chemistry, that a chemical change results in the formation of one or more new substance(s) by rearrangements of particles present in the reactants.

4.6.1 Tablet

In *Tablet*, students are asked about the origin of a gas produced when a tablet dissolves in water. The chemical event is not described, so students who capable of working out what the gas would be if they knew the compounds involved are not given any assistance. The actual chemical event is a reaction between two compounds occurring when the tablet is placed in water and the two solids dissolve.

RC	Description The gas...	%
P1	.. did not exist but formed in a reaction	4.0
P	Total	4.0
Q1a	.. was contained in the tablet	22.8
Q1b	.. was combined in the tablet as carbonate	9.3
Q	Total	32.1
S1a	.. formed in a reaction between water and tablet	7.3
S1b	.. was from the tablet and water	5.0
S	Total	12.3
T1a	.. was in solid form in the tablet	8.8
T1b	.. was joined to something / trapped in tablet	4.2
T1	*Total*	*13.0*
T2a	.. was in the water (displacement)	27.6
T2b	.. was hydrogen / oxygen from the water	4.2
T2	*Total*	*31.8*
T3	.. was from the air	1.0
T4	.. was carbon dioxide	-
T	Total	59.1
U1	Uncodeable	1.5
U2	No response	4.3
U	Total	5.8
	Overall total	100.0

n = 399

Table 4.7: First survey responses to *Tablet*

A total of 16% of the sample indicated that the gas was produced in a reaction. These were divided between codes P and S as some suggested, not unreasonably, that the reaction was between the water and tablet. Examples of the 4% of responses coded P include:-

> "The gas formed after the reaction of the tablet hitting the water ...so it wasn't there before the two substances reacted together." (064, P1)

> "It didn't exist, it was a product of the reaction." (057, P1)

Student 064 left open the question of whether the tablet and water reacted or not, but student 057 stated that the gas is just a product of the reaction. However, about 7% suggested that the gas:-

> "...did not exist but was formed by elements in the water and tablet combining.." (001, S1a)

A smaller proportion, 5%, suggested the gas was:-

> "In the water and the tablet" (019, S1b)

implying that parts of the water and tablet combined to make the gas. This low total percentage, 16%, suggests that many students found the origin of a gas difficult to explain.

Responses coded Q gave evidence of partial understanding of the chemical idea in stating that the gas came "from the tablet". This is true, but does not make clear that the gas did not exist as a gas in the tablet. For the same reason, answers such as:-

> "In a compound in the tablet (probably a carbonate)" (091, Q1b)

were also coded Q. No responses were coded R for this question, as no one answered in terms of aspect 2 alone.

About 42% of the sample gave responses which appeared to indicate some misunderstanding of the chemical idea. These answers implied that the gas existed initially and appeared because of a causal agent or event. Some of these explanations, offered by 13%, suggested that the gas was contained in the tablet in a different form, for example:-

> "Solid form in the tablet" (331, T1a)
>
> "The gas was in a different state and it was in the tablet." (005, T1a)
>
> "In the tablet (air space). " (007, T1a)

Students 331 and 005 seemed to imagine solid changing to gas when the tablet is added to water. Respondent 007 seemed to picture gas particles trapped in bubbles in the tablet being released when the tablet is dropped in water. As the solid dissolved away, the gas simply floated out. These students did not appear to perceive that a reaction occurred.

A second example, given by 28%, is that the gas was:-

> "In the water. The tablet displaced the gas...." (278, T2)

This student imagined that the tablet pushes out the gas, perhaps in the same way as some metals displace hydrogen gas from dilute acids. The tablet is an agent for forcing out a gas which is already there rather than a participant in a chemical reaction. The term "displacement" is applied inappropriately, but is perhaps used because it "sounds chemical". 4% of students took this further in identifying the gas as hydrogen or oxygen (T2b). 1% of respondents thought the gas came from the air (T3). How this could occur was not explained.

4.6.2 Copper

Table 4.8 shows that a high proportion of beginning A level students, about 62%, gave answers coded P for this question, by responding that the mass increased because of a reaction between copper and atmospheric oxygen, for example:-

> "The air. The copper turned into an oxide because it reacted with the oxygen in the air." (278, P1)

A contributory factor to this high figure could be that the reaction is familiar to many students through practical work done at GCSE.

RC	Description The black stuff came from .. / is..	%
P1	.. a reaction with oxygen	61.9
P2	.. a reaction between particles	0.5
P	**Total**	**62.4**
Q1	.. burning the copper	1.2
Q2	.. a reaction with gases / air	12.8
Q	**Total**	**14.0**
S1	.. a reaction with hydrogen	-
S2	.. a mixture of copper and oxygen	0.7
S	**Total**	**0.7**
T1a	.. the copper	1.8
T1b	.. the burning dish	1.2
T1c	.. impurities	1.2
T1	*Total*	*4.2*
T2a	.. is carbon / soot / carbon dioxide	9.8
T2b	.. the heat	2.0
T2	*Total*	*11.8*
T	**Total**	**16.0**
U1	Uncodeable	-
U2	No response	6.8
U	**Total**	**6.8**
	Overall total	**100.0**

n = 399

Table 4.8: First survey responses to *Copper*

Responses coded Q were explanations which used chemical language but did not clearly state that the reaction was between oxygen and copper. These state that the black stuff came from:-

> "The burning of the copper." (203, Q1)

> "The air and copper reacting." (105, Q2)

As with *Tablet*, no responses were coded R, as none showed understanding of the chemical event without also understanding the chemical idea.

Two response types gave evidence of misunderstanding the chemical event and were coded S. These included answers suggesting that a reaction between copper and hydrogen was responsible for the black stuff (S1). A few respondents suggested that the black stuff is a mixture of copper and oxygen, not a compound (S2).

T-coded responses are consistent with ideas that the black stuff was not formed in a reaction, but was due to a transformation event. T1a-c codes represent answers suggesting the black stuff came from the "burning dish", the copper itself, or "impurities". T3a and b code responses given by 12% of the sample which specifically suggest the black stuff came from (or is) soot, or carbon (T3a) and those stating the black stuff came from the heat (T3b). Post-second survey interviews (reported in section 5.4.2) with students suggest that these answers, which appear to be untaught, are deep-seated. The soot was said to come from the bunsen flame, which is a practical possibility, from the copper, or from the air:-

> "The black stuff is charcoal from the copper reacting with the air."
> (198, T3a)

> "Carbon in the air." (086, T3a)

These responses fall into Andersson's (1990) category of transmutation, the idea that one substance can be converted into another in a chemically implausible way. He reports that 10% of 12 - 15 year olds have this idea; these data indicate that this idea is persistent and continues to be convincing for some students beyond this age.

4.6.3 Hydrogen chloride

Table 4.9 shows that only about 5% of students starting A level give evidence for understanding the chemical idea being probed here. These responses clearly indicate that hydrogen ions or hydroxide ions are present in an acid and support this with appropriate explanations or equations for the second part. Code P2 represents correct answers to the first part only. Since no response to the second part was given, these answers do not show evidence of misunderstanding the chemical event.

RC	Description	%
P1a	H_3O^+ ions | displacement reaction / ionic equation	0.3
P1b	H^+ and Cl^- ions | displacement reaction / equation	3.5
P2	Hydrogen ions present | No response	1.0
P	Total	4.8
R1	No response | displacement reaction / equation	6.0
R	Total	6.0
S1a	H_3O^+ ions | Mg reacts with or displaces Cl_2 / Cl^- / O_2 / H_2O	0.8
S1b	H^+ and Cl^- ions | Mg reacts with / displaces Cl_2 / Cl^-	5.3
S	Total	6.1
T1a	HCl molecules | displacement reaction / equation	8.0
T1b	HCl molecules | Mg reacts with Cl_2	12.8
T1c	HCl molecules | other explanation / no response	7.5
T1	***Total***	***28.3***
T2a	HCl / water complex | any explanation	10.5
T2b	HCl & H_2O shown separately / H_2O alone | any expln	2.0
T2	***Total***	***12.5***
T3	Cl^+ & H^- ions | incorrect eqn / explanation	2.7
T4a	No response | incorrect equation / explanation	1.8
T4b	No response | H_2 released / Mg reacts with acid / Cl^-	9.5
T4	***Total***	***11.3***
T	Total	54.8
U1	Uncodeable responses to either part	1.8
U2	No response	26.5
U	Total	28.3
	Overall total	100.0

n = 399

Table 4.9: First survey responses to *Hydrogen chloride*

Responses to the first part of this question show whether students know hydrogen ions are present in acids. Students can respond correctly in terms of the chemical event, without first having drawn hydrogen ions in answer to part one. So, the 6% of responses giving no answer to part one but a correct answer to part two were coded R, since these gave no evidence of misunderstanding the chemical idea. Taking P and R coded responses together suggests that about 10% of the sample clearly understood that the magnesium/hydrochloric acid reaction involves displacement of hydrogen gas at the start of their A level courses.

The 6% of responses coded S gave evidence of understanding that hydrogen ions are present in hydrochloric acid, but that the metal reacts with chlorine or chloride ions, not hydrogen ions. These imply that the hydrogen gas is a by-product of a reaction between two reactive elements, chlorine (or chloride, a synonym for chlorine) and magnesium. Similar answers were found in the 29% coded T1. These indicated that hydrogen chloride molecules are present in acid, and argued that the chlorine "changes partners" to form a new molecule with magnesium, for example:-

> "the magnesium is more reactive than hydrogen. So magnesium reacts with the chlorine + the hydrogen is formed." (203, T1b)
>
> "The magnesium is more reactive than the chloride and releases the H." (331, T1b)
>
> "Magnesium combines with Cl = $MgCl_2$. Hydrogen is displaced." (319, T1a)
>
> "magnesium joins with chlorine and the hydrogen is given off alone." (039, T1b)

Students 203 and 331 link the production of gas with the relative reactivities of magnesium, hydrogen and chlorine. Hydrogen is perceived to be less reactive than the other two, so is "left over". Students 319 and 039 are less precise, choosing the words "combine" and "joins with" in lieu of "reacts" or "reactive".

Other responses coded T suggested that complex structures form between hydrogen chloride and water molecules (11%, T2a). Some students drew water molecules in the lower half and hydrogen chloride molecules in the upper half of the gas jar (T2b, 2%). Another small group of students drew ions with incorrect charges (T3, 3%). A final group, coded T4 (11%) did not respond to the first part and gave completely incorrect answers to the second part, or simply restated the question.

The 5% level of P-coded responses to *Tablet* and *Hydrogen chloride* suggest that explaining the formation of a gas as a product of a reaction is more difficult than explaining the formation of the solid product in *Copper*. The reactions in *Tablet* and *Hydrogen chloride* produce colourless gases. About one-third of students explained the formation of these gases by using the word "displacement", which to them may mean "pushing out a gas which is already there". They perceive the reaction as being between magnesium and chlorine (-ide). A solid changing colour as in *Copper* is easier to explain because the colour change indicates production of a "new substance". The information that mass has increased assists this idea and the rationale for air being involved is clear, as they are told the copper is "heated in air". The opportunities for misunderstanding this are perhaps reduced, because here it is necessary to assume the gas already existed.

A second common feature of responses to these questions is the tendency to explain the reaction in terms of the "wrong" reagents. This is seen in S-coded answers. Many respondents will have either seen or carried out the reactions in *Copper* and *Hydrogen chloride* for themselves, however, these data suggest that significant proportions at the start of their A level courses do not know what exactly is reacting and cannot give convincing explanations for the events they observe.

4.7 Conservation of mass in closed systems

Three questions probe students' ideas about chemical reactions from a different aspect - that of understanding that mass is conserved when a chemical change takes place. *Phosphorus*, *Precipitation* and *Solution* place this chemical idea in the context of closed systems, that is, systems involving no transfer of mass in or out. *Solution* probes ideas about dissolving, a process which is frequently considered to be a physical change. Cosgrove and Osborne (1981) among others showed that students aged up to 17 years old found explaining dissolving problematic, suggesting that this area was worth further investigation. In contrast to the chemical change questions, this set share a common structure, with a three-way multiple choice stem being followed by space for the student to explain their selection of one option. The coding schemes for these questions are shown in Tables 4.10 - 4.12 respectively.

4.7.1 Phosphorus

Phosphorus was adapted from Andersson (1984), who, in turn, had adapted the APU (Driver, et al, 1984) version of the question. From Table 4.10, we see that about 57% of the sample gave responses to *Phosphorus* consistent with understanding the chemical idea and were coded P. Most frequent were the "common sense" answers coded P1, which explain that the mass of the system is unchanged simply because the flask is sealed, for example:-

> "nothing has left the flask ...and nothing else has entered." (086, P1)
>
> "...because nothing could have escaped.." (012, P1)

These responses did not reflect any misunderstanding of the chemical event. It is possible that students responding in this way did not realise a chemical reaction takes place in the flask. Since evidence of any misunderstanding is absent, however, these responses must be coded P. The few responses which stated more formally that mass is conserved in a chemical reaction are coded P2.

RC	Description	%
P1	400 g the flask is sealed / nothing can escape	53.4
P2	400 g formal conservation statement	0.2
P3	400 g the number of particles is unchanged	3.5
P	Total	57.1
Q1	400 g uncodeable or no explanation	3.0
Q	Total	3.0
R1	400 g explanation in terms of chemical event	4.3
R	Total	4.3
S1	400 g misunderstanding of chemical event	6.8
S	Total	6.8
T1a	< 400 g because energy is lost from flask	2.0
T1b	> 400 g because energy is absorbed from the sun	0.8
T1	*Total*	*2.8*
T2a	< 400 g mass decreases because P / smoke dissolves	3.8
T2b	> 400 g because mass increases on dissolving	0.8
T2	*Total*	*4.6*
T3a	< 400 g because gas / liquid weighs less than solid	7.5
T3b	> 400 g solid weighs more than gas / liquid	0.2
T3c	< 400 g because water evaporates	0.5
T3	*Total*	*8.2*
T4a	< 400 g because phosphorus is used up	4.3
T4b	> 400 g because more reactant made / O_2 included now	1.5
T4	*Total*	*5.8*
T	Total	21.4
U1	> / < 400 g uncodeable or no explanation	4.2
U2	No response	3.2
U	Total	7.4
	Overall total	100.0

n = 399

Table 4.10: First survey responses to *Phosphorus*

Evidence for some students thinking in terms of the particles present was also found, for example:-

> "...no atoms could get in or out, so the mass could not have changed." (025, P3)

These respondents seemed to have a developed particulate model of matter, as they could apply this to an unfamiliar situation.

Respondents who selected the expected mass value but offered no explanation or a nonsense explanation were coded Q1. These answers are partial evidence of understanding and could not be coded P, as the student may have guessed this option.

Alternatively, he or she may genuinely understand the chemical idea, but could not be bothered to explain their choice.

About 4% of respondents, coded R1, selected the correct answer and explained this in terms of the chemical event, for example:-

> "nothing is being lost from the reaction, not even the smoke ...it dissolved back in the water." (130, R1)
>
> "Although it has changed form and density, the mass will remain the same." (136, R1)

Students responding in this way may have seen the chemical event, or used the information in the question to reason that phosphorus and oxygen react together. Conversely, the 7% coded S1 responded in terms of events taking place in the flask, but thought that the phosphorus was the white smoke, or simply that the phosphorus dissolved in the water, for example:-

> "The phosphorus is still present but it is disolve (sic) in water instead of being a solid." (129, S1)

By choosing 400 g the student indicates no misunderstanding of mass being conserved in the system, so understanding of aspect 1 is implicit in these answers.

Several types of response totalling 23% were coded T. These imply non-conservation of mass. The largest contributor to this group were the 8% (T3) of respondents who confused mass with density, most of whom explained that the mass increases (or decreases) because:-

> "Gas is less dense than a solid." (021, <400 g, T3a)
>
> "Change of state took place... lost weight as there was no longer a solid phosphorus." (035, <400 g, T3a)

These respondents did not realise that a reaction had occurred and focused entirely on the change from solid to "gas" explained in the preamble. Implicit in these answers is the notion that "white smoke" means gas, not a suspension of solid particles in air! Although these students may be conserving the actual amount of stuff present in the flask, their confusion of mass and density drew them to a response suggesting that mass had changed. Their meaning for the term "mass" is "weight", which means their thinking about conservation is at this stage unclear.

Around 6% of students thought that the phosphorus is used up in the events taking place. This group do not conserve mass. Examples of this type include:-

> "Oxygen would be used to burn phosphorus." (105, <400 g, T4a)

"Oxygen would be burnt up reducing the mass." (113, <400 g, T4a)

"the phosphorus may have reacted with oxygen in the flask thus increasing the mass." (041, >400 g, T4b)

These respondents seemed to have a good understanding of the chemical event, recognising that a reaction between phosphorus and oxygen takes place, but they misunderstood the chemical event. The notion of oxygen or phosphorus being "used up" is particularly clearly expressed and it is possible students thought of the white smoke as equivalent to the ashes left over when coal burns. The mass of the remaining visible product is, in the case of coal, much less than the mass of starting material.

A third response, given by 5% and coded T3 is the notion that mass decreases on dissolving, for example:-

"The phosphorus which was given off as smoke dissolved in water." (031, < 400 g, T3a)

This is a similar idea to the density problem discussed above. Ideas about dissolving are discussed in greater detail under *Solution* later on.

The least frequent response, T4, was given by 3% of the sample. These students used ideas about energy being produced or used up, for example:-

"Weight would be lost due to the energy loss during a reaction." (042, <400 g, T4a)

"The energy from the sun was absorbed." (0212, >400 g, T4b)

This idea is not incorrect, as a small amount of mass will be converted to energy when the reaction takes place. This mass, though, is far too small to be measurable by conventional means.

4.7.2 Precipitation

This question was devised for this study. First survey responses to *Precipitation* are given in Table 4.11.

RC	Description	%
P1	140 g no mass change / no gas given off	34.1
P2	140 g formal conservation statement	0.5
P3	140 g number of particles is unchanged	4.3
P	**Total**	**38.9**
Q1	140 g uncodeable or no explanation	3.5
Q	**Total**	**3.5**
R1	140 g no rxn / reactants & / product correctly named	2.7
R	**Total**	**2.7**
S1	140 g reactants & / product incorrectly named	1.8
S2	< 140 g a gas is released	11.0
S3	< 140 g water / liquid evaporates	1.5
S4	> 140 g air is involved in the reaction	1.7
S	**Total**	**16.0**
T1	< 140 g because energy is lost / used up / released	1.2
T2	< 140 g because dissolving causes mass decrease	0.3
T3	> 140 g solid weighs more than liquid	13.3
T4a	< 140 g because reactant(s) are used up	1.7
T4b	> 140 g an extra substance is present	3.0
T4c	> 140 g because new bonds have been formed	0.5
T4	***Total***	***5.2***
T5a	< 140 g mass decreases as space is used up	0.2
T5b	> 140 g because space was used up	0.8
T5	***Total***	***1.0***
T	**Total**	**21.0**
U1	> / < 140 g uncodeable or no explanation	6.6
U2	No response	11.3
U	**Total**	**17.9**
	Overall total	**100.0**

n = 399

Table 4.11: First survey responses to *Precipitation*

Table 4.11 shows that 39% of respondents gave an answer coded P. These explained that the mass was unchanged for one of three reasons, the most common being simply that there is no mass change because the same substances are present at the start and end, for example:-

> "...exactly the same reactants are present in the products." (086, P1)

A few students responded with a formal statement of conservation (P2) while others applied a particle model, for example:-

> "An exchange of ions takes place, however, no atoms are given off as gases...so the mass stays the same." (025, P3)

In the Q category are the 4% of responses selecting 140 g and offering no explanation. As with *Phosphorus*, these are partial evidence of understanding, as the student did not provide sufficient information for this response to be coded P.

About 3% responded in terms of the chemical reaction taking place, so were coded R. These students knew that the precipitate is barium sulphate, most by showing this in an equation for the reaction.

Four responses totalling 16% were coded S. Most frequent, contributing 11%, were explanations suggesting that the reaction produces a gas:-

> "Because a gas was produced when the precipitate was formed.."
> (075, S2)

These answers indicate that some students may consider evolution of a gas is characteristic of all chemical reactions, a point discussed further below. Implicit in this explanation is the notion that mass is conserved, since the mass of the system is said to decrease when the gas is produced. These students therefore provide evidence of understanding the chemical idea being probed, that mass is conserved, although their version of the chemical event was incorrect. The other S-coded responses occurred in approximately equal proportions. These included the idea that the sodium chloride produced is the precipitate (S1); that air is involved in the reaction (S4) and that water evaporates when the liquids are mixed (S3). These answers compare with those given to the chemical change set, in which students were unable to correctly identify the reactants.

Approximately 21% gave responses consistent with misunderstanding the chemical idea. Most of these ideas were also found in answer to *Phosphorus* and *Solution*. The most frequent explanation, totalling 13%, was the explanation that the mass would increase because:-

> "...a solid way (sic) more than liquid sol." (0331, T3b).

The formation of a solid in a precipitation reaction is a tangible event. Students who tend to confuse mass and density are perhaps likely to respond in this way, because solids "weigh heavier". As explained above (*Phosphorus*) this must be considered a misunderstanding of the chemical idea. Responses coded T4, 5% of the sample, include ideas about reactants being used up and the presence of a new substance, for example:-

> "Because ...some of the Na_2SO_4 and $BaCl_2$ atoms are used up in the process and released into the atmosphere." (065, T4a)

The idea that energy is used up features in 1% of answers, including:-

> "Because atoms of energy were released in the reaction." (057, T1a)

Responses coded T5, 1%, explained that space was used up so the mass either increased (T5b) or decreased (T5a). This idea was only found in answer to *Precipitation.*

4.7.3 Solution

Solution was devised for this study. The responses given to this question in the first survey are presented in Table 4.12.

RC	Description	%
P1	220 g no mass change occurs on dissolving	15.8
P2	220 g formal conservation statement	1.8
P3	220 g number of particles is unchanged	3.2
P4	220 g because 200 + 20 = 220 g	19.0
P	**Total**	**39.8**
Q1	220 g uncodeable or no explanation	5.1
Q	**Total**	**5.1**
R1	220 g because there is no reaction / gas prod	11.3
R	**Total**	**11.3**
S1	< 220 g because salt reacts with water	0.7
S2	< 220 g because a gas is released	18.0
S3	< 220 g because salt / water is lost / evaporates	2.5
S	**Total**	**21.2**
T1	< 220 g because energy / mass is lost in dissolving	7.0
T2a	< 220 g because the salt is now liquid	2.8
T2b	> 220 g because density increases	0.5
T2	***Total***	***3.3***
T3a	> 220 g because sodium chloride was added	0.7
T3b	> 220 g because the reaction increases mass	0.8
T3	***Total***	***1.5***
T4	< 220 g because salt takes up space in water	2.8
T	**Total**	**14.6**
U1	> / < 220 g uncodeable or no explanation	4.2
U2	No Response	3.8
U	**Total**	**8.0**
	Overall total	**100.0**

n = 399

Table 4.12: First survey responses to *Solution*

The question generates similar responses coded P to the other questions in this set. The proportion of P codes, 40%, is similar to that for *Precipitation.* Examples of responses coded P1 - 3 include:-

> "the weight remains even when it dissolves." (003, P1)
>
> "When solids dissolve [to form] solutions they don't disappear..." (032, P1)
>
> "The mass doesn't change. By dissolving no atoms are lost." (135, P3)

A fourth answer, P4, was given to *Solution* by 19% of the sample. In this response the two numbers 200 and 20 were added together:-

> "because the beaker + water weighed exactly 200 g and then 20 g of NaCl was added.." (093, P4)

The question almost prompts this type of answer by stating the two figures in the preamble. This is a type of common sense answer, but is given a separate code from P1 as the method by which the answer is derived is quite specific.

About 5% of respondents selected 220 g alone and were coded Q1 as explained previously for *Phosphorus* and *Precipitation.* A further 11%, coded R1, answered in terms of the dissolving process, noting specifically that no gas is evolved:-

> "I don't think that any gas would be given off to lose weight and nothing would increase it." (120, R1)

About 21% responded in terms consistent with misunderstanding the chemical event and were placed in the S category. The largest proportion of these, 18%, explained that a gas is produced:-

> "Sodium chloride is very reactive with water and a lot of gas is given off." (075, S2)
>
> "Sodium chloride reacts and lets off a gas." (041, S2)

This idea is also found in a similar number of responses to *Precipitation* and suggests not only that sodium chloride + water are the reactants in a chemical reaction, but also that gases are always produced. Some students may have mistaken sodium chloride for sodium metal, however, and explained accordingly that the gas would be hydrogen. The idea that water evaporates (S3), found in answers to *Precipitation,* was given by 3% and one student explained simply that "salt reacts with water." (S1).

A variety of responses totalling 15% were coded T. Some were also found in answers to *Phosphorus* and *Precipitation*, although the most frequent response in this case was in terms of energy or mass being used up, for example:-

"The sodium chloride is being dissolved, so the mass would decrease because breaking of the bonds gives off energy = endothermic." (104, T1a)

The mass/density confusion was apparent, too, in 3% of responses:-

"It dissolves to make a lighter substance." (063, T3a)

"Because the sodium chloride has dissolved, therefore making the mass lighter. As now the sodium chloride is contained in the water which is only 200 g." (102, T3a)

"Because the sodium chloride turns into liquid and is lighter." (073, T3a)

The change occurring on dissolving is less dramatic than forming a precipitate, so it is perhaps less likely that students will respond in these terms to *Solution* than *Precipitation.*

Phosphorus generated more P-coded responses than the other two questions in this set, perhaps because the flask being sealed presents a potent visual image leading to conservation-type answers. The most frequent misunderstanding to both *Precipitation* and *Solution* is that a gas is produced - a misunderstanding of the chemical event rather than the chemical idea. This leads to the conclusion not only that a proportion of students could not distinguish dissolving from a chemical reaction producing a gas, but also that these students thought all reactions produce gases. If, in GCSE courses most reactions students see do produce gases, this is the likely outcome of their experience.

The T-coded responses to this set indicate that a small proportion of beginning A level students confuse mass and density. This is lower than the figure of 20% found among 15-year olds by Andersson (1984) but is sufficient to suggest that for some the notion is persistent.

4.8 Reacting mass reasoning

These questions probe students' understanding of reacting mass reasoning, that is, the idea that elements react in fixed ratios by mass. This idea extends the principle of conservation of mass within a reaction, helping students understand why equations for reactions need to be balanced and the importance of relative atomic mass values. The chemical events are reactions between iron and sulphur and carbon and oxygen, which are described by equations in the questions. Relative atomic mass values are also provided. The coding schemes for this set are given in Tables 4.13 - 4.14.

4.8.1 Iron sulphide

Iron sulphide was adapted from Briggs and Holding (1986). The responses obtained in the first survey are shown in Table 4.13. About 52% of responses were coded P. These students indicated they understood the principle of reacting mass reasoning by noting that sulphur is in excess when the mass ratios of iron and sulphur are considered. The amount of information they gave varied, hence the range of responses coded P1 - P4.

RC	Description	%
P1	176 g / 2 moles FeS + 16 g S / excess S / 0.5 mole S	30.3
P2a	176 g FeS + sulphur	10.3
P2b	176 g FeS only	6.8
P2c	16 g/excess sulphur only	4.5
P	Total	51.9
Q1	2 x FeS only	2.8
Q	Total	2.8
T1a	192 g FeS	28.8
T1b	More than twice as much iron sulphide results	0.2
T1	*Total*	*29.0*
T2a	A different compound from FeS results	4.3
T2b	FeS with a different formula results	2.7
T2	*Total*	*7.0*
T3	Completely wrong figures used	1.3
T	Total	37.3
U1	Uncodeable	2.2
U2	No Response	5.8
U3	Iron sulphide only	-
U	Total	8.0
	Overall total	100.0

n = 399

Table 4.13: First survey responses to *Iron sulphide*

Only responses stating "2xFeS" were coded Q. The reasoning used to obtain this answer may not consider the extra mass of sulphur, so there was no clear evidence of understanding the chemical idea.

About 37% gave answers suggesting they did not know that reacting mass reasoning should be applied. A majority of these responses, totalling 29%, are coded T1, stated simply that the mass would be 192 g. These responses fail to account for the ratio of masses, so is evidence of misunderstanding of the chemical idea. However, it is possible that some students responding this way may know how to use the appropriate reasoning, but acted on instinct and added the two figures. Others may think that 192 g was the correct response, and did not know that any other reasoning was necessary. In the absence of full explanations, all these answers were coded T. The remaining 9% gave evidence of misunderstanding how elements react together. Most of these were coded T2, and suggested that a different compound from iron sulphide formed (T2a) or that the formula of iron sulphide changed (T2b). A few respondents became very confused by the numbers and tried to carry out a more complex calculation. These answers are coded T3.

4.8.2 Carbon

The *Carbon* question uses the reaction between carbon and oxygen to set the context and provide information for the question *Power Station*, which follows in the next section and came later in the test paper. In the first survey, Table 4.14 shows that 36% of responses are coded P.

RC	Description	%
P1	88 g, appropriate method • ratio / moles used	33.9
P2	Method appropriate, but answer ~ 88 g	2.5
P	Total	36.4
Q1	88 g / 2 moles, no method shown	5.5
Q2a	88 g, addition	24.1
Q2b	88 g/2 moles, but method incorrect /unclear	1.3
Q	Total	30.8
T1	Answer ~88 g, no method / method incorrect/ unclear	1.5
T2	» 88 g, any method	5.5
T3	44 / 56 / 72 g, any method	10.8
T4	« 88 g, any method	7.0
T	Total	24.8
U1	Uncodeable	-
U2	No Response	8.0
U	Total	8.0
	Overall total	100.0

n = 399

Table 4.14: First survey responses to *Carbon*

This is significantly less than the figure for *Iron sulphide*. Part of the difference may be attributed to the fact that the answer to *Carbon*, 88 g, can be obtained by adding the numbers in the question. About 24%, coded Q2, showed they had added 64 and 24. As for *Iron sulphide*, some of these students may know how to use reacting mass reasoning, but added instinctively. In this question, the right answer is obtained by this method, so these answers are partial evidence of understanding. A further 6%, coded Q1, gave no indication of working, while a few responses, coded Q3, obtained the correct answer by rather spurious methods.

In the T category are 25% of responses indicating misunderstanding of the chemical idea. Most of these answers showed a calculation, suggesting that students recalled something from their GCSE courses. However, the values obtained were either less than the starting masses of the materials, or substantially more than the mass of reactants. This suggests that these students carried out their method, but that they did not think about whether the answers they obtained were sensible. Responses coded T2, 11%, used relative atomic mass values but in an inappropriate way, obtaining answers of 44 (the relative molecular mass of carbon dioxide), 56 or 72 g (both of these figures are combinations of the mass values of carbon and oxygen gas). A further 6%, coded T2, produced answers much greater than 88 g, while 7% calculated the value to be much less than 88 g. Besides being incorrect answers to the question, all these responses are similar to non-conservation answers found in the previous set, since they imply that material is destroyed or created in the chemical reaction.

A significant proportion of students, about one-quarter, give answers which suggest they do not understand how the mass of products relates to the mass of reactants even in these simple reactions. Many of these offered non-conservation type responses, indicating that they have not been encouraged to think in terms of the chemical sense of answers to mathematical problems. This difficulty is also apparent in responses to the next set, concerned with conservation of mass in open system chemical reactions.

4.9 Conservation of mass in open systems

Two questions, *Power Station* and *Petrol*, probe students' ideas about conservation of mass in open system reactions. Both questions used the combustion of a fuel, where the mass of oxygen needs to be taken into account. *Power Station* takes the example of coal burning to produce carbon dioxide and *Petrol* utilises the burning of petrol to produce a mixture of exhaust gases. *Power Station* the idea is extended by inclusion of a calculation of product mass using reacting mass reasoning. A calculation is not required to obtain the expected answer to *Petrol*, only an indication of mass greater than 50 kg.

The chemical events are not described in the questions, but an understanding of the involvement of oxygen is implicit in the chemical idea. A student who does not recognise the role of oxygen misunderstands the chemical idea and the chemical event. Conversely, if the chemical event is understood, a student will realise that the mass of oxygen must be taken into account in estimating the mass of exhaust or carbon dioxide, assuming he or she thinks gases have mass.

The coding schemes and response types obtained at the first survey are presented in Tables 4.15 and 4.16.

4.9.1 Power station

Carbon, which is placed earlier in the test paper, provides the necessary data required to answer this question. Students must assume that for the purposes of this question, coal is 100% carbon. At this point it is worth describing how students might obtain the answer. One method is to find the number of moles of carbon present:-

$$1000 \times 10^6 \div 12 = 83.33 \times 10^6$$

then multiply this by the relative molecular mass of carbon dioxide:-

$$83.33 \times 10^6 \times 44 = 3667 \times 10^6 \text{ g} = 3667 \text{ tonnes.}$$

A second method reasons from the equation that carbon and oxygen react in a 1:1 mole ratio, so 83.33×10^6 moles of oxygen are required to react with the same number of moles of carbon. The mass of this number of moles of oxygen is:-

$$83.33 \times 10^6 \times 32 = 2667 \times 10^6 \text{ g.}$$

The mass of carbon dioxide equals the mass of oxygen plus the mass of carbon.

Next, we will look at the students' responses.

RC	Description	%
P1	3667 tonnes	9.8
P2	Close approximation to 3667	3.5
P	Total	13.3
Q1	3000 tonnes with or without working	5.8
Q2	Method appropriate, but answer 2333 / 2667 or similar	3.5
Q3	» 1000 tonnes	8.8
Q	Total	18.1
T1	< 1000 tonnes	26.6
T2	1000 tonnes	5.7
T3	Wrong method and wrong answer	3.8
T4	Calculation attempted, but not completed	1.3
T	Total	37.4
U1	Uncodeable	-
U2	No Response	31.3
U	Total	31.3
	Overall total	100.0

n = 399

Table 4. 15: First survey responses to *Power Station*

Table 4.15 shows that 10% of respondents obtained the correct answer and were coded P1. Also placed in the P category were the 4% of responses which used a method similar to one of those above, but produced an approximation, for example, 3800 or 4000 tonnes. Many students may have been unable to do the calculation required because they did not realise that the necessary information was provided, which may help to explain why the number of correct answers is relatively low. The link between this question and *Carbon* was not made explicit.

However, a further 18% gave answers providing partial evidence of understanding and were coded Q. About half of these, 9% of the sample, gave answers much greater than the expected value, including 44 000 tonnes. This is obtained by multiplying the relative molecular mass of carbon dioxide by the mass of carbon. This is part way to the expected value and indicates that students thought the mass of gas is greater than the mass of coal. However, the method is incorrect and the value far too high to be considered a reasonable estimate. The response coded Q1, 3000 tonnes, is closer to the correct value, but is also obtained by an incorrect method. In this case, the student assumes that 1 mole of carbon will react with two moles of oxygen, but that the atoms will have the same mass, hence 1000 tonnes of carbon + 2000 tonnes of oxygen gives 3000 tonnes of gas. This could be the students' way of producing an estimate, but since the question really requires reacting mass reasoning to be applied, this answer cannot be coded P. A third response type giving partial evidence of understanding are the values 2333 and 2667 tonnes. These are also close to the correct answer, but cannot be coded P again because the method used omits the mass of carbon from the answers.

About 37% of responses were coded T. Most of these, 27% of the sample, gave responses suggesting that the mass of gas would be less than the starting mass of coal, for example:-

> "Coal burns leaving CO_2, water and ash, so about 500 tonnes of CO_2 goes up the chimney + 250 tonnes of water vapour and about 250 tonnes of ash is left behind." (176, T1)

This respondent realised that "burn" means "combine with oxygen", but completely omitted the mass of oxygen from his or her estimates. Other answers used similar reasoning, but gave answers closer to 1000 tonnes:-

> "Approximately 900 tonnes if the coal is high quality there should be a high carbon content." (264, T1)

> "960 tonnes. Ashes and soot are left behind." (057, T1)

These students did not mention burning or oxygen, seeming to focus instead on the "leftovers" from burning coal. They did not realise that a chemical reaction has taken place.

Others arrived at their answer by mathematical means, expressing this type of reasoning in fractions, for example:-

> "1000 x 2/3 = 666.6 tonnes" (0090, T1)
>
> "1/2 - 3/4 original weight of coal." (0341, T1)

About 6% responded that the mass would be the same as that of the coal. This could be a "reflex" response from students who did not know how to answer the question, but merely restated the number given. This is a conservation answer at very least, since at least they did not suggest the mass would be less than the amount of starting material.

4.9.2 Petrol

Petrol was adapted from Andersson (1984). Calculation of the mass of exhaust gas by the second method given for *Power Station* (above) gives 225 kg of exhaust gas, assuming a formula for petrol of C_8H_{18}. This indicates the appropriate scale of responses, although students did not have to carry out a calculation to obtain the correct answer. Most students did not give an exact figure, but indicated "greater than" or "less than" as they thought best.

The first survey responses to *Petrol* are displayed in Table 4.16. Only 13% offered answers coded P, a figure similar to *Power Station*. Many coded P1 used a calculation or gave an equation in their answers, for example:-

> "All of the petrol burns therefore the weight must be at least 50 kg. The petrol burns in air this also weighs a substantial amount. NO_x, SO and SO_2 are emitted the oxygen increased the weight of emissions." (0014, >50 kg, P4)

One reason for the low level of P-coded responses, therefore, could be that students thought a calculation was necessary but were not provided with the data. Instead, they had to guess the answer. No responses were coded Q or R. For *Petrol*, the response ">50 kg" with no explanation was taken as evidence of understanding the chemical idea and so was coded P. This answer could not be selected from three options, like the equivalent answer to *Phosphorus*. Therefore, the chance of students guessing that the mass would increase are reduced. No responses were coded R because the chemical event and chemical idea are so closely intertwined that understanding one immediately assumes understanding of the other.

RC	Description	%
P1	> 50 kg calculation used	12.5
P2	> 50 kg petrol reacted - particle statement	0.3
P3	> 50 kg petrol reacted with air / oxygen	-
P	Total	13.8
Q1	> 50 kg uncodeable / no explanation	1.5
Q	Total	1.5
S1	> 50 kg petrol mixes with oxygen	0.5
S	Total	0.5
T1	< 50 kg petrol converted to light / heat / energy	3.0
T1	*Total*	*3.0*
T2	< 50 kg gas lighter than liquid / petrol vapourises or condenses	4.0
T2	*Total*	*4.0*
T3a	< 50 kg petrol is used up / burned away	3.5
T3b	50 kg petrol is used up / burnt	4.0
T3c	< 50 kg only a proportion / % of petrol is used	2.3
T3	*Total*	*9.8*
T4a	50 kg what goes in must come out / 1050 - 1000 = 50	19.8
T4b	50 kg petrol is converted to gas but mass unchanged	6.0
T4c	50 kg matter cannot be created or destroyed	0.5
T4d	50 kg petrol is burned / combusted / oxidised	11.8
T4	*Total*	*38.1*
T5a	50 kg no explanation / uncodeable	8.0
T5b	< 50 kg no explanation / uncodeable	3.8
T5	*Total*	*11.8*
T	Total	66.7
U1	Uncodeable	0.5
U2	No Response	18.0
U	Total	18.5
	Overall total	100.0

n = 399

Table 4.16: First survey responses to *Petrol*

One response, offered by two students, was coded S. They suggested that the petrol mixes with oxygen, rather than explaining that a reaction takes place. The students may mean "reacts", but as the earlier element, compound and mixture set makes clear, correct use of these terms is important.

A range of responses totalling 66% gave evidence of misunderstanding the chemical idea. Several were similar to those found in answer to *Power Station.* About 38% (T4) suggested that the mass of petrol is conserved and that no additional mass is involved in the change to exhaust gas. Students expressed this in several ways, including:-

> "What goes in must come out. The fuel cannot just disapper (sic), so it must have been given off as exhaust gases." (003, 50 kg, T4a)

"The exhaust gases come from the petrol put in the tank. Although "heated up into" gases the mass of gases will be the same." (194, 50 kg, T4b)

"The petrol is used as fuel for the car. To get energy out of the petrol it is burnt to form CO_2 and other gases. So the amount of petrol in the tank will be the same amount as is given out." (345, 50 kg, T4d)

Student 003 is one of 20% who used conservation type reasoning to support their choice of 50 kg. This may seem a logical response, but completely ignores the chemical reaction taking place and suggests these students did not really understand what happens in a car engine. About 6% responded like student 194. This answer explains the choice of 50 kg as though evaporation takes place, but that once the petrol has gone through the engine it becomes "exhaust gas" - it is unchanged in any other way. A further 12% used the term "burnt" or "burned" in their answers, like student 345. This response so goes far as to name one of the exhaust gases, but fails to acknowledge the role of oxygen. This may be an omission, but could also imply that these students did not think of oxygen as having mass which would "count".

Around 10% (T3) gave non-conservation answers, suggesting that the exhaust gases would have less mass than the petrol, or that the petrol was "burnt" for example:-

"The gases from the exhaust is the mass left over from what has been used (I think the exhaust fumes are 10% of the fuel)." (339, 5 kg, T3a)

The idea that the fuel is "used up" reflects the physical need to refill a petrol tank after a journey. This was taken further by students who connected burning and destruction of material, an explanation found in 4% of responses, for example:-

"most of the petrol would be burnt away compleatly (sic)." (212, 10 kg, T4a)

"The petrol is burnt and so the 50 kg has to go somewhere. Most of it is burnt, that that isn't is got rid of by exhaust gases." (215, 5 kg, T4a)

This "lay" idea of burning is similar to those found in answer to *Power Station* above which focus on the ash remaining when coal burns. For these students, the exhaust gas is the equivalent of ash and is the left-over product of burning the petrol. The notion of a chemical reaction occurring between oxygen and petrol is absent.

Two other responses were given by relatively small numbers of students. First, 4% (T2) indicated they confuse mass and density, for example:-

"When the petrol is burned carbon dioxide and water are formed which have a very small weight when all the CO_2 and H_2O are put together." (013, less than 50 kg, T2)

Although this student realised what some of the exhaust gases would be, he thought that these would have less mass than the petrol because they are gases. Second, about 3% thought that some of the petrol is converted to energy and heat:-

> "The mass went up 50 kg and lost 50 kg but not all of the petrol was turned into gas. Some of it was used to produce energy to run the engine." (265, 30 kg, T1)

> "Not all the petrol becomes exhaust gases a little becomes energy and is transmitted in a different form to make the car move." (208, 40 kg, T1)

The idea of petrol itself being converted to energy is a persuasive, because this is an obvious effect of putting petrol in an engine. However, the source of the energy was completely misunderstood by these students.

About 12% of respondents gave answers of 50 kg or less than 50 kg with no explanation. These are coded T5. A further 18% did not respond to this question in the first survey.

The proportion of responses coded P to this set is lower than that for the closed system questions. This suggests that many students were unfamiliar with the ideas being probed here, or at least, were unable to put whatever knowledge they have into a format which would answer the question. It is possible that more students than 13% could carry out the calculation required by *Power Station*, but did not because the data was not immediately available. However, as this figure is also found in answer to *Petrol*, it may be that this proportion is an accurate measurement of students' understanding of this area. Certainly, the responses to *Petrol* indicate that few students understand what happens to petrol in an internal combustion engine!

4.10 Chemical bonding

Students' ideas about covalent, ionic and hydrogen bonds were probed by questions which were devised for the study. Explicit examples were needed to probe students' thinking about this, so the chemical events are described in the questions. The question *Chemical bonds* is reported into two parts so that the covalent and hydrogen bonds can be treated separately. For convenience these are referred to as *Covalent bonds* and *Hydrogen bonds.*

4.10.1 Covalent bonding

Two questions, *Covalent bonds* and *Methane molecules* probe students' ideas about different aspects of covalent bond formation. The coding schemes for these are given in Tables 4.17 and 4.18.

Covalent bonds

Table 4.17 shows that about 20% of the students gave P-coded responses at the first survey.

RC	Description	%
P1	2 / 4 electrons shared	5.0
P2	Single / double covalent	14.8
P	Total	19.8
Q1	Single / double bond	55.4
Q2	Chemical bond	1.0
Q	Total	56.5
T1	1 / 2 electrons shared	7.8
T1	*Total*	*7.8*
T2a	Saturated bond	0.5
T2b	Simple bond	1.2
T2c	Weak / strong bond	-
T2	*Total*	*1.7*
T3a	Ionic bond	4.3
T3b	Link between two compounds	0.2
T3	*Total*	*4.5*
T	Total	14.0
U1	Uncodeable	7.8
U2	No response	2.0
U	Total	9.8
	Overall total	100.0

n = 399

Table 4.17: First survey responses to *Covalent bonds*

Table 4.17 shows that about 5% answered in terms of electrons being shared (P1), for example :-

> "2 shared electrons between atoms. 4 shared electrons between atoms." (319, P1)

Most, however, recognised the symbols as "single/double covalent" (15%, P2). A large proportion (55%) offered the response exemplified by student 301:-

> "A single bond between the element. A double carbon->carbon bond." (301, Q1)

These answers use common terminology, and clearly understand the meanings of the symbols. However, these answers are partial evidence, since they do not explain the symbols in terms of electrons being shared, so were coded Q. The answer "chemical bond" (1%) was also coded Q, since while this is not incorrect, it is unclear exactly what the student means and it appears as a guess because the respondent could not recall a more appropriate word.

There is no opportunity for students to misunderstand chemical events in answering this question - they either realise what the symbols represent or they do not. Therefore, no responses were placed in categories R and S. All remaining answers were coded T and total 14%. T1 codes the 8% of answers giving incorrect numbers of electrons. Responses labelling bonds with names which "sound chemical" but are incorrect amount to 2% and were coded T2. Answers placed in group T3 identified the bonds as "ionic" (T3a) or intermolecular (T3b).

Methane molecules

Table 4.18 shows that at the first survey about 34% of answers use ideas about stability and are coded P.

RC	Description	%
P1a	CH_4 is energetically the most stable formula	0.3
P1b	C and H are more stable as CH_4	8.5
P2	C needs 4 more e-'s, H needs 1 for noble gas configuration	25.1
P	**Total**	**33.9**
Q1	C needs four bonds / 4 more electrons	24.6
Q2	C has valency / oxidation no. of 4 / 4 links	12.0
Q	**Total**	**36.6**
T1	C has 4 bonding pairs / lone pairs 2 /6 / 8 / 10 / 18 / 2 electrons	-
T2	C / H is saturated	1.2
T3	More C in air / H travels in pairs /1:4 gives equal mass	7.5
T4	Because there are 4 H's and 1 C / other statement	6.3
T	**Total**	**15.0**
U1	Uncodeable	-
U2	No response	14.5
U	**Total**	**14.5**
	Overall total	**100.0**

n = 399

Table 4.18: First survey responses to *Methane molecules*

Response codes P1a and P1b express the stability idea explicitly, for example:-

> "CH_4 is the most stable form that C and H can form because C needs $4e^-$'s to be stable and 4H atoms can provide the $4e^-$'s that the carbon needs. It's electron sharing (covalent bonding)." (000, P1b)

Responses coded P2 put this slightly differently, associating the stability with noble gas electron arrangements:-

> "Carbon needs four electrons to become unreactive and take on a noble gas arrangement - hydrogen only has one electron and so you need 4 hydrogen atoms to each carbon \ CH_4." (002, P2)

Two response types totalling 37% showed evidence of partial understanding and were coded Q. These answers think of the formation of CH_4 only in terms of the carbon, and do not mention hydrogen, for example:-

> "Because the 'valency' or bonding capacity of carbon is four, meaning it requires four more electrons to covalently fill its outer shell of e^-'s." (005, Q1b)

These answers give no evidence of misunderstanding the chemical idea, but do not make clear that the stability of both elements has to be considered.

T-coded responses totalled 15%. Two response types contribute most of this figure. T4, 8% of the sample, suggested various reasons, including that there is more "carbon in air", that "hydrogens travel in 2's" or that the ratio 1:4 is significant. About 6% of the remainder (T5) offered no reason at all, effectively saying "it just is".

These questions indicate that symbols for covalent bonds are well-known, although the type of description given varies in the level of detail. Responses to *Methane molecules* indicate that fewer numbers of beginning A level students were able to explain why covalent bonds form in terms of the stability of the resulting molecule. About 15% had very poor levels of understanding about covalent bonds and appeared easily to confuse bond types.

4.10.2 Ionic bonds - Sodium and chlorine

One question, *Sodium and chlorine*, probes students' ideas about ionic bonds. Table 4.19 shows the response types obtained in the first survey.

RC	Description	%
P1	Energy is liberated in bond / ionic lattice formation	5.3
P2	e^- transfer Na to Cl, stable cmpd forms / redox reaction	12.0
P3	Ionic bond forms between Na and Cl	6.0
P	**Total**	**23.3**
R1	Na and Cl are reacting / form a compound	38.8
R2	The element(s) is / are reactive hence violent reaction	6.0
R	**Total**	**44.8**
S1	Hot Na has E_A req'd / Reaction is quick / endothermic	7.8
S	**Total**	**7.8**
T1	Heat breaks bonds / sodium is burning	2.3
T2	The particles expand / contract / collide / break / split	3.5
T	**Total**	**5.8**
U1	Uncodeable	4.0
U2	No response	14.3
U	**Total**	**18.3**
	Overall total	**100.0**

n = 399

Table 4.19: First survey responses to *Sodium and chlorine*

Table 4.19 shows that 23% of responses were coded P. These answers gave evidence of understanding the chemical idea, for example:-

> "The heat from the sodium breaks the covalent bond of some Cl_2 molecules these free chlorine atoms then gain an e^- from the sodium and become negatively charged these are then attracted to the + sodium ions and an ionic bond forms. The forming of this bond liberates energy which continues until all of one of the reagents has been used." (026, P1)

> "The release of energy is the violent reaction as the 2 elements combine..." (319, P2)

> "...the sodium is giving its spare outer shell electron to fill the gap in the chlorine's outer shell..." (029, P3)

> "The sodium ions are positively charged and the chlorine ions are negatively charged so they are attracted and form an ionic bond." (086, P4)

These answers include some or all of the statements in the correct answer. No responses demonstrated partial understanding of the chemical idea. However, two response types totalling 45%, were coded R. 39% explain that:-

> "The sodium and chlorine are reacting together." (203, R1)

These answers restate the question by defining the event in the gas jar as a "reaction". While this is true, stating that a "reaction" has occurred is not a full explanation, but at the same time these do not demonstrate misunderstanding of the fundamental idea. The remaining 6% in this category used the word "reaction" in a different way, for example:-

> "...The reaction is so violent because firstly sodium is very reactive and secondly it's hot..." (006, R2)

Sodium and chlorine are reactive, but saying this by itself does not explain events occurring in the gas jar.

Responses coded S amounted to 8%. These students misunderstood the chemical event, using ideas about kinetics, notably activation energy, in their answers, for example:-

> "The sodium is reacting with the chlorine to form salt. The heat of the sodium provides the activation energy." (048, S1)

> "...Hot sodium is just giving the two elements much more energy to react even quicker, that's why it is so reactive." (010, S1)

These students associated "violent" with "quick", and linked the information that the sodium is hot with the rate of reaction. These answers do not demonstrate misunderstanding of the chemical idea, so were not coded T, but these students have missed the intended meaning of the question.

About 6% of responses were coded T. These indicate misunderstanding of the chemical idea, suggesting, for example, that:-

> "The heat from the sodium is increasing the kinetic energy of the chlorine...The rapid expansion and contraction of atoms cause the reaction to be violent." (054, T2)

> "...The particles in each of the elements become so energised the[y] explode..." (277, T2)

These answers are given in particle terms, but at a very primitive level, attributing the energy from the heat, or the meaning of the word "violent" to the particles themselves. Brook, Briggs and Driver (1984) report that this "balloon-like" view of matter is used by up to 10% of 15-year olds. These data suggest that for some who select chemistry for study beyond 16 years this notion is persistent.

A few students, 2%, coded T1 used language associated with combustion or displacement, for example:-

> "There is a displacement reaction occurring..." (278, T1)

> "The sodium metal is burning in the chlorine gas and being oxidised..." (008, T1)

These students misuse words which have a specific meaning in chemistry. This judgement is harsh on respondents like 008, especially as he suggested the sodium is oxidised, but his association may be that chlorine is the same as oxygen, and he did not explain oxidation in terms of electron loss.

This question suggests that the formation of an ionic bond between sodium and chlorine is not well known. The question attempts to lead students into answering in terms of bond formation without actually asking for explanations in these terms. Students used to more direct questions may therefore have been swayed to answer, as many did, "Sodium and chlorine are reacting". However, only 6% gave evidence of misunderstanding the chemical idea, offering answers indicative of poor understanding of particle behaviour. This question, then, while it may not have drawn out all those who do know about ionic bond formation, seems to illustrate that a proportion of beginning A level chemists retain primitive particle ideas.

4.10.3 Intermolecular bonds

Three questions, *Hydrogen bonds*, *Chlorides* and *Boiling* probe students' understanding of the nature and effect of intermolecular bonding. Their coding schemes are given in Tables 4.20 - 4.22. Intermolecular bonds are not discussed in detail during GCSE courses, so students may be approaching this idea for the first time.

Hydrogen bonds

Table 4.20 shows the responses given to *Hydrogen bonds* at the first survey. These reflect the fact that many students are unaware of links existing between water molecules at the start of their A level courses.

RC	Description	%
P1	Hydrogen bond + explanation	6.0
P2	H-bond only - no explanation	4.0
P3	Intermolecular bond / polar attraction	7.8
P	**Total**	**17.8**
Q1	"Liquid" bond + explanation	9.6
Q2	Weak bond between molecules + explanation	12.7
Q3	van der Waals' / dipole / connecting bond	2.4
Q4	Cohesion / magnetic attraction / semi-permanent bond	8.9
Q	**Total**	**33.6**
T1a	Line 3 is an attraction force not a bond / not a real bond	8.4
T1b	Doesn't exist / is imaginary / temporary / repelling force	0.5
T1	***Total***	***8.9***
T2	Triple / covalent / ionic / molecular / weak / double / 1.5 bond	6.5
T2	***Total***	***6.5***
T3a	Shows water moves around / is in suspension	2.2
T3b	Shows water is rigid / is stronger than a covalent bond	3.4
T3	***Total***	***5.6***
T	**Total**	**20.0**
U1	Uncodeable	-
U2	No response / Don't know	28.6
U	**Total**	**28.6**
	Overall total	**100.0**

n = 399

Table 4.20: First survey responses to *Hydrogen bonds*

However, about 18% of the sample gave evidence of understanding the chemical idea, and were coded P, for example:-

> "This is a hydrogen bond. The hydrogen in water is very slightly charged, and the oxygen is oppositely charged, so they attract each other."
> (141, P1)

> "Polar attraction between the d$^-$ and d$^+$ on two water molecules."
> (004, P4)

Student 141 clearly understood the chemical idea. Student 004 used terminology demonstrating understanding that the line represents a hydrogen bond, but called it a "polar attraction".

About one-third of the responses were coded Q, for example:-

> "It is some sort of bond linking the water molecules together." (321, Q1)

> "A long weak bond that can easily be separated." (301, Q2)

These show partial evidence of understanding, in that the idea expressed is correct, but the explanations do not include ideas about how the bond is formed, so these are really "good guesses" on the part of the students.

About 9% (T1) of the sample described the hydrogen bond as

> ".. the attraction holding the water molecules together." (160, T1)

or

> "a force of attraction holding molecules close together." (020, T1)

but a covalent bond as a "bond". This may acknowledge the relative strengths of the two bond types, but implies that hydrogen bonds are not bonds. Some students took this further, for example:-

> "[line] 3 is an attraction magnetic/polarity [line] 1 is a sharing of electrons." (360, T1)

These students seem to suggest that hydrogen bonds do not involve electrons, whereas covalent and ionic bonds do involve electrons. Approximately 7% confused the types of bonds completely, suggesting that the hydrogen bond is an:-

> "Ionic bond. Line 3 is exchange of atoms." (153, T3)

Similar responses using ideas about covalent bonds were also found. A high proportion of students, 29%, did not respond to this question in the first survey, confirming that many had not seen this type of link before.

Boiling

The question *Boiling* was adapted from Cosgrove and Osborne (1981). The premise on which this question rests is that bubbles from boiling water contain steam. The responses given to this question at the first survey are presented in Table 4.21. The response "bubbles contain steam" was given by 26%, and was coded P. Water does contain dissolved oxygen, released in small bubbles as the liquid heats up, so responses stating "oxygen", a further 26%, were considered to be partial evidence of understanding, not evidence supporting misunderstanding of the chemical event. So, these answers were coded Q1. About 10% suggested that the bubbles contain "dissolved or evaporating gas" or "air". Again, these answers are not incorrect, but do not give clear evidence of understanding the chemical idea.

RC	Description	%
P1	Steam, water vapour, gaseous water	26.3
P	Total	26.3
Q1	Oxygen	26.3
Q2	Dissolved or evaporating gas	1.8
Q3	Air	8.3
Q	Total	36.4
T1	Heat, energy	1.0
T1	*Total*	*1.0*
T2a	Hydrogen	9.3
T2b	Oxygen and hydrogen	16.5
T2c	Oxygen or hydrogen	2.0
T2	*Total*	*27.8*
T3a	Carbon dioxide	3.3
T3b	Gas	3.0
T3	*Total*	*6.3*
T4	Nothing / vacuum	0.2
T4	*Total*	*0.2*
T	Total	34.3
U1	Uncodeable	0.2
U2	No response	1.8
U	Total	2.0
	Overall total	100.0

n = 399

Table 4.21: First survey responses to *Boiling*

Around 28% of responses were coded T2. These implied that water breaks up into hydrogen and oxygen on boiling. Such responses coincide with the T2 group of *Chlorides* which suggest that the vapour above the mixture of compounds would be composed of titanium and chlorine atoms because the covalent bonds in the molecules of $TiCl_4$ would break. Students may have responded to this question thoughtlessly - perhaps many would have answered differently had they been prompted at interview. However, this remains a striking finding - that more than one-quarter of beginning A level students explain water boiling in terms of intramolecular bond fracture.

About 6% thought that carbon dioxide or another named gas is present in the bubbles (T3). These answers do not explain where the gas comes from, so suggests that students simply wrote down the name of the first gas they could think of.

A smaller group, 1%, thought that the bubbles contain heat or energy (T1). They may mean that water turned into energy or heat, in a similar way to those answering *Petrol* (see below) thought that petrol turns into energy when a car engine is turned on.

Intermolecular bonding is not well known among beginning A level students. This is not surprising, since few are likely to have studied this type of bonding at GCSE. Some students, as answers to *Chlorides* indicate, readily recall differences between boiling points of covalent and ionic compounds, but this is the closest answer to the correct one that many students can give. These data indicate that about one-quarter of beginning A level students give answers suggesting covalent bonds break when a substance changes state. The evaporation of water is probably the most-widely taught example of change of state and may be included in work on particulate theory. Relatively few students can apply these very basic ideas in practice, which suggests that some may have serious difficulties with the demands of an A level chemistry course.

Chlorides

Chlorides is adapted from a University of London A level chemistry examination paper set in June, 1990. The coding scheme is given in table 4.22.

RC	Description	%
P1	Intermolecular bonds between $TiCl_4$ molecules break	2.0
P2	Intermolecular bonds in ionic solids are stronger	1.3
P	Total	3.3
Q1	Covalent substances have lower b.p.'s / more heat req'd	20.8
Q2	$MgCl_2$ only melts / lattice needs to break down	0.7
Q	Total	21.5
T1	Ionic bonds can't be broken by heating	6.8
T2	$MgCl_2$ ionises / is less reactive / already vapourised	13.8
T3	Covalent bonds weaker than ionic ones, so break	27.3
T4	Covalent bonds are stronger than ionic ones	4.0
T	Total	51.9
U1	Uncodeable	0.2
U2	No response	23.1
U	Total	23.3
	Overall total	100.0

n = 399

Table 4.22: First survey responses to *Chlorides*

Only 3% of students responded in terms of intermolecular bonds and were coded P. This low figure suggests that a majority of beginning A level students do not realise that intermolecular bonds exist between covalent molecules. About 22%, gave partial evidence of understanding of the chemical idea. Most of these, 21% (Q1) responded in terms of the physical characteristics of ionic and covalent compounds, for example:-

> "Because magnesium chloride needs a higher temperature to become a gas but titanium(IV) chloride does not." (278, Q1)

The information these answers give is relevant, but they do not address the issue as to *why* these different compounds require varying amounts of energy to change state. Several students' responses (Q2) were concerned with the ionic lattice of magnesium chloride, again giving correct factual information but not answering the question fully.

About half of the students, 52% gave responses indicative of misunderstanding the fundamental idea and were coded T. The most frequent, coded T3, was given by 27%, suggesting that ionic and covalent bonds break when vapourisation takes place, for example:-

> "Because ionic bonding is stronger than covalent bonding so it will take more heat energy to break the ionic bonds..." (223, T3)

These answers seem appropriate to students who do not know about intermolecular bonds - the only bonds they have heard of, covalent and ionic, feature in the question. The sensible answer is that one of these must be "stronger" than the other, because these students know that some compounds have higher boiling points than others and that this has "something to do with bonding". An implication arising from these answers is that many students think the vapour above a covalent substance is composed of individual atoms, a fact confirmed by responses to *Boiling.*

About 14% of students (T2) thought the question was asking about a reaction between the compounds, for example:-

> "The ionic compound will not react with the titanium chloride which is not ionic." (321, T2)

These students thought a reaction can only take place between compounds with similar bond types, an idea irrelevant to this question, but one which will need to be challenged during their A level course.

A further 7% (T1) suggested that an ionic bond cannot be broken regardless of the amount of energy put in, while 4% (T4) suggested the opposite, that covalent bonds are "stronger" than ionic ones.

A high level of "No response", 27%, was found to this question, perhaps because of the inclusion of titanium(IV) chloride, a substance which many students will not have encountered.

4.11 Thermodynamics

Two questions devised for this study, *Methane* and *Energy change,* investigate understanding about basic principles of thermodynamics. The coding schemes are given in Tables 4.23 and 4.24.

4.11.1 Methane

In each category, the response to the last part of the question is given first, followed by responses to the other two parts in order, that is, c, a, b. The reason for this is that part c explores most closely students' ideas about the source of the energy, which is the chemical idea being probed.

About 7% of beginning A level students responded correctly to part (c), suggesting that the chemical idea probed by *Methane* is not well-known. An example of this type of response is:-

> "Energy is needed to break the bonds in methane. A chain reaction has been started... Energy is released when bonds are made." (086, P2)

Students who gave correct answers to two parts of the question were coded Q, for reasons given above (for example in *Substances*).

Around 81% of students, a large majority, gave answers suggesting they misunderstood the chemical idea. The T1 group totalled 19%. These students suggested that the energy comes from breaking bonds in the methane, not from forming bonds, for example:-

> "The heat comes from the CH_4 as it is split." (349, T1c)

> "The energy is released by elements braking (sic) bonds. Energy is used by producing more bonds but not all." (262, T1b)

A clue as to why this idea is popular is given by the responses placed in the next group, T2, which totalled 14%. These suggested that methane is an "energy store", for example:-

> "The energy is displaced from the methane. It came from the methane where it was stored as potential energy." (302, T1c)

The origin of the energy is the sun, or plants or animals which "absorbed" the sun's energy and have decayed. Methane burning releases this "stored energy". An example of this is:-

"The energy originally comes from the sun and was absorbed by plant material. When the plant material decays it produces methane. Methane has chemical potential energy ... " (008, T2c)

RC	Description	%
P1	Energy is from bond formation	6.8
P2	Products are more stable than reactants	0.2
	Part a: E_A supplied / E splits molecules	
	Part b: rxn is exothermic / chain reaction / O_2 is unlimited	
P	Total	7.0
Q1	Answers as above to a and b only or to part c:	3.0
	Energy is from bond making and breaking	
Q	Total	3.0
T1a	Energy is from bonds in CH_4	2.2
T1b	Energy is from bond breaking | E splits molecules	3.3
T1c	Energy is stored in CH_4	13.3
	Part a: as above (P) / E speeds up reaction	
	Part b: as above (P) / CH_4 releases energy / xs energy is used	
T1	*Total*	*18.8*
T2	CH_4 is E store made from animals/sun	7.5
	Part a: heat required / flammable H_2 present	
	Part b: CH_4 is fuel / flammable / O_2 available	
T2	*Total*	*7.5*
T3	Energy is from CH_4 | Need O_2, fuel & heat | fire Δ kept going	5.3
T3	*Total*	*53*
T4a	From burning CH_4 | CH_4 always burns in air / until it runs out	19.3
T4b	Heat energy from burning	5.0
T4c	Heat is given out / from the flame	5.8
	Part a: as above (P) / Heat required	
	Part b: as above (P) / Heat of burning / flame keeps rxn going	
T4	*Total*	*30.1*
T5	From exo rxn | O_2 needs spark | gas has 2 flammable elements in it / is a hydrocarbon	1.7
T5	*Total*	*1.7*
T6	Only 1 part answered	16.3
T6	*Total*	*16.3*
T	Total	80.7
U1	Uncodeable for all three parts	2.0
U2	No response	7.3
U	Total	9.3
	Overall total	100.0

n = 399

Table 4.23: First survey responses to *Methane*

Students who perhaps have a more developed particle model of matter and can think in terms of bonds breaking apply this idea to give the answers coded T1. The notion of an "energy store" is potent, as it provides a plausible explanation about how energy from the sun is "transferred" to living organisms and then to methane we use. Many will need to change their thinking about this issue, as the information they so readily reproduce is chemically erroneous.

About 30% (T3) did not use ideas about energy stores, responding in more vague language that the energy comes "from the flame" or "the reaction", for example:-

> "Burning produces heat but I don't know why or how (or where)." (321, T3b)
>
> "The energy comes from the flame." (033, T3c)

These students are saying "it just does" - there is no reason, that is just what happens when methane burns, as though they have never thought about this before. A few students, 2% (T4) recognised that the reaction is exothermic, but this only puts a chemical-sounding label on the reaction. This group perhaps thought that stating "exothermic" is an explanation in itself.

A final group, 16% (T5) did not give an answer to all three parts, but gave T-coded answers to only one or two sections. Relatively few students (7%) did not respond to this question, suggesting that most were familiar with the reaction and thought they knew what was required. That a majority could not use the diagram to work out the correct answer to part (c) suggests that for them the arrows had no meaning or the opposite meaning to the correct one. This is confirmed by some responses to *Energy change.*

4.11.2 Energy change

This question gives basic enthalpy diagrams and probes students' ideas about the meaning of the arrows. Although diagram C could, in the absence of a numerical scale, also represent the reaction, no answers selecting C gave correct explanations, so all the C responses are coded Q, R or T. The first survey responses to *Energy change* are presented in Table 4.24.

About 18% selected diagram A and gave an explanation demonstrating understanding of the chemical idea, for example:-

> "A. Fewer bonds are broken than those made so more energy is released than taken in." (086, P1)

A further 18% gave answers coded Q. These demonstrated partial evidence of understanding in that they focussed on the length of the upward arrow, and attributed their decision to the amount of energy required to break bonds, or the "activation energy", for example:-

"C. Double chlorine atoms are broken into single." (132, Q1)

RC	Description	%
P1	A / C Low E_A, energy released on bond formation	1.2
P2	A / C Low E_A, exothermic reaction / stable compound forms	10.3
P3	A / C e^-'s lost & gained / low I.E. and high LE	0.8
P	Total	12.3
Q1	A/C Energy required to break Cl_2 bond / start reaction	2.5
Q2	A/C Energy required to heat Na / 2 states react	1.5
Q3	A Violent rxn / react easily / low E_A required	5.3
Q4	A/C Uncodeable / No explanation	14.0
Q	Total	23.3
R1	A Na & Cl are reactive	1.0
R2	A/C It is an exothermic reaction	5.5
R3	B Energy is conserved in the reaction	2.5
R	Total	9.0
S1	B/C The reaction doesn't give out much energy	6.3
S2	B Misunderstandings about e^- transfer / equation	
S3	A/C 2:1 moles reactants / 1 bond broken, 2 formed	5.0
S	Total	11.3
T1	B Bond breaking gives out energy	0.3
T2	B Rxn is in eqm / energy levels are equal	0.2
T3	B Long arrows => lots of energy made / used / reaction is violent	6.8
T4	B Uncodeable / No explanation	13.3
T	Total	20.6
U1	Uncodeable	0.2
U2	No response	23.3
U	Total	23.5
	Overall total	100.0

n = 399

Table 4.24: First survey responses to *Energy change*

About 9% (R1-3) responded in terms of the chemical event, demonstrating no misunderstanding of the chemical idea. Most of these restated the question, selecting A or C because they knew the reaction between sodium or chlorine to be exothermic. Around 3% noted that energy is conserved in the reaction. While this is true overall, this answer ignores the fact that energy is released when the ionic lattice forms. These students interpreted the diagrams such that B is the closest representation to their idea about this.

11% gave answers coded S, giving evidence of misunderstanding the chemical event. Respondents placed in group S1 did not realise that the reaction gives out energy, for example:-

"B. I don't think it is a particularly exothermic reaction, so it won't produce surplus energy." (008, S1)

"B. A and C are exothermic reactions. In the reaction 2 bonds are being broken and 2 made. This suggests there is no NET energy change." (041, S1)

Here, the choice of B implies that these students realised the importance of the gap between upward and downward arrows, so misunderstanding of the chemical idea is not apparent. The misunderstanding is of the reaction itself. Other responses coded S gave evidence of misunderstanding the equation, and the way in which sodium chloride forms, for example:-

"B. They both either want 1 electron or want to loose (sic) one electron." (012, S2)

Student 012 knew that electron transfer is involved, but not how. She was not thinking in thermodynamic terms, instead answering in terms of electron transfer, involved in the formation of ionic bonds. This student may think that the two arrows in B represent electron transfers, although if this were the case this response would be coded T. Respondents coded S3 used the ratio of moles to suggest that the equation relates directly to the diagrams. Most of these chose C as the upwards arrow is half the length of the downward one, corresponding to one mole of chlorine and two moles of sodium.

About 20% of responses were coded T. These include the same misunderstandings found in response to *Methane*, such as:-

"C. Making bond takes in energy." (104, T1)

"C. Because when a bond is created, energy is absorbed but some energy had to be given out to break the Cl_2 bond ..." (126, T1)

which suggest that making the bonds in sodium chloride requires energy. As the diagram gives the upward arrow first and the downward second, these answers imply that the upward arrow represents energy given out (bond breaking) and the downward arrow energy absorbed, the opposite position to the correct one. One student chose B, associating the closeness in lengths with an "equilibrium"-type position. More popular, given by 7%, was the misunderstanding that arrow length is associated with the amount of energy involved, for example:-

"B. The sodium had a very violent reaction with chlorine showing that for this reaction to take place, a lot of energy is needed. The longer arrows show the amount of energy. B has the longest arrows." (004, T3)

These students clearly understood that the reaction is exothermic, but did not know how the diagram relates to the reaction.

About 13% select B but gave explanations which could not be reliably coded and 23% did not attempt this question in the first survey.

The *Methane* question reveals that only 1:5 beginning A level students think that bond breaking releases energy and, conversely, that bond making requires energy. This finding supports that of Ross (1993). Such thinking is confirmed by responses to *Energy change*, which indicate that students interpret enthalpy diagrams in the same way. Students' difficulties with bond breaking and bond making may develop because the teaching that fuels are "energy stores" is so widespread. As students learn that reactions involve bond breaking and bond making, the next stage is to associate bond breaking with releasing energy "stored" in a fuel molecule. Extrapolation of this idea to other circumstances such as the sodium/chlorine reaction is thereafter no problem. The difficulty these students will have is changing their thinking through the thermodynamics parts of their A level courses.

The difficulties students have with enthalpy diagrams are also made apparent by these questions. Some respondents may not have seen diagrams like these before, but others will have come across very simple ones like those in *Energy change* at GCSE. The tendency seems to be for some students to associate lengths of arrows with energy and for others, a larger group, to misinterpret the meanings of the arrows. The extent to which these ideas are changed during A level chemistry courses will be monitored.

4.12 Equilibria and Rates of reaction

The questions *Reactions* and *Reaction rates* probe students' ideas about equilibrium reactions and rates of reaction respectively.

4.12.1 Reactions

The first survey responses to *Reactions* are shown in Table 4.25.

RC	Description	%
P1	Reverse rxn is thermodynamically feasible | reverse rxn *not* thermodynamically feasible/ large eqm constant for -> arrow	-
P	Total	-
Q1	Reactants not used up | fully used up	6.3
Q2a	First rxn is reversible | conditions need changing to go back to reactants	3.3
Q2b	Rxn reversible | can't easily turn back / strong bonds	6.5
Q2	*Total*	*9.8*
Q3	Two answers from Q1, Q2a or Q2b	4.7
Q	Total	20.8
R1	Product stayed gaseous | product changed state	0.8
R	Total	0.8
S1	N & H are equal quantities | products & reactants are not equal quantities	3.5
S	Total	3.5
T1	First rxn is reversible | Second / most rxn(s) aren't reversible / go one way	38.3
T2	Relatively low E_A required | high E_A required	2.0
T3	1 explanation only / 2 nonsense explanations	17.5
T	Total	57.8
U2	No response	17.1
U	Total	17.1
	Overall total	100.0

n = 399

Table 4.25: First survey responses to *Reactions*

The question *Reactions* gives equations and ΔH values for two reactions likely to be familiar to many students. ΔG values would be more accurate, but many A level courses do not now require understanding of free energy, so ΔH values were used as a compromise. However, their inclusion may tempt students to respond with ideas about activation energy, a kinetic phenomenon, rather than drawing them to thinking about equilibrium constants. This is considered in coding responses.

No student demonstrated understanding of the chemical idea, so there are no P coded responses at the first survey, confirming that the idea being probed does not feature in GCSE courses. However, most students were able to attempt the question, implying that they were familiar with the reactions shown.

About 17% showed partial understanding of the chemical idea and were coded Q. The Q2 group, 10%, explained that one reaction is harder to reverse than the other, for example:-

> "Most reactions do not form then break down and then reform again. Most reactions have to be broken down by other means, they don't break down on their own." (319, second part, Q2b)

These students realised that there is a need for input of some kind, and they may be using the ΔH values although they did not explicitly say so. Others, Q2a, expressed this in terms of changing conditions.

Three respondents gave answers using information about the chemical events, noting that water is gaseous while ammonia is not and so are coded R. About 4% of responses are coded S. These used the equations to try to explain the arrows, but misunderstood the meaning of the equations, for example:-

> "[a] because there are equal numbers of molecules on both sides.. [(b)] because they react with oxygen in the air which causes some imbalance." (036, T2)

The majority, 61% of the sample, gave evidence of misunderstanding the chemical idea. The most frequent of these was given by 38% (T1) of the sample, who responded that one reaction is reversible while the other one isn't, for example:-

> "because ...NH_3 can break down ...unlike water. Once the reaction has taken place it is stable and will not break down again. (306, T1)

> "The nitrogen/hydrogen reaction is dynamic and works both ways....The two elements react to form a product. It is a one way reaction and is not easily reversed." (008, T1)

> "..the Haber process .. is a reversible reaction ... [(b)] the reaction goes merely in one direction an equilibria cannot be set-up." (022, T1)

These students thought that the equilibrium arrow meant "something can break down" and a "->" arrow meant "this product can't break down." They had no understanding of the extent of reverse reactions, and linked the arrows with a degree of permanency of the product(s) of most reactions. Student 008 embellished his answer with the word "dynamic", lending a chemical coherency to his argument, while student 022 attempted this with "equilibria".

The T2 group was very small, suggesting that few students at this stage were swayed by the presence of ΔH values. This may be because at the beginning of an A level course the meanings of these figures are not well known. As students become more aware of the importance of this data, the frequency of this response type may increase.

About 18% of students responded (T3) to only one part of the question, or gave nonsense answers to both. This high figure and the 17% who offered no response confirms the level of difficulty of this question.

4.12.2 Reaction rates

Several factors control the rate of chemical reactions, including temperature, surface area and the presence of a catalyst. This question probes students' understanding of the influence surface area has on rate of reaction. *Reaction rates* uses graphs and familiar reactions to assess students' thinking about one aspect of kinetics. For coding purposes, the students' descriptions of the graphs are ignored, so only answers to the last two parts are used. The coding scheme is given in Table 4.26.

Only two responses were coded P, suggesting that students found this question difficult. Selecting the correct graphs depended on their realising the meaning of "rate" and making the distinction between the infinite surface area of a liquid/liquid reaction and the limiting surface area in a solid/liquid reaction. Graphs A and C appear to be similar, since both begin at zero and reach a peak. However, A is more appropriate to a catalysed reaction, as the maximum rate is retained over a relatively long period of time. These data show that post-GCSE few students are able to make these distinctions.

RC	Description	%
P1	B/C liquid / liquid phase rxn | solid / liquid, oxide layer	0.5
P	Total	0.5
Q1	B/C or B/A reactants used up quickly / acid neutralised | slow to start	5.8
Q2	B/C or B/A one / no /other explanations	19.5
Q	Total	25.3
T1	B/C / B/A most rctnts used at start | rxn starts vigorously	5.3
T1	***Total***	***5.3***
T2a	C/B rxn slow start | Mg reactive / used up	10.3
T2b	C/B heat increases rate | any explanation	0.5
T2c	C/B or B/B no explanations	12.5
T2	***Total***	***23.3***
T3	B/B rxn slows as rctnts decrease in conc. / SA | ditto	5.0
T3	***Total***	***5.0***
T4a	B/-, -/C, A/C with / without expln	7.8
T4b	Other combinations with or without explanations	16.3
T4	***Total***	***24.1***
T	Total	57.7
U1	Uncodeable	-
U2	No response	16.5
U	Total	16.5
	Overall total	100.0

n = 399

Table 4.26: First survey responses to *Reaction rates*

About 25% were coded Q. Most answers in this category (20%, Q2) selected the correct graphs, but offered one or no explanations. Hence, the evidence these provide for understanding the chemical idea is partial. The remaining 5% (Q1) offered simplistic descriptions of the graphs, for example:-

> "B. Reaction starts at highest and decreases slowly. C. Slow increase at start." (301, Q1)

and thus are distinct from Q2, but did not demonstrate understanding of aspect 1.

No responses were coded R and S. For this question, the chemical events and chemical idea are too closely intertwined to allow separation from one another.

More than half of the responses, 58%, were coded T. These include 10% (T1) who selected the opposite graphs and explained their choice by the reactivity of the magnesium, for example:-

> "B. Because the rate will decrease as the Mg ribbon is used up." (198, second reaction, T1)

The association is between a high starting point on graph B and the perceived high reactivity of magnesium. These students may think that "rate" implies "reactive" and their experience tells them that magnesium is reactive. Notably, some chose C for the first reaction because of their knowledge about magnesium, for example:-

> "C. I guessed. B. Magnesium is a very reactive substance..." (321, T1)

Code T2 represents the 5% who selected the same graph, B, for both reactions. These students seemed to think there is no difference between the reactions and that both would start at the fastest rate. Responses coded T3 (5%) chose B/C, but misinterpret the graphs, suggesting that the high point on B means "reactants are used up", continuing to say that the second reaction "starts vigorously". These students seemed to think about the slopes of the graphs, suggesting that the steepness of the downward and upward parts of graphs B and C measures the rate. Effectively, they offer the same explanation for both, as the implication of their explanations for B is that if the reactants are being used up the rate of reaction must also be high - which is precisely their explanation for graph C!

A substantial minority, 37% (T6) chose incorrect graphs but offered no explanations, or answered only part of the question incorrectly. These could not be reliably coded. A point to note is that very few students chose graph A for either reaction. This could be because it looks "too perfect", having straight lines and precise changes in direction - students may be more used to producing graphs from reactions or seeing graphs which do not have this sort of shape. A further 12% (T4) chose C/B or B/B but offered no explanation, presumably guessing.

The 17% offered no response and the high proportion of responses with no explanations confirms that some students had very little knowledge about the chemical idea being probed by the question. As their A level courses proceed, the level of these poor quality responses should decrease and the level of P-codes may be expected to increase.

4.13 Post-first survey interviews

Interviews with twelve students were carried out a few weeks after the first survey to establish whether their written answers accurately reflected their thinking. This was important, since the analysis of written responses would depend entirely on the fact that students wrote down what they meant to say. Verifying their answers enabled me to check that their responses were, as far as possible, unaffected by presentation or wording of the questions. At the time the interviews were carried out, early coding schemes were available only for questions probing ideas about the conservation of mass in open and closed systems and reacting mass reasoning. However, it was thought sensible to proceed with the interviews as quickly as possible after the first survey, so that any serious difficulties arising became apparent at the earliest opportunity. The strategy used in these interviews is discussed more fully in section 3.7.1.

The interviews are discussed below, using illustrative extracts of transcripts. Interviews relating to questions probing the same chemical idea are considered together.

4.13.1 Interviews about responses to Phosphorus, Precipitation and Solution

These questions probe students' ideas about the conservation of mass in closed system chemical events.

Phosphorus

About 8% of students, including number 43, selected "less than 400 g" and explained that solid phosphorus would be "heavier" than liquid or gas (T3a, Table 4.10). Student number 43 was interviewed to ascertain if his confusion of mass and density was genuine:-

> I: ..The next one was the *Phosphorus* question....[Audible groan] I know it's quite hard! This is where you've got this piece of phosphorus and it's in water and the sun's rays are focussed on it. And eventually the phosphorus catches fire and the flask is cooled down so you get this white smoke produced. And the question was about the mass of the flask afterwards. You said it was less than...
>
> S: I think I had a guess at this one. [Laughter]
>
> I: That's OK. You can change your mind. Tell me how you guessed it first. I mean was that just a guess or...
>
> S: I think .. I think what... erm I'm not sure whether this is right or not but I didn't know whether the phosphorus being a liquid would be lighter than the solid but I wasn't sure so I just had a guess..

By "guess" this student seems to mean that "less than 400 g" he was not certain this was the expected answer. The interview continued to discuss the events in the flask. Although the student was brought to realising that a reaction had occurred, he was still uncertain that mass would not change:-

> I: So if you have the air there would that be what it was reacting with or would the phosphorus have reacted with..
>
> S: I would have thought it would have reacted with the water rather than the air.
>
> I: Right. So what's made it react now rather than before, 'cos the water and the phosphorus were there before?

S: Well, the sun's given it the energy.

I: So would you change your mind about that then, the idea of it being less than?

S: I don't know ..erm [11 second pause] I'm not sure .. Maybe it wouldn't be less than, thinking about it, but.. I'm not sure whether it would be more either. Because its just the same things, isn't it?

I: Yes.

S: It's just combined in a different way.

I: Yes.

S: So it might be the same...I'm really not sure about that one.

He was not convinced and seemed to persist with his written response. His thoughts and written evidence appear to match. Our second example, student number 9, was one of about 7% who selected "400 g" and gave evidence of misunderstanding the chemical event (S1, Table 4.10). She was asked about her explanation that the "white smoke came from within the phosphorus" :-

I: The next one was this *Phosphorus* question. About a piece of phosphorus in some water in a flask. You said the mass was the same which was fine. "White smoke is not being added to the mixture, it comes from within the phosphorus." And it was this I wanted to ask you about really. About how.. what you saw.. what you thought was happening in the flask. And what you meant by this bit.

S: Well, I thought that the - how much did it weigh 400 grams so... nothing's been added to the total, the mass, so it isn't going to increase and nothing's really been taken away so it isn't going to decrease.

I: Yes.

S: So.. it comes from the reaction of the water and the phosphorus.

I: Right.

This student conserved mass, but thought that the reaction would be between phosphorus and water, not oxygen. Thus, her response should be coded S, not P. Nevertheless, her written answer supported her idea. Thirdly, student number 12 was one of about 3% who selected "more than 400 g" because "the energy of the sun was absorbed" (T1a, Table 4.10). She explained this as follows:-

I: The next one I was looking at was the *Phosphorus* question. I just wondered if you could explain a bit more about your answer.

S: I think that my result was a guess.

I: Right. So is that not a realistic idea?

S: No. Well .... I know that the force of the sun does have strength behind it because it can push things through space, but I wasn't sure, so I just guessed.

I: Right. Is there anything else which prompted you to think about that? I mean, like the idea of the phosphorus catching fire or something?

S: Um .... No, 'cause it's in a contained unit, so nothing could basically get out.

I: Right.

S: But I thought since sun might pass through the glass, then it might, but it was just a guess.

I: Right. Were you thinking that energy has mass?

S: Um ......

I: And energy going in added to the mass that was in there already?

S: Yes, 'cause it sort of does anyway.

This student was more reluctant to speak than some of the others, so I needed to prompt her with rather more leading questions than I used with other students. She realises that the flask is sealed, but thinks that energy from the sun becomes added to the mass in the flask. Although she, like student number 43, uses the word "guess" initially, it becomes clear that this is her thinking. Therefore, her verbal and written responses support one another. From these, and other examples which are not reported here, I concluded that students understood what was required by the question and that their written responses did reflect their thinking.

Precipitation

About 13% of beginning students (T3, Table 4.11) responded that the solid precipitate would be "heavier" than the two liquids, so the mass would increase. Student number 9 gave this answer and explained it as follows:-

I: The last question I wanted to look at was this one about *Precipitation.*[Interviewer reads through the question] And you suggested that the mass would be more after the reaction. Because "the precipitate is the mixture of the two salts, but solid, so it's heavier".

S: Mmm..

I: Can you tell me how you got to that? It's difficult isn't it?

S: Ermm.. Well the precipitate is a solid, which forms when things mix together and react together, so if you get..erm.. I can't... If you've got ice, say, and water and.. you got two samples of water and you froze one...then you'd have exactly the same amounts but the ice would weigh heavier..than the water if it was solid.I think that's what I'm trying to get at there.

This student supports her answer by giving an explanation in terms of water. She conserves the amount of stuff, but clearly is confusing mass and density. The discussion continued drawing her to the point of realising she had made a mistake. It concludes:-

I: ....And if all that lot weighs 140, what must all this lot weigh?

S: [17 second pause] Would that be 140 as well?

I: Yes. So what's the extra bit then? That you said was more than?

S: ... Because..erm..(Pause)..I don't know..

I: It's all right, you can change your mind if you like. That's fine.

S: ..That's..mmm.. I did 140 exactly first of all..

I: Yes.

S: I ticked that as you can see, so..

I: Yes. That's right.

S: That's probably right 140 grams. Is that?

I: Yes.. It's probably, I was thinking, what you think of - often when you pick up something, like a paperweight, it often takes you by surprise, because it's..

S: ..heavy.

I: Yes. I just wondered whether that was what you were thinking, that because you had got the solid the mass would be heavier..

S: Yes.

I: It's sort of like a density..

S: Mmm..Yes. That's what I was thinking actually.

The student took defensive action in explaining that she had ticked 140 g really, but agreed she had confused mass and density. Thus, her thinking supports her written answer.

Student number 3, our second example, was one of 11% (S2, Table 4.11) who gave the response that the mass would decrease "because a gas is given off". He was asked about this:-

I: So, you said here, "Some gas might be given off." Can you guess - suggest what gas you were thinking of there?

S: Sulphur, I would think! Sulphur.

I: Right. And so where would the sulphur have come from in these things here?

S: From the sulphate.

I: Right. OK. So what would be left behind, then, if sulphur was given off? Can you guess what the precipitate might be, what substance that would be?

S: It would be a compound of the sodium and this [points to barium chloride]. Or maybe chlorine's given off.

I: OK, right, yes. So is there anything in the question which made you put "less than", or do you want to change your mind about that now, or what?

S: Er ... No, I'd still put that.

I: OK. That's fine.

His written answer and thoughts about the reaction support one another. After a few weeks of A level chemistry, this student has not changed his thinking. Student number 28, however, gave a similar response, that a gas was produced, and shows in this extract that he thought mass would be conserved although his idea about the reaction was incorrect:-

I: OK. Right. So if you were doing that today, you'd still answer the same, would you?

S: Umm, well, obviously a gas must have been given off, so that led me to believe if a gas was given off something actually would come out of the ..

I: Cylinder .. Right.

S: Both of the things - so, it must have lost weight somehow.

I: OK. So if that's right, and that's the equation, would the mass have changed, at all?

S: Not when you look at it like that, no, no.

I: Right. 'Cos this weighs 140 and that lot would weigh how much?

S: 140.

I: OK. Right. So you answered that because you thought a gas was given off?

S: Mm

I: But you're happy that if there isn't a gas the mass would be the same?

S: Then it would be the same as before.

I: Right. OK.

This interview supports the placing of this response type in the S category, since such students do indeed misunderstand the chemical event, but know that mass is conserved.

Solution

Students found it difficult to discuss their responses to *Solution.* Several expressed difficulty with understanding the difference between "dissolve" and "react". For example, student number 48 explained:-

> I: Right, the next one I was looking at was the *Solution* question. Um, now, I just wondered here whether you could explain a little bit more about what you understand by the term dissolve. Does it mean the same as react, or is it different, or..?
>
> [27 second pause]
>
> S: Yeah, I've put that it would react, haven't I? As well as it would dissolve but it would just dissolve, wouldn't it? Cos its sort of like ...
>
> I: Yes, yes. So, dissolve and react aren't the same thing. OK. What's the difference between them, then?
>
> S: Well, if they react either something's given off or um, something else could happen, but if it dissolves then nothing really happens it just disappears.
>
> I: Right. So, would you - if it just disappears, would you stay with the answer less than 220?
>
> [7 second pause]
>
> S: I don't know actually, because ...[pauses for 11 seconds] if it dissolves it might make the mass a bit ... more wouldn't it?
>
> I: It *might*, yes. So, would you be wanting to change it to more than? Or would it be the same?
>
> [8 second pause]
>
> S: Mm. I don't really know about that.

Having selected "less than 220 g" with an idea that the sodium chloride reacts with water, he could not really explain why. Student number 28 represents the 18% coded S2 who thought that a gas would be released. When asked to say what the gas would be he said:-

> S: Um - sodium chloride - chlorine.
>
> I: Right, OK. So, if chlorine gas is given off, what's left behind in solution?
>
> S: Um - sodium - would it be sodium chloro - no - sodium chlorine? That would be left behind. I mean, not all of the chlorine would have been - only the amount that's been reacted, the rest would be left behind.

The discussion continued to explore the student's ideas about dissolving. He knew that the sodium chloride had dissolved, but thought of dissolving as a pre-requisite step to a reaction and went on to say that when a tablet was "dissolved" in water, it dissolved and reacted. However, he explained too that he thought the mass would be unchanged:-

I: Yes, you could. I mean, is the stuff still there if it's dissolved?

S: Yes, but in a different shape, it will have changed in some way.

I: Right. So if it's still there, is it still going to weigh the same?

S: Yes.

I: Right. Yes. I think you're right, I agree with you. So in that case, what's the difference between just bunging the sodium chloride in the water and stirring it up and making it dissolve and what you've said here? I mean, do you want to change your mind about that now, or what?

S: [8 second pause] I think "dissolved" I'd replace with reacted or something. Dissolving is if it's added in, but a reaction took place then gases may have been released. Maybe dissolving - but if a reaction took place...

This indicates he understands that mass is conserved, but that he remains confused about whether a gas would be released in this situation. This supports the classification of this response type as S, since the evidence is of misunderstanding the chemical event, not the chemical idea. Thus, from these and other interviews, we see that written responses do reflect student's thinking. Also, it seems that the extent of confusion about dissolving and reacting is more extensive than is apparent from the written answers alone.

4.13.2 Interviews about responses to Iron sulphide and Carbon

About 30% of the students gave the response "176 g + 16 g sulphur" and were coded P1, including student number 43. I asked her to explain her reasoning:-

S: [37 second pause] Well...[10 second pause] It says you've got 112 grams which is twice that. So you can only get 2 moles of that however much sulphur there is, so I just added the mass of the 2 moles of sulphur to get the 176 grams.

I: So there must be some left over.

S: Yes.

Clearly, this student had realised the importance of maintaining a ratio between the iron and the sulphur and so placing her response in the P category was justified.

About 29% responded like student number 28 with the response "192 g" (T1a, Table 4.13). He was asked to explain how he got this answer:-

S: [16 second pause] I just thought if you doubled up the two amounts then you'd have doubled the - doubled the result at the end. Isn't it?

I: Is 192 double that [Points to 88 g]?

S: Er - 196 g innit?

I: 8 plus 8 is 16 - so 16 - 176 g, yes.

S: Oh dear!

I: This is a bit of a problem, really, isn't it, 'cos you're quite right, it's all doubled up, but what's happened to the thing, I mean why isn't it 192? Where's the other - I mean, the difference is 16, isn't it, what's happened to the other 16 grams?

S: Umm..I see. It could have burnt away, it could have escaped somehow through reaction.

I: So you're saying it's not there any more? I suppose what it comes down to, another way of - sorry for jumping in here - is if that goes - doubles up to 112, what's double - we've already agreed that's doubled, does it follow that that doubles too [amount of FeS]?

S: It does follow, but it doesn't work out, does it?

I: Well - what's double that?

S: 64.

I: Right. OK. So, is it more important that you have the 64 reacting or that you have the 80 reacting?

S: Mathematically or real?

I: Well, either.

S: Well, the 64, I suppose.

I: Why?

S: Then it actually - well, one side of the equation's right, it actually - it works out. Logically, if that's doubled, that has to be as well in the reaction. Although you'll have uneven amounts, won't you? You'll have something left over at the end.

He realised he had made a mistake. The interview continued a little later as follows:-

I: So, that's what you meant at the time, is it, the 192?

S: Well, I [something inaudible] didn't notice that, so if you double that up you make that - I didn't consider it after that, I didn't check it, you know what I mean? I mean, if you double that, it looks about right so I just carried on.

So, it appears that this student did know about reacting mass reasoning, but simply forgot to apply it at the time. A similar example was found in an interview with student 97, who said:-

"Well, when it states that there's 80 grams of sulphur, I think when I actually did it I presumed the whole 80 grams was used up and I think that's why I added them together."

Thus, these interviews suggest that students who gave "192 g" did so because they simply forgot about reacting mass reasoning, rather than not knowing about it at all.

Carbon

One issue involved in coding responses to *Carbon* was that "88 g" alone is insufficient evidence of understanding the chemical idea (Q1, Table 4.14). Student 67 gave this response and explained his reasoning as follows:-

> S: So that would be the relative atomic mass - of carbon and the relative atomic mass of carbon dioxide. Umm - 12 grams gives 44, so how much would 24 give? Just double it and you get 88.
>
> I: Right. OK. You weren't tempted to add them then? 'Cos if you add them you get the right answer.
>
> S: No, I just did it like that.

This student gave "88 g" as an abbreviation, so his response should really be placed in the P category. Student number 3 gave the same response, which was discussed at interview:-

> I: So how did you get 88?
>
> S: 88?
>
> I: That is the right answer, you're quite right. I'd just be interested to know how you got there.
>
> S: I think I just worked out the mass of the carbon and the oxygen.
>
> I: Right.
>
> S: And added them together basically.
>
> I: Can you think of another way of getting the answer? Besides adding them together?
>
> S: No, I can't.

This student admits to adding them, and clearly does not know about reacting mass reasoning. So, a difficulty remains over coding this response. In common with responses of "192 g" to *Iron sulphide*, "88 g" or even "64 + 24 = 88" does not really indicate the thinking behind the answer. However, given the impossibility of interviewing every student, these answers must be coded consistently at face value.

4.13.3 Responses to Power Station and Petrol

Power Station

Student number 67 was one of 13% (P1, Table 4.15) who gave the response 3666 tonnes. He was asked:-

> I: How did you get the 3666?
>
> S: Oooh! [chuckles] Umm, I probably did 1000 over [can't hear]
>
> I: Yes, I think you probably did. Um...
>
> S: Um
>
> I: Because it doesn't look like a guess!
>
> S: No, I probably worked something out, but didn't write it down.
>
> I: All right. Well, just take your time and see if you can tell me how you did it.
>
> S: I had a carbon 12, carbon's 12. That'll become carbon plus your oxygen, gives CO_2. Then I did relative atomic mass of the carbon dioxide, which is, I don't know ..
>
> I: It's 44,
>
> S: 44, right, so, um, say 12 tonnes gives 44 tonnes, so one tonne of carbon gives 44 over 12, so for 1000 its 1000 times 44 over 12.
>
> I: Right, yes, OK, and that gives you 3666.

Clearly, this student knew how to carry out the calculation and could repeat the steps. His coding of P1 was justified.

Student 29 was one of about 6% who gave "3000 tonnes" as their answer (Q1, Table 4.15). He was asked:-

> I: I'm just wondering how you got the 3000.
>
> S: [Laughs] [17 second pause] Um... CO_2, coal's mainly carbon isn't it?
>
> I: Coal's mainly carbon, right. OK. So we've got carbon and that's giving CO_2, isn't it? So it reacts with what?
>
> S: With oxygen.
>
> I: Yes. So, where do we go from there?
>
> S: Well, I must have just thought that the oxygen would be twice as much as the carbon.
>
> I: OK. Right, so you have 1000 tonnes of that.

S: And 2000 of the oxygen.

I: Right. 2000 of that gives you 3000 of that [Pointing to the equation]. Is that because of the two there? [Points to the O_2]

S: Probably, yes.

This student thinks simply that the mass of oxygen will be double that of the carbon, and may have used the ratio in the equation to arrive at this. Again, the Q coding is justified, since this is partial evidence of understanding the chemical idea.

As a third example, student number 97 gave the response "10 tonnes" and was coded T1 (27%, Table 4.15). She was taken through the steps to produce the expected answer and was then asked:-

I: Can you suggest why that's perhaps an unreasonable answer? [points to the 10 tonnes]

S: Because its high quality coal. If it wasn't high quality coal then there would be lots of other different things produced as well as carbon dioxide so it was a bit of a guess I think!

Even then, this student did not realise the need for mass to increase because the reaction between coal and oxygen. Thus, she misunderstands the chemical idea and so a T coding is justified. The written responses to *Power station* seem therefore, to correspond well with students' thinking.

Petrol

Almost all the interviews carried out about this question focussed on T-coded responses, which totalled about 67% (Table 4.16). Student 28, for example, gave the response that the mass would be "40 kg, because petrol is converted to energy. He discussed this at interview:-

I: There's the question about petrol here [reads the question] I wanted you to suggest a mass of the exhaust gases and you suggested 40. So, um, there's obviously a difference here between 50 which we started off with and the 40 - what's happened to the rest?

S: Some will have burnt off as energy.

I: Yes.

S: Some will have gone there, some of the mass.

I: Right. OK. So ten goes to energy?

S: Some of it could have been wasted.

The discussion continued to the point of arriving at the expected answer, where he was asked:-

> I: Right, OK. So we're still saying all that's 50 and all of those gases are 40. And ten grams of the petrol is wasted, but we've got to take into account that air weighs something. OK, so how do you reason all that out?
>
> S: Um... Well, there's waste obviously, a lot has been used in energy and so much is wasted in noise or something.
>
> I: Right. So are you suggesting then that the energy weighs something?
>
> S: Mm Energy is carbon and hydrogen, isn't it, going to waste, so, heat, that's got some energy in it.
>
> I: So some of this [the petrol] has disappeared and changed into energy?
>
> S: Mm. That's right. When it burns.

Thus, he confirms his written answer. His views had not changed since writing his original response and he could not see the flaw in his thinking. Thus, the T coding of his response was justified, as this is clear evidence of misunderstanding the chemical idea.

Student number 43 gave the response "50 kg", but explained that the petrol was "burnt" (T3b, 4.0%, Table 4.16). When asked about this, he said:-

> S:[28 second pause] Well, I don't think I really knew what I was doing here. I sort of kind of guessed and thought well if I started of with 50, I suppose it would be more than 50 wouldn't it, because it would combine with the oxygen.
>
> I: Right.
>
> S: But I don't think I really thought about that.

He admits he had forgotten about the oxygen. Here, then, the student knows the meaning of "burnt", so his coding does not support his thinking. In contrast, however, student number 3 gave the mass "25 kg" and explained that the petrol was "used up" (T3a). At interview, he was taken through the content of exhaust gas, and we discussed the need to balance the reactants and products. I then asked him:-

> I: So, let's think about that. How do we get the 25, then? Where does the petrol get used up?
>
> S: Well, ... I don't know what I was talking about here! Well, I just thought if its being - does burning produce energy, or something?
>
> I: Yes.
>
> S: I see. Um... I don't know!

I: So, do you think - when you say petrol is used, do you mean it's disappeared?

S: It's, well, I don't know, used.

I: It's not there any more?

S: Mm.

I: Is that what you mean?

S: Something like that, yes.

I: All right. So are you thinking that all this lot here [points to exhaust gases in the equation] this bit of exhaust gas, that would all add up to 25 if you started of with 50 of that?

S: I'm - I thought the mass would be different because they're gases, I don't know why.

I: Is that because you think - is it because gases are "lighter" than liquids? Or you think of it that way?

S: Its something with less mass, that's all. It would be the same amount of atoms, but less mass.

This student admitted finally that contributing to his difficulty was a mass/density confusion. He realised the need to conserve the amount of stuff, but thought the gas would weigh less. This is a misconception, so his T coding was justified.

Written responses to *Petrol*, therefore, do reflect students' thinking about what happens in a car engine.

4.13.4 Post-first survey interviews - a summary

Clearly, the interviews provide a fascinating insight into students' thinking which deepens our understanding of their written responses. In almost all cases the interview supports the coding of the responses. The only area of difficulty revealed is the responses to the reacting mass reasoning questions where the figure alone does not always reflect the students' thinking.

Having carried out the interviews, I concluded that the written data was, as far as I could reasonably identify, a reflection of students' thinking and that the coding of responses was verified. Let us now examine in more detail the findings of the first survey.

4.14 Findings of the first survey

The first survey provides a baseline of students' understanding of basic chemical ideas post-GCSE. These data provide evidence of significant misunderstandings among beginning A level students, as well as indications that some respondents have alternative meanings and uses for some chemical terms. The key findings are discussed below.

Ideas about the particulate nature of matter

Responses to *Molecules* (section 4.5) suggests that a majority of beginning A level students can picture matter as being made up of discrete particles. A relatively small group ascribe rather primitive properties to particles, suggesting, for example, that copper atoms can change into carbon atoms (*Copper*, 10%), or that particles can explode (*Sodium and Chlorine*, 4%). While most students do not subscribe to these notions, responses to other questions indicate inconsistencies in the way particle ideas apply to chemical situations. These are explored in subsequent paragraphs.

Ideas about mass and density

Responses to the conservation of mass question sets show that about 10% of the sample confuse mass and density, suggesting that gases are lighter or solids heavier than liquids. The implication behind this is that particles somehow "lose mass" when a change of state occurs. The thinking of these students is dominated by perceptual evidence, for example, that when you pick up a solid you expect it to be "heavy"; similarly, if a reaction produces a gas, that gas will be "light". This idea is persuasive, and is found in answer to a several questions including *Power Station* and *Petrol*. The misunderstanding may also contribute to students' difficulties with reacting mass reasoning. Thus, if they are calculating the mass of a gas, for example in *Carbon* and *Power Station*, it is acceptable for the value to be less than that of the solid starting material.

Ideas about chemical reactions

Several misunderstandings about chemical reactions are apparent from the first survey. Some of these may arise because students have difficulties with the most basic principles, as discussed above. Others seem to arise because chemical reactions appear to be "mysterious", and so events are difficult to explain.

The evolution of a gas in a chemical reaction is a widely experienced phenomenon. Responses to *Precipitation* and *Solution* indicate that about 15% of students seem to take this to extremes, thinking that a gas is evolved when *any* chemical "reaction" takes place, as though this is a standard characteristic of all chemical reactions.

Chemistry teachers may be unwitting contributors to this problem, as most reactions demonstrated or included in practical lessons do produce gases! However, responses to *Tablet* suggest a deeper difficulty. About 13% of students appear to think that gases exist before a reaction occurs, either in a solid or a liquid. This implies that such students think gases arise through changes of state alone, rather than being produced by rearrangement of atoms. The idea therefore simplifies many chemical reactions to events best described as "when two substances are mixed, something which was already present in one or other substance is displaced". A spin-off from this is that a "displacement" reaction such as the magnesium/hydrochloric acid reaction in *Hydrogen Chloride*, may mean "pushing out" hydrogen gas which was already there but in an invisible form until the metal was added to force it out.

A second misunderstanding about chemical reactions is that matter can be "used up", a category which Andersson (1990) terms "disappearance". This also contradicts particle ideas, as the implication of this reasoning is that particles can be destroyed into nothing. Responses to *Phosphorus*, *Power Station* and *Petrol* show that between 4 and 27% of beginning A level students do not conserve mass in these reactions, suggesting that mass is "used up". This may be a specific feature of combustion reactions, as these involve production of solid waste, "ash" and gases which are invisible. Visual evidence suggests that the ash has a mass considerably less than the starting material, so something has been "used up". Any gases produced cannot be seen anyway, so may not exist. Allied to this idea is the suggestion that matter can be transformed into energy, heat or light, found in answers to *Petrol*, *Boiling* and *Phosphorus*. Although only 1 - 3% of the sample use this idea, it is a powerful model, as evidence from these specific instances is that heat, energy and light are all involved and must come from somewhere.

Ideas about chemical bonding and energetics

Although a majority of students can identify covalent bonds by conventional symbols, the existence of intermolecular bonds is virtually unknown to them. Students who do know about hydrogen bonds often describe them as "attractions not bonds", making an artificial distinction between intra- and intermolecular bonds. Responses to *Chlorides* and *Boiling* show that students are happy to explain changes of state in terms of breaking of intramolecular bonds, implying that the vapour above boiling substances is composed of atoms not molecules. This reasoning may be prevalent at this beginning stage because students do not know about any other type of bonding, and indeed responses to *Chlorides* indicate that some do recall differences between types of compound but are unable to explain them.

Responses to *Methane* show that 19% of students think of energy in a reaction coming from bond breaking, not bond making. This reflects information they may already possess that fuels are "energy stores". The effects of this on their future development will be monitored.

Uses of chemical terminology

Some students have meanings for words which are not in agreement with the standard chemical definitions. In some cases, such as "burning", the word is used in a lay fashion, as a label for a well-known event. Responses to *Petrol* show that many students know petrol is burned, but relatively few associate this with oxygen. The same word is also used by some students to explain what happens when sodium is lowered into chlorine gas (*Sodium and Chlorine*).

Responses to *Substances* and *Element and Compound* suggest that some students use "mixture" and "compound" synonymously, defining a compound as "a mixture of elements". They do not see the contradiction, and it may be that students giving this definition in *Element and Compound* proceed to struggle in answering *Substances*.

The word "reactive" is commonly used by students in explaining chemical events. It seems that only substances, usually elements, which can be defined as "reactive" can take part in chemical reactions, which given the limited experience of these students is not an unreasonable idea. However, their thinking is extended to mentally separating out the components of a compound because one of the elements in it falls into the "reactive" category. This is seen in answer to *Solution*, where sodium is selected and *Hydrogen chloride*, where chlorine is identified. The reasoning is even applied to *Reaction rates* as the high point on graph B is explained in terms of the "reactivity" of the magnesium.

These difficulties perhaps arise through the restricted range of reactions which students experience in their GCSE courses. "Burning" is limited to burning magnesium and the distinction between mixtures and compounds is rarely pursued. Many reactions necessarily involve "reactive" elements, because those can be completed in the time allowed; reactions producing gases are the most interesting and enable the most measurements to be made.

Conclusion

The first survey reveals that some beginning A level students do appear to have misconceptions about basic chemical ideas. In the next chapter, we will examine the extent to which these misconceptions are changed as the students progress through the Salters' Advanced Chemistry course.

Chapter 5

What changes occur in the SAC sample?

The previous chapter reported the responses of 399 beginning A level students to the test paper (Appendix 2). We will now examine how the responses of SAC students change as they proceed through their A level course.

5.1 The surviving students

Most of the sample reported in the previous chapter, 320, started the Salters' Advanced Chemistry course, while the remainder, seventy-nine, began a range of "Traditional"-type A level chemistry courses. As described earlier (section 3.5), test papers were sent to participating schools and colleges on two further occasions, in May, 1993 and February 1994. At each of these stages some loss in student numbers was observed, such that 250 SAC students of the original 320 and seventy Traditional students of the original seventy-nine provided answers to all three surveys. Here, we examine closely changes in responses of these 250 SAC students.

5.1.1 The pre-16 background of the SAC sample

First, we will look at the population of students who "survived" the study, that is, those who completed three test papers. Table 5.1 provides data about the (General Certificate of School Education) GCSE background of these students. The "Total" column shows the gender distribution of the sample by GCSE grade.

These data indicate that about 56% of the sample are male and that about 54% took double award Science GCSE. The grades obtained by the students were very high; about 45% obtained grade A, while a further 33% were awarded B grades. Thus, more than three-quarters of the total sample could be described as "high-achievers" prior to beginning the study.

	Grade	Single subject chemists		Double award scientists		Total %
		No.	%	No.	%	
Females	A	24	9.6	25	10.0	19.6
	B	15	6.0	20	8.0	14.0
	C	7	2.8	11	4.4	7.2
	D	2	0.8	-	-	0.8
	NR	1	0.4	-	-	0.4
		49	19.6	56	22.4	42.0
Males	A	20	8.0	43	17.2	25.2
	B	31	12.4	17	6.8	19.2
	C	10	4.0	15	6.0	10.0
	D	-	-	2	0.8	0.8
	E			1	0.4	0.4
	NR	-	-	-	-	
		61	24.4	78	31.2	55.6
	Total	110	44.0	134	53.6	97.6

Three females and three males (2.4%) did not provide information about their GCSE background.

Table 5.1: Pre-16 background and gender distribution of the SAC sample.

5.1.2 What the students had studied

Teaching staff were asked to provide information about the progress made between surveys. This information is tabulated in Appendix 5, which shows that by the second survey the great majority of SAC students had completed units 1 - 6 and that at the time of the third survey almost all had completed units 1 - 9 as well as their *Individual Investigations* and *Visiting the Chemical Industry.* Some had also studied unit 10, *Colour by Design,* and unit 11, *Medicines by Design* when the third survey was administered. None had studied the last two units, *Aspects of Agriculture* and *Oceans,* and so had not met equilibrium constants and their application to reactions, or revisited intermolecular forces for the last time.

This has a bearing on the changes which may be expected in answers to *Reactions* and the questions probing ideas about intermolecular forces such as *Chlorides* and *Hydrogen bonds.* These will be discussed as they arise.

It should also be noted at this point that differences will be observed at the first survey between this surviving sample and the full 399 reported earlier. A higher proportion of the surviving SAC sample gave P or Q-coded responses to some questions at the initial stage, so percentages will not match exactly. This, coupled with the excellent academic record of surviving students, suggests that many who did not complete the three surveys were the weakest students and perhaps were advised to leave or left of their own accord in the early stages of the course.

5.2 Reporting changed responses

Changes are found in students' responses to almost all of the questions. It will be helpful, therefore, to indicate the level of change regarded as "significant". To assist with this, χ^2 tests were carried out using the format reported in Appendix 6, which compares the starting and final percentages for responses coded P and "not P". Values for χ^2 are quoted at two "levels of significance", 0.05 and 0.01. At the 0.05 level (achieved when χ^2 equals 3.84) there is a risk of one in twenty that the result was obtained by chance alone. At the 0.01 level (when χ^2 equals 6.64) this risk reduces to one in 100. So, this provides a way of estimating the possible influence of SAC on students' thinking. If changes in the percentage of students offering P codes are significant, that is, values of χ^2 are greater or equal to those given above, then there is a strong likelihood that an outside influence such as SAC has caused them, as it is not likely that they are produced by chance alone. To simplify references to this test as we proceed through the questions, I will state if the value for χ^2 is significant and, if so, at what level. Readers may wish to consult Appendix 6 for further details.

The discussion about χ^2 tests assumes that if learning has occurred, the expected change will be in favour of the P, or, in some cases, Q, code. This is the most likely outcome. Students who responded in the first survey by expressing a misconception may have learned something between tests which led them to respond differently at the second and/or third surveys. To assist in identifying the source of any change, material from SAC is included where possible. Also, twenty-four students whose responses had changed markedly between first and second surveys were asked in interview to explain what had prompted their new answers. The interviews also explored students' understanding of the ideas being probed. Extracts from these are included. Students' written and verbal responses are referenced using a number. This number was given to each student at the first survey, so they range from 001 to 399.

Where little or no change in the proportion of P codes is observed, reasons for this are discussed. In general, this result implies that students did not learn anything to prompt a change in their answers to the question, perhaps because the idea does not feature in SAC. Alternatively, the question itself may elicit only one type of response, because the students perceive this as *the* answer to the question, not realising that any other chemical idea could be involved. However, the data tables may imply a "no change" result by hiding the fact that equal numbers of students moved between categories. To help gain a clearer picture of the extent of change, students' response codes were entered on to a Microsoft Works (version 3.0) database. This database was searched to provide information not immediately apparent from inspection of the data tables and is referred to where appropriate.

Let us now examine how the SAC sample responded to the test paper on all three occasions. The questions will be considered in the order used in chapter 4.

5.3 Differences between elements, compounds and mixtures

In this section, changes in responses to *Molecules*, *Element and Compound* and *Substances* are discussed.

5.3.1 Molecules

Molecules is a very straight-forward question probing students' ideas about differences between elements, compounds and mixtures at the molecular level. Table 4.1 shows little change in the proportion of P codes from first to third survey. The value for χ^2 is not significant at either the 0.05 or the 0.01 level. This suggests that little or no new material directly relevant to this question was learned during the two-year study.

RC	Description	1st %	2nd %	3rd %
P1	DBA A mixture of a compound and an element	75.2	69.2	72.0
P	Total	75.2	69.2	72.0
Q1	DBA No response	6.8	14.0	14.8
Q	Total	6.8	14.0	14.8
T1	DBA Incorrect explanation	12.4	9.6	9.2
T2	Multi-choice and explanation incorrect	5.2	7.2	4.0
T	Total	17.6	16.8	13.2
U1	Uncodeable	-	-	-
U2	No response	0.4	-	-
U	Total	0.4	-	-
	Overall total	100.0	100.0	100.0

n = 250

Table 5.2 Changes in the SAC sample responses to *Molecules*

About 96% of students (P, Q and T1 categories) answered the multiple-choice part correctly at the third survey, while a majority of students were coded P for all three surveys. This suggests that most students distinguish consistently between elements, compounds and mixtures. An increase in the proportion of Q codes is observed, perhaps because *Molecules* was perceived by some to be so easy that it was not worth answering in full on the second and third occasions.

Small fluctuations between categories occurred which are of interest. About 9% change from T to P and from P to T across the three surveys, suggesting that as many students "learned" the correct description of gas C as "unlearned" it. Students changing to a T code may be responding thoughtlessly at the second and third surveys and may, if interviewed, give the correct response. Only 2.4% are coded T for all three surveys. This small group could not apply anything new from their studies to answer this question differently, for example student 339, whose three responses were all coded T1, described gas C as:-

> "A compound where some atoms cannot join a different atom so they join with another atom which is the same." (1st survey)
>
> "Compound and mixture. (Not fully reacted)" (2nd survey)
>
> "Two elements mixed but not forming bonds with each other." (3rd survey)

This student does not have a clear idea about gas C, and has not clarified his thinking during his course. However, this student is an exception to the general pattern observed.

5.3.2 Element and compound

This question probes ideas about elements and compounds and investigates how students apply definitions to practical chemistry. The improvement in P codes shown in Table 5.3 is significant at the 0.01 level, suggesting that some students learned the correct response. About 54% of students at the third survey offer correct definitions of the terms “element” and “compound” (category P and Q1). About 29% (P1, P3 and Q3) give two correct tests. This suggests that the definitions are much easier to recall than knowledge about possible supporting tests. Around 17% (P1) give correct definitions *and* tests at the third survey. That students find this question relatively difficult compared to others in the survey is illustrated by the high proportion of persistent T-codes; about 22% were coded T for all three surveys and 30% were placed in this category at the third survey. This indicates that many students were unable to apply new learning in answering this question. To assess reasons for these data, we will look at SAC material relevant to this question, then examples of students' responses.

Students meet material relevant to *Element and Compound* in the first unit of the course, *The Elements of Life.* They learn about the Periodic Table, basic atomic structure and how atoms combine, although formal definitions of the terms "element" and "compound" are not given. Students may carry out an experiment to establish the formula of water by electrolysis (p 4, Activities). Later in the course, students meet mass spectrometry for the first time in unit 6, *What's in a Medicine?* (Story, p 4, Chemical Ideas, p 17 - 23 and Activities p 17 - 22). Students "use" the technique via a computer program to establish the formula for salicylic acid. This is supported by further examples of mass spectra of other organic compounds of varying degrees of complexity.

RC	Description	1st %	2nd %	3rd %
P1	E & C defined, two feasible tests suggested	3.2	11.6	17.2
P2	E & C defined, one feasible test suggested	22.0	17.6	15.6
P3	One correct definition, two feasible tests	3.2	7.2	8.8
P	Total	28.4	36.4	41.6
Q1	E & C defined, no feasible tests suggested	17.6	12.0	11.6
Q2	One correct definition, one feasible test	13.2	14.0	12.8
Q3	No correct definitions, two feasible tests	0.8	0.4	2.8
Q	Total	31.6	26.4	27.2
T1	One correct definition, no feasible tests	18.8	17.2	12.4
T2	No correct definitions, one feasible test	6.4	4.0	5.2
T3	No correct definitions, no feasible tests	14.8	15.6	12.0
T	Total	40.0	36.8	29.6
U1	Uncodeable	-	-	-
U2	No response	-	0.4	1.6
U	Total	0.0	0.4	1.6
	Overall total	100.0	100.0	100.0

n = 250

Table 5.3: Changes in the SAC sample responses to *Element and Compound*

At the first survey, about 43% offered correct definitions for both "element" and compound and a further 35% defined one, usually compound, correctly. This suggests that definitions had been recalled from GCSE. Students found the tests more difficult, however.

A key difficulty revealed by the first survey was students' tendency to describe tests to identify water and iron alone. Student 105 illustrates this. His suggested tests in the first and second surveys were:-

> "Iron - Reduction reaction. Water - electrolysis" (1st survey)
>
> "Iron - chromatography test. Boiling point. Water - electrolysis. Test for hydrogen. Chromatography." (2nd survey)

Student 105 was asked about his answers in an interview. In the following extract "I" represents "Interviewer" and "S" "Student".

I: Now, what were you thinking here? How could you show that iron is just one element on its own? I know you said a reduction reaction.

S: I think that's just a guess. I didn't really know what to do.

I: OK. Do you have a better idea now?

S: Yes.

I: How would the chromatography test work, then?

S: [pause] Could you put the iron - you couldn't put it in solution, could you?

I: No. It would be quite difficult.

S: No. But you could do the boiling point, couldn't you?

I: Yes, if you can heat it hot enough. How would the boiling point help?

S: If you looked in a data book for the boiling point of iron, if it was below it, there would be impurities in it. If it was really close to it you'd know it was pure.

I: Yes. Good. Can you think of any other tests that you could do? I mean not that you personally could do in the lab, I mean, you couldn't probably boil iron, but is there anything else that you've learned which helps you identify elements in a compound or elements in a mixture?

S: [pause]

I: Have you heard of mass spectrometry?

S: Yes.

I: Can you remember if you'd heard of it by the time you did that, or what?

S: Yeah. But we did that with carbon and carbon compounds.

I: So do you think it would work if you put a sample of iron in?

S: It should work, yeah.

I: How would it show if something was an element on its own?

S: You'd just get one line.

I: Right. OK...

The student has learned about using a mass spectrometer to identify carbon compounds, as expected from *What's in a Medicine* (Unit 6) but does not know that it can also be applied to elements. He is restricted to the application he knows, although he demonstrated understanding of the principles of mass spectrometry. As SAC only features mass spectrometry in the context of carbon compound analysis, this is perhaps not surprising. The limitation SAC places on students is also shown by the 33.6% (P2, Q2 and T2) who named one test alone at the third survey. The most frequent single "test" cited was the electrolysis of water, perhaps based on the activity in the first unit. These students had really only learned a way of confirming water as water, rather than a more widely applicable technique. As the above extract shows, mass spectrometry to identify the presence of different atoms has not been applied to anything other than carbon compounds, so this, in the student's mind, "won't work for water". By the third survey, student 105 gave "mass spectrum" as his test for both iron and water.

The problem for many students is applying knowledge; students faced with this unfamiliar setting may not realise that the test they learned recently is appropriate because the context is different - no carbon compounds are involved. Alternatively, students may be relatively unsure of the newest information - mass spectrometry - choosing instead to use "safer", longer established ideas about electrolysis or boiling points to answer the question.

5.3.3 Substances

This question probes students' ideas about the characteristics of elements, compounds and mixtures. These are not featured specifically in SAC, but it was anticipated that students learn these through general experience of the course. This is confirmed by data presented in table 4.3, which shows improvement in the proportion of P-coded responses to *Substances* over the three surveys, and decreases of 12% and 7% in T and Q-coded answers. The changed level of P codes is significant at the 0.01 level. A slight drop in P codes is noted by the last survey, with a concomitant increase in Q codes, suggesting that a few students at this stage simply ticked the correct boxes and did not offer explanations for their choice. Only 2% regress from P to T.

RC	Description	1st %	2nd %	3rd %
P1	Correct responses All information used	46.8	62.0	64.4
P2	Correct responses Most information used	11.2	15.6	12.4
P	Total	58.0	77.6	76.8
Q1	Correct responses Incomplete explanations	10.8	6.4	13.2
Q2	Incomplete responses Incomplete explanations	9.6	3.2	0.4
Q	Total	20.4	9.6	13.6
T1	Incorrect response pattern	21.6	12.8	9.6
T	Total	21.6	12.8	9.6
U1	Uncodeable	-	-	-
U2	No response	-	-	-
U	Total	0.0	0.0	0.0
	Overall total	100.0	100.0	100.0

n = 250

Table 5.4: Changes in the SAC sample responses to *Substances*

Changes in responses to *Substances* reflect positive learning experiences in the early part of the course. Student 105 selected these answers (omitting explanations):-

"Compound; metal element; mixture; non-metal element" (T1, 1st survey)

"Non-metal element; metal element; compound; mixture" (P1, 2nd survey)

He confirmed this in his interview:-

I: The first time you chose quite a different pattern, certainly for the 1st one. Can you say why you chose something different there?

S: [Pause] It doesn't conduct electricity, so it's unlikely to be a metal.

I: Right.

S: It's not a metal - its just one element so it would only have one product.

I: Right. So had you been taught this in the mean time?

S: I just think I made a mistake there.

I: OK. Right. And here was another one. There you chose mixture. It could, theoretically, be a mixture, but I don't think that's the best answer. You changed it the next time you did the question.

S: It could be a hydrocarbon couldn't it? That would produce water and carbon dioxide.

I: Right. So what prompted you to give this answer here? [2nd survey]

S: It was probably one of the units. *Developing Fuels*, which was about hydrocarbons and stuff.

I: Right. I see. So that was why you did that there [2nd survey]. But here, you didn't know, or just guessed? Or?

S: I just guessed.

I: OK. And this last one, you suggested it was a non-metal element, and you didn't know why - I just assumed you'd guessed that - is that?

S: I probably did, yeah.

I: And what about there? [2nd survey]

S: If you get more than one when you put it on chromatography paper it shows its impure.

I: Yes, that's right.

S: It was a mixture, because there are several spots.

I: So here, [1st] was it perhaps that you didn't know the word "chromatogram"?

S: We never did that until one of the units. I didn't know what it was.

The interview reveals that guesswork and error contributed to the first set of answers, but new knowledge was used to produce the second set.

Taking the three questions as a group, over the three surveys more students have learned the characteristics of elements, compounds and mixtures. The proportion of students with P-codes for all three questions increases from 4.8% at the first survey to 18.4% by the 3rd survey. The evidence suggests that although significantly higher proportions are able to identify elements, compounds and mixtures from descriptions and molecular pictures (*Molecules* and *Substances*), relatively few are able to describe tests to identify an element and a compound (*Element and compound*). Interview data implies that by the second survey SAC had not emphasised the broader uses of mass spectrometry and that many students could not apply the knowledge learned. This issue is discussed in more depth at the end of the chapter.

5.4 Chemical change

Three questions, *Tablet*, *Copper* and *Hydrogen chloride* probe students' ideas about chemical reactions. Each is considered separately.

5.4.1 Tablet

Tablet probes students' ideas about the origins of a gas in a chemical reaction. Table 5.5 shows almost no improvement in the numbers offering the correct answer. Using the total of P and Q codes in the χ^2 test reveals no significant change occurs between first and third surveys.

RC	Description The gas...	1st %	2nd %	3rd %
P1	..did not exist but formed in a rxn	1.6	1.6	2.0
P	Total	1.6	1.6	2.0
Q1a	.. was contained in the tablet	35.2	29.6	31.2
Q1b	..was combined in the tablet as carbonate	1.2	7.6	6.8
Q	Total	36.4	37.2	38.0
S1	.. formed in a reaction between water & tablet	10.4	12.0	12.0
S2	.. was from the tablet and water	3.6	6.8	11.2
S	Total	14.0	18.8	23.2
T1a	.. was in solid form in the tablet	9.6	12.0	12.0
T1b	.. was joined to something / trapped in tablet	3.6	2.4	3.6
T1	*Total*	*13.2*	*14.4*	*15.6*
T2a	.. was in the water	26.4	20.0	14.8
T2b	.. was hydrogen / oxygen from the water	2.0	3.6	3.2
T2c	.. was displaced from water	2.0	1.2	0.4
T2	*Total*	*30.4*	*24.8*	*18.4*
T3	.. was from the air	0.4	0.4	0.8
T3	*Total*	*0.4*	*0.4*	*0.8*
T4	.. was carbon dioxide	-	-	0.4
T4	*Total*	*0.0*	*0.0*	*0.4*
T	Total	44.0	39.6	35.2
U1	Uncodeable	1.2	0.8	0.4
U2	No response	2.8	2.0	1.2
U	Total	4.0	2.8	1.6
	Overall total	100.0	100.0	100.0

n = 250

Table 5.5: Changes in the SAC sample responses to *Tablet*

One possible reason for the low level of P-coded answers is illustrated by student 360, who gave these responses at the first and second surveys:-

> "The gas elements were part of the water molecule + alka-seltzer molecule" (S2)

> "It didn't exist as a gas. As it is formed from the tablet reacting with water + one of the by products being the gas." (P1)

At interview, she explained these answers as follows:-

> "I don't think I had the ability when I first started to say what I really wanted to say .. instead of saying the gas didn't exist, which I think is probably what I - what I felt there, but I couldn't express myself."

This student thought that her ideas hadn't changed, but that experience of the course improved her ability to explain what she was thinking on paper. This may help to explain the increase in S codes over the three surveys - when students give an S1 or S2 coded answer, they may mean "the gas didn't exist", but they cannot find the words to say so. The notion of a substance not existing but forming by rearrangement of atoms during a chemical reaction is obviously difficult to grasp and it is unlikely that this is discussed during an A level chemistry course. There is no evidence that this is included in SAC course materials. It is much easier, therefore, for students to explain the origin of a gas in terms of the tangible, or at least, imaginable, tablet and/or water. These data suggest that students progress from associating the production of gas with hydrogen or oxygen in the water (T2) to identifying the event as a chemical reaction between the tablet and water (S1). Student 277 illustrates this in his interview:-

> I: The first time you said it was in the water and the next time you said there wasn't any gas.
>
> S: I think what I meant there was, when I looked at that 1st time round, it was just a case of seeing the air bubbles and I thought, it's an obvious one, the gas is in the water, you can see it, but the 2nd time, I thought where has the gas come from originally, and I thought, well, it's a reaction between the tablet and the water and that's where the gas has come from, the reaction between the two.

Difficulty arises because the two chemicals which react to form the gas are not named, so from a chemical point of view too, an S1 response like this is perhaps as close as students could be expected to get to the expected answer. Even so, the correct answer remains that the gas did not exist prior to the reaction, though its components did. The easier option which avoids the question is taken by 84% (Q, T and S2 categories) who focus on the materials available using either the tablet or water as the basis for their response.

The degree of uncertainty among respondents about this question is illustrated by the large changes in response patterns between categories Q and T. About 12% are coded Q in the first survey but T in the 3rd survey, while 10.4% move from T to Q. In contrast to *Substances* (discussed above) changes are not only in the positive direction (T to Q), but rather confirm that students remain confused and that some could not be certain at the end of their course that a chemical reaction had taken place.

Approximately 27% of students have not changed their answers; 12.4% and 14.8% offer three answers coded Q and T respectively. This implies that any learning about chemical reactions which took place on the SAC course did not affect the response of about one quarter of the students to this situation. What is clear from this question is that the origin of a gas in a reaction is difficult to explain, but, as later questions illustrate, is a readily recognised feature of chemical reactions, perhaps even a firm characteristic.

5.4.2 Copper

SAC mentions the reaction between copper metal and oxygen very briefly in Unit 3, *Minerals to Elements* :-

> "Have you noticed what happens when you heat a piece of copper? You get a mixture of red and black colours - Cu_2O and CuO." (Story, p 16)

This appears in a box of information about copper metal. The idea of oxides forming when methane reacts with air is discussed in detail in the previous unit, *Developing Fuels* (Chemical Ideas, p 39). This suggests that observed changes in students' responses to this question are not likely to be due to extensive teaching.

Responses to *Copper* show improvement in the proportion of P codes, significant at the 0.01 level. Further, about 50% gave three P-coded answers, indicating that many students found this a straight-forward question. The proportion coded P at the third survey, 75%, is one of the highest observed in the study, although this represents a slight decrease over the peak found at the second survey. This high point may arise because early teaching on formation of oxides is still relatively fresh in students' minds, whereas by the third survey some students respond more casually with the Q2 response "a reaction with gases".

RC	Description The black stuff came from.. / is..	1st %	2nd %	3rd %
P1	a reaction with oxygen	63.2	77.6	74.8
P2	a reaction between particles	-	-	-
P	Total	63.2	77.6	74.8
Q1	.. burning the copper	2.0	0.8	2.0
Q2	.. a reaction with gases / air	12.4	4.4	8.8
Q	Total	14.4	5.2	10.8
S1	.. a reaction with hydrogen	-	0.4	-
S2	.. a mixture of copper and oxygen	1.2	-	-
S	Total	1.2	0.4	-
T1a	.. the copper	2.4	2.8	0.4
T1b	.. the burning dish	0.8	-	1.2
T1c	.. impurities	1.6	0.4	0.4
T1	*Total*	*4.8*	*3.2*	*2.0*
T2a	.. carbon / soot / carbon dioxide	9.6	11.6	8.8
T2b	.. the heat	1.6	-	-
T2	*Total*	*11.2*	*11.6*	*8.8*
T	Total	16.0	14.8	10.8
U1	Uncodeable	0.8	-	0.8
U2	No response	4.4	2.0	2.8

U	Total	5.2	2.0	3.6
	Overall total	100.0	100.0	100.0

n = 250

Table 5.6: Changes in SAC sample responses to *Copper*

Decreases in Q and T-coded answers are also observed, although about 11% of students are coded in each of these categories at the third survey. These comprise students who changed their answers between surveys, rather than a group who responded incorrectly on three occasions. The improvement overall, therefore, is due to a net increase in P-codes, as some students changed their answers from Q to T or P to Q as the study proceeded. We will examine these shifts in more detail.

Only six students are coded T for all three surveys, suggesting that most of the T-codes in the third survey are given by students whose answers were coded P or Q in earlier tests. About 9% of the sample moved from Q in the first survey to T in the 3rd while around 4% changed from P in first or second to T in the third. Thus, about 13% make a "new" mistake, perhaps mis-reading the question, or changing their ideas about the chemical event. Student 331 illustrates this change. She responded:-

> "Oxygen in the air reacting with the Cu" (P1, 1st survey)

> "The unburnt carbon in the burning of air - incomplete combustion of gas" (T2a, 2nd survey)

At interview, she confirmed her second answer, saying,

> "It's carbon off the flame of the Bunsen isn't it?"

Later in the interview, after a discussion about incomplete combustion, which her group have studied since the first survey, the student realises she has made a mistake:-

> I: So what I'm wondering is what the black stuff could be, you said here it's carbon.

> S: It probably could have been copper couldn't it?

> I: Well, not the copper, but -

> S: (interrupts) But if it appeared in the dish - oh -... read properly!

She continues, explaining that the black stuff is not carbon, that carbon might appear on the *underside* of the dish, and admits that she would not have identified the black stuff as copper oxide, despite her first answer to the question. At the third survey, she repeats her error. This student seems to both mis-read the question and be unclear about the origin of the "black stuff". Her first answer was perhaps intuitive, her later ones based on mis-application of learned knowledge.

These data suggest that the formation of a new solid compound is much easier to explain than the origin of a gas. The improved level of correct answers arises because students develop better ideas about chemical reactions generally and therefore it is more obvious that the reaction here is between copper and oxygen.

5.4.3 Hydrogen chloride

This question probes students' ideas about acids and in doing so reveals their thinking about dissolving of covalent molecules and displacement reactions. An understanding of two chemical concepts is needed to answer the two parts of *Hydrogen chloride* correctly. One is the idea that acids contain hydrogen ions, or more properly, oxonium ions, H_3O^+. The second is that hydrogen gas can be displaced from acids by metals which have more negative electrode potentials. SAC uses hydrogen chloride as an example when acids and bases are first discussed in unit 3, *Minerals to Elements* (Chemical Ideas, p 36):-

> "Hydrogen chloride is a gas and contains HCl molecules. Water is almost totally made up from H_2O molecules. Yet a solution of hydrogen chloride in water - hydrochloric acid - is an electrolyte so it must contain ions. There must be a reaction between the HCl molecules and the H_2O molecules which produces these ions. The reaction was shown in equation 4.3.
>
> $$HCl \quad + \quad H_2O \quad -> \quad H_3O^+ \quad + \quad Cl^-$$"

The next paragraph begins:-

> "You may not previously have come across the ion with the formula H_3O^+. It is present in every solution of an acid in water...The acid donates H^+ to H_2O to form H_3O^+."

Discussion continues to make the point that the oxonium ion is responsible for acid behaviour. The formation of the oxonium ion is revisited and the relative strengths of acids and bases are discussed towards the end of the course in unit 13, *The Oceans,* where the pH scale is introduced (Chemical Ideas, p 54 - 55). The ionisation of water is mentioned on page 57.

Electrochemical cells are introduced in unit 7, *Using Sunlight,* (Chemical Ideas, p 33) followed by explanation of the standard hydrogen electrode on page 35. Although many examples of reactions between half-cells follow (p 36 - 42), no instance of hydrogen gas being displaced by a metal is shown. When electrochemical cells are revisited in Unit 10, *The Steel Story* (Story, p 19 and Chemical Ideas p 47 and

Activities p15) the context has changed to explaining the variable oxidation state of the transition elements.

Table 5.7 shows that the proportion of P codes given in answer to *Hydrogen chloride* increases from 8% to about 25% over the three surveys. The value for χ^2 is significant at the 0.01 level, suggesting that SAC course content has had some impact. This is confirmed by interview data. For example, student 349 explained in interview that his change to a P coded answer was in part attributable to the section on electrochemical cells in unit 7, *Using Sunlight* (p 33 - 36):-

> I: I was wondering what you were thinking about what hydrochloric acid was like there and whether you had learned anything more about it in the mean time.
>
> S: Um. It was after we did all the stuff on electrochemical cells. We did all about ions in aqueous solution, that's probably where I got the answer.

RC	Description	1st %	2nd %	3rd %
P1a	H_3O^+ ions | displacement reaction / ionic eqn	-	3.2	5.2
P1b	H^+ and Cl^- ions | displacement reaction / eqn	6.0	10.4	11.6
P2	Hydrogen ions present | No response	2.0	2.0	8.0
P	Total	8.0	15.6	24.8
R1	No response | displacement reaction / equation	0.4	0.8	1.2
R	Total	0.4	0.8	1.2
S1a	H_3O^+ | Mg reacts with or displaces Cl_2 / Cl^- / O_2 / H_2O	-	2.0	2.8
S1b	H^+ and Cl^- ions | Mg reacts with / displaces Cl_2 / Cl^-	4.0	5.6	9.6
S	Total	4.0	7.6	12.4
T1a	HCl molecules | displacement reaction / equation	8.4	13.6	11.6
T1b	HCl molecules | Mg reacts with Cl_2	7.2	11.6	11.6
T1c	HCl molecules | other explanation / no response	12.0	12.8	16.4
T1	*Total*	*27.6*	*38.0*	*39.6*
T2a	HCl / water complex | any explanation	13.2	11.2	3.2
T2b	HCl & H_2O shown separately / H_2O alone | any expln	1.6	2.8	2.0
T2	*Total*	*14.8*	*14.0*	*5.2*
T3	Cl^+ & H^- ions | incorrect eqn / explanation	1.6	2.0	0.8
T4a	No response | Mg reacts with acid / Cl^- / O_2	10.4	3.6	1.6
T4b	No response | H_2 released	6.8	2.0	2.4
T4	*Total*	*17.2*	*5.6*	*4.0*
T	Total	61.2	59.6	49.2
U1	Uncodeable responses to either part	4.0	2.0	1.6
U2	No response	22.4	14.4	10.8
U	Total	26.4	16.4	12.4
	Overall total	100.0	100.0	100.0

n = 250

Key: The symbol I denotes divisions between answers to parts of the question.

Table 5.7: Changes in SAC sample responses to *Hydrogen chloride*

However, given that the oxonium ion is clearly identified as being responsible for acid behaviour twice in the course, that only about 37% (P and S codes) state this in the third survey is surprising. Factors influencing this may include the request for a diagram, which students may have found off-putting; alternatively, the notion that hydrogen chloride is and remains molecular in solution is too persuasive to relinquish. In answer to the second part, about 30% (P, R and T1 codes) explain that a displacement reaction has occurred at the third survey. While this is a considerable improvement on the 16.8% observed at the first survey, this figure may have been higher if appropriate examples were included in course material. Student 306 illustrates this. He gave these answers to the second part:-

> "It is released from the acid when the magnesium reacts with the acid." (1st survey)
>
> "The Mg reacts with the Cl^- forcing out the H^+ ions which join together to produce the H_2" (2nd survey)

He was asked at interview to explain how he arrived at these answers. The interview includes this excerpt:-

> I: Have you done anything about electrochemical cells?
>
> S: Er, yeah.
>
> I: Right, so would that help with this? Would it be the magnesium and the chlorine, chloride reacting, or would it be the magnesium and ..
>
> S: If I had about 3 hours and an electrode potential sheet I might be able to tell you! But off hand I can't remember.

Although the student knows that electrode potentials are involved, his practical knowledge is limited to use of these figures. He has not seen or discussed the reaction, and implies that he does not understand that electrode potentials measure the tendency of metals to displace hydrogen gas. He is therefore still uncertain, thinking that chloride or hydrogen ions might react with the magnesium.

A third student, 344, is yet further behind. Her written answers to the second part were:-

> "The magnesium reacts with the acid." (1st survey)
>
> "Magnesium displaces the hydrogen." (2nd survey)

The second answer is expressed correctly, but her diagram showed molecules of hydrogen chloride drawn as small circles close together. At interview, this student could not describe the difference between hydrogen chloride and hydrochloric acid. She can remember work about acids and bases, but gets these confused:-

> I: I just wanted to check whether that's still your idea [that hydrochloric acid contains molecules of hydrogen chloride], or whether you had changed at all from that.
>
> S: [pause] I'm not too sure. It sounds to me like they're different and I can't think what they would be.
>
> I: OK. So it sounds just from the names [hydrogen chloride and hydrochloric acid] that they should be different?
>
> S: Yes.
>
> I: Right. OK. What do acids have in them, usually?
>
> S: An OH group.
>
> I: OH group. OK. Anything else? Are you sure about that? What do alkalis have then?
>
> S: I don't know! [laughter]
>
> I: Right, well, acids have these - they have hydrogen ions, and alkalis have these. So where in hydrochloric acid do these come from?
>
> S: [pause]
>
> I: Do they come from the hydrogen chloride or do they come from the water?
>
> S: Water I should think.

This student cannot, despite the content of the first seven units of the SAC course, name the ions which characterise an acid. Her second survey answer about magnesium displacing hydrogen is not supported by other learning; rather, it appears as a rote-learned response. Thus, student 344 is placed in the majority T1 category, which we will now consider in more detail.

The most persistent misconception, found with increasing frequency through the study, is that hydrogen chloride dissolves in its molecular form (T1, 40% 3rd survey). More students appear to complete their A level course with this idea than with the scientifically correct thinking. In fact, the notion of molecular hydrogen chloride is a plausible model, as displacement reactions are readily explained by the willingness of the metal to "swap partners" with the chlorine. This would be much harder to imagine if the hydrogen and chloride ions were already separated.

Table 5.7 shows that the largest increase in this type of answer occurs between the first and second surveys. However, 29.2% are coded T for all three surveys, suggesting that the ideas of this large group about hydrochloric acid were unaffected by any of the material described above. The information presented by SAC is merely added to the model, and does not prompt change in thinking. Indeed, as we have seen, SAC does not even discuss the displacement of hydrogen gas by metals, so students are not challenged to consider weaknesses in their model for this type of reaction.

Also of interest is the increase in proportion of S answers. This group understand the fundamental idea, but not the chemical event, thinking that the magnesium "displaces the chlorine". This notion, held by a total of 24% by the 3rd survey (S and T1b), is perhaps persuasive because chlorine and magnesium are widely known as two "reactive" elements, so a reaction between them is not unexpected. In fact, the reaction between magnesium and chlorine gas is explained as a redox reaction in unit 3, *From Minerals to Elements* (Chemical Ideas, p 31), while the reactivities of the halogens are investigated in the this unit (Activities, p 6 - 7), and the electrode potentials of the halogens are given in Unit 7 (Chemical Ideas, p 39). This information may give the impression that magnesium and chloride ions would react together, and, in the absence of any information about a metal displacing hydrogen would perhaps seem a plausible answer.

Hydrogen chloride attracted a relatively large number of no responses at the first survey (22.4%). This can, in part, be explained by the position of the question as the last in the test paper, but is perhaps also due to a number of students who simply did not know how to respond in any case. Table 5.7 shows a decrease in U codes to 12.4% by the third survey.

The responses to this group of questions corroborate the findings already discussed that reactions producing gases are indeed more difficult to explain than those producing solids. Difficulties arise because most gases cannot be "seen" except as bubbles under the surface of a liquid. Describing where a gas comes from is hard even when the elements involved in a reaction are named, as in *Hydrogen chloride*. These data indicate that in these tricky instances students opt for the most "obvious" source of gas - the "solid tablet" or "chlorine, because it's reactive". The responses to *Hydrogen chloride* also indicate the problems students have with dissolving. These are discussed further in the next group. Precisely what students learn from the SAC course material is also at issue. Examples which would assist students answering *Hydrogen chloride* are not included in SAC material, and there is evidence of confusion among respondents. A gradation in the effect of SAC material is observed. Some students were able to apply information about electrochemical cells and obtain the correct answer to part two. Others recognise the importance of electrode potentials, but do not know how to use these to arrive at an answer. Yet others, for example student 344, can only realise there is a difference between the gaseous and aqueous forms of hydrogen chloride, but are unable to articulate this.

5.5 Conservation of mass in closed systems

Three questions, *Phosphorus*, *Precipitation* and *Solution*, were used to probe development of students' ability to conserve mass in closed systems.

5.5.1 Phosphorus

The *Phosphorus* question appears to require little more than the application of simple reasoning to arrive at the correct answer. As the flask is sealed, nothing can escape, so all the mass in the flask must be measurable before and after the reaction.

RC	Description	1st %	2nd %	3rd %
P1	400 g the flask is sealed / nothing can escape	57.2	55.6	66.4
P2	400 g formal conservation statement	0.4	3.2	4.0
P3	400 g the number of particles is unchanged	4.0	7.2	5.2
P	Total	61.6	66.0	75.6
Q1	400 g uncodeable or no explanation	1.6	4.4	3.0
Q	Total	1.6	4.4	3.0
R1	400 g explanation in terms of chemical event	3.2	5.2	2.0
R	Total	3.2	5.2	2.0
S1	400 g misunderstanding of chemical event	5.2	3.2	3.2
S	Total	5.2	3.2	3.2
T1a	< 400 g because energy is lost from flask	2.4	2.0	1.6
T1b	> 400 g because energy is absorbed from the sun	0.8	0.4	0.4
T1	*Total*	*3.2*	*2.4*	*2.0*
T2a	< 400 g mass decreases because P dissolves	5.6	1.2	1.6
T2b	> 400 g because mass increases on dissolving	0.4	0.4	-
T2	*Total*	*6.0*	*1.6*	*1.6*
T3a	< 400 g because gas / liquid weighs less than solid	5.6	8.4	2.8
T3b	> 400 g solid weighs more than gas / liquid	0.8	-	-
T3c	< 400 g because water evaporates	-	1.2	0.8
T3	*Total*	*6.4*	*9.6*	*3.6*
T4a	< 400 g because phosphorus is used up	5.2	3.2	2.4
T4b	> 400 g because more reactant made/ O_2 included now	2.4	0.8	1.2
T4	*Total*	*7.6*	*4.0*	*3.6*
T	Total	23.2	17.6	10.8
U1	> / < 400 g uncodeable or no explanation	3.2	1.6	2.8
U2	No response	2.0	2.0	0.8
U	Total	5.2	3.6	3.6
	Overall total	100.0	100.0	100.0

Table 5.8: Changes in SAC students' responses to *Phosphorus*

Table 5.8 shows an increase in the proportion offering this type of response from about 62% to around 76% by the third survey. The χ^2 test indicates that the change in the level of P codes is significant at the 0.01 level. The increase in P codes is almost entirely at the expense of the T group, which decreases from 23% to about 11%. The proportions coded Q, R and S remain almost constant. These data indicate that learning has taken place. The table also suggests that most of the increase in P-codes is due to students coded T in the first and second surveys changing their ideas by the end of their course. About 14% change from T to P by the third survey, most of these changing at the first stage. For example, student 105 gave these written answers:-

> "Oxygen would be used to burn phosphorus." (<400 g, 1st survey)
>
> "You have added nothing to the phosphorus so it should be the same mass." (400 g, 2nd survey)

At interview, this student could not identify a reason for this change, but knew his first answer was incorrect:-

> I: So the first time you did this you said it would be less than 400 g, "Oxygen is used up."
>
> S: Would it stay the same? Cos you've added nothing to it.
>
> I: Right. Can you think of anything that you've done which might have made you change that?
>
> S: Probably not, no.
>
> I: OK. So what were you thinking here [1st survey]? Have you got any idea?
>
> S: I thought the oxygen would, you know like, go, it would be burned. But it wouldn't.
>
> I: No. It wouldn't...So you don't really know what's made you think differently about that?
>
> S: No.

At the third survey, student 105 maintained his idea that the mass would be unchanged. The change in his thinking occurred between first and second survey, but no material from SAC could be identified by him as assisting this.

The range of responses to *Phosphorus* suggests that a number of students do not see the situation quite so simply, and perhaps are unaided by the fact that the conservation of mass in chemical reactions is not taught in SAC in an explicit way. Unit 2 *Developing Fuels* (p 37) assumes that students understand conservation of mass, as the following extract shows:-

"What mass of carbon dioxide is produced when 64 g of methane are burnt in a plentiful supply of air?

Step 1	CH_4 (g) + $2O_2$ (g)	-> CO_2 (g) + H_2O (l)
Step 2	1 mole	1 mole
Step 3	16 g	44 g
Step 4	64 g	(44 x4) = 176 g

So, 176 g CO_2 are produced when 64 g CH_4 are burned."
(*Developing Fuels*, p 39)

Clearly, the product concerned, carbon dioxide, has greater mass than the starting material, methane. The mass of oxygen is not discussed. Students are expected to know that the mass of oxygen is now combined with the mass of carbon, but this is not explained. This presentation may be misleading, as it is not clear where the additional mass has come from; students are only told the mass of one product. Some students may transpose this information to the *Phosphorus* context, reasoning, as student 243 illustrates, that the oxygen must "count" after the reaction, whereas it was irrelevant before:-

"more than 400 g. If the phosphorus caught fire it combined with the oxygen in the flask and as the oxygen was gaseous its mass was originally irrelevant. As it has combined with the phosphorus it is now in solid form and will weigh something." (1st survey)

"400 g. Because there were the same number of atoms before and after the reaction the mass can't change." (2nd survey)

Although the student's first answer was given before he began the course and his second answer is correct, at interview he was far from confident about this change:-

I: I think if I read that correctly what I felt you were saying there is that once the oxygen has reacted it then counted, whereas before it didn't.

S: That's probably what I thought, yes.

I: And here you said it was 400 g [reads 2nd answer]. So, can you explain?

S: Um, well, I think I might have thought that the oxygen atoms because they're in the gas, they don't have any effect on the weight of the thing, because they're not actually bearing down on anything, um, but then when they combine with phosphorus they are.

I: Right.

S: So that's [1st one] probably more likely to be the right answer!
[laughter]
I: So what do you think about this answer [2nd], then, now?

S: Um, [reads 2nd answer]

I: Is that true?

S: The same number of atoms in the end, yes, and the mass is the same overall, that's if the - hmm! Er, both seem logical to me.

I: Yes I can see what you mean!

S: If I was doing it again, now I think that of those two choices I think I might go for this one - the first one.

I: OK. Have you learned anything about the conservation of mass, or energy in the course or anything like that?

S: Not that I can recall.

I: Right. And this - you haven't seen this reaction or anything like it?

S: I might have seen something like it. But I can't remember exactly what!

I: That's all right. So you'd want to go for that because here you've got this gas which isn't "counting" in the flask, whereas when it's reacted then it is.

S: Yes.

I: ..because you've got phosphorus oxide as opposed to phosphorus and oxygen separately.

S: Yes.

At the third survey, this student changes back to his first survey answer, explaining his choice of "more than 400 g" at the third survey as follows:-

> "The white smoke would have been the oxide of the phosphorus. When the oxide was in smoke form it wouldn't have weighed much, but as it redisolved (sic) back into water it did. The oxygen content of the oxide means it will be heavier because before the O_2 didn't weigh anything."

The SAC presentation may lead students to think that the oxygen does not weigh anything because it does not have a mass on the left-hand side of the equation in the example given above. More convincing (and less confusing) for such students would be to introduce calculations like the above showing the mass of all the reactants and products involved. This would demonstrate that mass is conserved and prove that the carbon dioxide "weighs more than methane" due to rearrangement of atoms, not because of oxygen "counting" after the reaction. Of course, an obvious difference between the SAC example and *Phosphorus* is that the system in the latter is sealed, whereas the methane/oxygen reaction is implicitly open. That the flask is sealed may mask the true proportion of students who think like number 243, as this prompts the common sense answer "nothing can escape" or "the flask is sealed, so no change". The effect of the SAC example may be more significant when the open system reactions are considered in section 5.6.

5.5.2 Precipitation

By the third survey, exactly 54% of the SAC sample give P-coded responses, a large improvement on the 28% in this category at the first survey. This change is significant at the 0.01 level when χ^2 is calculated for responses P/not P. When the R codes are included, the proportion selecting the correct response and giving an acceptable explanation rises to 66% at the third survey. With the inclusion of the Q group, table 5.9 shows that 70% select "140 g exactly" at the third survey.

RC	Description	1st %	2nd %	3rd %
P1	140 g no mass change / no gas given off	24.8	32.0	42.0
P2	140 g formal conservation statement	0.4	1.6	4.0
P3	140 g number of particles is unchanged	2.8	6.4	8.0
P	Total	28.0	40.0	54.0
Q1	140 g uncodeable or no explanation	2.8	4.0	4.0
Q	Total	2.8	4.0	4.0
R1	140 g no rxn / reactants &/ product correctly named	13.6	15.2	12.0
R	Total	13.6	15.2	12.0
S1	140 g reactants &/ product incorrectly named	0.8	2.4	2.0
S2	< 140 g a gas is released	13.6	9.2	6.8
S3	< 140 g water / liquid evaporates / is lost in transfer	2.4	1.2	2.0
S4	> 140 g air is involved in the reaction	1.2	0.4	-
S5	< 140 g error in RMM calculation	-	0.4	-
S	Total	18.0	13.6	10.8
T1a	< 140 g because energy is lost / used up / released	0.8	0.4	2.0
T1b	> 140 g energy is taken in	-	-	0.4
T1	*Total*	*0.8*	*0.4*	*2.4*
T2	< 140 g because dissolving causes mass decrease	-	-	-
T2	*Total*	-	-	-
T3	> 140 g solid weighs more than liquid	17.2	12.8	9.6
T3	*Total*	*17.2*	*12.8*	*9.6*
T4a	< 140 g because reactant(s) are used up	1.2	-	0.4
T4b	> 140 g an extra substance is present	3.6	3.2	1.2
T4c	> 140 g because new bonds have been formed	0.4	0.4	-
T4	*Total*	*5.2*	*3.6*	*1.6*
T5a	< 140 g mass decreases as space is used up	-	-	-
T5b	> 140 g because space was used up	0.4	-	-
T5	*Total*	*0.4*	-	-
T	Total	23.6	16.8	13.6
U1	> / < 140 g uncodeable or no explanation	3.6	4.4	4.8
U2	No response	10.4	6.0	0.8
U	Total	14.0	10.4	5.6
	Overall total	100.0	100.0	100.0

n = 250

Table 5.9: Changes in SAC students' responses to *Precipitation*

Only 15.2% give P coded answers on three occasions. This means that most of the P-codes in the third survey are contributed by students whose thinking has changed. Table 5.9 indicates that the increases in P-codes after the second and third surveys are very similar, perhaps because SAC features precipitation reactions once in each half of the course. Students meet the formation of a precipitate for the first time in unit 3, *From Minerals to Elements*, where students carry out an activity which includes reacting halide ions with silver nitrate solution (Activities, p 7 and Chemical Ideas, p 44). This information may have contributed to the increase in P codes at the second survey. Precipitates are revisited in Unit 10, *Colour by Design* (Story, p 6) in the context of forming new compounds to use in paintings. A related activity is the production of azo dyes (Unit 10, Activities, p 37), which form as brightly coloured precipitates.

However, students interviewed after the second survey attribute their changed thinking more to common sense than material learned during the course. Students 243 and 331 for example, said at the first survey that the solid would be heavier than liquid (T3), so the mass would be more than 140 g. By the second survey, both students had changed to the correct answer. Student 243 attributed his second answer to "common sense":-

> I: The first time you said - you were asked to say what had happened to the mass -
>
> S: It should stay the same.
>
> I: Right. OK. You said that this time -
>
> S: Because it's both liquid - the atoms are all in liquid - there are no gases or anything to confuse myself with, so it should stay the same.
>
> I: Here you said the solid would weigh more.
>
> S: That's not true because there are the same number of atoms.
>
> I: Right, OK. So this is the one you would want to stick with?
>
> S: Yes.
>
> I: So is this something you have learned about in the course, or not?
>
> S: I might have done, I can't really remember! [laughter] It just seems to be common sense.

This student cannot explain exactly what has made him change his mind, but is confident that he knows his thinking to be correct. This is supported by student 331, who used similar terms:-

I: So is that something you've learned since the course started, or are you just not aware that you changed your thinking about that?

S: I don't think it's so much something I've learned, as something I've woken up to.

So, students who demonstrated some confusion about mass and density at the start of their course do change their minds later, but not because of the SAC material. Rather, the increase in P-codes has arisen through intuition - "it just is like that". Students who have not developed this idea for themselves continue to respond with the idea that solid "weighs more". About 5% are coded T3 on all three occasions, suggesting that for these students the mass/density confusion can be persistent and persuasive.

Two students whose first responses were coded S2 at the first survey were also interviewed about their change to a P1 code at the second survey. One, student 105, admits that he thought reactions gave off gases:-

I: OK. So this one here, the first time you said when you make a precipitate its less than 140 and you said that gas is given off. And there you said it's the same, 140, and "you haven't added anything". So can you -

S: It would just be the same. Because you've just poured one into the other.

I: Yes.

S: And if they both add up to 140 g and you put them in one, they would still add up to 140.

I: Yes, you're right here. But I was thinking here [1st] what did you think the gases might be, did you have any thoughts about that?

S: It's just a guess.

I: OK. So did you perhaps think it was a gas because all the reactions you'd seen up to that point gave off gases? Do you think, or?

S: It could have been.

I: Had you seen any precipitation reactions at all?

S: Not at the time. I did think that reactions gave off gases, that we've done before.

Although this student did change his mind, Table 5.9 shows that this notion is used by almost 7% at the third survey. As only four students were coded S2 for all three surveys, most of this 7% must arise from students developing this thinking during the course. These students could be responding intuitively on these latter occasions, not thinking about the question in terms of the knowledge they have learned. Alternatively, these ideas could develop because SAC material fails to assist students in the development of the idea that precipitation reactions do not give off gases.

Despite precipitation reactions featuring in SAC, students' ideas about this type of reaction, specifically, the confusion between mass and density and the characteristics of chemical reactions seem to develop more through maturation than direct influence.

5.5.3 Solution

SAC features the dissolution of an ionic lattice early on, in unit 3, *From Minerals to Elements* (Chemical Ideas, p 39 -42). Sodium chloride is used as an example:-

> "When an ionic substance dissolves, the ionic lattice is broken apart to produce individual ions in solution. The ions change from having definite positions in a highly ordered structure, like the NaCl lattice, to being spread out in a beaker of solvent, like water." (p 39)

The discussion continues, illustrating the solvation of ions on p 41. The presentation does not discuss the conservation of mass during dissolving; that students already understand this to be the case is evidently assumed. However, it is clear from this that sodium chloride does not give off a gas on dissolving. Students meet dissolving again in unit 12, *Aspects of Agriculture* (Chemical Ideas, p 38 - 41) where the hydration of ions in solution is discussed, and in unit 13, *The Oceans*, (Chemical Ideas, p 52 - 53) where they learn to calculate the solubility products.

Table 5.10 shows only an 8% increase in P codes from the first to the third survey. This relatively small improvement is reflected in the value for χ^2 which is not significant at either the 0.05 or the 0.01 level. However, students do appear to change from categories R and S, for example number 278, who gave these written answers:-

> "The sodium chloride [no further explanation]" (Less than 220 g, 1st survey)
>
> "This is because assuming none of the solution was lost the mass will not change unless something is lost." (220 g exactly, 2nd survey)

At interview, this student was asked to explain this change:-

> I: I think you'll see there's been a bit of a change there!
>
> S: [pause]
>
> I: So the first time you said it was less than, this time you say it's 220 exactly. And there's no diagram there and a really good diagram here!
>
> S: Yes. Well, this is the first one, isn't it. I found that quite hard, cos I knew when I was doing it we haven't done this yet, I haven't done anything like this before, I didn't really have a clue about reactions, what actually goes on inside them, water. But when we did this we'd already covered the one with - showing the polar water molecules, why things dissolve, and we'd

done all the enthalpy and that sort of thing, so I knew quite a lot when I did that, but not a lot when I did that. I don't know why I put that there.

I: OK. Did you think that gas might be produced, or something like that?

S: Yes.

I: That's what a lot of people have said.

S: Yes, yes.

I: You were perhaps thinking it reacts with the water and gives off a gas?

S: Yes, cos I thought - I considered it being 220 g, but I thought something must be given off because it's a reaction - something's got to happen! [laughter]

I: So here you're quite happy that the mass would be the same?

S: Yes.

I: And that's something you learned in one of the units?

S: Yes.

The SAC material has evidently contributed to the second, correct, response of this student. He can recall discussing the solvation of ions and realises that a gas is not produced.

RC	Description	1st %	2nd %	3rd %
P1	220 g no mass change on dissolving	16.8	25.6	26.8
P2	220 g formal conservation statement	-	2.0	2.4
P3	220 g number of particles is unchanged	2.4	4.0	6.4
P4	220 g because 200 + 20 = 220 g	21.6	11.2	12.4
P	Total	40.8	42.8	48.0
Q1	220 g uncodeable or no explanation	4.0	5.2	6.8
Q	Total	4.0	5.2	6.8
R1	220 g there is no reaction / gas prod	12.0	10.8	7.2
R	Total	12.0	10.8	7.2
S1	< 220 g salt reacts with water	1.6	1.6	0.4
S2	< 220 g a gas is released	16.0	20.0	14.8
S3	< 220 g salt / water is lost / evaporates	3.6	2.8	2.8
S4	220 g reaction occurs	0.4	-	0.4
S5	> 220 g air or water is involved	0.4	0.4	0.4
S	Total	22.0	24.8	18.8
T1a	< 220 g energy is lost	0.8	1.2	0.8
T1b	< 220 g mass is lost in dissolving	7.2	5.6	3.6
T1c	> 220 g energy is taken in	-	-	1.2
T1	*Total*	*8.0*	*6.8*	*5.6*
T2a	< 220 g the salt is now liquid	2.4	2.0	0.4
T2b	> 220 g density increases	-	-	0.4
T2	*Total*	*2.4*	*2.0*	*0.8*
T3a	> 220 g sodium chloride was added	1.2	3.2	4.8
T3b	> 220 g the reaction increases mass	1.2	-	0.8
T3	*Total*	*2.4*	*3.2*	*5.2*
T4	< 220 g salt takes up space in water	1.2	1.2	2.0
T4	*Total*	*1.2*	*1.2*	*2.0*
T	Total	14.0	13.2	14.0
U1	> / < 220 g uncodeable or no explanation	3.6	2.4	3.6
U2	No Response	3.2	0.8	1.6
U	Total	6.8	3.2	5.2
	Overall total	100.0	100.0	100.0

n = 250

Table 5.10: Changes in SAC students' responses to *Solution*

Student 205 gave the response less than 220 g "because mass is lost in dissolving" at the first survey and changed to 220 g exactly at the second survey, with the explanation:-

> "As the sodium chloride + water remain in the same form at the end of the experiment than at the beginning."

She discussed this change at interview:-

I: I don't know if you're able to say - which answer would you stick with now?

S: This one. [2nd] I don't think it would become less than what it is.

I: Mm.

S: But I don't know!

I: No, you're right! This one, I was just wondering what you were thinking there and whether you had learned something in between which has made you change your mind. It seemed to me what you were saying is that that weighs something when you have it on it's own, then when you put it in water and all these things split up and you've got Na and Cl all over the place - they don't weigh as much.

S: Yes, that's what I thought then.

I: Right. But you're happy to say that that's not the case now?

S: Yes.

I: Right, so what's gone on in between?

S: I don't know! Maybe I just thought about it more logically, this doesn't sound very logical, so maybe I've - I mean, I don't think it was anything that I learned in the chemistry course that -

I: That seems like common sense now?

S: Yes.

I: And that seemed like common sense then?

S: I suppose so! I mean, I don't know, maybe it was -

I: It's a very hard thing to explain, why you've done that .. does it look silly to you now?

S: It does! And completely different!

This student cannot explain where her new idea came from, like student 243 who could not explain his answer to *Precipitation*. The change is best described as being due to maturing in thought. The same maturing process is responsible for a different type of change exemplified by student 277. His first answer was coded P4, but at the second survey his answer changed to S2. He said,

> "I think the second time I was trying to look for more of a complicated answer. I thought it was too simple to say it was the same, I don't know why."

Some students, it seems, know too much to be able to answer a straight-forward question correctly; the correct answer appeared to be too straightforward to be probable. This may help to explain why the proportion of S2 answers has changed very little across the three surveys - students thought there must be a reaction! This raises a question about what students have learned - the course material is quite clear that no reaction (or at least, no gas) is liberated when sodium chloride dissolves, although some students persist in thinking this. The first principle these students apply to answer questions with unfamiliar content is to revert to a naive idea which has no bearing on anything they have done in lessons. Another reason could be that as students progress through the course they meet increasingly complex reactions involving several reagents. This may cause a small number to perhaps lose sight of basic ideas. The number answering like this cannot be quantified, as every student answering in this way would need to be interviewed to ascertain their thinking. So, the observed changes in response to *Solution* could arise because some students simply lose the intuitive ideas they had at the beginning of the course, while others look for complications where none were intended. The course material does not seem to impinge directly on either of these.

The responses to *Solution* add to those found in answer to *Hydrogen chloride*, in demonstrating that the process of dissolving is difficult for students to understand. The examples used in these questions, dissolving of a gas and a solid, both resulted in the formation of a solution containing ions. The source of students' difficulties may be the breaking up of molecules in this way. It may be that where molecules stay "in one piece" students are less prone to making the kind of errors observed here at such a high level.

As a group, these questions show that most students complete their SAC course with the idea that mass is conserved in closed systems. The proportions selecting the correct answer from the multiple-choice offered are 84% (*Phosphorus*), 74% (*Precipitation*) and 62.4% (*Solution*) at the third survey. The relatively high figure for *Phosphorus* must be caused by the fact that the obvious answer is "the flask is sealed". Both *Precipitation* and *Solution* describe systems which are open to the atmosphere, even though only the reagents named in the questions are involved. This disallows the "obvious" answer, permitting students to give responses such as "a gas is released". However, this type of incorrect response does imply conservation of mass, as discussed before. Therefore, perhaps the more significant finding is that between about 11 and 15% of students completing SAC think that gases are released when sodium chloride dissolves or when a precipitate is formed; further, that about 10% still confuse mass and density. The direct influence of SAC material on making students change their thinking appears to be limited.

5.6 Reacting mass reasoning

The questions *Iron sulphide* and *Carbon* probed students' use of reacting mass reasoning across the three surveys.

5.6.1 Iron sulphide

Table 5.11 shows significant improvement in the proportion of P-coded responses across the three surveys. The value for χ^2 is significant at the 0.01 level. About 72% can use reacting mass reasoning by the end of the course. The increase in P-codes arises because almost 21% of the sample changed from T in the first survey to P by the third survey, most of these learning that the response "192 g" was not correct. Few students, 2%, changed from P in the first survey to T code at the third, suggesting that the majority of students change their responses because they have learned about reacting mass reasoning.

RC	Description	1st %	2nd %	3rd %
P1	176 g / 2 moles FeS +16 g S / 0.5 mole S	33.6	36.0	34.4
P2a	176 g FeS + sulphur	2.0	2.8	2.4
P2b	176 g FeS only	11.2	23.2	33.6
P2c	16 g/excess sulphur only	4.4	2.8	1.2
P	Total	51.2	64.8	71.6
Q1	2 x FeS only	1.6	3.2	4.8
Q	Total	1.6	3.2	4.8
T1a	192 g FeS	30.8	21.6	14.8
T1b	More than twice as much iron sulphide	1.6	0.4	0.8
T1	*Total*	*32.4*	*22.0*	*15.6*
T2a	A different compound from FeS	2.4	0.4	-
T2b	FeS with a different formula	3.6	2.4	0.8
T2	*Total*	*6.0*	*2.8*	*0.8*
T3	Completely wrong figures used	1.6	1.2	0.4
T	Total	40.0	26.0	16.8
U1	Uncodeable	2.8	1.6	1.6
U2	No Response	4.0	3.2	4.4
U3	Iron sulphide only	0.4	1.2	0.8
U	Total	7.2	6.0	6.8
	Overall total	100.0	100.0	100.0

n = 250

Table 5.11: Changes in SAC students' responses to *Iron sulphide*

SAC presents balancing equations and calculation of reacting masses in Unit 2, *Developing Fuels* (Chemical Ideas, p 37 - 9). The sequence calculating the mass of carbon dioxide produced from 64 g of methane was quoted earlier. Mole calculations are used thereafter in various activities, including "Copper(II) sulphate and water: an investigation of energy changes" (Unit 3, p 18 - 9) and "An Aspirin Assay" (Unit 6, *What's in a Medicine*, p 31) and is assumed in unit 12, *Aspects of Agriculture*, where equilibrium constants are calculated (Chemical Ideas, p 47). Students therefore have opportunities to practice using moles at various points throughout the course.

Students whose responses had changed between the first and second surveys were asked to explain what had contributed to their different answers. The mind of student 205 went completely blank at first, but she was able to talk through her answers with help. She knew that this work had been done early on:-

> I: Now. The thing is, what I was wondering was, did you know about this sort of thing, everything reacting in moles?
>
> S: Well, I didn't when I did this, but I did then, because we'd done stuff like this during the year.
>
> I: Right. OK. can you think where you did it?
>
> S: I think we did it at the beginning, we were just learning about moles.

Student 208, from a different college, also attributed his change to material learned during the course:-

> "We learnt how to do - how to balance equations, working out products, how much more you'd get, why you'd cut it [e.g. the moles of sulphur] in half."

However, after the second survey, student 349 was still confused. He had changed his answer to T1a, 192 g, at the second survey, but responded with a P1-coded answer at the first survey. He was asked:-

> I: So which do you think is the right answer now?
>
> S: Er - it should be - that one, that one's the correct one, the second one, cos, er 112 + 80 grams added together makes that.
>
> I: So what were you thinking here then? [the 1st answer] Can you remember?
>
> S: No! I'm shocked at that!

The student was taken through a discussion about moles and mass, without explaining the need to preserve a ratio of moles of product to reactants. The discussion continued:-

> I: So, according to the equation, would 2 moles of iron react with 2.5 moles of sulphur? The equation tells us it's one, one and one.
>
> S: Yes.

I: So we're now saying we've got 2, 2-and-a-half, making only 2 of that.

S: Yes.

I: Is there something wrong with that?

S: Yes, because it should be 2, 2, 2.

I: OK. So then we'd have half a mole of sulphur left.

S: Yes.

I: So what's wrong with that answer then?

S: Um, it doesn't balance - it doesn't follow that. It says, 2 + 2.5 = 2, which it doesn't.

[laughter]

I: OK. So is that wrong then? [2nd answer, 192 g]

S: Yes. I'm lost!

This student was brought to the point of realising he did not understand the principle involved. He could not resolve the situation without help. This illustrates the confusion remaining for some students where mole calculations are concerned. This same student admitted he might have "rushed" his second answer (192 g), but the discussion at interview implies he had completely forgotten that ratios are important.

Most of the 17% giving T coded answers are students whose thinking has not changed from the first survey - about 9% are coded T1a on all three occasions. Either all these students "rushed" every time, and did know about mole ratios, but simply didn't say so, or, perhaps more likely, their thinking for some reason had not been altered by any material from SAC.

5.6.2 Carbon

This straight-forward question was included in the survey to provide the information needed to answer *Power Station*, which follows in the next section.

RC	Description	1st %	2nd %	3rd %
P1	88 g / 2 moles - ratio or moles used	40.4	63.2	60.8
P2	Ratio or moles used but answer ~ 88 g	1.6	2.4	0.8
P	**Total**	**42.0**	**65.6**	**61.6**
Q1	88 g / 2 moles, no method shown	8.8	6.0	8.8
Q2a	88 g, addition	14.0	11.6	11.6
Q2b	88 g/ 2 moles - method incorrect / unclear	1.2	1.2	0.4
Q	**Total**	**24.0**	**18.8**	**20.8**
T1	Answer ~88 g, no method / incorrect / unclear	0.8	0.4	-
T2	» 88 g, any method	7.6	4.4	6.8
T3	44 / 56 / 72 g, any method	11.2	6.4	6.0
T4	« 88 g, any method	5.2	3.2	1.6
T	**Total**	**24.8**	**14.4**	**14.4**
U1	Uncodeable	2.4	-	0.4
U2	No Response	6.8	1.2	2.8
U	**Total**	**9.2**	**1.2**	**3.2**
	Overall total	**100.0**	**100.0**	**100.0**

n = 250

Table 5.12: Changes in SAC students' responses to *Carbon*

Table 5.12 shows an increase to about 62% in the proportion of P coded answers by the third survey. Most of the increase is due to almost 13% of the sample whose responses were coded T at the first survey but changed their thinking to a P coded answer at the third survey. The improvement is significant at the 0.01 level. The increase in P-codes suggests that more students are able to carry out the calculation using a method consistent with understanding reacting mass reasoning. About 13% changed from T at the first survey to a P code at the second. Interview evidence indicates that some of these early T-coded answers at the first survey were due to student error, rather than misunderstanding the question. Student 301 changed his response from 44 g (T5) at the first survey to 88 g (P1) at the second. He explained this change at interview:-

> S: Yes, I think that's just a stupid mistake, cos I can definitely remember doing that in our GCSE course.

Student 344 gave the answer 56 g (T5) at the first survey and 88 g (P1) at the second. She is able to identify her mistake more accurately, but also indicates that her method is one which uses ratios rather than moles:-

> S: Well, that one's right [2nd answer], like I've doubled the carbon and I haven't doubled the oxygen. I've just done it for one O_2.
>
> I: How do you know to double it? What tells you to double it when you've done it the second time?
>
> S: Well, I've doubled everything, that's why! [laughs]

I: OK. Well have a bit of time to think about it.

S: Well, it does say 24 g grams, yes.

I: So how do you know that means double?

S: Cos one mole of carbon is 12 g, so two moles must weigh 24 g.

I: OK. So how do you know it's two of everything?

S: Cos that's your original formula - you've got two carbons, so you've got two oxygens.

I: So you have to double everything. Right. Good. Did you know how to do that before, then, before you started doing A level?

S: Um, a bit, when I thought about it!

I: So you knew about it being one mole -

S: Not about moles. But I knew how to write formulae and get them to balance and stuff, but I didn't know anything about moles.

This student uses the phrase "original formula" to mean "mole ratio". She uses moles to provide a short-cut to the answer recognising that there are two moles of carbon and so doubles the mass of carbon dioxide. Many students coded Q1 may have used this strategy in obtaining the correct answer, but simply did not write down their method.

Only three students, 1.2%, were coded T for all three surveys, while only six (2.4%) were coded T for the second and third surveys, indicating that most of the 14% whose responses were placed in this category at the third survey had responded differently on both the earlier occasions. Some students may respond incorrectly due to a simple arithmetic error, for example "forgetting" that two moles of carbon were given in the question and calculating the mass of carbon dioxide given by one mole (44 g). By whatever means these incorrect answers are achieved, these data indicate that 14% of students completing SAC do not realise that their answers are nonsense in practical terms.

These data illustrate the impact of early teaching about reacting mass reasoning more clearly than the *Iron sulphide* question. Here, we see a definite decrease in T-coded responses at the second survey, precisely at the point where the early units were studied. However, the T-code figure remains unchanged at the third survey, while the P-coded proportion actually decreases slightly. One possible reason for this is that students in the later stages of SAC will have been carrying out much more complex calculations than this question presents, and so may have put down the first answer which seems sensible (perhaps "88 g" alone, hence the increase in Q1) because the question was "too easy" to require much attention. Alternatively, some may have found the calculations increasingly difficult, such that any question involving numbers is not answered confidently, resulting in ill-considered responses.

It is clear, though, from these two questions that while about 20% of the sample learn to use reacting mass reasoning, about 15% cannot answer these simple questions correctly at the end of the course. The tendency to use a basic algorithm, addition of the two numbers in the question, is still apparent (*Iron sulphide*, T1a, *Carbon* Q2a) while other students (*Carbon* T2 and T3) cannot compute the relative molecular mass of carbon dioxide and double the number.

5.7 Conservation of mass in open systems

Students' understanding of mass conservation in open system reactions was investigated using two questions, *Power Station* and *Petrol.*

5.7.1 Power Station

The proportion of students offering P-coded answers to this question has increased significantly from 14% at the first to about 43% at the third survey, confirming the findings of the previous section that more students are able to use reacting mass reasoning. This observation is supported by the value for χ^2 which is significant at the 0.01 level. The main increase occurs between first and second surveys, following the work on calculations in the early SAC units reported above. The increased P-code proportion arises from students in all three other categories changing their answers. About 12% change from T to P; around 8% move from U to P and about 12% from Q to P. A few students move in the opposite direction.

RC	Description	1st %	2nd %	3rd %
P1	3667 tonnes	10.0	30.0	34.0
P2	Close approximation to 3667	4.0	12.4	9.2
P	Total	14.0	42.4	43.2
Q1	3000 tonnes with or without working	7.2	4.0	5.6
Q2	2333 / 2667 or similar with working	3.2	9.6	10.0
Q3	Other value > 1000 tonnes	9.6	6.0	5.6
Q	Total	20.0	19.6	21.2
T1	< 1000 tonnes	26.8	14.0	7.6
T2	1000 tonnes	7.2	7.2	4.4
T3	Other incorrect method and answer	2.4	4.8	6.4
T4	Calculation attempted, but not completed	0.4	2.8	6.0
T	Total	36.8	28.8	24.4
U1	Uncodeable	3.2	-	2.0
U2	No Response	26.0	9.2	9.2
U	Total	29.2	9.2	11.2
	Overall total	100.0	100.0	100.0

n = 250

Table 5.13: Changes in SAC students' responses to *Power Station*

Several examples of students changing between T and P categories were explored at interview. Student 105 gave "3000 g" as his answer at the first survey, and "3.6 x 10^9 g" the second time. He explained this difference at interview:-

> I: OK. Cos - can you say why 3000 g wouldn't be a sensible answer?
>
> S: Cos it's less than 1000 tonnes!
> [Laughs]

I: Right! So here you got it right. What did you do to get that answer? How did you reason it?

S: I worked out the moles of carbon, turned that into grams and divided by 12, then I timesed it by 44, which is the mass of CO_2, so you get the total grams of CO_2 produced.

He attributed his new thinking to work he had done in the *Developing Fuels* unit. Student 223 gave the answer "4000 tonnes" (Q3) at the first survey, and at the second survey did this calculation:-

"1000/12 = 83 moles [crossed out] deducting sulphur = 80
(12 + 32) x 80 = 3520 tonnes" (P1)

The student explained at interview that her first answer was an estimate:-

I: The question I'm wondering is how you got the 4000 tonnes, it's not so far wrong.

S: Yeah, um, because, um carbon's 12, isn't it?

I: Yes.

S: and oxygen's 16. So, I probably didn't know that! I've - I probably couldn't remember, yeah, I knew it's 12, cos I can see it here, and 16 times 2 is 32, so I probably knew that the oxygen was 16, so I was probably looking - um, I probably did the wrong ratio, actually, oh, no I might not have done, because I'll have probably added them up to get carbon dioxide's rmm which is 44 so and the ratio of carbon to CO_2 relative molecular mass is 12 to 44, which I thought is about 1:4, so from 1000 tonnes of that I'm going to get 4000 tonnes of CO_2.

I: OK. I get it.

Student 344 used a similar method to answer *Carbon*, although this answer is more sophisticated because of the additional step involved in reasoning that the relative molecular masses of carbon and carbon dioxide are in a ratio of 1:4, rather than the ratio of moles in a simple equation. Student 344 is not able to apply her technique to *Power Station*, becoming confused by the idea that coal is an alkane and therefore the mass of 1000 tonnes has to be split between carbon and hydrogen:-

I: Now, I'm wondering why you put 900 tonnes there! [laughter]

S: I think I probably just guessed!

I: But you can see why that's a silly answer?

S: [pauses]

I: Why can't it be 900 tonnes?

S: [pauses]

I: What's the mass you've got to start with?

S: 1000 tonnes.

I: 1000 tonnes. OK. And - what's coal, do you know?

S: Er - [pauses] alkanes.

I: Alkanes. OK. So if that's what you've got here, and that reacts with oxygen, and you get CO_2, what happens to the mass of the coal, then, when it burns? What happens to the mass?

S: Um. Increase.

I: OK. So why is 900 a bit silly as an answer?

S: Because it's a decrease.

I: I was thinking there - whether it was a guess, I was thinking it might be a guess.

S: Yes.

I: OK. Let's go on to what you did the second time. And I don't know if you can tell me how you got this answer? What did you do there?

S: Well, I split the 1000 up into what they would be, the C and H and added oxygen to the carbon. [Answer showed carbon 750, H 25]

I: Right. OK. Do you know how to put moles into that part? How would you use moles to get an answer? What would you have to do?

S: [pauses] I'd balance it first to get the correct equation, then get the masses and make it to a thousand.

While this student recognised the need to balance the equation and could then use mole ratios to arrive at a simple correct answer she was unable to convert mass values into moles or apply the ratio-type reasoning to relative molecular mass values, the "short-cut" answer in this case.

Table 5.13 shows almost no change in any category between second and third surveys, suggesting that "saturation" has been achieved. Students seem to progress as far as respondent 344, that is, they answer *Carbon* or even *Iron sulphide* correctly, but cannot go beyond this. At the second stage, the number of students changing from Q and T to the P category are exactly matched by the numbers responding P in the second survey then Q or T in the third. So, as many students learn how to answer this question between the second and third surveys as "unlearn" it. The lack of positive change at this stage may arise because as students progress through the course they meet more complex calculations, leaving behind the basic ideas about reacting mass and "forget" how to work out the answer. SAC does not revisit the basic calculation of reacting masses in later units, choosing instead to present only the more complex issues such as equilibrium constants.

About 24% give T coded responses at the third survey. This relatively large figure confirms the high level of difficulty of *Power Station.* Almost 13% are coded T for all three surveys, so about half of the final T-coded answers are contributed by students whose thinking has not changed throughout the course. Hence, this proportion of students do not learn how to use reacting mass reasoning in the very early stages of SAC and do not "pick it up" later on.

5.7.2 Petrol

The story of SAC unit 2, *Developing Fuels*, uses petrol as an example of a modern day fuel. The unit explains the role of oxygen in getting energy from fuels (Story, p 2-3), describes the origin of petrol and lists the types of molecules it contains. The combustion of petrol in a car engine is discussed in detail (p 11 - 12) and one of the assignments (p 13) begins:-

> "Many people learn to drive cars without the faintest knowledge of what happens in the engine."

A question in this assignment focusses on the air-petrol mixture entering the cylinder:-

> "Why is it important to supply a petrol and air in correct proportions to the cylinders?" (p 13)

The chemical ideas section of this unit includes writing balanced equations; examples featuring the combustion of fuels are given, along with examples including alcohols and nitrogen burning in oxygen. The unit continues, as described earlier, to teach calculation of reacting masses and enthalpy changes from the context of burning fuels. The impact of this unit on students' responses to *Petrol* is described below.

The responses to *Petrol* follow a similar pattern to those for *Power Station.* A large increase in P-coded responses from about 12% to 31% between first and second surveys, but very little change in any category is observed between second and third. Most of the first stage increase is contributed by 18.4% of the sample who gave a T-coded answer at the first survey but changed to a P-coded answer at the second survey. The increase in the proportion of P- coded responses is significant at the 0.01 level.

RC	Description	1st %	2nd %	3rd %
P1	> 50 kg calculation used	0.8	6.4	11.2
P2	> 50 kg petrol reacted - particle statement	-	-	-
P3	> 50 kg petrol reacted with air / oxygen	10.8	24.8	25.2
P	Total	11.6	31.2	36.4
Q1	> 50 kg uncodeable / no explanation	1.6	1.2	2.8
Q	Total	1.6	1.2	2.8
S1	> 50 kg petrol mixes with oxygen	1.2	0.4	0.8
S	Total	1.2	0.4	0.8
T1	< 50 kg petrol converted to light / heat / energy	3.6	1.6	2.4
T1	*Total*	*3.6*	*1.6*	*2.4*
T2	< 50 kg gas lighter than lqd / petrol vapourises / condenses	3.6	4.4	4.0
T2	*Total*	*3.6*	*4.4*	*4.0*
T3a	< 50 kg petrol is used up / burned away	3.2	1.2	0.4
T3b	50 kg petrol is used up	2.4	2.0	1.6
T3c	< 50 kg only a proportion / % of petrol is used	0.8	2.4	2.4
T3	*Total*	*6.4*	*5.6*	*4.4*
T4a	50 kg what goes in must come out / 1050 - 1000 = 50	25.6	21.2	17.2
T4b	50 kg petrol converted to gas but mass unchanged	6.0	6.0	3.2
T4c	50 kg matter cannot be created or destroyed	-	1.2	0.8
T4d	50 kg petrol is burned / combusted / oxidised	12.4	10.4	9.2
T4	*Total*	*44.0*	*38.8*	*30.4*
T5a	50 kg no explanation / uncodeable	6.8	5.2	5.6
T5b	< 50 kg no explanation / uncodeable	5.2	3.2	3.6
T5	*Total*	*12.0*	*8.4*	*9.2*
T	Total	69.6	58.8	50.4
U1	Uncodeable explanation only	0.4	-	-
U2	No Response	15.6	8.4	9.6
U	Total	16.0	8.4	9.6
	Overall total	100.0	100.0	100.0

n = 250

Table 5.14: Changes in SAC students' responses to *Petrol*

Several students interviewed about their change from T to P attributed their new ideas to material included in the unit. For example, student 321 gave this answer at the first survey:-

> "I don't really know, but logically I would think that the 50 kg going in would mean 50 kg coming out..." (T6a)

At the second survey, her answer was:-

> "The petrol vapour has to combine with oxygen from the air, to be able to burn. Therefore the exhaust gases given off must have a mass >50 kg..." (P4)

She explained this change at interview:-

> S: Mm, that was something that came up in the course.
>
> I: Right.
>
> S: I didn't know anything about it mixing with the air before.
>
> I: So it came up in the course, do you know where it did?
>
> S: It was one of the early units.
>
> I: The fuels one?
>
> S: Yes, oh that, yes.
>
> I: OK. Can you see that there is quite a lot wrong with this answer then?
>
> S: Yes, I can now!

This suggests that many of those offering answers coded T4a at the first survey were ignorant of the involvement of air. Instead, these respondents conserved the mass of petrol on a "what goes in must come out" basis.

Student 301 also changed his thinking between first and second surveys. He gave this response on the first occasion:-

> "10 kg. All the petrol is burnt and 40 kg of water is produced and the othe [sic] 10 kg is gasses [sic] such as carbon dioxide and monoxide." (T3a)

This response differs from that of student 321 as the products of combustion are mentioned, but clearly there is no understanding that oxygen in these compounds must have come from somewhere. These substances have been rote-learned as products of combustion, but no thought has been given as to the reaction in which they formed. At the second survey, he responded:-

> "75 kg. It is more because the fuel reacts with oxygen when it is egnited [sic] increasing its mass." (P4)

When interviewed, student 301 immediately attributed this difference to the *Developing Fuels* unit:-

> I: ... the first time you said it was 10 kg and the next time you said 75.
>
> S: Yes.
>
> I: So what's happened in between there?
>
> S: Well, first of all I thought, well, cos all of it's gone, so it's not going to have as much - be as high as it was before - but in the second one I was thinking, well you've got the oxygen as well, as it burns, it combusts with the oxygen so you increase the actual mass of it.

I: So that was something you learned in the course?

S: In the fuels section.

I: Does this idea seem strange to you now?

S: Yeah! It does! [laughs] I can see what I was thinking, but why?

Clearly, this unit has influenced students' ideas about the combustion of petrol. A further 13.2% change from T to P code between the second and third surveys. However, on this occasion, 6.8% revert from P to T, perhaps because the *Developing Fuels* unit is no longer immediately recalled. Most of these, 4.4%, give responses coded T4, suggesting that they have "forgotten" to include the mass of oxygen.

Only 7.2% were coded P for all three surveys, indicating that most of those who were coded P at the third survey had learned the correct answer during the course. However, almost 31% were placed in the T category for all three surveys. Most of these students had not learned any new material which had prompted them to change their thinking about this question. Possibly, like those changing to a T-code from the P category in earlier surveys, some of these students do "know" that oxygen needs to be included in the mass of gas, but simply "forgot" to include it.

These questions reveal relatively poor understanding of open system chemical reactions. Most students cannot calculate the mass of carbon dioxide produced by 1000 tonnes of coal correctly, nor do most include the mass of oxygen in the mass of exhaust gas produced by 50 kg petrol. The questions themselves may not have assisted students: *Power Station* gives neither the relevant equation or relative molecular masses; *Petrol* does not mention oxygen, a reaction, or any relevant formula. Both questions, therefore, may have "tempted" the student seeking to answer in haste to give an incorrect response. It has to be said, however, that neither question demands the complexity of an A level question - both require knowledge of very simple chemical reactions and well-known atomic mass values. So, the level of correct responses is poor and points to a low level of mathematical capabilities among a majority of A level chemistry students in the case of *Power Station* and a failure to realise the involvement of oxygen in the case of *Petrol*.

5.8 Chemical bonding

A number of questions probed students' ideas about chemical bonding. These feature covalent, ionic and intermolecular bonds. Each bond type is considered separately.

5.8.1 Covalent bonding

Aspects of chemical bonding are taught throughout SAC, beginning in the first unit, *The Elements of Life* (Chemical Ideas p 49 - 54). Here, students are introduced to ionic and covalent bonding and the idea that covalent bonds can be polarised. Examples of dot and cross diagrams of molecules with single and double covalent bonds are given, including ammonia, carbon dioxide, nitrogen and hydrogen. Students are told:-

> "Chemists often draw structures in a simpler way [than dot and cross diagrams] by using lines to represent a pair of electrons shared between two atoms. A single line represents a single covalent bond. Double and triple lines represent double and triple covalent bonds." (Chemical Ideas, p 52)

The next, final section of this unit introduces the idea that bonds can be "polar", because the atoms involved in a covalent bond are of different sizes and have differing numbers of protons in the nuclei. The unit explains:-

> "In general, different atoms will attract bonding electrons unequally. One atom will acquire a slight negative charge because it has a greater share of the bonding electrons. The other atoms will become slightly positively charged... Bonds like this are called polar bonds." (p 53)

Water is named as a compound which features polar bonds and a water molecule is shown with dipoles on the hydrogen and oxygen atoms. Bond polarity is met again in Unit 4, *The Atmosphere* (Chemical Ideas, p 47) in the context of heterolytic fission, and is used in unit 5, *The Polymer Revolution* (Chemical Ideas, p 58 - 65) to help explain intermolecular forces, including hydrogen bonding (this account is described in greater detail in the next section). Double bonds are discussed in more depth in unit 5, *The Polymer Revolution* (Chemical Ideas p 43 - 48), where students are told:-

> "The four electrons in the double bond count as one region of negative charge." (p 44)

The shapes of simple covalent molecules are described in unit 8, *Engineering Proteins* (Chemical Ideas, p 44 - 46). Knowledge about covalent bonds is assumed in several other units. Thus, students will have met covalent bonds on several occasions in their course. We will now examine how this information affects the performance of SAC students in answering questions about covalent bonds.

Covalent bonds

Table 5.15 shows that the proportion of students giving P-coded answers increases from first to third survey. This change is significant at the 0.01 level. The largest increase, from 18.4% to 53.2%, occurs between the first and second surveys, but additional students respond with a P-coded answer at the third survey.

RC	Description	1st %	2nd %	3rd %
P1	2 / 4 electrons shared	8.8	43.2	51.6
P2	Single / double covalent	9.6	10.0	14.0
P	Total	18.4	53.2	65.6
Q1	Single / double bond	43.6	33.2	24.8
Q2	Chemical bond	1.2	0.8	-
Q	Total	44.8	34.0	24.8
T1	1 / 2 electrons shared	14.8	7.6	7.2
T1	*Total*	*14.8*	*7.6*	*7.2*
T2a	Saturated bond	2.8	0.4	0.4
T2b	Simple bond	-	-	0.4
T2c	Weak / strong bond	1.2	0.4	-
T2	*Total*	*4.0*	*0.8*	*0.8*
T3a	Ionic bond	4.4	1.2	-
T3b	Link between two compounds	2.0	3.2	0.8
T3	*Total*	*6.4*	*4.4*	*0.8*
T	Total	25.2	12.8	8.8
U1	Uncodeable	9.6	-	0.4
U2	No response	2.0	-	0.4
U	Total	11.6	-	0.8
	Overall total	100.0	100.0	100.0

n = 250

Table 5.15: Changes in SAC students' responses to *Covalent bonds*

The increase in P codes is made up from students changing from Q, T and U groups. The largest contribution is that of 17.2% who were coded Q1 at the first survey and P1 at the second survey. About 11% change from T to P1 and a similar proportion from U to P. No students changed from P to other categories at this stage. However, although students acknowledge their ideas have changed, at interview most do not attribute this to particular course materials or units. This is best illustrated by three students whose responses changed at this stage.

Student 306 was coded Q1 at the first survey and P1 at the second. His written responses were:-

> "a single bond
> "a double bond" (Q1, 1st survey)

"A covalent bond between two atoms in a molecule (sharing of an electron) each.
"A double bond between two atoms in a molecule (sharing of two electrons each)" (P1, 2nd survey)

The proportion giving the response "single / double bond" (Q1) decreased over the three surveys. This answer was the most frequent response at the first survey, suggesting that the symbols for single and double bonds were recognised easily from GCSE, but that students learned to use more accurate chemical language as the course progressed. At interview, student 306 explained that although he knew about covalent bonds at GCSE he didn't give this as an answer because the term didn't come immediately to mind:-

I: You've given quite a lot more information the second time.

S: [pause] It's hard to tell at first with "Explain as fully as possible" what they're actually asking for. Er. I would have known that was covalent back then if I'd have thought about it, I think, because I knew that much, I also knew about hydrogen bonding, I don't know why I didn't put it down.

I: Right. So that's something you had done at GCSE?

S: Yeah, I had done that at GCSE. We were sort of - we did modules, rather than an actual chemistry course. You did do a lot of the stuff, but cos you did it now and again and you didn't do it very often, you just sort of would forget about it.

I: So you didn't really make the link between them because it's difficult to remember.

S: Well, it's a long time since I did chemistry when I first started the course as well, I'd forgotten a lot of the stuff.

I: Yes.

The terms "single" and "double" bond are perhaps seen as an abbreviation for the full name. Later on, this student said that his second survey answers arose from material about bonding which had "been developed" during the course, although he didn't identify any specific unit. Our second example is student 344, who used the term "valency" in her descriptions at the first survey:-

"A single valency bond eg the sharing of 1 electron"

"A double valency bond eg the sharing of 2 electrons" (T1)

At the second survey, her written responses were:-

"A covalent bond. A sharing of 2 electrons"

"2 covalent bonds. A sharing of 4 electrons. Line 2 cannot rotate" (P1)

She was invited to explain these responses at interview:-

> I: I'm wondering there, what made you use the term "valency" the first time?
>
> S: Cos we'd done it in GCSE. Just sort of like said that that was what it was called, you know.
>
> I: That what was called?
>
> S: The bonding.
>
> I: Right. So they didn't say it was covalent bond, they just described it as a valency bond?
>
> S: Yes.

This student recalled a label that had been applied to the bonds at GCSE. Later in the conversation, following a discussion about hydrogen bonds (which will be reported later), she was asked:-

> I: OK. So where have you learned about bonding then, where have you got these ideas from?
>
> S: I can remember we did hydrogen bonding in polymers. But the other ones, I think we just gradually more -
>
> I: So it's something you've gradually learned about and you can't pin it down?
>
> S: No.

Like student 306, she is unable to name a unit in which covalent bonds are studied. Thirdly, student 278 changed from U at the first survey to P1 at the second. His written responses were:-

> "The bonding between two elements.
> "Don't know." (U1, 1st survey)
>
> "This is a single covalent bond.
> This is a double covalent bond. One has two electrons bonded, line 2 has four electrons bonded. 2 is stronger than 1. 2 is one plane [sic] and cannot rotate." (P1, 2nd survey)

This student recognised that his poor level of understanding had changed and explained this difference:-

> I: Now I think you'll see there's quite a bit of change there.
>
> S: Right. [laughs] Well, I didn't have a clue here! [pauses] I think we did use line bonds before at my old school. We had done bonding before.
>
> I: OK. So where did you learn about bonding in the course?

S: It was in the first few units. Quite concentrated, on bonding.

I: Did you just do covalent bonding at that time, or did you do other types as well - did you do other types as well?

S: Um, that was a bit later on.

I: So you did them separately?

S: Yes.

I: OK. So here, you hadn't done hydrogen bonding at all at GCSE?

S: No, or double. Or put a name to this.

I: So this was completely new when you got to A level?

S: [laughs] Yes, it was. We started off by saying about the electrons fitting together to fill the outer shells and I was familiar with that, cos we've done that and the models of the atoms and the electrons. But I'm not sure we did anything about double bonds. I think we did but it was quite confusing, because we were trying to draw them. But we hadn't done anything on hydrogen bonds, or polar ones.

The inability of students to name specific units where bonding is studied may be because SAC features covalent bonds in such a large number of places that students do not recall learning about them at any particular point. Also, the contexts are not directly related to bonding in the same way as, for example, the Story of *Developing Fuels* (unit 2) relates to the *Petrol* and *Methane* questions, so there is no direct "aide memoire" to assist recall.

A number of students give the same response on all three occasions. About 6% gave three P1-coded answers, confirming that most of the P1 responses in surveys two and three arise from students having learned new information. About 10% gave Q1-coded responses for all three surveys, suggesting that this group saw no reason to increase the amount of detail in their answers despite the work done. Only four students (1.6%) gave three answers coded T. This implies that almost all of the original 25.2% coded T changed their answers at either the second or third surveys, and also that most of the 8.8% coded T at the third survey had responded with a correct or partially correct answer earlier on. We will examine this group next.

The most frequent T-coded answer in each of the three surveys is that single and double bonds involve only one or two electrons respectively (code T1). About 7% give this response at the third survey. Most of these, around 5%, give this response for the first time, changing from P (3.6%) and Q (1.6%). These students may have recalled that "a double bond is twice a single bond" but had "forgotten" the actual numbers of electrons involved, perhaps in a similar way to some students who "forgot" to include oxygen in the *Power Station* or *Petrol* questions.

Perhaps more revealing are the 5% (twelve students) who changed from Q1 to T1 at the second survey, since we can also look at the third survey responses of this group. Only four correct their mistake and change to P1, while six repeat their first response, Q1, and two are coded T at the third survey. Those who change back to Q may still think that one/two electrons is correct, but give the response "single/double bond" masks this. The two giving a T code at the third survey seem to have misconceptions about covalent bonding.

Thus, *Covalent bonds* indicates that a high proportion of students studying SAC complete the course understanding the difference between single and double covalent bonds, although this learning cannot be tied to specific units. Most, about 52%, can explain this in terms of the number of electrons. About 25% give the vague answer "single/ double bond" which, as the preceding discussion illustrates, represents little or no progress from GCSE and may hide misunderstandings about the numbers of electrons involved. About 9% give erroneous answers on completion of SAC. The next question, *Methane molecules,* explores how students apply knowledge about covalent bonds to an understanding of energetics in the formation of a simple, well-known molecule.

Methane molecules

This question explores students' ideas about the energetics of covalent bond formation. Table 5.16 shows an increase in the proportion of P-codes from 12% to about 30% at the third survey, while the proportion of T-coded responses decreases from 13% to about 2%. These changes are significant at the 0.01 level. The percentage of Q-coded answers is high throughout, showing a peak of about 71% at the second survey.

The question attempted to probe students' understanding of the idea that energy is released when covalent bonds form and that this is related to a stable electron configuration. Relatively few students give a P-coded response at the third survey, with 16% describing CH_4 as the "most stable" and about 12% acknowledging that noble gas electron configurations result in CH_4 alone.

RC	Description	1st %	2nd %	3rd %
P1a	CH_4 is energetically most stable	-	0.4	1.6
P1b	C and H are more stable as CH_4	6.4	10.0	16.4
P2	C & H need 4 & 1 more e^-'s for noble gas configuration	6.0	8.4	11.6
P	Total	12.4	18.8	29.6
Q1	C needs four bonds / 4 more e^-'s	46.8	60.4	51.6
Q2	C has valency / oxidation no. of 4 / 4 links	8.8	10.8	9.6
Q	Total	55.6	71.2	61.2
T1	C has 4 bonding pairs / lone pairs 2/ 6 / 8 / 10 / 18 e^-'s	1.6	2.4	0.4
T2	C / H is saturated	-	-	-
T3	More C in air / H travels in pairs /1:4 is equal mass	2.0	-	-
T4	Because there are 4 H's and 1 C / other statement	9.6	1.6	2.0
T	Total	13.2	4.0	2.4
U1	Uncodeable	6.8	1.6	3.6
U2	No response	12.0	4.4	3.2
U	Total	18.8	6.0	6.8
	Overall total	100.0	100.0	100.0

n = 250

Table 5.16: Changes in SAC students' responses to *Methane molecules*

The issue of stability of molecules features in unit 4, *The Atmosphere*, where, in a section about free radicals, students are told:-

> "Filled out electron shells are more stable than unfilled ones. Free radicals are reactive because they tend to try and fill their outer shells by grabbing an electron from another atom or molecule." (Chemical Ideas, p 49)

Thus, the observed increase in responses coded P1b and P2 arise because students are encouraged to link "stability" with the number of bonds carbon atoms can make and electron configurations. Student 205 illustrates this. She gave these written answers:-

> "becaus [sic] 4 atoms of hydrogen are needed with one atom of carbon. to [sic] produce methane. CH_3, CH_2 or CH would not produce methane because they are not the right number of atoms." (T5, 1st survey)

> "because carbon has a valency of four and needs four bonds to be attached to the hydrogen." (Q1b, 2nd survey)

At interview, she explained the change:-

> I: Right. So this is a question about why methane is CH_4 as opposed to any of those other things here. Now the first time you had a go at this you said it was because four atoms of hydrogen are needed to balance with the carbon, and that's OK, and here you said simply it's a valency of four. So have you learned the term valency in between?

S: Yes! [Laughs]

I: Right. OK. So is that the complete answer, then, that it's got a valency of four or is there anything else you might want to add?

S: No. Cos it could have double bonds.

I: Could it make a double bond with hydrogen?

S: [pauses] No. It can't, can it!

I: Right, so you couldn't have that - why couldn't you have that?

S: Cos hydrogen's only got one.

This student thinks of her answer as complete - no other explanation is necessary than the valencies of the elements involved. She did not pick up the hint that this was perhaps not the complete answer! Later, the conversation was brought back to the issue of stability:-

I:...And do you know anything else about why it's CH_4 rather than CH_3 or any of these others? Are these stable?

S: Yes, this one's more stable. [The CH_4]

I: Because -?

S: Because of that extra electron.

I: So if you had CH_2 you'd have two more electrons and if it was that you'd have three.

S: Yes.

I: OK. So you learned about valency. Have you learned about stability of compounds, as well?

S: Yes.

I: Do you know where you've learned those things?

S: Which unit?

I: Yes. Or what was it related to, what bits of er -

S: Maybe it was when we did about free radicals and the ozone layer. I think maybe it could have been there, stability.

Although the notion of stability did not come to mind immediately, this student knew that CH_4 would be the most stable of the molecules listed and could recall learning about this in *The Atmosphere* unit. Over the sample as a whole, 6.4% make the change to P at the second survey from Q, T or U at the first survey, while 11.6% move from these groups to P at the third survey.

However, despite these increases, the Q-coded answers represent the highest proportion in all three surveys. About 29% give three Q-coded responses, suggesting that these students knew about the numbers of bonds made by a carbon atom prior to starting the course and that the SAC material did not encourage a change in their thinking. The increase in Q codes at the second survey arises because students move to this category from P (6%), T (10%) and U (12%). Most of these changes are to the Q1 code, which represents the simplistic answer "carbon needs four bonds". Some students have learned the term "valency" between surveys and so are coded Q2. The term "valency" is not mentioned in SAC, so its inclusion must come from teachers. As described above, several of the early units of SAC feature aspects of bonding, and methane in particular, in unit 2, *Developing Fuels*:-

> "The structure of methane may be represented by a 'dot/cross' formula. This shows all the outer electrons in each atom and how electrons are shared to form the covalent bonds." (Chemical Ideas, p 53)

As previous questions have indicated, this unit is frequently cited by students as influencing their ideas and many may learn about the ability of carbon to make four covalent bonds from this section.

About 18% change from Q to P between second and third surveys. This is counterbalanced by about 8% who change in the opposite direction. SAC discusses the shape of molecules in unit 8, *Engineering Proteins*, and this may provide the impetus for this second stage increase. Methane again features in the discussion:-

> "The arrangement of electrons in methane can be represented by a 'dot-cross' diagram as [dot-cross diagram given]. There are four groups of electrons around the central carbon atom - the four covalent bonding pairs." (Chemical Ideas, p 44)

This is almost an exact repeat of the paragraph quoted earlier (see previous page) from unit 2. Hence, the ability of carbon to form a stable structure is reinforced.

Clearly, as the changes from the P-coded responses indicate, not all students make the same degree of progress. A few, for example student 331, regress further in their responses to *Methane molecules*. This student gave these written answers at the first and second surveys:

> "Because Carbon has 4 electrons and the[y] latch on to H = [diagram of CH4 with lines for covalent bonds] if it was 3/2/1 it would be [diagram of CH3] and unsaturated." (Q1, 1st survey)

"Because a carbon atom has 4 pairs of electrons. :C̣: They like to covertently [sic] bond with hydrogen if they made C=H [CH3 showing double bond to one hydrogen] it would be unstable and so would H = C = H as double and triple bond are v. reactive." (T1, 2nd survey)

At interview she was asked about this change. Initially, the student could not see anything wrong with her second answer and believed this to be correct:-

I: You said first time to this one [1st answer] and the next time [2nd answer]

S: [pause] That's probably meant to say unstable! Um, where we probably - again, I'm sure I must have learned my whole chemistry in fuels, but it's the sort of thing, isn't it, and ..states of things, ... I don't know the exact place in the course, you know, all learning about double bonds and all that.

I: Right. So if you look at this molecule here - is that - are these things what you really think [2nd answer]? Four pairs of electrons is quite different to four electrons [1st answer]

S: [laughs] Well, obviously, I'd go with the four pairs, cos that's the - that's where you just learn it basically.

I: Right. Do you mean a carbon atom on it's own has four pairs of electrons?

S: I'm trying to think. Yes. One solitary carbon atom.

Next, the student was led to the point where she realised her mistake. In this part of the interview, she could not name the group where carbon is found on the Periodic Table nor the number of electrons in the outer shell of one atom. When these were established, the interview continued:-

S: Oh mad, I'm going backwards!

I: It's OK! And the other thing is, can you see anything wrong with that compound? [2nd answer]

S: The bond angles are wrong!

I: Yes, anything else?

S: Hydrogen can't make two bonds! [laughs]

I: Right!

S: Oh nightmare! It was only the idea that counted!

I: Yeah, I think what you meant was that that is too reactive, so it wouldn't -

S: Yeah, cos it has lone pairs on it -

I: It would have two free electrons which it hasn't bonded...

S: The thing is after a while you learn so many different theories and things you get them all back to front anyway.

This student knew she had made several mistakes in her answer when led to look at them again. Her third response was coded Q1, so her second answer could be the result of a mental "blockage", perhaps under interview pressure. However, with her final comment this student implies that she has learned so many "different theories and things" that she had lost sight of the basic, correct ideas. While the proportion of T-codes at the third survey is small for this question, this type of difficulty may assist in explaining the relatively high levels of T responses for other questions.

Notably, few students are coded T for this question at any stage. The 9.6% who offer very simplistic answers (T4) at the first survey are greatly reduced by the second and third. The persistent popularity of the Q-type responses suggests that the answer "Carbon needs four bonds or four more electrons" is, for many the only explanation. That 29.2%, close to one-third, give this type of answer in all three surveys illustrates the limits within which many students operate in answering this question. *Methane molecules* may invite this type of response, and a different phraseology, for example, "explain in energy terms why methane forms molecules with the formula CH_4" might have encouraged more students to offer a P-coded answer.

However, if the levels of third survey P-codes for *Covalent bonds* and *Methane molecules* are considered together, we see that many more students are able to describe single or double covalent bonds in discrete molecules than can explain why four bonds should form in methane. The idea being probed by *Methane molecules* is an extension of the basic knowledge explored by *Covalent bonds.* The comparatively low final number of P codes in answer to the extension question suggests that students find the idea of molecular stability difficult to grasp. They seem to develop basic tools with which to answer covalent bonding questions, but cannot link this knowledge effectively with energetics. This may be because SAC does not make the connection explicit, instead, the course reinforces knowledge appropriate to the very basic Q1 response-type. Alternatively, as the interview with student 205 suggests, the question may not have probed students' understanding about molecular formulae effectively, leaving many with the opportunity to give an answer at a level below that of their true knowledge.

5.8.2 Ionic bonds

Table 5.17 shows that about 76% of students' responses fall into either the P or R category at the first survey while 82% offer a P or R-coded answer at the third survey. The increase in P-coded responses is significant at the 0.01 level, although the largest changes occur within categories R and P - students simply move between these as their course proceeds.

RC	Description	1st %	2nd %	3rd %
P1	Energy is liberated in bond / ionic lattice formation	2.4	2.4	12.8
P2	e^- transfer Na to Cl, stable compound forms / redox rxn	13.6	15.6	10.8
P3	Ionic bond forms between Na and Cl	4.8	8.4	10.4
P	**Total**	**19.8**	**29.2**	**34.0**
R1	Na and Cl are reacting / form a compound	52.8	45.2	46.8
R2	The element(s) is / are reactive hence violent rxn	2.8	0.8	1.2
R	**Total**	**53.6**	**46.0**	**48.0**
S1	Hot Na has E_A required / rxn is quick / endothermic	3.2	6.8	4.8
S2	Covalent bond forms	2.8	4.4	1.6
S	Total	**6.0**	**11.2**	**6.4**
T1	Heat breaks bonds / sodium is burning	0.8	0.8	0.4
T2	Particles expand / contract / collide / break / split	2.8	1.6	-
T3	Heat energy used to make bonds	-	-	0.4
T	**Total**	**3.6**	**2.4**	**0.8**
U1	Uncodeable	2.0	3.6	0.8
U2	No response	12.0	7.6	10.0
U	**Total**	**14.0**	**11.2**	**10.8**
	Overall total	**100.0**	**100.0**	**100.0**

n = 250

Table 5.17: Changes in SAC students' responses to *Sodium and chlorine*

Before examining these data in more detail, we will look at how ionic bonding is taught in SAC. Ionic bonds are first mentioned in Unit 1, *The Elements of Life.* The chemical ideas section (p 49 - 50) begins by explaining that some metal and non-metal atoms lose and gain electrons. The section continues:-

> "When metals react with non-metals, electrons are transferred from the metal atoms to the non-metal atoms. The cations and anions which are formed are held together by electrostatic attraction." (p 49)

After dot-cross diagrams showing the formation of sodium chloride and magnesium fluoride, students are told:-

> "Each sodium atom loses one electron and each chlorine atom gains one electron, so the compound formed has a formula NaCl." (p 50)

A picture of the NaCl lattice is given, with an explanation of the arrangement in terms of attraction and repulsion between the sodium and chloride ions. This section ends with this information:-

> "The overall result of all these attractions and repulsions is what holds the ionic compound together... It is not, for example, simply the attraction between the two ions in the NaCl dot-cross diagram." (p 50)

Thus, students learn that ionic solids, and sodium chloride in particular, exist as ionic lattices rather than as discrete molecules. In unit 3, *From Minerals to Elements*, students are introduced to the idea of lattice energies in the context of dissolving. This section explains:-

> "We measure the strength of ionic attractions in a lattice by the lattice energy of the solid. The lattice energy, ΔH_{LE}, is the energy released when 1 mole of solid is formed by the coming together of the separate ions... So we define lattice energy as the enthalpy change involved in processes such as:
>
> $Na^+ (g) + Cl^- (g) \rightarrow NaCl (s)$ for NaCl, $\Delta H_{LE} = -780\ kJmol^{-1}$ ...
>
> "All lattice energies are large exothermic quantities..." (p 39)

Therefore, the information students need to arrive at a P-coded answer is presented at various points in the early units. The impact of this material on students' responses will now be explored.

At the first survey, most students state simply that sodium and chlorine are "reacting" or "forming a compound" (R1). About 17% maintain this answer, giving R codes in all three surveys. This group, like those mentioned above (*Methane molecules*, Q category), only think in terms of the simple event taking place, and see no reason to change their answer. This suggests that the SAC material has not affected the ideas of these students, or that they cannot perceive a link between the material they have studied and the question. Alternatively, students may respond this way because the question does not elicit their "best" response, which would reflect understanding of energetics ideas, although equally possibly students may not know how to describe the events in any other way. However, this group are in a minority, as these data indicate that 36% of the R-coded students respond differently after the first survey.

Student 223 exemplifies the R-P shift at this stage. Her written responses were:-

> "The chlorine and sodium atoms are rushing violently to get to each other to release or gain electrons and bond with each other to produce sodium chloride. The reaction is faster has [sic] it is heated so the atoms move faster, violently." (R1, 1st survey)

"Na is reacting with the Cl_2 forming bonds releasing a lot of energy which keeps the reaction going on vigorously." (P1, 2nd survey)

Her first response is close to being coded P3, except that it does not make clear which atom gains and which loses an electron. Also, she suggests that the reaction is violent because the sodium is heated. At the second survey, her answer is based on the understanding that the energy for the reaction comes from bond formation. This student explained her new ideas at interview:-

I: Right, but here you say it's forming bonds, releasing a lot of energy which keeps the reaction going on vigorously.

S: Yeah, then I was probably more thinking about how exothermic the reaction's going to be to form, like the lattice thing, I probably knew then that it's probably very exothermic, so you're going to produce more energy so you're going to - so that one batch of energy that you produce you're going to break more of the molecules, so the whole thing's going to be over quicker, as opposed to the heating.

I: So there you're thinking it's the energetics, rather than the fact that it is hot?

S: Yes, yes.

I: OK. Right, so have you learned about that sort of thing in the course, this idea of not confusing kinetics with thermodynamics?

S: Yes, I should think I have, it probably hasn't dawned on me that that's what been happening, but yeah, I've been looking at it at a different way, because then I knew why things give out energy and why things are hotter, while here all I've been taught was that when things are hot they are fast. I was probably thinking of rate of reactions - you heat something up and it goes faster.

This student has recalled that energy is released when an ionic lattice forms and has also connected the amount of energy with the vigour of the reaction.

The P-code increase between second and third surveys is not due to a shift from R to P. About 7% change from R to P at the third survey but these are counter-balanced by 8% who move from P to R. The additional P-coded answers at the third survey are contributed by 6% who answer S or U at the second survey, some of these changing to P1. This suggests that the change at the first stage is due to students who already have some understanding of events taking place in the gas jar moving towards a more detailed idea expressed in either bonding or energetics terms, while the later increase comes from students who expressed a misconception or who could not answer the question in earlier surveys.

At both stages some students change from P to R or S. About 7% give P coded answers at the first survey and change to R at the second, while 2.4% move to S. Between second and third surveys, the same proportion, 7%, change from P to R (as mentioned above) and three students, 1.2%, move to the S category. Student 278 illustrates one reason for this movement away from the correct answer although his responses changed from R to S between first and second surveys. His written responses were:-

> "There is a displacement reaction occurring where the sodium is reacting with the chlorine." (R1, 1st survey)
>
> "[Drawing of Na and Cl forming a covalent bond] Cl needs one more electron to fill its outer shell and Na has that electron." (S2, 2nd survey)

This student was asked to explain this transition at interview:-

> I: So here you said this was a displacement reaction - I was wondering what you meant by that.
>
> S: [pauses]
>
> I: And I was wondering where you'd learned about this idea of electron transfer? Whether it means you still agree with that?
>
> S: [laughs, pauses] Oh, it was a violent reaction and I thought - a redox reaction, so it's quite violent, especially when you got - it needs only one electron to get a full shell and one that has got one electron to do it. So, yeah, I think I still do agree with it.
>
> I: OK. What sort of bond have you drawn here?
>
> S: [pauses] I don't really know!
>
> I: Is it covalent, or ionic or?
>
> S: Covalent.
>
> I: So here - the idea of a displacement reaction, what's being displaced by what?
>
> S: I think I could remember - we didn't do many reactions at my old school, but we named a few as acid-base, displacement, so I think it was just a good guess - or not a good guess!
>
> I: OK. So for you that was a sort of label - the best label you could put on that reaction?
>
> S: Yes.

He was quite clear that the bond between sodium and chlorine is covalent rather than ionic. He also used this idea to explain his response to the *Solution* question, in which he had drawn a molecule of sodium chloride, with appropriate dipole moments, surrounded by water molecules. For this student, sodium chloride formed as discrete molecules. The slight increase in S-coded answers at the second survey may arise because students confuse the bond types learned in the early units of the course.

A second reason for the move away from the P-coded answers may be that some students give the response "An electron transfers from sodium to chlorine" at the second survey, following the recent teaching on ionic bonding. By the third survey, this material is no longer immediate, so students give the R1 response "sodium and chlorine are reacting", because the detail has been "forgotten".

This question attracts a very low proportion of S and T-coded answers. The most significant are those associated with the confusion between energetics and kinetics (S1) and the formation of covalent bonds (S2). These low levels imply that the reaction between sodium and chlorine is relatively well-known and unproblematic for students. Alternatively, these data may indicate that students' ideas about ionic bonds need to be probed more explicitly than *Sodium and Chlorine* permits, as the question is phrased such that "a reaction is occurring" may seem to students to be a completely adequate response. Nevertheless, these data indicate that only about 13% of students associate the formation of an ionic bond with the release of energy.

5.8.3 Intermolecular bonding

Hydrogen bonds are first mentioned in SAC Unit 2, *Developing Fuels*, to explain the relatively high boiling points of alcohols:-

> "Hydrogen bonds are not as strong as covalent bonds, but are stronger than other attractive forces between covalent molecules. These forces must be broken when a liquid boils and the molecules escape from the liquid to form a gas." (Chemical Ideas, p 64)

The chemical ideas section of unit 5 (p 58 - 65), *The Polymer Revolution*, explains how intermolecular forces arise due to electronegativity differences. Students are then introduced to dipole-dipole interactions and hydrogen bonding using hydrogen fluoride and water as examples. The existence of hydrogen bonding is revisited in unit 13, *The Oceans*, where the variation in boiling points of hydrides is discussed. The anomalous behaviour of water is explained:-

> The hydrogen bonding in water is particularly strong because there are two lone pairs of electrons... so intermolecular interactions are maximised. Water molecules are close together in the liquid, but they become widely separated in the vapour. For this to happen, the strong intermolecular hydrogen bonding has to be overcome.." (Unit 13, Chemical Ideas, p 48 - 49)

This introduces students to enthalpy of vapourisation and specific heat capacity.

Understanding of intermolecular forces is assumed throughout units 8 - 13 and is used to explain the structure and properties of different substances, for example, silicon dioxide and carbon dioxide in *Aspects of Agriculture* :-

"..silica, SiO_2, has strong covalent bonds linking every atoms to several others in a giant structure that goes on indefinitely. This makes the atoms hard to separate: silica is hard and very difficult to melt. On the other hand, carbon dioxide has strong covalent bonds between C and O atoms - so it doesn't decompose into carbon and oxygen. But it has only weak intermolecular bonds between each CO_2 molecule. This makes the molecules easy to separate, so CO_2 has a low melting and boiling point and is a gas at room temperature." (Unit 12, Chemical Ideas p 32 - 33)

From this, students learn that weak intermolecular forces cause substances to have low melting and boiling points.

Hydrogen bonds

This question shows a very large increase in the proportion of P-coded responses by the third survey. The changes are significant at the 0.01 level. The increase arises from students moving to P from all three other categories: about 24% move to P from U, 8.4% from T and 17.2% from Q. Only 3.2% change from P to another category.

RC	Description	1st %	2nd %	3rd %
P1	Hydrogen bond + explanation	6.0	34.8	40.4
P2	H-bond only - no explanation	4.0	23.6	28.0
P3	Intermolecular bond / polar attraction	7.6	6.0	0.4
P	**Total**	**17.6**	**64.4**	**68.8**
Q1	"Liquid" bond + explanation	9.2	0.4	-
Q2	Weak bond between molecules + explanation	11.2	0.8	0.4
Q3	van der Waals' / dipole-dipole bond	1.6	3.2	1.6
Q4	Cohesion / magnetic attrctn / semi-perm bond / attractn	4.4	1.2	0.4
Q	**Total**	**26.4**	**5.6**	**2.4**
T1a	Line 3 is an attraction force not a bond / not a real bond	7.2	19.2	24.0
T1b	Doesn't exist / is imaginary / temporary / repelling force	1.2	0.8	-
T1	***Total***	***8.4***	***20.0***	***24.0***
T2	Triple / cvlnt / ionic / dative / delocalis'd / dble / 1.5 bond	6.0	2.8	2.0
T2	***Total***	***6.0***	***2.8***	***2.0***
T3a	Shows water moves around / is in suspension	2.0	0.4	-
T3b	Shows water is rigid / is stronger than a covalent bond	-	1.6	0.8
T3	***Total***	***2.0***	***2.0***	***0.8***
T	**Total**	**16.4**	**24.8**	**26.8**
U1	Uncodeable	7.2	1.6	0.4
U2	No response / Don't know	32.4	3.6	1.6
U	**Total**	**39.6**	**5.2**	**2.0**
	Overall total	**100.0**	**100.0**	**100.0**

n = 250

Table 5.18: Changes in SAC students' responses to *Hydrogen bonds*

These data suggest that most students learn about hydrogen bonds in the first few months of their course as indicated above from the course material.

The large number of U codes in the first survey is greatly reduced at the second and remains low at the third. In fact, all 39.6% of those giving U-coded answers at the first survey changed their answer at the second, most, 24.4%, to a P-coded response. About 10% of this U-group offer a T-coded answer while the remainder change to the Q category. This confirms the view stated in the previous chapter that these students had not seen this type of bonding before, but could respond correctly after teaching.

About 29% coded P at the second survey repeat their response on the third occasion, indicating that these students retain their understanding about hydrogen bonds. However, about 16% who are coded P at the second survey change their answer to T1a at the third survey, while a further 16% change from T to P. Therefore, the proportion coded P in the second and third surveys differ considerably due to those moving between the correct answer and the idea that "a hydrogen bond is an attraction not a bond " (T1a). Student 344 gives this response at the third survey. Her written responses were:-

> "The weak bond between molecules which signifies liquid or solid substances." (Q2, 1st survey)
>
> "Hydrogen bonding. A small ionic force. Line 1 is covalent, line 3 is a bit ionic." (P2, 2nd survey)
>
> "A hydrogen bond. Line 3 is an attraction, not a bond." (T1a, 3rd survey)

This student was invited to explain her first and second answers in an interview:-

> I: Right. OK. So you said somewhere - here you said this one was a bond, and here you said this one was a force. Is there a difference between a bond and a force?
>
> S: One is more stable. A force is weaker.
>
> I: Right. So why have you used a bond there and a force here when you're talking about the same bond?
>
> S: Yes. Well, I haven't done that sort of bonding, I don't think.
>
> I: Right, so you hadn't seen those before? You're quite right, it does make something a liquid, that's a good guess. Here you knew a bit more didn't you, about what a hydrogen bond was. OK. Can you - you said here, this bond, the covalent bond and 3 is a bit ionic. Do you know if covalent bonds can be a bit ionic?
>
> S: Yes, it's true, yes.
>
> I: So what do you mean here when you say this - there's a difference between a covalent bond and a hydrogen bond?
>
> S: Well I think I meant that it's not really a bond, it's a bit ionic but it does attract each other but it's not really a bond.

I: Right. So you have an idea in your mind of what a bond is. What is your idea about what a bond is then?

S: When, they're joined together and wouldn't want to come apart unless there was some chemical reaction or other.

I: OK. So these bonds here [hydrogen bonds] you don't think of as bonds - is that because they can come apart more easily?

S: Yes.

We see in this extract the prelude to her third survey response, which was coded T1a. At this stage, she expresses her idea about hydrogen bond using the term "force", and is clear that a hydrogen bond "isn't really a bond". The last part of the interview indicates that this distinction is important to the student as it assists her in explaining differences in bond strength, described here as "coming apart". By the third survey, the word "force" is replaced by "attraction" in her written response. This student appears to have learned that hydrogen "bonds" cannot be considered to be "bonds" in the same sense as covalent and ionic bonds and that they are really just "attractions". The student does not appreciate that hydrogen bonds are another example of electrostatic attractions which characterise all bond types.

The increase in T1a responses is significant. The words "attractive force" are used on one of the occasions in SAC where hydrogen bonding is introduced (see above), but the course does not emphasise this terminology. Students seem to acquire the idea through classroom activity rather than working through the unit materials, as student 349 illustrates. At the first survey, this student did not offer a response, but at the second he gave this answer to the last part of the question:-

"Line 1 is covalent and involves share of electrons (very strong compared to line 3) whereas line 3 is attractions between bond, doesn't involved [sic] sharing of electrons."

He was asked about this response at interview:-

I: ...How do you know a hydrogen bond doesn't involve sharing of electrons?

S: Because we were told!

I: OK. So there is a difference in your mind between a covalent bond and a hydrogen bond, then?

S: Yes. A hydrogen bond is like attractions between charges, different charges.

I: Right. So, if we draw a water molecule-

S: They're like magnets.

The indication here is that his teacher told him that electrons are not shared, and that the hydrogen bond is an "attraction". The prevalence of this answer (offered by 24% at the third survey) suggests that students do not complete SAC with a clear idea that all types of bonding involve "attractions", and that it is only the relative strengths and type of particles involved which vary.

However, responses to *Hydrogen bonds* demonstrate that a majority of A level students can identify and describe hydrogen bonds at the end of their course. Student 331 is typical of this large group. She gave these answers in the first and second surveys:-

> "Ionic bond as element[sic] like to have 8 electrons in outer ring." (T3, 1st survey)
>
> "There are hydrogen bonds when the H atom is slightly +ve (∂^+) and O ∂^-. The +ve -ve charges attract one another and make intermolecular bonds." (P1, 2nd survey)

This significant change had a great impact on the student, who described this at interview:-

> S: Yes this is the sort of thing I don't think in my whole life I'll ever forget after doing A level chemistry, because you can't help knowing so much about bonds, whether it's right here or not I don't know, but - [pause] You see this is the pure fact, this is something like we obviously learnt about covalent bonds when we were, I mean, like ionic bond, but we didn't learn about interstructural bonds like H-bonds, and dipole-dipole and things like that, we just didn't learn about them at GCSE. So, it seems really strange that I wouldn't have known about that...

Hydrogen bonds have become so much a part of her chemical knowledge that she cannot imagine what life was like before knowing about them!

Boiling

Students' ideas about the bubbles from boiling water are probed in this question. Table 5.19 shows an 18% increase in the proportion of P-codes and a decrease in T-codes of about 12% across the three surveys. This improvement is significant at the 0.01 level. The number of Q codes decreases slightly between first and second surveys, but is unchanged at the third survey.

RC	Description	1st %	2nd %	3rd %
P1	Steam, water vapour, gaseous water	27.6	39.2	45.6
P	Total	27.6	39.2	45.6
Q1a	Oxygen	25.6	20.0	18.4
Q1b	Dissolved or evaporating gas	2.0	2.0	2.0
Q1c	Air	7.2	8.4	10.0
Q	Total	34.8	30.4	30.4
T1	Heat, energy	0.4	-	0.4
T1	***Total***	***0.4***	-	***0.4***
T2a	Hydrogen	6.4	8.0	7.6
T2b	Oxygen and hydrogen	19.6	13.6	8.4
T2c	Oxygen or hydrogen	2.8	2.0	2.4
T2	***Total***	***28.8***	***23.6***	***18.4***
T3a	Carbon dioxide	2.8	1.2	1.6
T3b	Gas	2.8	2.8	1.2
T3	***Total***	***5.6***	***4.0***	***2.8***
T4	Nothing / Vacuum	-	0.4	0.4
T4	***Total***	-	***0.4***	***0.4***
T	Total	34.8	28.0	22.0
U1	Uncodeable	0.8	0.4	0.8
U2	No response	2.0	2.0	1.2
U	Total	2.8	2.4	2.0
	Overall total	100.0	100.0	100.0

n = 250

Table 5.19: Changes in SAC students' responses to *Boiling*

About 20% give P coded answers on all three occasions. These students' ideas about the contents of bubbles in boiling water were unchanged. Around 32% of the sample included in the P codes at the second survey were also coded P at the third survey, suggesting that once the idea was learned, this thinking is retained. Student 344 exemplifies this. She gave these written answers in the first and second surveys:-

> "Air that has been expanded by the heat and hot air rises." (Q1c, 1st survey)
>
> "Gaseous H_2O" (P1, 2nd survey)

At first, when interviewed about these responses, this student read her answers as being the same, although later she explained that air was dissolved in water:-

> I: So this is just asking about what's in the bubbles when water boils.
>
> S: Um, well, yeah, basically I put the same thing really, I just expressed it differently. I've known what it was for quite a while.
>
> I: It's just that you've said there that it's air and here you said gaseous water.

S: Yeah.

I: Did you think it was water as a gas before?

S: Yeah. I thought it was just like gas, you know. But I've obviously, sort of like, put it more specifically in the second one.

I: So do you still think air is there as well?

S: Yes. Well, it's dissolved in the water.

I: So you can't think of any difference, you've not really learned anything different?

S: No.

At the third survey, this student gave the answer "water vapour". However, her interview does suggest that for some students the answers "air" and "water vapour" are interchangeable. If so, this may help to explain why the level of change in the P direction is approximately equal at both stages - without any specific teaching, students gradually move towards the correct answer without realising their original error. Most of the additional P coded answers at the second survey were contributed by about 12% of respondents who changed from the T category. Only about 4% changed Q from to P at this stage. At the third survey, we find that about 7% of Q and 5% of the T coded respondents change to P.

About 16% of respondents give Q-coded answers on three occasions, suggesting that for these students the response that dissolved oxygen or air is in the bubbles is an adequate answer. They have learned no alternative material which persuades them to answer differently.

The proportion of T codes decreases, but at the third survey 22% still give a T-coded answer. The responses of most of these students indicate they think that the water splits up into hydrogen and/or oxygen. However, only about 9% give three T-coded answers, while only 6% are coded T2 for all three surveys. This implies that students give T-coded answers for some reason at either the second or third survey having responded correctly or with a Q-coded answer at other times. Student 321 gives an example of this. Her written answers at the first and second surveys were:-

"Oxygen" (Q1a, 1st survey)

"Water vapour (hydrogen + oxygen)" (T2b, 2nd survey)

At interview, she realised the errors she had made in both these answers:-

I: ...I'm just wondering where you thought this oxygen might have come from.

S: I don't know cos thinking about it now, if it carried on like that you'd only have hydrogen left! [laughs] I don't know. I think I looked at that and thought, you know, water turns into steam, so there's bubbles coming out must have been the water vapour.

I: Right, so why did you go on to put hydrogen and oxygen, then?

S: Um, I don't know! No, I couldn't tell you! Cos that implies like two separate gases.

I: Yes it does.

S: Which I wasn't really about!

I: OK. So that's not what you were thinking? You were thinking it was water vapour?

S: Yes.

I: Is it true that some of it could be oxygen anyway?

S: I don't know!

I: It's just that people say that oxygen is dissolved in water.

S: Oh yes.

I: I was wondering if you were thinking of that?

S: I hadn't thought of it like that!

I: So have you learned anything about water evaporating, or state changes generally?

S: No. It's all a bit vague, I find the Salters' course, I never can remember any set topic or anything, it's just - all goes along as one, and separate ideas keep coming back and eventually it might make sense!

I: So do you feel it hasn't made sense for you at the moment, then?

S: The first year didn't, but it's starting to do now.

This interview suggests that students may have given a Q or T-coded answer without thinking, even though they do know that the bubbles contain water vapour. The extent to which this kind of "mistake" has been made cannot be estimated without interviewing every student responding in this way, although about 10% change from Q to T at the second survey and a further 4% change at the third survey. However, student 388 illustrates the opposite - that some students give an answer which appears to indicate understanding, but in reality they hold a misconception. This student gave these two responses:-

"Hydrogen & oxygen gas." (T2b, 1st survey)

"AIR (Atmospheric, dissolved in the water)" (Q1c, 2nd survey)

At interview he was asked to explain this change:-

> I: The first time you said that when water boils you get hydrogen and oxygen and the next time you said it was air which has been dissolved in the water.
>
> S: That's better, isn't it?
>
> I: It is better, yes!
>
> S: Um, well, hydrogen and the oxygen, that's the steam that's coming off which is as hydrogen and oxygen rather than the bubbles. And when something's heated, it's not so easy for a substance to dissolve, the amount of solubility potential, or something like that, is not so great, so obviously air is coming off, because not so much can dissolve in the water because it's hotter.
>
> I: So you don't think water does split up like that then when it boils? [The interviewer did not hear clearly the first part of the student's previous statement]
>
> S: No.
>
> I: OK. So besides air, once you've boiled off all the air that was in it, what will the bubbles be then?
>
> S: [pauses] I don't know! Hydrogen!
>
> I: What happens when something boils?
>
> S: It changes from a liquid to a gas.
>
> I: Right. So what will the bubbles be?
>
> S: Water?

This extract indicates that the student has learned something about the solubility of gases in water and uses this in his second response. In saying, "That's better", he may mean that his second answer is "more scientific" - he certainly uses scientific-sounding words in his explanation. In the course of his explanation, he makes clear his idea that water splits into hydrogen and oxygen on boiling, and is surprised when he is led to the correct idea at the end of the extract. Therefore, there appears to be an equal chance that students giving Q-coded responses may know that the bubbles contain water vapour or that they think water splits up on boiling.

The above response is also significant because it implies that some students operate a faulty model of the liquid-gas state change. This model suggests that oxygen (or air) can be dissolved in water, but this co-exists with the notion that water molecules break up on evaporation. Student 388 describes the hydrogen / oxygen mixture as "steam". This type of response is found in answers to *Chlorides*, discussed next.

The changes seen here are less extensive for this question than those observed in others, for example, *Hydrogen bonds*. This is perhaps because the effect of intermolecular bonding on boiling points is taught in units 12 and 13, as described earlier (see beginning of this section), so students ideas about this may not have been affected directly by any input at the time the three surveys were carried out.

Chlorides

Table 5.20 shows a large increase in the proportion of P-coded responses, although the final level is low compared to most other questions in the study. The changes are significant at the 0.01 level when changes in the proportions offering P and Q codes are considered. Besides this improvement, the question also generates an increase in the number of T codes from first to second survey, and slight drop at the third survey, suggesting that students answer *Chlorides* using incorrect ideas rather than correct ones. We will explore reasons for this.

RC	Description	1st %	2nd %	3rd %
P1	Intermolecular bonds between $TiCl_4$ molecules break	0.8	4.4	13.2
P2	Intermolecular bonds in ionic solids are stronger	0.4	3.6	3.2
P	**Total**	**1.2**	**8.0**	**16.4**
Q1	Covalent subs have lower b. p.'s / more heat req'd	21.2	14.0	13.6
Q2	$MgCl_2$ only melts / lattice needs to break down	0.8	2.0	4.0
Q	**Total**	**22.0**	**16.0**	**17.6**
T1	Ionic bonds can't be broken by heating	12.8	18.8	14.8
T2	$MgCl_2$ ionises / is less reactive / already vapourised	1.6	2.8	1.6
T3	Covalent bonds weaker than ionic ones, so break	24.0	28.4	30.8
T4	Covalent bonds are stronger than ionic ones	5.6	8.4	7.6
T	**Total**	**44.0**	**58.4**	**54.8**
U1	Uncodeable	12.4	8.8	4.4
U2	No response	20.4	8.8	6.8
U	**Total**	**32.8**	**17.6**	**11.2**
	Overall total	**100.0**	**100.0**	**100.0**

n = 250

Table 5.20: Changes in SAC students' responses to *Chlorides*

Few students relative to other questions change to a P code at the second or third surveys. About 4% change from T to P and only 1.6% from Q to P at the second survey, while only 5.6% and 2.4% change from these categories at the third survey. One student whose thinking did change between first and second survey was number 223. Her written responses were:-

"Because ionic bonding is stronger than covalent bonding so it will take more heat energy to break the ionic bonds while the covalent bond will break causing the vapour." (T1, 1st survey)

"$MgCl_2$ has a much higher boiling point because ionic bonding is stronger as the ions bond in a continuous lattice making the whole structure strong while in covalent compounds the atoms are held together by strong covalent bonds in molecules, To boil the compound the molecules have to be separated which means only the weaker intermolecular bonds need to be broken (covalent bonds are not broken)" (P1, 2nd survey)

At interview, this student could recall precisely why she gave her first answer and explained what had caused the change:-

S: ...it's the um, attractions between the molecules. I probably was thinking that then [covalent bonds break], but wasn't thinking that then [2nd time] because yeah, I'll have thought - yeah, because again at GCSE, all we did for this, I remember doing this is class, all we did was a table, and it just said, simply, covalent, ionic, strength of bond, and boiling point, so I immediately related covalent bonding with the boiling points when I should have related the bonding between molecules. I don't think we'd done intermolecular bonding, actually, there, but we've definitely done it there, it's definitely the bonding between the molecules, so here [1st survey] I probably will have been thinking that, and again, just by rote, thinking back what have I learnt as GCSE, right, so that's that. But here, it'll have been because you're breaking, in the ionic lattice, you're actually breaking the bonds between the two atoms, but in the covalent one you're breaking the much weaker bonds between the molecules, you're not actually touching the covalent bonds, so the vapour is going to be - I probably thought here that you broke up the titanium into that, and then it reforms in the vapour form, so it reacts again.

I: I see, so in fact your vapour is still $TiCl_4$, molecules, but in order to get that vapour you first have to split the molecules -

S: Split it then form it again.

This interview reveals two interesting points. First, prevalence of the T-coded answers, at least, those in the first survey, can be attributed to ideas learned at GCSE. Inadvertently, students have learned that because covalent compounds have much lower boiling points than ionic ones, covalent bonds break when substances boil. Second, this student confirms the model of evaporation suggested in some answers to *Boiling*, namely, that molecules break up when they become gas, but reform again. The breaking up is an essential part of the state change. Before discussing further data, we will examine the responses of another student who was asked to explain his answers at interview. Student 278 gave these written answers:-

"Because magnesium chloride needs a higher temperature to become a gas but titanium(IV) chl. does not." (Q1, 1st survey)

"The bonding between $MgCl_2$ molecules is stronger than the bonding between ($TiCl_4$)." (P2, 2nd survey)

At interview he was asked about these responses:-

> I: You're right ionic solids would need a higher temperature to boil than covalent ones.
>
> S: [pauses] Well, here I knew about - I explained what happened, and here that's an explanation of what happened, cos we'd done between intermolecual - you know, between the molecules, the attractions.
>
> I: Right, so you're saying that intermolecular attractions between these are weaker than those, than - the ones in the ionic solid are stronger. So when you think of an ionic solid are you thinking of it as lots of $MgCl_2$'s stuck together, or do you have some other idea about what an ionic solid looks like?
>
> S: Well I think when I did this, to be honest I did think it was like that, but it's more - now I've cleared that up. That was quite a weak point.
>
> I: OK. So what are you thinking now?
>
> S: That it's a lattice. It's a cloud of electrons.

At the time of the second survey, this student admits he thought of the ionic chloride as being composed of discrete molecules, but had since changed his thinking. However, this idea satisfies the model of evaporation proposed earlier, since the ionic bonds are between the "atoms" of magnesium and chlorine and therefore would be broken, in the same way covalent bonds are broken, when the substance boils. The difficulty for students, therefore, is moving away from this "atomistic" model towards realising that intermolecular forces are responsible for the low boiling points of covalent molecules. An additional problem for students is that ionic solids exist as lattices of many ions held by strong electrostatic attractions and so there are no "intermolecular forces" of the van der Waals' or hydrogen bonding type present to make a fair comparison with covalent substances.

As the following data will indicate, it is possible that a significant proportion of students may complete A level with this faulty model. Most of the increase in the T-coded responses at the second survey is contributed by 11.6% of students who gave a Q coded answer in the first survey. These students seem to have been uncertain about the answer and the new material about bonding studied between surveys has caused a shift to the T category rather than a move to the P category. The persuasive nature of the T-coded responses is demonstrated by the proportion retaining T-coded answers. Almost 19% give T-coded answers at all three surveys. About 28% are coded T for both first and second surveys. Around 38% give T-coded answers at the second and third surveys. These data imply that students learn that "covalent bonds are weaker than ionic bonds" rather than "covalent bonds are stronger than intermolecular forces". The first statement may arise from the early teaching about bonding, while the contrast between intermolecular and general intramolecular bond strength is left until towards the end of the course (for example, the extract from *Aspects of Agriculture* given above at the beginning of this section). Most students may not have studied this final unit see Appendix 5) and indeed this is reflected in their answers.

However, students may find this question difficult to answer correctly because intermolecular bonds are not mentioned, whereas the types of intramolecular bonds are named. Therefore respondents are "cued" to respond in terms of covalent and ionic bonds rather than intermolecular bonds. A further difficulty which may contribute to the high level of incorrect answers is that many may not have heard of titaniumIV chloride, and so are not led to think about intermolecular bonds being responsible for the variation in boiling points in the way that they might if water or ammonia were included. The context is therefore unfamiliar, so students try to respond using any information which is recognisable, namely the bond types, rather than think about the question any more deeply.

The changes in responses to the three questions about intermolecular bonds show considerable variation. Responses to *Hydrogen bond* suggest that this idea is well learned, such that a majority can recognise a hydrogen bond and explain how it is formed. However, only about half of the students can apply this knowledge to even the most simple example, that of water boiling. Further, very few students know about the effects of any other intermolecular bonds than hydrogen bonds, so most are unable to answer *Chlorides* correctly. Thus, there appears to be a contradiction in students' minds. They know on the one hand that hydrogen bonds are responsible for high boiling points, but on the other think that covalent bonds break when water boils. These two ideas may not be contradictory - students may reason that hydrogen bonds cause water to have a higher boiling point than other compounds of similar molecular mass, but also that all molecules break up to constituent atoms on boiling in any case. However, many students' ideas about changes in state appear not to be modified during an A level course.

5.9 Thermodynamics

Students' developing ideas about basic thermodynamics were probed using the questions *Methane* and *Energy change.*

5.9.1 Methane

Ideas about energy changes feature early on in SAC. Unit 2, *Developing Fuels* begins by stating:-

> "We think of fuels as energy sources but, of course, they can't release any energy until they have combined with oxygen. So really we should think of fuel-oxygen systems as energy sources. As you can see in Chemical Ideas F2, the energy released when substances burn comes from the making of bonds with oxygen." (Story, p 3)

This is supported by an accompanying assignment. In the Chemical Ideas section (p 46 - 50) where students consider the question "Where does the energy come from?" and learn about bond energies. Burning methane is used as an example:-

> "When you use a match to ignite a fuel, you are supplying the activation energy that is needed to break bonds so new bonds can begin to form... Once one or two bonds have broken, new bonds can start to form and this usually gives out enough energy to keep the reaction going." (p 48)

This is followed by an energy profile for the combustion of methane similar to that used in the test paper.

Ideas about energy changes are developed in unit 3, *From Minerals to Elements,* where enthalpy of solution and lattice energies are introduced. In unit 4, *The Atmosphere,* students learn about bond breaking in the context of formation of free radicals. In unit 7, *Using Sunlight,* students are asked to compare the amounts of energy released by burning hydrogen and petrol by calculation using standard enthalpies of combustion. So, students have several opportunities to learn about enthalpy changes during the course.

Table 5.21 shows that almost half of the sample give P-coded answers by the third survey, and that most of these give the response coded P1. This is a significant increase from the first survey, when 82% were coded T. These changes are significant at the 0.01 level.

RC	Description	1st %	2nd %	3rd %
P1	Energy is from bond formation	5.6	43.6	46.4
P2	Products are more stable than reactants	0.4	1.6	3.2
	Part a: E_A supplied / E splits molecules			
	Part b: rxn is exothermic / chain rxn / O_2 is unlimited			
P	Total	6.0	45.2	49.6
Q1	Answers as above to a and b only or to part c: Energy is from bond making and breaking	4.0	8.4	9.2
Q	Total	4.0	8.4	9.2
T1a	Energy is from bonds in CH_4	-	1.2	1.6
T1b	Energy is from bond breaking | E splits molecules	4.0	6.8	4.4
T1c	Energy is stored in CH_4	12.8	16.0	18.8
	Part a: as above (P) / E speeds up reaction			
	Part b: as above (P) / CH_4 releases energy / xs E is used			
T1	*Total*	*16.8*	*24.0*	*24.8*
T2	CH_4 is E store made from animals/sun	6.4	1.2	0.8
	Part a: heat required / flammable H_2 present			
	Part b: CH_4 is fuel / flammable / O_2 available			
T3	Energy is from CH_4 | Need O_2, fuel & heat | Fire Δ kept going	5.6	0.8	0.4
T4a	From burning CH_4 | CH_4 always burns in air / until it runs out	14.4	5.2	1.6
T4b	Heat energy from burning	4.8	2.8	2.4
T4c	Heat is given out / from the flame	6.8	1.2	1.2
	Part a: as above (P) / Heat required			
	Part b: as above (P) / Heat of burning / flame keeps rxn going			
T4	*Total*	*26.0*	*9.2*	*5.2*
T5	From exo rxn | O_2 needs spark | gas has 2 flammable elements in it / is a hydrocarbon	8.4	2.0	2.4
T6	Only 1 part answered	18..8	7.2	6.8
T	Total	82.0	45.6	40.4
U1	Uncodeable for all three parts	2.0	-	-
U2	No response	6.0	0.8	0.8
U	Uncodeable	8.0	0.8	0.8
	Overall total	100.0	100.0	100.0

n = 250

Key: The symbol / denotes "or"; that is, alternative answers which are equally acceptable.
The notation (P) means that responses were identical to those coded P.

Table 5.21: Changes in SAC students' responses to *Methane*

Student 223 illustrates the change made from T to P code in this interview extract:-

I: Where does the energy come from to keep the reaction going?

S: From the bonds that have been formed, so like you break a few bonds, they form other products, they give out more energy, break a few more bonds and that keeps on going.

I: Now, in the last bit you said energy is "stored". And you're quite clear about that because you tell me that it's those bonds that are broken which give out energy, and here you say that it's energy released when -

S: [Interrupts] Yeah I knew - I came to this college not understanding this completely, because I didn't understand how energy was given out. For some reason I though if you broke the bonds you'd give out energy, which wasn't true, because it confused me at GCSE...because everyone said "Energy was stored in bonds", so I thought if you break it you release energy, but you haven't at all.

I: Right, but have you learned this on the course, then, somewhere, these ideas?

S: Yes, definitely those ideas, yeah!

This student pin-pointed *Developing Fuels* (unit 2) as the source of her new ideas about energy in reactions. She could articulate her change in thinking and was quite clear her new knowledge provided a much better answer than her previous ideas. Between first and second surveys, 35% changed from T to P, suggesting that the early SAC units are effective in teaching ideas which students apply in answering this question. A further 12% change from T to P between second and third surveys. Also, most students who give a P-coded response repeat this answer in later surveys; 4.8% give two P answers at the first and second surveys, with 32.4% doing so at second and third. This indicates that many students retain the knowledge learned between surveys.

While these data are encouraging, almost 27% give T-coded responses on all three occasions, so this group have not learned anything new to make their answers change. The tenacity of the T-type responses is also illustrated by the numbers who give two T-coded answers. About 39% are coded T for both first and second surveys, while 30% gain two T codes for the second and third surveys. Student 208 illustrates one difficulty which may contribute to this high proportion of T-codes. In this interview extract we find him arguing that bond breaking both requires and releases energy:-

I: So here, how can energy be put in to break bonds, and yet you say energy comes from breaking bonds?

S: [Pause] How do you - [dries up]?

I: Well, here, it seems to me that what you're saying is that activation energy means you've got to put energy in to break bonds.

S: Mm.

I: If you've got to put energy in to break bonds, how can you also say that energy comes from broken bonds?

S: Er, um, when you put something into it, it breaks the bonds releasing energy, and that energy that's been released breaks bonds next and continues the reaction, that's what I would say.

This student is confused about where the energy comes from in a reaction. His model is that energy is needed to break bonds initially, but once broken, energy is released. This causes him problems when he is asked to explain what happens when bonds form:-

I: So what does this diagram suggest happens when bonds form?

S: You - lose energy.

I: You lose energy from where to where?

S: The reaction takes energy to make bonds, so it can make bonds easier with oxygen rather than with hydrogen possibly?

I: Could be. Hang on. If those are the products of the reaction, that's what you get when you burn this. Now, let's just think about that. You said [earlier] the overall reaction was exothermic, so if bonds are forming when you go down from there to there, what does that tell you about bonds forming?

S: Takes energy up. Uses energy.

I: Uses energy. But what does exothermic mean?

S: Um, giving out energy.

I: Right. So it can't be both.

S: No! It's giving out energy, it can't be using energy.

This student knows that burning fuels releases energy to the environment, but because of his faulty model cannot link the exothermic character of the reaction with bond formation. He is asked slightly later,

I: So you still think that when you break bonds you give out energy?

S: Mm.

I: Right.

S: It could be the other way round, of course, but I think it's right, anyway!

He finally acknowledges he may have made an error, but concludes that his thinking is indeed correct. Nothing has changed his reasoning. The difficulty students have is realising that energy comes from bond formation, not bond breaking. This student seemed to be stuck with this faulty model.

This erroneous reasoning seems to begin at GCSE. As student 223 pointed out, they are told "fuels are energy stores". When at A level students are faced with the idea that bonds break in order for a reaction to occur, the most plausible explanation is that energy comes from the bonds and is "released" on breaking, in the way one breaks an egg and releases the contents. They reason that this must be so because fuels are energy stores. These data indicate that a high proportion of students completing A level do not move from this confused model - almost 19% give the response "Energy is stored in methane" (T1c) at the third survey.

5.9.2 Energy change

Table 5.22 shows significant changes in responses to *Energy change* over the three surveys. The proportions responding with P, Q and R codes increase, while those giving S and T coded answers decrease, suggesting that students appear to be moving towards the correct answer and changing their misconceptions. The χ^2value for the change in P-codes confirms this, being significant at the 0.01 level.

We will look first at the P-coded answers. Most of the increase in P-codes occurs between first and second surveys, supporting the finding for *Methane* (above). The majority of new P-coded responses at the second survey come from the Q and R categories, while only five change from S to P. Relatively few students (4.4% and 1.2%) change from T to P at either stage. However, only 4% are coded P for both first and second surveys. This suggests that many of the first P-codes could be guesses. Retention of a P-coded answer is much greater at the next stage, when more than half of those placed in the P category at the second survey are coded P at the third survey. This may indicate that later teaching on energetics in SAC helps to develop further students' ideas about this question, but the lack of explicit teaching prevents any additional major increase.

RC	Description	1st %	2nd %	3rd %
P1	A/ C Low E_A, energy released on bond formation	1.2	4.8	8.0
P2	A/ C Low E_A, exothermic rxn /stable compound forms	10.8	18.4	19.6
P3	A/ C e^-'s lost & gained / low I.E. and high LE	0.4	0.4	0.4
P	Total	12.4	23.6	28.4
Q1	A/ C Energy required to break Cl_2 bond / start rxn	4.4	21.2	14.4
Q2	A/ C Energy required to heat Na / 2 states react	1.2	2.4	0.4
Q3	A/ C Violent rxn / react easily / low E_A required /	-	-	0.4
Q4	A/ C Uncodeable / No explanation	16.0	17.2	18.4
Q	Total	21.6	40.8	33.6
R1	A/ C Na & Cl are reactive	1.6	2.8	2.4
R2	A/ C It is an exothermic reaction	6.8	8.4	8.0
R3	B Energy is conserved in the reaction	0.4	-	-
R	Total	8.8	11.2	10.4
S1a	B/ C Rxn doesn't give out much energy	1.6	1.6	2.4
S1b	B Rxn needs lots of energy to start	4.4	4.0	3.6
S2	B e^- transfer / equation misunderstood	3.2	0.4	1.2
S3	A/ C 2:1 moles reactants / 1 bond broken, 2 formed	5.2	1.2	3.6
S	Total	14.4	7.2	10.8
T1	B Bond breaking gives out energy	-	-	-
T2	B Rxn is in eqm / energy levels are equal / no. of bonds broken = no. of bonds formed	3.2	2.8	0.8
T3a	B Long arrows => lots of energy made / used / rxn is violent / Small gap => low energy input	6.0	2.0	1.2
T3b	A / C A shows high energy barrier / lots of energy required to start rxn	0.8	2.8	4.0
T3c	A / C Bond breaking => energy is given out	-	-	0.4
T3	*Total*	*6.8*	*4.8*	*5.6*
T4	B Uncodeable / No explanation	10.8	3.2	4.8
T	Total	20.8	10.8	11.2
U1	Uncodeable	0.4	0.4	0.4
U2	No response	21.6	6.0	5.6
U	Total	22.0	6.4	6.0
	Overall total	100.0	100.0	100.0

n = 250

Table 5.22: Changes in SAC students' responses to *Energy change*

It is likely that many students, for example, number 278, had not seen this type of diagram before answering *Energy change* for the first time. He changed from an S3-coded answer to P at the second survey and in an interview explained his initial choice of diagram C:-

> S: [pause] Well here I put that because of the equation, 2NaCl. I thought it would be twice as big, or twice as something, I picked that one because there was a ratio of 2:1.
>
> I: Right. I see, because you didn't know what these diagrams meant?

S: No, I hadn't a clue!

I: No. Right. That's what I would have expected.

S: And on this one, it was a violent reaction, and I'd seen the diagrams before and this is a violent reaction giving energy out so the arrow would be going down.

I: Right. So what's the little arrow going up?

S: That was the activation energy.

This student changed his thinking at the second survey because he had learned a meaning for the arrows in the diagram. However, he is not confident about the type of compound formed. The interview continued:-

I: Right. What sort of bonds are made? You said "many bonds are made", what sort of bonds are they?

S: [pauses] Covalent probably.

This response was not uncommon among interviewees. The difficulty this illustrates is discussed below.

The increase in Q coded responses is greater than that for those coded P. Also, Q-coded responses are most frequent at all three surveys. The high percentages of Q codes relative to P, R, S and T arise because many students change to Q at both the second and third surveys. A contributory factor to the high numbers of Q codes is the inclusion of students who select diagram A or C but offer no explanation or an uncodeable answer (Q4). Choosing a diagram alone is the easiest option for students who do not think about the question in depth, so this answer may mean "I don't really have any idea, but graph A (or C) looks sort of right." Student 198 illustrates this in her interview:-

S:..I didn't know how to class this - this reaction, whether it was a large amount of energy or small, or medium.

I: Right, so you just opted for medium?

S: Yes! [laughs]

This approach seems to be used by about the same proportion of students at each survey, although these are different students in each case.

A large increase in Q1 responses occurs between the first and second surveys, and a decrease is observed at the third survey. Between 2.4% and 3.6% of students from each of the categories P, R, S and T change to Q1 at the second survey, while 5.6% move from U. This change is perhaps prompted by SAC unit 2, *Developing Fuels*, which states:-

"All reactions need energy to stretch and break bonds and start them off: this is called the activation energy." (Chemical Ideas, p 48)

Much of the decrease at the next stage is explained by 6.4% who change to P, suggesting that for these students the Q1 response type is a half-way point. Few students change to R, S or T at this stage. However, code T3b shows that an increasing number of students at the third survey think the diagram shows a "high energy barrier", which is incorrect for this reaction.

The persistent popularity of the Q responses compared to those coded P may occur because the fundamental idea probed by *Energy change*, that energy is released on bond formation, is more difficult to grasp than the need for energy to break a bond (code Q1). However, *Methane* showed that about 50% of the sample knew this when methane itself was the context. These data suggest that students do not transfer their knowledge to this situation, where a fuel is not involved. Further, student 278 may associate covalent bonds with this type of diagram, as that is the context in which he learned about them, hence the response reported above.

Relatively few students select diagram B in any survey. In the S category about 7% at the third survey seem to misunderstand the reaction taking place (codes S1 and S2) while a further 4% interpret the diagram in terms of the numbers of moles of reactants (S3). In contrast to *Methane*, few students respond that bond breaking gives out energy. Most students who think that the long arrows represent lots of energy also change their minds (code T3a).

Responses to these thermodynamics questions show that about half of the sample can explain where energy comes from in fuel-oxygen systems, but cannot do so for a simple reaction between two well-known chemical elements. The reaction between sodium and chlorine is not discussed explicitly in SAC in terms of the energy released on combination, whereas the combustion of fuels receives detailed treatment. Students are not, it seems, encouraged to apply the ideas learned in the context of fuels to other reactions. Responses to *Energy change* indicate that students develop ideas about activation energy and know that this is linked to bond breaking.

5.10 Equilibria and Rates of reaction

Basic ideas about equilibria and rates of reaction were probed using one question each; *Reactions* and *Rates of reaction* respectively. Changes in students' responses to these questions are considered in this section.

5.10.1 Reactions

The intention of *Reactions* was to probe the development of students' ideas about equilibrium reactions. SAC features equilibria in several units, beginning in unit 4, *The Atmosphere*. Here, students are introduced to the idea of dynamic equilibrium in the context of chemical reactions in the ozone layer. In the Chemical Ideas section (p 57 - 61) students learn that:

> "When the system is in equilibrium, the molecules enter and leave at the same rate." (p 59)

Several examples are given, including the reaction between carbon dioxide, water, hydrogen carbonate ions and hydrogen ions, which is described as being "reversible" (p 59). Next, students learn how to calculate a simple equilibrium constant for this reaction using a theoretical exercise. Equilibrium constants are met again in unit 12, *Aspects of Agriculture*. Students learn how to calculate K_c and K_p for a range of reactions and examine how concentration and temperature affect these values. The nitrogen/hydrogen reaction is used as an example (p 49 and p 54 - 55). Finally, students meet equilibria in unit 13, *The Oceans*, where they are encouraged to make the link between entropy and equilibrium using the water/ice system as an example. Having considered how SAC approaches equilibrium, we will now look at the data produced for *Reactions*.

RC	Description	1st %	2nd %	3rd %
P1	Reverse rxn is thermodynamically feasible | reverse rxn *not* thermodynamically feasible / large eqm constant for -> arrow	-	0.8	4.8
P	Total	-	0.8	4.8
Q1	Reactants not used up | fully used up	2.0	3.6	10.4
Q2a	1st rxn is reversible | conditions, e.g. energy, needed to go back to reactants	4.8	9.6	11.2
Q2b	Rxn reversible | rxn can't easily turn back / strong bonds / systems are open and closed	7.2	18.8	18.0
Q3	Two answers from Q1, Q2a or Q2b	0.4	-	-
Q	Total	14.4	32.0	39.6
R1	Product stayed gaseous | product changed state	3.2	2.8	1.6
R	Total	3.2	2.8	1.6
S1	N & H are equal quantities | products & reactants are not equal quantities	0.8	0.8	0.8
S	Total	0.8	0.8	0.8

T1	1st rxn is reversible | 2nd / most rxn(s) aren't reversible / go one way	54.4	48.0	39.6
T2a	Relatively low E_A required | high E_A required	-	-	-
T2b	Answer based on rates of reaction	-	0.4	-
T3	1 explanation only / 2 nonsense explanations	12.4	8.8	10.4
T	**Total**	**66.8**	**57.2**	**50.0**
U1	Uncodeable	0.4	0.4	-
U2	No response	14.4	6.0	3.2
U	**Total**	**14.8**	**6.4**	**3.2**
	Overall total	**100.0**	**100.0**	**100.0**

n = 250

Key: The symbol "I" signifies answers to different parts of the question.

Table 5.23: Changes in SAC students' responses to *Reactions*

Table 5.23 shows very little change in the proportion of P codes, while the number offering Q-coded answers increases significantly across the three surveys. The change in the total of Q and P codes is significant at the 0.01 level. Although a decrease in T-coded responses is observed, 50% of the sample give this type of answer at the third survey. Two reasons for this are discussed; first, the question may lead students towards Q-coded answers rather than those coded P; second, the fundamental idea being probed is difficult compared to those of other questions like covalent bonds. These will be considered in detail after further discussion about the data.

At the first survey most students offer T-coded answers based on the simple description that "the first reaction is reversible". At this stage, most do not see there is a need for any other explanation - the first reaction just happens to be one which can "go both ways". This suggests that students put these reactions into a special category for which certain rules apply. About 27% are coded T for all three surveys, indicating that some students did not progress from this idea. The early work on equilibria in unit 4 (described above) may have assisted students in retaining this response, as the label "reversible" is applied to equilibrium reactions. For this group, the label is sufficient in this instance, although it is possible that some of these respondents could offer more information if invited at interview.

Some changes in students ideas are observed. About 20% change from T to Q between the first and second surveys, while only 6% move from Q to T. This implies that a number of students could apply new information in answering the question on the second occasion. Approximately 17% change from Q to T between second and third surveys. As the accounts of SAC teaching on equilibria and energetics show, students will have met ideas about activation energy prior to the second survey.

Although the great majority of students do not answer in terms of the feasibility of reactions, these data show that about 40% (Q total, third survey) develop ideas about stability of products. This is expressed in different ways. For example, student 306 uses the idea of high activation energy in his answer at the second survey. In his interview, he explained:-

> S: It's saying that it goes either way and the other one goes just to water.
>
> I: And here you said it needs a high activation energy and there you said it was stable. So whether its saying the same again and you just put more -
>
> S: Well, it's simpler to say something has a high activation energy, which would make it - but I would not have known about the high activation energy then, I'd have just known it was stable, and there I knew it was stable, but it's because of the high activation energy.
>
> I: Is that because these figures were - had some meaning for you the next time? Or did you still not take that into account?
>
> S: I don't think I ever really looked at the figures, I'd have just looked at the arrows and guessed.

For this student, having a single arrow in the reaction producing water implied stability of the product. He did not use the data in his answer. Other students were able to use the data given to reason a response also in terms of activation energy, for example number 205, who explained:-

> I: So this is about two reactions between hydrogen and nitrogen and hydrogen and oxygen. And you're asked to say why we put an equilibrium arrow there and not here. So the first time you said because it's reversible, the next time you also said it was reversible. Now this time for this one you said that a lot of reactions need energy to convert them back, here you didn't say that. So I'm just wondering where you got the idea about it needing energy from.
>
> S: Right. We learnt it. The activation energy, which I didn't know before.
>
> I: OK. So did the figures mean anything to you at the time then?
>
> S: What at the beginning?
>
> I: Yes.
>
> S: No.
>
> I: But they did -
>
> S: Later on. I didn't understand what this meant, well I mean we'd done at GCSE but I didn't, you know, really know what it was.
>
> I: OK. So do you know where you did this sort of thing about energy?
>
> S: Activation energy?
>
> I: Mm.

> S: Well, we did about equilibrium recently [pauses] - I think it was - it wasn't *Steel story*, it was the one before that. But activation energy we did at the beginning.

This student clearly associates activation energy with the figures, and makes the link between these and the reverse reaction. This is about the best many students could offer. A difficulty in setting this question was whether inclusion of the data would be helpful. A number of students seem to have made use of the information, but it may have led them towards answering in terms of activation energies rather than equilibrium constants. As mentioned previously (*Methane*), activation energy is taught early in unit 2, *Developing Fuels.* Activation energies are compared in unit 4, *The Atmosphere* (Story, p 13), while equilibrium features later in the same unit (Chemical Ideas, p 57 - 61). Thus, students will have met equilibrium constants before answering *Reactions* for the second time, but as these data indicate, they seem hesitant in applying these ideas in answering this question.

These data suggest that most students apply energetics reasoning to answer this question rather than ideas about equilibria. This is perhaps encouraged by inclusion of the enthalpy change data, but also indicates that ideas about activation energy are more readily learned and retained than those about equilibrium constants. SAC does not study equilibrium constants for reactions other than those "labelled" as equilibrium reactions, so inevitably students do not realise the link. They will complete the course having learned about a small number of "special" reactions which fit the contextual applications, rather than knowing that all reactions are equilibrium reactions to some extent.

However, in retrospect, perhaps a more powerful question would have given K_p values for the reactions instead of enthalpy changes. As these data imply, students did not know what the enthalpy values meant at the start of the survey anyway, so would not have been unduly influenced by the inclusion of other equally meaningless data. The effect of SAC on students' ideas about equilibria could perhaps have been more closely estimated.

5.10.2 Reaction rates

Rates of reaction features in three units in SAC. Students are introduced to the idea of reaction rate in Unit 4, *The Atmosphere* (Story, p 12). Under the heading "What determines how quickly reactions happen?", students are told that collisions between particles are necessary:-

> "For a reaction to occur, the two particles must first collide so that they come into contact with each other. This will happen more often if there are more particles in a given volume..."

The section goes on to explain the need for activation energy to be met if collisions are to be successful. The context for this is the reaction between ozone and oxygen or chlorine. This serves as an introduction to reaction kinetics and is not developed in the Chemical Ideas section of this unit.

In unit 8, *Engineering Proteins*, students meet rate of reaction again, this time in the context of enzyme-catalysed reactions:-

> "In a catalysed reaction, reactants need less energy before they can turn into products than they do in an uncatalysed reaction." (Story, p 35)

The discussion leads up to a definition of order of reaction which is developed in the chemical ideas section where the main input on reaction rates is found. Here students learn "How to make a reaction go faster" and write rate equations; they consider order of reaction, half-life, rate-determining steps and learn more about activation energies. Reactions between calcium carbonate and hydrochloric acid, bromide/bromate and propanone/iodine among others are used to illustrate the points being made. Finally, in unit 12, *Aspects of Agriculture*, students return to collision theory and develop the link between reaction rate, temperature and catalysis, using the Haber process as the context.

Given this basis, we will examine how SAC students' responses to the question *Reaction rates* change through the surveys.

RC	Description	1st %	2nd %	3rd %
P1	B/C lqd / lqd phase rxn | solid / liquid, oxide layer	1.2	0.8	2.4
P	Total	1.2	0.8	2.4
Q1	B/C or B/A reactants used up quickly / acid neutralised | slow to start	13.2	12.4	14.4
Q2	B/C or B/A one / no / other explanations	13.2	18.8	16.8
Q	Total	26.4	31.2	31.2
T1	B/C / B/A most reactants used at start | rxn starts vigorously	0.4	1.6	2.4
T1	***Total***	***0.4***	***1.6***	***2.4***
T2a	C/B rxn slow start | Mg reactive / used up	8.4	9.2	8.8
T2b	C/B heat increases rate | any explanation	-	-	0.4
T2c	C/B or B/B no explanations	18.8	13.6	18.0
T2	***Total***	***27.2***	***22.8***	***27.2***
T3	B/B rxn slows as rctnts decrease in concn / SA | ditto	3.6	5.6	5.2
T3	***Total***	***3.6***	***5.6***	***5.2***
T4a	B/-, -/C, A/C with / without expln	8.0	6.8	6.0
T4b	Other combinations with or without explanations	18.0	20.4	14.8
T4	***Total***	***26.0***	***27.2***	***20.8***
T	Total	57.2	57.2	55.6
U1	Uncodeable	-	0.4	-
U2	No response	15.2	10.4	10.8
U	Total	15.2	10.8	10.8
	Overall total	100.0	100.0	100.0

n = 250

Table 5.24: Changes in SAC students' responses to *Reaction rates*

Table 5.24 shows little change in any category across the three surveys. Few students give P-coded responses at any survey. The level of Q-coded answers increases slightly, while a slight decrease in T-codes is observed. The changes in the total level of Q and P codes is not significant at either the 0.05 or 0.01 level. However, some students did change their answers to *Reaction rates* at the first stage. The largest alterations occur between groups Q and T - 16.4% moved from T to Q and 11.6% changed from Q to T between the first and second surveys. Most students give the same answer at both second and third surveys, with the largest change again being observed between Q and T groups. An equal proportion, 12.4%, change from Q to T and T to Q.

The difficulty with *Reaction rates* lies in the fundamental idea being probed. Students do not realise that the phases of reactants influence the shape of graphs of reaction rate against time, which is not covered by SAC, as the above account demonstrates. So, there is little opportunity in comparison to other questions for respondents' ideas to change. However, interviews suggest that students know surface area to be an important factor in controlling rate of reaction, even though they cannot make the connection between the graphs and the reactions. This is illustrated by student 115, who selected graph A for both reactions at the first survey, but chose B and C respectively at the second survey. In interview, he admitted these had been a guess. This excerpt is preceded by a brief discussion about the calcium carbonate/hydrochloric acid reaction, and continues:-

> I: So that's adding a solid to a liquid, isn't it? Here you've got two liquids added together. Does that help?
>
> S: No.
>
> I: Well, all I'm thinking of is whether you knew that it - if you have two liquids, it's a liquid/liquid reaction and that means that all the particles can mix together much more quickly and so at the very start of the reaction the rate is going to be extremely high, like it is on graph B, because the liquid molecules mix together so quickly. The reacting molecules are there together. Whereas if you put in a solid lump, what's the limiting thing there, that limits the rate of the reaction? Do you know?
>
> S: No.
>
> I: OK. Have you heard about surface area? Do you know anything about that?
>
> S: Oh, yes. Surface area.. the smaller the bits the larger the surface area will be, so the more surface there is for the other atoms and molecules to react on.
>
> I: Right, that's it. So here, can you say why C is perhaps the best graph for that? Its along the lines of what you just said, actually.
>
> S: When something's added it gets broken up and as it's broken up the um, rate increases because there's more surface area.

Although he can explain about surface area, this student cannot link his knowledge to the graph shape, even with heavy prompting. Other students, for example, 203, realise when prompted that an oxide layer has to be removed from the magnesium:-

> I: Now, what do you know about magnesium?
>
> S: It's reactive!
>
> I: Suppose we cleaned the ribbon before we started?
>
> S: I don't know - it goes shiny.
>
> I: So what's the dull stuff on the surface?
>
> S: The oxide layer. Oh, so that's got to come off.
>
> I: Right. So what happens to the rate of this one?
>
> S: Would it be slow to begin with? And then increase due to the - cos first you've got the oxide layer on -

I: Yes, it would dissolve that off first, and then it would - then you'd get the reaction. It could only go so fast ...

S: So it would be A.

This suggests that the question did not encourage students to demonstrate their full understanding, so many perhaps did know more than their answers indicated. The requirement to explain the shapes of the graphs may have been a deterrent, as students wrote more about this than in answer to the later parts where graph selection was required. Nevertheless, *Reaction rates* does provide interesting information about how students interpret graphical information. For example, the reactivity of magnesium influenced about 9% of students at each survey. Student 349 explained his choice of graph B for the magnesium/hydrochloric acid reaction at the first survey as follows:-

S: I think before I came here I realised that magnesium was quite a reactive metal, that's probably why I put B, because straightaway you get a reaction, but I didn't know too much about Na_2CO_3.

I: OK. That's the one which is commonly done, isn't it? You do that a lot in school.

S: It's all you get to do!

A more common error, made by about 27% at the first and third surveys, was to select graph C for the reaction between sodium carbonate solution and hydrochloric acid. Student 203 explained this choice in her interview:-

I: ...so we can forget all those things for the moment and just think about the surface area. Now if you look at this graph [meant equation] you've got two liquids reacting together. What can you say about the surface area?

S: It's very large.

I: Yes, huge, in fact. So if that's huge, then what can you say about the rate of reaction at first?

S: It'll go very quickly.

I: Right. So what graph fits that best?

S: Um, C.

I: Well, rate is zero at the beginning.

S: Oh, I see. So, I thought that when you put them in, you'd start at zero, the rate, and then you'd go from there. So it would be B.

I: Right. OK. So if you had those two -

S: I got both wrong!

I: What you just said, about thinking the reaction has to start, that's really important, because if that's how you think of it then you've told me something quite interesting about how students think of these sorts of things.

S: Ah, yeah, well! I don't know why I put these, but I don't think I would have chosen B at all, cos I would have thought that if you mix them immediately, then as soon as you mix it's at nought, because it hasn't actually started.

Her idea is that the rate is at zero when the reagents are mixed. Even though she recognises that the surface area would be very large, this does not mean (to her) that the initial rate would be high.

Therefore, *Reaction rates* reveals an interesting contrast. Some students associate the idea of high reactivity with fast reaction rate. Others, even though they know rate will be fast, think of reaction rates as starting at zero. This latter view appears to be more popular, perhaps because students are encouraged to think of graphs as starting at zero and increasing rather than starting at a maximum and decreasing. Two factors may contribute to this. First, students may interpret the graphs in the question as measuring the volume of gas given off, like those shown in Unit 8, *Engineering proteins* (Chemical Ideas, p 52). In such graphs, the volume of gas is recorded as zero at the start, increasing to a plateau as the reaction proceeds. This would lead students to select graph A or C if there were no special reason to do otherwise. Second, respondents do not realise that the graphs in *Reaction rates* show rate against time, and, even if they do, fail to connect the initial rate with the type of reaction occurring.

5.11 Conclusions

The preceding discussion illustrates that while substantive improvements have occurred in the responses given by the SAC students to some of these questions, their answers to others change relatively little. Before considering if these results are typical of A level students as a whole (the subject of chapter 6), we will draw some conclusions.

As a way of evaluating the changes, I discuss the results in three sections based on the extent of change in the level of P-codes (or, in the case of some questions, Q-codes) over the three surveys. The basic ideas are divided into groups where "large", "moderate" or "small" changes are found. While this is somewhat subjective, as it assumes a measure of what constitutes "large", "moderate" or "small" changes, and may therefore make distinctions which appear artificial, this is a useful guide for making comparisons, as it enables basic ideas showing similar degrees of change to be drawn together. This helps to reveal areas of strength and weakness in the performance of SAC students.

5.11.1 Basic ideas showing large increases

Large changes in the proportion of P-codes are those of the order of 50%. This means that about half of the student population changed to a P-coded response by the third survey. Changes of this size were observed for two basic ideas: chemical bonding and thermodynamics.

About 50% more students gave P-coded responses to *Covalent bonds* and *Hydrogen bonds* at the third survey than did so at the first survey. This implies that the SAC presentation of chemical bonding changes students' ideas. Improvements are seen in the quality of the language students use to describe bonds and in their ability to compare bond strength and characteristics. SAC revisits chemical bonding on a number of occasions, drip-feeding in the aspects relevant to the contexts used in specific units. That this is effective is seen in students' responses to these questions.

Responses to *Methane* also show about a 50% improvement in the level of P-codes by the third survey. This suggests that SAC is effective in developing the idea that energy is released when chemical bonds form, rather than energy being stored in bonds waiting to be released. Ideas about energy changes are revisited on several occasions, allowing this basic idea to be reinforced.

5.11.2 Basic ideas showing moderate increases

Moderate increases of between 20 and 30% in the levels of P-codes are found in response to the questions involving reacting mass reasoning, namely *Carbon* and *Iron sulphide*. The levels of P-codes to these questions begin at a higher level than those for chemical bonding and thermodynamics, so clearly there is less scope for improvement. Nevertheless, that increases of this level occur suggests that SAC is effective in assisting students with the development of this basic idea. Students complete GCSE with varying levels of experience of calculations in chemistry. The early units of SAC attempt to place all students on a level footing prior to extending the range of calculations later in the course.

Students' responses to *Petrol* and *Power Station*, which probe their thinking about conservation of mass in open system chemical reactions, also show a moderate level of improvement. Ideas about combustion receive extensive coverage in unit 2, *Developing Fuels*, and this is cited by students as the source of their second survey answers. That this knowledge is retained is shown by the maintenance of the second survey P-code levels at the final stage. However, although the level of P-coded responses to these questions began at a low level, around 13%, the moderate increase means that only about 40% of the sample give the expected answers at the third survey. This suggests that for a majority of students open system reactions present a persistent problem.

About 26% more students gave P-coded answers to *Precipitation* at the third survey. Although precipitation reactions do feature in SAC, it is unlikely that the conservation of mass in such reactions is discussed. SAC units make no specific mention of this. Students asked about their changed responses attribute their new ideas to "common sense" rather than something they have studied in lessons. This seems particularly associated with students who initially appeared to confuse mass and density. A second contributor to the increase is the move away from the notion that "all reactions give off gases". Students who begin A level thinking this way may change as experience of a wider range of reactions shows them that this notion is faulty. Thus, this change may in part be due to SAC, but is also affected by the maturation of students' thinking.

The level of Q-coded responses to *Reactions* shows an increase of 26%, although the proportion of P-coded answers is almost unchanged. Students had not completed their study of equilibria by the time the third survey was administered and so were perhaps not best equipped to give the P-coded answer. The move to the Q-code does suggest that students' ideas about reactions were developing, and this may be attributed to the SAC presentation of equilibrium reactions.

5.11.3 Basic ideas showing small increases

An increase in the level of P-codes of less than 20% I consider to be small. Admittedly, some increases fall close to the 20% threshold, so this division could be described as an arbitrary one, but for the purposes of this discussion it will be retained.

The increase in the levels of P-coded answers to *Hydrogen chloride*, *Solution*, *Sodium and chlorine* and *Energy change* are 17%, 7%, 14% and 16% respectively. The basic ideas probed by these questions all feature in SAC in various units, so this level of increase is perhaps surprisingly low, especially given that the starting levels are no worse than those for questions such as *Methane* and *Covalent bonds* which generated much larger improvements in the proportion of P-codes. Let us explore possible reasons for this.

First, this group of four questions all feature the formation of ions or ionic compounds. It may be that the basic ideas involved here are much more difficult for students to grasp than, say, the notion of a bond forming by sharing electrons. Both *Solution* and *Hydrogen chloride* involve the formation of ions in solution, by the dissolution of an ionic lattice and the breaking up of a covalent molecule. *Sodium and chlorine* and *Energy change* both feature the formation of an ionic lattice of sodium chloride. The much higher levels of P-codes to *Methane* and *Covalent bonds* implies that the formation and breaking up of discrete molecules is much easier to explain than the equivalent for ionic solids. Evidence in this chapter points to students thinking that all substances comprise discrete molecules, while recognising that the bonds in between atoms (or ions) may be of different characters. The responses to *Hydrogen chloride* indicate one outcome of this, namely that although students may "know" acids contain hydrogen ions, they persist in thinking that these remain bonded to, for example, chloride ions until something is added to displace them. This implies that the notion of discrete molecules existing in everything is persuasive and appears to be difficult to change. The situation is not assisted by equations which show "NaCl" as an entity; students may readily translate this to the idea that "NaCl" means "molecules of sodium chloride" rather than a ratio of ions in a lattice.

Second, the questions themselves could be responsible for the low level of change. *Hydrogen chloride* was placed last in the paper and so may not have received students full attention. *Solution* and *Hydrogen chloride* both asked for diagrams, which may have put students off giving an answer. *Sodium and chlorine* did not explicitly ask students to use bonding ideas, while *Energy change* could have been problematic because no scale was provided for the energy diagrams. In contrast, questions generating higher levels of P-coded answers at the third survey were perhaps more direct. Of course, I cannot say what the results may have been had the questions been asked differently. Nevertheless, it is intriguing that all four should have generated relatively low levels of improvement, and so it is perhaps not unjustified to suggest that a link exists between them.

The questions *Chlorides* and *Boiling* showed improvements of 15 and 19% in the level of P-codes. These probe basic ideas about the effects of intermolecular bonds on substances. SAC makes extensive references to hydrogen bonding, and this is reflected in the large increase found in answers to *Hydrogen bonds.* The relatively low increases observed for these questions implies that although students learn what a hydrogen bond is, they are less certain about the influence hydrogen bonds have on boiling points and find it difficult to recognise the effect of any other intermolecular bond. Again, had the questions directed students towards answers in terms of intermolecular bonds, the level of P-coded responses may have been greater, but even at interview students showed weaknesses in their understanding of this area. So, these relatively small increases cannot be due to the phrasing of the questions alone.

The proportion of P-coded responses to *Methane molecules* improved by about 18%, a low figure compared to that for *Covalent bonds*. This could be due to two factors. First, although SAC revisits chemical bonding in several units, the link between stability of electron configurations and bonding is only made once, in unit 4, *The Atmosphere*. Other references to the numbers of bonds forming in methane are restricted to dot-cross diagrams. The success of revisiting ideas is clear from the effects on responses to *Methane* and *Covalent bonds*. If ideas about molecular stability were also revisited the improvement in students' thinking might match that observed in other bonding questions.

Students' responses to *Element and compound* and *Substances* improved by 14% and 19% respectively. The ideas being probed by these questions are not discussed explicitly by SAC, although relevant material is featured. Thus, these levels of increase seem to arise because students are better able to apply basic knowledge gained through general experience of the course, rather than explicit discussion of the basic ideas involved.

Other questions also generated low levels of improvement. *Molecules* exhibited a decrease of 3% while *Copper* showed an increase of only 9%. *Phosphorus* produced a 14% improvement. In these cases, the starting level of P-codes was high, between 60 - 75%, suggesting that the basic ideas being probed were well-known from GCSE. So, the exclusion of these basic ideas from SAC material could be considered to be justified.

Finally, responses to *Rates of reaction* showed very little change over the three surveys. Questions featuring the basic idea about factors affecting rates of reaction were difficult to write, and this one may also be considered unsatisfactory in some respects - namely that it presented unfamiliar graphical information. However, the idea being probed is relevant - students studying chemistry may be expected to understand what graph shapes mean and relate these to relevant reactions. The difficulties students had with this is clear from Table 5.24. A factor which may have influenced the response levels may be that the final mention of reaction rates does not arise until unit 12, *Aspects of Agriculture*, which students had not studied.

5.11.4 The strengths and weaknesses of SAC

Clearly, several strengths of SAC are apparent from students' responses to some questions. The approach to covalent bonding and thermodynamics is successful, in that a high percentage of students seem to understand the basic chemical ideas being probed. Key features influencing the development of students' understanding are unit 2, *Developing Fuels*, and the revisiting of ideas on several occasions, which helps to reinforce the early work.

The SAC approach to reacting mass reasoning and discussion of open system chemical reactions is also effective in developing students' ideas. Again, the early units, *Elements of Life* and *Developing Fuels*, are cited by students as being useful, although carrying out calculations at various points in the course may also help.

SAC seems to have less influence on developing students ideas about ionic substances, despite extensive references in several units. Whether these difficulties apply to SAC students alone or are typical of all A level students will become apparent in the next chapter. Also, SAC does not develop ideas about intermolecular forces beyond students' being able to correctly describe a hydrogen bond. Hydrogen bonding features in several contexts used in SAC, reinforcing the chemical idea taught early on. Other types of intermolecular bond do not receive such extensive coverage and responses to *Chlorides* illustrate the weakness of SAC in this area.

5.11.5 Concluding comments

This chapter has discussed extensively the changes observed in SAC students' responses to questions about basic chemical ideas over their two year course. Some basic ideas appear to be thoroughly learned by SAC students, while others prove more resistant to development. In the next chapter we will see if these changes are typical of A level students or whether they are unique to those studying SAC. Thereafter, we will be well-placed to comment on the influences A level chemistry courses in general have on the learning of students.

Chapter 6

SAC and Traditional students compared: What differences are observed?

The previous chapter provided a detailed description of the learning of basic chemical ideas by students following SAC. Appreciable gains are observed in some areas, smaller ones in others. However, studying changes in SAC students alone leaves several questions unanswered. For example, are the changes described in the previous chapter reasonable, that is, are they better or worse than might be expected? Also, how good is SAC at prompting conceptual change about the basic chemical ideas? To answer these, a baseline is needed against which the changes in performance of SAC students can be judged. Such a baseline may be provided by a sample of students following non-SAC or "Traditional" A level courses. By comparing the learning gains of the SAC and Traditional students we are better placed to evaluate the extent of learning generated by SAC. In this chapter, the frequencies of response types given by two samples, one SAC, the other Traditional, are set alongside each other. This enables us to see if the gains observed for SAC students are typical of those for A level students as a whole.

6.1 The two samples

The responses of two samples, one SAC and the other Traditional, are described in this chapter. In this section I describe how the samples were matched.

6.1.1 Matching the student groups

The responses of 399 beginning A level students were reported in data chapter 1. This group comprised 320 SAC students and 79 Traditional students. Of these, 250 and 70 gave responses to the test paper on all three occasions. The two populations vary in their GCSE science background, as shown in Table 6.1: different proportions of the SAC and Traditional samples studied single subject chemistry and double award science at GCSE. Thus, the pre-A level science background of the SAC and Traditional groups do not match. To provide a good baseline to judge the performance of the SAC students matched samples are required, otherwise any difference in responses could be attributable to the GCSE background rather than the effect of the A level courses.

	Grade	SAC No.	%	Trad No.	%
Single subject Chemistry	A	44	17.6	22	31.4
	B	46	18.4	10	14.3
	C	17	6.8	3	4.3
	D	2	0.8	-	-
	NR	1	0.4	1	1.4
Total		110	44.0	36	51.4
Double award Science	A	68	27.2	20	28.6
	B	37	14.8	5	7.1
	C	26	10.4	7	10.0
	D	2	0.8	-	-
	E	1	0.4	-	-
Total		134	53.6	32	45.7
Course + grade unknown		6	2.4	2	2.9
Overall total		250	100.0	70	100.0

n (SAC) = 250 n (Trad) = 70

NR = No response

Table 6.1: Pre-16 subject and grade distribution of the whole SAC and Traditional samples

The numbers of SAC students were sufficient to allow selection of a group of seventy students which exactly matched the GCSE profile of the Traditional sample. Taking each subject and grade in turn, a random selection technique was employed to obtain the matched group. Beginning with the single subject chemists, the code numbers of the forty-four SAC students who achieved grade A were noted on separate pieces of paper and placed in a container. A colleague was asked to draw out twenty-two numbers. These students' scripts were used in the matched sample. The same procedure was repeated for the students achieving grade B (ten numbers were picked from forty-six), and C (three were picked from seventeen). This gave thirty-six SAC students who had studied single subject chemistry at GCSE. Thirty-two SAC students who studied Double award GCSE were selected in the same manner. To complete the seventy required, two students from the six who had not given GCSE course or grade were selected.

6.1.2 What the students had studied

Appendix 5 provides information about the progress of the SAC and Traditional samples in terms of the chemical ideas covered by each stage of the study. By the second survey, all the Traditional students had studied atomic structure and bonding, while most had covered thermodynamics. At the third survey, almost all of the Traditional students had completed the work relevant to the basic chemical ideas being probed. By the final survey, SAC students had completed units 1-9, *Visiting the Chemical Industry* and their *Individual Investigations*, while some had also completed units 10 and 11 (*Colour by Design* and *Medicines by Design*). Therefore, apart from responses to *Reactions*, which depends on an understanding of equilibrium constants, there is little evidence to suggest that the SAC and Traditional students differed widely in terms of their chemical backgrounds at each stage.

6.1.3 Non-controlled factors

Although the samples were matched by GCSE grade, other factors might also influence students' performance, particularly at the first survey. Differences in performance on the test paper may be afffected by, for example, whether students "felt like" doing a "test". A student on an "off-day" will not perform as well as he or she might. Also, one or two commented in interviews after the first survey that the paper was "just another thing we had to fill in", which suggests a frame of mind not entirely adjusted to thinking about aspects of chemistry. Such students may not have given their best possible responses at the first survey. Other students may have been better prepared mentally, perhaps by two minutes of brief explanation. Also, some teachers may have a teaching style which allowed students to be more familiar with the diagrams and the type of questions used in the paper. Students used to such a style may perform better than others for whom the test paper comprised "weird" questions. These factors have not been controlled and so may contribute to the "noise" which is apparent between SAC and Traditional students at the first survey. Indeed, some of these factors may continue to affect students' performance at later stages. So, even though the groups are matched by GCSE grade, some differences are likely to be observed between the samples at the first survey. One way of assessing the significance of these differences is discussed in the next section.

6.2 Establishing the baseline for comparison

In this chapter, data is presented for the questions in the same way as before, except that totals for the categories P, Q, R, S, T and U are given rather than individual figures for each response code. Differences in the proportions offering the various response types will be apparent between the SAC group reported earlier and the selected group of seventy used here. This is to be expected, as the scientific background of the selected students is quite different from that of the full SAC sample. More importantly, the data tables show differences at the first survey between the Traditional and SAC samples. That is, the percentages offering the various response types are not identical, and, in some cases, they are not even close to identical. Therefore, ground rules for regarding the differences between the groups as significant must be established.

Differences between the SAC and Traditional groups at the first survey vary in size. Some appear to be small, of the order of 1 - 5%, for example, most of those in table 6.2, while others, such as the Q-codes for *Tablet* in table 5.3, are quite large, above 15%. Two points can be made about these. First, if the samples were perfectly matched, no difference would arise. Therefore, it appears that, as the previous section suggests, the samples are imperfectly matched. Hence the second point arises. To establish if the second and third survey responses differ significantly from those in the first, an average measure of difference between the two populations on the first survey would be a useful guide. This average figure can be called the "error variance" and, as shown below, has a value of about 6%. This error variance suggests that each figure included in the data tables should be regarded as accurate to about +/- 6%.

As a first step in estimating the value for the error variance, the average difference between response codes for each question was calculated. For example, Table 6.2 presents the data for *Molecules*. We see that the proportions offering P codes at the first survey differ by 7%, the Q codes by 6% and the T codes by 1%. The average difference for this question is (6 + 7 +1) /3 = 4.7. Repeating this process for all twenty-three questions yields values ranging from 2.0 - 11.3%. The mean of these numbers is 5.88%, which, rounded up, is 6%.

This approach is not a recognised statistical technique; in fact, this situation does not lend itself easily to any of the standard approaches. The χ^2 test, for example, would be difficult to apply because the responses are given by two different populations which as section 6.1.3 indicates, are subject to some variation. This test would include measurement of the statistical significance of the variation between the two populations rather than the significance of the changes in response levels alone. The error variance provides a guideline for identification of significant differences between the samples. If, for example, the proportion of P-codes for a question increases by more than 12%, twice the error variance, the change can be considered significant and should be discussed. Also, the error variance allows us to focus on differences between the two samples. If there is a discrepancy of more than 12% between them, this is considered to be significant and so requires comment. Differences smaller than the 12% guideline will not always be discussed, as they fall within the range of error.

Having established a baseline for comparison, we will now examine the data for the SAC and Traditional samples. The questions are discussed in the same order as in the two preceding chapters.

6.3 Differences between elements, compounds and mixtures

Table 6.2 compares SAC and Traditional responses to *Molecules*, *Element and Compound* and *Substances* over the three surveys.

	Code	SAC 1	Trad 1	SAC 2	Trad 2	SAC 3	Trad 3
Molecules	P	76	83	73	72	79	84
	Q	7	1	14	14	12	9
	T	17	16	13	14	9	6
	U	-	-	-	-	-	1
Element & Compound	P	30	40	43	47	50	59
	Q	34	29	24	26	24	29
	T	36	31	33	24	23	12
	U	-	-	-	3	3	-
Substances	P	60	66	83	76	81	83
	Q	21	16	4	17	9	10
	T	19	19	13	7	10	7
	U	-	-	-	-	-	-

n = 70

Table 6.2: Percentages of SAC and Traditional students giving each response type to *Molecules, Element and Compound* and *Substances*

Applying the error variance of 6% to the first survey figures for *Molecules* indicates no significant difference exists between the samples. Although the proportion of P-codes differ by 7%, each percentage is only accurate to +/-6%, so this discrepancy is within the accepted range.

At the second survey, both groups show a decrease in the level of P-coded answers accompanied by an increase in the number of Q-codes, implying that both SAC and T students tended to answer only the multiple-choice section at this point. By the third survey, the level of P-coded responses has returned to the original figure, showing little difference between the two groups. The level of T-coded answers has decreased in both. Therefore, neither course type influences student performance on this question, perhaps because the high proportion of P-codes implies the basic idea being probed is well-established at the GCSE stage.

The differences observed in response levels to *Element and Compound* fall within the 12% limit in all cases, so changes over the three surveys are comparable between the groups. The pattern of change across the response types is similar; an increase in the proportion of P-codes occurs at both second and third surveys. Between the second and third surveys the increase appears to be due to a shift from the T category in both samples. The similarity here may arise because students in both samples will have met mass spectrometry in lessons taught between the first and second surveys. The levels of Q codes remain relatively unchanged between the second and third surveys, suggesting that some students do not progress beyond offering "electrolysis" as the test for water and giving a correct definition for "compound".

Responses to *Substances* show very little variation between the two samples, with only one difference greater than 12%. The largest increase in P codes occurs between first and second survey, suggesting that the early units of SAC and the topics taught on Traditional courses have similar effects on students' answers to this question. Retention of the information is shown by the fact that the level of P codes remains high at the third survey. The level of Q codes at the second survey differ by 13%, suggesting that more Traditional than SAC students ticked the correct boxes at this stage rather than giving full explanations.

These data indicate that neither course type influences students' thinking about the distinctions between elements, compounds and mixtures more than the other. High numbers of students gain P-coded answers in both *Molecules* and *Substances* at the first survey, suggesting that the distinctions are relatively well-developed at GCSE. Therefore, compared to later questions, relatively few students need to change their ideas about this during their A level course. Slight differences are observed in the points at which changes in response levels occur, but all three questions give almost identical levels of P-coded answers at the third survey.

6.4 Chemical change

Table 6.3 compares SAC and Traditional students' responses to the three questions which explore understanding of different chemical reactions: *Tablet*, *Copper* and *Hydrogen chloride*.

At the first survey, the Q and T-coded responses to *Tablet* show differences of around 12%. These suggest that more SAC than Traditional students begin by offering responses close to the expected answer, while more Traditional students start their A level course with misunderstandings about this question. Subsequent surveys show these discrepancies to be resolved as students proceed through their courses, resulting in similar levels of understanding that a reaction is taking place, as the following discussion indicates.

	Code	SAC 1	Trad 1	SAC 2	Trad 2	SAC 3	Trad 3
Tablet	P	1	4	-	6	3	7
	Q	40	29	36	30	43	39
	S	14	9	20	21	20	19
	T	42	54	43	37	34	32
	U	3	4	1	6	-	3
Copper	P	73	72	82	82	81	79
	Q	10	17	3	7	7	12
	S	-	-	-	-	-	-
	T	14	11	14	9	9	5
	U	3	-	1	3	3	4
Hydrogen chloride	P	10	4	22	21	27	42
	R	-	-	-	-	2	1
	S	4	10	7	26	13	20
	T	62	59	59	40	49	30
	U	24	27	12	13	9	7

n = 70

Table 6.3: Percentages of SAC and Traditional students giving each response type to *Tablet, Copper* and *Hydrogen chloride*

Little difference is observed in the proportion offering P coded answers to *Tablet* over the three surveys, with few in either group giving this response. Initially, 40% of the SAC students give Q-coded answers, a figure which remains almost unchanged by the third survey. In contrast, the level of Q codes given by Traditional students increases from 29% to 39%. This means that Traditional students seem to move towards an understanding of this chemical reaction. At the second survey, both groups show an increase in the S-coded response, with more students explaining that the gas is "produced in a reaction between water and the tablet". This shift is much greater for the Traditional students, and arises because students move from the T category to S at the second survey.

The initial large difference in T-codes is reduced by the third survey because many of the Traditional students change their answers in between. This can be seen by examining the proportions giving responses coded T2 in more detail. At the first survey, 36% of the Traditional group were coded T2. This figure decreased to 13% by the third survey. The equivalent figures for the SAC group are 24% (first survey) and 23%, indicating that Traditional courses are more successful at moving students away from the idea that the gas was "in the water" (T2a) or was "hydrogen or oxygen from the water" (T2b). Therefore, SAC students' ideas about *Tablet* are unchanged compared to those of the Traditional students.

Figures for *Copper* show little variation in any category. By the third survey, about 80% of both groups give P-coded responses, an increase of about 8% on the first survey figure. The change occurs in the first few months of the course, and arises because students move from the Q category. The improvement could occur because students learn to express themselves in more precise language, than, for example, explaining that the black stuff comes from "burning the copper" (Q1) or a "reaction with air" (Q2). Relatively few students offer T-coded answers at any stage, although in both groups the most frequent T-type response was that the "black stuff is carbon" (T2a). This was given by 10% of both groups at the first survey and 5% of both at the third survey.

Both groups show an increase in the proportions of P-codes in answer to *Hydrogen chloride*, but 15% more Traditional students give this response by the third survey. This difference in proportion is more than expected allowing for error variance and is confirmed by inspection of the T-coded answers, as discussed below. These data suggest that Traditional courses are more effective than SAC in teaching that hydrochloric acid contains the oxonium ion, H_3O^+, and that hydrogen gas is displaced when magnesium is added.

Although no students offer R-coded responses at either the first or second surveys and very few do so at the third, an increasing proportion give S-coded answers. Table 6.3 shows that more Traditional than SAC students give S-coded answers. The most frequent S-coded answer in both groups shows H^+ and Cl^- ions in the diagram section accompanied by an explanation that "Magnesium reacts with or displaces chlorine (or chloride)" (S1b). The frequency of this response alone increased in both groups, suggesting that although students learn that hydrogen ions are present in acids, they may remain unable to explain displacement reactions correctly.

About 60% of both groups give T-coded responses at the first survey, confirming that the increase in P-codes is a result of the A level course, not a difference in starting position. For the Traditional students, this proportion decreases to 40% at the second survey and by a further 10% at the third survey. However, for the SAC group, the level of T-codes remains almost constant at the first stage, and decreases only to 49% at the third survey. Most of these respondents, 40% of the sample, suggest that the hydrogen chloride is molecular when in acid.

For both groups, the high proportion of U codes at the first survey has decreased considerably by the third survey, suggesting that students were taught ideas relevant to the question as their courses proceeded. However, the high levels of T-codes given at the third survey by both groups implies that many students find the notion of covalent molecules forming an ionic solution difficult to grasp.

Responses to this group of questions shows no significant difference in answers to *Tablet* and *Copper*. This indicates that both groups have equal difficulty in explaining the origin of a gas in a chemical reaction, and that neither course type assists students in resolving this. The copper/oxygen reaction presents little difficulty for either student population, confirming the findings reported earlier (section 4.6.2) that the appearance of a new solid is relatively easy to explain compared to a gas. Responses to *Hydrogen chloride* demonstrate that despite the content of the early SAC units (described in section 5.4.3), a significantly higher proportion of Traditional students know at the end of their course that acids contain hydrogen ions and that these are involved in displacement reactions.

6.5 Conservation of mass in closed systems

Table 6.4 shows changes in SAC and Traditional sample responses to *Phosphorus*, *Precipitation* and *Solution*.

	Code	SAC 1	*Trad 1*	SAC 2	*Trad 2*	SAC 3	*Trad 3*
Phosphorus	P	59	65	71	67	74	70
	Q	1	3	2	3	6	4
	R	3	1	1	4	3	4
	S	7	1	2	1	4	-
	T	26	23	23	20	9	13
	U	4	7	1	5	4	9
Precipitation	P	24	56	40	59	61	54
	Q	1	2	-	1	4	7
	R	17	1	14	6	11	13
	S	13	10	10	14	9	7
	T	32	17	20	14	9	13
	U	13	14	16	6	4	6
Solution	P	39	42	45	41	50	59
	Q	4	4	9	6	7	4
	R	16	4	10	6	7	4
	S	20	17	24	16	14	14
	T	13	22	11	21	16	16
	U	8	11	1	10	6	3

n = 70

Table 6.4: Percentages of SAC and Traditional students giving each response type to *Phosphorus*, *Precipitation* and *Solution*

Most matched sample responses to *Phosphorus* fall into either the P or T category, suggesting that students either understand the principle of conservation or do not. Few show partial understanding or misunderstand the chemical event. Further, little difference is observed across the surveys between the samples, suggesting that neither course type influences students' ideas to a greater extent than the other. However, the level of T-coded responses given by the SAC sample decreased markedly over the three surveys from 26% to 9%. Most of this change occurred between second and third surveys. Most of these students moved to the P category, although Table 6.4 indicates that a few gave Q-coded responses at the third survey. Although a smaller decrease of 10% in the level of T-codes is observed for the Traditional sample, the final proportion is not significantly different to that for the SAC sample.

A large difference in P-codes for *Precipitation* is observed at the first survey which strongly suggests that Traditional students have a better understanding of precipitation at the beginning of their A level course than their SAC counterparts. Possible reasons for this are discussed in detail in a concluding section. Despite this, the data indicates that significant numbers of SAC students change their thinking through the course, such that the level of P-codes by the third survey falls within 12% of the value for the Traditional students. In contrast, almost no change is observed in the level of P codes offered by the Traditional sample.

An alternative explanation for the difference in P codes at the first survey is suggested by the values for the R category. Recall that the R code is given to responses which name the products of the reaction correctly, perhaps by giving an equation for the reaction. Thus, R-coded answers are correct responses given in a different way to those coded P. About 17% of the SAC students name the products of the reaction at the first survey, compared with only 1% of the Traditional group. When the figures for the R and P codes are added together, the difference between the matched samples is greatly reduced; 41% of the SAC group and 57% of the T group give correct answers at the first survey. These figures increase to 72% for the SAC sample and 67% for the T sample. Therefore, the difference between the samples is not as great as the levels of P codes suggests.

The proportion of S-coded answers varies little over the three surveys, decreasing to 9% (SAC) and 7% (Traditional). The idea that precipitation reactions give off gases was the most popular S-coded response. Table 6.4 indicates that progressively fewer students give this response by the third survey.

The initial level of T-coded answers shows a difference of 15% between the two groups. Most of this is explained by the response coded T3, "more than 140 g, because solid is heavier than liquid". About 27% of the SAC group but only 13% of the Traditional group gave this answer at the first survey. These figures decreased to 4% and 6% respectively by the third survey, suggesting that most students following both types of course develop correct thinking about mass and density.

Responses to *Solution* show little difference between the samples in most categories at the first survey. As observed for *Precipitation*, more SAC students give R-coded responses at this stage, although similar numbers give this type of answer at the third survey. The proportion of P-codes increases for both groups, although the routes by which the increases are attained differ. The SAC group move to the final figure, 50%, in two equal stages, whereas the increase for the T group occurs between the second and third surveys only. This may arise because SAC revisits ideas relevant to *Solution*, whereas Traditional students may only meet ideas relevant to solubility late on in their courses.

Similar levels of Q and U-coded answers are observed in all three surveys for both samples. Although there is an initial variation of 12% in the level of R-coded answers, this is reduced by the third survey, suggesting that the SAC students move away from answers stating that "no gas is produced". Change is also observed in the level of S-coded responses, the SAC group increasing to 24% at the second survey before falling back to 14%, the same level as the T group. These figures suggest that more SAC students learn that dissolving does not involve release of a gas (S2), or "a reaction" (S4). About 14% of each group give this type of response at the third survey, however, which indicates that this type of reasoning remains plausible for some students.

Overall, the level of P codes for *Solution* must be considered disappointing. Although more Traditional than SAC students give the correct answer, 30% of both groups give evidence of misconceptions in their thinking about dissolving ionic solids at the third survey. This reinforces the point made above in discussion of responses to *Hydrogen chloride*. Taken together, these two questions reveal that the dissolution of a substance into ions requires special attention in A level chemistry courses, and that to date neither SAC or Traditional approaches are effective in teaching this basic chemical idea.

Overall, these data indicate that about two-thirds of both groups conserve mass in the situations described in these questions. As the levels of improvement are similar, students' reasoning is not affected differently by any variation in teaching styles or course materials. Students interviewed about their answer to these questions cannot always recall having "learned" the relevant idea, suggesting that changes in ideas about conservation arise through a maturing process and development of intuitive thinking, perhaps as a result of continued experience of chemical reactions. However, 13% and 30% give S or T coded answers to *Phosphorus* and *Solution* respectively at the third survey. These answers are consistent with misconceptions about conservation, implying that some ideas are resistant to change. The relatively high level of third survey T-codes for *Solution* suggests that dissolving appears to present special difficulties for some students, many of whom persist in thinking that a chemical reaction evolving a gas occurs when salt is put in water.

6.6 Reacting mass reasoning

Table 6.5 shows the responses of the matched samples to *Iron sulphide* and *Carbon.*

	Code	SAC 1	*Trad 1*	SAC 2	*Trad 2*	SAC 3	*Trad 3*
FeS	P	56	61	69	79	86	79
	Q	1	7	4	7	1	10
	T	37	19	19	10	7	6
	U	6	13	8	4	6	5
Carbon	P	50	54	64	73	64	73
	Q	29	19	20	14	23	10
	T	16	23	16	11	10	14
	U	5	4	-	2	3	3

n=70

Table 6.5: Percentages of SAC and Traditional students giving each response type to *Iron sulphide* and *Carbon*

Responses to *Iron sulphide* show large increases in the proportion of P codes for both SAC and Traditional samples. The SAC group improve from 56% to 86% in two stages, while the Traditional group increase from 61% to 79% occurs between the first and second surveys. This suggests that both courses influence students' use of reacting mass reasoning but that greater improvement is attained by the SAC group.

For both samples, the improvement in the proportion of P coded answers is at the expense of the T-coded responses. About 18% more SAC than Traditional students begin A level with poor understanding of reacting mass reasoning, about 29% giving the answer "192 g" compared with only 13% of the Traditional group. This large initial difference will be discussed in more detail towards the end of the chapter. By the third survey, 7% of the SAC sample give this response type compared with 3% of the Traditional group. This indicates that both are effective in promoting development of reacting mass reasoning, although SAC students seem to out-perform Traditional students in this area.

The response pattern for *Carbon* shows much higher levels of Q codes than for *Iron sulphide,* because the correct answer can be obtained by adding together the numbers 64 and 32 given in the question. The answer "88 g" alone does not indicate if the student knows how to use reacting mass reasoning. Table 6.5 shows that the two groups begin with similar levels of P codes and that no significant difference is observed subsequently.

The level of Q codes for the Traditional sample decreases across the three surveys, but the corresponding figures for the SAC group fluctuate, giving a final difference of 13% between the two. This suggests that more SAC students are inclined to give the addition-type answer. About 23% of the Traditional sample begin by offering a T-coded response. About 16% miscalculate giving either 44 g, 56 g or 72 g as their answer. Only around 9% of the SAC group respond in this way at the first survey. These data may indicate that SAC students tend to add the numbers, obtaining the correct answer "by accident" while more Traditional students attempt to carry out the calculation, obtaining an incorrect answer by an appropriate method, perhaps being recalled after several months of disuse. This may mean that a higher proportion of Traditional students had learned how to use reacting mass ratios at GCSE, supporting the point made above. If this is so, then the 9% imbalance in the final level of P-codes could be explained as follows: the Traditional students, more familiar with the correct method from the beginning, change more easily to the correct answer than the SAC students, because they were revising a method they already knew. Many members of the SAC group, learning reacting mass calculations for the first time at A level, retained the tendency to add the numbers, as even by the third survey they had not been able to apply the correct method.

Taking the two questions together reveals a contradiction. A higher proportion of SAC students answer *Iron sulphide* correctly at the third survey, while more Traditional students give a P-coded answer to *Carbon* at this stage. As the previous chapter indicated, students need to understand the principle of reacting mass reasoning to answer *Iron sulphide* correctly. Therefore, the responses to this question are likely to be a better representation of the actual level of understanding than those to *Carbon.* The lower level of correct answers to *Carbon* may arise either because students tend to add the numbers, or because students use the appropriate reasoning but write down the answer "88 g" as an abbreviation. If this second reason is the case, then it appears to apply to more SAC students than Traditional ones.

6.7 Conservation of mass in open systems

Table 6.6 shows changes in the matched sample responses to *Power Station* and *Petrol.*

	Code	SAC 1	*Trad 1*	SAC 2	*Trad 2*	SAC 3	*Trad 3*
Power Station	P	17	26	50	34	37	43
	Q	23	13	19	17	24	27
	T	31	39	27	31	30	17
	U	29	23	4	18	19	13
Petrol	P	11	17	36	27	30	41
	Q	3	-	1	-	3	-
	S	1	-	-	-	3	-
	T	66	66	52	60	52	43
	U	19	17	11	13	12	16

n = 70

Table 6.6: Percentages of SAC and Traditional students giving each response type to *Power Station* and *Petrol*

Table 6.6 shows that the level of P codes for *Power Station* given by the Traditional sample increases steadily across the three surveys, while that for the SAC group begins at a lower figure, 17%, increases to a maximum at the second survey then decreases to 37%. The final levels are approximately equal, suggesting that the second SAC unit, *Developing Fuels,* which features the burning of coal is responsible for the mid-point peak, but that the effect is short-lived. There is no way of knowing exactly what relevant material may have been taught to the Traditional students, but we see that the effects of both approaches result in similar levels of attainment.

About 10% more SAC students begin by giving Q-coded responses but by the third survey the levels are approximately equal. This suggests that some shift towards the Q category occurs in the Traditional group during the study. Table 6.6 indicates that students moving from the T-coded responses contribute to this, as a large decrease in T-codes is observed between second and third surveys. In contrast, despite the early teaching in SAC, the level of T-codes remains almost unchanged across the three surveys. This may be because students move from U to T as a result of teaching, because at the first survey, some respondents may have had no idea about the question, but at later surveys the content at least is familiar, so they feel able to make an attempt at an answer. However, by the third survey, approximately equal proportions of both samples give uncodeable responses.

Taken together, these data indicate that students find this question difficult despite receiving teaching. The final level of P-codes is low relative to other questions.

Clearly, the early units of SAC influence students' responses, but this appears to be short-lived.

Table 6.6 shows that both SAC and T groups begin A level with a very poor level of understanding of the reaction which takes placed between petrol and oxygen in a car engine, with only 11% and 17% gaining P-codes at the first survey. These values increase over the second and third surveys, following the same pattern as noted for *Power Station*, namely, that the SAC group increase at the point where explicit teaching is received, while the T group increase steadily over the whole study.

About 66% of both samples give T-coded answers at the first survey. About 40% of these groups give a conservation-type response, explaining that the mass of petrol would be 50 kg because, for example, "what goes in must come out" (T4a), or "matter cannot be created or destroyed" (T4c). This proportion decreases to about one-third of the samples by the third survey. A higher level of T-codes is observed among the SAC sample at the third survey because more SAC than Traditional students give answers consistent with misconceptions. For example, about 9% of the SAC group suggest that the mass would be less than 50 kg because "petrol is converted to light, heat, energy" (T1) or because "gas is lighter than liquid" (T2). A further 8% give "50 kg" or "less than 50 kg" (T5). At the third survey, no Traditional students give the responses coded T1 or T2, while only about 4% are coded T5.

These data suggest that although SAC students receive explicit teaching about the reaction between petrol and oxygen, this is less effective in the longer term than a traditional syllabus in changing students' ideas about combustion. However, the difference in the final level of P codes is not significant, and the figures for both groups are low. This, and the relatively high levels of conservation-type responses may imply that students gave the response "50 kg" without thinking carefully about the question giving an inflated proportion of this answer.

Taken together, however, the response levels to *Power Station* and *Petrol* indicate that both Traditional and SAC students have poor understanding of open-system chemical reactions. The input of specific chemistry in this area on SAC yields an initial advantage for both questions, as seen in the higher P-code levels at the second survey. That these figures are not maintained implies that contextual learning of this material occurs only at the time, and is quickly forgotten by some students as the contexts and chemical ideas change. In contrast, although the Traditional group also show relatively poor levels of understanding, the final P-code level is higher for both questions, and shows steady increase, indicating that their learning of this idea may perhaps be at a deeper level.

6.8 Chemical bonding

As in the preceding data chapters, the questions probing intra- and intermolecular bonds are considered separately.

6.8.1 Intramolecular bonding

Table 6.7 shows changes in matched sample responses to *Covalent bonds, Methane molecules* and *Sodium and chlorine.*

	Code	SAC 1	*Trad 1*	SAC 2	*Trad 2*	SAC 3	*Trad 3*
Covalent bonds	P	14	19	64	62	71	65
	Q	56	51	29	24	16	31
	T	23	23	7	13	11	4
	U	7	7	-	1	2	-
Methane molecules	P	9	23	23	47	31	41
	Q	59	54	66	51	61	49
	T	19	4	3	1	-	6
	U	13	19	9	-	8	4
Sodium & chlorine	P	23	19	37	24	33	34
	R	53	50	43	54	44	50
	S	9	6	7	7	6	10
	T	4	14	2	5	1	2
	U	11	11	11	10	16	4

n = 70

Table 6.7: Percentages of SAC and Traditional students giving each response type to *Covalent bonds, Methane molecules* and *Sodium and chlorine*

Both SAC and Traditional samples show very large increases in the proportions offering P coded answers to *Covalent bonds* over the three surveys. Most of the increase occurs between first and second surveys, indicating that SAC and Traditional students study covalent bonding early on. Although the groups differ in the percentages of P-codes, these differences are not statistically significant, suggesting that both course types are equally effective in developing ideas about covalent bonds.

Table 6.7 shows that a smaller proportion of Q-coded answers is given by the SAC group. This implies that SAC may be more successful than Traditional approaches in encouraging students to move from the "single / double bond" response to "single / double covalent bond" (P1) or to accurately describe the numbers of electrons involved (P2). Clearly, students move away from the simplistic response "single and double bond" (Q1), given by over half the respondents at the first survey. The popularity of this response suggests that these names are taught to students at GCSE in place of the more accurate term "covalent". Traditional students tend to revert to the Q1 answer at the third survey, as the proportion of Q-codes increases to 31% at this point. The equivalent figure for the SAC sample is 16%, suggesting that SAC students retain or change their answers even in the later stages of the course. This may be prompted by the revisiting of bonding ideas in later units, for example, *Engineering Proteins* (unit 8), while Traditional students "forget" because they covered all aspects of bonding and structure in their first term.

Decreases in the levels of T-coded responses are also observed. About 12% of both groups explained that the bonds "shared one/two electrons" (T1) at the first survey. By the third survey, this decreased to 3% of the T sample and 9% of the SAC sample, which may imply that Traditional courses assist students in moving from this misconception more successfully than SAC courses.

Responses to *Methane molecules* show that 23% of Traditional students but only 9% of SAC gain P codes at the first survey. This large difference is unexpected and will be discussed in more detail in a concluding section. By the third survey, this difference has decreased to 10%. No student in either sample was coded P1a, "CH_4 is energetically the most stable" although 13% of the Traditional sample explained that "C and H are more stable as CH_4" (P1b) and a further 10% stated that "C & H need 4 &1 more electrons for a noble gas configuration" (P2). Comparative figures for the SAC sample are 3% and 6% respectively. These values suggest that more Traditional students than SAC students begin their A level with correct understanding about the stability of molecules. This seems to give them an initial advantage, as the next stage, understanding the link between bond formation and stability, is only a relatively small step away. For SAC students, most of whom begin with the idea that "carbon needs four bonds" (48%, Q1) or the vague statement that "there are 4H's and 1C" (14%, T4), the transition to the P code is much harder to make. The final figures for the P1a code offer some support for this - about 11% of the Traditional sample but only 3% of the SAC sample give this response.

That the level of P1a responses is low means that almost all the P-coded answers at the third survey are coded P1b or P2. About 14% of the SAC sample and 17% of the Traditional sample move to these codes at the second survey, suggesting that relevant material taught on both courses in the intervening time period has similar effects. For both groups, the proportions giving T-coded responses decrease, indicating that students coded T early on shift to another category, most likely to Q, by the third survey.

These data imply that learning about the stability of molecules does take place, although in both course types this appears to be limited to discussing the noble gas formulae of the atoms in a molecule. Links to energetics are not made by many students, but more Traditional than SAC students give this type of answer. SAC may emphasise the Q-type answer, as this group increases as the course proceeds, whereas Traditional courses stress the need for stability obtained by filling electron shells.

Taken together, the questions probing students' ideas about covalent bonds show that by the end of the study about two-thirds of both samples can describe a covalent bond in terms of the number of electrons involved, or in more precise language than they used at the beginning of their course. However, responses to *Methane molecules* indicate that most seem to do this because they are thinking in terms of atoms achieving noble gas electron configurations, and so link the numbers of electrons in the bond with the "need" for atoms to have "full shells". This is acceptable, but these data show that most students are limited to this type of reasoning alone, and are not encouraged to link bond formation to attainment of energetic stability. As will be seen, this may contribute to students' difficulties with thermodynamics. Both course types seem to induce similar effects, implying that the SAC method of revisiting bonding ideas when considering structure of molecules in later units does not enhance students' performance greatly.

Students' ideas about the formation of ionic bonds were explored by the question *Sodium and Chlorine*. Table 6.7 shows relatively little change in the proportion giving P-coded answers, the SAC group increasing from 23% to 33% at the third survey, and the Traditional group from 19% to 34%. For both groups, most of this increase occurs because more students offer the P1-coded response "Energy is liberated in bond / ionic lattice formation". Most of the beginning P-codes in both samples are given by students who explain that an electron transfers between sodium and chlorine (P2). The proportion of SAC students offering this response changes over the three surveys, increasing from 17% to 24% then declining to 14%. By comparison, 11% of the Traditional group give this response at each stage. This suggests that relevant material in the early units of SAC influence some students towards this response, but that this information is "forgotten" by the third survey.

The most frequent response for both groups is the R-coded answer "sodium and chlorine are reacting / forming a compound". The proportion of the Traditional sample giving this response fluctuates around 50%, while the level for the SAC group decreases from 53% to 44% by the third survey. This supports the point made above that SAC material influences students' thinking, encouraging a shift to the P category.

The consistent high levels of R codes indicate that *Sodium and chlorine* perhaps does not probe students' ideas about ionic bond formation as well as the equivalent question for covalent bonds, *Methane molecules.* A more successful phraseology might have been "explain in terms of bonding what is happening in the gas jar", which would prompt students towards giving bonding - type answers. The relatively low levels of P codes may not reflect the actual levels of understanding about ionic bond formation, as both groups seem to be equally drawn to the R-coded answer.

The questions investigating intramolecular bonds indicate that students following both courses develop an understanding of the mechanics of bond formation. They learn to use more accurate language to describe the formation of both covalent and ionic bonds in terms of sharing or transferring electrons, and recognise that atoms "like" to have full shells. However, they are not encouraged to link bond formation with release of energy and increase in stability.

6.8.2 Intermolecular bonds

Table 6.8 shows changes in matched sample responses to *Hydrogen bonds, Boiling* and *Chlorides.*

	Code	SAC 1	*Trad 1*	SAC 2	*Trad 2*	SAC 3	*Trad 3*
Hydrogen bonds	P	13	29	54	64	70	67
	Q	29	20	7	10	3	9
	T	21	21	37	26	26	23
	U	37	30	2	-	1	1
Boiling	P	21	29	36	56	46	60
	Q	36	46	30	33	27	21
	T	40	25	33	9	23	16
	U	3	-	1	2	4	3
Chlorides	P	-	9	6	16	17	27
	Q	20	23	21	30	16	30
	T	51	46	64	40	53	34
	U	29	23	9	14	14	9

n = 70

Table 6.8: Percentages of SAC and Traditional students giving each response type to *Hydrogen bonds, Chlorides* and *Boiling*

Table 6.8 shows an initial difference of 16% between the Traditional and SAC groups in P-coded responses to *Hydrogen bonds.* This will be discussed in detail in a concluding section. Nevertheless, the proportions of both samples giving P-coded answers to *Hydrogen bonds* increase significantly over the three surveys to about 70%.

The proportion of Q codes decreases in both samples from first to third survey. This category comprises students who explained that the bond was "a liquid bond" or was "a weak bond between molecules" (Q2). These responses were given by 10% of the Traditional sample and about 21% of the SAC sample at the first survey. By the third survey, only one Traditional student gave the Q2 response, and no student gave the answer coded Q1. Table 6.8 shows that the level of T codes is almost unchanged from first to third survey in both samples, reaching a peak of 37% for the SAC sample at the mid-way stage. Further, an increasing proportion of both groups gave the response "Line 3 is an attraction, not a bond" (T1a). This answer accounted for 24% of the SAC sample and 17% of the Traditional sample at by the third survey. As the previous chapter demonstrated, this suggests that students on both course types acquire this idea from their teachers, not the course materials.

Hydrogen bonds attracted a large number of U-coded answers at the first survey, because many students had not seen this type of bond before. The difference in U-codes at the first survey may arise because slightly more of the Traditional sample had met hydrogen bonds prior to A level. By the third survey, almost all students were able to attempt the question, reflecting increasing familiarity with this bond type.

The question *Boiling* probes students' thinking about the common physical phenomenon of bubbles appearing in boiling water. Indirectly, this explores their ability to apply knowledge about hydrogen bonding to water changing state from liquid to gas. Table 6.8 shows that consistently more Traditional students give the correct answer, coded P. The proportion of P codes given by the Traditional sample increases from 29% to 60%, while for the SAC sample the proportion increases from 21% to 46%. The values for the Traditional sample are similar to those observed for *Hydrogen bonds*, while the SAC sample seems to give poorer quality responses to *Boiling* than *Hydrogen bonds*. This may indicate that SAC students cannot apply teaching about hydrogen bonding to this question as effectively as Traditional students.

Levels of Q-coded responses decrease in both samples over the three surveys. About 25% of both samples begin A level with the response "the bubbles are oxygen" . The proportion giving this answer decreases to 14% of the SAC sample and 6% of the Traditional sample by the third survey. This suggests that students move towards the more accurate response coded P.

Exactly 40% of the SAC sample give T-coded answers at the first survey. This proportion decreases to 23% by the third survey. Almost all the T category answers, 37% at the first survey and 20% at the third, are coded T2, implying that these students think water molecules break up when evaporation takes place. The equivalent figures for the Traditional sample are 19% and 10%. This support the fact that a higher proportion of SAC than Traditional students begin and end their course with this idea. Although SAC is evidently successful in changing students' thinking to some extent, the residual level of the T2 answer remains high relative to that of the Traditional sample. One possible reason for this might be that students do not learn about the effects of hydrogen bonding on the boiling point of water until late on in the course in a different context, so could not assimilate this information by the third survey. In contrast, Traditional students tend to learn about the nature and effects of hydrogen bonding at one sitting, so perhaps can make the appropriate connections more readily.

The low level of correct responses to *Chlorides* indicates that this was perceived to be a difficult question. However, about 10% more Traditional students than SAC students give P-coded responses at all three surveys, indicating that a higher proportion of this sample begin A level with an understanding of intermolecular bonds.

The level of Q codes shows an intriguing pattern. The proportion of the SAC sample giving this answer decreases slightly from 20% to 16% over the three surveys, while the figures for the Traditional sample increase from 23% to 30%. This suggests that Traditional students move towards the Q category. All the Q -coded answers for the Traditional sample are coded Q1, "covalent substances have lower boiling points", suggesting that students learn this during the course and apply the information here. While this answer is not incorrect, it is not the full explanation.

However, the SAC sample retain a much higher level of T-coded answer than the Traditional group over the three surveys. The initial difference is only 5%, which falls well within the error variance level, but by the third survey this has increased to 19%, reaching a peak at the mid-point of 24%. Closer scrutiny of the T-category responses reveals that most are "Ionic bonds can't be broken by heating" (T1) or "Covalent bonds are weaker than ionic ones, so break" (T3). At the first survey, 16% of the SAC sample were coded T1 and 27% T3; at the second survey, these changed to 27% and 30%; and the final percentages were 16% and 26%. So, the increase in proportion of T-coded answers at the second survey was almost entirely due to more students giving the T1 response. In contrast, very few Traditional students give the T1 answer at any stage - the equivalent values are 4%, 6% and 0% for the first, second and third surveys respectively. However, 33% of the Traditional sample give the T3 response at each of the surveys. Thus, the T1 response is common to SAC students alone, but both groups give T3-coded answers. These data suggest that SAC materials prompt some students to think that "ionic bonds cannot be broken by heating". Such a misunderstanding may develop through misapplication of information learned about ionic lattices, which, as the previous chapter showed , is taught in early units. The values for the T3 code, though, illustrate that neither course type helps students rescind the response "covalent bonds are weaker...".

Responses to *Chlorides* indicate that neither course type appears to be very successful in leading students to the correct answer. Traditional students seem to complete A level with less difficulties than SAC students, as the preceding discussion indicates. When the three questions concerned with intermolecular bonds are considered together, we see that hydrogen bonding is well-learned by both samples, but is relatively poorly applied by the SAC group in answer to *Boiling*. Evidence from the response patterns to *Chlorides* suggests that hydrogen bonding is the only type of intermolecular bonding which is readily described by students.

6.9 Thermodynamics

Table 6.9 shows changes in matched sample responses to *Methane* and *Energy change*.

	Code	SAC 1	*Trad 1*	SAC 2	*Trad 2*	SAC 3	*Trad 3*
Methane	P	6	16	41	40	57	44
	Q	6	-	11	1	7	1
	T	83	79	48	56	34	49
	U	5	5	-	3	2	6
Energy Change	P	10	20	26	20	26	31
	Q	19	23	37	39	43	29
	R	11	16	17	13	10	10
	S	7	9	3	13	7	13
	T	21	17	10	13	6	16
	U	32	15	7	2	8	1

n = 70

Table 6.9: Percentages of SAC and Traditional students giving each response type to *Methane* and *Energy change*

Table 6.9 shows large increases in the proportion of P codes for *Methane* in both samples over the three surveys. The increase for the SAC group is greater than that for the Traditional group. About 54% of the SAC students give the response "Energy is from bond formation" at the third survey compared with about 40% of the Traditional group.

These large increases in P codes occur almost entirely because students are moving from the T category to P at either the second or third surveys. About 80% of both groups give T-coded answers at the first survey. At this stage, the most frequent response among the SAC students is code T6, given to students who do not answer the final part of the question. About 10% of the Traditional sample give this type of response. By the third survey, this figure decreases to 7% of the SAC sample and 6% of the T students.

The T-coded responses illustrate the difficulties some students have with the source of energy in reactions. The response T1 includes the explanations that energy "is from bonds in CH_4" (T1a), "comes from bond breaking" (T1b) or is "stored in CH_4" (T1c). Together, this code group accounts for 16% of the SAC sample at the first survey, 29% at the second and 20% at the third. The comparable figures for the Traditional sample are 16%, 22% and 32%. The level for the SAC group reaches a peak at the point immediately after teaching. The high point for the Traditional sample occurs at the end of the study, suggesting that some of these students developed the idea in the latter stages of their course, well after teaching. Nonetheless, these figures demonstrate that the notion of energy being "contained" in bonds is persuasive regardless of course type. The SAC approach seems to dissuade students from this point of view more effectively than that used in Traditional courses.

Responses to *Energy change* show some increase in the level of P-codes, but these are much less marked than those observed for *Methane*. The initial 10% difference between the SAC and Traditional groups arises because about 13% of the Traditional sample recognise the reaction to be exothermic, while a further 7% give answers coded P1, "energy is released on bond formation" or P3, "electron(s) are lost / gained". Only about 9% of the SAC group give a P2 answer, while one other student is coded P3. These figures indicate that some of the Traditional group may have been taught about this reaction in detail at GCSE. At the second survey, the position is reversed, with the SAC sample giving the higher level of P-codes. At this point, the most popular answer is again P2, given by 17% of the SAC sample and 13% of the Traditional students. This improvement for the SAC group occurs after teaching about the energetics of the formation of ionic compounds in unit 3, *From Minerals to Elements* , suggesting that this material does influence some students' responses to this question. This implies that work on the formation of ionic lattices may be carried out later among the Traditional students and that the SAC group do not have a second opportunity to change their ideas.

The level of Q-coded answers given by the SAC sample increases steadily across the three surveys from 19% to 43%. The increase arises because more students are coded Q1 by the third survey, that is, students selected diagram A or C, explaining that "energy is needed to break the Cl_2 bond or start the reaction". The proportion offering this response increased from 3% at the first survey to 20% by the third. The pattern for the Traditional group is different. Here, the increase in Q-coded responses is due to an extra 6% who give the Q4 response. This falls within the error variance range, so effectively this is not a significant change. These data therefore imply that more SAC than Traditional students respond with ideas about individual bond enthalpies.

Relatively small proportions of both groups give responses coded R. These students focus on the reaction itself, rather than the diagram, most selecting A or C and explaining that "Sodium and chlorine are reactive". By the third survey equal numbers of both samples are coded R1 and R2. Of greater interest are the differences between the proportions giving S-coded answers. The levels for the SAC group remain low throughout, whereas an increasing number of the Traditional students are placed in this category. At the third survey, about 9% of the Traditional group and 2% of the SAC sample select diagram B and explain "the reaction needs lots of energy to start". This may indicate that the presentation of energetics in SAC prevents students from acquiring this type of reasoning.

Changes in the levels of T-coded responses also occur. For the SAC group, the proportion decreases from 21% to 6% by the third survey, mostly because students move away from the T4 response in which diagram B is selected and accompanied by an uncodeable explanation. The level for the Traditional group drops slightly at the second survey, but returns to 16% by the third survey. About 13% of the Traditional sample give a response coded T4 at this final stage, confirming perhaps, that SAC tends to assist students in developing correct ideas about energy diagrams, while more Traditional students persist with misconceptions.

The proportions offering no response to *Energy change* decrease markedly over the three surveys, indicating that most students at least recognised the type of diagram by the end of their courses and could attempt an answer. About 79% of the SAC sample and 69% of the Traditional sample changed to the P, Q or R category by the third survey. For the SAC group this represents an increase of 39% over the first survey value, but for the Traditional group the increase is only 10%. This shows that although the SAC group began at some disadvantage, the course enabled them to apply appropriate reasoning by the end of their studies.

These questions show that SAC is perhaps more successful than Traditional-type courses at developing correct ideas about thermodynamics. More Traditional students seem to complete their courses thinking that energy comes from bond-breaking, and more misinterpret an energy diagram. The SAC students give more correct answers to *Methane*, where the context of the question matches that of the unit teaching most of the thermodynamics, but have difficulty applying this knowledge to the different type of reaction shown in *Energy change*. The improvements observed for the SAC sample are particularly encouraging given that a higher proportion of Traditional students appear to begin their A level courses with some knowledge of thermodynamics and therefore could be expected to perform more effectively at the final stage. Evidently, this beginning knowledge does not confer any advantage on the Traditional students.

6.10 Equilibria and Rates of reaction

Table 6.10 shows changes in matched sample responses to *Reactions* and *Reaction rates.*

	Code	SAC 1	*Trad 1*	SAC 2	*Trad 2*	SAC 3	*Trad 3*
Reactions	P	-	-	-	3	1	7
	Q	11	21	34	39	44	56
	R	3	-	6	1	-	-
	S	-	-	-	-	-	-
	T	72	60	53	54	52	30
	U	14	19	7	3	3	7
Reaction Rates	P	1	1	-	4	6	6
	Q	26	30	29	32	36	38
	T	59	58	59	60	44	53
	U	14	11	12	4	17	3

n = 70

Table 6.10: Percentages of SAC and Traditional students giving each response type to *Reactions* and *Reaction rates*

The level of P codes for *Reactions* shows very little change for either sample, with only one of the SAC students and 7% of the Traditional sample being placed in this category at the third survey. Reasons for the low proportions of P codes were discussed earlier. Large changes in the levels of Q-coded answers are observed, with higher proportions of the Traditional sample giving this type of response at every survey. Closer scrutiny of the response types reveals that at the first survey, 11% of the Traditional sample and 7% of the SAC group give the responses "the first reaction is reversible" and "conditions need changing to go back to the reactants". By the third survey, 17% of both samples respond in this way. The final difference in Q-coded percentages occurs because 21% of the Traditional sample and only 10% of the SAC group explain that "the reactants are not fully used up" in the nitrogen / hydrogen, but "are fully used up" in the oxygen / hydrogen reaction (Q1). This response is an alternative way of saying that some reactions go to completion, while others do not, which is close to an explanation based on values for K_p.

Very few students give R or S-coded answers in either group over the three surveys. This indicates that both samples are polarised between partial understanding and expressing misconceptions. At the first survey, 61% of the SAC sample explained in answer to the first part of the question that "the first reaction is reversible" and to the second part that "most reactions are not reversible" (code T1). This answer simply states what is obvious from the inclusion of reversible arrow in the hydrogen / nitrogen reaction, and therefore is a way of restating the question. At the second survey, the proportion decreased significantly, to 43%, and remained almost unchanged at 44% by the third survey. By contrast, 39% of the Traditional group were coded T1 at the first survey, increasing to 43% at the second survey but decreasing to 23% at the final stage. The difference in the number of T1 responses accounts for the large variation in T-category proportions observed at the third survey. These figures suggest that more SAC students are content to simply describe the obvious, while their Traditional counterparts can offer explanations closer to the expected answer.

These data suggest that although neither sample gives the correct answer in high proportions, more of the Traditional sample approach an acceptable explanation. One reason for this may be that equilibria is taught very late on in the SAC course, so it may well be that even by the third survey some (or all) of the SAC sample may not have studied the topic in detail.

Table 6.10 shows that few students in either sample give P-coded responses to *Reaction rates*. The way in which SAC students learn about rates of reaction was described in the previous chapter. These data show that similar effects are observed among Traditional students, indicating that neither course type assists students in making links between the shapes of graphs and chemical events. Levels are approximately equal in all categories, and relatively little change occurs in any response type. The largest difference is observed in the proportion offering T-coded responses at the third survey. Here, about 9% of the SAC sample, but 16% of the Traditional group, give responses coded T4b, which, as Table 5.24 shows, represents responses which cannot be given any other code. This may suggest that the Traditional students were marginally more uncertain about interpreting the graphs than the SAC group, but without firmer data obtained, for example, by interview, reasons for this difference remain unclear. These data therefore indicate no difference in the effects of Traditional or SAC approaches on students' ideas about rates of reaction. One possible explanation for these figures is that neither sample had studied rates of reaction in depth by the time of the third survey. Traditional courses and SAC both leave kinetics until the last few months, so large changes in students' responses are unlikely.

6.11 Conclusions

This chapter shows that the performance of the SAC students is comparable to that of the Traditional students in most basic chemical ideas probed by this study. That is, for most questions, similar changes in responses were found, although some points of difference between the SAC and Traditional groups remain. These are discussed below. Conclusions about differences in performance of the Traditional and SAC students on these questions must be somewhat tentative, because, as explained below, the small size of the Traditional group makes the findings prone to differences between participating schools. Nevertheless, some useful points can be made. First, though, we will examine the differences which are apparent between the matched samples at the first survey.

6.11.1 First survey differences

Differences greater than the 12% threshold established in section 6.2 are observed at the first survey in some of the coding categories of seven of the twenty-three questions. In the case of three questions, *Precipitation*, *Methane molecules* and *Hydrogen bonds*, the Traditional students give between 14% and 31% more P-coded responses at the initial stage than the SAC students. In responses to *Tablet*, *Iron sulphide*, *Boiling* and *Energy change*, Traditional students give between 12% and 18% fewer Q, T or U codes than the SAC sample. These data indicate that the Traditional sample seem to perform consistently better than the SAC group at the first survey, and it appears, therefore, that the samples are not perfectly matched. Factors other than those discussed in section 6.1.3 are now considered.

First, students following Traditional A level courses may have also studied traditional-style GCSE courses. So, although the groups are matched on performance in GCSE, the actual content of the Traditional students' GCSE courses may lead them to perform better in some areas.

Second, a higher proportion of Traditional students attended independent (private) schools, experiencing better continuity of teaching than their SAC counterparts. Thus, at the start of the survey, the Traditional students were more inclined to adopt a positive attitude towards the research because it was being presented to them by a teacher they already knew in familiar surroundings. A higher proportion of SAC students moved from an 11 - 16 school to a Sixth Form College for their A level courses and so were given the first survey by a stranger in a strange place. In this environment, more students are more likely not to give their best performance.

These reasons offer the most likely explanations for the better performance of the Traditional group at the first survey. However, subsequent surveys showed that in most cases the discrepancy was resolved, suggesting that these early advantages did not affect students' final responses and that the performance of SAC students at third survey equalled that of the Traditional sample. Let us now discuss some other outcomes of the comparison.

6.11.2 Points of difference between the SAC and Traditional samples

From the figures presented in the data tables in this chapter, it appears that the SAC sample shows greater levels of improvements in the proportions of P-codes given to four questions, *Methane, Hydrogen bonds, Precipitation* and *Iron sulphide* while the Traditional students show greater improvement in response to *Hydrogen chloride.* Using the conclusion to chapter 5 as a guide, let us examine these in more detail.

First, the high levels of increase found in the matched sample responses to *Methane* and *Hydrogen bonds* are similar to those found for the SAC sample as a whole. For both questions we find that the SAC students out-perform their Traditional counterparts in terms of the improvement observed in the level of P-codes. Each question will be considered in turn.

The increase observed for *Hydrogen bonds* is 57% while that for the Traditional group is 38% (Table 6.8). Even allowing for error variance of 12% this is still a marked difference and strongly implies that the SAC approach of revisiting hydrogen bonds on several occasions is indeed more successful than the more Traditional one of studying all aspects of chemical bonding early on. This is reflected in the pattern of change in the P-codes: the level for the SAC group increases over the three surveys, whereas the Traditional group improve only between the first and second. Student 331 also said in her interview that "hydrogen bonds keep popping up all over the place", presumably because she kept meeting new examples of hydrogen bonds as she worked through the units.

For *Methane,* Table 6.9 shows a 51% increase in P-codes for the SAC group over the three surveys, while the Traditional sample improve by only 28%. Again, this difference is markedly larger than the 12% margin allowed for error variance. In chapter 5 I reported that SAC students frequently cited unit 2 of the course, *Developing Fuels,* as a trigger for learning about energy in chemical reactions. The context used in this unit is a familiar one - the story of petrol - and this seems to assist students' learning about basic thermodynamics in a way which a more Traditional approach using concepts alone does not.

assist students' learning about basic thermodynamics in a way which a more Traditional approach using concepts alone does not.

A higher proportion of SAC students also improve their answers to *Precipitation*. A moderate increase of 26% was observed for the whole sample; Table 6.4 shows a larger figure of 37% across the three surveys. Even though these figures differ, it is quite striking that no change is found in the level of P-codes given by the Traditional sample over the three surveys. This implies that SAC develops students' ideas about precipitation reactions while Traditional courses do not. However, it must be noted that the starting level for the Traditional sample was much higher - this is one of the points of difference noted above - so perhaps all we are seeing is the effect of a reduced scope for improvement among the Traditional students.

Table 6.5 shows the levels of increase in P-codes for the question *Iron sulphide*. The SAC sample increases by 30% over the three surveys while the Traditional sample begins at about the same level and increases by 18%. The difference appears to be significant, but inspection of Table 5.11 shows an improvement of around 20%. So, the discrepancy between the two samples may perhaps be only attributable to error variance. In other questions involving reacting mass reasoning, SAC students do not show a markedly different level of improvement.

Traditional students seem to out-perform the SAC sample in one question only, *Hydrogen chloride*. The observed increase in the level of P-codes of 38% for the Traditional group is significantly higher than the 17% found for the SAC sample. Table 5.7 indicates that the whole SAC sample also increases by 17% over the three surveys. So, the Traditional approach to learning about the dissolving of a covalent molecules to make an acid seems to be more successful. It is difficult to assess reasons for this, other than to suggest that SAC students may learn about widely applicable chemical ideas (such as the release of energy on bond formation and the nature of a hydrogen bond) through frequent re-visiting, while Traditional students can perhaps identify individual examples of chemistry such as the formation of hydrochloric acid more readily. Perhaps the SAC students revisit certain chemical ideas so often they lose sight of other equally significant ones. Responses to *Hydrogen chloride* were also discussed in a group of questions each including ideas about ions and ionic compounds. This will be raised again in the next section.

6.11.3 Points of similarity between SAC and Traditional samples

The data presented in this chapter suggests that points of difference between SAC and Traditional students are few, and that therefore the findings described in chapter 5 are generally applicable to A level students as a whole. Before the final chapter, in which I consider how the findings relate to the literature review (chapter 2) and those described in chapter 3, it is worth summarising the key ones here.

First, responses to *Hydrogen chloride* apart, ionic bond formation and the behaviour of ionic compounds appears to be difficult for students to describe. The changes in P-codes observed for the matched samples in answers to *Energy change, Solution* and *Sodium and chlorine* are all similar to those described in chapter 5, indicating that this is problematic for all A level students. For sample, exactly 30% of both SAC and Traditional students give S and T-coded responses to *Solution* at the third survey, many of whom think that sodium chloride "gives off a gas" or that mass is not conserved when the solid dissolves in water.

Second, neither course type seems to encourage the development of ideas about intermolecular forces other than hydrogen bonds. Evidence for this is found in the comparable levels of increased P-codes for *Chlorides* and *Boiling.* While responses to *Hydrogen bonds* reveal that students give adequate explanations and descriptions of this intermolecular bond type, *Chlorides* reveals that both groups are reluctant to name any other form of intermolecular link. Even though the question does not ask for "van der Waals' forces" to be named, students do not appear to be aware that intermolecular bonds are responsible for the differences in boiling points. This may be because students are well-trained to identify hydrogen bonds almost to the exclusion of any other type, and cannot respond easily when these are absent. The comment of the SAC student 331 that "hydrogen bonds keep popping up" may well be true for the SAC students, but seems to be to the detriment of their recalling other intermolecular links. Table 6.8 suggests that the problem may be slightly less pronounced for the Traditional students, who give less T-coded responses than the SAC students at the third survey.

A third common area of difficulty is understanding open system chemical reactions. Responses to *Petrol* and *Power Station* show little difference in the levels of P-codes at the third survey, even though *Power Station* involves a calculation. Although more of the Traditional students give P-coded responses to both questions at the third survey and more SAC students give T-coded answers at this stage, only about 40% of each group get the questions correct. The influence of the contextual approach used in SAC to teach ideas about combustion appears to be limited, as decreases are observed in the proportions of P-codes given in answer to both questions between the second and third surveys. However, Table 6.6 implies that the Traditional approach is no more successful. One possible reason for students' difficulties may be that both questions feature reactions in which a gas (oxygen) is a reactant and gases (carbon dioxide, and, for *Petrol,* water vapour) are products. Chapter 2 reported that gases are the hardest state of matter to understand, as there is no tangible reason for supposing that gases have mass. Other reactions in the test paper feature gases either as reactants or products, not both. Thus, these two questions compound the difficulty, resulting in low levels of P-codes.

6.11.4 Contexts can be an advantage ....

The learning of chemical ideas in SAC is firmly rooted in a contextual approach. The advantage of this is clear where thermodynamics concepts are involved, as more SAC than Traditional students complete their course with the correct ideas about bond breaking and bond making (responses to *Methane*). SAC students learn about thermodynamics in the context of the petrol / oxygen fuel system, and, in the same unit (*Developing Fuels*, unit 2), learn that other hydrocarbons such as methane also provide energy when burned in oxygen. The source of the energy is clearly identified as making oxygen / carbon and oxygen / hydrogen bonds.

6.11.5 ...but also restrictive...

SAC students are secure in their application of the bond breaking/bond making idea while the context is fuel-based. Responses to *Energy change* indicate that more Traditional students respond that energy is given out in bond formation in this reaction, which is between sodium and chlorine, not oxygen and a fuel. This suggests that some SAC students may be able to apply knowledge within one context, specifically that in which they were taught. They are unable to "carry" knowledge from one context to another and apply the same principle in a different situation.

SAC students' responses to *Power Station* show that an increase in the level of P codes occurs at the second survey, immediately after students have studied the *Developing Fuels* unit, where this type of calculation is met for the first time. The context of the question, combustion of fuels in oxygen, matches that of the unit. Table 6.6 shows that the level of P-codes decreases at the third survey, and that students revert to Q, T and U-coded responses. In contrast, the level of P codes among the Traditional students increases at both the second and third surveys. These data imply that some SAC students forget how to answer *Power Station* once the context is no longer immediate. At the time of the third survey, SAC students were studying units entitled *Aspects of Agriculture* and *Oceans*, in which the contexts are unrelated to fuels and oxygen. The move away from P-coded answers may arise because students meet calculations in other contexts, but cannot recall how the method applied to earlier ones. Some students are limited to applying knowledge in the current context.

A third example of students being restricted to application of knowledge to specific contexts is found in responses to *Element and Compound.* Higher proportions of the Traditional group gain P-codes here because they are able to name mass spectrometry as an appropriate technique for identification of elements and compounds. As the interview with student 105 showed, SAC students learn about mass spectrometry in the context of carbon and carbon compounds, not with elements and other inorganic compounds, and some seem to think that mass spectrometry applies to this application alone.

6.11.6 Overall effects

Responses to some questions provide evidence that use of contexts in SAC may cause students to restrict their application of knowledge to that context alone. This suggests that for some chemical ideas the use of contextual material needs careful handling. Students may thoroughly learn the chemical idea within a firm structure provided by the context, but are unable to reproduce this learning when the structure is removed. This can be prevented if, as in the case of chemical bonding, the chemical idea is revisited in more than one context.

However, few questions show significant differences between the levels of P-codes across the three surveys, suggesting that distinctions between the SAC and Traditional groups are limited and the SAC approach does not seem to positively or negatively affect students' performance on these questions overall. Perhaps more significant are the ways in which similar levels of P-codes are attained, as inspection of the data tables and the preceding discussion indicates.

The merits of a contextual or concept-led approach to the subject can be considered from these data. It seems clear from this chapter that SAC is at least as good as Traditional courses at prompting change in students' understanding of basic chemical ideas and in thermodynamics appears to be appreciably better.

Chapter 7

Conclusions

This final chapter will have two sections. First, I will place the findings in the context of the literature reviewed in chapter 2, drawing together the concluding sections of the three preceding chapters and discussing answers to the research questions described in chapter 1. Second, I will look critically at the approach used and describe ways in which the methodology could have been improved.

7.1 Answers to the research questions

Chapter 1 set out three research questions which the study would address and attempt to answer. Here, I will summarise the findings of the data chapters, and use these, along with the review of the literature (chapter 2), to see how far these questions can be answered.

7.1.1 The understanding of beginning A level students

Section 2.12 suggests that some beginning A level students may not have a clear understanding of the chemical reaction, perhaps the central idea of chemistry. They may not, for example, apply particle ideas consistently; they may confuse mass and density; they may misuse chemical vocabulary. In section 4.14, I discussed the key findings of the first survey. These support and extend the evidence from the literature and establish the proportions of beginning A level students with misconceptions about the basic chemical ideas investigated. It may be worth summarising these again here.

A naive view of matter

Two aspects of beginning A level students' ideas about matter are worth discussing here. First, some students apply particle ideas inconsistently; second, a high proportion of students find the evolution of gases difficult to explain.

Responses to *Molecules* (section 4.5.1) suggest that about 70% of beginning A level students can distinguish between pictorial images of the particles comprising elements, compounds and mixtures. This figure is significantly higher than the 30%

of 15 year olds reported by Briggs and Holding (1986) (section 2.4). Although this high level suggests that a majority of beginning A level students know that matter is made up of particles, some students seem to misapply this notion. For example, about 6% suggest in answer to *Sodium and Chlorine* that particles can expand, or explode (section 4.10.2); about 10% suggest that atoms can change into those of another element (from copper to carbon in the responses to *Copper*); and approximately 10% seem to think that matter can be destroyed (*Petrol*).

Gases seem to present difficulties for many beginning A level students. About 15% think that a gas is produced in any chemical "reaction" (*Solution, Precipitation*), while 13% imagine that a gas which is evolved is present prior to a chemical event and is simply pushed out, or displaced, rather than being formed by rearrangement of atoms or ions. de Vos and Verdonk (1987a) describe this as students' tendency to conserve the identity of all substances in a reaction (section 2.5.2). Two factors may contribute to these ideas. First, students' naive views of matter means that although they know about atoms, they do not use this knowledge in explaining chemical phenomena. In describing the origin of a gas, students need first to recognise that the reactants which produce it are made up of atoms or ions. Their next step is to realise that these are rearranged. Students explain the origin of a gas by thinking that it already exists somewhere in the reactants, an idea which does not involve them in thinking about particles. Second, the literature review points to gases being problematic because most of them are invisible (section 2.2). Visible evidence for the production of a gas is usually clear, colourless bubbles arising from a liquid. Students have no concrete way of knowing either what the gas may be (unless they carry out a test) or where it came from. The only way they can see that it exists is to look at the bubbles. This "invisibility" compounds the non-particulate view of matter, and lends support to the idea of the pre-existence of the gas.

Differences between elements, compounds and mixtures

This study indicates that about 70% of beginning A level students recognise the particles present in a mixture, a figure which compares favourably with that of about 50% for 15 year olds (Briggs and Holding, 1986). However, responses to *Element and Compound* (section 4.5.2) suggest that although pictorial representations of the particles are well-known, only about 40% of students can give correct definitions for "element" and "compound" and only around 11% offer acceptable tests to distinguish between them. The ability to give the correct definitions depends on the students' memories and assumes that students will have been taught the correct definitions during their pre-16 course. Poor recall and lack of teaching may therefore contribute to the 40% figure. Even allowing for this, the low figure 11% for the tests for an element and a compound is striking. It may in part be explained by the level of difficulty of the second part of the question. To produce a correct answer, students need first to realise that elements comprise one type of atom and compounds more than one. Then they have to recall a way of testing for the number of types of atoms present in a substance. At the start of an A level course, many students do not know a suitable technique.

Chemical change

Several aspects of beginning A level students' understanding of chemical reactions were probed during the study. A brief summary is given here.

A majority of beginning A level students conserve mass when presented with a closed system chemical reaction such as that shown in *Phosphorus* (section 4.7.1). This represent a significant improvement on the 33% of 15-year olds reported by Andersson (1984) and Driver (1985) (section 2.6.1). However, difficulties arise for students when the reaction system is not sealed, or when a change of state is apparent. For example, about 10% confuse mass and density, thinking that a solid is heavier than a liquid, and so this group believe that mass will increase when precipitation occurs (*Precipitation*). Others, around 13%, think that a gas is produced during a precipitation reaction or during dissolving, and therefore suggest that mass decreases when these events occur. Students' tendency to focus on the visible product of a reaction, reported in the literature review (for example, in section 2.12) may contribute to these responses.

Reactions involving oxygen cause further problems for beginning A level students. About 40% of 15 year olds were reported to think that the mass of steel combined with oxygen would be less than the starting mass of steel (section 2.7.2). The involvement of oxygen was not well known. Responses to *Petrol* suggest that beginning A level students are also unaware of the role of oxygen in combustion; about 38% gave responses which implied that oxygen was not involved. A further difficulty for some students is that combustion reactions "leave behind" a solid "product", usually described as "ash". About 10% think this means that the starting material has been burnt away or used up (*Petrol*). Their poor understanding of the gaseous state may contribute to this thinking, since students may believe that, because they cannot be seen, gases do not have mass. Thus, when one product of a reaction is a gas, the mass will decrease. Everyday perceptions of coal and wood burning to leave "ash" behind may also contribute to this reasoning.

Students' poor understanding of the rearrangement of atoms during a chemical reaction was reported in section 2.5.3. Evidence supporting this is found in responses to *Tablet*, in which about 30% of the sample implied that the gas pre-existed and was simply "pushed out" when the tablet was dropped in water (section 4.6.1). The same idea was found in some answers to *Hydrogen chloride*, which seemed to use "displacement" to mean "pushing out a gas which is already there".

Hydrogen chloride highlights beginning A level students' poor understanding of acids, which was discussed in section 2.5.3. Only 5% indicated that hydrogen ions are present in hydrochloric acid, while 28% thought that hydrogen chloride molecules were present. This response is an improvement on the non-particulate model reported by Nakleh (1992) and that of Hand and Treagust (1988), who note also note the absence of particle ideas in their 16 year old sample.

Difficulties with stoichiometry

The possible causes of students' difficulties with stoichiometry were noted in section 2.8. The responses of this population of beginning A level students to *Iron sulphide* suggest that about half can use reacting mass reasoning when given a simple situation, However, responses to *Power Station* imply that where no data is given far fewer students are able to apply the appropriate reasoning. Although this is perhaps unsurprising, this does indicate that many beginning A level students do experience difficulties with mole calculations.

Chemical bonding

Compared to other basic chemical ideas, little work had been carried out on students' ideas about chemical bonding prior to this study. About 55% of beginning A level students recognise symbols for single and double bonds (*Covalent bonds*, section 4.10.1), and describe them in these terms. They do not call them "covalent" bonds, and nor do they describe the numbers of electrons involved. The idea that carbon atoms "need" to form four bonds is apparent in about 25% of responses to *Methane molecules*. About 12% know that ionic bonds involve electron transfer, but not that energy is released when ionic bonds form. Responses to *Hydrogen bonds* indicate that around 21% of beginning A level students recognise the existence of intermolecular bonds between water molecules, although most of these (13%) simply explain the links as "weak bonds".

The low level of understanding of intermolecular bonds contributes to students' poor understanding of changes of state. About 28% think that steam comprises hydrogen and or oxygen (*Boiling*, section 4.10.3) and around 25% of beginning A level students describe vapour formation in terms of intramolecular bonds breaking (*Chlorides*, section 4.10.3).

Thermodynamics

Responses to several questions (including *Petrol* and *Phosphorus*) found that about 3% of beginning A level students think energy is absorbed or used up when chemical reactions occur. While this is much lower than the that two-thirds of 15 year olds who do not conserve energy (Brook and Driver, 1984), these questions did not specifically probe ideas about energy conservation. This study focused instead on students' ideas about the origin of the energy produced in the combustion of methane. About 13% of beginning A level students described methane as an "energy store", while about 30% thought that the energy came from "burning". These findings support the work of Ross (1993), who proposes that students are taught about "fuel-oxygen systems" rather than "energy stores".

Equilibria and Rates of reaction

Many responses to the questions probing students' ideas about equilibria and rates of reaction were coded T or U, suggesting poor understanding of these chemical ideas. Most beginning A level students gave simplistic responses to *Reactions*, stating that one reaction was "reversible" and the other was not. About 10% suggested that it may be more difficult to reverse one reaction than the other, but no-one explicitly used the ΔH data to support this. About 10% of students responded to *Reaction rates* (section 4.12.2) in terms of the reactivity of magnesium, choosing the graph with a high starting point for the second reaction. About 24% gave answers which were incomplete.

A summary of beginning A level students' understanding

Some students do not have a well-developed particle view of matter. This creates difficulties for them in understanding the differences between elements, compounds and mixtures and explaining what occurs in chemical reactions. Other students do not conserve mass in chemical reactions, and may confuse mass and density. Many students have poorly developed ideas about acids, combustion reactions and dissolving. Although students know about single and double bonds, many seem unaware that electrons are shared in covalent bonds and also find ionic bonds difficult to explain. Students cannot explain where energy comes from in combustion reactions. Equilibria and rates of reaction are also poorly understood.

Having established the level of understanding beginning A level students have of basic chemical ideas, we will consider next how their thinking changed during their experience of SAC.

7.2.2 Changes in the SAC students

Having established a baseline, my second objective was to find out in what ways student learning was influenced by the context-theory approach used in SAC. Chapter 5 details the changes in responses of the SAC sample to the diagnostic questions. Section 5.11 describes the findings in detail. Here, I summarise the changes under the headings used in the previous section.

A naive view of matter

Fewer students use particle ideas inconsistently by the end of a SAC course. No students use ideas about particles exploding or increasing in size at the third survey (*Sodium and chlorine*, section 5.8.2), although about 9% suggest that atoms change into those of another element (*Copper*, section 5.4.2) and 4% think particles can be destroyed (*Petrol*, section 5.7.2). While it is possible that these misconceptions may have changed in the light of students' learning in SAC, comparison of the data tables for these questions in chapters 4 and 5 suggests that students using poorly developed particle models of matter may have left their course after the first survey, or for some other reason did not complete three test papers. For example, tables 4.19 and 5.17 (1st survey column) show different percentages of students giving the T2 code; these correspond to fourteen and seven students respectively.

Students' difficulties with gases appear to have changed relatively little. Although about 6% of third survey responses suggest a gas is produced in response to *Precipitation*, the figure for *Solution* remains at around 15% and responses to *Tablet* are also almost unchanged (Table 5.5). These data imply that students have not learned that atoms are rearranged in chemical reactions and that this explain how gases are formed.

Differences between elements, compounds and mixtures

At the third survey, about 19% of students give correct definitions and acceptable tests for "element" and "compound". Although this represents some improvement on the level observed at the first survey, this suggests that many students remain unable to link particulate images of substances with physical tests to confirm the number of types of atom present. A contributory factor to this may be that SAC only features mass spectrometry in the context of carbon compound analysis and does not extend this to identification of isotopes of specific elements.

Chemical change

Some improvements are found in students' understanding of chemical changes. First, up to three-quarters of students know that mass is conserved in closed system chemical reactions (*Phosphorus*). Fewer students confuse mass and density, although responses to *Phosphorus* and *Precipitation* indicate that this misconception is not completely eradicated by the third survey. The proportion of students who think a gas is released when a precipitation reaction occurs has decreased to about 7%, but the comparable figure for *Solution* (code S2, Table 5.10) remains almost unchanged. This may indicate that some students persist in reading "sodium" instead of "sodium chloride" in the *Solution* question and so think that hydrogen gas is liberated.

Some students who did not understand the involvement of oxygen in combustion had learned the chemist's viewpoint by the third survey. Accepted responses to *Petrol* increased to about 36%, while the level of responses implying that oxygen was not involved decreased to around 30%. The notion that petrol was "burnt away" also decreased to about 4% at the third survey. Tables 4.16 and 5.14 suggest that students leaving their course or failing to complete three surveys may contribute to this change.

Third survey responses to *Tablet* suggest that a majority of students have not learned that atoms rearrange during a chemical reaction (section 5.4.1). Responses to *Hydrogen chloride* support this, as a similar proportion of students use the notion of displacement of gas in the same way as in the first survey.

Table 5.7 shows that about one-quarter of students complete SAC with the basic chemical idea that hydrochloric acid contains hydrogen ions. However, the idea that hydrogen chloride molecules are present is persistent; about 40% offer this response at the third survey. These data imply that the effect of SAC on students' ideas about acids is patchy.

Little change is observed in the proportions of students offering any response to *Solution* (Table 5.10), suggesting that although SAC features the dissolution of ionic lattices, the material does not affect students' thinking appreciably. Added to the increase in those suggesting that molecules of hydrogen chloride are present in hydrochloric acid, and we find that dissolving of either a gas or a solid presents persistent difficulties for students.

Difficulties with stoichiometry

By the third survey, about 72% of SAC students use reacting mass reasoning (*Iron sulphide*, section 5.6.1), while 43% can calculate the mass of carbon dioxide produced by 1000 tonnes of coal (*Power Station*, section 5.7.1). While these data represent a significant improvement in students' understanding, a substantial minority complete SAC without changing their thinking. Students' difficulties with stoichiometry have been alleviated, but not eradicated.

Chemical bonding

Very large increases are observed in the proportion giving accepted responses to questions probing ideas about chemical bonding: about half of the students completing SAC describe covalent bonds in terms of the numbers of electrons being shared by two atoms (*Covalent bonds,* section 5.8.1); around one-third use ideas about electron configurations or stability when explaining why methane has the formula CH_4 (*Methane molecules*, section 5.8.1); about 34% use accepted ideas in describing the formation of ionic bonds (*Sodium and chlorine*, section 5.8.2). These data indicate that SAC successfully develops students' ideas about intramolecular bonds, although a number of students still find the formation of ionic bonds relatively harder to explain.

Students' thinking about intermolecular bonds also shows significant improvement in the level of accepted ideas. Almost 70% correctly describe hydrogen bonds in water (*Hydrogen bonds, section* 5.8.3) and about 45% think that steam is in the bubble produced when water boils (*Boiling*, section 5.8.3). However, some problems remain, . About 24% of students have acquired the idea that hydrogen bonds are an "attraction, not a real bond" and 22% persist with the notion that intramolecular bonds break when a state change occurs, suggesting that the development of students' ideas about chemical bonding is not completely satisfactory. In particular, few students appear to have developed any understanding of van der Waals' forces; many seem to think that hydrogen bonds are the only type of intermolecular bond.

Thermodynamics

The notion of energy being absorbed or used up during chemical events is retained by about 2% of students (*Petrol* and *Phosphorus*), implying that this idea remains plausible. Responses to *Methane* (section 5.9.1) indicate that about 50% of students have learned that energy is produced in bond formation, while the proportion suggesting that energy is from "burning" decreased to only 5% by the third survey. This is a substantial improvement on the first survey figures and can largely be attributed to early SAC units. However, students' progress is not completely positive, since about one-quarter of the sample suggested at the third survey that energy came from bond breaking, or was "stored" in methane, an increase of about 16% on the first survey figure.

Equilibria and Rates of reaction

Relatively little change is observed in the level of accepted responses to *Reactions* and *Reaction rates* over the three surveys. Although about 40% of students (*Reactions*, section 5.10.1) realise that one reaction is more difficult to reverse than the other, a further 40% persist with a simplistic response which focuses on the reversible arrow alone. These figures suggest that *Reactions* remained a difficult question for students; few used the ΔH data and only 5% gave an accepted response at the third survey.

Responses to *Reaction rates* were almost completely unchanged in any category. Interviews with students confirmed that some associated high reactivity with fast reaction rate, while others thought that reaction rates always begin at zero, regardless of the reactants. This question indicates that students completing A level are not able to link graph shape with the type of reaction occurring.

Effects of the context-theory approach

The above summary suggests that the context-theory approach seems to be most effective in developing students' basic ideas about chemical bonding and thermodynamics. This may be because the SAC approach allows these ideas to be revisited several times, and therefore permits students' thinking to develop during the course. SAC students' experiences of thermodynamics in particular appear to be sufficiently "powerful" for them to overthrow their misconceptions about energy (see section 1.3) in favour of a chemist's view.

A moderate improvement is found in students' understanding of reacting mass reasoning. Calculations, as the literature review notes (section 2.8), pose notable difficulties for students. SAC permits students to develop their calculation skills by beginning with the relationship between moles, relative molecular mass and mass measured in grams in the first unit and progressing gradually towards calculation of reaction rates and equilibrium constants towards the end of the course. This evidently benefits students, although some still appear not to have grasped the basic skills by the third survey.

Small improvements are observed in students' ideas about elements, compounds and mixtures, chemical changes and dissolving. The low level of change may in part be explained by the fact that some of the chemical ideas probed may not receive explicit attention in SAC. For example, the application of mass spectrometry to elements is not mentioned; the rearrangement of atoms during chemical reactions is not discussed; the conservation of mass in dissolving is not considered. However, it is also apparent that some chemical ideas are featured in course materials and little or no effect on students' understanding is observed. The dissolution of ionic lattices and the formation of acids are two examples. Reasons for this lack of progress are unclear.

Almost no change at all is observed in students' ideas about equilibria and rates of reaction. One reason for this is that students had not completed all the units of the course by the third survey, and the later units completed the coverage of these chemical ideas. So, as students had not studied the relevant material in full, it is unlikely that their responses would change significantly.

Finally, some students seem to have acquired misconceptions about specific chemical ideas through their study of SAC; about 25% describe a hydrogen bond as "an attraction, not a real bond"; and one-quarter described methane as an "energy store". These notions are most likely to have developed because students misinterpreted teacher's intended meanings.

So, it appears that SAC promotes extensive change in two fundamental ideas probed by the study. While others show moderate improvement, several chemical ideas are less changed. This, and the acquisition of misconceptions by some students, suggests that the context-theory approach does not always influence students' learning in a positive way. Next, therefore, we need to establish if these findings are also applicable to students following Traditional approaches.

7.2.3 Changes in SAC students relative to Traditional students

Section 6.11.2 discusses in detail the points of difference between the SAC and Traditional students at the third survey. Few chemical ideas probed by this study show significant differences in the learning of SAC and Traditional samples. The context-theory approach appears to give SAC students an advantage over their Traditional counterparts in learning about thermodynamics, hydrogen bonding and precipitation reactions. Traditional students out-perform the SAC sample in response to *Hydrogen chloride*, suggesting that the Traditional approach is more effective in helping students to develop ideas about the formation and behaviour of solutions of ions.

Three common difficulties persist for both groups of students. First, apart from responses to *Hydrogen chloride*, Traditional and SAC students' understanding of ionic compounds remains undeveloped. This finding coincides with that of Taber (1993a) whose case study of one student (section 2.9.2) revealed poor development in her understanding of ionic bonds during her A level course. Second, neither group of students' ideas about intermolecular bonds extend beyond knowledge of hydrogen bonds. This contrasts with the work of Taber (section 2.9.3) whose case study student could describe the existence of van der Waals' forces between molecules of iodine. It may be that the implicit nature of the questions exploring this area contributed to this finding. Had more direct questions probing understanding about other intermolecular bonds been used, students' progress in this area may have been more clearly characterised. Third, both Traditional and SAC students find open system chemical reactions difficult to explain. Responses to both *Petrol* and *Power Station* show relatively little change over the three surveys. Besides the reasons for this discussed in section 6.11.3, the lack of change may be attributed to the wording of *Petrol* (discussed above, section 7.1.1) and to the requirement in *Power Station* to carry out a calculation without the data being immediately available.

Thus, almost all of the changes in understanding observed in the SAC sample can be generalised to a population of A level students as a whole. This study provides evidence that students' understanding of almost all the basic chemical ideas improves during an A level chemistry course. The context-theory approach seems to give students an advantage in two areas, and is not significantly detrimental to their progress in others. SAC presents students with a wider range of learning experiences than a Traditional course and attempts to develop a broad view of chemistry as a subject relevant to today's world. So, if these succeed in motivating students towards chemistry, and SAC students' progress in understanding is equal to that of Traditional students, then the aims of the course can be said to have been realised.

7.2 A critique of the study

With hindsight, some aspects of the study could have been improved. Possible improvements concern both the test questions and the overall research strategy.

7.2.1 The test questions

Several factors associated with some of the test questions may have influenced students' responses. These will be discussed in turn.

Wording of the questions

Several questions, *Phosphorus, Petrol, Sodium and chlorine, Chlorides* and *Methane molecules,* do not explicitly ask for the response (or responses) in terms of the chemical idea. Specifically, *Methane molecules* and *Sodium and chlorine* do not ask for responses using ideas about covalent and ionic bonds. *Chlorides* does not ask students to explain how intermolecular bonds affect boiling point; and *Phosphorus* and *Petrol* make no mention of oxygen. It could be argued, therefore, that the observed response patterns were influenced by the phrasing of these questions, and, for example, that if the bonding questions included the relevant terminology, students would have been better focussed towards the P-coded responses. Let us consider this in more detail, discussing the bonding questions first.

The literature review notes (section 2.12) that some students when given chemical terminology will use it to produce a "chemical" sounding answer without understanding chemists' meanings for these words. So, if *Methane molecules* had read "Explain in terms of covalent bonds why ...." some students may have simply responded "CH_4 has more covalent bonds than CH_3". This response does not yield any information about the students' understanding; it simply repeats facts given in the question. By leaving the question more "open" and not including specific terminology, students were permitted to respond in whatever way they considered to be the most appropriate. Including the words "covalent bond" may have induced a much smaller range of responses, and hidden the students' use of "valency" and their ideas about electron configurations. Further, it is possible that some students may have been put off answering the questions if technical-sounding words were included. Evidence for this is supplied by responses to *Substances*, where "chromatogram" caused difficulties (section 5.3.3) and *Precipitation* where the word "precipitation" was not well-known (unreported interview). So, in the case of *Chlorides*, where students were given the relatively unknown compound titaniumIV chloride to consider, adding "intermolecular bonding" may have caused an increase in the already relatively high level of no responses.

A second aspect of the wording of questions which may have affected students' responses is found in *Phosphorus* and *Petrol*. These questions include "noise" which may distract the student. The correct responses to these questions involve oxygen, yet the preamble to neither makes no mention of the gas. Instead, *Phosphorus* focuses students' attention on the phosphorus and the smoke produced, while *Petrol* describes only the mass of petrol and the car. The wording of these questions may have caused some students to give responses which were coded S or T. For example, the paraphrased response "the phosphorus dissolved in the water, so no change in mass" would be coded S1, but a student responding this way may have done so because these words are used in the question. However, relatively few students may be affected, as the level of S codes was low (around 5% or less) in all three surveys. More seriously, the response to *Petrol* "what goes in must come out" (T4a, Table 4.16) was given by between 17% and 26% of the SAC sample. Although this is a conservation answer, the involvement of oxygen is absent. If the equation for the reaction between petrol and oxygen had been included, some of these students may have realised their error and included the mass of oxygen in the total mass of exhaust gases. Others, who thought that oxygen does not have mass anyway, would not have changed their response.

I retained these questions in their original formats used by Andersson (1984) and Driver et al (1984) in order to be able to compare the responses of students aged 16 - 18 with those of younger students. This would indicate if A level courses influenced students' thinking about these reactions. So, although *Phosphorus* and *Petrol* can be considered flawed, the responses to them provide a useful guide to the development of students' ideas about open and closed system reactions.

Including data in the questions

Two questions, *Energy change* and *Reactions*, can be criticised on the grounds of the data provided. More strictly, in the case of *Energy change*, no data was provided for students about the scale of the energy changes shown in the diagrams. Several students commented on the difficulty this caused them at interview (section 5.9.2); they did not know how to decide if the energy changes were large or small. In devising the questions my thinking was to keep them simple to attract as many answers from beginning A level students as possible. So, although some students who were familiar with the diagrams may have appreciated a scale, others who had not seen such things before may have found this even more confusing.

Reactions provided enthalpy change data for the two reactions. As the question was investigating ideas about equilibria, ΔS or K_p values would have been more appropriate. However, many students do not learn about entropy and free energy, so many may not have been able to use the data anyway. By including ΔH values, I did give students some information on which they could base a response.

Could other questions have been included?

With hindsight, it may have been fruitful to include questions probing students' ideas about the purity of substances, the conservation of energy and van der Waals' forces. Questions on each of these topics would have added depth to the characterisation of students' understanding of several chemical ideas. A probe examining ideas about the purity of substances would have provided information about students' perceptions of the differences between elements, compounds and mixtures from an alternative perspective. A question exploring students' understanding of the conservation of energy would have added to the information about the source of energy in a chemical reaction, and particularly would have helped to explore the idea that energy is required to break chemical bonds. Including a question about van der Waals' forces would have helped to ascertain if students did learn about intermolecular bonds other hydrogen bonds.

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I attempted to consider all aspects of the chosen chemical ideas which could be probed at the time the test paper was devised. Almost all the questions included in the test paper yielded valuable data; and it is only these data which reveal the gaps mentioned above.

In conclusion, however, although some questions were flawed in one respect or another, the majority were clear and unambiguous. All of the questions yielded a range of responses and produced consistent response types over the three surveys. Interviews and scrutiny of the scripts indicated that most students could answer most of the questions, suggesting that despite the weaknesses indicated, the test paper was a valid instrument for data collection.

7.2.2 The overall strategy

Two main weaknesses in the overall strategy will be discussed. These are improvements in the role of the interviews and in the data analysis.

The role of the interviews

The interviews took place after the first and second surveys. The post-first survey interviews sought to verify students' responses to only a few questions (section 4.13) while those post-second survey explored students' responses to the full range of probes.

The study could perhaps have been strengthened if the focus for the interviews had been more consistent. An improvement would have been to interview the same students on both occasions. Thus, I could have used the interviews to follow changes in the thinking of a small sub-group of students throughout their A level course. This would have given extra support to the data presented in chapter 5. However, this strategy would have had the underlying assumption that the students selected for interview after the first survey would continue to provide useful information after the second. I had no way of guaranteeing that students' thinking would change. The approach I adopted, in which students whose thinking had changed were selected for the post-second survey interviews, yielded very valuable information.

An additional step would have been to interview students post-third survey. Although this was a possibility, I did not do this for two main reasons. First, scrutiny of the test papers suggested that the changes in students' responses were of similar type to those found after the second survey, so further interviews seemed unlikely to produce new information. Second, on a practical level, the interviews were very time-consuming both to transcribe and analyse. The third survey was timed to be as late as possible in the course to allow for maximum coverage of the chemical ideas and data analysis. There was no time to return after this to include a third set of interviews; by this stage the students had left their schools and colleges and were awaiting their examination results.

Data analysis issues

The data tables, student responses and interviews in chapters 4 and 5 provide extensive information about changes in students' understanding of basic chemical ideas. An additional analysis could have included exploring the extent to which an individual student's responses occur across more than one question. There are two ways in which this may have been useful. First, there is some overlap between questions in different groups: for example, *Energy change* and *Sodium and chlorine* explore students' ideas about the reaction between sodium and chlorine; and *Solution, Precipitation* and *Copper* all probe students' thinking about chemical reactions. Finding common themes in students' responses to questions in different groups may help to characterise their difficulties in more detail. Second, examination of students' reasoning across two or more questions probing the same chemical idea would have helped to identify more accurately students who had a misconception about a chemical idea; giving the same type of response more than once reduces the possibility that chance alone contributed to their answer.

Although the database would permit such an analysis, it was not carried out for two principal reasons. First, the possible number of cross-question comparisons is very large and while some connections are certainly more useful than others, it is nonetheless difficult to see how far such links should extend. Second, if I had looked at cross-question comparisons in responses after the first survey, to preserve continuity the same analysis would have been required on data from both the second and third surveys if the longitudinal nature of the work was to be preserved. Further, it was not clear what questions such analysis would have addressed.

Therefore, given the already extensive data already available, as presented in chapters 4 - 6, it was decided not to carry out extensive cross-question analysis.

7.3 Concluding comments

This study has provided fascinating and valuable data about the understanding 16 - 18 year olds students have of basic chemical ideas. The project has revealed that some students' ideas about some aspects of chemical bonding and thermodynamics undergo radical change during the Salters' A level chemistry course. These changes outstrip those of students following Traditional courses. This suggests that the context-theory approach provides especially powerful learning experiences for students, which prompts them to restructure their ideas towards more accepted viewpoints. However, misconceptions about other chemical ideas are not greatly changed by the time students complete their studies. Prominent among these are ideas about ions and ionic substances, the understanding of open system chemical reactions and the role and types of intermolecular bonding. SAC could be usefully developed further to promote development of students' understanding of these areas.

There is a need, in addition, for students to be presented with more explicit treatment of the fundamental chemical ideas like the differences between elements, compounds and mixtures, the conservation of mass in chemical reactions, and the rearrangement of atoms during chemical reactions. Students of all chemistry courses would benefit if they were given the opportunity to express any misconceptions and were encouraged to change them. The challenge now for chemical educators is to develop teaching strategies which meet the needs of these students. Only then will the findings of this study have served their purpose.

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Salters Advanced Chemistry Syllabus is published by the Oxford and Cambridge Local Examination Board

Salters Advanced Chemistry units:
1. The Elements of Life
2. Developing Fuels
3. From Minerals to Elements
4. The Atmosphere
5. The Polymer Revolution
6. What's in a Medicine?
7. Using Sunlight
8. Engineering Proteins
9. The Steel Story
10. Colour by Design
11. Medicines by Design
12. Aspects of Agriculture

13. The Oceans
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Appendix 1

Test papers A, B, C, D and E used in the pilot study

NAME ________________
(Optional)

Salters Advanced Chemistry Evaluation

Trial questions - set A

Thank you very much for helping with the evaluation.

Salters Advanced Chemistry is a new A level course under trial at schools around the country. Part of the evaluation of the course involves finding out how effectively basic chemical ideas are learned by its students.

The main study will begin in September 1992. Students taking the course will be asked to respond to questions like these at various stages during the two years. At this stage, the questions are being trialled. In answering them, please think carefully and **write what YOU THINK is the best answer.**

It would also help if you could provide the following information:-

(Delete as appropriate)

Date: __________ Male / Female

Name of school or college __________________

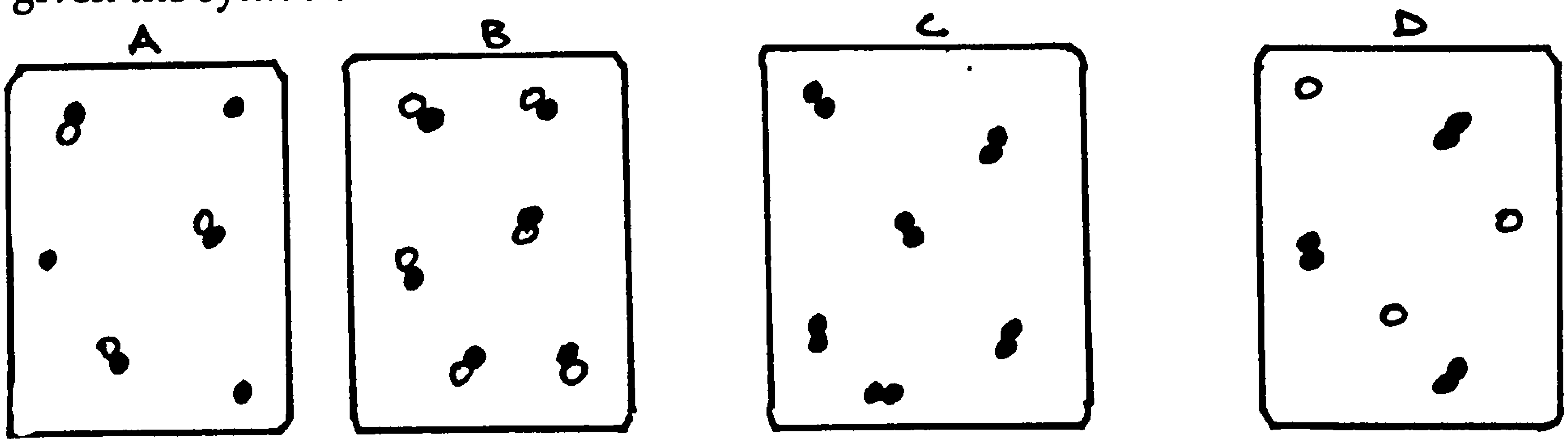
Year of A level course First/ Second

What subjects are you studying other than chemistry?
Please give subject and level e.g. A, AS, BTEC National

What GCSE science course or courses did you take?
Please also give the grades you obtained.

If you would like your answers returned to you, please write your name clearly on this front cover.

1. The diagrams lettered A - D represent the contents of four containers of gas. The gases are made from two chemical elements. The atoms of the elements are given the symbols ○ and ●.



Identify which container holds:-

(a) a mixture of the two elements;______

(b) a compound;_______

(c) one element alone._______

What do you think is in the container which you did not choose?

2. There are four parts to this question. In each part, you are asked to say if you think the substance described is a metal element, a non-metal element, a mixture of substances or a compound. You are also asked to explain your choice.

A **A yellow solid which does not conduct electricity, but burns in oxygen to give one product.**

Substance A is :-
a compound ☐ a non-metal element ☐ a metal element ☐ a mixture ☐

Explanation

B **A silvery grey solid which conducts electricity and burns in oxygen to give one product.**

Substance B is:-
a compound ☐ a non-metal element ☐ a metal element ☐ a mixture ☐

Explanation

C A colourless liquid which burns when ignited to give carbon dioxide and water.

Substance C is:-
a compound ☐ a non-metal element ☐ a metal element ☐ a mixture ☐

Explanation

D A dark blue liquid which produces several spots on a chromatogram.

Substance D is:-
a compound ☐ a non-metal element ☐ a metal element ☐ a mixture ☐

Explanation

3. Magnesium (Mg) is a chemical element. Water (H_2O) is a compound.

(a) Explain what you understand by the terms "element" and "compound".

Element

Compound

(b) What test (or tests) could a chemist do on a sample of magnesium to show that it is an element?

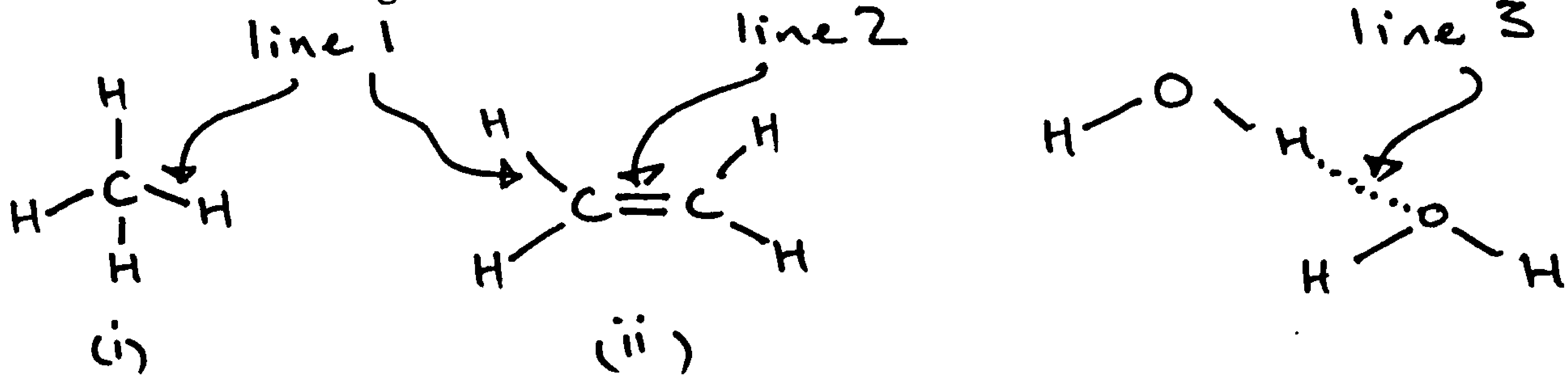
(c) What test (or tests) could a chemist do on a sample of water to show that it is a compound?

4. Imagine you could see an atom of carbon.

Describe :- (a) what you think it would look like;

(b) what physical properties it would have.

5. For each of these diagrams of molecules:-



(a) Name the substance shown;

(i)_______________ (ii)_______________ (iii)_______________

(b) Explain as fully as possible what you think the lines marked 1, 2, and 3 are trying to represent.

Line 1

Line 2

Line 3

(c) Explain the differences, as you understand them, between:-

(i) line 1 and 2;

(ii) line 1 and 3.

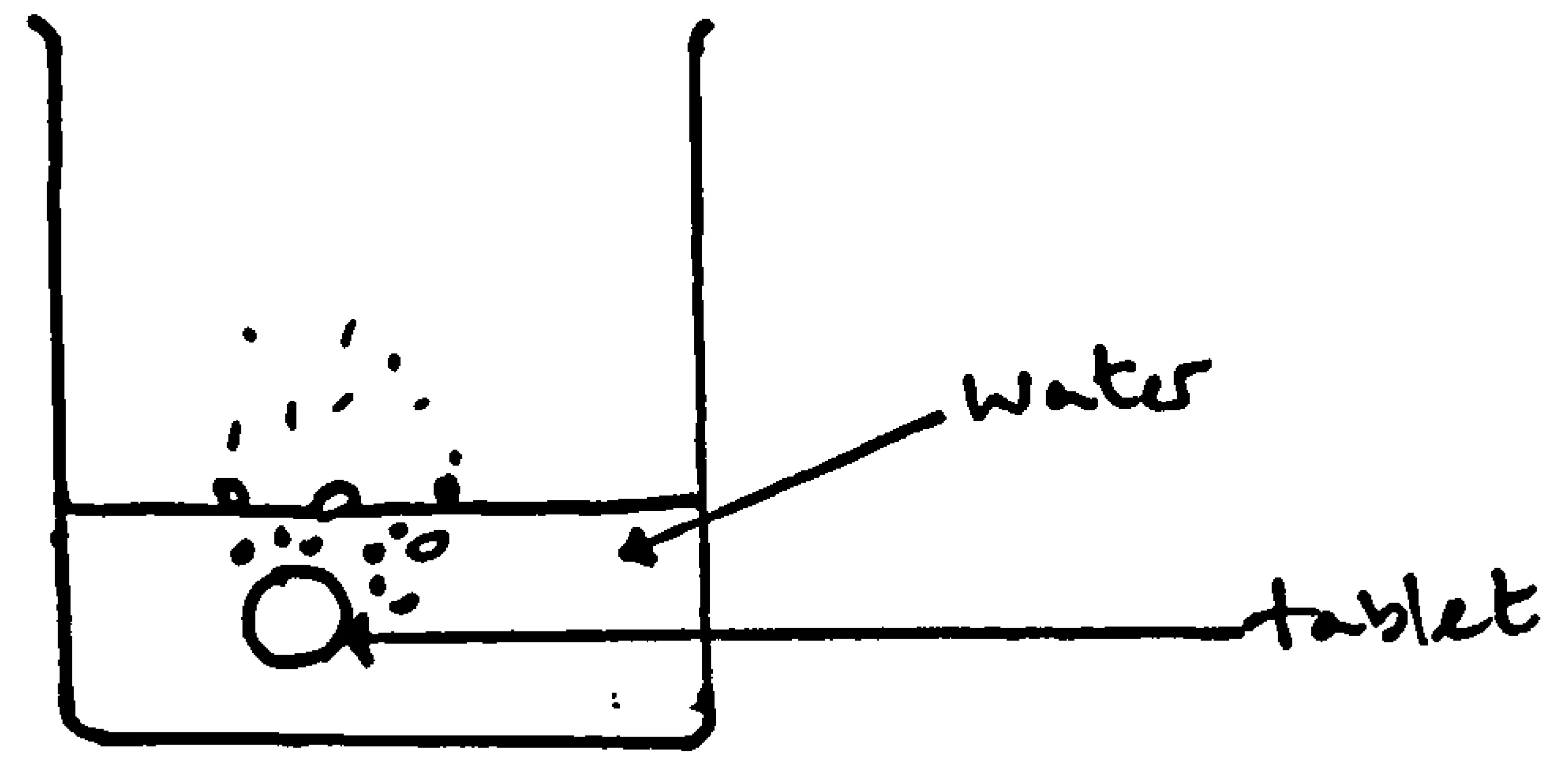
6. When a piece of hot sodium metal is placed in a gas jar of chlorine, a violent reaction takes place and spots of white substance (sodium chloride) are spattered on the inside of the jar.

Explain as fully as you can why the reaction between sodium and chlorine is so violent.

7. Natural gas is mainly methane, CH_4.

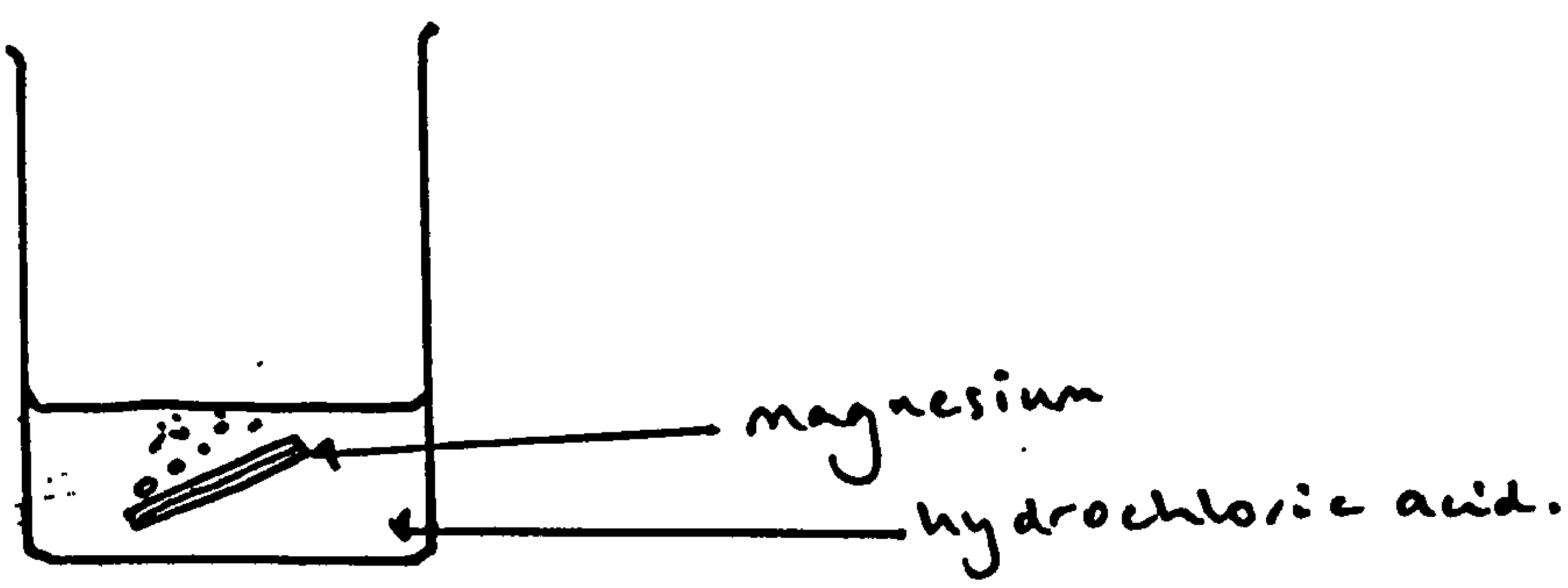
Explain as clearly as you can why carbon and hydrogen form molecules with the formula CH_4 rather than CH_3, CH_2 or CH.

8. An alka-seltzer tablet is dropped into a beaker of water. Bubbles of gas are seen and after a while the tablet disappears.



Where has the gas come from?

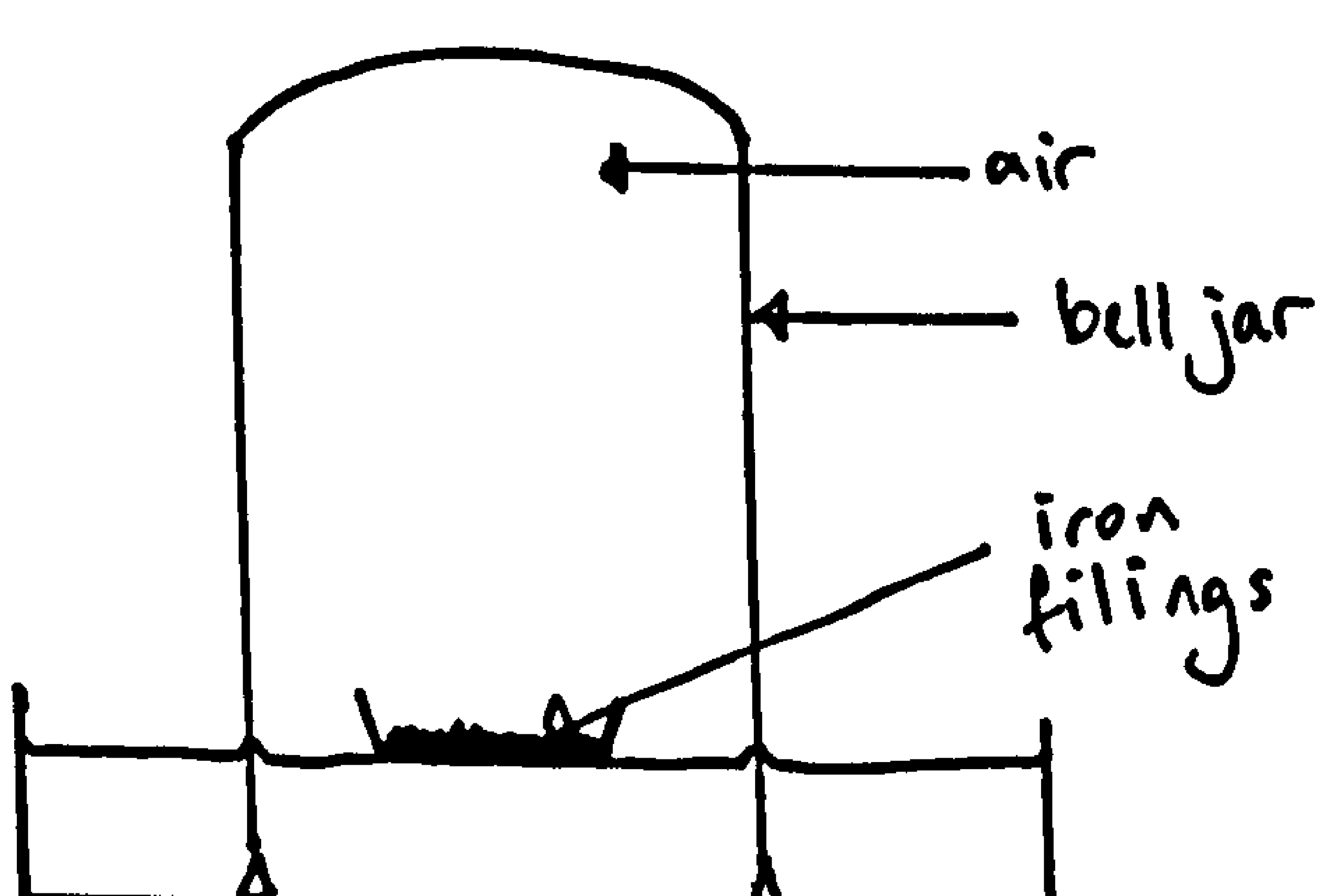
9. A piece of magnesium ribbon is added to dilute hydrochloric acid. The magnesium dissolves. Bubbles of gas can be seen.



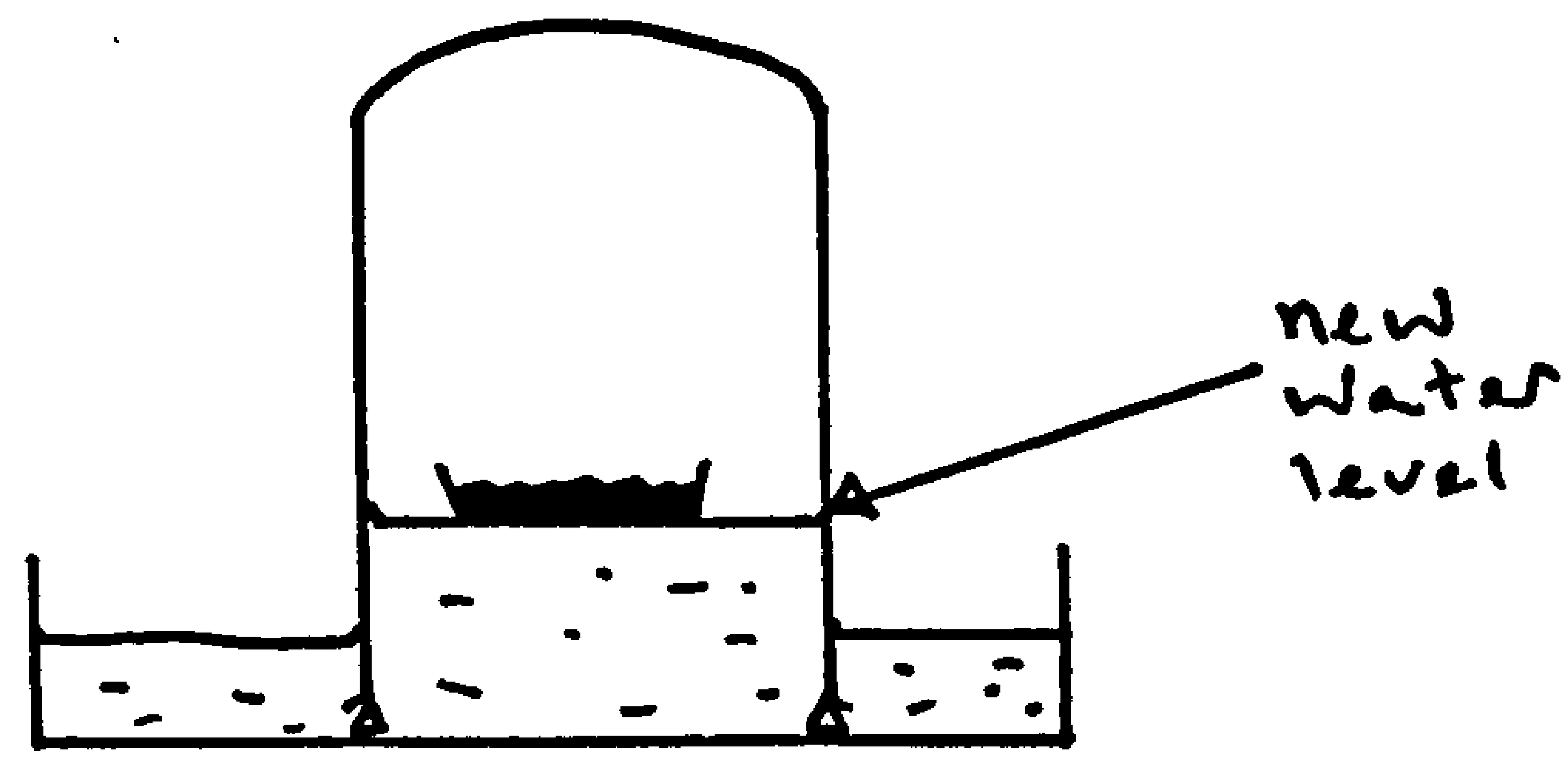
Where was this gas before the reaction?

10 (a) Moist iron filings are placed in a dish. The dish is floated on water and covered with a bell-jar. A few days later, the water level in the bell-jar has increased and the mass of the iron is found to be greater.

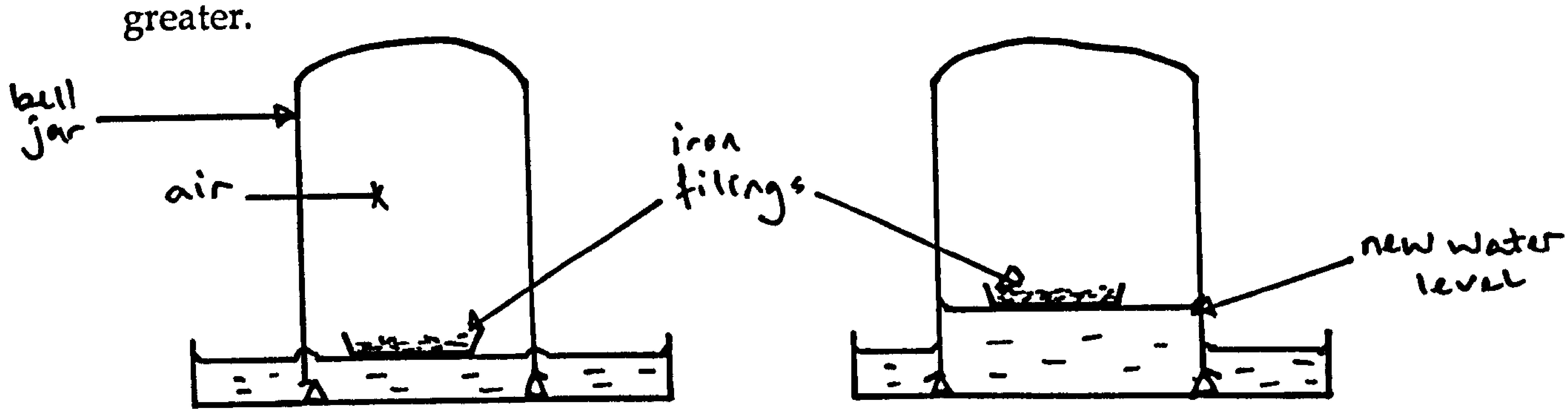
Why has the mass of the iron increased?



Explain your answer.



(b) In a separate experiment, more iron filings are mixed with powdered zinc in a dish. The dish is floated on water and covered with a bell-jar. A few days later, the water level in the bell-jar has increased and the mass of metal is found to be greater.



(i) What changes are likely to have taken place to the metals in the dish?

(ii) Explain why you think these changes have occurred.

11. Methane is natural gas. When methane burns, the equation for the reaction is:-

$$CH_4\,(g) + 2O_2\,(g) \longrightarrow CO_2\,(g) + 2H_2O\,(l)$$

A student needs to use a gas cooker. He (or she) turns the gas on. Methane comes out of the gas tap and mixes with the air. Although both reactants are present, the reaction does not begin until a gas lighter is used to make a spark.

Explain why a spark is needed to make the methane burn.

Why is only *one* spark needed?

The flame is hot. Energy is transferred to the environment near the flame.

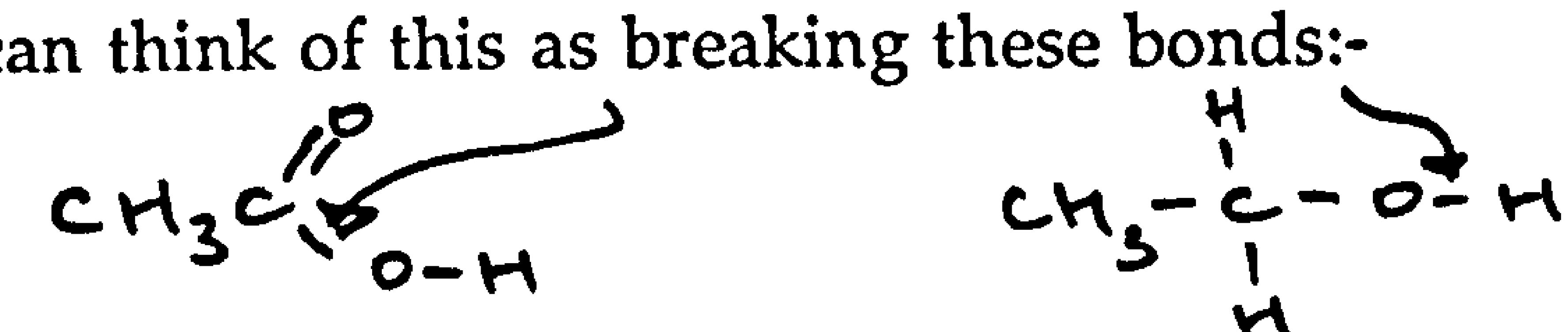
Where was this energy before the reaction?

12. An ester, a sweet-smelling compound, is produced when ethanoic acid (CH_3COOH) reacts with ethanol (C_2H_5OH). Water is also produced in the reaction. The equation for the reaction is:-

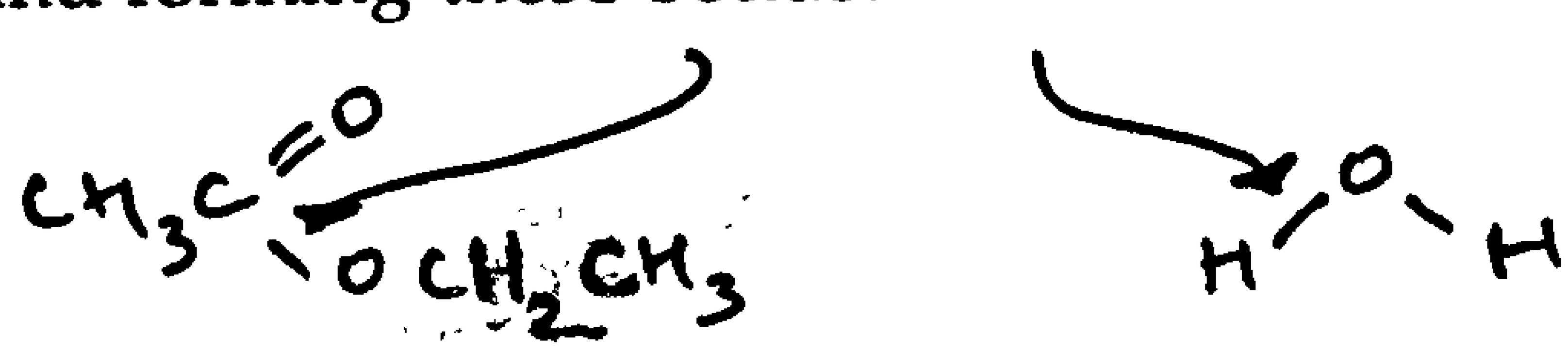
$CH_3COOH\ (l)\ +\ C_2H_5OH\ (l) \longrightarrow CH_3COOC_2H_5\ (aq) + H_2O\ (l)$

In this reaction the OH group of the acid is replaced by the C_2H_5O group of the alcohol and the OH group combines with the H from the alcohol to give water.

We can think of this as breaking these bonds:-



and forming these bonds:-



Explain why the overall enthalpy change for the reaction is approximately 0 $kJmol^{-1}$.

And finally...

please use this page for comments about the questions.

For example, you may like to comment on whether you found the questions:-

clear and easily understandable;
thought-provoking;
difficult to answer;
like exam questions;
too easy.

Approximately how long did you spend in total on the questions?

Once again, thank you for your time and assistance.

Mrs. V. Barker
Research Fellow
Department of Chemistry
University of York
York YO1 5DD

NAME ________________
(Optional)

Salters Advanced Chemistry Evaluation

Trial questions - set B

Thank you very much for helping with the evaluation.

Salters Advanced Chemistry is a new A level course under trial at schools around the country. Part of the evaluation of the course involves finding out how effectively basic chemical ideas are learned by its students.

The main study will begin in September 1992. Students taking the course will be asked to respond to questions like these at various stages during the two years. At this stage, the questions are being trialled. In answering them, please think carefully and write what YOU THINK is the best answer.

It would also help if you could provide the following information:-

(Delete as appropriate)

Date: __________ Male / Female________

Name of school or college ________________

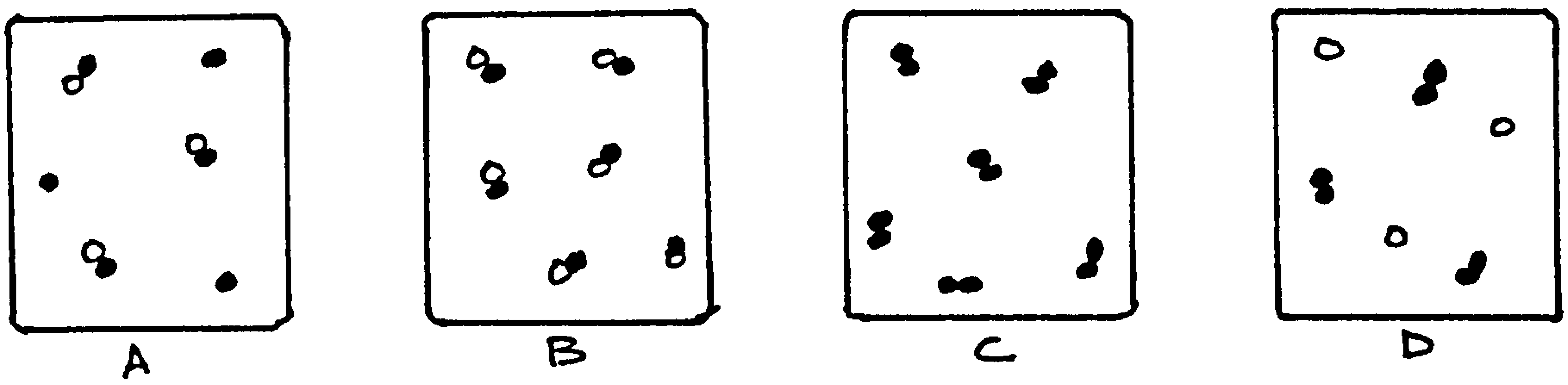
Year of A level course First/ Second

What subjects are you studying other than chemistry?
Please give subject and level e.g. A, AS, BTEC National

What GCSE science course or courses did you take?
Please also give the grades you obtained.

If you would like your answers returned to you please write your name clearly on this front cover.

1. The diagrams lettered A - D represent four different gases. The symbols o and • are used to represent atoms of gas.



Identify which gas is:-

(a) a mixture of two elements;_____

(b) a compound;_____

(c) one element alone._____

There is one gas you have not chosen. What do you think is represented by that diagram?

2. There are four parts to this question. In each part, you are asked to say if you think the substance described is an element, a mixture of substances or a compound. You are also asked to explain your choice.

A A yellow solid which does not conduct electricity, but burns in oxygen to give one product.

Substance A is :-
a compound ☐ a non-metal element ☐ a metal element ☐ a mixture ☐

Explanation

B A silvery grey solid which conducts electricity and burns in oxygen to give one product.

Substance B is:-
a compound ☐ a non-metal element ☐ a metal element ☐ a mixture ☐

Explanation

C A colourless liquid which burns when ignited to give carbon dioxide and water.

Substance C is:-
a compound ☐ a non-metal element ☐ a metal element ☐ a mixture ☐
Explanation

D A dark blue liquid which produces several spots on a chromatogram.

Substance D is:-
a compound ☐ a non-metal element ☐ a metal element ☐ a mixture ☐

Explanation

3. Magnesium (Mg) is a chemical element. Water (H_2O) is a compound.

(a) Explain what you understand by the terms "element" and "compound".

Element

Compound

(b) What test (or tests) could a chemist do on a sample of magnesium to show that it is an element?

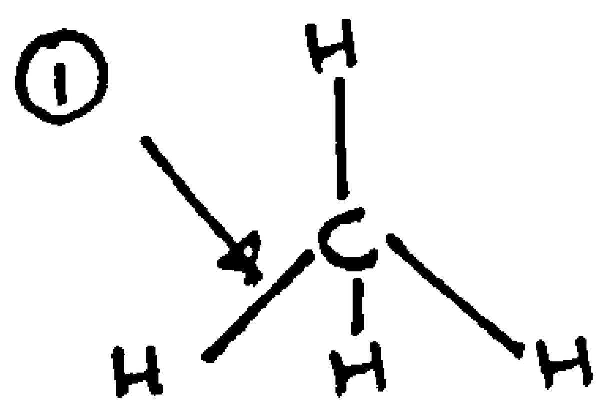
(c) What test (or tests) could a chemist do on a sample of water to show that it is a compound?

4. Imagine you could see an atom of carbon.

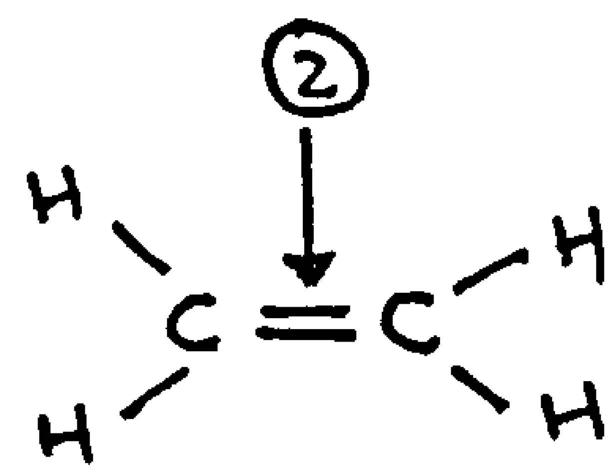
Describe :- (a) what you think it would look like;

(b) what physical properties it would have.

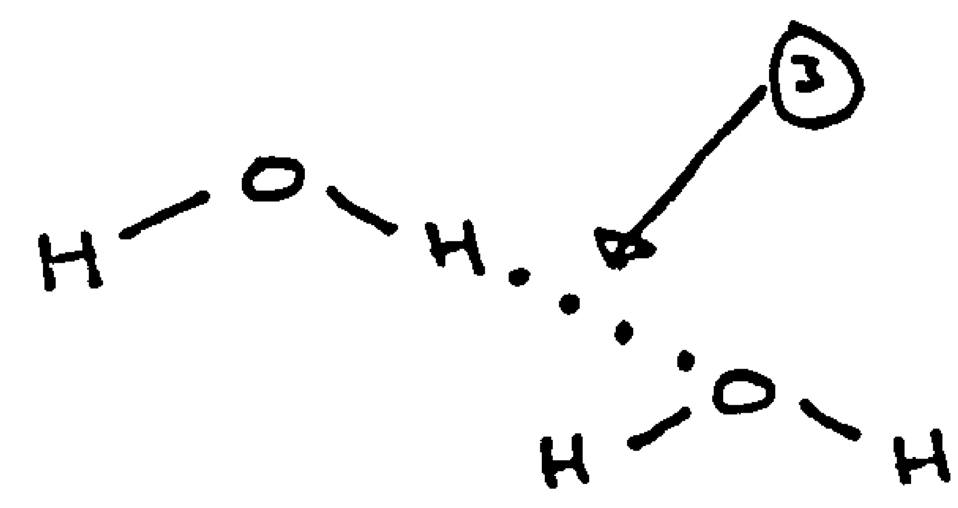
5. For each of these diagrams of molecules:-



(i)



(ii)



(iii)

(a) Name the substance shown;

(i)________________ (ii)________________ (iii)________________

(b) Explain as fully as possible what you think the lines marked 1, 2, and 3 are trying to represent.

Line 1

Line 2

Line 3

(c) Explain the differences, as you understand them, between:-

(i) line 1 and 2;

(ii) line 1 and 3.

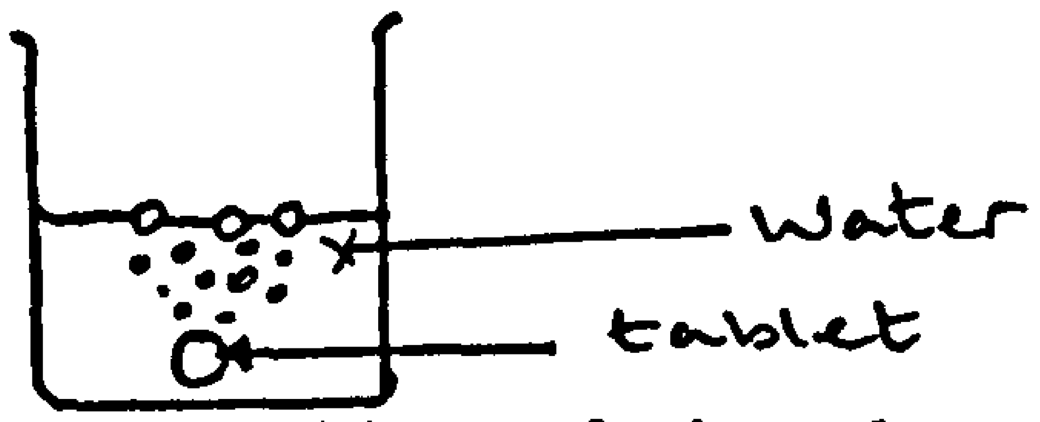
6. When a piece of hot sodium metal is placed in a gas jar of chlorine, a violent reaction takes place and spots of white substance (sodium chloride) are spattered on the inside of the jar.

Explain as fully as you can why the reaction between sodium and chlorine is so violent.

7. Natural gas is mainly methane, CH_4.

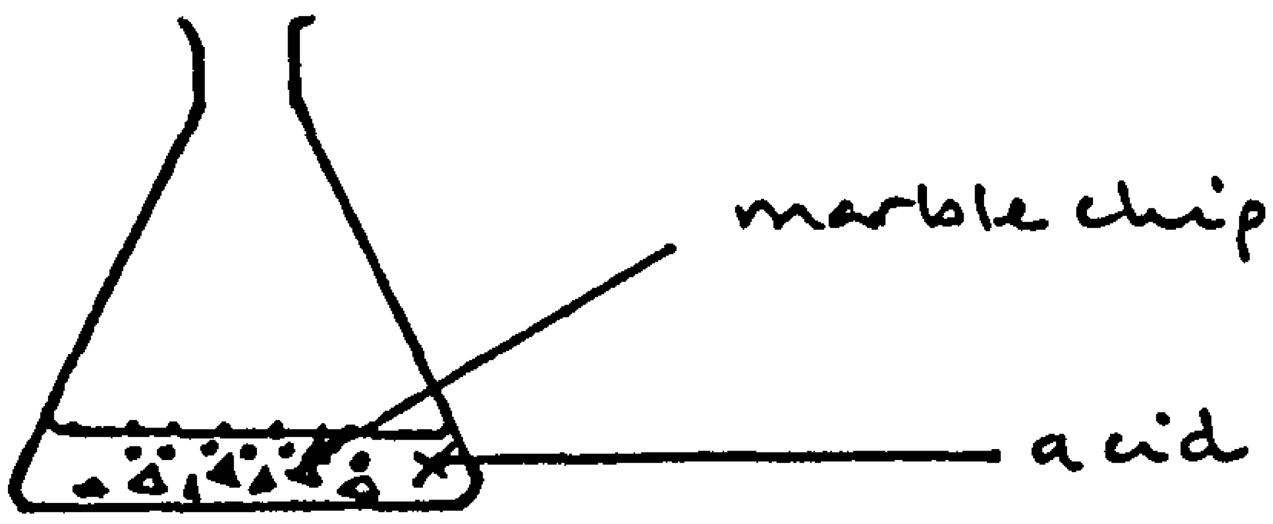
Explain as clearly as you can why carbon and hydrogen form molecules with the formula CH_4 rather than CH_3, CH_2 or CH.

8. An alka-seltzer tablet is dropped into a beaker of water. Bubbles of gas are seen and after a while the tablet disappears.



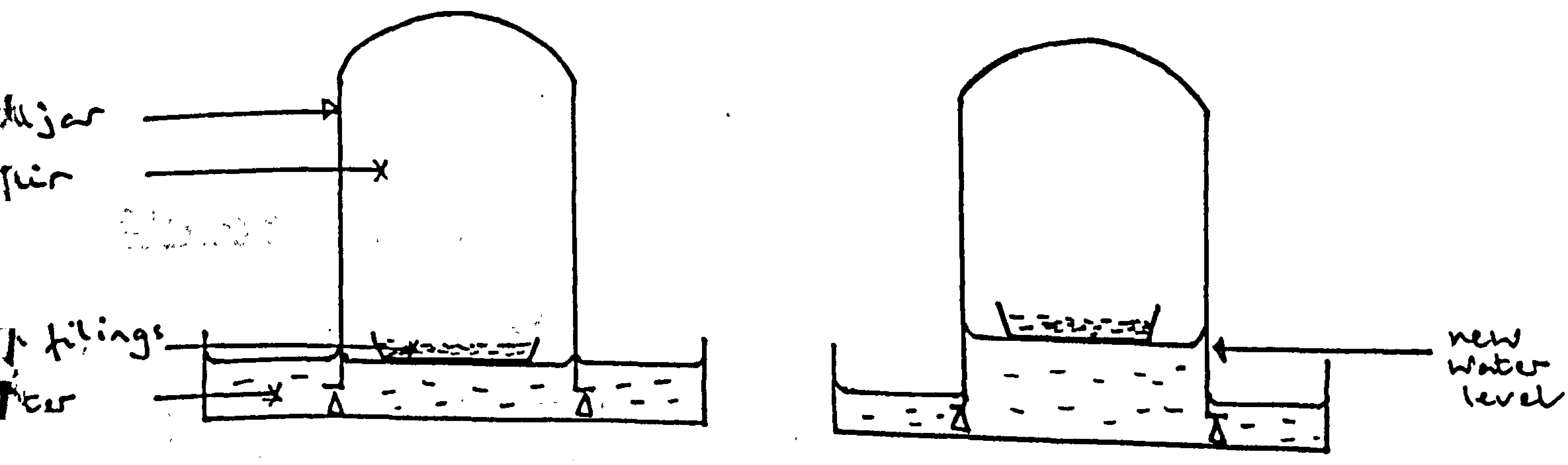
Where was this gas before the reaction?

9. Dilute hydrochloric acid is added to marble chips in a flask. Bubbles of gas are produced.



Where has the gas come from?

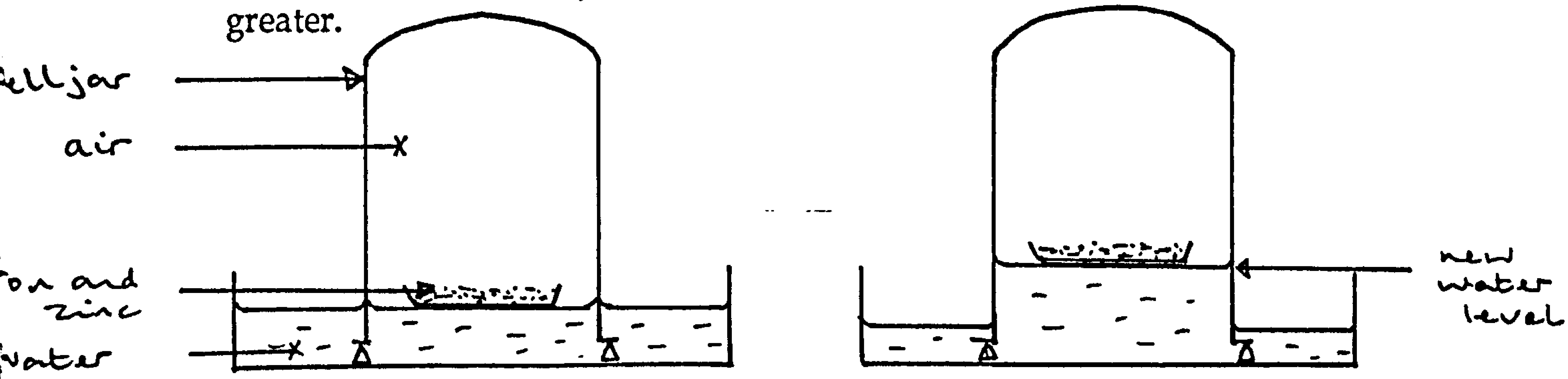
10 (a) Moist iron filings are placed in a dish. The dish is floated on water and covered with a bell-jar. A few days later, the water level in the bell-jar has increased and the mass of the iron is found to be greater



Why has the mass of the iron increased?

Explain your answer.

(b) In a separate experiment, more iron filings are mixed with powdered zinc. The dish is floated on water and covered with a bell-jar. A few days later, the water level in the bell-jar has increased and the mass of metal is found to be greater.



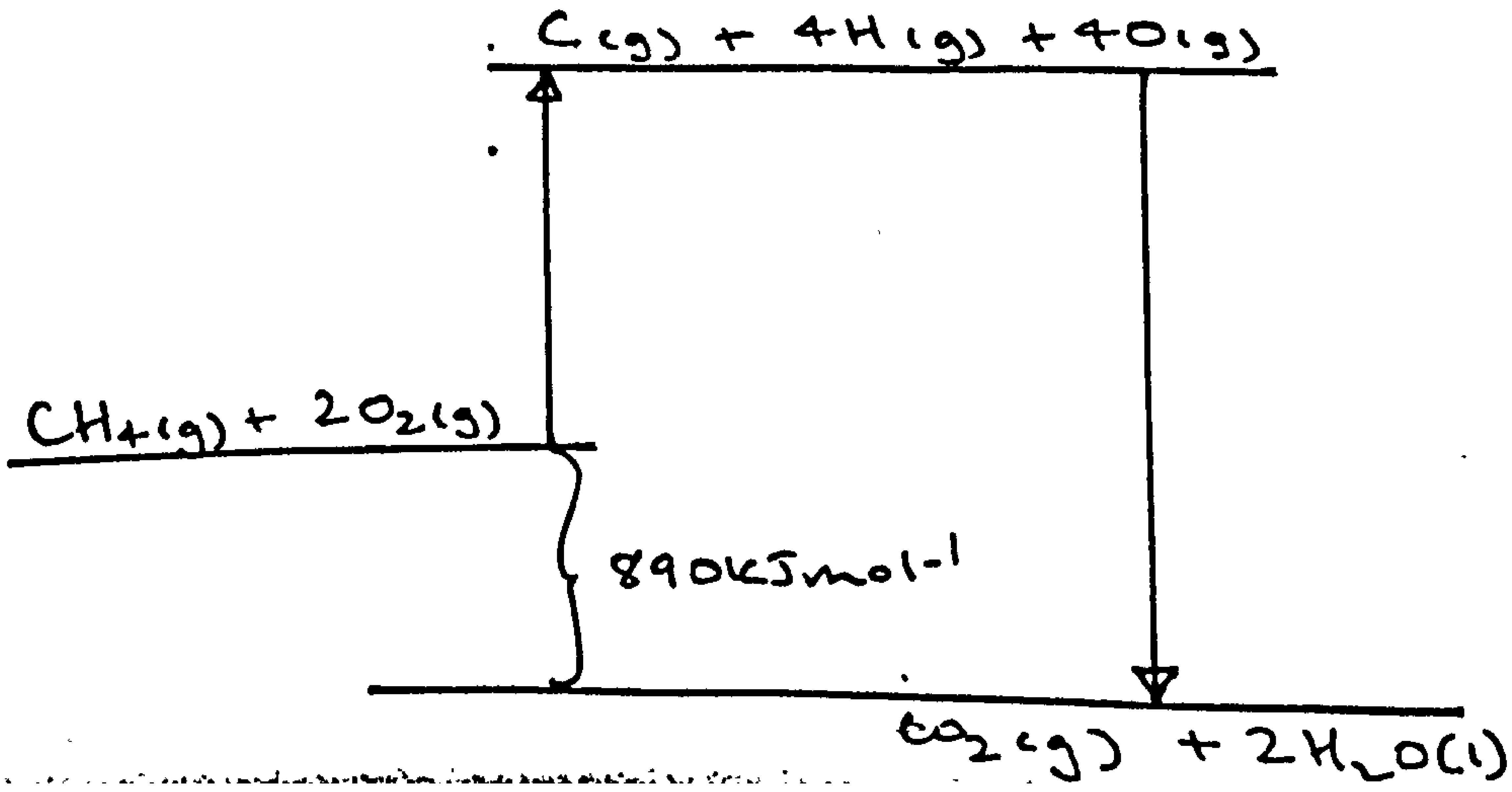
(i) What changes are likely to have taken place to the metals in the dish

(ii) Explain why you think these changes have occurred.

11. The diagram below has been taken from a chemistry textbook. It is from a section on energetics and is about the combustion of methane, CH_4

The equation for the combustion of methane is:-

$CH_4 (g) + 2O_2 (g) \longrightarrow CO_2 (g) + 2H_2O (l)$



Use the diagram to explain:-

(a) why methane needs to be lit before it burns;

(b) why methane will continue to burn until the supply is exhausted;

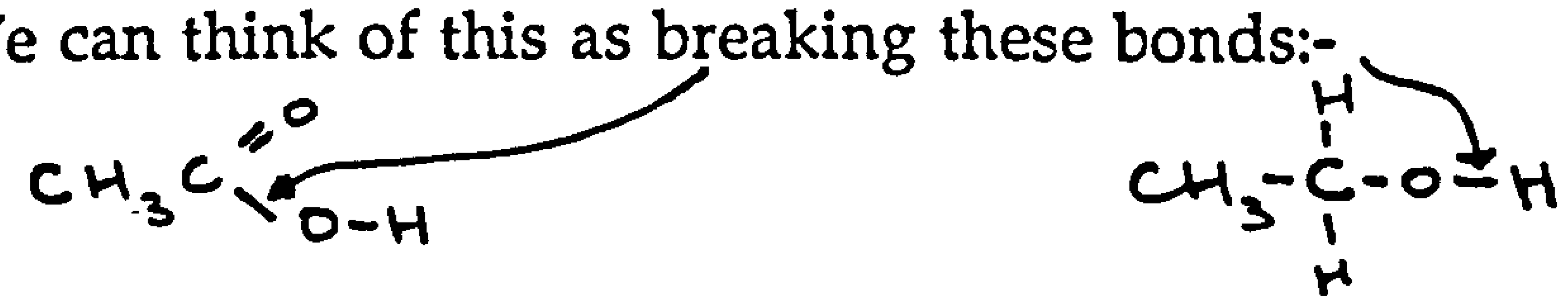
(c) why methane is a fuel.

12. An ester, a sweet-smelling compound, is produced when ethanoic acid (CH_3COOH) reacts with ethanol (C_2H_5OH). Water is also produced in the reaction. The equation for the reaction is:-

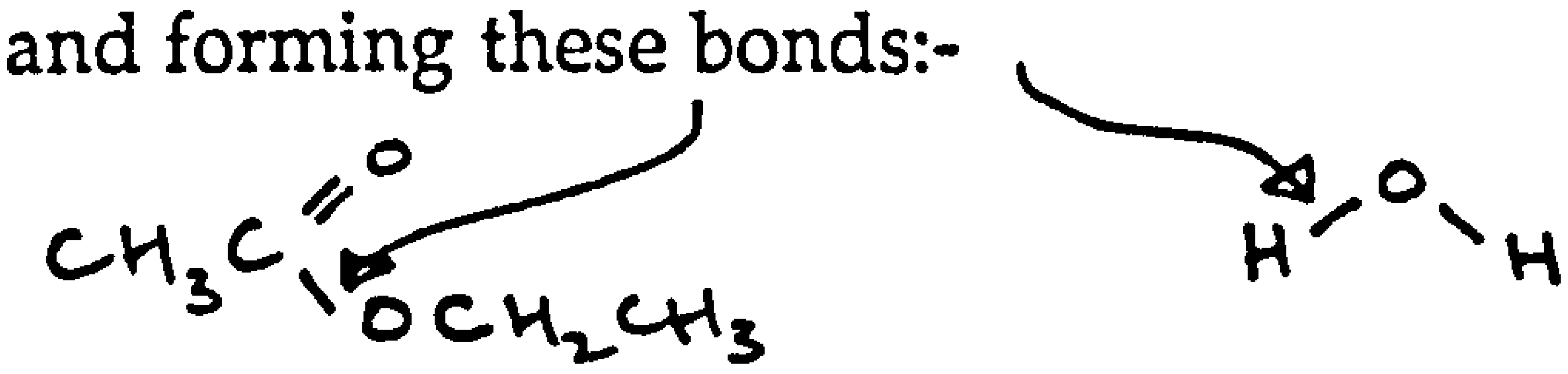
$$CH_3COOH\ (l) + C_2H_5OH\ (l) \longrightarrow CH_3COOC_2H_5\ (aq) + H_2O\ (l)$$

In this reaction the OH group of the acid is replaced by the C_2H_5O group of the alcohol and the OH group combines with the H from the alcohol to give water.

We can think of this as breaking these bonds:-



and forming these bonds:-



Explain why the overall enthalpy change for the reaction is approximately 0 $kJmol^{-1}$.

And finally...

please use this page for comments about the questions.

For example, you may like to comment on whether you found the questions:-

clear and easily understandable;
thought-provoking;
difficult to answer;
like exam questions;
too easy.

Any information may be useful!

Once again, thank you for your time and assistance.

Mrs. V. Barker
Research Fellow
Department of Chemistry
University of York
York YO1 5DD

NAME ____________________
(Optional)

Salters Advanced Chemistry Evaluation

Trial questions - set C

Thank you very much for helping with the evaluation.

Salters Advanced Chemistry is a new A level course under trial at schools around the country. Part of the evaluation of the course involves finding out how effectively basic chemical ideas are learned by its students.

The main study will begin in September 1992. Students taking the course will be asked to respond to questions like these at various stages during the two years. At this stage, the questions are being trialled. In answering them, please think carefully and write what YOU THINK is the best answer.

It would also help if you could provide the following information:-

(Delete as appropriate)

Date: __________ Male / Female________

Name of school or college __________________

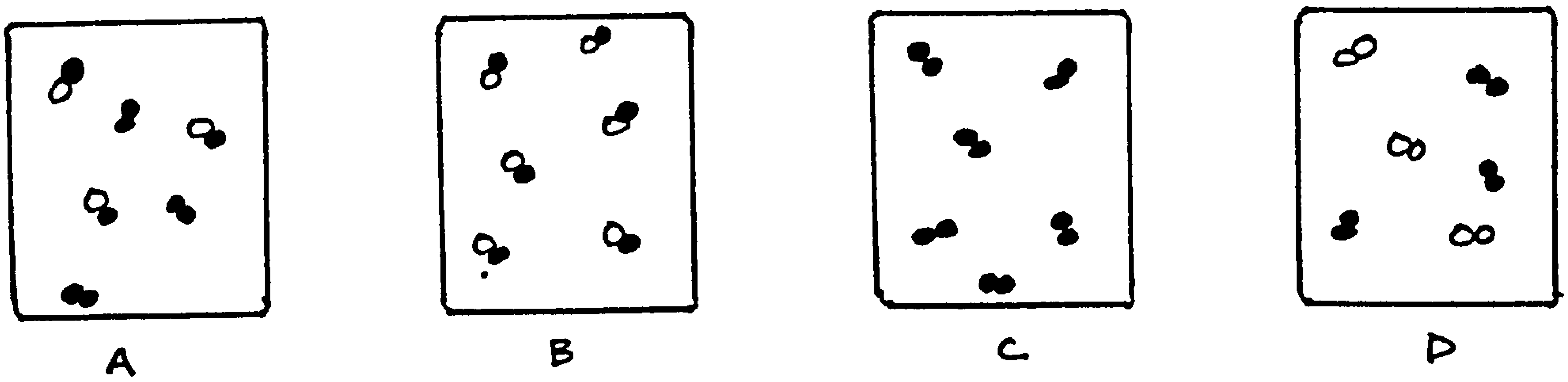
Year of A level course First/ Second

What subjects are you studying other than chemistry?
Please give subject and level e.g. A, AS, BTEC National

What GCSE science course or courses did you take?
Please also give the grades you obtained.

If you would like your answers returned to you please write your name clearly on this front cover.

1. The diagrams lettered A - D represent the contents of four containers of gas. The gases are made from two chemical elements. The atoms of the elements are given the symbols ○ and ●.



Identify which container holds:-

(a) a mixture of the two elements;______

(b) a compound;_______

(c) one element alone._______

What do you think is in the container which you did not choose?

2. There are four parts to this question. In each part, you are asked to say if you think the substance described is an element, a mixture of substances or a compound. You are also asked to explain your choice.

A A yellow solid which does not conduct electricity, but burns in oxygen to give one product.

Substance A is :-
a compound ☐ a non-metal element ☐ a metal element ☐ a mixture ☐

Explanation

B A silvery grey solid which conducts electricity and burns in oxygen to give one product.

Substance B is:-
a compound ☐ a non-metal element ☐ a metal element ☐ a mixture ☐

Explanation

C A colourless liquid which burns when ignited to give carbon dioxide and water.

Substance C is:-
a compound ☐ a non-metal element ☐ a metal element ☐ a mixture ☐

Explanation

D A dark blue liquid which produces several spots on a chromatogram.

Substance D is:-
a compound ☐ a non-metal element ☐ a metal element ☐ a mixture ☐

Explanation

3. Magnesium (Mg) is a chemical element. Water (H_2O) is a compound.

(a) Explain what you understand by the terms "element" and "compound".

Element

Compound

(b) What test (or tests) could a chemist do on a sample of magnesium to show that it is an element?

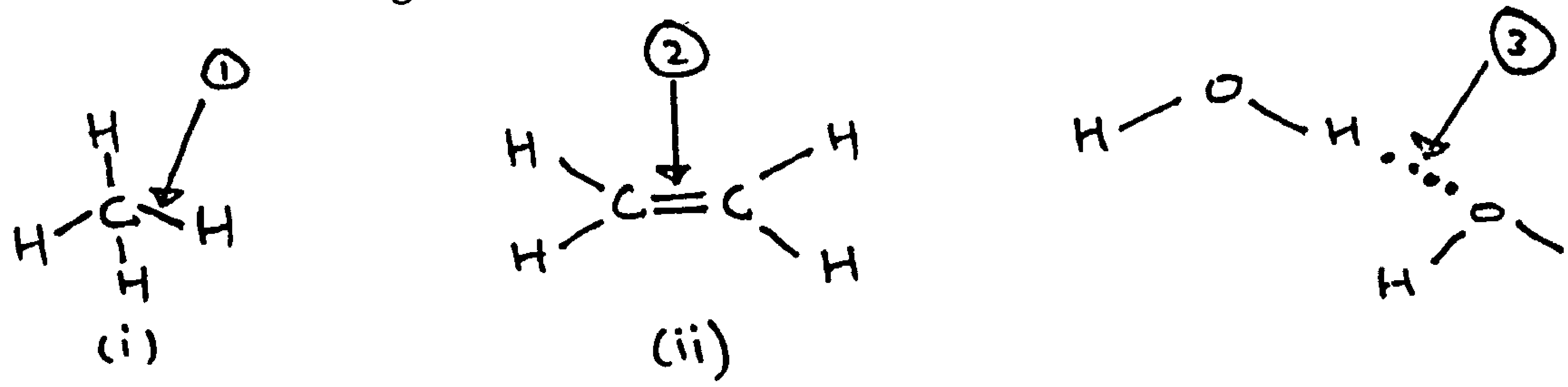
(c) What test (or tests) could a chemist do on a sample of water to show that it is a compound?

4. Imagine you could see an atom of carbon.

Describe :- (a) what you think it would look like;

(b) what physical properties it would have.

5. For each of these diagrams of molecules:-



(a) Name the substance shown;

(i)________________ (ii)________________ (iii)________________

(b) Explain as fully as possible what you think the lines marked 1, 2, and 3 are trying to represent.

Line 1

Line 2

Line 3

(c) Explain the differences, as you understand them, between:-

(i) line 1 and 2;

(ii) line 1 and 3.

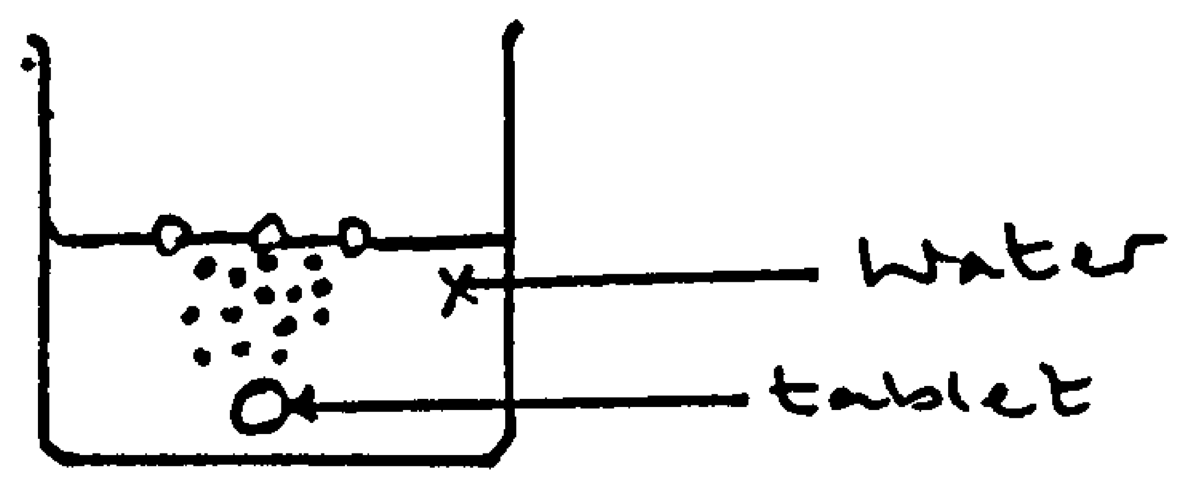
6. When a piece of hot sodium metal is placed in a gas jar of chlorine, a violent reaction takes place and spots of white substance (sodium chloride) are spattered on the inside of the jar.

Explain as fully as you can why the reaction between sodium and chlorine is so violent.

7. Natural gas is mainly methane, CH_4.

Explain as clearly as you can why carbon and hydrogen form molecules with the formula CH_4 rather than CH_3, CH_2 or CH.

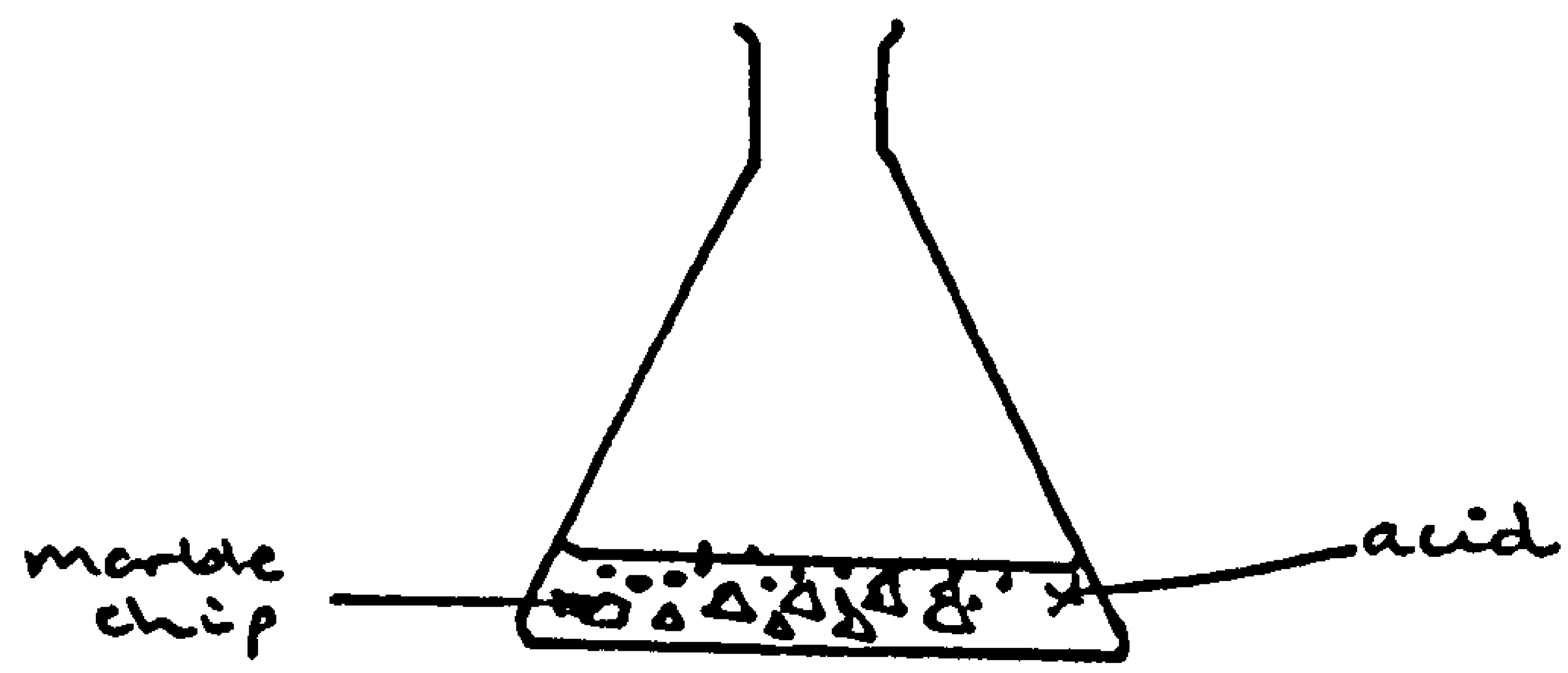
8. An alka-seltzer tablet is dropped into a beaker of water. Bubbles of gas are seen and after a while the tablet disappears.



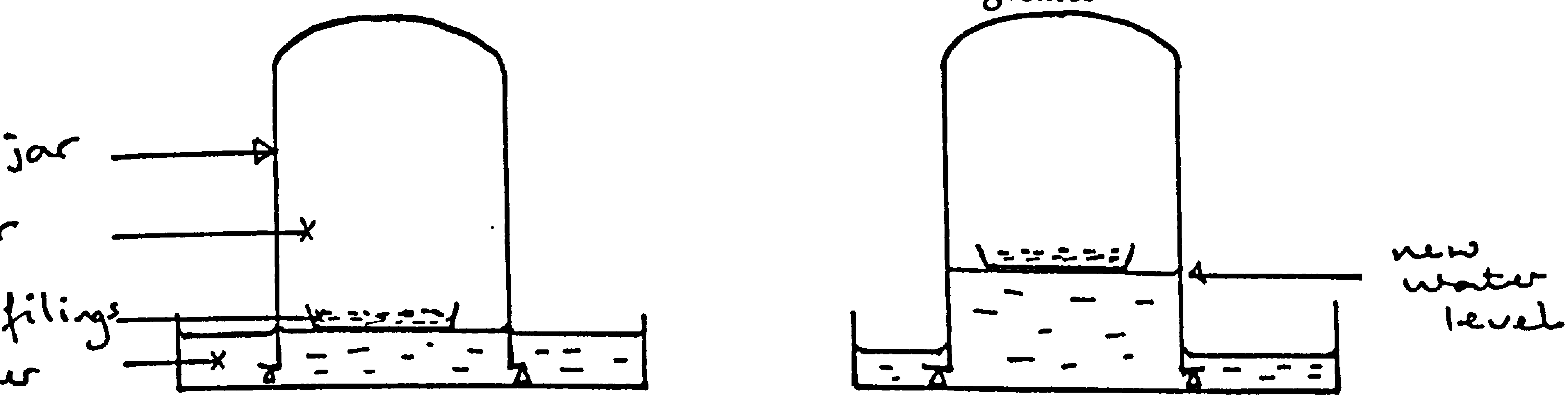
Where has the gas come from?

9. Dilute hydrochloric acid is added to marble chips in a flask. Bubbles of gas are produced.

Where was this gas before the reaction?



10 (a) Moist iron filings are placed in a dish. The dish is floated on water and covered with a bell-jar. A few days later, the water level in the bell-jar has increased and the mass of the iron is found to be greater



Why has the mass of the iron increased?
Explain your answer.

(b) In a separate experiment, more iron filings are mixed with powdered zinc. The dish is floated on water and covered with a bell-jar. A few days later, the water level in the bell-jar has increased and the mass of metal is found to be greater.

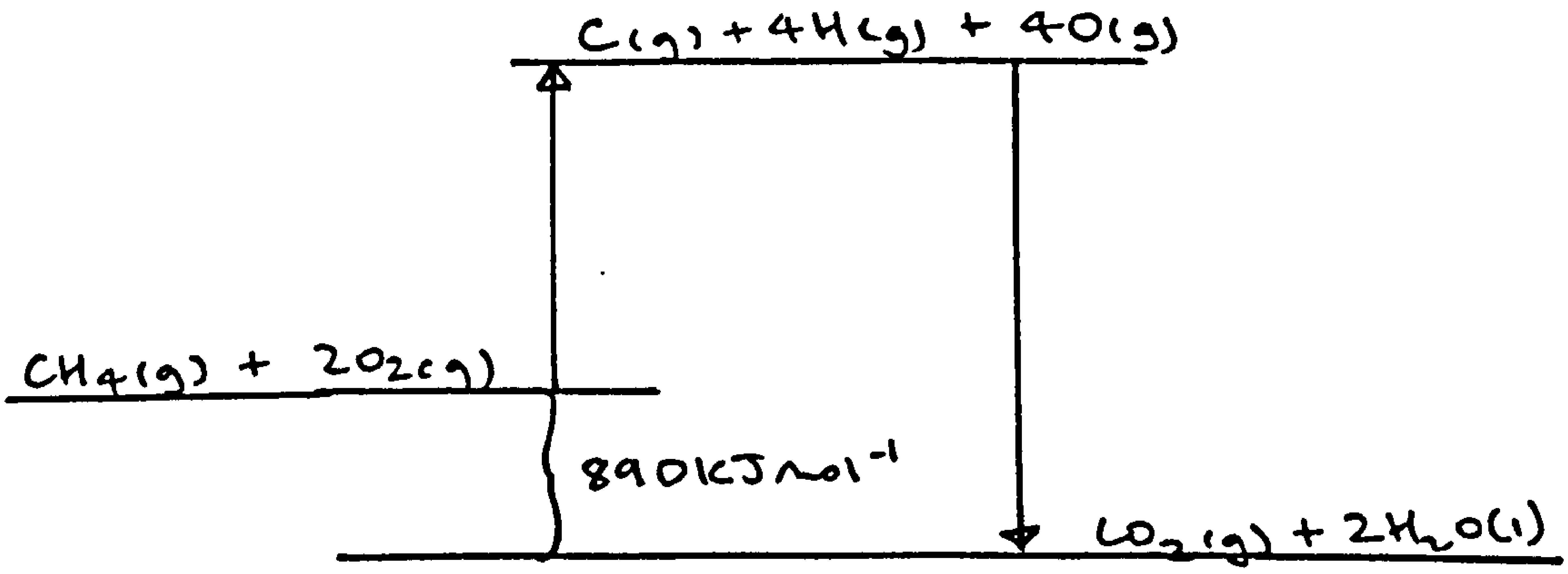
(i) What changes are likely to have taken place to the metals in the dish?

(ii) Explain why you think these changes have occurred.

11. The diagram below has been taken from a chemistry textbook. It is from a section on energetics and is about the combustion of methane (CH_4)

The equation for the combustion of methane is:-

CH_4 (g) + $2O_2$ (g) ----> CO_2 (g) + $2H_2O$ (l)



(a) What quantity is being shown on the Y- axis (vertical) of this diagram?

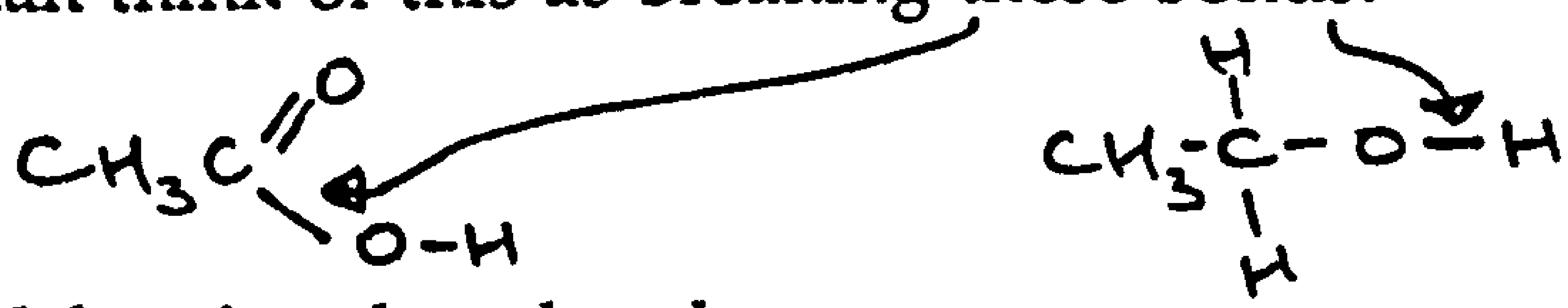
(b) Explain as fully as you can what you think this diagram is telling you about the combustion of methane.

12. An ester, a sweet-smelling compound, is produced when ethanoic acid (CH_3COOH) reacts with ethanol (C_2H_5OH). Water is also produced in the reaction. The equation for the reaction is:-

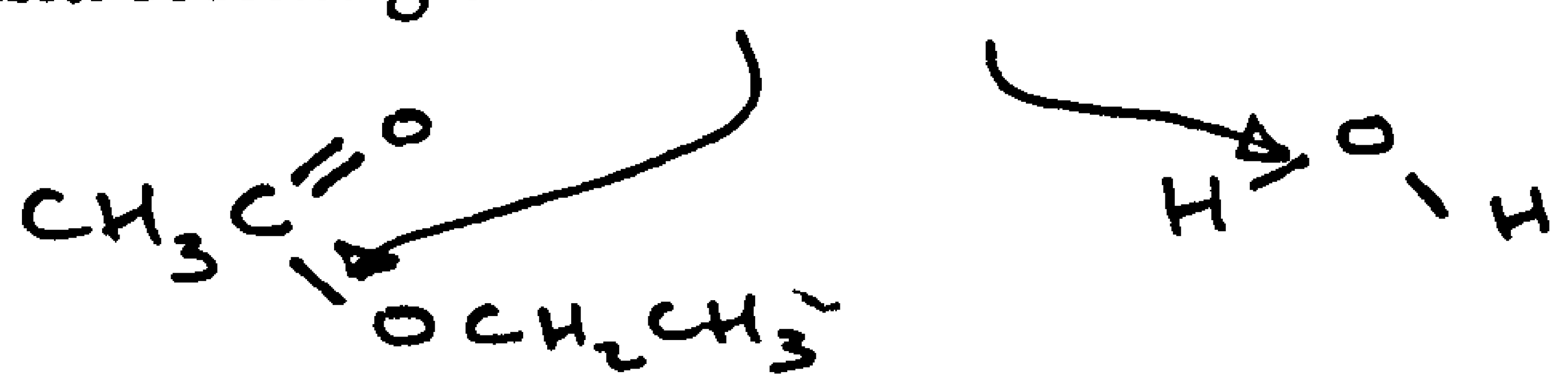
CH_3COOH (l) + C_2H_5OH (l) ---> $CH_3COOC_2H_5$ (aq) + H_2O (l)

In this reaction the OH group of the acid is replaced by the C_2H_5O group of the alcohol and the OH group combines with the H from the alcohol to give water.

We can think of this as breaking these bonds:-



and forming these bonds:-



Explain why the overall enthalpy change for the reaction is approximately 0 $kJmol^{-1}$.

And finally...

please use this page for comments about the questions.

For example, you may like to comment on whether you found the questions:-

clear and easily understandable;
thought-provoking;
difficult to answer;
like exam questions;
too easy.

Any information may be useful!

Once again, thank you for your time and assistance.

Mrs. V. Barker
Research Fellow
Department of Chemistry
University of York
York YO1 5DD

NAME..

Salters Advanced Chemistry Evaluation

Trial questions - set D

Thank you very much for helping with the evaluation.

Salters Advanced Chemistry is a new A level course which is under trial at schools around the country. Part of the evaluation is to find out how effective the course is at teaching the basic chemical ideas.

Students are being invited to help the evaluation by trialling questions which could be used in the main study which will begin in September, 1992.

The questions aim to encourage answers which are based on chemical ideas rather than recall of facts. They may therefore seem a little strange or perhaps confusing. **So, please think carefully about each question and write what *YOU THINK* is the best answer .**

It would also help if you could provide the following information:-

Date ___________

Name of school or college ________________________________

Year of A level course First/ Second

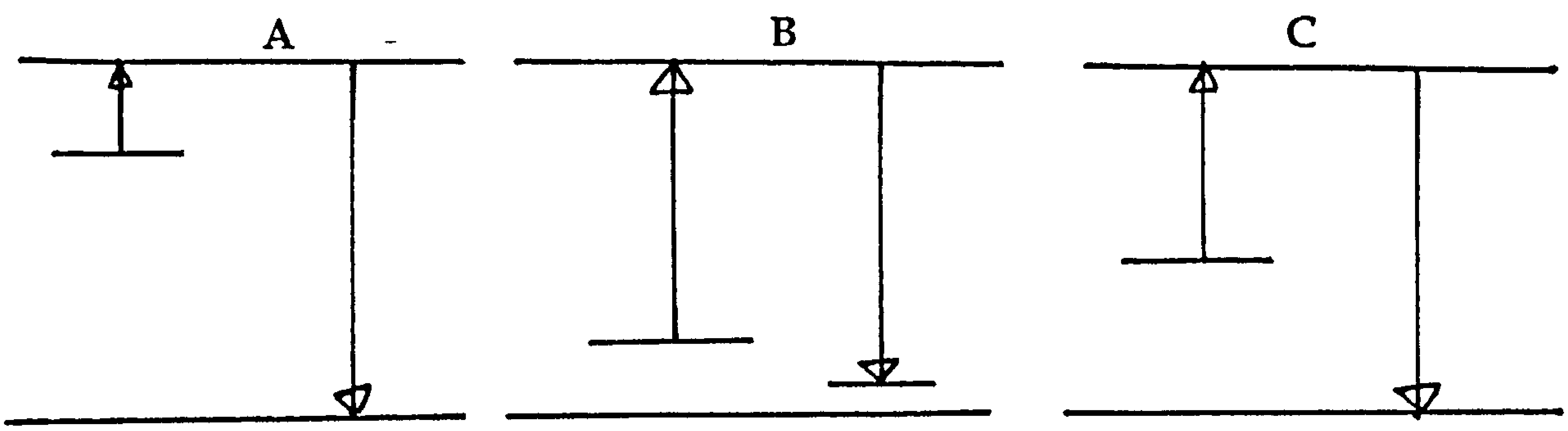
What subjects are you studying other than chemistry?
Please give subject and level e.g. A, AS, BTEC National

What GCSE science course or courses did you take?
Please also give the grades you obtained.

Note here the time you start: ....
It is helpful to know how long the questions take!

All the information you will need to answer these questions is contained in the paper.

1. The three diagrams below represent the energy changes which take place during three chemical reactions.



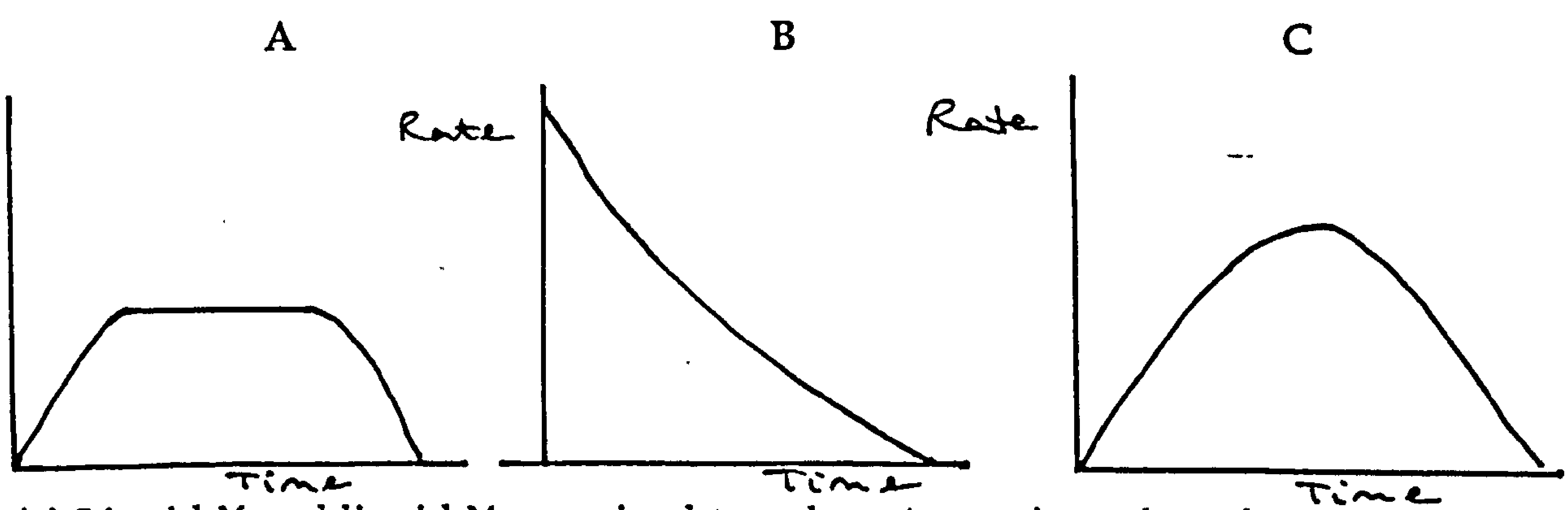
Which of these energy diagrams do you think most closely represents the reaction between sodium and chlorine?

$2Na(s) + Cl_2 (g) \longrightarrow 2NaCl (s)$ Energy diagram A / B / C

Please give the reason for your answer

2. Here are three graphs which show how the rate of a chemical reaction changes.

Look at the graphs and select the one you think best represents the reactions shown below.



(a) Liquid X and liquid Y are mixed together. A reaction takes place.

Answer Graph .... represents this reaction best.
Explain why you think this.

(b) $Mg (s) + 2HCl (aq) \longrightarrow MgCl_2(aq) + H_2 (g)$

Answer Graph .... represents this reaction best.
Explain why you think this.

3. Use the equation below to estimate the mass of carbon dioxide produced when 24g of high quality coal is burned in 64g of oxygen gas.

Relative atomic mass values are :- C = 12, O = 16.

$$C\,(s) + O_2\,(g) \dashrightarrow CO_2\,(g)$$

4. Chemicals X and Y react to produce the compound XY. 50g of X and 70g of Y produce 120g of XY.

X	+	Y	------->	XY
50g	+	70g	------>	120g

What would you get when 100g of X and 150g of Y are made to react?

X	+	Y	------->	XY
100g	+	150g	------>	________

5. Aqueous solutions of two salts, A and B, are placed in separate measuring cylinders on a top pan balance. The total mass is recorded as 140g.

Solution A is poured into solution B. Both measuring cylinders remain on the balance. A precipitation reaction takes place.

What will the mass reading be after the reaction?

- ☐ Less than 140g
- ☐ 140g exactly
- ☐ More than 140 g

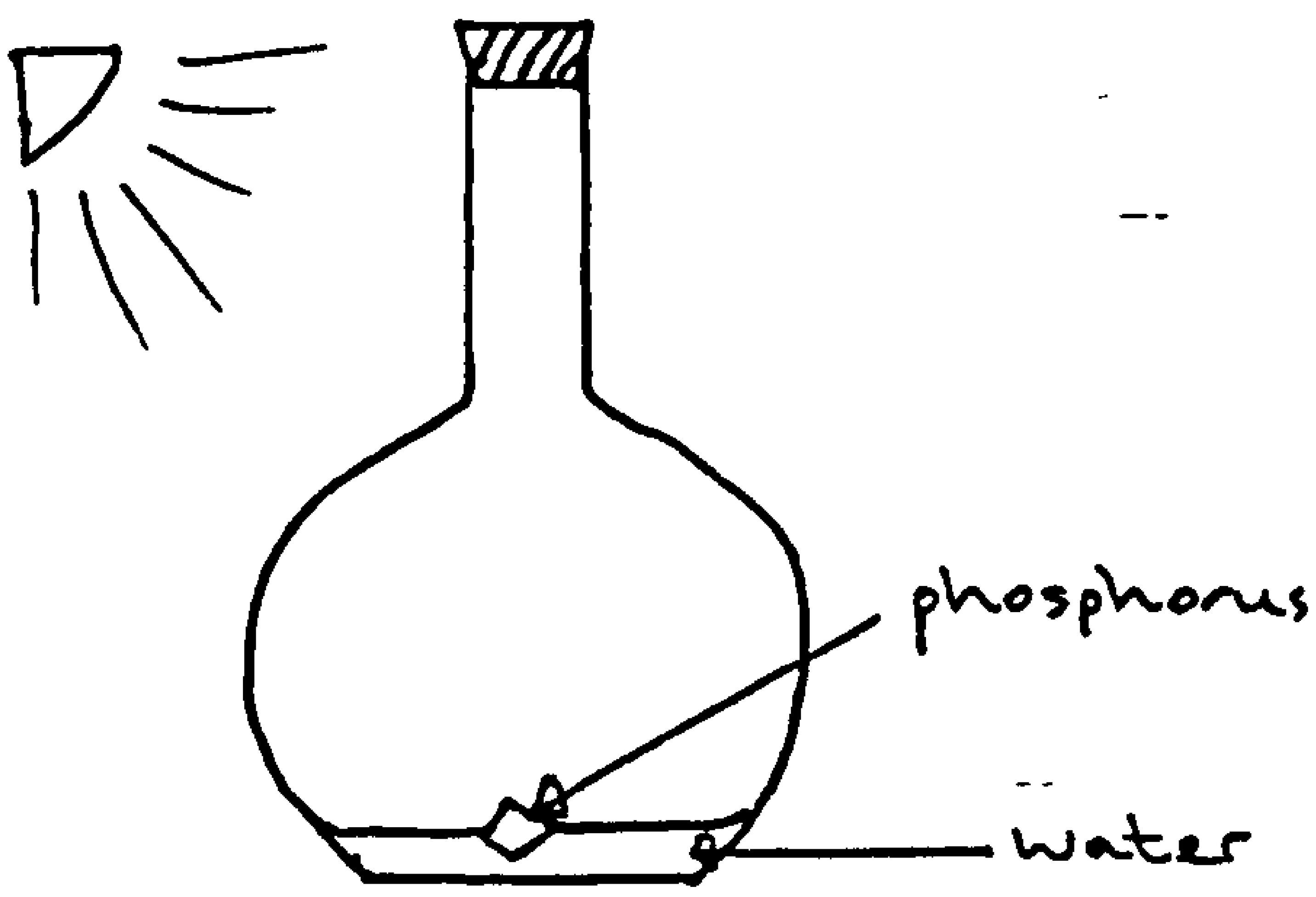
Explain why you think this.

6. A car with a mass of 1000kg has 50kg of petrol put in its tank. The car is driven until the tank is completely empty. The car then has a mass of 1000kg again. What is the approximate weight of the exhaust gases given off while the car is being driven?

The approximate mass of exhaust gases is ....

Explain your reasoning as fully as possible.

7. A piece of phosphorus and some water were placed in a flask. The flask was sealed with a rubber stopper. The mass of the flask and contents was 400g. The sun's rays were focussed on the phosphorus which caught fire. The white smoke produced slowly dissolved in the water. The flask was cooled and its mass measured again.



Would you expect the mass to be:

- ☐ More than 400g
- ☐ 400g
- ☐ Less than 400g

Give the reason for your answer.

8. A coal-burning power station burns 1000 tonnes of high quality coal each day.

What mass of carbon dioxide will be produced from the flue chimney?

9. The bonding in magnesium chloride is ionic. The bonding in titanium (IV) chloride is covalent.

A mixture of the two chlorides is heated to 1000 ^{o}C.

Explain in *terms of their bonding* why the vapour above the mixture consists only of titanium (IV) chloride.

10. The reaction $N_2 (g) + 3H_2 (g) \rightleftharpoons 2NH_3 (g)$

is called an "equilibrium" reaction.

The reaction $O_2 (g) + 2H_2 (g) \longrightarrow 2H_2O (l)$

is not an equilibrium reaction.

Explain as best you can why these two reactions are different.

How long did you spend on the questions?

Many thanks again for your help.

Mrs. V. Barker,
Research Fellow,
Department of Chemistry
University of York
York YO1 5DD

NAME..

Salters Advanced Chemistry Evaluation

Trial questions - set E

Thank you very much for helping with the evaluation.

Salters Advanced Chemistry is a new A level course which is under trial at schools around the country. Part of the evaluation is to find out how effective the course is at teaching the basic chemical ideas.

Students are being invited to help the evaluation by trialling questions which could be used in the main study which will begin in September, 1992.

The questions aim to encourage answers which are based on chemical ideas rather than recall of facts. They may therefore seem a little strange or perhaps confusing. So, please **think carefully about each question and write what *YOU THINK* is the best answer.**

It would also help if you could provide the following information:-

Date ___________

Name of school or college ________________________________

Year of A level course First/ Second

What subjects are you studying other than chemistry?
Please give subject and level e.g. A, AS, BTEC National

What GCSE science course or courses did you take?
Please also give the grades you obtained.

Note here the time you start: ....
It is helpful to know how long the questions take!

All the information you will need to answer these questions is contained in the paper. You may use diagrams to help your answers wherever you like.

1. Magnesium (Mg) is a chemical element. Water (H_2O) is a compound.

(a) Explain what you understand by the terms "element" and "compound".

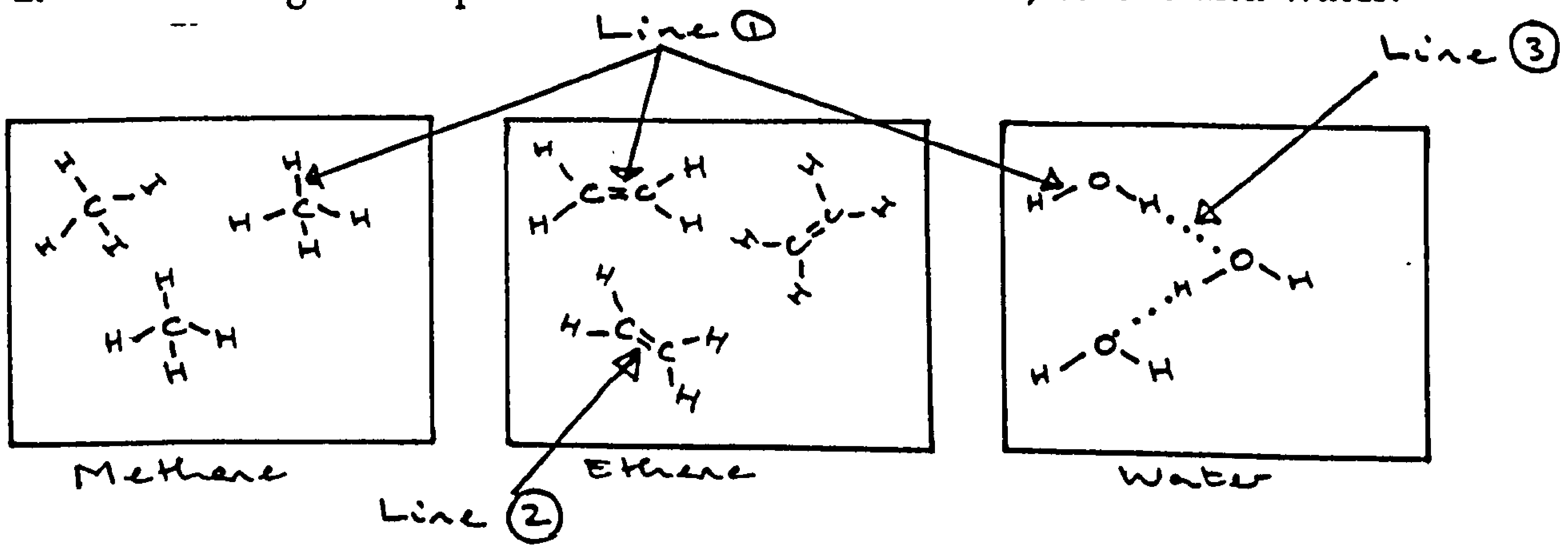
Element

Compound

(b) What test (or tests) could a chemist do on a sample of magnesium to show that it is an element?

(c) What test (or tests) could a chemist do on a sample of water to show that it is a compound?

2. The diagrams represent molecules of methane, ethene and water.



(a) Explain as fully as possible the meanings of the lines marked 1, 2 and 3.

Line 1

Line 2

Line 3

(b) What differences are there between

(i) Line 1 and line 2

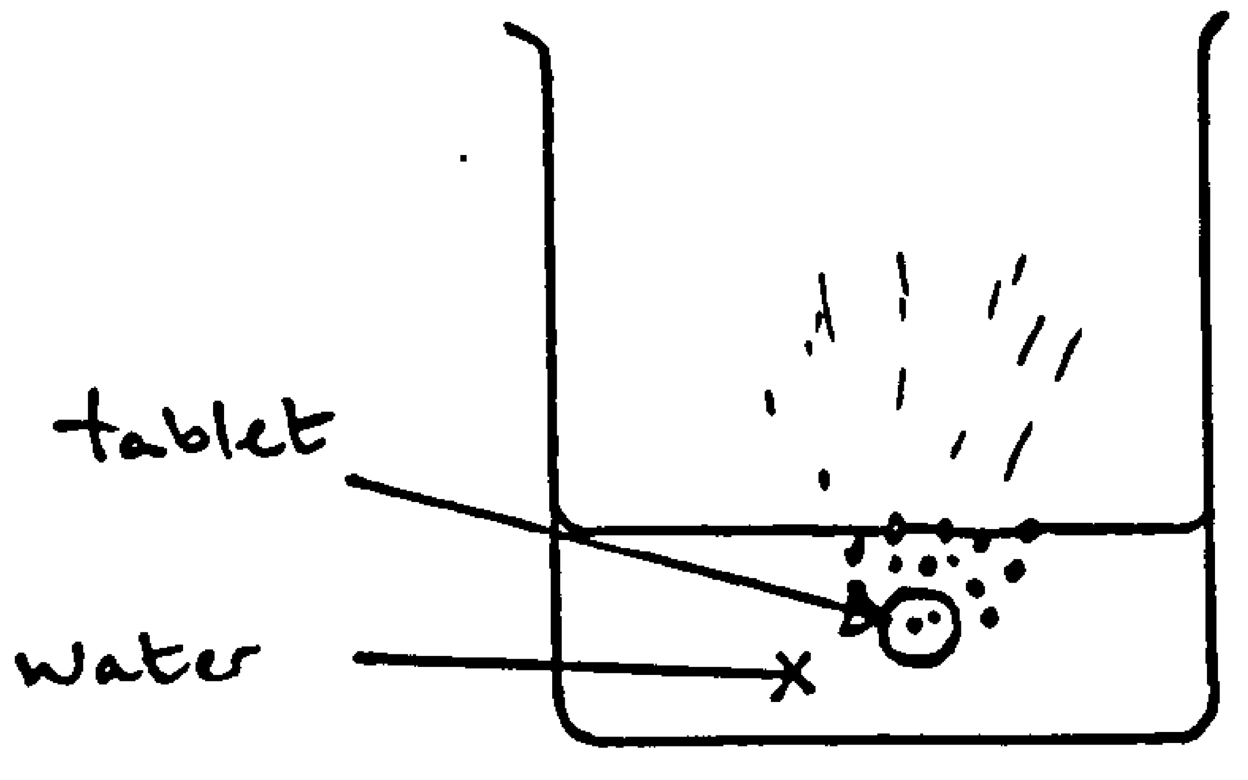
(ii) Line 1 and line 3? (I already know that line 3 is not a line but dots...)

3. The bonding in magnesium chloride ($MgCl_2$) is ionic.
The bonding in titanium IV) chloride ($TiCl_4$) is covalent.

A mixture of the two chlorides is heated to 1000 ^oC.

Explain in *terms of their bonding* why the vapour above the mixture consists only of titanium (IV) chloride.

4. An aspirin tablet is dropped into a beaker of water. Bubbles of gas are seen and after a while the tablet disappears.



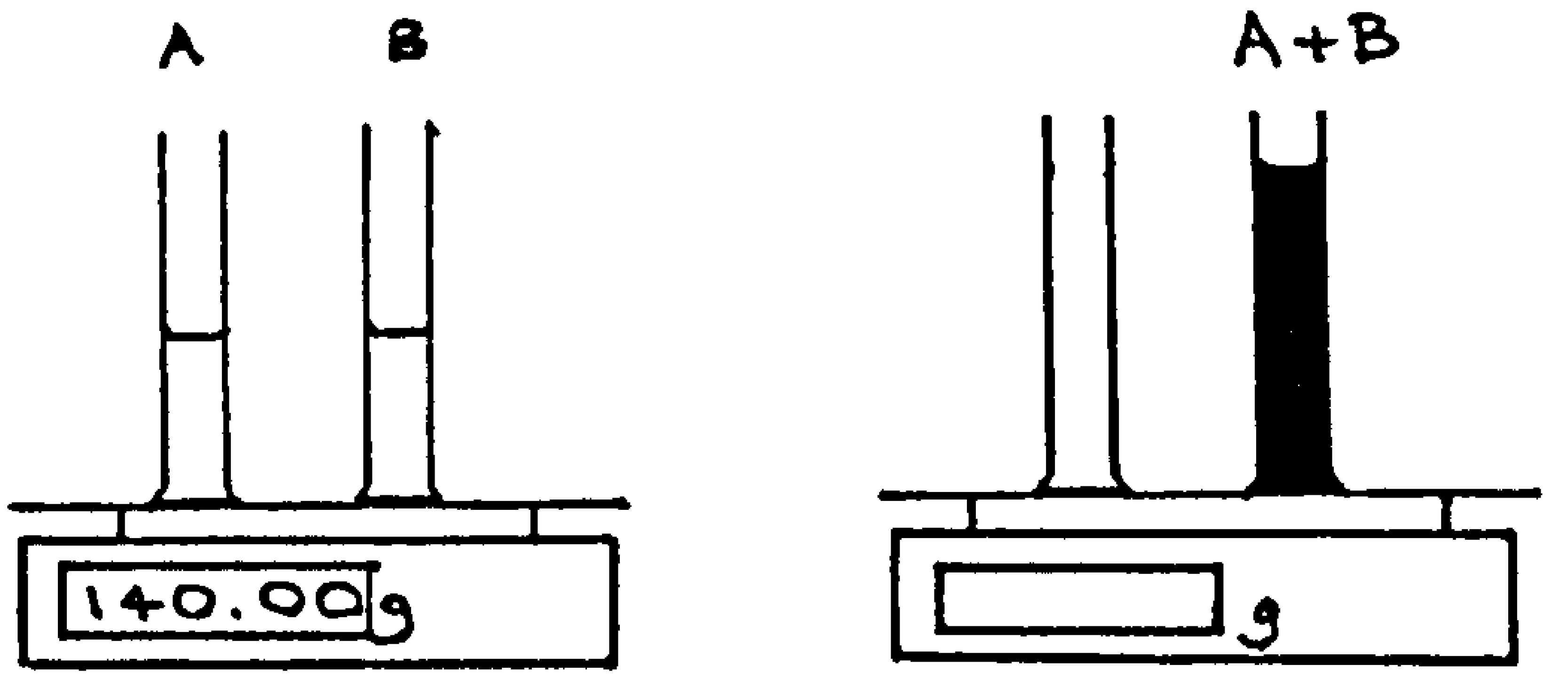
Where has the gas come from?

5. Use the equation below to estimate the mass of carbon dioxide produced when 24g of high quality coal is burned in 64g of oxygen gas.

Relative atomic mass values are :- C = 12, O = 16.

$C\ (s) + O_2\ (g) \longrightarrow CO_2\ (g)$

6. Aqueous solutions of two salts, A and B, are placed in separate measuring cylinders on a top pan balance. The total mass is recorded as 140g.



Solution A is poured into solution B. Both measuring cylinders remain on the balance. A precipitation reaction takes place.

What will the mass reading be after the reaction?

- ☐ Less than 140g
- ☐ 140g exactly
- ☐ More than 140 g

Explain why you think this.

7. Chemicals X and Y react to produce the compound XY. 50g of X and 70g of Y produce 120g of XY.

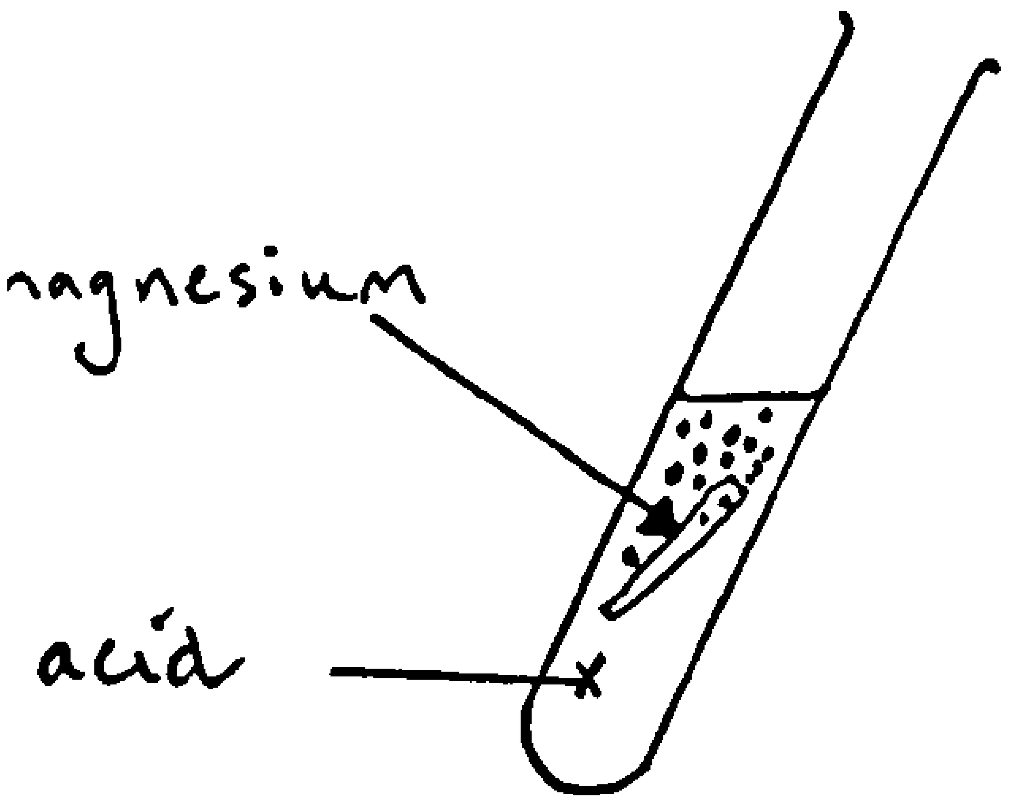
X + Y ------> XY
50g + 70g -----> 120g

What would you get when 100g of X and 150g of Y are made to react?

X + Y ------> XY
100g + 150g ------> ________

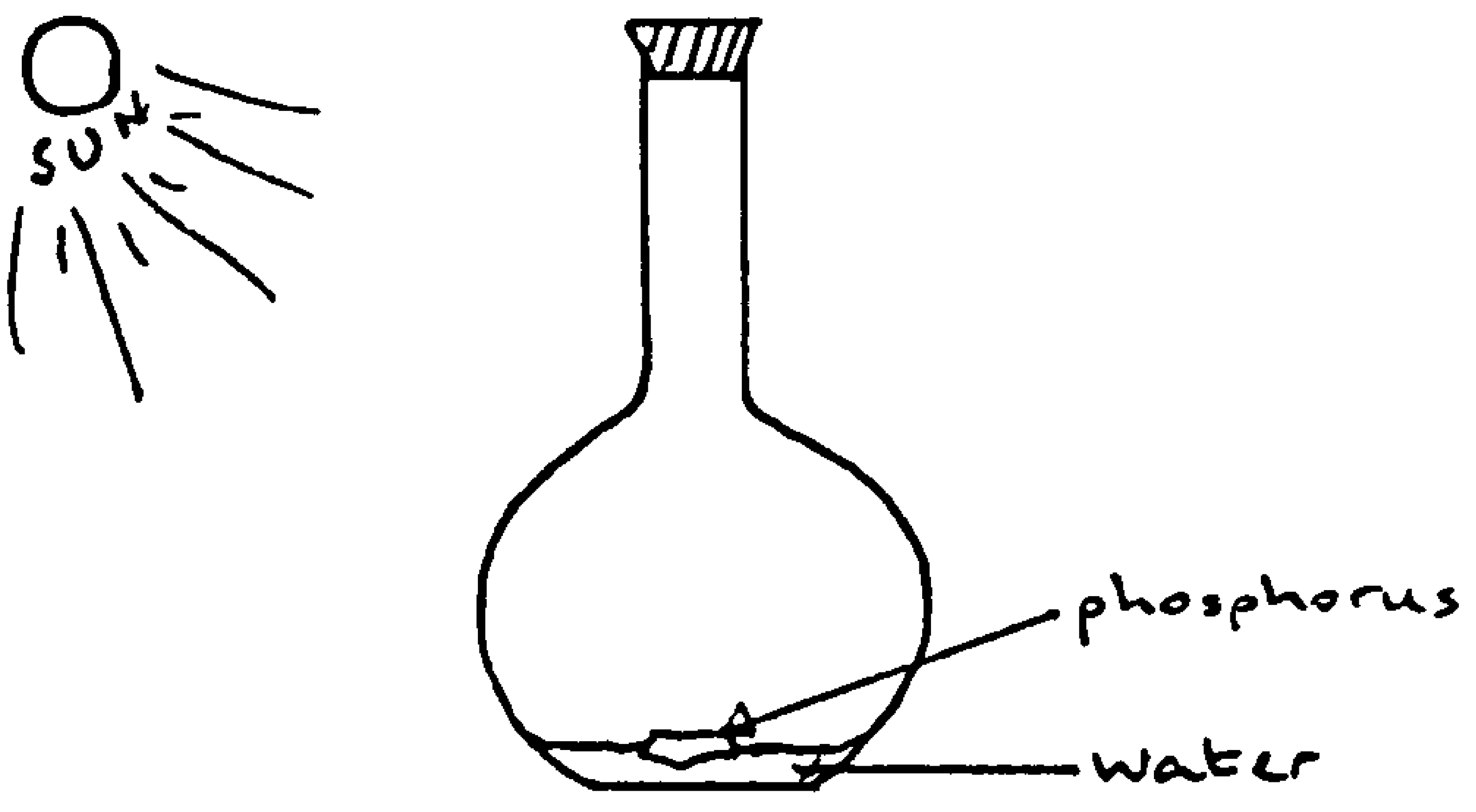
Explain how you thought this out.

8. A piece of magnesium ribbon is added to dilute hydrochloric acid. The magnesium dissolves. Bubbles of gas can be seen.



Where was the gas before the reaction?

9. A piece of phosphorus and some water were placed in a flask. The flask was sealed with a rubber stopper. The mass of the flask and contents was 400g. The sun's rays were focussed on the phosphorus which caught fire. The white smoke produced slowly dissolved in the water. The flask was cooled and its mass measured again.



Would you expect the mass to be:

☐ More than 400g

☐ 400g

☐ Less than 400g

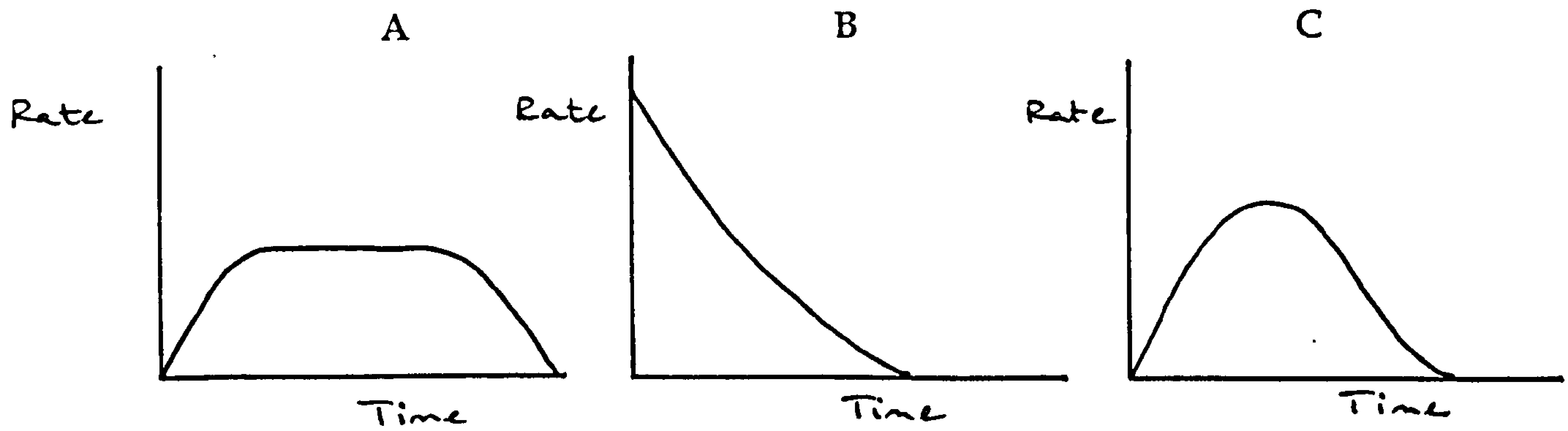
Explain why you think this.

10. When a piece of hot sodium metal is placed in a gas jar of chlorine, a violent reaction takes place and spots of white substance (sodium chloride) are spattered on the inside of the jar.

Explain as fully as you can what is happening in the gas jar.

11. Here are three graphs which show how the rate of a chemical reaction changes.

Look at the graphs and select the one you think best represents the reactions described below.



(a) Liquid X and liquid Y are mixed together. A reaction takes place.

Answer Graph .... represents this reaction best.
Explain why you think this.

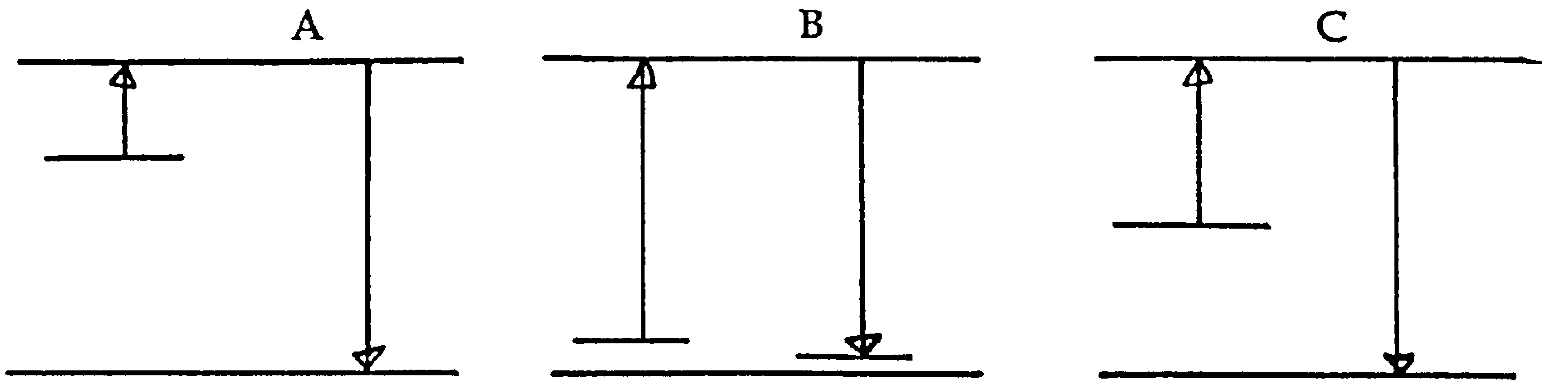
(b) $Mg\,(s) + 2HCl\,(aq) \dashrightarrow MgCl_2(aq) + H_2\,(g)$

Answer Graph .... represents this reaction best.
Explain why you think this.

12. Natural gas is mainly methane, CH_4.

Explain as clearly as you can why carbon and hydrogen form molecules with the formula CH_4 rather than CH_3, CH_2 or CH.

13. The three diagrams below represent the energy changes which take place during three chemical reactions.



Which of these energy diagrams do you think most closely represents the reaction between sodium and chlorine?

$2Na(s) + Cl_2(g) \longrightarrow 2NaCl(s)$ Energy diagram A / B / C

Please give the reason for your answer

14. A car with a mass of 1000kg has 50kg of petrol put in its tank. The car is driven until the tank is completely empty. The car then has a mass of 1000kg again. What is the approximate weight of the exhaust gases given off while the car is being driven?

The approximate mass of exhaust gases is ....

Explain your reasoning as fully as possible.

15. A coal-burning power station burns 1000 tonnes of high quality coal each day.

What mass of carbon dioxide will be produced from the flue chimney?

16. The reaction $N_2 (g) + 3H_2 (g) \rightleftharpoons 2NH_3 (g)$

is called an "equilibrium" reaction.

The reaction $O_2 (g) + 2H_2 (g) \longrightarrow 2H_2O (l)$

is not an equilibrium reaction.

Explain as best you can why these two reactions are different.

17. Methane is natural gas. When methane burns, the equation for the reaction is:-

$$CH_4 (g) + 2O_2 (g) \longrightarrow CO_2 (g) + 2H_2O (l)$$

A student needs to use a gas cooker. He (or she) turns the gas on. Methane comes out of the gas tap and mixes with the air. Although both reactants are present, the reaction does not begin until a gas lighter is used to make a spark.

Explain why a spark is needed to make the methane burn.

Why is only *one* spark needed?

The flame is hot. Energy is transferred to the environment near the flame. Where was this energy before the reaction?

How long did you spend on the questions? ....
Thanks again for your help.

Mrs. V. Barker
Research Fellow
Department of Chemistry
University of York
York YO1 5DD

Appendix 2

Test papers used in the three survey

NAME: ____________________

DATE: ____________________

START TIME: ______________

An investigation of students' ideas about A level chemistry topics

Time required: Approximately 1 hour

Before you start please read the letter on the next page.

Note: All the information you need is in the question paper.

Vanessa Barker

September 1992

Department of Chemistry
University of York
York YO1 5DD

An investigation of students' ideas about A level chemistry topics

Dear Student,

You may be wondering why you are being asked to complete this test. If so, let me explain.

I am a chemistry teacher working on a three year research project to find out what it is that students actually learn when they study A level chemistry. The study will take place over two years, so I will be asking you to complete similar tests a maximum of three more times during your A level course.

To try to find out what students really understand, I have designed this test paper. The questions will hopefully encourage you to put your own ideas about some of the topics in chemistry on to paper. If you are thinking, "But I don't have any ideas!" or "I don't know any chemistry (or not much)!", don't panic. This is not an exam. It has nothing to do with the A level papers you will take in eighteen months time.

What I am asking you to do is to answer honestly every question using your chemical common sense. Don't look for tricks - none are intended - and lengthy answers are not expected! There may seem to be a lot of pages, but the print is big and there are lots of pictures and plenty of space.

Two pieces of advice - firstly, don't spend too long on any one question. You should get through the whole thing in about an hour. Secondly, if you genuinely have no idea about a question, just write "I don't know". This means I will know you have read the question. Which reminds me, thirdly, READ THE QUESTIONS CAREFULLY!

It would also be a great help to me if you could complete the enclosed student information survey. This will help me to ensure I have designed the test to be fair to everyone taking it. The information you give will remain confidential and will only be used for the research study.

Finally, thank you very much for completing the test.

Yours sincerely,

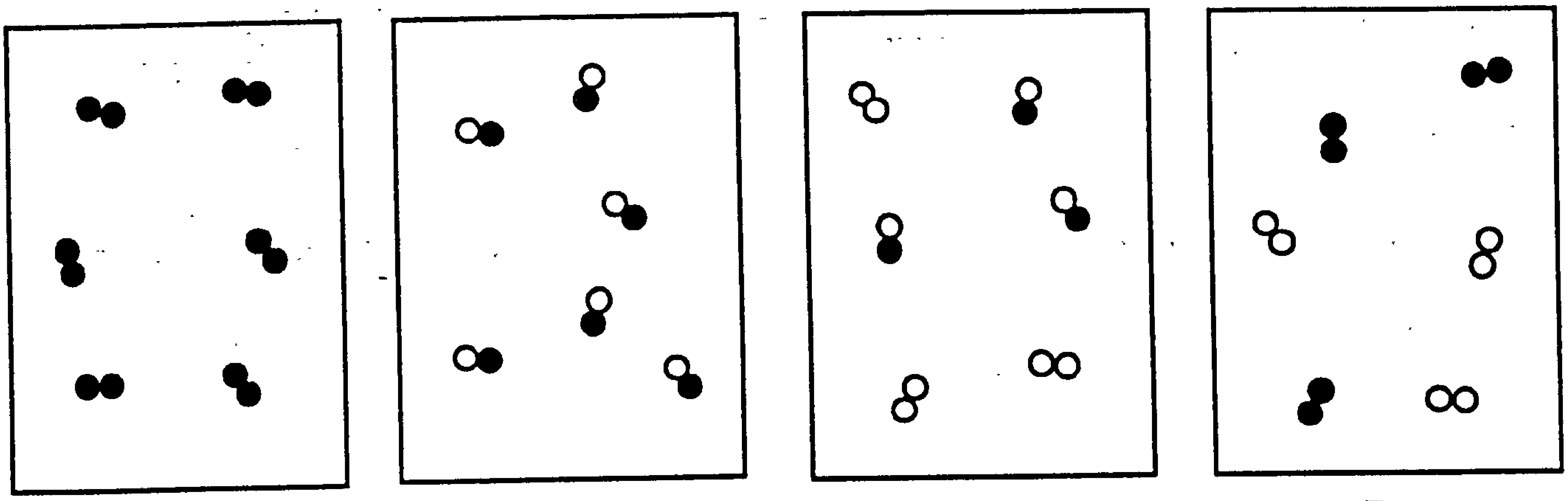
Vanessa Barker

Mrs. V. Barker

Research Fellow
Department of Chemistry
University of York
York YO1 5DD

Molecules

The diagrams lettered A - D represent four different gases. All four of the gases are made from two chemical elements. The atoms of the elements are given the symbols ○ and ●.



A B C D

Identify which gas is:-

(a) a mixture of the two elements; ______

(b) a compound; ______

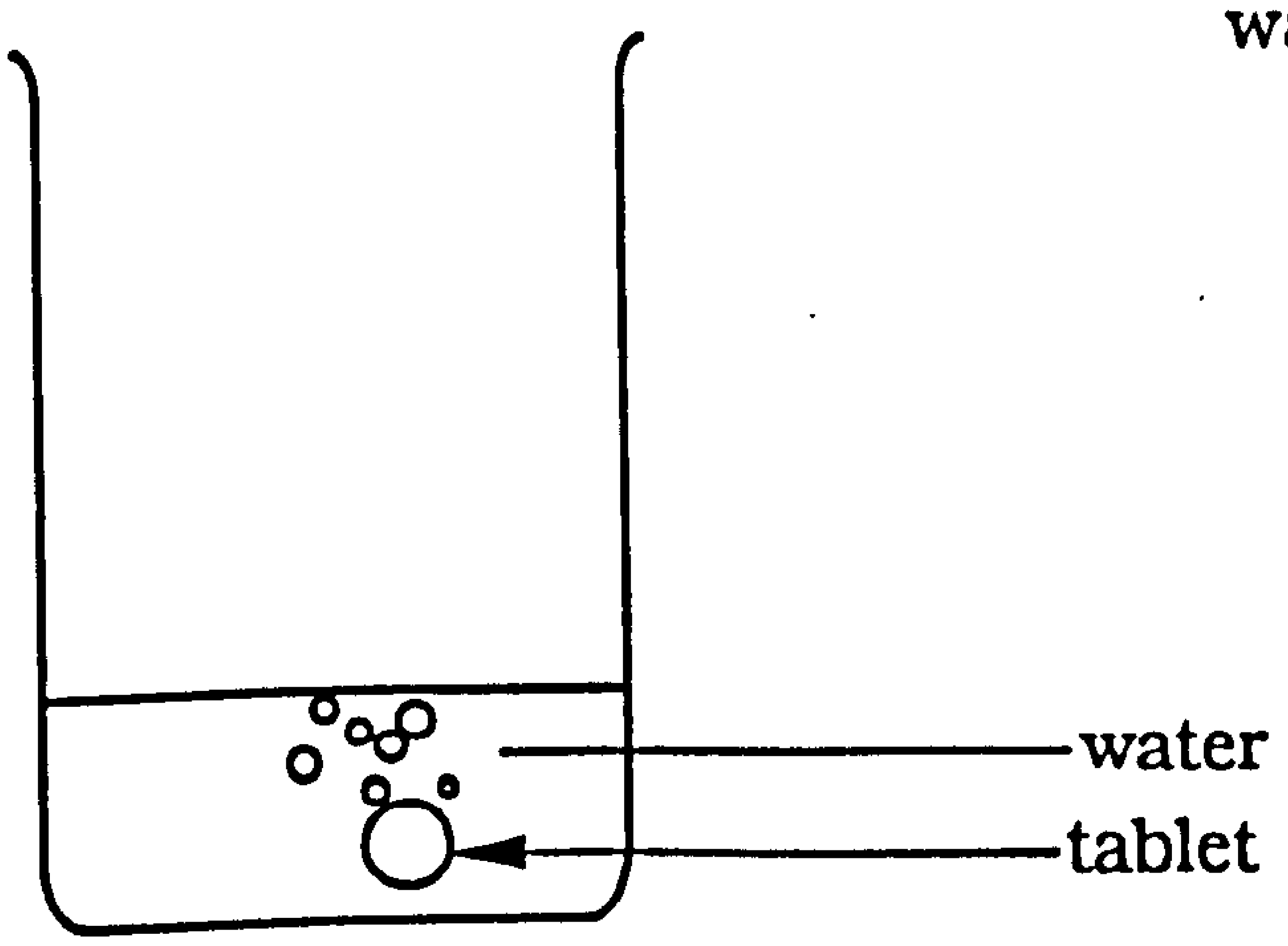
(c) one element alone. ______

There is one diagram which you haven't chosen. What do you think is represented by that diagram?

Tablet

An Alka-Seltzer tablet is dropped into a beaker of water. Bubbles of gas are seen and after a while the tablet has completely dissolved.

Where was this gas before the tablet was dropped in the water?



Substances

For each of the substances described below, tick the box you think best fits the description of the substance. Also, explain how you decided which box to tick.

A **is a yellow solid which does not conduct electricity, but burns in oxygen to give one product.**

Substance A is :-

a compound ☐ a non-metal element ☐ a metal element ☐ a mixture ☐

Explanation

B **is a silvery grey solid which conducts electricity and burns in oxygen to give one product.**

Substance B is:-

a compound ☐ a non-metal element ☐ a metal element ☐ a mixture ☐

Explanation

C **is a colourless liquid which burns when ignited to give carbon dioxide and water.**

Substance C is:-

a compound ☐ a non-metal element ☐ a metal element ☐ a mixture ☐

Explanation

D **is a dark blue liquid which produces several spots on a chromatogram.**

Substance D is:-

a compound ☐ a non-metal element ☐ a metal element ☐ a mixture ☐

Explanation

Carbon

Use the equation below to estimate the mass of carbon dioxide produced when 24g of carbon is burned in 64g of oxygen gas. The equation for the reaction is:-

$$C\,(s) + O_2\,(g) \longrightarrow CO_2\,(g)$$

Relative atomic mass values are :- C = 12, O = 16.

Element and compound

Iron (Fe) is a chemical element. Water (H_2O) is a compound.

Define the terms "element" and "compound".

Element

Compound

What test (or tests) could a chemist do on a sample of iron to show that it is an element?

What test (or tests) could a chemist do on a sample of water to show that it is a compound?

Boiling

When water boils, bubbles appear in the liquid.

What is in the bubbles?

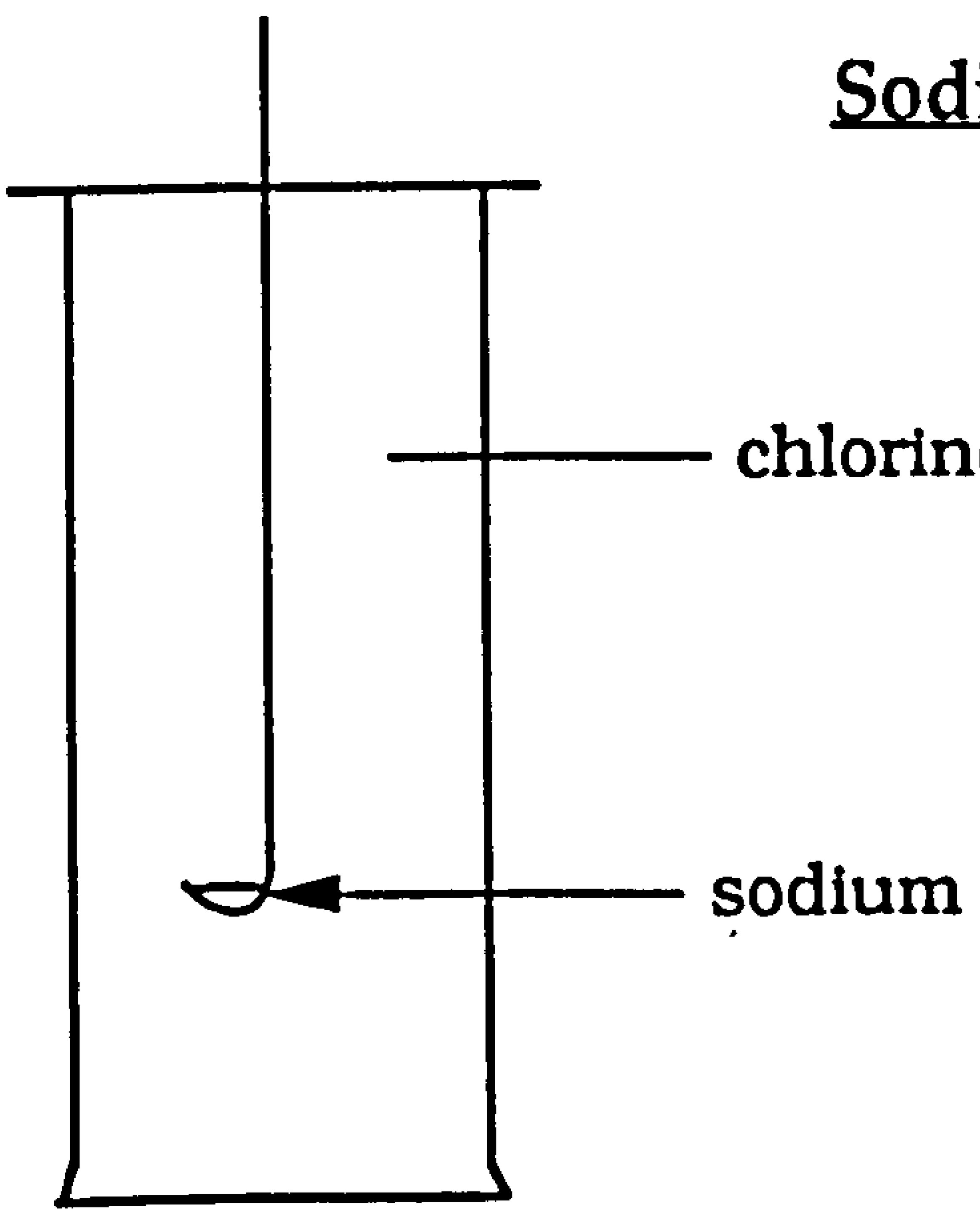
Petrol

A car with a mass of 1000 kg has 50 kg of petrol put in its tank. The car is driven until the tank is completely empty. The car then has a mass of 1000 kg again. What is the approximate mass of the exhaust gases given off while the car is being driven?

The approximate mass of exhaust gases is ....kg

Explain your reasoning as fully as possible.

Sodium and chlorine



When a piece of hot sodium metal is placed in a gas jar of chlorine, a violent reaction takes place and spots of a white substance (sodium chloride) are spattered on the inside of the jar.

Explain as fully as you can what is happening in the gas jar.

Iron sulphide

Iron and sulphur react to form the compound iron sulphide. 56g of iron and 32g of sulphur produce 88g of iron sulphide.

$$\begin{array}{lcl} Fe\,(s) + S\,(s) & \longrightarrow & FeS\,(s) \\ 56g + 32g & \longrightarrow & 88g \end{array}$$

What would you get when twice as much iron, 112g, and more than twice as much sulphur, 80g, are made to react?

Solution

20g of sodium chloride is dissolved in water. The mass of the water and beaker before any sodium chloride is added is 200g.

(a) What is the total mass of the sodium chloride solution and beaker?

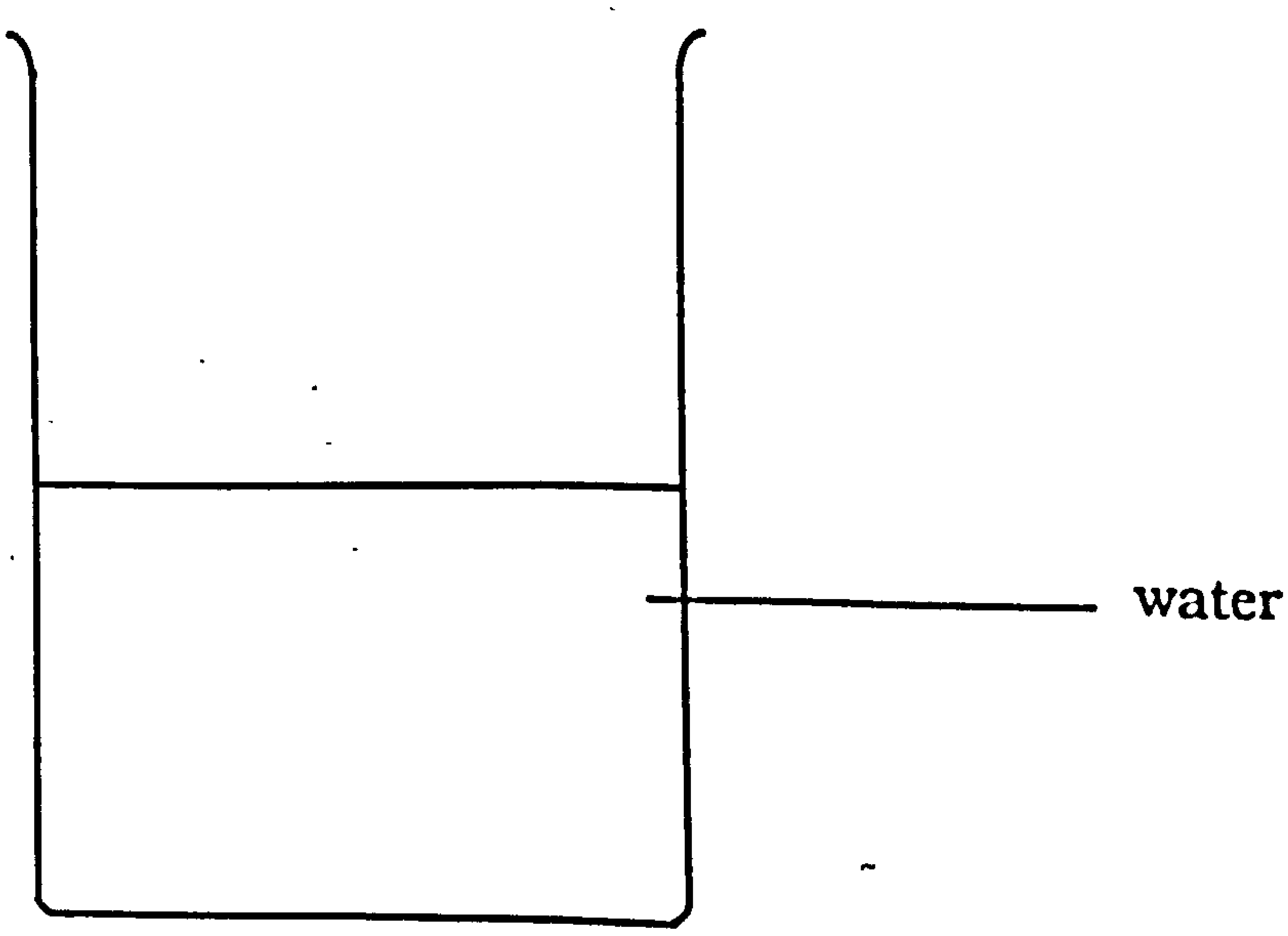
☐ Less than 220g

☐ More than 220g

☐ 220g exactly

Explain why you think this.

(b) Use the diagram of the beaker to show what you think happens when the sodium chloride is dissolved in water.
You can show water particles too if you like.



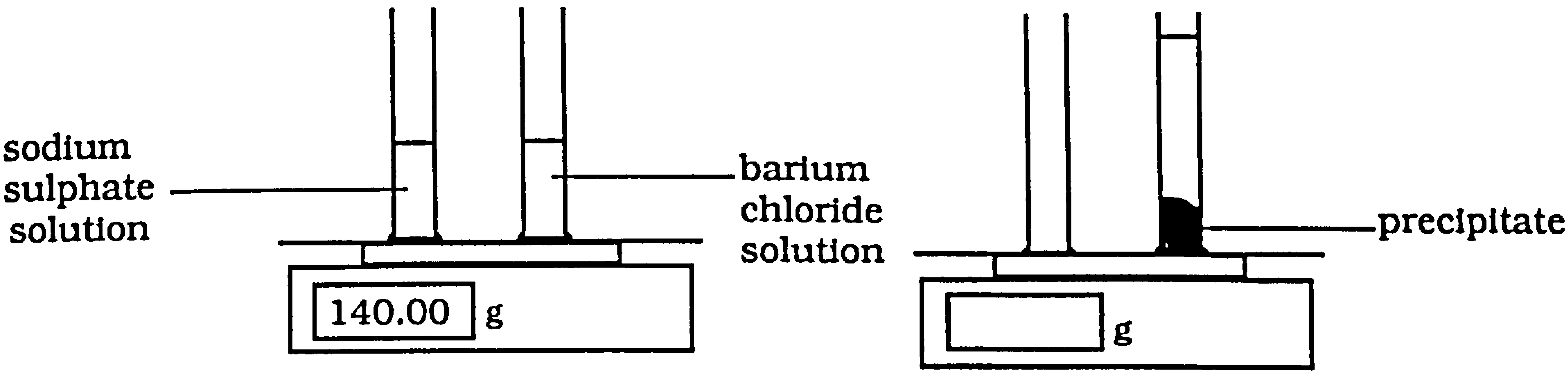
Methane molecules

Natural gas is mainly methane, CH_4.

Explain as clearly as you can why carbon and hydrogen form molecules with the formula CH_4 rather than CH_3 CH_2 or CH.

Precipitation

Aqueous solutions of two salts, sodium sulphate (Na_2SO_4 (aq)) and barium chloride ($BaCl_2$ (aq)), are placed in separate measuring cylinders on a top pan balance. The total mass is recorded as 140g.



The sodium sulphate solution is poured into the barium chloride solution. Both measuring cylinders stay on the balance. A precipitation reaction takes place.

What will the mass reading be after the reaction?

- ☐ Less than 140g
- ☐ 140g exactly
- ☐ More than 140g

Explain why you think this.

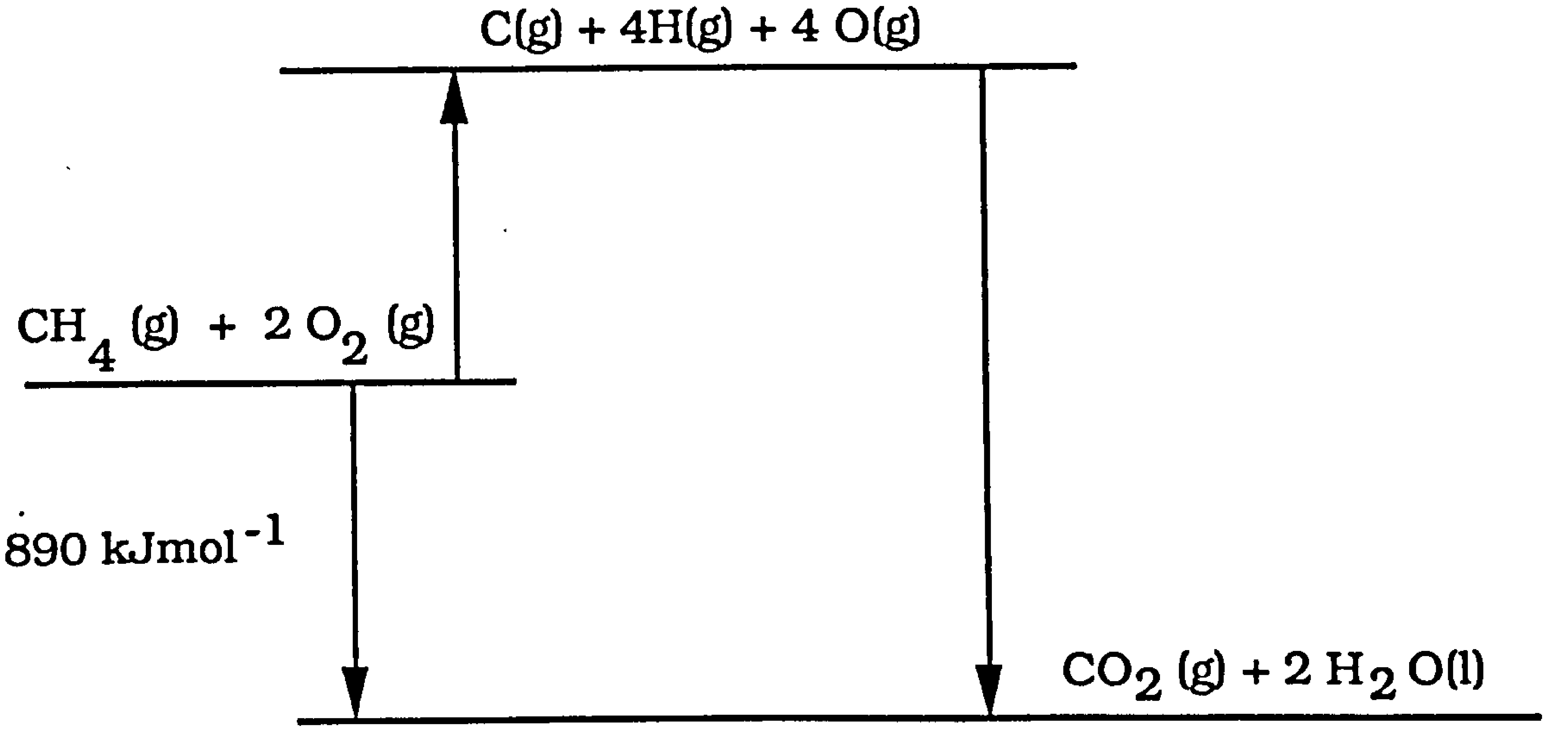
Where was the precipitate before the reaction occurred?

Methane

Methane is natural gas. When methane burns, the equation for the reaction is:-

$$CH_4\,(g) + 2O_2\,(g) \longrightarrow CO_2\,(g) + 2H_2O\,(l)$$

This reaction can be represented on a diagram like this one from a chemistry textbook:-



Explain why

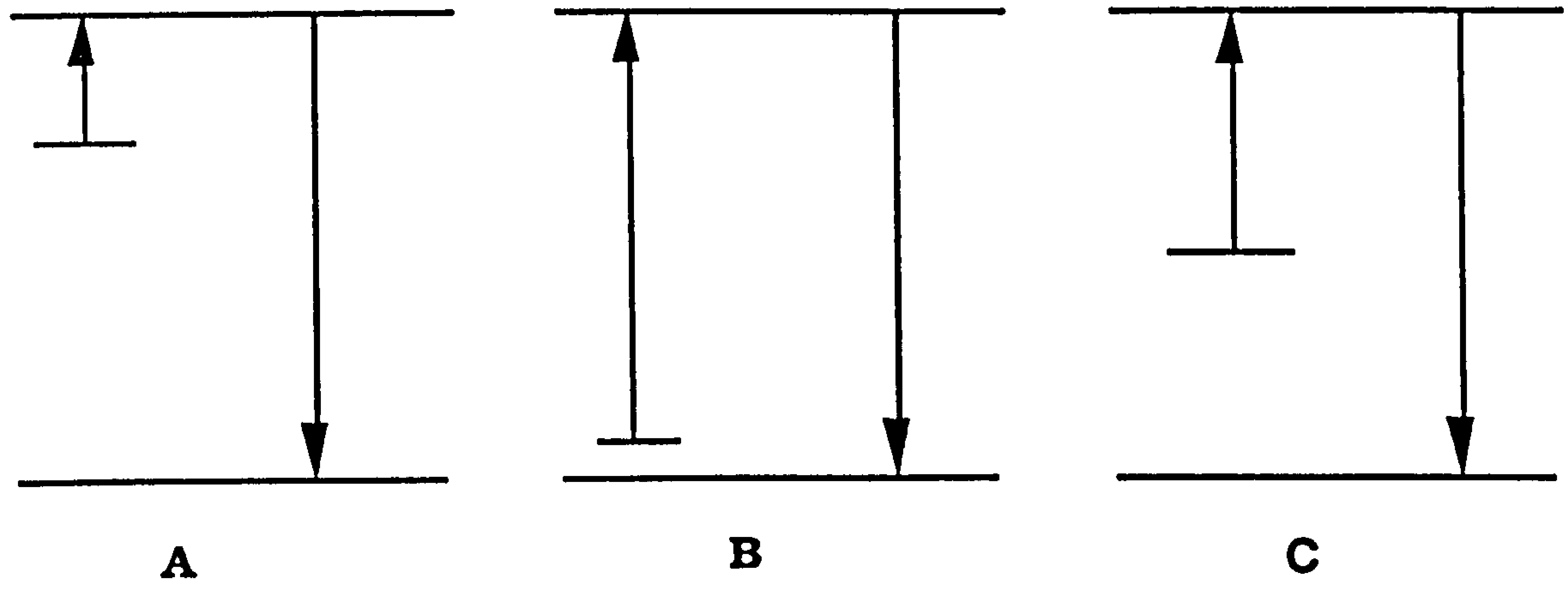
(a) a spark or match flame is needed to start methane burning;

(b) methane will continue to burn until it is all used up.

(c) The diagram shows that the burning of methane releases energy to the environment.
Explain as best you can where this energy comes from.

Energy change

The three diagrams below represent the energy changes which take place during three chemical reactions.



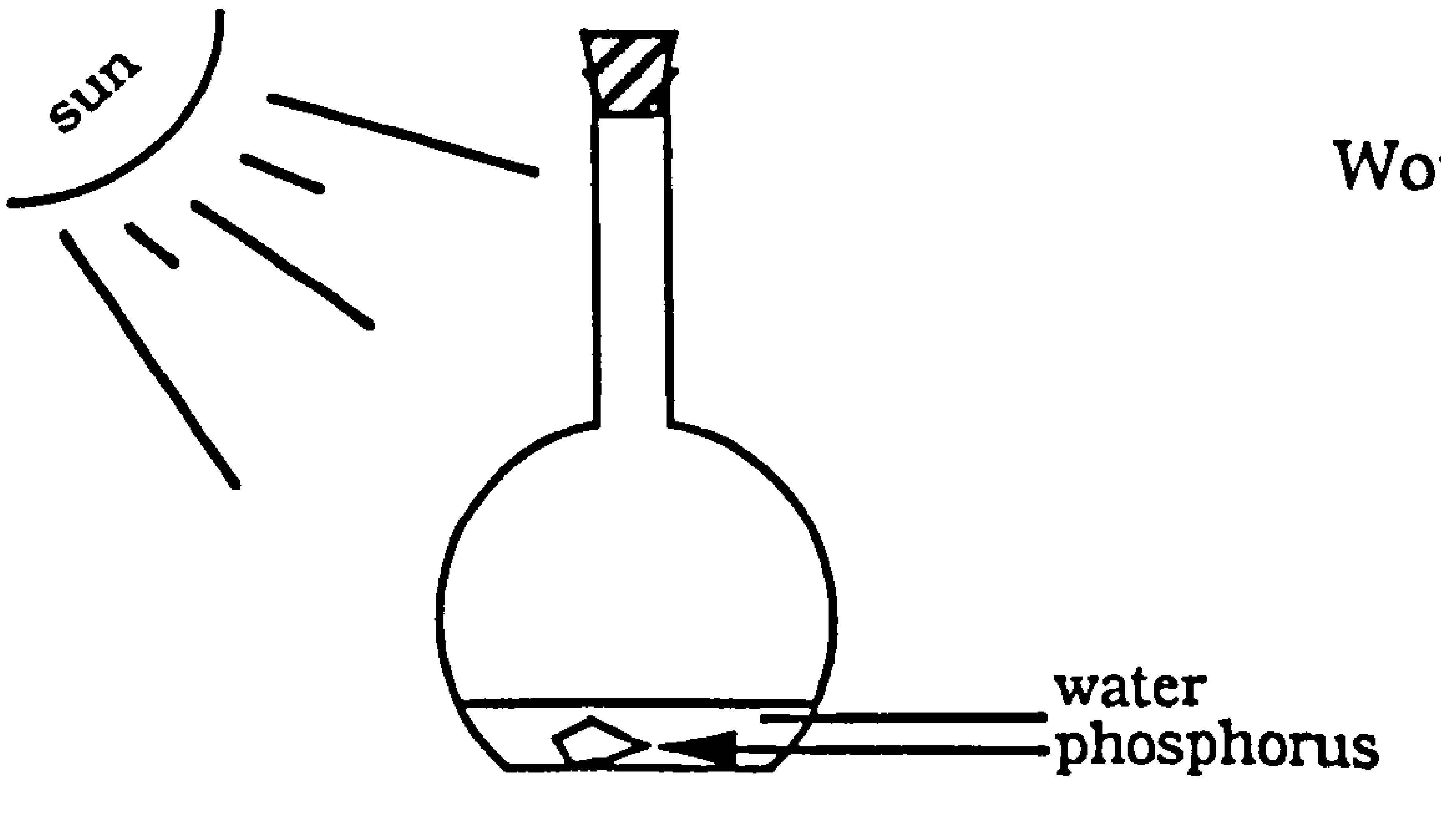
Which of these energy diagrams do you think best represents the reaction between sodium and chlorine?

$2Na(s) + Cl_2(g) \longrightarrow 2NaCl(s)$ Energy diagram A / B / C

Please explain how you decided.

Phosphorus

A piece of phosphorus and some water were placed in a flask. The flask was sealed with a rubber stopper. The mass of the flask and contents was 400g. The sun's rays were focussed on the phosphorus which caught fire. White smoke was produced which slowly dissolved in the water. The flask was cooled and its mass measured again.



Would you expect the mass to be:

☐ more than 400g

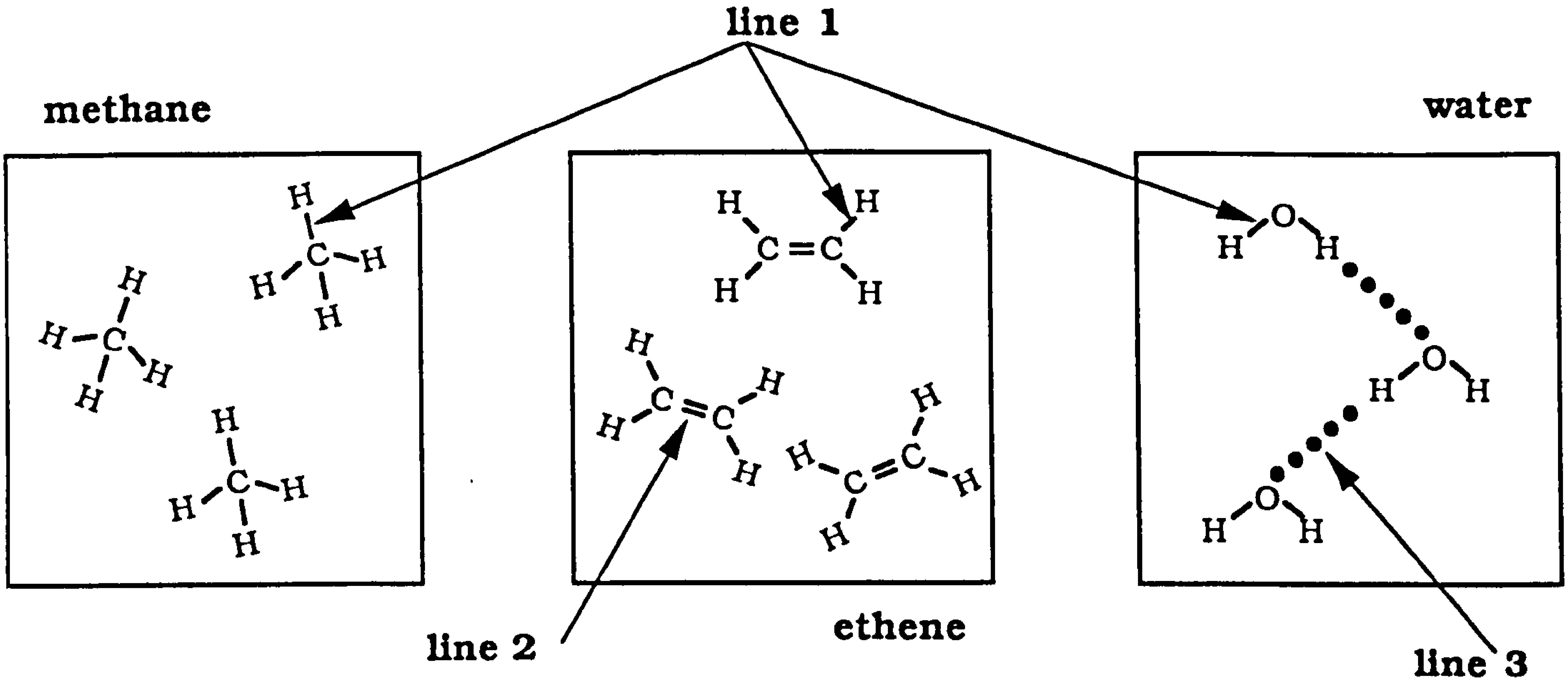
☐ 400g

☐ less than 400g

Explain why you chose your answer.

Chemical bonds

The diagrams represent molecules of methane, ethene and water.



(a) Explain as fully as possible the meanings of the lines marked 1, 2 and 3.

Line 1

Line 2

Line 3

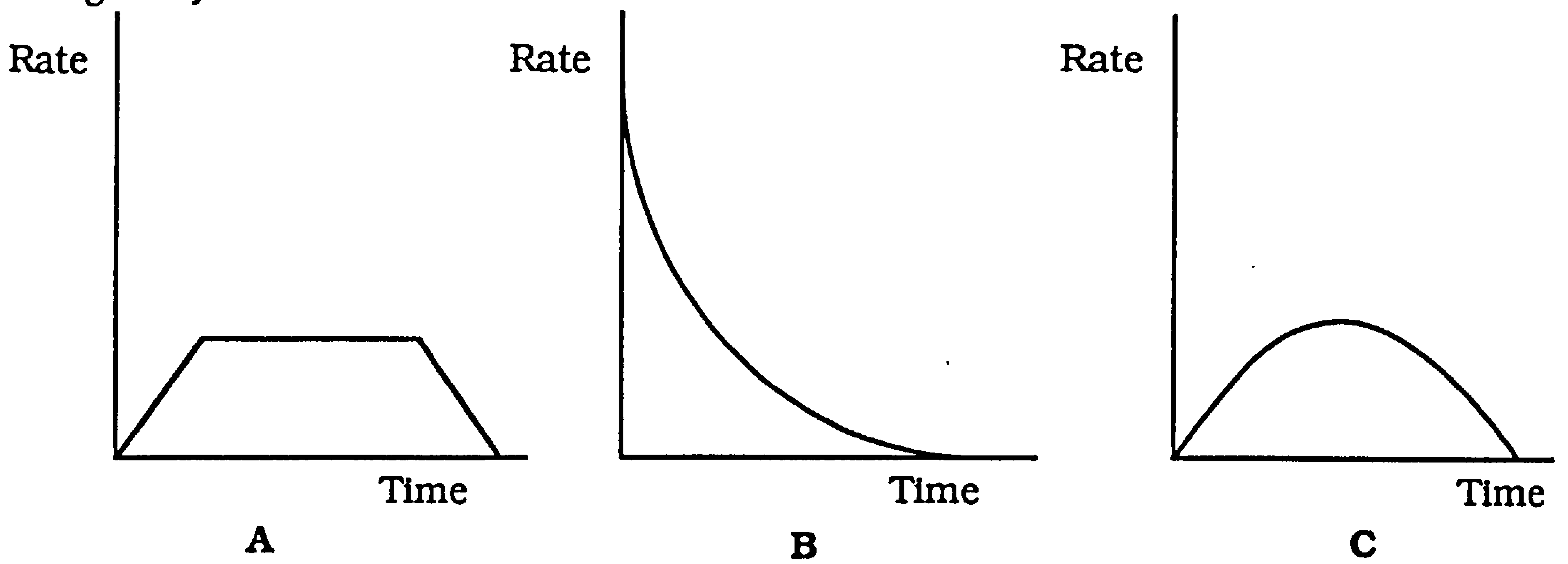
(b) What differences are there between:-

(i) line 1 and line 2;

(ii) line 1 and line 3? (I already know that line 3 is not a line but dots...)

Reaction rates

Here are three graphs which show how the rate of a chemical reaction changes as time goes by.



Describe in words what each graph says about how the rate of a chemical reaction changes as the reaction goes on.

Graph A

Graph B

Graph C

Choose the graph you think best represents the reactions shown below.

(a) A solution of sodium carbonate is added to dilute hydrochloric acid.

$$Na_2CO_3(aq) + 2HCl\ (aq) \longrightarrow 2NaCl(aq) + H_2O(l) + CO_2(g)$$

Answer Graph .... represents this reaction best because..

(b) A piece of magnesium ribbon is added to dilute hydrochloric acid.

$$Mg\ (s) + 2HCl\ (aq) \longrightarrow MgCl_2(aq) + H_2\ (g)$$

Answer Graph .... represents this reaction best because..

Chlorides

The bonding in magnesium chloride ($MgCl_2$) is ionic. The bonding in titanium(IV) chloride ($TiCl_4$) is covalent.

A mixture of the two chlorides is heated to 1000 ^{o}C.

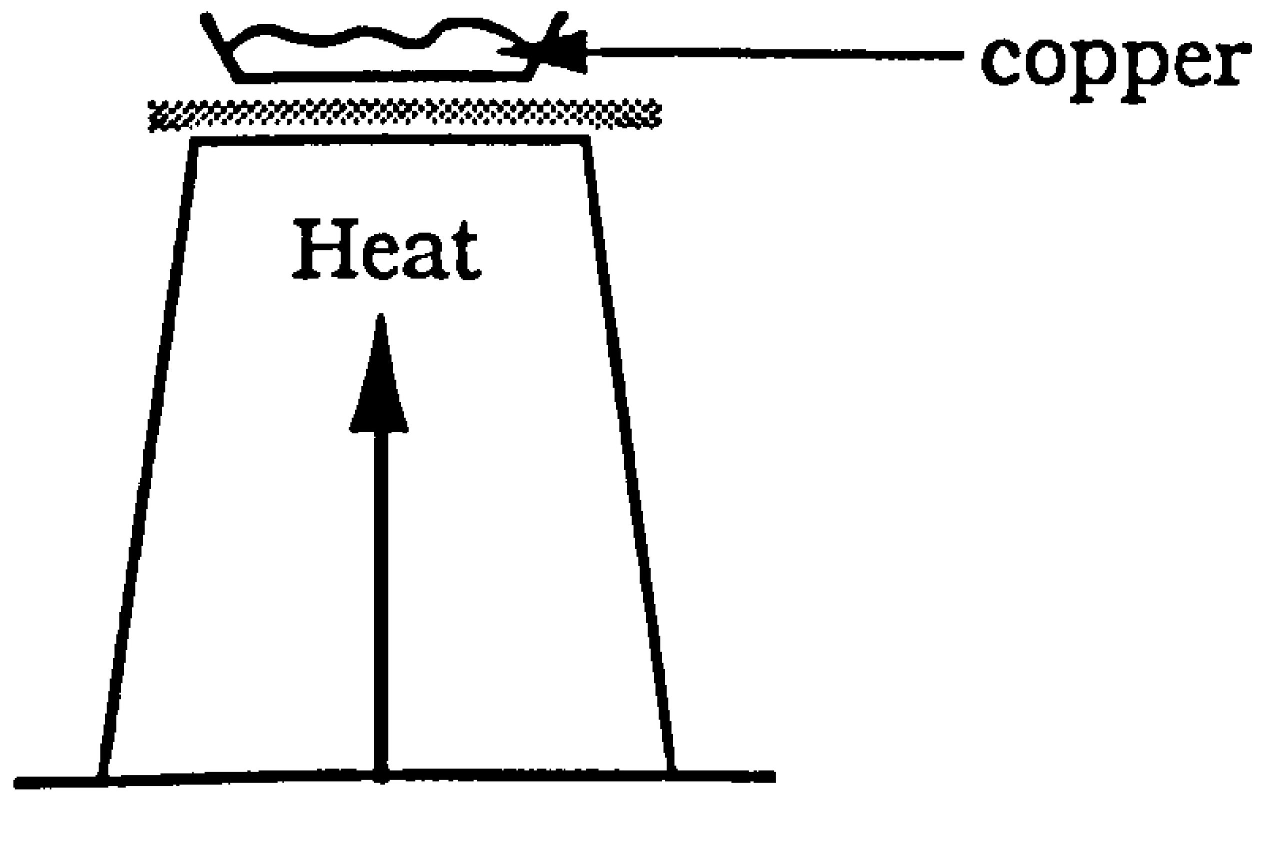
Explain why the vapour above the mixture consists only of titanium(IV) chloride.

Power station

A coal-burning power station burns 1000 tonnes of high quality coal each day.

Estimate the mass of carbon dioxide which will go up the flue chimney each day.

Copper



Powdered copper metal has an orange-red colour. Some powdered copper metal was placed in a small dish. The mass of the dish and copper was 40g. The dish (and metal) were heated in air.

After a few minutes, black stuff appeared in the dish. The mass of the dish and contents had gone up to 45g.

Where did the black stuff come from?

Reactions

Hydrogen gas reacts with nitrogen and also with oxygen. The equations for the reactions are:-

$$N_2\,(g) + 3H_2\,(g) \rightleftharpoons 2NH_3\,(g) \qquad \Delta H = -92\ kJmol^{-1}$$

$$O_2\,(g) + 2H_2\,(g) \longrightarrow 2H_2O\,(l) \qquad \Delta H = -572\ kJmol^{-1}$$

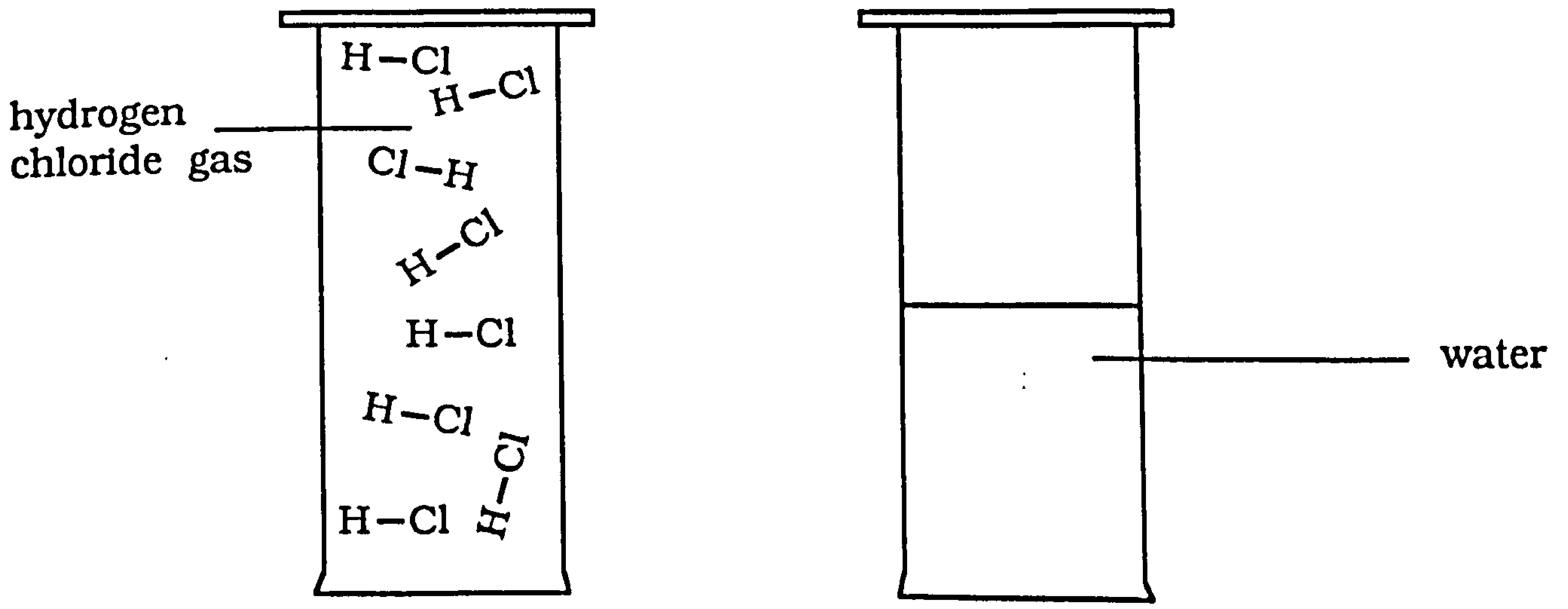
(a) Why is an equilibrium arrow ($\rightleftharpoons$) used in the nitrogen/hydrogen reaction but not in the oxygen/hydrogen reaction?

(b) Most reactions are written with an ordinary arrow ($\longrightarrow$) like in the oxygen/hydrogen reaction and are not called "equilibrium" reactions.

Explain as best you can why this is so.

Hydrogen chloride

Water is added to a gas jar of hydrogen chloride gas. The gas dissolves in the water forming hydrochloric acid.



(a) Use the second diagram to show how hydrochloric acid is formed from hydrogen chloride and water. You can show water particles too if you wish.

(b) A piece of magnesium is added to the hydrochloric acid. A reaction takes place producing hydrogen gas.

Explain how the hydrogen gas is formed.

FINALLY

Note here the time you finished ______

How long did you spend on the questions? _______

On a scale of 1 (very easy) to 5 (very hard), how difficult did you think the questions were?

Please ring the number:-

1	2	3	4	5
very easy	easy	average	hard	very hard

Once again, thank you very much for your answers.

STUDENT INFORMATION SURVEY

Please delete as appropriate.

Male / Female

Name of school or college ________________________________

Have you changed to a new school or college for A levels? YES / NO
Please give the name of your last school or college if you have changed.

Is English your first language? YES / NO
Please give your first language if it is not English.

What GCSE courses did you take? Please also give the grades you obtained.

SUBJECT	GRADE	SUBJECT	GRADE

Did you study GCSE SALTERS Science/Chemistry? YES/NO

Which A level chemistry syllabus are you studying?

What subjects are you studying now in addition to chemistry?
Please give subject and level e.g. A, AS, BTEC National

Explain why you decided to take A level chemistry.

What are you hoping to do when you finish your A levels?
Please say if you wish to study a particular subject, or get a job......

NAME: ____________________

DATE: ____________________

START TIME: ______________

An investigation of students' ideas about A level chemistry topics

Stage 2

Time required: Approximately 1 hour

Before you start please read the letter on the next page.

Note: All the information you need is in the question paper.

Vanessa Barker

April 1993

Department of Chemistry
University of York
York YO1 5DD

An investigation of students' ideas about A level chemistry topics

Dear Student,

Last September you very kindly completed this test paper. I was very impressed that almost everyone tried nearly all the questions. Your responses have helped to build up an overall picture of the understanding of chemistry beginning A level students have.

You are now about half-way through your course, and I would like to find out if your ideas about the chemical topics in the paper have changed. So, I am asking you to try the questions again. Towards the end of your course, early next year, I will ask you to do the paper a third time. I hope you will be able to do everything by then!

As before, you may not have covered all the topics - but please answer as many questions as you possibly can, using chemical common sense. If you really can't answer a question, please write "I don't know", which at least reassures me you have read this letter and the question!

Two pieces of advice - first, don't spend too long on any one question. The paper should take about an hour to finish (it would help if you could put the total length of time you spend on the paper in the space at the end). Second, READ EACH QUESTION CAREFULLY!

Finally, can I reassure you that your answers will only be used for this research study and will remain confidential. There is no link between this paper and any A level examination paper.

Finally, thank you very much for completing the test.

Yours sincerely,

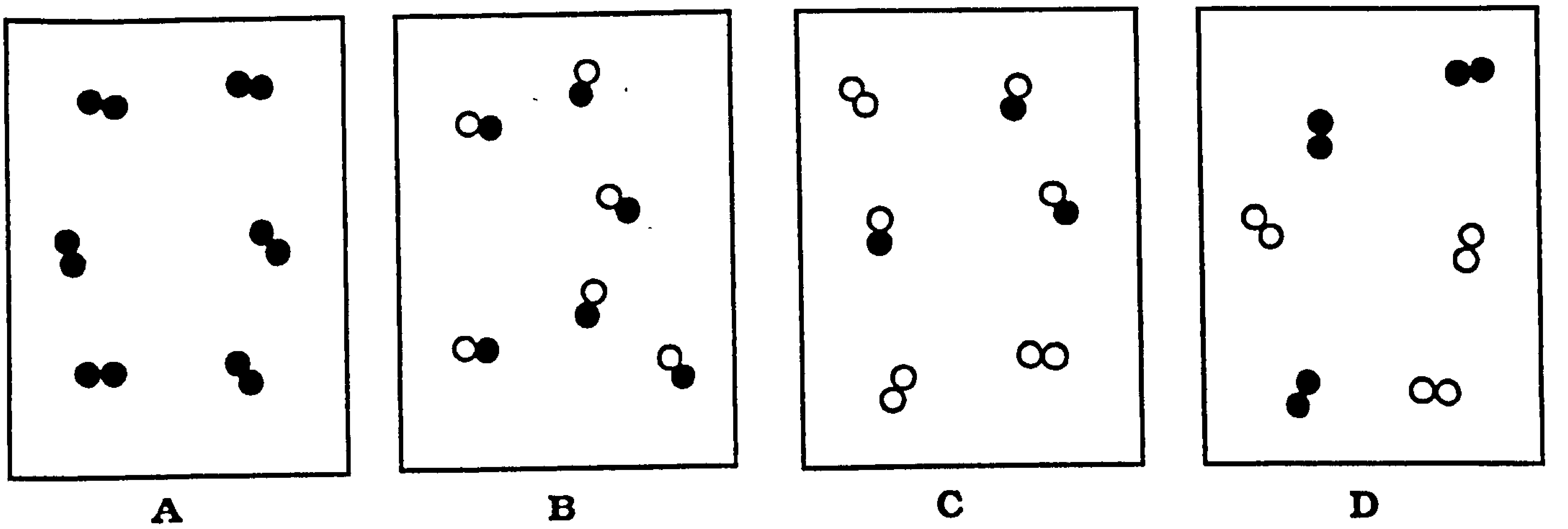
Vanessa Barker

Mrs. V. Barker

Research Fellow
Department of Chemistry
University of York
York YO1 5DD

Molecules

The diagrams lettered A - D represent four different gases. All four of the gases are made from two chemical elements. The atoms of the elements are given the symbols ○ and ●.



Identify which gas is:-

(a) a mixture of the two elements; ______

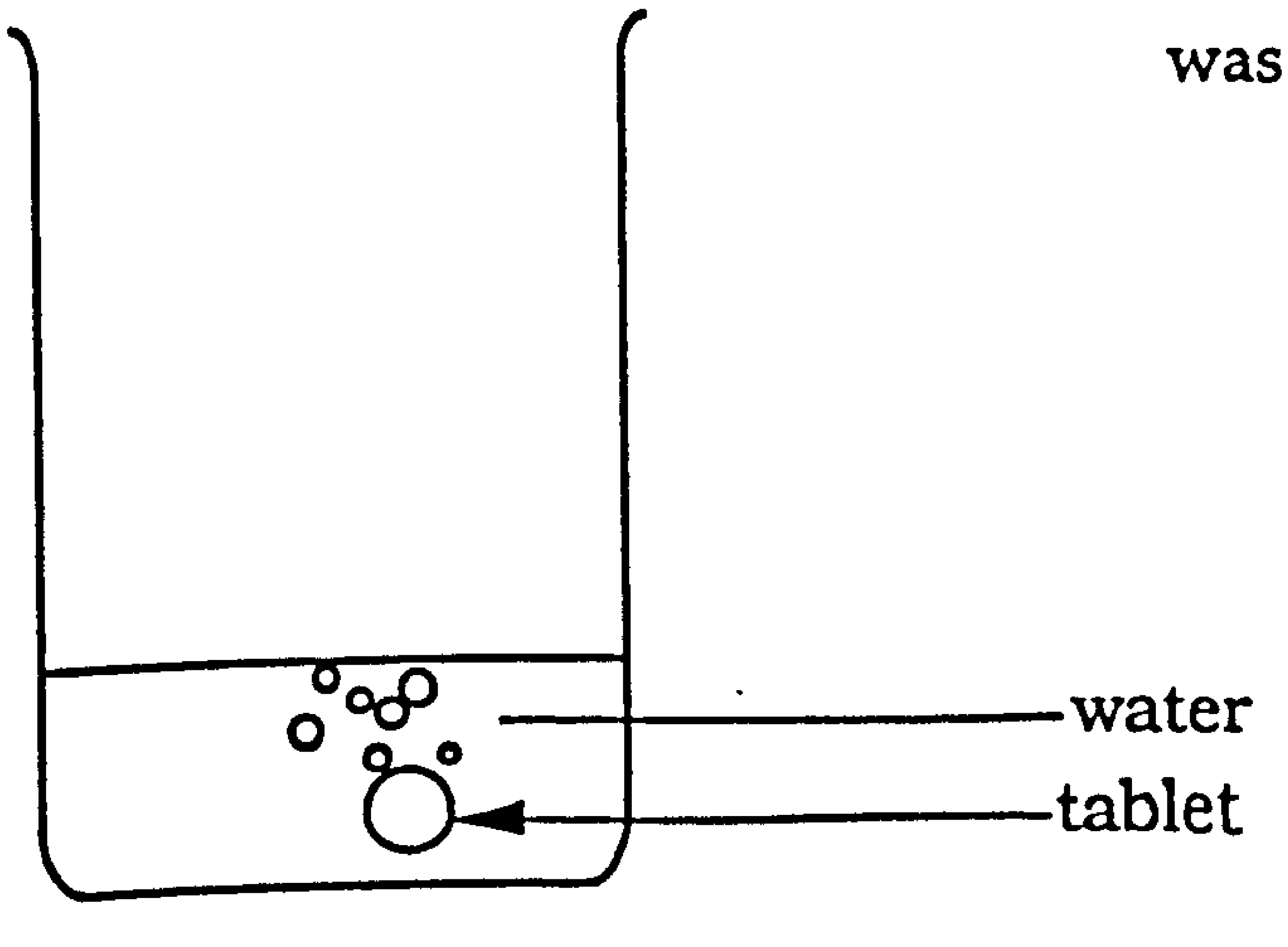
(b) a compound; ______

(c) one element alone. ______

There is one diagram which you haven't chosen. What do you think is represented by that diagram?

Tablet

An Alka-Seltzer tablet is dropped into a beaker of water. Bubbles of gas are seen and after a while the tablet has completely dissolved.



Where was this gas before the tablet was dropped in the water?

Carbon

Use the equation below to estimate the mass of carbon dioxide produced when 24g of carbon is burned in 64g of oxygen gas. The equation for the reaction is:-

$$C\,(s) + O_2\,(g) \longrightarrow CO_2\,(g)$$

Relative atomic mass values are :- C = 12, O = 16.

Element and compound

Iron (Fe) is a chemical element. Water (H_2O) is a compound.

Define the terms "element" and "compound".

Element

Compound

What test (or tests) could a chemist do on a sample of iron to show that it is an element?

What test (or tests) could a chemist do on a sample of water to show that it is a compound?

Substances

For each of the substances described below, tick the box you think best fits the description of the substance. Also, explain how you decided which box to tick.

A **is a yellow solid which does not conduct electricity, but burns in oxygen to give one product.**

Substance A is :-

a compound ☐ a non-metal element ☐ a metal element ☐ a mixture ☐

Explanation

B **is a silvery grey solid which conducts electricity and burns in oxygen to give one product.**

Substance B is:-

a compound ☐ a non-metal element ☐ a metal element ☐ a mixture ☐

Explanation

C **is a colourless liquid which burns when ignited to give carbon dioxide and water.**

Substance C is:-

a compound ☐ a non-metal element ☐ a metal element ☐ a mixture ☐

Explanation

D **is a dark blue liquid which produces several spots on a chromatogram.**

Substance D is:-

a compound ☐ a non-metal element ☐ a metal element ☐ a mixture ☐

Explanation

Boiling

When water boils, bubbles appear in the liquid.

What is in the bubbles?

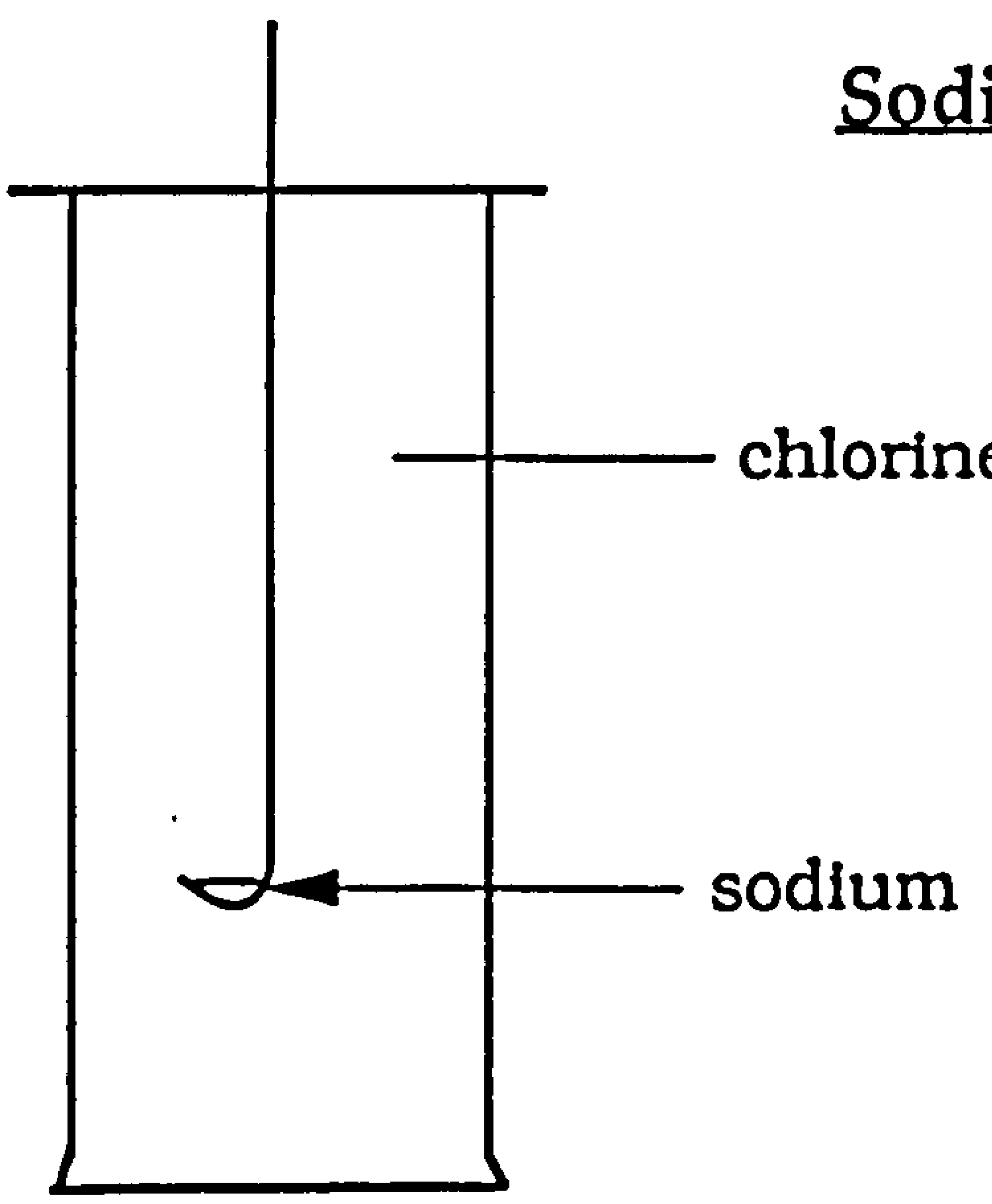
Petrol

A car with a mass of 1000 kg has 50 kg of petrol put in its tank. The car is driven until the tank is completely empty. The car then has a mass of 1000 kg again. What is the approximate mass of the exhaust gases given off while the car is being driven?

The approximate mass of exhaust gases is ....kg

Explain your reasoning as fully as possible.

Sodium and chlorine



When a piece of hot sodium metal is placed in a gas jar of chlorine, a violent reaction takes place and spots of a white substance (sodium chloride) are spattered on the inside of the jar.

Explain as fully as you can what is happening in the gas jar.

Iron sulphide

Iron and sulphur react to form the compound iron sulphide. 56g of iron and 32g of sulphur produce 88g of iron sulphide.

$$
\begin{array}{lclcl}
Fe\,(s) & + & S\,(s) & \longrightarrow & FeS\,(s) \\
56g & + & 32g & \longrightarrow & 88g
\end{array}
$$

What would you get when twice as much iron, 112g, and more than twice as much sulphur, 80g, are made to react?

Solution

20g of sodium chloride is dissolved in water. The mass of the water and beaker before any sodium chloride is added is 200g.

(a) What is the total mass of the sodium chloride solution and beaker?

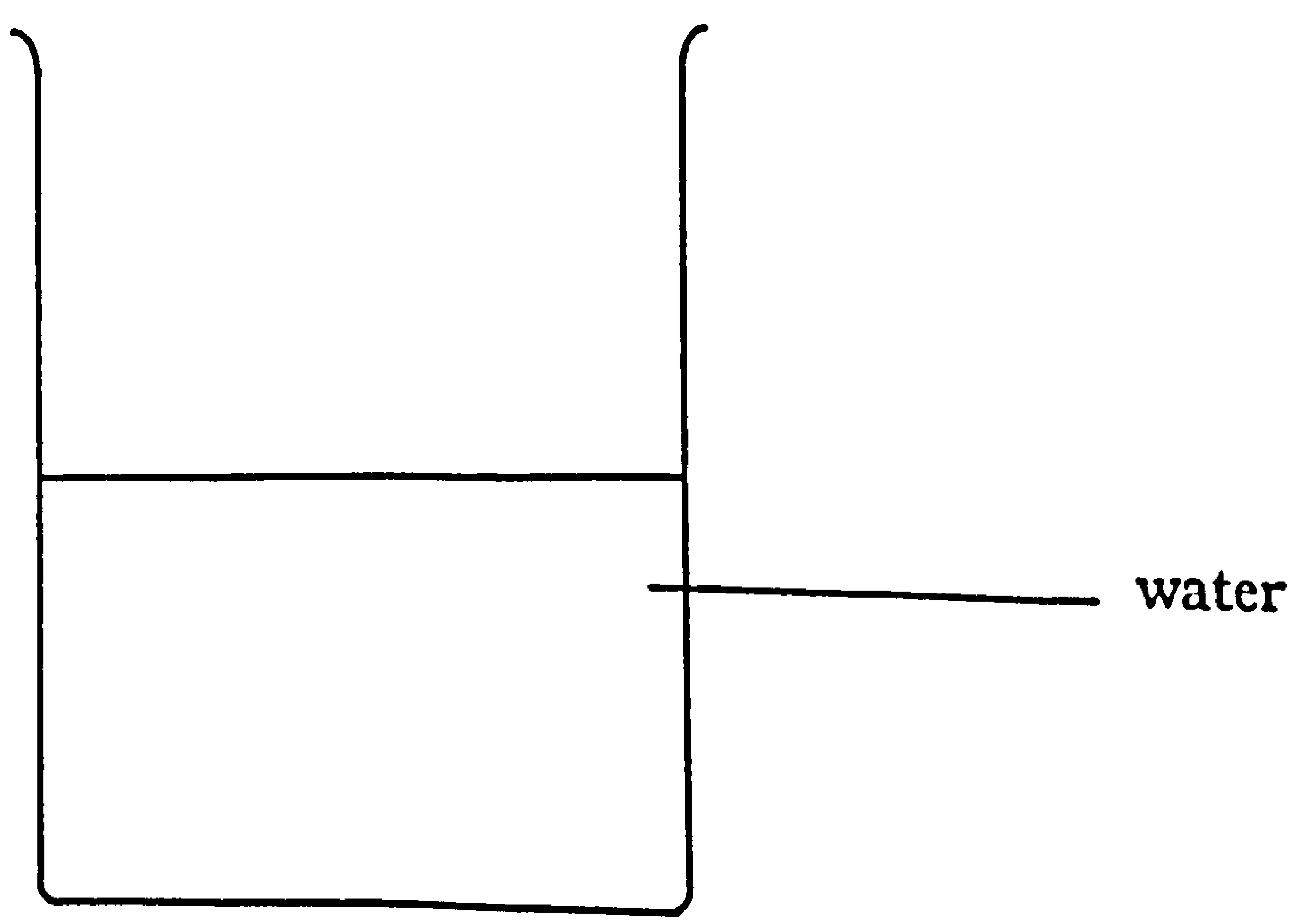
☐ Less than 220g

☐ More than 220g

☐ 220g exactly

Explain why you think this.

(b) Use the diagram of the beaker to show what you think happens when the sodium chloride is dissolved in water.
You can show water particles too if you like.

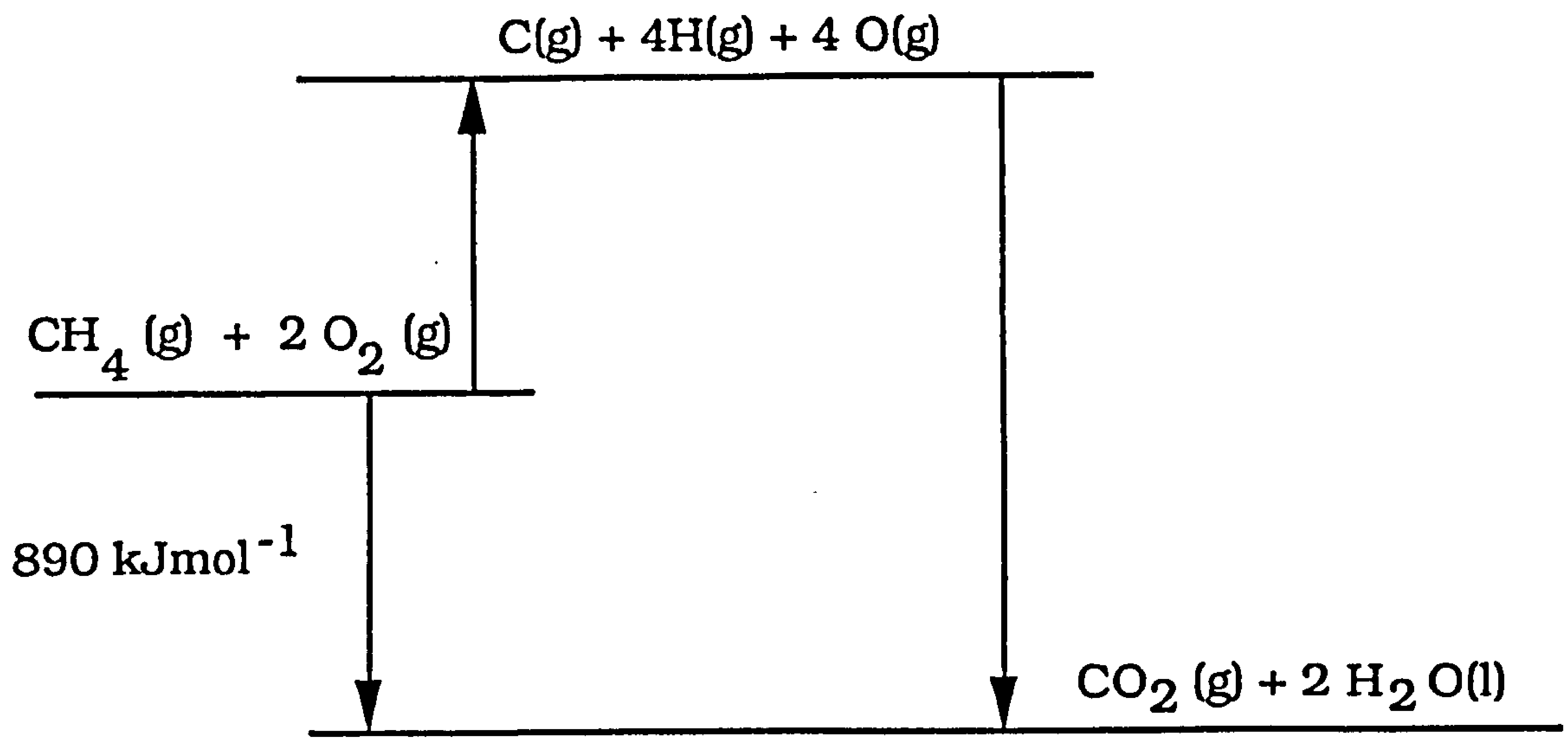


Methane

Methane is natural gas. When methane burns, the equation for the reaction is:-

$$CH_4\,(g) + 2O_2\,(g) \longrightarrow CO_2\,(g) + 2H_2O\,(l)$$

This reaction can be represented on a diagram like this one from a chemistry textbook:-



Explain why

(a) a spark or match flame is needed to start methane burning;

(b) methane will continue to burn until it is all used up.

(c) The diagram shows that the burning of methane releases energy to the environment.
Explain as best you can where this energy comes from.

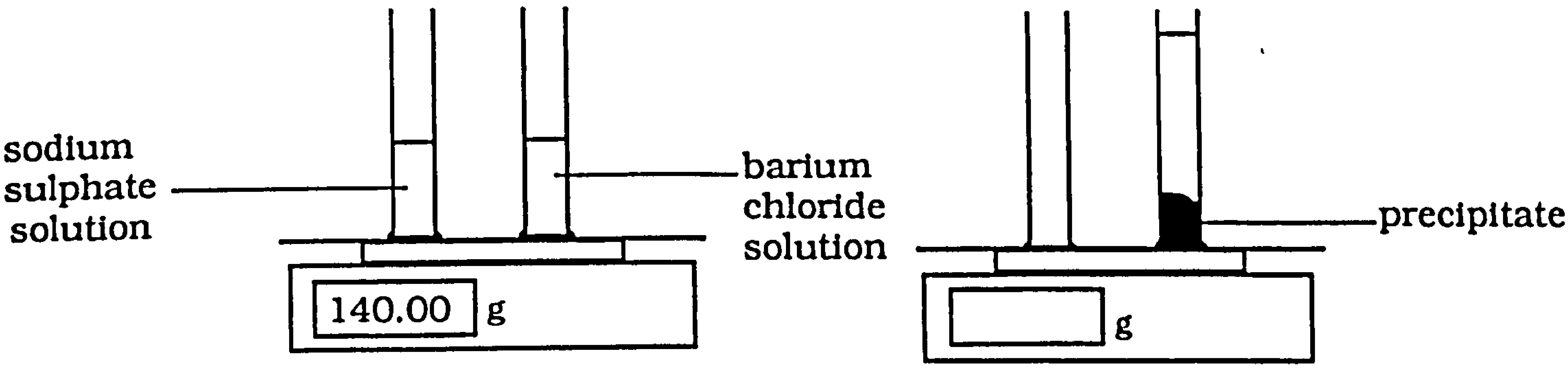
Methane molecules

Natural gas is mainly methane, CH_4.

Explain as clearly as you can why carbon and hydrogen form molecules with the formula CH_4 rather than CH_3 CH_2 or CH.

Precipitation

Aqueous solutions of two salts, sodium sulphate (Na_2SO_4 (aq)) and barium chloride ($BaCl_2$ (aq)), are placed in separate measuring cylinders on a top pan balance. The total mass is recorded as 140g.



The sodium sulphate solution is poured into the barium chloride solution. Both measuring cylinders stay on the balance. A precipitation reaction takes place.

What will the mass reading be after the reaction?

☐ Less than 140g

☐ 140g exactly

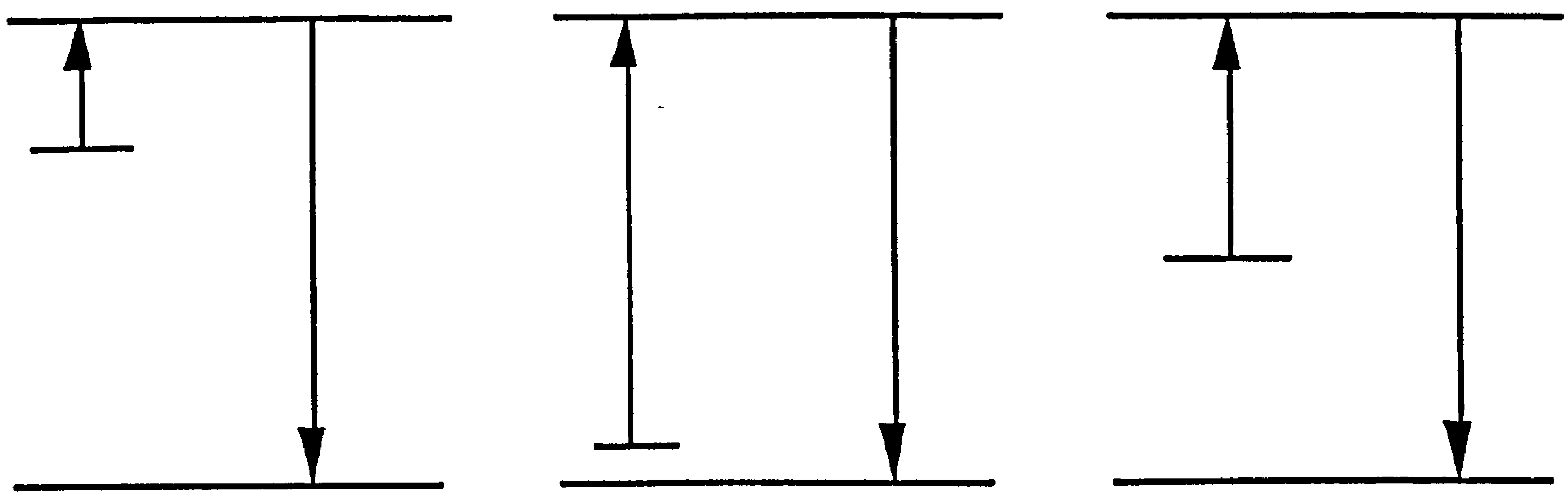
☐ More than 140g

Explain why you think this.

Where was the precipitate before the reaction occurred?

Energy change

The three diagrams below represent the energy changes which take place during three chemical reactions.



A B C

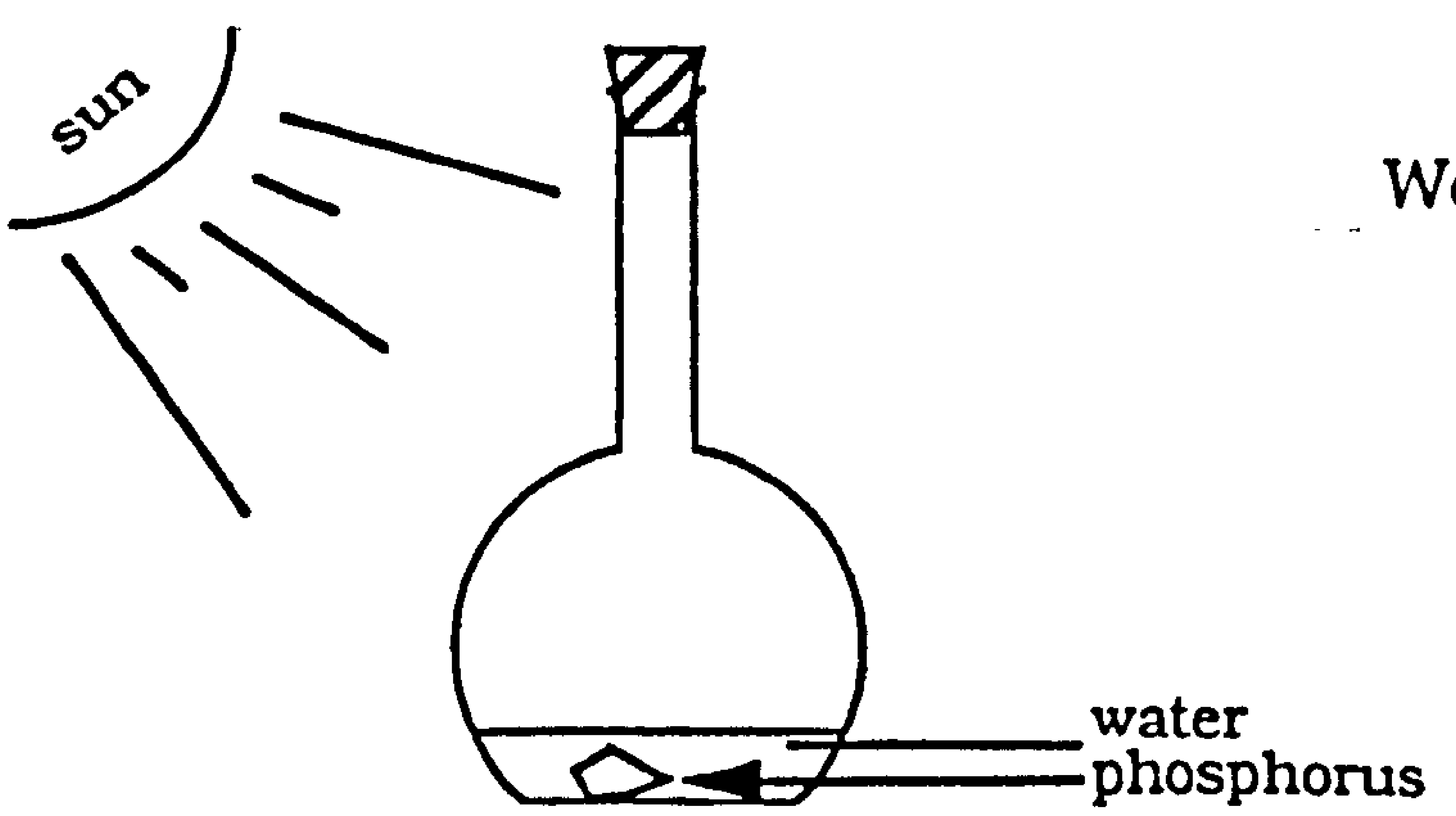
Which of these energy diagrams do you think best represents the reaction between sodium and chlorine?

$2Na(s) + Cl_2(g) \longrightarrow 2NaCl(s)$ Energy diagram A / B / C

Please explain how you decided.

Phosphorus

A piece of phosphorus and some water were placed in a flask. The flask was sealed with a rubber stopper. The mass of the flask and contents was 400g. The sun's rays were focussed on the phosphorus which caught fire. White smoke was produced which slowly dissolved in the water. The flask was cooled and its mass measured again.



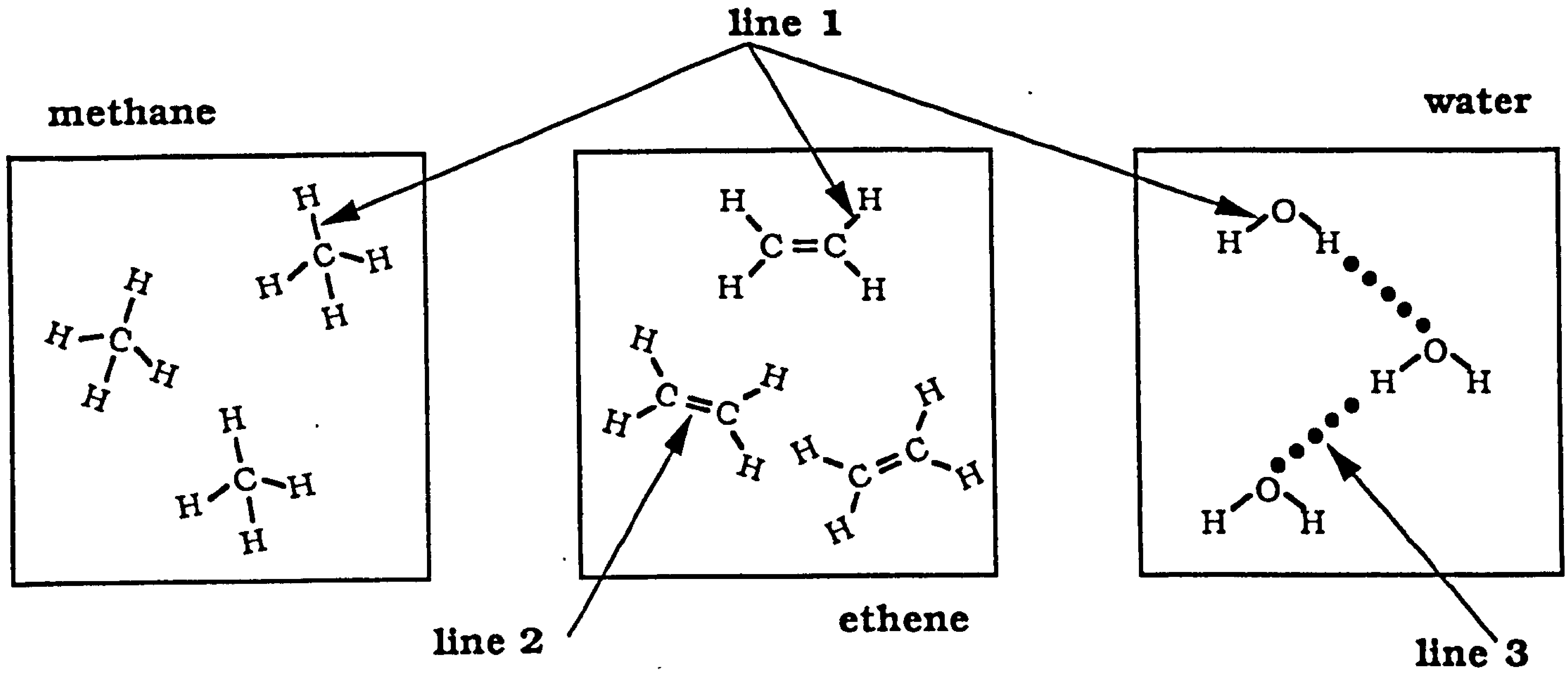
Would you expect the mass to be:

- ☐ more than 400g
- ☐ 400g
- ☐ less than 400g

Explain why you chose your answer.

Chemical bonds

The diagrams represent molecules of methane, ethene and water.



(a) Explain as fully as possible the meanings of the lines marked 1, 2 and 3.

Line 1

Line 2

Line 3

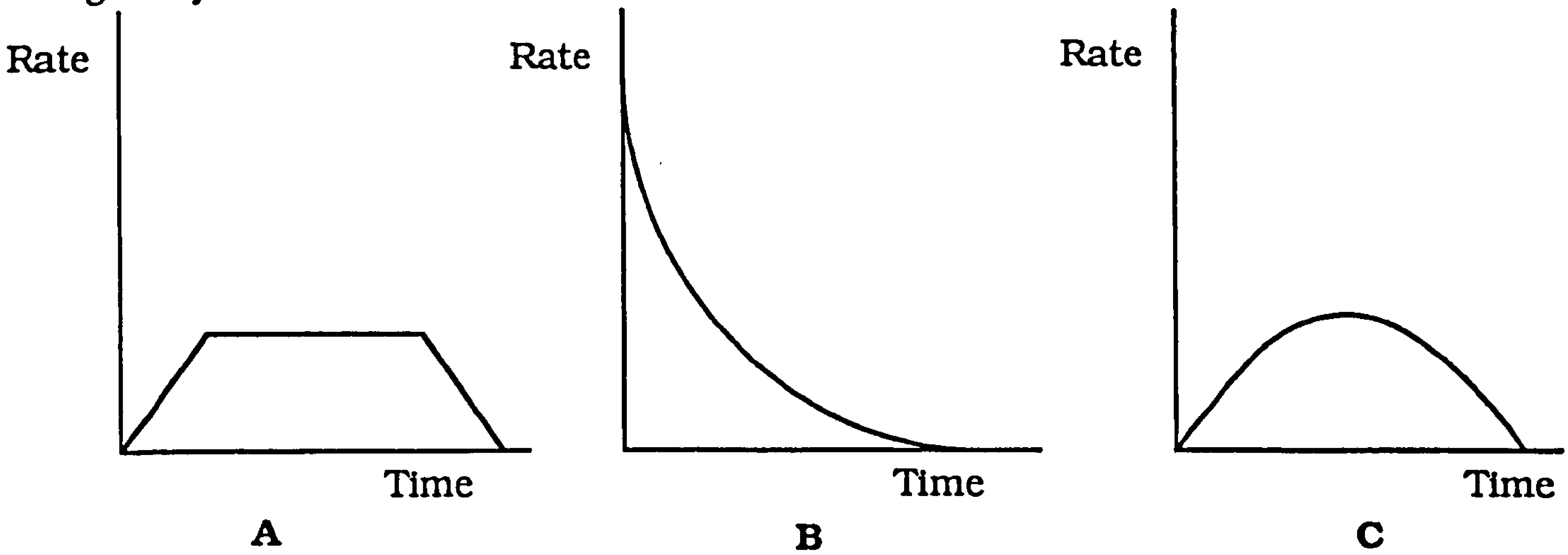
(b) What differences are there between:-

(i) line 1 and line 2;

(ii) line 1 and line 3? (I already know that line 3 is not a line but dots...)

Reaction rates

Here are three graphs which show how the rate of a chemical reaction changes as time goes by.



Describe in words what each graph says about how the rate of a chemical reaction changes as the reaction goes on.

Graph A

Graph B

Graph C

Choose the graph you think best represents the reactions shown below.

(a) A solution of sodium carbonate is added to dilute hydrochloric acid.

$Na_2CO_3(aq) + 2HCl\ (aq) \longrightarrow 2NaCl(aq) + H_2O(l) + CO_2(g)$

Answer   Graph .... represents this reaction best because..

(b) A piece of magnesium ribbon is added to dilute hydrochloric acid.

$Mg\ (s) + 2HCl\ (aq) \longrightarrow MgCl_2(aq) + H_2\ (g)$

Answer   Graph .... represents this reaction best because..

Chlorides

The bonding in magnesium chloride ($MgCl_2$) is ionic. The bonding in titanium(IV) chloride ($TiCl_4$) is covalent.

A mixture of the two chlorides is heated to 1000 ^{o}C.

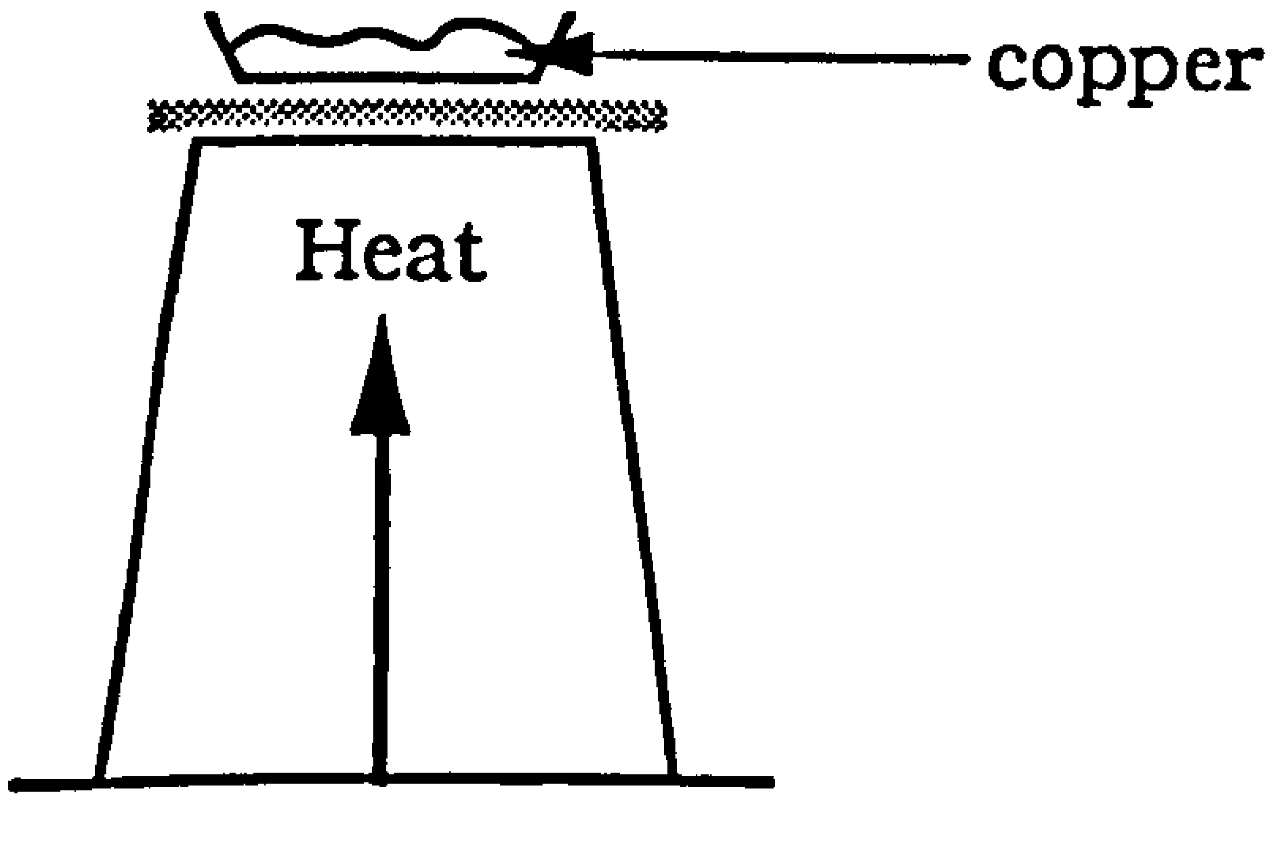
Explain why the vapour above the mixture consists only of titanium(IV) chloride.

Power station

A coal-burning power station burns 1000 tonnes of high quality coal each day.

Estimate the mass of carbon dioxide which will go up the flue chimney each day.

Copper



Powdered copper metal has an orange-red colour. Some powdered copper metal was placed in a small dish. The mass of the dish and copper was 40g. The dish (and metal) were heated in air.

After a few minutes, black stuff appeared in the dish. The mass of the dish and contents had gone up to 45g.

Where did the black stuff come from?

Reactions

Hydrogen gas reacts with nitrogen and also with oxygen. The equations for the reactions are:-

$$N_2 (g) + 3H_2 (g) \rightleftharpoons 2NH_3 (g) \qquad \Delta H = -92 \text{ kJmol}^{-1}$$

$$O_2 (g) + 2H_2 (g) \longrightarrow 2H_2O (l) \qquad \Delta H = -572 \text{ kJmol}^{-1}$$

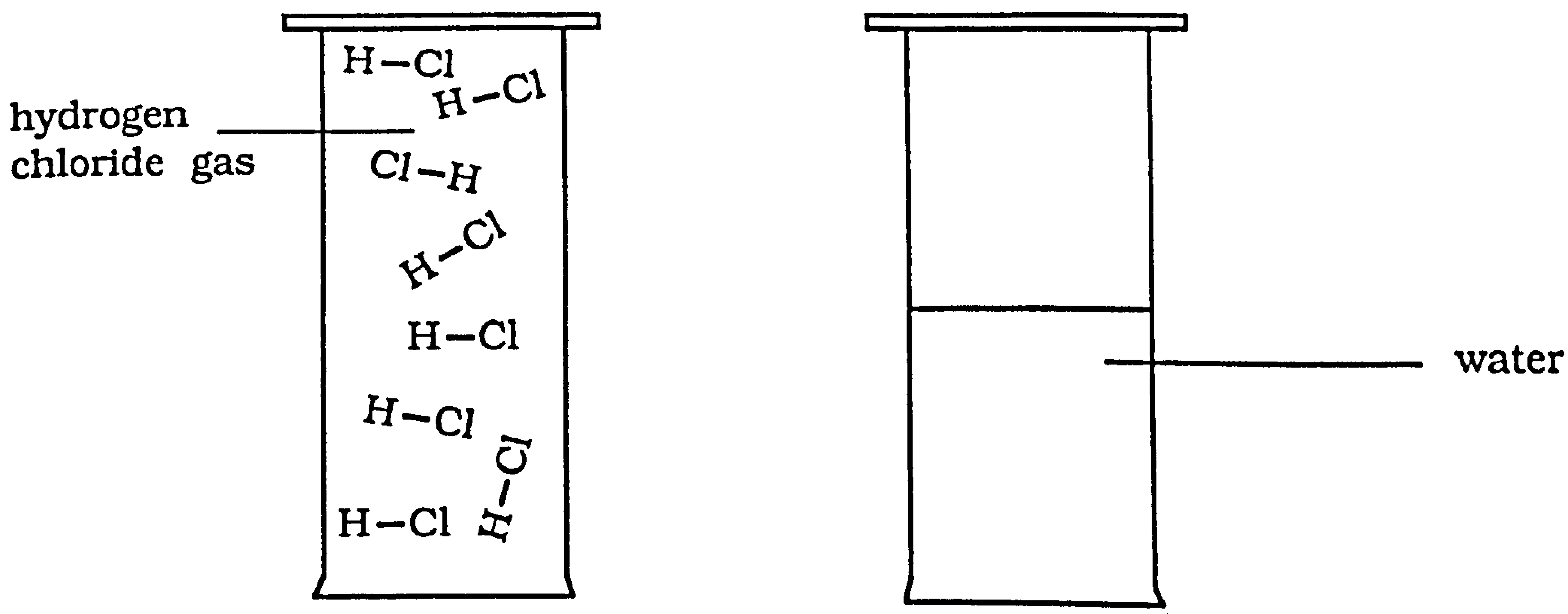
(a) Why is an equilibrium arrow ($\rightleftharpoons$) used in the nitrogen/hydrogen reaction but not in the oxygen/hydrogen reaction?

(b) Most reactions are written with an ordinary arrow ($\longrightarrow$) like in the oxygen/hydrogen reaction and are not called "equilibrium" reactions.

Explain as best you can why this is so.

Hydrogen chloride

Water is added to a gas jar of hydrogen chloride gas. The gas dissolves in the water forming hydrochloric acid.



(a) Use the second diagram to show how hydrochloric acid is formed from hydrogen chloride and water. You can show water particles too if you wish.

(b) A piece of magnesium is added to the hydrochloric acid. A reaction takes place producing hydrogen gas.

Explain how the hydrogen gas is formed.

FINALLY

Note here the time you finished _____

How long did you spend on the questions? _______

On a scale of 1 (very easy) to 5 (very hard), how difficult did you think the questions were?

Please ring the number:-

1	2	3	4	5
very easy	easy	average	hard	very hard

Once again, thank you very much for your answers.

NAME: ____________________

DATE: ____________________

START TIME: ______________

An investigation of students' ideas about A level chemistry topics

Stage 3

Time required: Approximately 1 hour

Before you start please read the letter on the next page.

Note: All the information you need is in the question paper.

Vanessa Barker

January 1994

Department of Chemistry
University of York
York YO1 5DD

An investigation of students' ideas about A level chemistry topics

Dear Student,

In your Lower Sixth year you were very helpful in completing this test paper twice - at the beginning and towards the middle of your A level course. The information you gave is contributing to a detailed picture of students' understanding of some chemistry topics and is helping to assess different ways in which chemistry is taught in the sixth form.

I know this is asking a great deal of you, especially just after your mock exams, but I would very much appreciate your answering the paper a third (and last!) time. This will complete the picture begun with the first two surveys.

I hope that by this stage you will have studied most, perhaps all, of the areas covered in the test paper. Please answer as many questions as you possibly can, using chemical common sense. I know you may be aware of giving the same answer for the third time, but ***it really is important that you give as full explanations as you can, however simple and obvious they may now seem to you.***

If you really can't answer a question, please write "I don't know", which at least reassures me you have read this letter and the question!

As before, don't spend too long on any one question. The paper should take about an hour to finish (it would help if you could put the *total* length of time you spend on the paper in the space at the end). Second, <u>read each question carefully</u>! Thirdly, on the back page are some questions which ask about the course you have taken and your plans for the future. It would really help the study if you could answer these as best you can.

As with both previous surveys, your answers will only be used for this research study and will remain confidential. There is no link between this paper and any A level examination paper.

Finally, thank you very much indeed for completing the test and participating in the study. I wish you every success with your A levels this summer.

Yours sincerely,

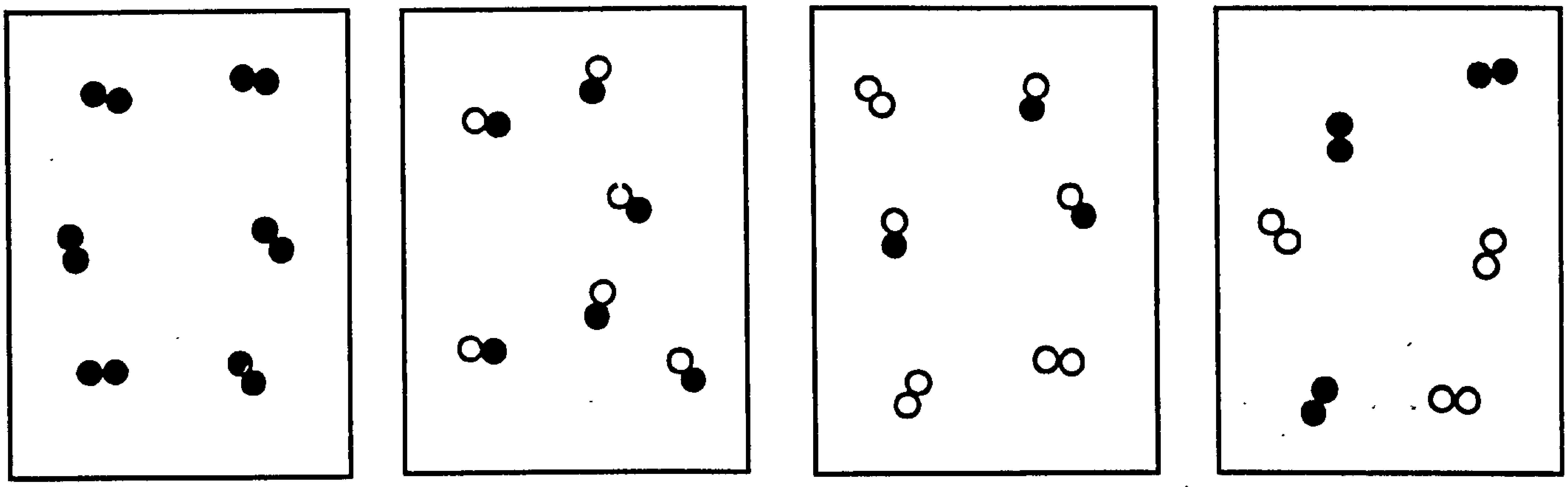
Vanessa Barker

Mrs. V. Barker

Research Fellow
Department of Chemistry
University of York
York YO1 5DD

Molecules

The diagrams lettered A - D represent four different gases. All four of the gases are made from two chemical elements. The atoms of the elements are given the symbols ○ and ●.



A B C D

Identify which gas is:-

(a) a mixture of the two elements; ______

(b) a compound; ______

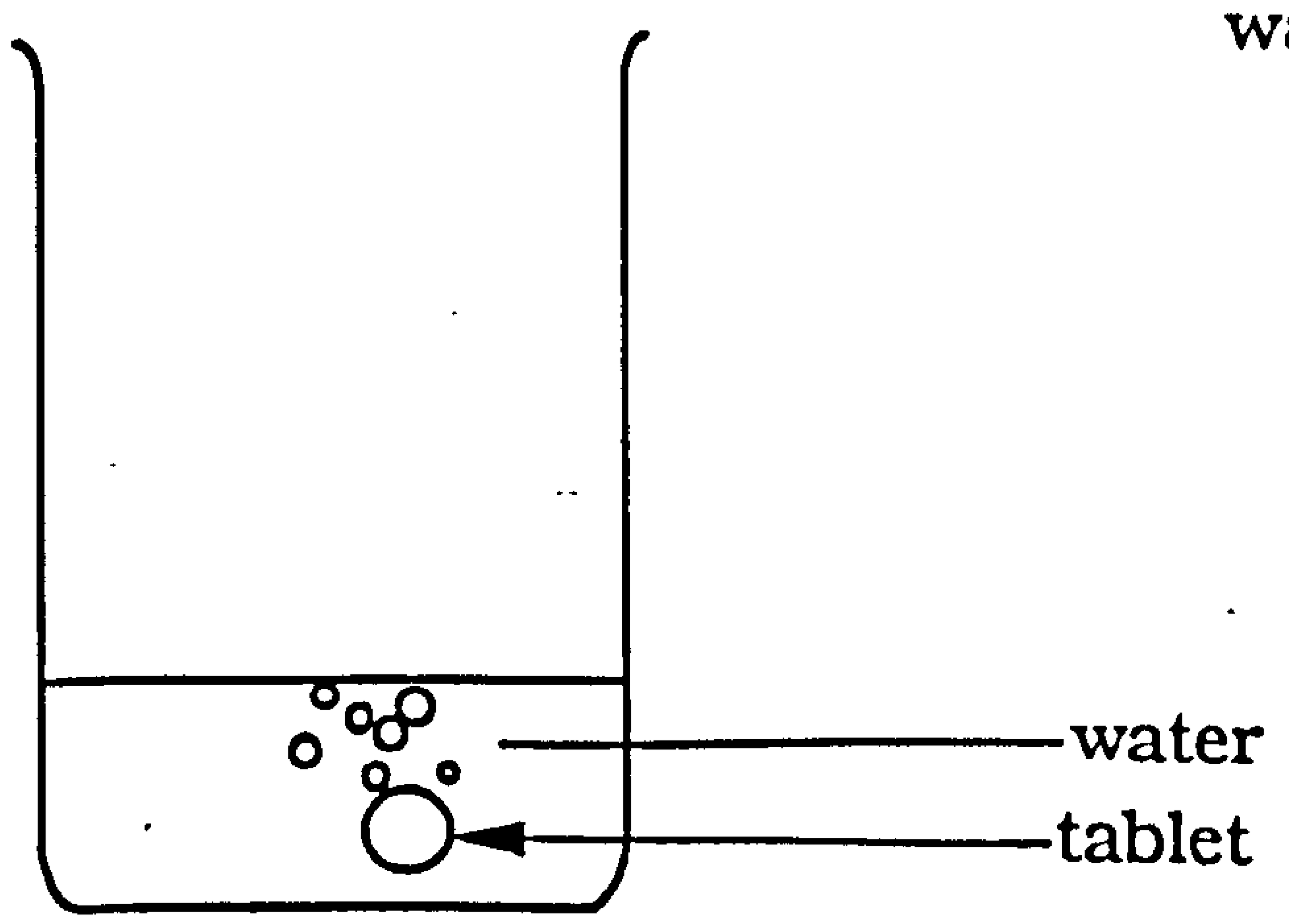
(c) one element alone. ______

There is one diagram which you haven't chosen. What do you think is represented by that diagram?

Tablet

An Alka-Seltzer tablet is dropped into a beaker of water. Bubbles of gas are seen and after a while the tablet has completely dissolved.

Where was this gas before the tablet was dropped in the water?

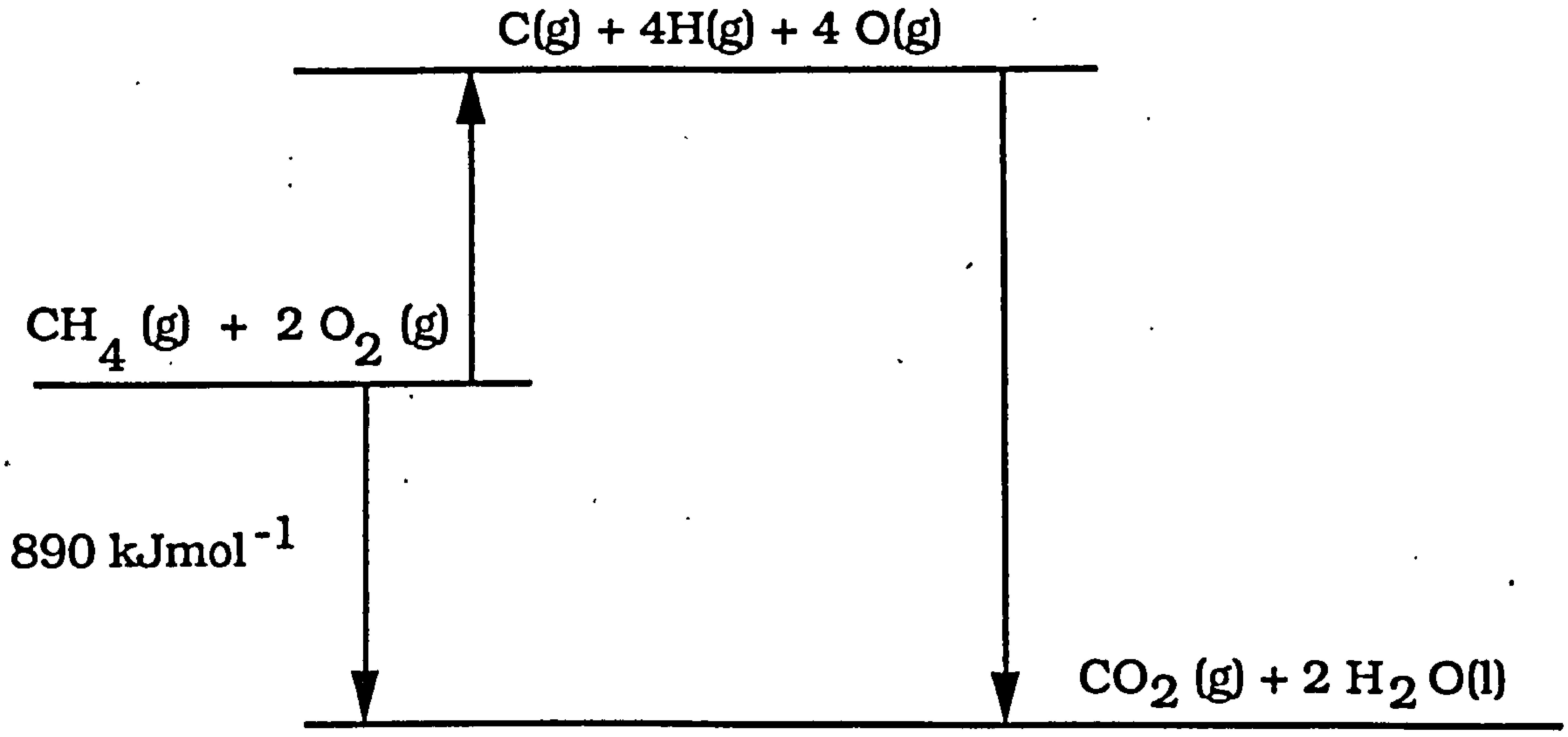


Methane

Methane is natural gas. When methane burns, the equation for the reaction is:-

$$CH_4\,(g) + 2O_2\,(g) \longrightarrow CO_2\,(g) + 2H_2O\,(l)$$

This reaction can be represented on a diagram like this one from a chemistry textbook:-



Explain why

(a) a spark or match flame is needed to start methane burning;

(b) methane will continue to burn until it is all used up.

(c) The diagram shows that the burning of methane releases energy to the environment.
Explain as best you can where this energy comes from.

Substances

For each of the substances described below, tick the box you think best fits the description of the substance. Also, explain how you decided which box to tick.

A **is a yellow solid which does not conduct electricity, but burns in oxygen to give one product.**

Substance A is :-

a compound ☐ a non-metal element ☐ a metal element ☐ a mixture ☐

Explanation

B **is a silvery grey solid which conducts electricity and burns in oxygen to give one product.**

Substance B is:-

a compound ☐ a non-metal element ☐ a metal element ☐ a mixture ☐

Explanation

C **is a colourless liquid which burns when ignited to give carbon dioxide and water.**

Substance C is:-

a compound ☐ a non-metal element ☐ a metal element ☐ a mixture ☐

Explanation

D **is a dark blue liquid which produces several spots on a chromatogram.**

Substance D is:-

a compound ☐ a non-metal element ☐ a metal element ☐ a mixture ☐

Explanation

Carbon

Use the equation below to estimate the mass of carbon dioxide produced when 24g of carbon is burned in 64g of oxygen gas. The equation for the reaction is:-

$$C\,(s) + O_2\,(g) \longrightarrow CO_2\,(g)$$

Relative atomic mass values are :- C = 12, O = 16.

Element and compound

Iron (Fe) is a chemical element. Water (H_2O) is a compound.

Define the terms "element" and "compound".

Element

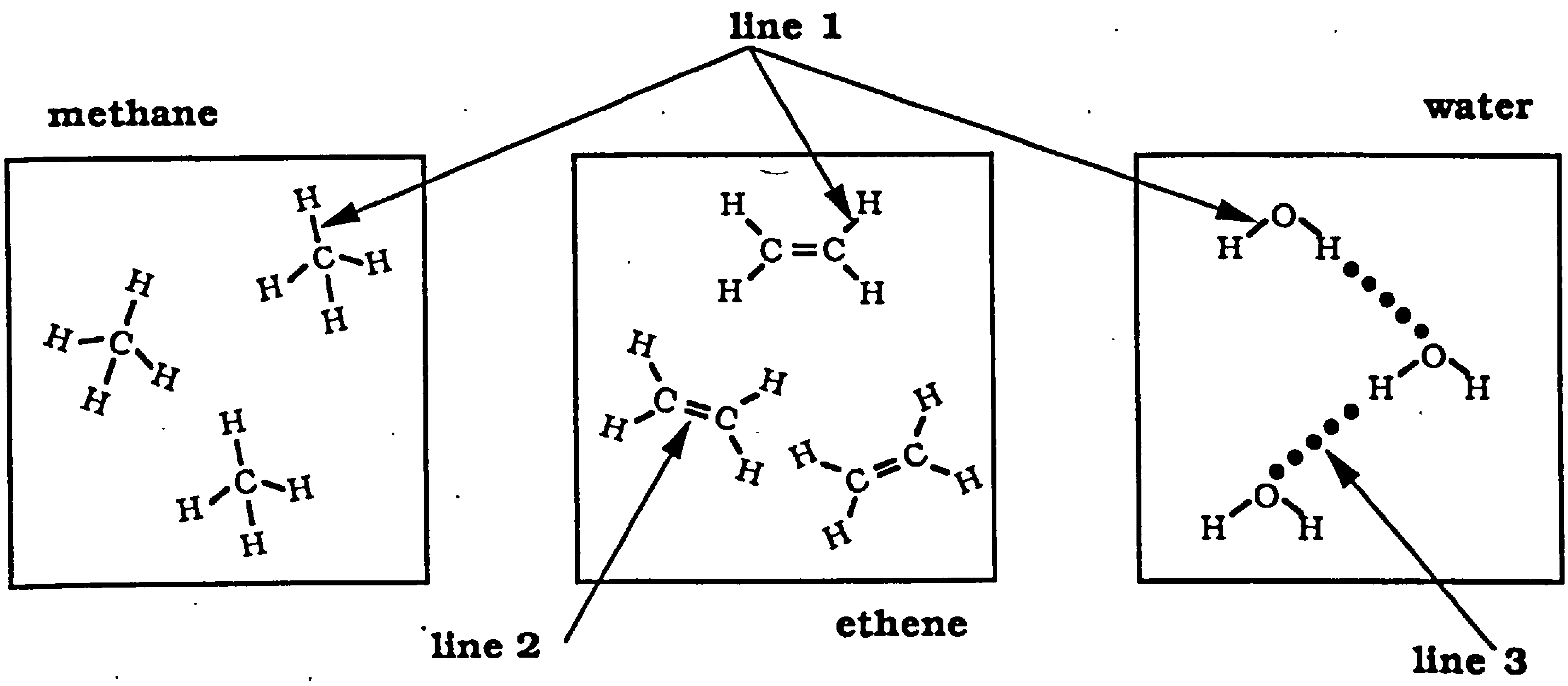
Compound

What test (or tests) could a chemist do on a sample of iron to show that it is an element?

What test (or tests) could a chemist do on a sample of water to show that it is a compound?

Chemical bonds

The diagrams represent molecules of methane, ethene and water.



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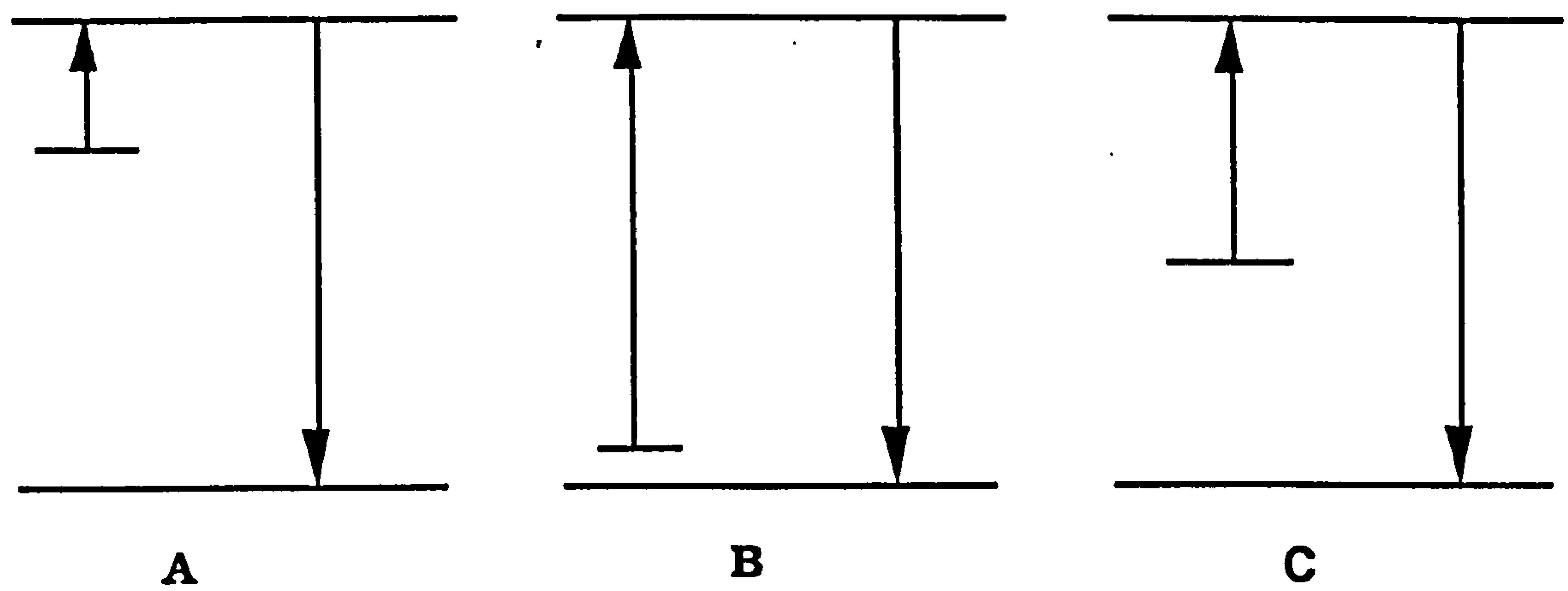
Energy change

The three diagrams below represent the energy changes which take place during three chemical reactions.



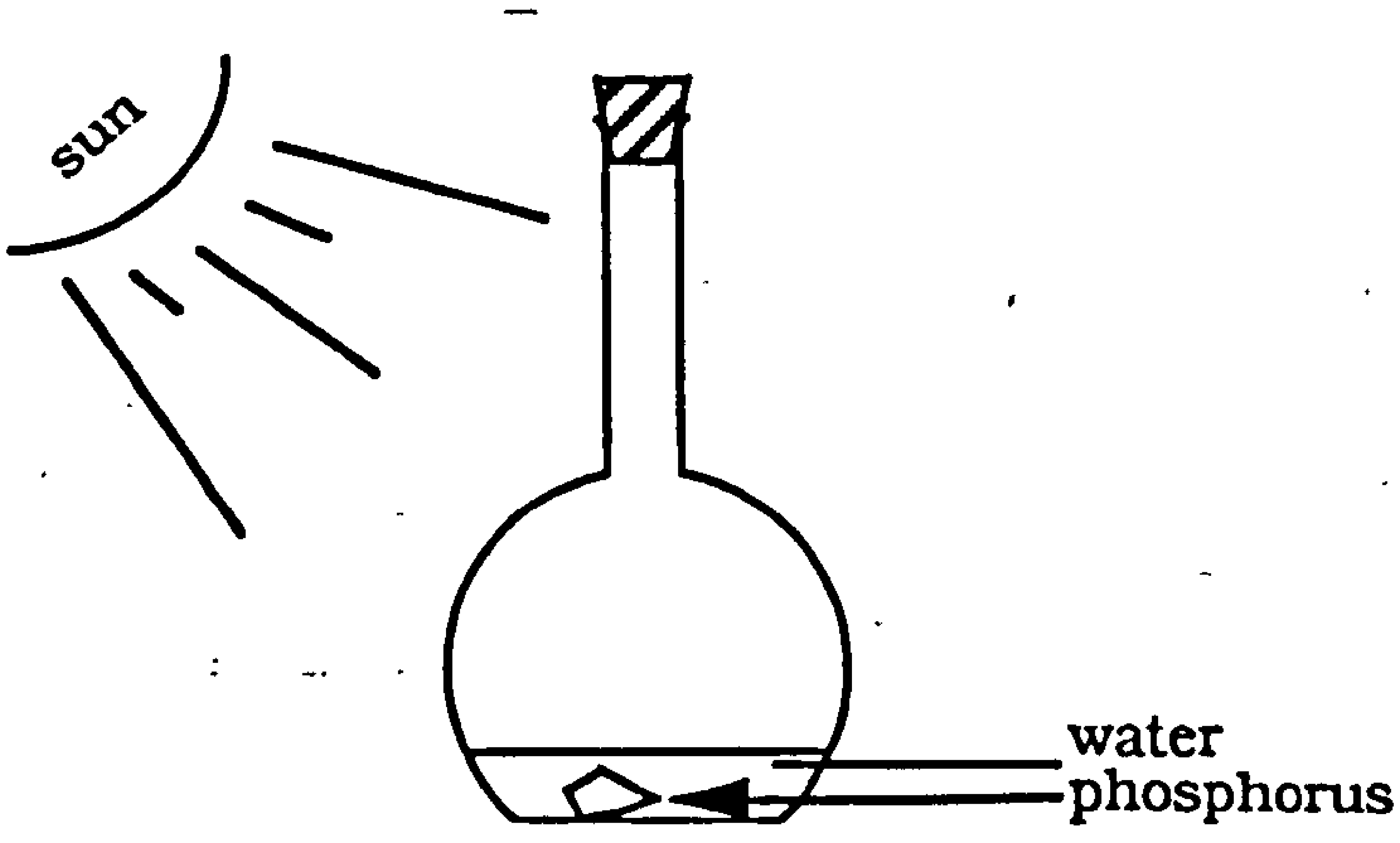
Which of these energy diagrams do you think best represents the reaction between sodium and chlorine?

$2Na(s) + Cl_2(g) \longrightarrow 2NaCl(s)$ Energy diagram A / B / C

Please explain how you decided.

Phosphorus

A piece of phosphorus and some water were placed in a flask. The flask was sealed with a rubber stopper. The mass of the flask and contents was 400g. The sun's rays were focussed on the phosphorus which caught fire. White smoke was produced which slowly dissolved in the water. The flask was cooled and its mass measured again.



Would you expect the mass to be:

☐ more than 400g

☐ 400g

☐ less than 400g

Explain why you chose your answer.

Iron sulphide

Iron and sulphur react to form the compound iron sulphide. 56g of iron and 32g of sulphur produce 88g of iron sulphide.

$$Fe\,(s) + S\,(s) \longrightarrow FeS\,(s)$$
$$56g + 32g \longrightarrow 88g$$

What would you get when twice as much iron, 112g, and more than twice as much sulphur, 80g, are made to react?

Solution

20g of sodium chloride is dissolved in water. The mass of the water and beaker before any sodium chloride is added is 200g.

(a) What is the total mass of the sodium chloride solution and beaker?

☐ Less than 220g

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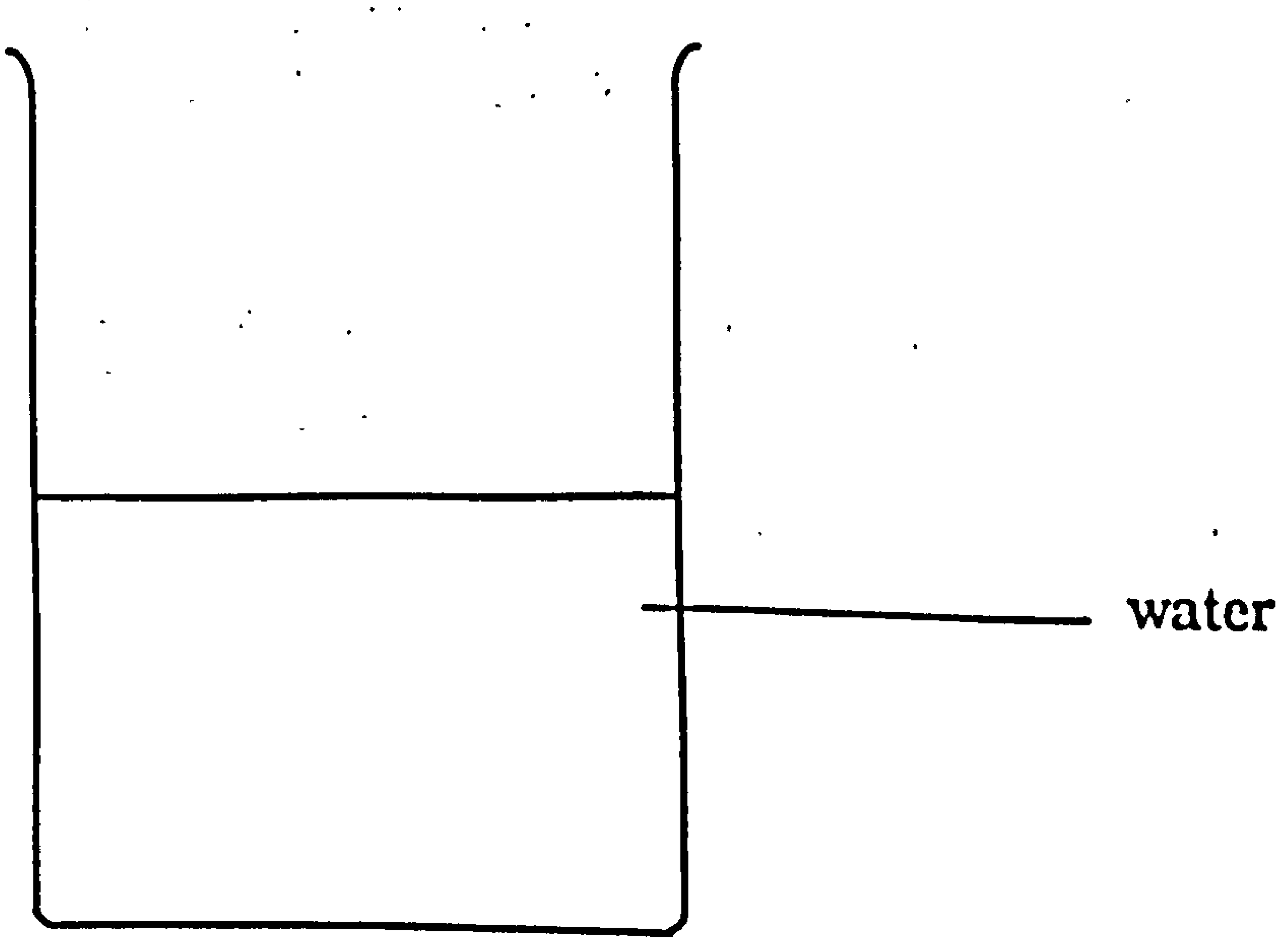
Explain why you think this.

(b) Use the diagram of the beaker to show what you think happens when the sodium chloride is dissolved in water.
You can show water particles too if you like.



Chlorides

The bonding in magnesium chloride ($MgCl_2$) is ionic. The bonding in titanium(IV) chloride ($TiCl_4$) is covalent.

A mixture of the two chlorides is heated to 1000 ^{o}C.

Explain why the vapour above the mixture consists only of titanium(IV) chloride.

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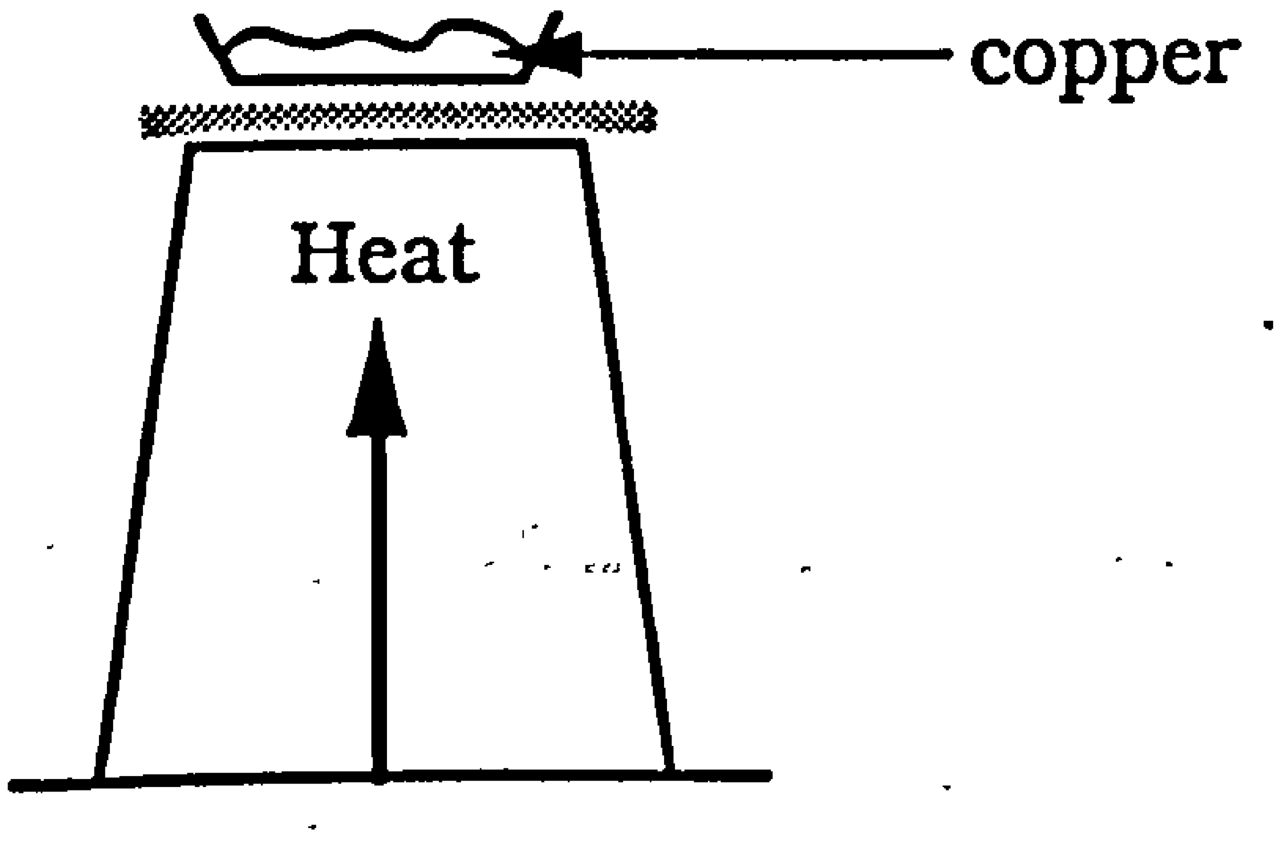
Copper



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Where did the black stuff come from?

Boiling

When water boils, bubbles appear in the liquid.

What is in the bubbles?

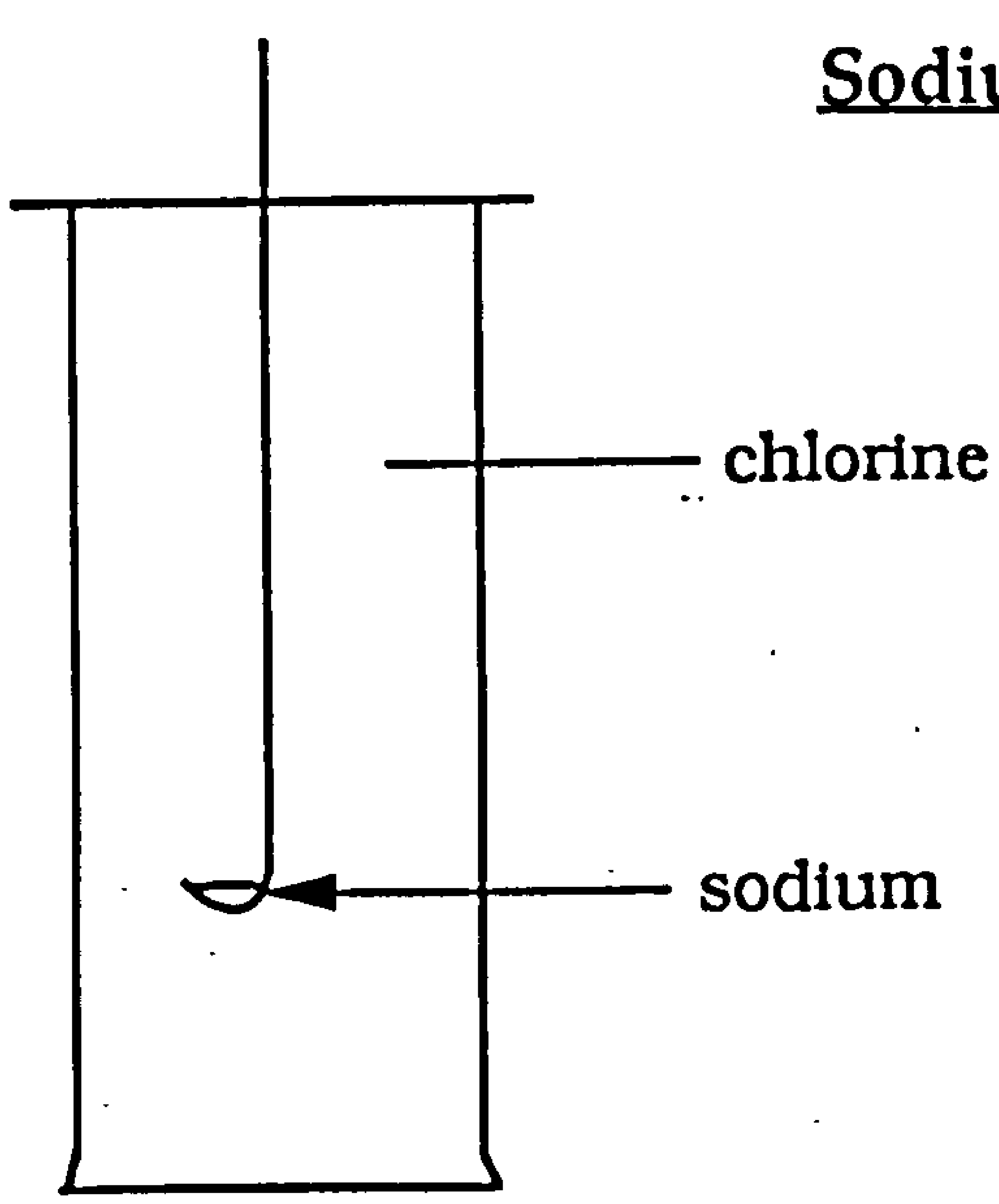
Petrol

A car with a mass of 1000 kg has 50 kg of petrol put in its tank. The car is driven until the tank is completely empty. The car then has a mass of 1000 kg again. What is the approximate mass of the exhaust gases given off while the car is being driven?

The approximate mass of exhaust gases is ....kg

Explain your reasoning as fully as possible.

Sodium and chlorine

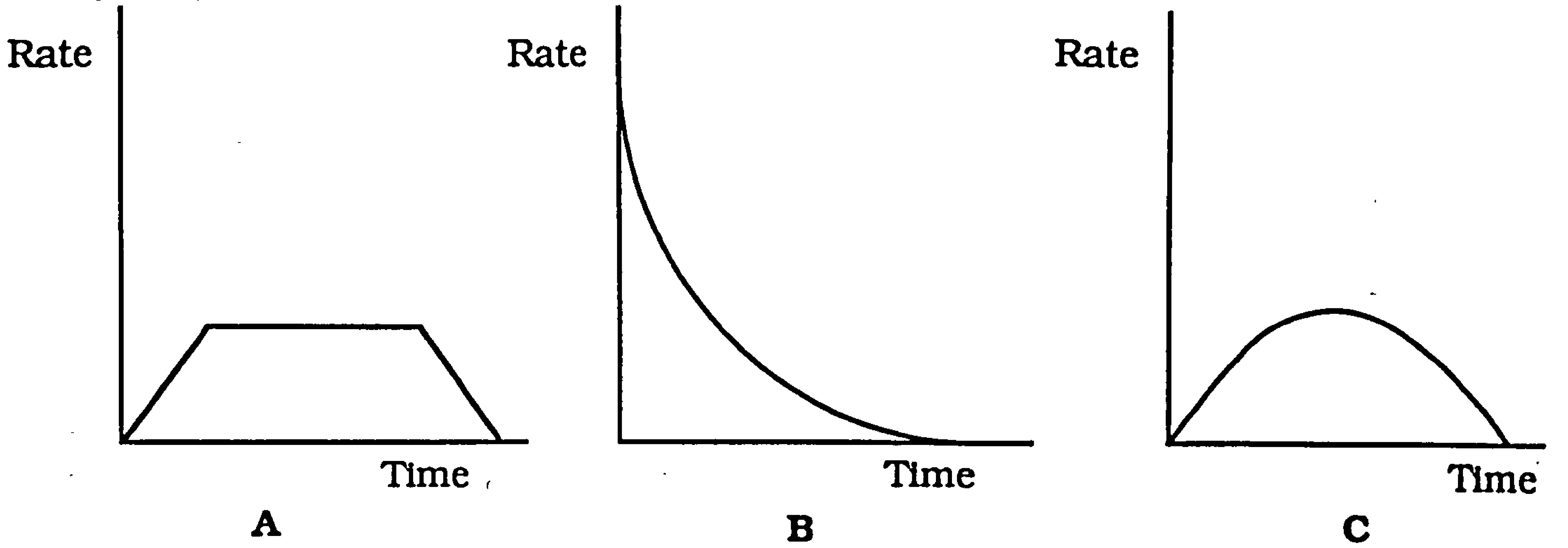


When a piece of hot sodium metal is placed in a gas jar of chlorine, a violent reaction takes place and spots of a white substance (sodium chloride) are spattered on the inside of the jar.

Explain as fully as you can what is happening in the gas jar.

Reaction rates

Here are three graphs which show how the rate of a chemical reaction changes as time goes by.



Describe in words what each graph says about how the rate of a chemical reaction changes as the reaction goes on.

Graph A

Graph B

Graph C

Choose the graph you think best represents the reactions shown below.

(a) A solution of sodium carbonate is added to dilute hydrochloric acid.

$$Na_2CO_3(aq) + 2HCl\ (aq) \longrightarrow 2NaCl(aq) + H_2O(l) + CO_2(g)$$

Answer Graph .... represents this reaction best because..

(b) A piece of magnesium ribbon is added to dilute hydrochloric acid.

$$Mg\ (s) + 2HCl\ (aq) \longrightarrow MgCl_2(aq) + H_2\ (g)$$

Answer Graph .... represents this reaction best because..

Methane molecules

Natural gas is mainly methane, CH_4.

Explain as clearly as you can why carbon and hydrogen form molecules with the formula CH_4 rather than CH_3 CH_2 or CH.

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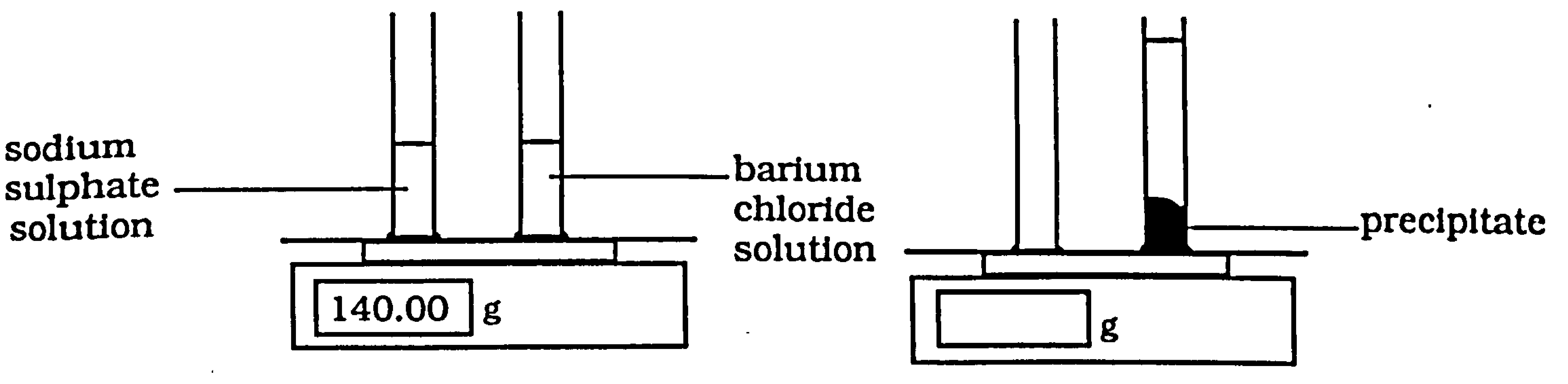


The sodium sulphate solution is poured into the barium chloride solution. Both measuring cylinders stay on the balance. A precipitation reaction takes place.

What will the mass reading be after the reaction?

☐ Less than 140g

☐ 140g exactly

☐ More than 140g

Explain why you think this.

Where was the precipitate before the reaction occurred?

Reactions

Hydrogen gas reacts with nitrogen and also with oxygen. The equations for the reactions are:-

$$N_2\,(g) + 3H_2\,(g) \rightleftharpoons 2NH_3\,(g) \qquad \Delta H = -92\ kJmol^{-1}$$

$$O_2\,(g) + 2H_2\,(g) \longrightarrow 2H_2O\,(l) \qquad \Delta H = -572\ kJmol^{-1}$$

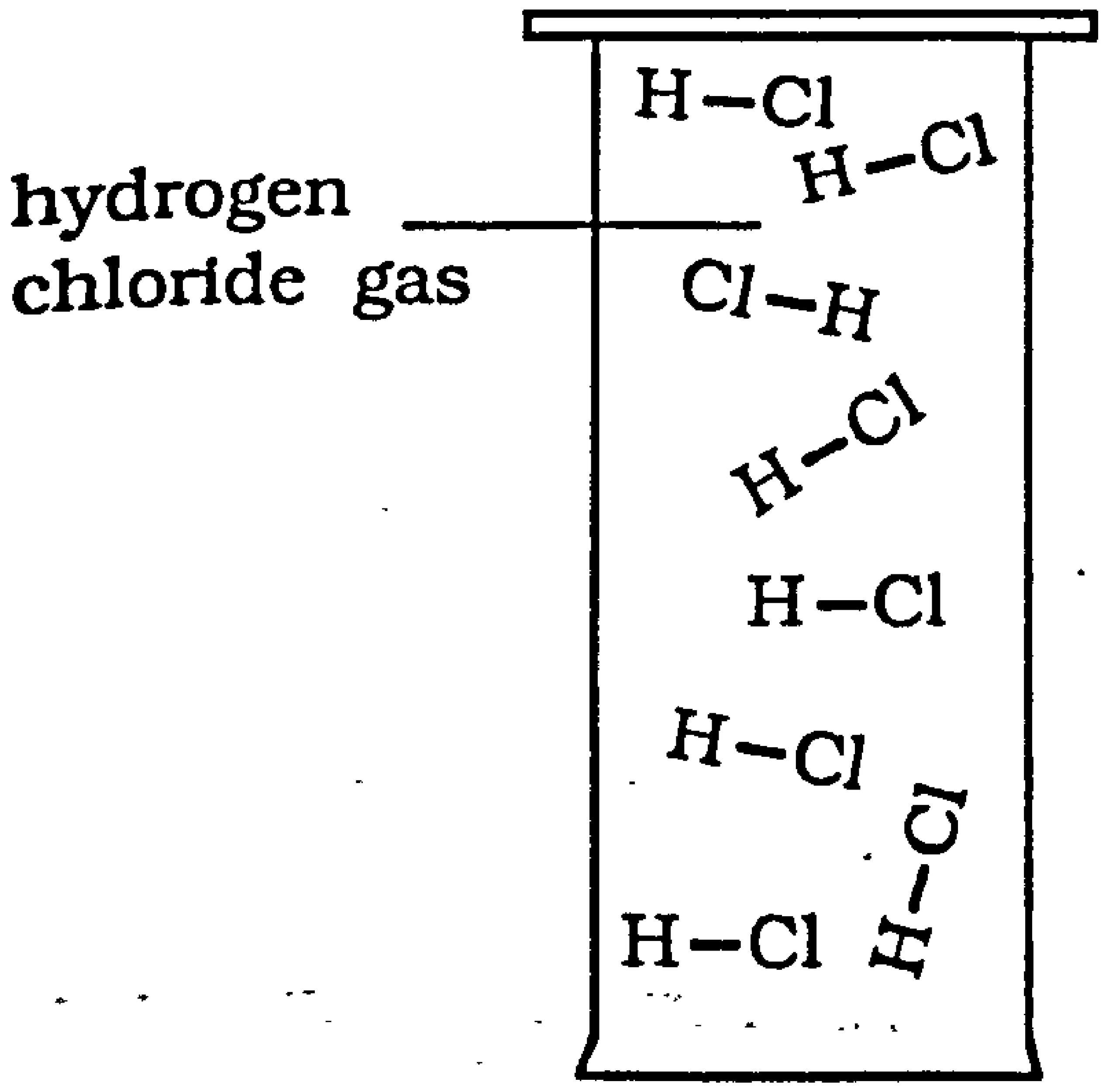
(a) Why is an equilibrium arrow ($\rightleftharpoons$) used in the nitrogen/hydrogen reaction but not in the oxygen/hydrogen reaction?

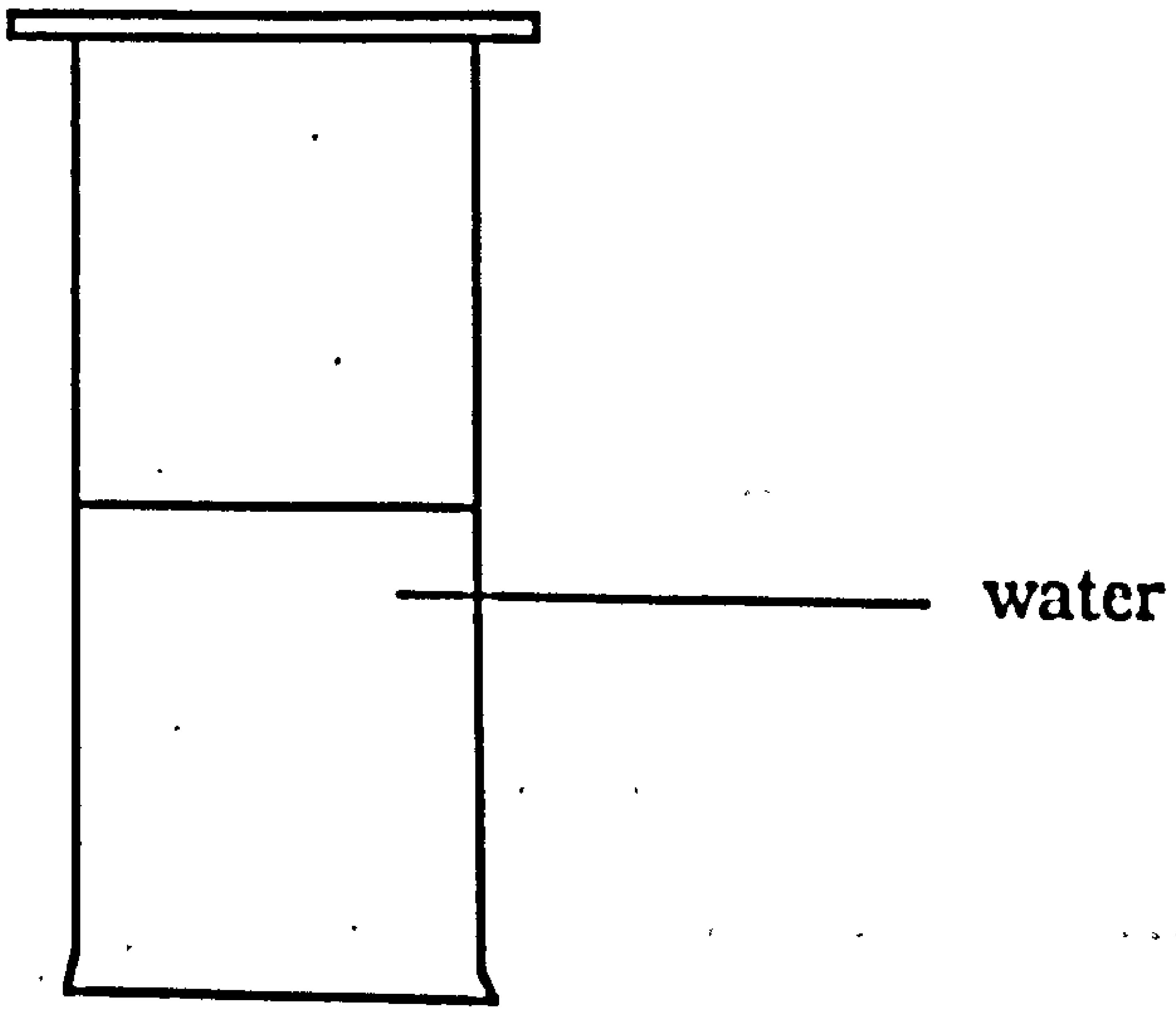
(b) Most reactions are written with an ordinary arrow ($\longrightarrow$) like in the oxygen/hydrogen reaction and are not called "equilibrium" reactions.

Explain as best you can why this is so.

Hydrogen chloride

Water is added to a gas jar of hydrogen chloride gas. The gas dissolves in the water forming hydrochloric acid.





(a) Use the second diagram to show how hydrochloric acid is formed from hydrogen chloride and water. You can show water particles too if you wish.

(b) A piece of magnesium is added to the hydrochloric acid. A reaction takes place producing hydrogen gas.

Explain how the hydrogen gas is formed.

FINALLY

1. Note here the time you finished _____ How long *in total* did you take? _______

2. On a scale of 1 (very easy) to 5 (very hard), how difficult did you think the questions were? Please circle one number.

1	2	3	4	5
very easy	easy	average	hard	very hard

3. On a scale of 1 (very little) to 5 (very much), how much have you enjoyed your A level chemistry course? Please circle one number.

1	2	3	4	5
very little	a little	some parts	quite a lot	very much

4. What has been the most important factor influencing your enjoyment of the course?

   The course itself/ Your teacher(s)/ Your career choice/ Other ________________
   (Delete as appropriate)

   Please explain this as best you can.

5. What grade are you hoping to get in chemistry in the summer? ___________

6. What are you expecting in your other A levels/other subjects studied?

7. What are you hoping to do when you have finished your A levels? Please say if you intend to continue studying (what and where, if possible!) or get a job.

8. Has your A level chemistry course influenced your choice of career? Yes/No
   Please explain!

Once again, thank you very much for your help.

Appendix 3

The schools and colleges participating in the study were:-

Astor School, Dover
Balby Carr School, Doncaster
Belle Vue Girls School, Bradford
Bootham School, York
Bushey Hall School, Watford
Caldew School, Carlisle
Chasetown High School, Walsall
Codsall High School, Wolverhampton
Douai School, Reading
Glengormley High School, Northern Ireland
Greenhead College, Huddersfield
Harvey Grammar School, Folkestone
Headington School, Oxford
Hellesdon High School, Norfolk
Huntington School, York
John Leggott College, Scunthorpe
Kingshurst City Technology College, Birmingham
Long Road Sixth Form College, Cambridge
Malvern College, Malvern
Oakham School, Oakham
Oundle School, Peterborough
Pimlico School, London
Reigate College, Reigate
Ryde School, Isle of Wight
St.Chad's RC School, Runcorn
St. Paul's Girls School, Edgbaston
Solihull Sixth Form College
Southway School, Plymouth
Stafford College, Stafford
Tideway School, Brighton
Trinity RC School, Nottingham
Tuxford Comprehensive School, Newark
Wilberforce Sixth Form College, Hull
Worthing Sixth Form College, Worthing
Wycombe Girls High School, High Wycombe

I record my thanks to all the staff and students from these establishments who gave their time so willingly to ensure the data was collected.

Appendix 4

Letters sent to schools and colleges during the study:

Letters 1 - 3 are invitations to participate in the study

Letter 4 provided instructions for the first test

Letter 5 provided instructions for the second test and mid-course survey

Letter 6 accompanied the second progress report

Letter 7 provided instructions for the third test and final survey

Letter 8 thanked schools and colleges for their help.

Letter (1)

THE SALTERS' ADVANCED CHEMISTRY PROJECT

UNIVERSITY OF YORK

DEPARTMENT OF CHEMISTRY
HESLINGTON, YORK, YO1 5DD
Telephone (0904) 432512
Telex 57933 YORKUL Fax (0904) 432516

3rd April, 1992

Dear Colleague,

Evaluation of the Salters Advanced Chemistry Project

I am undertaking a three-year research study involving the Salters Advanced Chemistry course. The objective of the study is to follow through the 1992 - 1994 cohort of Salters students investigating their progress in understanding the chemical concepts taught by the course.

I write to invite you to allow your students to participate in the study.

The students would be asked to sit a written test of approximately 1 hours duration on four separate occasions during their A level course. The first test would be in September, at the start of their A level studies. All copies of the tests will be sent from York. Return postage will also be paid.

The test questions will be designed to examine chemical ideas and will not be based on recall of factual information.

The student responses can be returned if requested.

The member of staff administering the first test would be asked to give each student a code number, for use on subsequent occasions. I do not need students' names, but I do need to be able to chart the progress of each student's ideas. The study is completely independent of the A level examination and students' responses will not be used for any other purpose.

Reports on the progress of your group of students can be provided.

This is the first occasion that the ideas of UK sixth form science students have been studied in this way. The information gained will lead to a deeper understanding of how students learn chemistry at this level, as well as indicating the effectiveness of the Salters Advanced Chemistry course.

I very much hope you will be willing to take part in what could be an exciting project. If you require any further information, please telephone me at the above address and I will be pleased to help.

I would be grateful if you could return the attached slip to let me know your decision.

Yours Faithfully,

Vanessa Barker

Mrs. Vanessa Barker
Research Fellow

Reply slip - Evaluation of the Salters Advanced Chemistry Project

Name .... School/College ....

I am/ am not willing for my 1992 - 1994 students to participate.

Approximate number of students expected..............................

Signature .... Date..

Letter ②

THE SALTERS' ADVANCED CHEMISTRY PROJECT

UNIVERSITY OF YORK

DEPARTMENT OF CHEMISTRY
HESLINGTON, YORK, YO1 5DD
Telephone (0904) 432512
Telex 57933 YORKUL Fax (0904) 432516

15th June, 1992

Dear Colleague,

Evaluation of the Salters Advanced Chemistry Project

I am undertaking a three-year research study involving the Salters Advanced Chemistry course. The objective of the study is to follow through the 1992 - 1994 cohort of Salters students investigating their progress in understanding the chemical concepts taught by the course.

I write to invite you to allow your students to participate in the study.

The students would be asked to sit a written test of approximately 1 hours duration on four separate occasions during their A level course. The first test would be in September, at the start of their A level studies. All copies of the tests will be sent from York. Return postage will also be paid.

The test questions will be designed to examine chemical ideas and will not be based on recall of factual information.

The student responses can be returned if requested.

The member of staff administering the first test would be asked to give each student a code number for use on subsequent occasions. I do not need the students' names, but I do need to be able to chart the progress of each student's ideas. The study is completely independent of the A level examination and students' responses will not be used for any other purpose.

Reports on the progress of your group of students can be provided.

This is the first occasion that the ideas of UK sixth form science students have been studied in this way. The information gained will lead to a deeper understanding of how students learn chemistry at this level, as well as indicating the effectiveness of the Salters Advanced Chemistry course.

I very much hope you will be willing to take part in what could be an exciting project. If you require any further information, please telephone me at the above address and I will be pleased to help.

I would be grateful if you could return the attached slip to let me know your decision. A return envelope is provided.

Yours Faithfully,

Vanessa Barker

Mrs. Vanessa Barker
Research Fellow

Letter (3)

THE SALTERS' ADVANCED CHEMISTRY PROJECT

UNIVERSITY OF YORK

DEPARTMENT OF CHEMISTRY
HESLINGTON, YORK, YO1 5DD
Telephone (0904) [redacted] 432595
Telex 57933 YORKUL Fax (0904) 432516

29th June, 1992

Dear Colleague,

Evaluation of the Salters Advanced Chemistry Project

I am undertaking a three-year research study involving the Salters Advanced Chemistry course. The objective of the study is to follow through the 1992 - 1994 cohort of Salters students investigating their progress in understanding the chemical ideas taught by the course.

I write to invite you to allow your students to participate in the study. I would be pleased if any non-Salters 6th form chemists you may have could also be included.

The students would be asked to sit a written test of approximately 1 hours duration on four separate occasions during their A level course. The first test would be in September, at the start of their A level studies. All copies of the tests will be sent from York. Return postage will also be paid.

The test questions will be designed to examine chemical ideas and will not be based on recall of factual information.

The student responses can be returned if requested.

The member of staff administering the first test would be asked to give each student a code number for use on subsequent occasions. I do not need the students' names, but I do need to be able to chart the progress of each student's ideas. The study is completely independent of the A level examination and students' responses will not be used for any other purpose.

Reports on the progress of your group of students can be provided.

This is the first occasion that the ideas of UK sixth form science students have been studied in this way. The information gained will lead to a deeper understanding of how students learn chemistry at this level, as well as indicating the effectiveness of the Salters Advanced Chemistry course.

I very much hope you will be willing to take part in what could be an exciting project. If you require any further information, please telephone me at the above address and I will be pleased to help.

I would be grateful if you could return the attached slip to let me know your decision. A return envelope is provided.

Yours Faithfully,

Vanessa Barker

Mrs. Vanessa Barker
Research Fellow

Chairman of the Steering Committee: Professor D. J. Waddington (0904 432500)
Project Director: J. S. Holman (0494 772862) Project Manager: P. E. Nicolson (0904 432526)

Letter (4)

THE SALTERS' ADVANCED CHEMISTRY PROJECT

UNIVERSITY OF YORK

DEPARTMENT OF CHEMISTRY
HESLINGTON, YORK, YO1 5DD
Telephone (0904) 432560
Telex 57933 YORKUL Fax (0904) 432516

1st September, 1992

Dear

Evaluation of the Salters' Advanced Chemistry Project

Following my July letter, I enclose with pleasure copies of the first test paper and a pre-paid return envelope.

For statistical purposes, I have produced two papers with the questions in a different order in each. I have sent equal numbers of both types. Please distribute these randomly at the time of the test. If students wonder why their neighbour is doing a different question to them, point out that it is only the order of questions which differs - the overall content is identical. There is deliberately no obvious outward way of telling the difference between the papers.

I give below some guidelines for adminstration. I would be grateful if you could follow these as far as possible to ensure parity between schools.

1. The test will require one double period, that is, approximately one hour to one hour and fifteen minutes. Some students may finish within this time. Please adopt exam conditions and do not allow students to take the papers home.

2. Please give the test as close to the start of the A level course as can be managed, preferably in the students' first "proper" lesson.

3. In each test paper is a copy of a Student Information Survey. Ask students to complete this and to replace it inside the test paper.

4. Please reassure students that their responses to the test and survey are received in complete confidence and are for research purposes only.

5. Please post the completed tests and surveys (with any spare copies) back to me in the envelope provided to arrive by Monday, 21st September. If this is impractical for your school or college, do let me know.

I think that is just about everything - doubtless after posting I will think of something I've missed out!

Please feel free to make comments about the test, its content, format, how it was received and so on, and enclose these with the papers.

Analysis of all the answers will take some time, but I will endeavour later this term to produce a short report for each school/college on the responses produced, which I hope will be of interest.

I anticipate that the next test will be in late April - early May, that is, towards the end of Lower Sixth, but before exams. If this timing is likely to be a problem, could you let me know?

Finally, thank you very much indeed for your time and co-operation.

Yours sincerely,

Vanessa Barker

Letter (5)

UNIVERSITY OF YORK

HESLINGTON, YORK, YO1 5DD

Telephone (0904) 430000

Telex 57933 YORKUL Fax (0904) 433433

DEPARTMENT OF EDUCATIONAL STUDIES

Department direct line (0904) 433460
Personal direct line (0904) 432560
Department Fax (0904) 433459

26th April, 1993

Dear

Evaluation of the Salters' Advanced Chemistry Project

I enclose with pleasure copies of the second test paper and (a) pre-paid return envelope(s). Please get in touch by telephone if you need any more copies.

As before, I have produced two papers with the questions in a different order in each and have sent equal numbers of both types. Please distribute these randomly at the time of the test. The overall content of the two papers is identical and there is deliberately no obvious outward way of telling the difference between them.

I give below some guide-lines for administration. I would be grateful if you could follow these as far as possible to ensure parity.

1. The test will require one double period, that is, approximately one hour to one hour and fifteen minutes. Some students may finish within this time. Please adopt exam conditions and do not allow students to take the papers home.

2. As previously, please reassure students that their responses to the test and survey are received in complete confidence and are for research purposes only.

3. Please post the completed tests (with any spare copies) back to me in the envelope provided to arrive by Monday, 17th May. If this is impractical for your school or college, do let me know.

At this stage I would like to know which topics have been covered. If you could complete the enclosed sheet giving brief details that would be very helpful.

I am continuing to analyse the first responses. A paper on the conservation of matter questions is available and copies will be sent with the final test papers. However, if you would like a copy in advance, please let me know on the survey sheet. I do need to preserve the study as a longitudinal one, so if you read the paper before the research is complete, please resist the temptation to teach the topic explicitly, otherwise I could end up with an intervention study instead! Other papers on bonding, energetics and element/compound/mixture will be available in due course. If you are interested in receiving these, please indicate to this effect on the survey.

I aim to send third and final copies of the test in late February next year, which I hope will fit in with mock timetables. There is a space on the response sheet to indicate likely mock dates .

Once again, thank you very much indeed for your time and co-operation. If you would like any further information, please do let me know.

Yours sincerely,

Vanessa Barker

Evaluation of the Salters' Advanced Chemistry Project
Mid-course survey

School/College ....Today's date...............

Staff contact name..

I have entered the syllabus name(s) and number(s) of students. Please provide the other information and adjust student number if necessary.

Syllabus .... Number of students ....

Number of teaching groups ....

Number of teachers per group.........

Total lesson time for chemistry per week ....

Topics/units covered up to 1st May, 1993 (Continue overleaf if necessary)

Syllabus .... Number of students.............

Number of teaching groups ......

Number of teachers per group......

Total lesson time for chemistry per week ....

Topics/units covered up to 1st May, 1993 (Continue overleaf if necessary)

I would like to receive a copy of the Conservation of Matter paper as soon as possible. Yes/No

I would like to receive copies of other research papers relating to the survey when they become available.

Yes/No

Our 'A' level mock exams for 1994 are likely to be between

....

Please enclose this with the test papers. Thank you for your help.

Letter (6)

UNIVERSITY OF YORK
HESLINGTON, YORK, YO1 5DD
Telephone (0904) 430000
Telex 57933 YORKUL Fax (0904) 433433

DEPARTMENT OF EDUCATIONAL STUDIES

Department direct line (0904) 433460
Personal direct line (0904)
Department Fax (0904) 433459

17th December, 1993

Dear Colleague,

Re: Evaluation of Salters Advanced Chemistry

I write enclosing a second progress report on the research study, which I hope you will find interesting. This paper gives details of students' responses to all 22 questions and shows how responses have changed between the first and second surveys. It also pinpoints some common difficulties and indicates differences at this stage between Traditional and Salters' students.

I will be sending the final test papers out in January. I would be very grateful if you could strongly encourage your students to give as full answers as possible, especially if they think they don't need to because they have already answered the questions twice before! If you think it might help, I could always arrange for a supply of Mars bars to help them along! It really is important that the data for this third survey is as good as that of the other two, as this will provide the clearest indication of the progress made.

I would also appreciate it if you could resist the temptation to go through some of the difficulties with the students involved in the survey, as this may affect the outcome. However, please do use results of the study to help in teaching lower sixth form groups and below. If I can be of any further help in this, do let me know.

Finally, you may be interested to know that I will be giving a presentation of some of the data at the ASE meeting in Birmingham. The talk will be on Saturday, 8th January at 11am, in room LR3. Please do come if you are at the ASE - I would like to say a public "thank you" to those involved and I think the discussion could be helped by having participating teachers present.

Thank you very much indeed for your continued support. I hope you have a restful Christmas break.

Yours sincerely,

Vanessa Barker

Letter (7)

UNIVERSITY OF YORK
HESLINGTON, YORK, YO1 5DD
Telephone (0904) 430000
Telex 57933 YORKUL Fax (0904) 433433

DEPARTMENT OF EDUCATIONAL STUDIES

Department direct line (0904) 433460
Personal direct line (0904) 432560,
Department Fax (0904) 433459

20th January, 1994

Dear

Evaluation of the Salters' Advanced Chemistry Project

I enclose with pleasure copies of the third test paper and (a) pre-paid return envelope(s). Please get in touch by telephone if you need any more copies.

As before, I have produced two papers with the questions in a different order in each and have sent equal numbers of both types. Please distribute these randomly at the time of the test. The overall content of the two papers remains the same as before and there is deliberately no obvious outward way of telling the difference between them.

The guidelines for administration are the same as for the previous two tests. I would be grateful if you could follow these as far as possible to ensure parity between schools.

1. The test will require one double period, that is, approximately one hour to one hour and fifteen minutes. Some students may finish within this time. Please adopt exam conditions and do not allow students to take the papers home.

2. As previously, please reassure students that their responses to the test and survey are received in complete confidence and are for research purposes only.

3. Please post the completed tests (with any spare copies) back to me in the envelope provided to arrive by Friday, 11th February. If this is impractical for your school or college, do let me know.

It would help in addition if you could complete the enclosed short questionnaire about topics covered so far in the course. This will give me an idea as to the progress made to date, so I can discuss this knowledgeably in further reports. I have also asked students to complete a short questionnaire on the inside back cover of the test papers. The information gained from this will be used as a guide to assessing how A level courses influence students' 18+ progress.

Students who have recently completed mocks may be rather fed up of exams, so I hope they will not object too strongly to doing this paper for a third time! It really is important to the study to get the same high quaility of responses as for the first and second surveys, so I would really appreciate your encouraging students to answer as fully as possible and especially to provide explanations where requested, even if the answers now seem very simple indeed!

If you have been able to read or dip into the latest report, I think you will agree the study is producing fascinating data. It would be marvellous to have another excellent set of responses to complete the work and obtain a full picture of changes in students' understanding.

Once again, thank you very much indeed for your time and co-operation. If I can provide any further information about the study or the test please do let me know.

Yours sincerely,

Vanessa Barker

The Salters' Advanced Chemistry Project
Final survey

School/College ....Today's date................

Staff contact name ....

Syllabus .... Number of students ....

Topics/units covered up to mid-February, 1994 (Continue overleaf if necessary)

Please complete this section for any other A level chemistry courses taught in your school or college.

Syllabus .... Number of students..............

Topics/units covered up to mid-February 1994 (Continue overleaf if necessary)

Please enclose this with the test papers. Thank you for your help.

Letter (8)

UNIVERSITY OF YORK
HESLINGTON, YORK, YO1 5DD
Telephone (0904) 430000
Telex 57933 YORKUL Fax (0904) 433433

DEPARTMENT OF EDUCATIONAL STUDIES

Department direct line (0904) 433460
Personal direct line (0904) 432560
Department Fax (0904) 433459

10th May, 1994

Dear Colleague,

Re: Evaluation of Salters Advanced Chemistry

I write to say thank you very much indeed for your help in the last two years with this research project. Thank you especially for finding the time in the last few months to get your students to do the test for the third time - please do let them know I really have appreciated their responses! I wish them every success with their exams this summer.

About 350 students have been followed through their A level courses, which makes this a very large study. I have coded all the scripts and am about to start doing final analysis on the data for a thesis based on the development of students' ideas about the concepts investigated. I hope to get all this done by September when I can go back to normal life at the chalk face!

I will produce a final report for you similar to the paper sent last December covering all three surveys. I would hope you will receive this in the Autumn term.

The data is of very high quality and is a tribute to all the staff and students involved. Thank you once again for your contribution.

Yours sincerely,

Vanessa Barker

Appendix 5

Progress of the students at the second and third survey stages

1. SAC students

The table shows the number of schools who had completed the units up to and including the unit where the number appears. For example, five schools had completed the units numbered 1 -4 by the second survey.

No.	Name	2nd survey	3rd survey
1	Elements of Life		
2	Developing Fuels		
3	From Minerals to Elements		
4	The Atmosphere	5	
5	The Polymer Revolution	6	
6	What's in a Medicine?	8	
7	Using Sunlight	6	
8	Engineering Proteins		
9	The Steel Story		8
10	Colour by Design		
11	Medicines by Design		8
12	Aspects of Agriculture		3
13	The Oceans		6
	Visiting the Chemical Industry		
	Individual Investigation		2
	Total	**25**	**27**

Notes:

1. Two schools did not give sufficiently clear information to be recorded in the second survey column.

2. The content of the units relevant to the study is discussed throughout chapter 5.

3. Most schools had completed Visiting the Chemical Industry and the *Individual Investigation* by the time of the third survey, in addition to the units shown.

2. Traditional students

The topics relevant to the study completed by the Traditional students at the second and third survey stages are shown in the following table:-

Chemical content	2nd survey	3rd survey
Mole calculations	2	5
Atomic structure	5	5
Structure and bonding	5	5
Periodicity	4	5
Gas laws	4	5
Alkanes and alkenes	5	5
Equilibria	2	5
Thermochemistry	3	5
Kinetics	0	5

Notes:

1. Two schools were following the UCLES Modular syllabus and did not give information which could be placed in this table.

2. Some schools did not list every topic, but explained what they had not covered by the third survey.

3. Traditional students were following one of these syllabuses: JMB (B), ULEAC, Oxford Local, UCLES Modular, Oxford and Cambridge.

Appendix 6

χ^2 tests on SAC sample responses

A completed calculation using raw figures is shown for two questions, *Molecules* and *Element and compound.* A table of the results for all other questions follows.

The calculations compared the P-coded responses with those not coded P over the first and third surveys. Where the number of P coded responses was less than 5% of the population, χ^2 was calculated for the sum of P + Q responses against those not coded Q or P.

The values of χ^2 at the 0.05 and 0.01 levels of significance are 3.84 and 6.64.

Molecules

	survey 1	survey 3	
P	188 a	180 b	368
not P	62 c	70 d	132
	250	250	500

Expected values:

a = (368 x 250) / 500 = 184
c = (132 x 250) / 500 = 66

b = (368 x 250) / 500 = 184
d = (132 x 250) / 500 = 66

$\chi^2 = \Sigma((A-E)^2 / E)$

$\chi^2 = 0.09 + 0.09 + 0.24 + 0.24 = \mathbf{0.66}$

This value is not significant at either level.

Element and compound

	survey 1	survey 3	
P	70 a	105 b	175
not P	180 c	145 d	325
	250	250	500

Expected values:

a = (175 x 250) / 500 = 87.5
c = (325 x 250) / 500 = 162.5

b = (175 x 250) / 500 = 87.5
d = (325 x 250) / 500 = 162.5

$\chi^2 = \Sigma((A-E)^2 / E)$

$\chi^2 = 3.5 + 3.5 + 1.88 + 1.88 = \mathbf{10.76}$

This value is significant at the 0.01 level.

Question	χ^2 value	Is the value significant? 0.05	0.01
Substances	21.0		*
Tablet	0.2		
Copper	8.4		*
Hydrogen chloride	25.7		*
Phosphorus	11.4		*
Precipitation	34.9		*
Solution	2.6		
Iron sulphide	21.9		*
Carbon	19.1		*
Power Station	52.1		*
Petrol	40.6		*
Covalent bonds	114.2		*
Methane molecules	22.8		*
Sodium and chlorine	12.4		*
Hydrogen bonds	133.5		*
Boiling	17.3		*
Chlorides	7.1		*
Methane	118.2		*
Energy change	19.6		*
Reactions	50.9		*
Reaction rates	2.1		