A CROSS-SECTIONAL STUDY OF THE UNDERSTANDING OF CHEMICAL KINETICS AMONG TURKISH SECONDARY AND UNDERGRADUATE STUDENTS

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ABSTRACT

The purpose of this study is to evaluate secondary school and undergraduate students' conceptual understandings of chemical kinetics in the light of the aims of the Turkish chemistry curriculum. This purpose is addressed through a cross-sectional design. So as to identify the intended development of the subject of chemical kinetics within the school and university courses, the science curriculum, chemistry textbooks and students' notes were analysed and interviews were conducted with teachers/lecturers who had taught chemical kinetics unit at the participating institutions. Based on a conceptual analysis of the domain, key scientific ideas in chemical kinetics were identified and a number of open-ended diagnostic questions were designed to provide contexts through which students' understanding about each of the key scientific idea could be investigated. The study is based mainly upon the written responses given by 191 upper secondary school students (ages 15-16) and pre-service chemistry teachers (age 17+) to a series of written tasks involving concepts and phenomena in chemical kinetics. A sub-sample of the students was also interviewed in order to obtain further information regarding their ideas about chemical kinetics.

Conceptual analysis of the domain suggested that the rates of chemical reactions can be explained by a qualitative approach (Particulate Modelling) and may also be understood in terms of a quantitative approach (Mathematical Modelling): ultimately these two approaches are amalgamated in some levels. In order to achieve a full scientific understanding, students need to have some understanding of several modes of modelling. However, this is not often reflected in the curriculum. In some areas of the domain there is a mismatch between the objectives of the curriculum, teaching and the outcomes of the curriculum.

In a broad sense, the students following the curriculum made progress from secondary through university level. This progression was different in different areas of chemical kinetics. (1) Changes in the nature of explanations offered by students and (2) changes in the conceptual content of explanations offered by students were identified. I found progression in the forms of justification used across the educational levels, with school students tending to justify propositions by simple prototypical examples, or by drawing upon taken for granted everyday knowledge. By contrast, undergraduates were more likely to provide explanations based upon theoretical models and entities within established chemical ideas. Though both school and undergraduate students were more likely to give a correct answer to how a change in the reaction conditions (e.g. increasing the initial concentrations of reactants) would influence the reaction rates, yet they had difficulties in providing explanations about the dynamic nature of the reaction system. The results indicated that several conceptual difficulties exhibited by the school students persisted in the undergraduates. Furthermore, the results suggest that students' lack of understanding in thermodynamics and chemical equilibrium significantly influences their ideas about chemical kinetics.

Some possible implications for planning the curriculum and teaching are proposed in the light of the results of the study. Avenues for further research are also identified. The findings can be drawn upon by teachers, lecturers, textbook writers, researchers, and curriculum designers in planning more effective teaching activities.

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CHAPTER 1

INTRODUCTION

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1.0 INTRODUCTION

This research describes a cross-sectional study of the development[1] of Turkish students' understanding of chemical kinetics, following relevant teaching, from upper secondary to university level.

So as to identify the intended development of the subject of chemical kinetics within the school and university curriculum, the chemistry curriculum, chemistry textbooks, and students' notes were examined based on a conceptual analysis of the domain and interviews were carried out with a few teachers and lecturers. In order to evaluate the effectiveness of the curriculum in meeting its aims in the area of chemical kinetics, a group of written diagnostic questions, termed "probes", were designed and deployed. The sample includes secondary school students (Grade 10, ages 15-16), and first-year (age 17+) and third-year (age 19+) pre-service chemistry teachers. Follow-up interviews were also conducted with a number of students in order to probe their understanding in more depth.

1.1 RATIONALE FOR THE STUDY AND RESEARCH QUESTIONS

1.1.1 The choice of the research area

Chemical reaction rates and the factors that affect them constitute an important area of the chemistry curriculum. Due to its importance in the understanding of the nature of chemical reactions and reaction processes, chemical kinetics is included in both school and university curriculum, in most countries (Justi, 2002). A large amount of research in chemistry education has investigated students' ideas about various science topics, for instance, chemical change, chemical equilibrium, and thermodynamics. By contrast, relatively little empirical research has been carried on students' understanding of

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[1] I use the word "development" to refer to changes in the ways in which students reason in the field of chemical kinetics. No implication about cognitive development is intended.

chemical kinetics (Justi, 2002; Van Driel, 2002; de Jong *et al.*, 2002). Whilst, students experience difficulties in understanding of chemical kinetics both at school (de Vos & Verdonk, 1986; Justi, 2002) and university levels (Lynch, 1997), further research is required in order to give insights into the ways in which students conceptualise the domain at school and university levels. The key assumption behind this study is that examination of the nature of explanations offered by students about chemical kinetics at different educational levels can provide information for teachers and curriculum designers to design teaching activities to overcome students' difficulties in this field and to match the curriculum to the needs of students.

1.1.2 Aims of the study

This study aims to evaluate secondary school and undergraduate students' conceptual understandings of chemical kinetics in the light of the aims of the Turkish chemistry curriculum. In other words, the study aims to find out how effective the curriculum has been in meeting its aims in terms of students' understanding. If it is not being effective, this study could identify in what aspects it is not being effective so that the data can be interpreted in terms of the content structure of the domain, of the structure of the curriculum, and of the materials used during teaching (e.g. textbooks, examinations papers). As a consequence, relative strength and weaknesses of the education system in the area of chemical kinetics can be characterised and the results can improve understanding of the outcomes of the chemistry education at school and university. Such information can inform decisions about where and how improvements to the chemistry curriculum can be made.

The university students who participated in this study will become chemistry teachers when they graduate. Teachers' subject matter knowledge (SMK) is an essential element in teaching and learning processes in that their SMK either enhances or hinders their students' learning (Haidar, 1997; de Jong *et al.*, 2002). Indeed, research in other areas of science suggests that some of the conceptual difficulties encountered by students appear to be associated with those of their teachers (de Jong *et al.*, 2002). Therefore, we need to make sure that the prospective teachers possess an appropriate scientific understanding of chemical kinetics in order to help their students to learn these concepts properly. The key assumption is that the curriculum developers' awareness of the students' point of view may substantially influence the design of the teaching of a particular science content (Duit, Komorek, Wilbers, 1997). Accordingly, this study aims to provide better understanding of school and university students' ideas of chemical kinetics so as to inform the ability of curriculum development to meet students' needs. Indeed, there is convincing evidence to show that students who have followed teaching whose design was based on educational theories and research results about students' difficulties in understanding a particular science content (i.e. content-specific research) show significantly better conceptual understanding than is achieved with conventional teaching (Andersson & Bach, 2005).

1.1.3 Research questions

The aim set out above is addressed through the following research questions:

(1) What kind of development is intended in the subject of chemical kinetics within the school and university curricula, in Turkey?

(2) What are secondary school and university students' understandings of chemical kinetics and how do they change in relation to relevant teaching at school and university level? This specifically involves finding out;

  (i) What kind of conceptual difficulties do students experience in chemical kinetics?
  (ii) How well do students understand and use chemical kinetics in a range of contexts?

(3) What are the implications for the effective teaching of chemical kinetics at school and university level?

1.1.4 The choice of the research method

In order to address the research aim and questions, either a cross-sectional or a longitudinal study could be carried out. Since students' understanding of chemical kinetics is investigated over a long time span, about five years (from Grade 10 to university third year), a longitudinal study would not be practical for this Ph.D. project. Another reason for using a cross-sectional design is to increase the number of respondents in order to get a representative picture across different educational levels. It should be emphasised that as the study is cross-sectional, which allows for investigation of students' responses to particular tasks, at different educational levels, data cannot reflect changes in the explanations offered by individual respondents. Doing this would require longitudinal studies.

1.2 A SUMMARY OF THE FORTHCOMING CHAPTERS

Following this introductory chapter, Chapter 2 reviews the relevant literature in science and chemistry education. This chapter provides information on what kind of insights have been gained from the literature in order to design the current study, presents an overview of existing research on chemical kinetics relevant to the study, and discusses how the study can contribute to the field of teaching and learning chemical kinetics at school and university levels. This chapter also reviews different methodologies for probing understanding and analysing data.

This study uses a cross-sectional methodology. Chapter 3 describes and justifies the research methods, the research instruments and data sources used for addressing the research questions and aims. Furthermore, a range of methodological questions relating to data collection, sampling, administration of research instruments, data analysis, and validity and reliability issues are discussed in this chapter.

In framing data collection and analysis about students' understanding of chemical kinetics, it is necessary to make an analysis of the scientific concepts that define the domain at school and university level. This conceptual analysis is described in Chapter 4. Chapter 4 also discusses data gathered from interviews with teachers and lecturers.

In the following five chapters (Chapters 5, 6, 7, 8, and 9), the gathered data and findings are discussed in the light of each research question. The findings emerged from interviews with students and from the analysis of documentary evidence are also presented in each chapter. Indeed, all gathered information is assimilated and findings are developed by triangulation. Information is drawn in the form of tables and figures in order to illustrate and clarify the text where thought to be beneficial.

Chapter 5 presents students' responses concerning the reaction rate and its relationships with the concentrations or pressure of reactants/ products. Chapter 6 reports students' responses on the probes which were designed to probe their understanding of the effect of temperature on the rates of reactions. Students' understanding of the effect of surface area of solid reactants on reaction rates is discussed in Chapter 7. Chapter 8 discusses students' understandings of the concepts of activation energy and catalysis. The last chapter of results, Chapter 9, reports the analysis of students' responses to the probes which were designed to elicit their understandings of rate equations and reaction mechanisms.

Finally, Chapter 10 summarises the key findings of the study and discusses their implications for teaching and learning chemical kinetics. This chapter also provides a methodological critique of the study, and identify some areas suitable for further research.

CHAPTER 2

LITERATURE REVIEW

CHAPTER 2

LITERATURE REVIEW

2.0 INTRODUCTION

The aims of this chapter are to discuss the relevant literature in science and chemistry education in order to provide information on what kind of insights have been gained from the literature in order to design the current study, and to discuss how the current study can contribute to the field of teaching and learning chemical kinetics at school and university levels. The chapter is structured into five sections. The first section discusses research on students' conceptions and how those have influenced approaches to teaching science. The next section provides some possible outcomes of cross-sectional studies for curriculum development. The third section considers approaches used to elicit students' conceptual understanding in particular areas of science, and approaches to data analysis. The following section presents an overview of existing research on chemical kinetics relevant to the present study. Finally, the conclusion briefly pulls together some of the more general messages emerging from this review.

2.1 STUDIES ON STUDENTS' CONCEPTIONS AND THEIR INFLUENCES ON APPROACHES TO TEACHING SCIENCE

In the past decades, a significant programme of research has been conducted on students' preinstructional conceptions in various science content domains and on how these conceptions change as a result of science teaching. Thus, science educators have become increasingly aware of the importance of students' (preinstructional) conceptions of natural phenomena and events[1] (for a review of the literature on students' and teachers' conceptions in science, see Pfundt & Duit, 2004). In other words, researchers and curriculum developers started making use of such information in order to improve science teaching and learning (e.g. Driver & Oldham, 1986; Andersson & Bach, 2005).

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[1] Nevertheless, transforming findings from research into classroom practice and the gap between outcomes of the research on students' domain-specific knowledge and the practice of science education has presented a challenge (Duit & Treagust, 1998).

The development of teaching sequences has become the focus of several empirical and theoretical studies. There is considerable evidence to show that it is possible to improve students' learning against specified curriculum goals when the design of teaching sequence is informed by evidence from educational theory and research data (see, for example, *the International Journal of Science Education*, 2004, Special Issue on teaching-learning sequences). The proposed approaches could be used by other researchers to develop teaching sequences in other areas of science from the same viewpoints. Examples of such work include the framework of "developmental research" (Lijnse, 1995); the model of "educational reconstruction" (Duit *et al.*, 1997); and the design of teaching based on the notion of "learning demands" (Leach & Scott, 2002). Such approaches share some common features. For instance, great attention is given to:

(1) the clarification of science subject matter structure (i.e. an analysis of the particular content to be taught),

(2) students' conceptions about the domain (e.g. empirical investigation of students' conceptions and/or reviewing literature in this field), and

(3) making links between insights from research, and the development of instruction.

The process of designing, implementing and evaluating a teaching sequence is cyclical (Lijnse, 1995). Since one of the possible outcomes of the present study is to provide evidence for further research for designing teaching sequences/strategies for chemical kinetics, it is worth giving a brief review of literature on designing teaching sequences, informed by research evidence. As there is a lack of empirical research on students' ideas in chemical kinetics, the results of the present study can be used as a starting point for designing teaching sequences in this field.

2.1.1 Designing research informed teaching sequences

In many empirical studies, the data gathered tend to assess the effectiveness of a teaching sequence at promoting students' learning, rather than permit analysis of causal factors. Such research ignored what actually went on in the classroom; it simply looked at the outcomes of the teaching. This makes replication of teaching sequences problematic. This is because effective teaching involves having a sound understanding of how and why certain activities lead to conceptual understanding, and what factors influence their effectiveness (Kyriacou, 1997). There are a small number of studies reported in the literature which go beyond that by making explicit the actual design of teaching sequence and by providing an understanding of the key issues which underpin the nature of teaching and student learning. One of these studies/models is discussed below. One of the reasons for specifically discussing this model is that some of its components have provided a general frame to address some questions faced during the present study and to consider some of these questions during the study: for instance, how the structure of a content domain (e.g. chemical kinetics) might be analysed, what types of explanations or representations are provided in textbooks, what are their limitations, how are these explanations related to the scientific explanations, how the textbook explanations take into account potential students' learning difficulties, what kind of insights can be gained from these studies (i.e. developmental research or research informed teaching practice) in order to design the present study on evaluating students' understanding of chemical kinetics in the context of the aims of the Turkish chemistry curriculum?

The Model of Educational Reconstruction (Kattmann et al., 1995; Duit et al., 1997):

Many researchers share the view that educational practice should be more research informed by considering the relationship between research and application of research in classroom practice (Andrews, 1998 in Bennett, 2003). Indeed, there is an increasing interest in teaching as a research informed practice. The model of "educational reconstruction" provides a general framework for shaping research and curriculum development in a particular area of science. The key features of the model are composed of three closely interconnected components: (1) analysis of content structure, (2) empirical investigations into students' conceptions, and (3) construction of instruction.

(1) Analysis of content structure

Content analysis of science subject matter is a key issue if instruction of a particular science content is to be developed, because it is necessary to identify the main key ideas and their relationships (both from science perspectives (i.e. the scientific knowledge shared by scientists) and from educational perspectives (i.e. the knowledge to be taught at schools)). Our understanding of the structure of the content (from science perspective and from educational perspectives) and of the students' point of view may significantly influence the design of teaching in this field. This content analysis may be guided by aims and objectives of the curriculum. The following questions may guide this conceptual analysis:

- *Which are the scientific theories, principles, notions and concepts on a specific subject, and what are their limitations?*
- *What are the key scientific ideas?*
- *In which contexts are the scientific concepts used?*
- *Which ethical and social implications are associated with the scientific conceptions?* (Kattmann *et al.*, 1995, p.5)

Accordingly, analysis of content structure searches for the key features of a particular content and takes into account not only epistemic dimensions (function and meaning of the scientific concepts), but also ethical, social, environmental, or industrial implications of the concepts.

(2) Empirical investigations

This component includes investigating students' (pre)conceptions and views on teaching and learning science. This empirical investigation would provide an answer to some of the following questions:

- *How are the scientific concepts represented in students' perspectives?*
- *Which conceptions are used by the students?*
- *Which perspectives do students have about science itself?*
- *How do alternative conceptions of students correspond with scientific conceptions?* (ibid. 6).

The significant feature of this empirical investigation is to explore qualitatively the distinct ways in which students conceptualise the field, though not necessarily to identify their quantitative distribution (i.e. to find out quantities in which certain conceptions exist in a population).

(3) Construction of instruction

Analysis of content structure, empirical investigations into students' conceptions and educational theories can provide guidelines in order to (re)construct instruction in order to improve students' conceptual understanding of the domain. This phase of the model describes, discusses and theoretically justifies the design of the instructional activities. The following questions would be considered during the reconstruction of science teaching:

- *Which are the most relevant elements of the students' conceptions to be respected?*
- *Which opportunities are opened by certain elements of students' conceptions or perspectives?*
- *Which conceptions of students correspond with scientific conceptions in such a way that they can be used for a more adequate and fruitful learning?*
- *What are the conditions (e.g. interests, motivations, and the classroom discourse) that have to be arranged in order to support learning the intended science content.* (ibid. 7)

The constructed teaching sequence needs to be tested and validated. As a result, the components of the model can be modified and reconstructed. The educational reconstruction is a dynamic process within its components. As Tiberghien (2000) argues, the cyclical process of design and improvements of teaching activities for each domain of physics can be an endless task.

As the present study uses a cross-sectional design, I will now review what kind of insights can (or cannot) be gained from a cross-sectional study.

2.2 CROSS-SECTIONAL STUDIES AND THEIR POSSIBLE OUTCOMES

Though many studies have been conducted on students' ideas about specific areas of science, a more limited number of studies has investigated the development of students' ideas over a period of time (Bennett, 2003). Longitudinal and cross-sectional studies have been used for this purpose. In other words, these studies identify how understanding of specific ideas changes as students move through the curriculum. However, each of these approaches has its own particular advantages and disadvantages. For instance, cross-sectional studies cannot be seen as describing pathways in the development of individual students' conceptions. Doing this would require longitudinal studies; however these studies could be difficult to carry out due to the possible loss of subjects over the long time intervals. For instance, a longitudinal design would not be practical for the present study, due to a long time span from Grade 10 to university third year which is about five years.

In order to evaluate the success of a curriculum at achieving its objectives, it is necessary to look at some aspects of students' learning. Several cross-sectional studies have been undertaken on students' domain-specific knowledge in other areas of science, and the data from these studies provided important information when decisions are made in planning teaching activities and sequencing the curriculum (see, for example, Abraham *et al.*, 1994; Driver *et al.*, 1994a; Driver *et al.*, 1994b). From the diversity of reported studies, the characteristic features identified in the following paragraphs have emerged in students' domain-specific knowledge across different educational levels. However, it should be pointed out that the majority of these studies have focused on primary and/or secondary school students' point of view, unlike the subject of the present study which targets upper secondary and pre-service chemistry teachers. Therefore, some of the findings gathered from these studies would not be relevant to my study.

- Evidence from cross-sectional studies suggests that students' ideas within specific content domains tend to follow similar patterns. Though, there may be variations from individuals to individuals, the general picture that has emerged from research indicates that there are similar patterns in the development of students' ideas. This supports the view that students' conceptions about natural phenomena are not completely idiosyncratic, nor are they in many cases heavily culturally dependant. Within particular science domains there are commonly occurring ways of modelling and interpreting phenomena that are found among students from different countries, languages, and educational systems (i.e. Nussbaum, 1979; Vosniadou and Brewer, 1992). For example, Vosniadou and Brewer (1992) claim that the process of students' initial mental models of earth to a mental model of a spherical earth is a slow and gradual process and this gives rise to intermediate synthetic models of the earth. Synthetic models are formed when students try to reconcile the information coming from adults that the earth is a sphere with their conceptions.

- A range of entities corresponding existence in the world of the learner, i.e. in their ontologies, extends and changes as the learner's reasoning evolves (Leach *et al.*, 1995). An example of such ontological change cited is the moving from the idea that "air is nothing" to seeing that "air is a substantive matter". A similar pattern was seen in pupils' notion of energy. Moving from the idea that energy is a substance with mass to believing the scientific view of energy is an example of such ontological change. The absence of ontological entities may constrain learners' understanding of a particular area of science.

- Research suggests that younger students tend to provide explanations drawing upon observable features of the phenomena rather than explaining the reasons behind it (i.e. referring to scientific theories/models). Younger students tend to use what is called common-sense reasoning or everyday ways of explanation in order to interpret a specific task rather than using some scientific terms, concepts, or principles that they have learned during their schooling. For example, they may use "the notion of a vacuum sucking, when explaining drinking orange juice with a straw" rather than "referring to the notion of air pressure". Furthermore, younger children tend to offer an explanation which reflects a linear causal chain of explanation. For example, considering a simple food web involving grass, rabbits, mice, hawks, etc., Leach *et al.* (1996b) asked students (aged 5-16) to predict population changes in terms of relationships of these species. Consequently, they found that "pupils tend to frame their explanations in terms of individual organisms rather than populations of organisms, and make predictions in terms of linear cause-effect sequence rather than changes throughout the food web" (ibid.140). Rozier and Viennot (1991) identified similar linear causal reasoning about thermodynamic problems among undergraduate students.

- Older students are more likely to use their conceptions consistently across different contexts. For instance, Palmer (1997) investigated students' reasoning about forces and found that younger students (15-16-year-olds) were influenced by contextual features such as speed, weight and position of moving object, the direction of motion and their own experience of the context. However, he found that older students (pre-service science teachers) were generally less affected by context and more consistent in their reasoning. Moreover, older students (or experts) are more likely to transform models in one mode of representation into equivalent representation in other modes (Kozma & Russell, 1997).

- As students move through the curriculum, their views of the nature and status of scientific knowledge also evolve (Driver *et al.*, 1996). This includes changes in their views of the purpose of scientific work, the nature of scientific enquiry, the nature of explanations and theories, and the nature of coordination of explanation and evidence for the development and testing of knowledge claims.

- Though there are improvements as a results of instruction, both in terms of students' learning, and their attitudes towards science, many alternative conceptions[2] (in various areas of science domains) and everyday ways of explanation are still prominent among school students, pre-service and even in-service science teachers despite years of schooling (as demonstrated by many studies, e.g. Southerland *et al.*, 2001). When students are introduced, in school or elsewhere, to the scientific view of concepts and phenomena, they start to organise and structure their own knowledge by using present conceptual frameworks to interpret new information in ways that make sense of them. It would be oversimplifying to say that the new concept replaces an earlier one. Learners may have different ways of talking, thinking, and representing the material world, and accordingly the new concept does not necessarily replace previous one, rather learners make choices to use them in contextually appropriate ways (Mortimer, 1995). In this respect, progression in learning involves changes in existing modes of thinking and having an understanding of scientific modes of thinking and talking.

In the next section, a number of possible implications of the results of cross-sectional studies for the design of science curriculum and instruction are considered.

2.2.1 Implications of cross-sectional studies for the design of curricula and instruction

Curriculum planning and designing teaching has significantly changed over time. Bennett (2003, p.43) states "conventionally, curriculum planning has involved bringing together groups of people with expertise in science education and asking them to make recommendations about curriculum content". However, there are some examples of the use of findings from research in developing curriculum, as summarised in the following paragraphs. It is important to emphasise that a wide range of factors including social and cultural aims, employment needs, the nature of science subject matter to be taught as well as the process of knowledge acquisition in science, is usually taken into account for

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[2] In this thesis, the term "alternative conceptions" is used to describe ideas that students develop before or after teaching on a particular scientific topic, which differ significantly from that which is socially agreed by the scientific community.

decision making about curriculum content in school science courses (Driver *et al.*, 1994a).

Cross-sectional research on students' ideas in a particular domain could provide information about the patterns in the development of students' understanding in this domain. Leach *et al.* (1997) claimed that:

> *...[S]uch insights about the everyday ontology and epistemology commonly used by students at particular ages can be used to inform teaching interventions by highlighting possible mismatches between students' everyday knowledge and the assumptions underpinning the curriculum.* (p.161)

One example is the interrelationship that exists among matter cycling process, decay and the conservation of matter. The research on ecology shows that students have difficulties in understanding matter cycling process (Leach *et al.*, 1996a). For example, the younger students (aged 5-7) were unfamiliar with some of the phenomena related to the decay process. When talking about the fate of matter in the decay process, many students were less likely to conserve matter in their explanations. Thus, an appreciation of the familiarity of students with appropriate phenomena involving decay and an appreciation of the conservation of matter are essential prerequisites to conceptual understanding of matter cycling, therefore these ideas need to be introduced in the curriculum before the concept of matter cycling. Another cross-sectional study in the subject matter of astronomy suggests that students understand the spherical shape of the earth concept only after they have acquired an elementary notion of gravity (Vosniadous, 1991). Otherwise, students may have difficulties in understanding "how people live on the sides and bottom of the spherical earth without falling off'. Vosniadous (1991) also pointed out the interrelationship between the earth's shape and the explanation of the day/night cycle. She claimed that the mental model of a spherical earth is a prerequisite to understanding the scientific explanation of the day/night cycle. Otherwise students may form alternative conceptions. Accordingly, possible curriculum sequencing would be first introducing the notion of gravity, then the shape of the earth concept and finally the day/night cycle.

Though, this would not be the case for the present study (as the focus of interest is upon adolescents and adult chemistry learners' ideas about chemical kinetics), cross-sectional studies could provide information for whether particular ideas to be introduced appropriate for a certain age. For example, research evidence shows that reasoning about atomistic ideas of matter tends to emerge in students' explanations at around ages 9-11 (Holding, 1987). It is therefore suggested that there is "probably little to be gained educationally from the investment of effort required to introduce such notions at much earlier ages. It may be more efficient to use the teaching time available to focus on the development of other notions" (Driver *et al.*, 1994a, p. 95).

Research on the development of students' ideas in science shows that the process of knowledge acquisition does not involve a sudden and dramatic shift, but rather it is slow and piecemeal process (Vosniadou, 1991). Accordingly, cross-sectional studies can give insights to the pace at which a particular scientific concept develop. Driver *et al.* (1994a) suggest that giving an appropriate amount of teaching time to the concepts which are central to students' scientific understanding in a wide range of topics is educationally worthwhile. Furthermore, Vosniadou and Ioannides (1998) propose that designing curricula that focus on the deep exploration and understanding of a few, key concepts in a particular domain rather than curricula that cover a great deal of concepts in a superficial way may be more efficient and profitable. The curriculum that covers a great deal of concepts does not give students enough time to achieve a qualitative understanding of the concepts being taught; rather it leads to alternative conceptions. They claim that this approach makes teachers very anxious about covering the all concepts and as a result of that they do not have enough time to monitor students' understanding.

Leach & Lewis (2002) made a distinction between learning the laws, theories and concepts of science which many science curricula extensively focus on and learning how that knowledge is used in actual situations. Knowing a concept in the abstract, and using it appropriately in a given situation are different things. As Driver *et al.* (1994a, p.97) pointed out "learning science involves more than learning science concepts". The research shows that in many cases (younger) students' use of epistemological knowledge is very different from experts. As discussed earlier older students and experts are more likely to use their conceptions consistently across different contexts. Cross-sectional studies on students' epistemological knowledge and the ways of explanation can provide information for curriculum planning and designing teaching in order to enhance students' metacognitive skills.

Having given an overview of the possible outcomes of cross-sectional studies, I now review approaches used to elicit students' conceptual understanding in particular areas of science and approaches used to analyse data gathered.

2.3 ASSESSING LEARNING – PROBING UNDERSTANDING

The purpose of this research study is to evaluate secondary school and undergraduate students' conceptual understandings of chemical kinetics in the light of the aims of the Turkish curriculum. In order to find out what the curriculum aims to achieve, identification of instructional (teaching) objectives is necessary.

Bloom (1956) proposed a classification system for educational objectives (knows as Bloom's Taxonomy of Educational Objectives). Bloom constructed three domains to study learning in education: the affective, the psychomotor, and the cognitive domains. The affective domain concerns with changes in interest, attitudes, motivations, and emotions. The psychomotor domain includes physical movement, coordination, and use of the motor-skill areas (e.g. playing a musical instruments or operating a word-processor). The cognitive domain deals with the recall or recognition of knowledge and the development of intellectual abilities and skills. The cognitive domain which is most central to the curriculum and diagnostic test development is further divided into categories or levels: (1) Knowledge, and (2) Intellectual abilities and skills: (i) comprehension, (ii) application, (iii) analysis, (iv) synthesis, and (v) evaluation. In the 1960s and 1970s, a development view based on this perspective (i.e. moving from general and ambiguous instructional objectives towards more specific instructional objectives) was influential in design of a number of curricula (Popham, 1995). This taxonomy also provided a useful structure to categorise examination questions.

Nevertheless, it is worth noting that "if we encouraged teachers to use instructional objectives that were too specific, the results would be an abundance of small-scope behavioral objectives" (Popham, 1995: p.79). Popham proposes that it would be more useful to frame objectives broadly enough so that teachers can organise instruction around them. He argues that it would be more useful to teachers if they narrow instructional objective down to only two categories: (1) knowledge (i.e. recalling facts, concepts, methods and processes) and (2) anything higher than knowledge (i.e. intellectual abilities and skills, such as, applying the knowledge in different situations or knowing how to use this knowledge). Hence, narrowing instructional objectives down would be helpful for planning assessment targets. In other words, a small number of significant instructional objectives (i.e. feasible and measurable objectives) can provide a useful framework for deciding what to teach, how to teach and what to assess.

Analysis of the Turkish curriculum (see chapter 4) indicated that chemistry education aims to introduce students not only to the abstract concepts involved in explaining the phenomenon of rate of reaction, but also to the ways in which students can apply these concepts to various situations and contexts. Therefore, it would be more appropriate to investigate how well students understand the concepts in chemical kinetics and also to investigate how appropriately they use their ideas in a range of contexts. The assessment frameworks employed in some areas in science education and in this study are discussed in the following section.

2.3.1 Approaches to probing conceptual understanding in science

There are many ways of gathering information about students' understandings of scientific concepts and phenomena. Studies of students' ideas in science have a long history, perhaps originating with Piaget's early studies. During that time a wide range of methods (e.g. written diagnostic questions, interviews about concepts, interviews about instances and concept mapping) has been used to access different aspects of students' reasoning and to probe their conceptual understanding in science (see, White & Gunstone, 1992, for detail). As Lijnse (1995) puts it:

> *To be able to build on students' knowledge, and to use their constructions productively, we should first know what they really mean when they say what they say.* (p.193)

The question naturally arose: what kind of research approaches and instruments are appropriate in order to gather information for understanding "what students really mean when they say what they say"? Driver and Erickson (1983) made a distinction between approaches designed to probe students' ideas as conceptually and phenomenologically framed data collection approaches. Studies in which students' ideas are elicited based on the structure of students' propositional knowledge are called conceptually framed approaches. Conceptually framed studies involve eliciting students' knowledge about a concept, a scientific term or a problem, for example, asking students what is understood about particular scientific concepts such as 'entropy', 'photosynthesis' or 'momentum' (i.e. eliciting students' propositional knowledge). Concept mapping (Novak & Gowin, 1984) and word association (Cachapuz & Maskill, 1987) can be given as examples of such approaches.

In contrast to such conceptually framed approaches, there are those that are termed phenomonologically framed approaches[3] where the stimuli presented to students are natural phenomena or events rather than the concepts used in science to explain the phenomena. Those approaches aim to explore which knowledge students use so as to explain a phenomenon presented. Driver and Erickson (1983) explain that the purpose of such studies is to elicit students' knowledge-in-action. When the respondents interpret a natural phenomenon, no restraint is placed upon the way they respond. Vosniadou's (1991) study on young children's concept of the earth and the day/night cycle can be given as an example of the phenomenological approach to data collection. Children were asked to explain certain phenomena, such as the disappearance of the sun during the night, the appearance of the moon, the alteration of day and night and the shape and movement of the earth. Interviews about events can be given as an example of such approaches.

Conceptually framed approaches can elicit what Bloom (1956) describes as knowledge objectives (e.g. recall or recognise chemical concepts), but they may also elicit students' intellectual abilities and skills in the context of a specific problem or task (e.g. eliciting students' ability to interpret empirical data). Phenomenologically framed approaches can also elicit students' intellectual abilities and skills, but this time in the context of a phenomenon or an event where minimal contextual support is given. It is important to note that each of these approaches has some methodological difficulties and limitations. For instance, when a student does not explain a phenomenon or an event presented based on scientific concepts and principles which had been taught during teaching, we could not say that the student did not have these concepts and principles. In fact (s)he

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[3] In the literature different terms are used for phenomenologically framed approaches or questions such as contextually framed approaches, contextually framed questions, context-based questions or contextualised questions.

may have had the scientific knowledge, but did not or could not apply it to the phenomenon. Therefore, it would be more appropriate to use these two approaches together or to assess students' ideas in different contexts in order to probe their understanding of a particular science domain.

Consequently, depending on specific purposes, different probing methods within a continuum between conceptually framed and phenomenologically framed approaches may be employed in order to access different aspects of students' understanding (see Figure 2.1). Indeed, the present study is aimed at not only exploring students' understanding of given chemical kinetic concepts, but also exploring how appropriately they use these ideas in different situations/contexts[4] where the relevant concepts are not presented. Moreover, to better describe how student reason about chemical kinetics, I have developed the probes that allow me to gain insight into student reasoning on many different aspects of the topic at once. By using different probes that ask about the same basic ideas, it is possible to see the extent to which students reason consistently about chemical kinetics.

2.3.2 Approaches used for data analysis

In this study I have found it useful to draw on the well established distinction between nomothetic and ideographic data analyses (Driver & Easley, 1978). Nomothetic approaches involve assessing students' understanding in terms of the "congruence of their responses with accepted scientific ideas" (ibid. 62). For instance, Warren's (1972) analysis of university entrant students' ideas about heat and internal energy can be given as an example for nomothetic data analysis. In contrast with such nomothetic approaches on data analysis, ideographic approaches involve exploring students' conceptualisations in terms of their own terms without assessment against established scientific ideas (i.e. normative science). Tiberghien's (1985) analysis of students' interpretations of phenomena concerned with heat are more ideographic in that she gave a particular interest in some of the representations and types of interpretations which students used relating to the phenomena. Indeed, the present study is intended to allow

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[4] Rodrigues & Bell (1995) state that in the literature, the word "context" can mean a variety of things, such as the classroom, the learning environment, or the relevance of an activity. However, in this thesis by "context" I mean a task (or a situation) in different settings in which different cueing is given. In other words, "context" refers simply to the situational settings of probes.

subjects to respond to the probes in their own way, using their own terminology that they thought appropriate. The intention was that as a result of this the subsequent analysis would be ideographic, exploring the content of the subjects' reasoning in their own terms and language.

Figure 2.1 depicts the relationships between conceptually and phenomenologically framed data collection approaches, and nomothetic and ideographic data analysis. It should be emphasised that irrespective of the approaches used for data collection, data analysis may be nomothetic or ideographic. For instance, the students' responses to the "rusty water pipe probe", a phenomenologically framed probe, (see Appendix 3a) can be analysed nomothetically or ideographically (see Section 6.1, for detail). When we categorise students' responses as (i) responses including scientifically acceptable ideas, (ii) responses including scientifically incorrect ideas, (ii) uncodeable responses (in that case 50.9 % of the school students' explanations included scientifically acceptable ideas and 39.8% of their explanations included scientifically incorrect ideas), we can say that the data analysis is nomothetic. However, when we categorise students' responses as (i) descriptive/empirical, (ii) explanatory/theoretical (iii) uncodeable responses (such as 56.5% of the school students' responses is descriptive, 34.0% of them are explanatory and the rest of them are uncodeable) we can say that the data analysis is ideographic. This issue is further discussed in Section 3.7 in the design and methodology chapter.

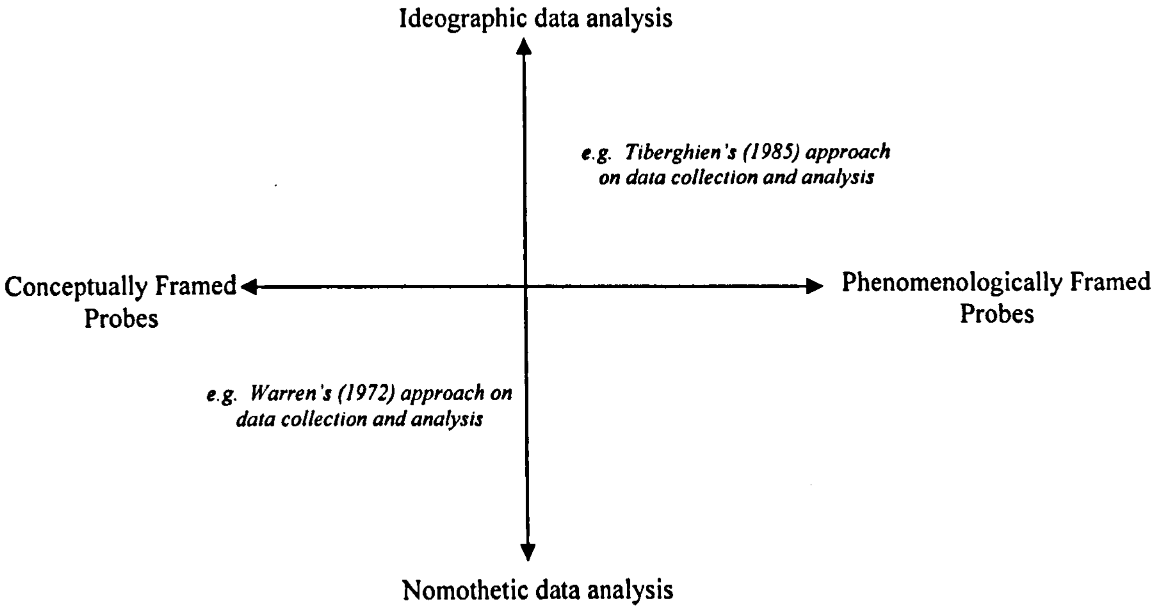

Figure 2.1 Conceptually and Phenomenologically framed data collection approaches and nomothetic and ideographic data analysis

In the next section, I review research on chemical kinetics in terms of the aims of the study.

2.4 RESEARCH ON CHEMICAL KINETICS

As briefly summarised in this chapter of the thesis, the ideas held by children, adolescents, and adults concerning a wide range of areas including chemistry have been extensively examined by researchers over the past years (see Pfundt and Duit, 2004). It seems quite understandable why students' ideas concerning chemical phenomena have become a research focus, since the literature has indicated that many students from all levels, from secondary level to university, struggle to learn chemistry and many do not succeed (Nakhleh, 1992). Specifically, students have difficulties in making links between phenomenological level of chemistry (i.e. observable changes in substances) and theoretical aspects of chemistry which explains observable changes in terms of various theories and models.

Secondary school (Andersson, 1990; Watson *et al.*, 1997; Boo & Watson, 2001) and undergraduate (Carson & Watson, 1999; Johnson, 2000) students' understanding of chemical change has been the subject of research in recent years. Overwhelmingly, studies have revealed that students' understanding of chemical change is very poor–even amongst those who have successfully passed public examinations (Johnson, 2000). Johnson's (2000) study shows that the underlying problem for students' lack of understanding (aged 16-18) in chemical change is located with the specification of the chemistry curriculum. He argues that the curriculum does not directly specify the key ideas that students need to have and develop so as to understand chemical change. By not fully and appropriately understanding fundamental concepts and key ideas, many students have trouble with understanding the more advanced concepts that build upon these fundamental concepts and ideas (Thomas and Schwenz, 1998). Indeed, studies show that the physical chemistry course, where undergraduate students tackle more advanced concepts in thermodynamics and kinetics is perceived by many students to be one of their most difficult courses (Moore & Schwenz, 1992; Sozbilir, 2002).

Because chemical kinetics is one of the most fundamental concepts in chemistry, it is regularly taught in both school and university courses in Turkey, as elsewhere (Justi, 2002). Understanding of how to control a reaction rate is very important knowledge in a range of areas from fundamental research to industrial processes. As Atkins and Jones (1999) put it "chemical kinetics gives us insights into how chemical reactions take place at an atomic level, so it brings us to the heart of chemistry" (p.594). Theories of kinetics (e.g. the collision theory and the transition-state theory) are fundamental ideas, because those theories give insight into how a chemical reaction occurs based on kinetics and thermodynamics. Thus, it is vital to gain knowledge, by means of kinetic theories, of the main factors that influence reaction rates (Laidler, 1969). Given the importance of chemical kinetics and the diverse nature of the concepts and relationships that comprise it, relatively little empirical research has been carried out on students' ideas of chemical kinetics (Justi, 2002). Specifically, studies that focus on undergraduate students' understanding of chemical kinetics are rare. Nevertheless, chemical kinetics both in school (Finley *at al.*, 1982; deVos & Verdonk, 1986; Justi, 2002) and university courses (Lynch, 1997) has been regarded as a difficult topic area for students to understand. A comprehensive review of this area can be found in Justi (2002).

For the purpose of this review, the literature on chemical kinetics is categorised into nine different perspectives. This categorisation is substantially based on Justi's (1997) categorisation of the studies about chemical kinetics[5]. These categories do not lead to a distinct set of domains, and some research papers may be placed in two different categories by different authors. The categories are summarised below.

(i) Insights into students' understanding about chemical kinetics from studies focusing on chemical equilibrium

Secondary school and undergraduate students' ideas about reaction rates were often quoted in the studies focusing on chemical equilibrium (for a review of the literature on students' ideas in chemical equilibrium, see Garnett *et al.*, 1995 and van Driel & Gräber, 2002). For instance, Hackling and Garnett (1985) conducted a research study with Year 12 chemistry students (17-year-olds) in Australia in order to probe their understanding of chemical equilibrium. The researchers developed some propositions, which lead to an understanding of chemical equilibrium and the application of Le Chatelier's Principle.

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[5] Alternatively, research on chemical kinetics can be categories as (after Justi, 2002):

(1) School level: a) students' ideas, b) teachers' ideas, c) the curriculum/textbooks' perspective,
(2) University level: a) students' ideas, b) teachers' ideas, c) the curriculum/textbooks' perspective.

The propositions were based on "*the reaction between nitric oxide and chlorine forming nitrosyl chloride:* $2NO_{(g)} + Cl_{(g)} \rightleftharpoons 2NOCl_{(g)} + heat$" (sic.) (ibid. 206)

After instruction in the topic, they conducted interviews with 30 students from ten chemistry classes. A number of alternative conceptions were identified from the students' responses. Alternative conceptions identified related to chemical kinetics were:

- The forward reaction rate increases with time from the mixing of the reactants until equilibrium is established;
- When the concentration of nitric oxide is increased the rate of the reverse reaction is decreased;
- When the temperature is increased the rate of the forward reaction is decreased;
- When the volume is decreased the rate of the reverse reaction is decreased;
- When a system is at chemical equilibrium and a change is made in the conditions, the rate of the favoured reaction increased but the rate of the other reaction decreases (e.g. when the temperature is increased the rate of the endothermic reaction increases but the rate of the exothermic reaction decreases).
- A catalyst can affect the rates of the forward and reverse reactions differently, and hence leads to a different equilibrium yield.
- Catalysts cause the formation of a higher percentage of product in the equilibrium mixture (Johnstone *et al.*, 1977a).
- Catalysts have no effect on or decrease the reverse rate in an equilibrium reaction (Johnstone *et al.*, 1977a).

It is worth underlining that mainly similar conceptual difficulties were found amongst university students and chemistry teachers from various countries (e.g. Quilez & Solaz, 1995). Hackling and Garnett (1985) concluded that many of these ideas could have arisen from a rote application of Le Chatelier's Principle with little understanding of the sub-microscopic processes occurring within the system.

In order to identify students' systematic errors when solving chemical equilibrium problems, BouJaoude (1993) has carried out a research with 189 first year chemistry students in the USA. He used a demographic questionnaire and Test of Logical

Thinking (TOLT). The questionnaire consisted of one chemical kinetics and three chemical equilibrium problems. The reason for using this kinetic problem was that the course instructor had followed the conventional approach in which chemical equilibrium was explained in terms of kinetics rather than thermodynamics. The results revealed that several students neglected to control variables in the rate equation when using the experimental results. Many students did not find the given experimental results relevant and reverted to using the rate constant in writing the rate expression. In addition, the results showed that there was limited correlation between TOLT scores and the students who answered the question correctly. Students who committed mistakes involving controlling variables scored significantly on the TOLT. Thus, he claimed that students could not apply formal thinking abilities to solve the problems.

(ii) Conceptual analysis of chemical kinetics and of specific relevant ideas such as activation energy, catalysis, and rate controlling step of a reaction

Drawing upon a conceptual analysis of chemical kinetics, Logan (1984) states that the field has an unusually complex structure in that it is composed of two distinct, but complementary, lines of development: the "empirical" and "the "theoretical". As he puts it:

> *This is the need to appreciate the fact that the mathematical equations employed in reaction kinetics, and even the parameters occurring in these equations, belong to one of two distinct groups. One of these is purely empirical framework of relationships used to describe the interrelation of (mostly) experimentally accessible parameters, such as reactant concentration and time. The other group are the equations that emerge from various theories of reaction kinetics. Logically these two are mutually exclusive* [independent]*: although the approaches are complementary, they differ fundamentally in a way that is not always appreciated, perhaps because reaction kinetics is unique among the various topics of physical chemistry in being clearly divided into these two distinct lines of development, the 'empirical' and the 'theoretical'.* (ibid. 20)

He argues that few chemistry syllabuses facilitate an understanding of this underlying structure of reaction kinetics. Accordingly, students (may) have conceptual difficulties in relating these two approaches.

Haim's (1989) analysis of the representation of the concept of catalysis in textbooks reveals that the effect of a catalyst on a reaction is usually mentioned on the diagram shown in Figure 8.5 (see chapter 8). He argues that such diagrams do not depict "the most important feature of catalyzed reaction, namely, that they involve sequences of several activated complexes and intermediates" (p.936). Such diagrams, which do not provide sufficient evidence for the mechanism of a reaction, can give students the impressions that the catalysed and uncatalysed reactions proceed via the same mechanism (a one-step mechanism). He argues that these diagrams might be one of the reasons for students' lack of knowledge and commitments to alternative conceptions about the role of catalysts in chemical reactions. Haim (1989) proposes that it is necessary to emphasise the impact of catalysts on reaction mechanisms.

(iii) The historical development of chemical kinetics and the presentation of kinetics in teaching

Through the historical development of chemical kinetics, various models have been developed, evaluated and modified (or replaced). Adopting Lakatos' Theory of Scientific Research Programmes as the analytical approach, Justi and Gilbert (1999b) proposed eight historical consensus models in the area of chemical kinetics. These historical models can be characterised as follows. Early ideas of chemical kinetics were vague and based on the vague idea of affinity (e.g. affinity is viewed something like 'love' between substances) and on an anthropomorphic view of matter, which is the idea that things are like people. Within the *anthropomorphic* model, reaction rate was described in terms of the readiness of the substances to interact with each other. In the *affinity corpuscular model,* the reaction rate was described in terms of chemical affinity of particles and the readiness of the particles. The *first quantitative model* introduced a mathematical relationship between reaction rate and the number of particles reacting in a period of time. The first ideas about the relationships between mechanism and reaction rate were emphasised in the *mechanism model.* In the *thermodynamic model* chemical change was viewed as a process in which reacting molecules collide with each other with sufficient energy. The *kinetic model* introduced the Arrhenius pre-exponential factor and the idea of frequency of collisions between reacting molecules. The *statistical mechanics model,* essentially a quantitative approach, based on quantum mechanisms and viewed a chemical reaction as the motion of a point in phase space. The models summarised above had some limitations. The *transition state model* was an attempt to overcome these limitations. The transition state emphasised the relationships between thermodynamic and kinetic variables and viewed a chemical reaction resulting from collision of molecules in terms of an activated complex. A reaction rate can be calculated by focusing on the activated complexes.

In a case study conducted in a class of 15-16-year-old students in Brazil, Justi (1997) investigated the models of chemical kinetics expressed by the teacher and the textbook. When Justi and Gilbert (1999b) analysed the textbook, they found that the author of the textbook used a completely different model from the historical models that were summarised above. However, the author used characteristics of several distinct historical models in the textbook. The teacher's expressed models, similar to the textbook case, were found not to be any of the previously defined historical models, but rather what they termed a *hybrid model.* A hybrid model which is commonly presented to students, is not a curricular model, that is a simplified version of one distinct historical model. It is instead something which includes the characteristics of several distinct historical models. Justi & Gilbert (1999a) claim that this approach would not allow the history and philosophy of science to make a full contribution to chemistry education and it would not allow students to understand the historical development of chemical kinetics. Thus, their claim was that the hybrid model presented by the teacher and the textbook cannot help students to understand chemical kinetics. The results of the study revealed that all the hybrid relationships found in the research involved the collision theory. As a result, they suggested that " ...from the point of view of teaching chemistry to adolescents the collision theory is an interesting approach to chemical reactions. The association with simple and well-known mechanical systems makes it easy to be understood". (ibid. 173)

(iv) Analogies that might be used in the teaching of chemical kinetics

The use of analogies can play an important role in assisting students in understanding some of the abstract concepts. Whilst they can facilitate students' understanding of science concepts, there is a potential danger to using analogies. For instance, some students take the analogy too far and are unable to separate it from the content being learned or other students only remember the analogy not the *target* content (Thiele & Treagust, 1995).

The literature highlights a range of types of analogies of kinetics including pictorial (e.g. Fortman, 1994), verbal (e.g. Olney, 1988), personal, bridging, and multiple analogies (e.g. Last, 1983, 1985). Auto collisions, used as analogies for chemical kinetics, have often been compared to the bimolecular collisions in mechanisms. For example, Fortman (1994) suggested a pictorial analogy for facilitating students' understanding the effect of concentration on reaction rates. The story happens in a car park; first there are two cars are moving around, then there are many cars in the car park moving around. His claim is that if "few cars, collisions less likely" and "more cars, collisions more likely". I wonder how often car accidents happen in a car park and why people drive fast in a car park. I believe that if this analogy aims to teach "the effect of concentration on reaction rate", and "not all collisions result in reaction", it would not achieve its aim. Analogies should be developed carefully in order to support effective teaching. Analogies to kinetics and mechanisms abound, but the relationship between these analogies and their intended targets (aims) are arguable (e.g. some analogies suggested by Last, 1983; Olney, 1988; Fortman, 1994). Although many analogies have been used in teaching chemical kinetics, little research has been conducted in regular classroom settings about how chemistry teachers use those or how written materials are used by teachers and students. Besides, limited research evidence is available on evaluation of these analogies in terms of students' learning.

(v) Dynamic representation of particles/models in chemical kinetics

Within the scope of chemical kinetics there are many different concepts and relationships, most of them an abstract nature. It, therefore, demands an understanding of various concepts and relationships related to them. For instance, students may either read or hear phrases such as, "chemical reaction results from effective collisions between particles of reactants", "kinetic energy" and "reactions may occur in more than one step". Lynch (1997) argues that in typical chemistry textbooks, this dynamic nature of chemical kinetics is not well suited to a static presentation through the use of diagrams and figures. Since chemical kinetics is concerned with interactions of molecules at the particulate level, it is not possible for learners actually to see how reactions occur at the sub-microscopic level. Therefore, the learners must be able to create their own representations to gain some understanding of the topic. Lynch (1997) investigated the relationship between cognitive styles, methods of instruction, and visual skills on learning chemical kinetics at university level. Participants were undergraduate students who enrolled in a general chemistry course in a university in the USA. The results indicated that participant who worked with a computer lesson scored significantly higher than those who did not work with computers. Lynch claims that through the use of computer animations students are able to see collisions and motions of particles in a reaction at the molecular level. This can help students' understanding of chemical kinetics.

(vi) Teaching about chemical kinetics by use of experiments

There is a large repertoire of experiments in the literature that can be used for teaching chemical kinetics (e.g. Hoppe & Malati, 2005). However, in the literature there is little data available on evaluation of their significance for the learning of chemical kinetics or related ideas. Many of these experiments are designed in laboratory guide or cookbook format. De Vos and Verdonk (1985, p.238) claim that "much attention has been paid to guided discovery as a teaching method, however, teachers have been given little concrete advice on how to carry this out". Accordingly, de Vos and Verdonk (1986) present a teaching strategy to help students learn the effect of heat on reactions. Their approach requires teachers to avoid a traditional approach based on understanding detailed terminology and instead to present chemical events in a way which enables students to discover the essence of the concept by themselves. In the classroom situation, the social dimension was considered by de Vos and Verdonk to be an important aspect of the learning process of individual students. Therefore, the students carried out the experiments and answer the questions in small groups of three or four. De Vos and Verdonk (1985) pointed out that

> *"[S]tudents should be encouraged to discuss chemical phenomena among themselves using their own terminology. The teacher should create situations in which students discover deficiencies in their own vocabulary when trying to communicate their observations and ideas"* (p.238).

The researchers propose that chemical knowledge can be expressed schematically in terms of questions (Q), answers (A), and experiments (E). In the traditional approach, an experiment is introduced after a question has been asked and an answer has been provided: the Q-A-E sequence. However, the approach suggested by them propose that a teacher designs an experiment that does not answer questions but raises them: E-Q-A, or E1-Q-E2-A sequence. The discourse between the teacher and students was not clearly mentioned in the article however, and this teaching approach has been criticised by Barker (2002) as not giving enough time and space to develop and consolidate students' learning about one idea before the next is presented. Barker claims that assumptions are made at each stage that students have learned as the teacher intended. Moreover, the role of students' pre-instructional knowledge is neglected. Progress could be made by developing this strategy further in order to teach chemical kinetics.

This section of the chapter has summarised the literature concerning research on the teaching and learning of chemical kinetics in school and university level. It has not given a detailed account of the research addressed below (sections vii, viii, ix), because it is thought that this work is not within the scope of the study. The majority of these papers require advanced mathematical knowledge and skills, not likely to be common among school students and chemistry teachers.

(vii) **Different mathematical treatments for kinetics equation** (e.g. Barth, 1992; Northrop, 1993)

(viii) **Terminology and units of chemical kinetics** (e.g. Dumon *et al.*, 1993)

(ix) **Studies of the rates of specific chemical reactions** (e.g. Field, 1989; Reeve, 1991).

2.5 EMERGING ISSUES FROM THE LITERATURE REVIEW

In this chapter, I have reviewed studies on teaching and learning sequences and studies on students' conceptions and patterns of reasoning across different educational levels. It should be noted that my study is not about designing teaching sequences in chemical kinetics or teaching. One of the reasons for undertaking the literature in these fields (i.e. studies for domain-specific curriculum development) was that some of the frameworks, as summarised earlier, can be exported to design a curriculum or evaluate a curriculum at a microscopic level (i.e. domain-specific) in the way, for example, Driver *et al.*, (1994a) started to do so for the school level curriculum. Indeed, I agree with the view that developing effective teaching sequences and curriculum development are essentially research activities (Driver & Oldham, 1986; Lijnse, 1995; Driver & Scott, 1996), because effective teaching involves having a understanding of key issues underpin the nature of effective teaching in particular domains (e.g. addressing how and why certain activities lead to learning, and what factors influence their effectiveness). In addition, there is convincing evidence to show that using findings from research from science teaching can improve students' learning in science.

In this chapter, approaches used to elicit students' conceptual understanding in particular areas of science and the issues on the ways of data analysis have been discussed. Such approaches would be useful to guide me in order to design the present study, particularly to design research instruments (e.g. see section 3.3), and to consider the ways of data analysis.

In the last section of this chapter, studies on teaching and learning chemical kinetics have been summarised. The literature review suggests that research on chemical kinetics usually does not go beyond an analysis of chemistry textbooks (e.g. Logan, 1984; Haim, 1989), or teachers/lecturers' personal experience on their students' difficulties (e.g. Copper & Koubek, 1999), or students' ideas of reaction rates were quoted in the literature in the context of research into students' views of chemical equilibrium (e.g. Quilez & Solaz, 1995), or in most cases the developed teaching materials are only available in local languages (e.g. Van Driel & de Vos, 1989a; 1989b). Relatively little empirical research has been carried on (1) students' conceptions in chemical kinetics and (2) how their understandings of chemical kinetics improve as they move through the curriculum (Van Driel, 2002; Cakmakci, 2005). As Justi (2002) argues, "if there is a feeling that students have problems in learning chemical kinetics, then surely such problems should be clearly characterised, instead of emerging only from what teachers happen to notice in their classes" (p.306). As a result, it is intended that this study will provide empirical evidence about school and undergraduate students' understanding of chemical kinetics with reference to the characteristics of the domain and to the approaches used in the curriculum. The results can enable us to find out how effective the curriculum has been in meeting its aims in terms of students' understanding. If it is not being effective, the results allow us to identify the weaknesses of the education system in the area of chemical kinetics. Thus, the results can be interpreted with reference to the curriculum, teaching and to the content structure of chemical kinetics. The key assumption is that curriculum developers' awareness of the students' point of view would help them to design teaching activities to overcome students' difficulties in this domain.

CHAPTER 3

RESEARCH DESIGN AND METHODOLOGY

CHAPTER 3
RESEARCH DESIGN AND METHODOLOGY

3.0 INTRODUCTION

The purpose of this chapter is threefold: (1) to set out the main aim of the study and research questions, (2) to provide an overview of the research design and methods employed to address the research questions, and (3) to describe some methodological issues that arise from the design, and how these were addressed.

3.1 AIMS OF THE STUDY AND RESEARCH QUESTIONS

The aims of the study and the research questions, introduced in Chapter 1, are as follows.

This study aims to evaluate secondary school and undergraduate students' conceptual understandings of chemical kinetics in the light of the aims of the Turkish chemistry curriculum. The study addresses the following research questions:

(1) What kind of development is intended in the subject of chemical kinetics within the school and university curricula, in Turkey?

(2) What are secondary school and university students' understandings of chemical kinetics and how do they change in relation to relevant teaching at school and university level? This specifically involves finding out;

  (i) What kind of conceptual difficulties do students experience in chemical kinetics?
  (ii) How well do students understand and use chemical kinetics in a range of contexts?

(3) What are the implications for the effective teaching of chemical kinetics at school and university level?

It is intended that the findings from the study can be used to inform teaching interventions, by highlighting possible mismatches between the objectives of the curriculum and students' level of understanding in chemical kinetics at school and university levels. As mentioned earlier, the students who comprise the sample also includes university students who are prospective chemistry teachers attending a five year pre-service teacher-training program. After graduating, they will use their knowledge about science for educating secondary school students. Therefore, identifying and characterising their conceptual difficulties would enable curriculum designers and lecturers to design teaching to address these difficulties and to ensure that they will not pass those on to their students.

3.2 DESIGNING THE STUDY IN ORDER TO ADDRESS THE RESEARCH QUESTIONS

The research aim and questions set out above are addressed through a cross-sectional design. A rationale for this methodological choice, pros and cons of cross-sectional studies and possible implications of these studies on the design of science curriculum and instruction are discussed in Sections 1.1.4 and 2.2.

Drawing upon the ideas set out above, the following research instruments were designed to address the research questions. Three data sources were used, namely (official) documents, students' responses to diagnostic questions, and students' and teachers' responses to interviews questions (see Table 3.1). The issue of why and how these research instruments were employed is the concern of the following sections (Sections 3.2.1, 3.2.2 and 3.2.3).

The first component of the research contains a detailed analysis of the curriculum for chemical kinetics so as to (1) identify the key scientific ideas in chemical kinetics, (2) to explore the types of explanations (or representations) that have been provided in the textbooks, (3) to explore the ways in which the explanations are related to the scientific explanations, (4) to specify their limitations, and (5) to identify the intended development of the subject within the school and university courses. That is why documentation was chosen as a data source.

The second component includes empirical investigation of students' conceptual understanding of chemical kinetics. Open-ended diagnostic questions were used as a main data collection instrument, in conjunction with individual interviews with a number of students. Moreover, interviews were conducted with a few teachers and lecturers in order to investigate their views and experiences on teaching and learning chemical kinetics.

3.2.1 Addressing the first research question

The first research question (RQ1) is mainly concerned with the intended development of chemical kinetics within school and university curricula. To seek answers to the RQ1, an approach consisting of analysis of the curriculum, and interviews was employed. Thus, answers to the RQ1 were derived from analysis of data obtained from the documentary evidence as well as from the interviews with teachers and lecturers. These data are reported in Chapter 4. A conceptual structure of chemical kinetics and the decisions on which aspects to investigate are also discussed in Chapter 4.

3.2.1.1 Analysis of the curriculum

Among the educational literature, there are different curriculum representations. For instance, Goodlad (1979; 1994) classified curriculum as societal or system level (macro); institutional or school level (meso); and classroom level (micro) (quoted by van der Akker, 1998, p. 421). In a similar view, three models of the curriculum have been propounded: the intended curriculum, the implemented curriculum and the attained curriculum (Third International Mathematics and Science Study [TIMSS], 1999). The intended curriculum is that laid down in official documents such as the National Curriculum of Turkey. Evidence of the intended curriculum can be obtained from analysis of official documents or textbooks. The implemented curriculum is that the actual instructional process in the classroom. Evidence of the implemented curriculum can be obtained from systematic observation of lessons, analysis of students' notes or interviews with teachers. The attained curriculum (i.e. outcomes of the curriculum) is concerned with the knowledge, skills and understanding exhibited by students, whether acquired in the classroom or outside it.

Drawing upon the TIMSS categorisation, for this study the intended development of students' knowledge of chemical kinetics reflects two of these three levels of the curriculum: the intended curriculum and the implemented curriculum. Turkish school students follow a common science curriculum, which is developed and approved by the Ministry of National Education. However, there is no national or centralised curriculum for universities in Turkey. Thus, with respect to the curriculum, although there is no written national curriculum available for universities, textbooks could be seen as the intended curriculum for universities. Therefore, for this study, data for the intended curriculum were obtained from analysis of the school science curriculum and school and university chemistry textbooks. In addition, teachers and lecturers' written lesson plans were collected and analysed. Data for the implemented curriculum were obtained through an analysis of students' notes and interviews with teachers and lecturers (see Chapter 4). Data for the outcomes of that curriculum in terms of students' learning were obtained from analysis of diagnostic tests, analysis of existing data (e.g. examination papers) and interviews with students and teachers/lecturers (see Section 3.2.2). The outcomes of that curriculum are reported in Chapters 5, 6, 7, 8, and 9.

Textbooks define much of the content, sequence and aims of the curriculum (Behar, 1994). Textbooks have a role in both the intended and the implemented curricula. In Turkey, school textbooks follow the intended curriculum very closely (TIMSS, 1999; MEB, 2004). Chemical kinetics is first introduced in the curriculum in secondary school (Grade 10, ages 15-16); therefore chemistry textbooks for Grade 10 (Kizildag & Dursun, 2000) were analysed. Chemical kinetics is taught again in detail in the first year in a *general chemistry* course and in a *general chemistry laboratory* course in a five-year pre-service chemistry teacher-training program. Furthermore, the concept is introduced in a *physical chemistry* course and in a *physical chemistry laboratory* course in the third year of the teacher-training program (see Appendix 1, for detail). Therefore, a content analysis of these two undergraduate textbooks (Mortimer, 1989; Atkins, 2001), and the laboratory books (Alkan *et al.*, 1996; Gurses & Bayrakceken, 1996) was also undertaken. Other data which were used includes students' course notes and their examination papers.

3.2.1.2 Interviews with teachers and lecturers

In order to seek answers to the RQ1, it was also decided to consult teachers and lecturers in order to explore their views on the sort of understanding they aimed to instil in their students. Research data were obtained from tape-recorded semi-structured interviews with individual teacher and lecturer. The focus of interviews questions is discussed in Section 3.2.2.3.

3.2.2 Addressing the second research question

The second research question (RQ2) is concerned with the outcomes of the curriculum for chemical kinetics in terms of students' learning at school and university. To seek answers to the RQ2, an approach consisting of written diagnostic questions, and interviews was employed.

3.2.2.1 Written diagnostic questions

A wide range of methods (e.g. written diagnostic questions, individual interviews, group interviews, and concept mapping) has been developed and refined to probe students' conceptual understanding in science (see Section 2.2, for a review on approaches used to probing conceptual understanding). Written diagnostic questions are widely used in education for revealing students' ideas in science, for example, multiple choice questions (e.g. Hestnes *et al.,* 1992), two-tier diagnostic questions (e.g. Tan *et al.*, 2002) and open-ended diagnostic questions (e.g. Andersson, 1986). However, in this study, open-ended diagnostic questions (diagnostic test) were chosen as a main data collection instrument, in conjunction with follow-up interviews with a sub-set of students. This was done for a number of reasons. First, two-tier or multiple choice tests were deemed unsatisfactory, since little or no previous research in the field existed, making initial design of multiple choice or two-tier diagnostic tests problematical (Treagust, 1988). Second, by attempting to probe students' conceptual understanding of chemical kinetics, open-ended diagnostic questions allow freedom for students to express themselves; therefore the information gathered is more likely to give a fuller insight into the students' views (Denscombe, 1998). The students can answer in as much detail as they want without prompting. By contrast, the use of multiple choice or two-tier questions would force students into a limited range of answer choices that would require them to respond in language defined by the researcher.

Diagnostic tests are regarded as easy to administer and data collection is less time consuming than interviews (Cohen *et al.*, 2000). Since there was time restriction in collecting data from overseas, the diagnostic test was appropriate. Another reason for using diagnostic tests was to increase the number of respondents in order to get a representative picture and to make an objective and quick analysis of data. Despite the advantages of using diagnostic test as a data collection tool, there are certain disadvantages as well. For example, open-ended diagnostic questions demand more effort from respondents than multiple choice questions and therefore they may reduce the willingness of the respondents to answer the questions or take part in the research. Furthermore, the interviewer is able to answer questions about the purpose of the interview and any misunderstandings experienced by the interviewee, but it is impossible to address any misunderstandings when administering diagnostic tests (Cohen *et al.*, 2000). However, that is not the case for the present study, because I was in the classrooms during administration of the diagnostic tests in order to observe students' behaviour, and answer any question they had. Written diagnostic questions have the disadvantage of not allowing the researcher to probe responses in more detail, though that is not the case for this study which uses follow-up interviews with a selected sub-set of students who have provided written answers to the diagnostic tests.

3.2.2.2 Interviews with students

A small-scale interview study was conducted with a number of students. The probes used in interviews were the same as those used in the diagnostic tests. The aims of interviews were (1) to obtain further information regarding students' ideas about chemical kinetics, (2) to check that students have understood the probes, and (3) to check for appropriate interpretation of the written responses. The data also gave insight into (4) how confident students were when responding to the probes.

In science education two types of interviews are commonly used; these are 'interviews about concepts' and 'interviews about instances or events' (White & Gunstone, 1992). An interview about a concept approaches to probe students' knowledge about a concept. For example, a student is asked what is understood about a particular scientific concept such as 'activation energy' or 'reaction rate'. An interview about an instance or event aims to investigate the student's understanding of a concept, which checks whether the student can not only recognise whether the concept is relevant or present in specific instances/phenomena but also whether the student can justify his/her decision. For example, a young pupil is shown a series of line drawings depicting various objects or episodes and asked whether there is a plant in the drawing. Another example would be asking students how plants grow.

In the present study, the probes that used in interviews were the same as those used in the diagnostic tests; involved both conceptually *and* phenomenologically framed probes (see also Section 2.2). Therefore, the interview method employed share some elements of both interviews about a concept and interviews about instances.

Though interviews are possibly the most effective way of probing students' ideas, because they offer the possibility of simultaneously probing students' meanings and allow exploring students' ideas greater depth than in the case with other methods of data collection (Denscombe, 1998; Cohen *et al.*, 2000), there are some problems with their applications. One disadvantage of individual interviews is the fact that numbers in the sample need to be kept within reasonable bounds. Moreover, as another disadvantage of interview, it is considered to be a highly subjective method and also there is always the danger of bias (Bell, 1999). Many factors can influence the participant's responses. For instance, the same question put by different researchers, but with different emphasis and in a different tone of voice can produce different responses (Bell, 1999). Therefore, during interviews the researcher was particularly careful about the way questions were put and about the language being used.

3.2.2.3 Interviews with teachers and lecturers

Semi-structured interviews were conducted with a few teachers and lecturers who had taught the chemical kinetics unit at the participating institutions in order to investigate their personal experiences on students' conceptual difficulties as well as possible sources of such difficulties and possible solutions to these difficulties. Moreover, the interviews concerned with their previous experiences of teaching chemical kinetics, such as teaching methods used and sequence of the content. A semi-structured interview schedule (see Appendix 4) was developed, tested and gradually improved during pilot application. The interviews mainly focused on:

- Teachers/lecturers' academic backgrounds
- Their views on the sequence of the chemistry curriculum and the content in chemical kinetics
- Teaching methods used in chemical kinetics (e.g. the usage and nature of practical work or demonstrations).

- Their personal experiences of students' common difficulties in chemical kinetics
- Their views on the nature of assessment
- Their suggestions for the effective teaching of chemical kinetics.

3.2.3 Addressing the third research question

The third research question (RQ3) is concerned with the possible implications of the results for the effective teaching of chemical kinetics at school and university. Answers to the RQ3 were derived from an analysis of the whole data set with reference to the existing literature in science education.

Research question	Research instruments and data sources used to address the research aims/questions
1	• Documentation/Conceptual analysis of chemical kinetics (e.g. textbooks, curriculum materials, policy statements, students' notes, examination papers, teachers' written lesson plans) • Interviews with teachers/lecturers
2	• Written diagnostic questions (diagnostic tests) • Interviews with students • Interviews with teachers/lecturers
3	• Analysis of the whole data set

Table 3.1 The research instruments and data sources used for addressing the research aims/questions

3.3 DESIGN OF DIAGNOSTIC INSTRUMENTS FOR DATA COLLECTION

In this research, one focus of interest is upon the knowledge that adolescents and adult chemistry learners draw upon in explaining a range of key ideas, concepts and phenomena that are the subject of chemistry teaching at school and university. So as to probe students' conceptual understanding in chemical kinetics, a number of diagnostic questions were designed. The development of these diagnostic instruments had two phases. The first phase involved conceptual analysis of the domain in order to identify the key scientific ideas in chemical kinetics. This conceptual analysis and the key scientific ideas are discussed in Chapter 4 and Appendix 2. The second phase encompassed the development of the diagnostic questions and drew upon the key scientific ideas in chemical kinetics that had been identified. The next section addresses issues related to the development of diagnostic questions.

3.3.1 Approaches to probing conceptual understanding

The conceptual analysis of chemical kinetics proposed three *sub-domains* (see Chapter 4.1, for detail):

(1) Rates of chemical reactions and factors affecting them
(2) Particulate modelling to explain the nature of the rate of a reaction, and
(3) Mathematical modelling to represent or quantify the rate of a reaction.

A hierarchy between them was sketched on a concept map (see Figure 3.3) and "*Key Scientific Ideas in chemical kinetics*" were identified (see Section 4.1). As a result, appropriate probes were devised to provide opportunities for the key scientific ideas to be used. Since the study aims to allow subjects to respond to the probes in their own ways, using any terminology that they thought appropriate, the probes were designed, in an open-ended format. The probes were often intended to reflect the use of knowledge rather than merely possessing knowledge. The probes were designed to allow the investigation of students' ideas in different contexts; therefore any given idea was addressed through more than one probe (see Table 3.4). For instance, as shown in Table 3.4, students' ideas about the effect of temperature on reaction rates were addressed in two different probes: the "rusty water pipe probe" and the "nitrogen monoxide probe-C".

Driver and Erickson (1983, p.43) claimed that "students may develop conceptual structures as a result of instruction and other experiences which can be internally consistent and quite elaborate but they do not necessarily relate these to actual phenomena". For that reason, the probes targeted both students' scientific knowledge about the topic and how they apply this knowledge in a novel situation. Therefore, a combination of different types of probes (i.e. conceptually and phenomenologically framed probes) were developed and used in the study[1]. It was felt to be appropriate to use conceptually framed probes, because within the scope of chemical kinetics there are many different concepts and relationships, most of them of an abstract nature. The aim

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[1] For detail see Section 2.2 which is concerned with different approaches used to probing students' conceptual understanding of science and involves different perspectives on data analysis.

of those conceptually framed probes was to find out how well particular ideas that had been taught, had been understood by students. For example, students were asked to explain the concept of "reaction rate" or "activation energy". The reason for using phenomenologically framed probes was to explore which knowledge students use when given minimal contextual support within the probe and to find out how appropriately they use their scientific knowledge in the phenomena presented. These probes were mainly designed to assess students' ability to deploy chemical knowledge and understanding within a relevant context/phenomenon (using Driver and Erickson's (1983) term, students' *theories-in-action*). For instance, students were asked to explain "why the outside of the hot water pipe would rust more than the outside of the cold water pipe".

Since a small number of studies have been carried out in this field, it was not possible to use previously designed diagnostic questions. As a result, the researcher designed most of the probes in the diagnostic tests. The probes were designed to cover the key scientific ideas identified from the conceptual analysis of the domain. The context of the probes was confined to the chemical kinetics taught at upper secondary school to reduce the possible effects of students' unfamiliarity with context on their reasoning. The same diagnostic tests were conducted on school and undergraduate students. By using the same probes, it is possible to compare students' explanations across different educational levels. These probes were also used as interview questions for students. This would help to interpret students' written responses.

In the diagnostic tests, each probe was given a name rather than a number to help give a user-friendly and non-threatening style (Barker & Millar, 1999). Probe names are used throughout this thesis. Moreover, the attention was given on the context and language used upon the probes. The content validity of the probes was judged throughout the first and second pilot studies by discussion with Turkish chemistry teachers and lecturers (see Sections 3.4 and 3.5).

Having given a brief outline of the diagnostic tests, I now give a more detailed account for the purpose of each probe so that reasons behind designing and structuring them can become clear. The features of the probes are mentioned below (see also Table 3.4). Some probes worked reasonably well (at the pilot/main studies); the following section does not therefore include details of the issues which arose during the pilot and main studies for such probes. All students in the first pilot study were allowed to complete the diagnostic test in one session. However, the results showed that the time given to complete the diagnostic test was too short, and all of the probes were considered too much for one session (see Section 3.5, for detail). Therefore, it was decided to divide the diagnostic test into two parts. In the second pilot study and in the main study two diagnostic tests were used.

3.3.2 The written probes (see Appendices 3a and 3b)

3.3.2.1 The Diagnostic Test-1

THE REACTION RATE PROBE:

The probe consisted of two parts, one of which asked students to define the notion of reaction rate and the other part asked how the rate of a reaction changes during reaction time. The aims of this probe were to investigate how students understand and model reaction rate and to investigate their knowledge about the relationships between reaction rate, and the concentration of reactants and time.

THE RUSTY WATER PIPE PROBE:

This probe was adopted from the study by Andersson (1986) about students' understanding of chemical reactions. However, the probe was modified for the purpose of the study. The probe aimed to elicit students' understanding of the effect of temperature on reaction rates. It asked respondents to explain why the outside of the hot water pipe would rust more than the outside of the cold water pipe. The probe required students to describe the relationships between temperature and reaction rate. This probe was piloted in two formats: with a number of given statements about chemical kinetics and without statements. These two formats of the probe can be seen in Table 3.2. In the alternative format, students were given a number of statements relating to some aspects of kinetic-molecular theory and collision theory. In responding to the probe, they had to select the appropriate ideas and relate them to the given situation. Because students found the alternative probe (the one with statements) quite easy and almost all of the students correctly related it with one or more of the given statements, (in the light of the pilot study results) it was decided to use the probe without statements in the main study. That would allow me to find out how appropriately the students deploy their scientific knowledge in a relevant phenomenon, when minimal contextual support is given in the task. This format of the probe was framed in phenomenological terms, focusing observation and discussion on the phenomenon of rusting.

Rusty water pipe:	**Rusty water pipe (The alternative probe):**
When a house was newly built both the hot and the cold water pipes in the kitchen were shiny. After a while, the **outside of these pipes** had become dull and rusty (covered with a thin, brown coating). The outside of the hot water pipe was more rusty than the outside of the cold water pipe. Explain why the **outside** of the hot water pipe was **more rusty** than the **outside** of the cold water pipe. Please give as much detail as you can! …………………………………………………………… …………………………………………………………… …………………………………………………………… …………………………………………………………… …………………………………………………………… …………………………………………………………… …………………………………………………………… …………………………………………………………… ……………………………………………………………	**After many experiments, scientists now think that:** • *all things are made of small particles* • *these particles move in all directions* • *they move faster at higher temperatures* • *these particles collide with each other* • *they need a minimum energy for reaction* • *iron rusts due to a reaction between iron, water and oxygen.* Use any of these ideas to answer the following question: When a house was newly built both the hot and the cold water pipes in the kitchen were shiny. After a while, the **outside of these pipes** had become dull and rusty (covered with a thin, brown coating). The outside of the hot water pipe was more rusty than the outside of the cold water pipe. Explain why the **outside** of the hot water pipe was **more rusty** than the **outside** of the cold water pipe. Please give as much detail as you can! …………………………………………………………… ……………………………………………………………

***Table 3.2** Two different versions of the rusty water pipe probe (used in the pilot study)*

THE NITROGEN MONOXIDE PROBE:

The nitrogen monoxide probe presented students with a graph; they had to assess how the data support the scientists' conclusion about the reaction order. The probe was slightly modified after the pilot study. In the pilot study, the reaction was presented as follows:

$$2NO_{(g)} \xrightarrow{Pt} N_{2\,(g)} + O_{2\,(g)}$$

However, during the administration of the diagnostic tests, many students wanted to know whether the reaction was an endothermic or an exothermic reaction. Thus, it was judged appropriate to give this information in the probe:

$$2NO_{(g)} \xrightarrow{Pt} N_{2\,(g)} + O_{2\,(g)} \quad \Delta H<0 \text{ (Exothermic)}$$

However, it should be pointed out that this change may affect students' responses. This issue is discussed in Sections 6.2 and 9.1.3. It should be emphasised that although the given reaction is a reversible reaction, the reaction is represented as a one-way reaction and it is assumed that the reaction proceeds to completion. This decision is taken to confine the context of the probe in chemical kinetics rather than extending it to the notion of chemical equilibrium.

The nitrogen monoxide probe included four sub-questions, one of which was designed for exploring students' knowledge about reaction order. Other sub-questions (the nitrogen monoxide probe-B, C and D) asked how an increase in the initial concentration of NO, temperature, or the amount of solid catalyst would affect the rate of the given reaction.

THE REACTION RATE-TIME PROBE:

The purpose of the probe was to find out to what extent students know and understand the relationship between the rate of a reaction and reactant concentration. The probe presented students with experimental data; they had to assess the data and find out how the reaction rate changes with time. They were asked to describe both textually and graphically, how the reaction rate changes during time. The purpose of this probe was the same as the "Reaction rate probe-B"; however the context of the probe was different. The difference was that in the reaction rate probe-B students were asked about the relationship between reaction rate and time in a word-format rather than given experimental data.

THE REACTION MECHANISMS PROBE:

This probe was designed for probing students' understanding of reaction mechanisms and the rate determining step. It was a conceptually framed probe that presented the students with data which they had to assess and from which they had to deduce a possible reaction mechanism.

3.3.2.2 The Diagnostic Test-2

THE MAGNESIUM OXIDE PROBE:

This probe aimed to explore students' understanding of the relationship between reactant surface area and reaction rate for a heterogeneous reaction. It required students to explain whether granulated MgO or powdered MgO reacts with hydrochloric acid faster and to give reasons for their answers. The probe was set in a school science context.

THE VESSEL PROBE:

The vessel probe, a conceptually framed probe, was mainly designed for eliciting students' understanding of the effect of pressure on gaseous reactions. A reaction was set up in two closed containers under two different set of initial conditions and students were asked to explain in which set of conditions the reaction would occur faster. They were also asked to justify their answers by persuading the student(s) its correctness.

THE DE-SCALER PROBE:

This was designed to elicit students' understanding of the effect of concentration on reaction rate. The probe was set in an everyday context and aimed to find out how students interpret the relationships between the concentration of reactants and reaction rate. The purpose of this probe was the same as the "nitrogen monoxide probe-B"; however the context of the probe was different.

THE ACTIVATION ENERGY PROBE:

The probe aimed to explore how students understand and model activation energy and relate it to reaction rates. It was a conceptually framed probe.

THE CATALYSIS PROBE:

This was designed for exploring students' ideas about the effect of catalysts on reaction rates, the yield of products, activation energy and mechanisms of the reaction. It was a conceptually framed probe.

THE ENTHALPY PROBE:

The diagnostic test used for the pilot studies did not include this probe, which was adopted from the study by Sozbilir (2001) about students' understanding of key chemical ideas in thermodynamics. However, the probe was modified for the purpose of the study (see Table 3.3). The probe was aimed at eliciting students' understanding of the concept of activation energy and enthalpy. It was a conceptually framed probe and asked students whether they could compare rates of these two chemical reactions by using the variables presented.

The Enthalpy Probe:

Consider these two reactions, occurring at the same temperature;

Reaction 1: $C_{(g)} + P_{(g)} \longrightarrow B_{(g)}$ $\Delta H < 0$ (Exothermic)

Reaction 2: $G_{(g)} + V_{(g)} \longrightarrow Q_{(g)}$ $\Delta H > 0$ (Endothermic)

On the basis of this information some students are comparing the rates of these two reactions.

Serap says: "Reaction 1 is faster, because exothermic reactions occur faster than endothermic reactions"
Mine says: "The rates of these reactions are the same, because they occur at the same temperature"
Burcu disagrees: "No, it is not possible to compare the rates of these reactions, because there is not enough information given in the question"
The students are having some problems!
Answer the question below to help the girls to understand!
a) What is your opinion about the rates of these two reactions? Please explain your answer as fully as you can!

....
....
....
....

Two Hypothetical Reactions (by Sozbilir (2001))

The chemical equations given below represent two hypothetical reactions. The two reactions occur at the same temperature.

Reaction 1: $A + B \longrightarrow C + D$ Exothermic

Reaction 2: $E + F \longrightarrow G + H$ Endothermic

a) On the basis of this information, can you compare the rate of these two reactions? If so how? Explain your answer as carefully as you can.

b) What do you think about the spontaneity of these two reactions? Explain your answer as carefully as you can.

Table 3.3 The enthalpy probe (adopted from the study by Sozbilir (2001))

It should be underlined that students' ideas about each of the key scientific ideas were explored in more than one probe. However, as shown in Table 3.4, some of the probes were dominated by particular key ideas. The reason is that some ideas such as theories of kinetics (e.g. the collision or transition-state theory/model) are fundamental ideas in kinetics, and therefore they potentially would arise in students' responses to many probes, whereas others such as the notion of reaction mechanisms and the rate determining step are less central; therefore it would only arise in students' responses if I specifically create a probe.

3.4 TRANSLATION OF THE PROBES

When the probes had been developed, they were translated into Turkish. The Turkish and English versions of the diagnostic tests were given to one school chemistry teacher and three university chemistry lecturers whose English was advanced, (1) to ensure the accuracy of the translation and (2) to check the content validity of the probes against the curriculum. After their comments, the Turkish version of the diagnostic tests was modified. Once considered suitable for presentation to students, the diagnostic tests were administered to a small number of students (the first pilot study).

The sub-domains of the study	**The Key Scientific Ideas in Chemical Kinetics**	**Probes**										
		Diagnostic Test-1					**Diagnostic Test-2**					
		Reaction rate	**Rusty water pipe**	**Nitrogen monoxide**	**Reaction rate -Time**	**Reaction mechanisms**	**Magnesium Oxide**	**Vessel**	**De-scaler**	**Activation energy**	**Catalysis**	**Enthalpy**
Factors affecting the rates of chemical reactions	Surface area of solid reactants or a solid catalyst			+			+					
	Concentrations or pressure of reactants	+		+	+			+	+			
	Temperature at which the reaction occurs		+	+								
	Catalyst			+							+	
	Definition of reaction rate	+										
Particulate Modelling	Collision Model	+	+	+	+		+	+	+			
	Activation energy									+	+	+
	Transition-state Model		+	+							+	
	Reaction mechanisms and the rate-determining step					+					+	
Mathematical Modelling	Rate equation (Rate law)			+	+							
	Rate constant / Arrhenius equation		+	+								
	Reaction order	+		+								
Design of the probes	*Based on previously reported work*		+									+
	Designed	+		+	+	+	+	+	+	+	+	

Notes: After the pilot study, one more probe, the enthalpy probe, was added to the diagnostic tests.

***Table 3.4** The features of the probes designed for data collection*

3.5 PILOTING THE RESEARCH INSTRUMENTS

Piloting of the research instruments has several functions, principally to increase the reliability, validity and practicality of the research instruments (Cohen *et al.*, 2000). The purpose of the pilot study is to determine whether the contexts of the probes are familiar to students and to obtain some assessment of the validity and reliability of the data to be collected. The purpose of the pilot study is mostly:

- to check the clarity of the research instruments;
- to finalise the wording of the probes and avoid ambiguities;

- to find out how long the research instruments take to administer;
- to check out the practicality and feasibility of the data collection instruments;
- to assess ease of scoring and interpreting replies.

In addition to these purposes, drawing upon data gathered from the pilot study, methods and strategies for data analysis would be developed as precisely as possible before the main study.

As pointed out earlier, due to the small number of empirical studies in this field, it was not possible to use previously designed diagnostic questions. This means that many probes had not been tested before; therefore, piloting the research instruments was crucially important for this study. Thus, two pilot studies were carried out in order to test the designed research instruments.

Each probe was first reviewed by the two supervisors of the researcher, who commented on its suitability with regard to content, format and language. In addition, before the first pilot study one Turkish secondary school chemistry teacher served as judge on the content validity of the probes against the curriculum. In fact, the probes were piloted on 20 students; the further piloting conducted on 95 students both in secondary school and university in Turkey (see Table 3.5, for detail). This led to modification to the probes in response to confusions and problems identified.

During the pilot studies, the content, layout, structure and wording of the probes were also discussed with chemistry teachers and lecturers in Turkey. In the light of the pilot studies, any required modifications were made in the probes. It was also intended that a few interviews would be conducted with students and teachers during the pilot study to improve the researcher's interviewing skills. Moreover, a number of interviews were carried out with teachers and lecturers, in order to develop a schedule of appropriate interview questions and to foster a suitable interview technique, as well as to develop and refine suitable prompts which could be used in the main study.

Administration of the diagnostic tests (Pilot study)

The diagnostic test was piloted in Turkey in June 2002 (the first pilot study). The test was administered by one of my colleagues to 11 secondary school students (Grade 10), 2 university first year and 2 university third year students. Moreover, another colleague also administered the test to 5 first year university students. In other words, the sample was chosen in one secondary school and two different universities. When the first pilot study was conducted, chemical kinetics had been taught both in secondary school and university courses. All students in the first pilot study were allowed 60 minutes to complete the diagnostic test, which consisted of ten probes. The first pilot study provided some useful insights. The first insight was that the time given to complete the diagnostic test was too short, and ten probes were considered too much for one session. Hence, it was decided to divide it into two parts; each part contains five probes. These two diagnostic tests were piloted in October/November 2002. For the pilot study, two classes (n=23+27=50) in secondary school, one class in university second year (n=23) and one class in university fourth year (n=22) were selected. When the pilot study was conducted, the actual sample (Grade 10, university first and third year students) had not been taught chemical kinetics, therefore the research instruments were piloted on students who had been taught chemical kinetics in the previous academic year (Grade 11, university second and fourth year students). The number of students who took part in the pilot study is given in Table 3.5. The students were given 45 minutes to complete each diagnostic test. Secondary school students completed the second diagnostic test in a different day, however, undergraduate students were asked to complete a second test after 15 minutes break.

		For diagnostic tests sample		***For interview sample***
Level	***Age***	***First pilot study***	***Second pilot study***	***Pilot study***
Grade 9	*14-15*			
Grade 10	*15-16*	11		
Grade 11	*16-17*		23+27	3
Uni 1st year*	*17+*	5+2		
Uni 2nd year	*18+*		23	3
Uni 3rd year	*19+*	2		
Uni 4th year	*20+*		22	2
Uni 5th year	*21+*			
TOTAL		***20***	***95***	***8***

*Notes: * Uni: University (pre-service chemistry teacher-training program). The students interviewed were a subset of students who had provided written answers to the diagnostic tests.*

Table 3.5 The sample size for the pilot studies

Administration of interviews (Pilot study)

After the administration of the diagnostic tests, a surface analysis of responses had been done and possible interviewees were selected (3 secondary, 3 university first year and 2 university third year students). The class teacher/lecturer was contacted to make appointments for interviews with students. Interviews took place on a one-to-one basis, usually in a laboratory or an empty classroom and students' permission to tape-record the interview was sought in each case. Interview times varied between half an hour and 45 minutes. At the beginning of each interview, students were given a brief explanation of the aims of the interview. For instance, the interviewee was told that I would ask him/her to elaborate on what (s)he had already written on the diagnostic tests. The interviewee was assured that his/her responses would be kept confidential. The interviewee was also asked to express his/her views (if he/she needed to do so) by writing down (e.g. formulae, or drawings).

Since the aim of the pilot study was to ascertain the suitability and the understandability of the probes, after each interview the interviewee was encouraged to comment on the probes and how they could be improved. All the comments made by the interviewees had been assessed and a decision was made as to the probes inclusion in the final form of the diagnostic tests. During the pilot studies, the content, layout, structure and wording of the probes were also discussed with the chemistry teachers and lecturers in the participating institutions.

Moreover, one secondary school chemistry teacher and one university lecturer who had taught chemical kinetics unit were interviewed. To give them some time about their answers, the general agenda for the interview was given to them a few days before the day fixed for interviews. The interviews were carried out in an empty lab or an office and lasted between half an hour and 45 minutes. Interviews were audio tape-recorded with their permissions. Drawing upon the results, the interview schedule was improved and modified before the main study.

3.6 MAIN STUDY

The aim of this section is to provide information about the participants and the procedures followed in the main study.

3.6.1 Sampling

There are two main methods of sampling: a probability (also known as a random sampling) and a non-probability sampling (also known as a purposive sampling or opportunity sampling) (Cohen *et al.*, 2000). It is difficult for an individual researcher working on a small-scale project to achieve a true random sample (Bell, 1999). In this study, a purposive sampling strategy was used to select schools/universities and students. However, efforts were made to select as representative a sample as possible. This kind of sampling is generally acceptable as long as the make-up of the sample is clearly stated and the limitations of such data are realised (Bell, 1999).

All school students who participated in this study majored in mathematics and science. As mentioned earlier, chemical kinetics is first taught in secondary school (Grade 10), then university first and third year in pre-service chemistry teacher-training program. The rationale for choosing Grade 10, university first year and university third year students is to provide information on how their understandings of chemical kinetics improve in relation to relevant teaching at school and university. Overall sample size and details of samples for diagnostic tests are shown in Table 3.6.

School students were selected from two different schools in a town, located in northern Turkey. Schools/classes were selected to represent a mixture of socioeconomic areas (i.e. low to middle income areas, different school facilities) and to cover different students' profile (i.e. different students' performances: lower-medium-higher ability). Both schools were mixed upper secondary schools. The study was conducted during spring semester of the school year. All 108 students took the diagnostic tests at the conclusion of about four-week unit on chemical kinetics (3 chemistry lessons per week, each lesson takes 45 minutes). They used the same textbook; *Kimya: Lise 2 (Chemistry: Lycee 2)* by Kizildag & Dursun (2000). Facilities (science labs, computer labs, library, etc.) in School-1 were better than in School-2. Although the students in two classes in School-1 (around 30-35 students in each class) did experiments on chemical kinetics, the students in School-2 did not do any experiments on the concept due to lack of resources and overcrowded classes (more than 50 students in a classroom). As regards to the sample, students in Class-A, in School-1 had followed the same syllabus, but they were, from an academic point of view, much brighter. After primary school, these students were chosen in terms of their grades obtained from primary school (overall grade must be at least 4 out of 5) in order to enrol into a "special upper secondary school" (in Turkish: "super lise"). Students in special upper secondary schools have to take one-year English language course before the first year of upper secondary school. Therefore, when the main study conducted, students in Class-A, in School-1 were around 16-17-year-old.

The university, situated in western Turkey, was identified as being typical of university in Turkey. On the basis of the Student Selection Examination (ÖSS) results, it is about an average university (ÖSYM, 2002). Some constraints (e.g. time, budget, difficulties in travelling) did not allow collecting data from many schools and universities.

A sub-sample of the students who had provided written answers to the diagnostic tests was also interviewed. This sub-sample was selected to represent diversity in responses to the written probes. The rationale for this selection is discussed in Section 3.6.3.

Level	***Age***	***Sample size for the diagnostic tests***	***Sample size for individual interviews***
Grade 9	*14-15*		
Grade 10	*15-16*	27+33+48=108	2+4+4=10
Grade 11	*16-17*		
Uni 1st year*	*17+*	48	7
Uni 2nd year	*18+*		
Uni 3rd year	*19+*	35	7
Uni 4th year	*20+*		
Uni 5th year	*21+*		
TOTAL		***191***	***24***

*Notes: * Uni: University (pre-service chemistry teacher-training program).*
The students interviewed were a subset of students who had provided written answers to the diagnostic tests. Moreover, 3 school teachers and 2 university lecturers who had taught the chemical kinetics unit in the participating institutions were interviewed.

***Table 3.6** The sample size for the main study*

3.6.2 Administration of the diagnostic tests

Data were collected from school students in April 2003 and from undergraduates in May 2003. Data were collected 5-6 weeks after secondary school students had been taught chemical kinetics; data were collected immediately after formal classroom teaching for university students. Before the study, the research project was introduced by the researcher and students were assured that their responses would be kept confidential and their responses would not be used for any formal assessment. Silence was formally requested while students completed the diagnostic tests. Each diagnostic test was designed to take approximately 45-50 minutes to complete, and could thus be administered in one lesson. Secondary school students completed the second diagnostic test in a different day, however, undergraduate students were asked to complete a second test after 10-15 minutes break.

3.6.3 Administration of interviews

Interviews with students (Semi-structured interviews)

Student interviews were used to check for appropriate interpretation of the written responses and to probe students' understanding in more depth. Whilst, some probes were conceptually and others were phenomenologically framed, the interview technique used in this study included both interviews about concepts and interviews about instances (White & Gunstone, 1992).

After the diagnostic tests were completed, a surface analysis of responses had been done and possible interviewees were identified. A sub-sample of the students (10 SS, 7 UF and 7 UT)[2] was selected for individual interviews. In other words, 12.5% of the sample was interviewed. This sub-sample was chosen to represent diversity in responses to the written probes. For example, in the case of the "reaction rate-time probe", one UF was selected from those who wrote that "the reaction rate increases as the reaction progresses", another UF was selected from those who argued that "the reaction rate is constant as the reaction progresses", and another one was selected from those who stated that "the reaction rate decreases". The main consideration was to ensure the coverage of the all probes and to select as representative a sub-sample as possible. Other factors affecting selection included students' perceived willingness to talk freely about their ideas. For that case the teacher's help was sought.

The class teacher/lecturer was contacted to make appointments for interviews with students. Interviews took place on a one-to-one basis, usually in a laboratory or an empty classroom and students' permission to tape-record the interview was sought in

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[2] SS refers to secondary school students and UF and UT refer to university first year and university third year students respectively.

each case. When necessary to clarify any ambiguities, students were asked to elaborate on their responses until a clear understanding of the student's point of view was obtained. However, if students were not able to explain their thought in detail then they were not pressured. The interviews lasted between 30 and 45 minutes.

Interviews with the teachers and lecturers (Semi-structured interviews)

In order to determine their views on the issues for effective teaching and learning chemical kinetics, three school teachers and two university lecturers who had taught the chemical kinetics unit in the participating institutions were interviewed. The interviews were semi-structured and aimed at determining their personal experiences on teaching chemical kinetic, experiences on their students' learning difficulties in this field, and possible solutions to such difficulties. To give them some time about their answers, the general agenda for the interview was given to them a few days before the day fixed for interviews. The interviews were carried out in an empty lab or an office and lasted around half an hour. Interviews were audio tape-recorded with their permissions. Teacher/lecturer interview schedule can be seen in Appendix 4. It should be noted that during interviews a number of stimulus materials (e.g. chemistry topics written on cards, concepts in chemical kinetics written on cards or examination questions) was used. However, teachers/lecturers were reluctant to talk about the chemistry topics written on cards, or concepts in kinetics written on cards. They stated that they have taught (or will teach) chemical kinetics with the same structure identified in the curriculum/textbooks.

3.7 DATA ANALYSIS

This section describes how the coding schemes are developed and how analysis of the data is carried out. The advantages and disadvantages of the coding schemes applied are discussed along with the reasons why different coding schemes are developed and used.

The probes used in this study range from conceptually framed to phenomenologically framed. In parallel with this, analysis of students' explanations in chemical kinetics range from nomothetic to ideographic ways of data analysis (Section 2.3.2). In order to evaluate the effectiveness of the curriculum in meeting its aims in the area of chemical kinetics, conceptually framed probes were designed to probe students' understanding of kinetic concepts. In order to find out how successful students were in answering these probes, and to find out how their performances change from school to university, a nomothetic data analysis was carried out. That would allow me to determine the incidence of particular concepts and significance of any changes between different educational levels. So as to find out the nature of students' explanations and the nature of students' difficulties, an ideographic data analysis was carried out. It was considered that would supplement and extend the nomothetic analysis.

However, the results from these conceptually framed probes do not give insights into how robust the students' conceptions are and how far they can deploy them distantly from school science context. In order to investigate that phenomenologically framed probes (i.e. a phenomenon or an event is presented to students rather than the concepts used in science to explain the phenomenon) were used. Finding out whether students use these ideas properly, as required by the curriculum, a nomothetic data analysis was necessary, however exploring the nature of their explanations and the nature of their difficulties, an ideographic data analysis was crucially important. That is why a combination of different types of probes and coding schemes were developed and used in order to address the research aim and questions.

In this study, two different coding schemes were used: the *coding scheme-A* and the *coding scheme-B*. The rationale for using two coding schemes is discussed in the following sub-sections. Figure 3.1 illustrates the basic organisation of the data analysis. In a broader sense analysis of students' explanations of phenomena concerned with chemical kinetics is more ideographic comparing with analysis of their explanations of concepts with regard to chemical kinetics topic. In other words, phenemenologically framed probes were analysed in an ideographic way by using the coding scheme-A, yet conceptually framed probes were analysed nomothetically by using the coding scheme-B. However, irrespective of the types of probes, the probes testing the same ideas were analysed by using the same coding scheme (the coding scheme-A) in order to compare students' explanations across these probes. This issue is discussed in Section 3.7.3.

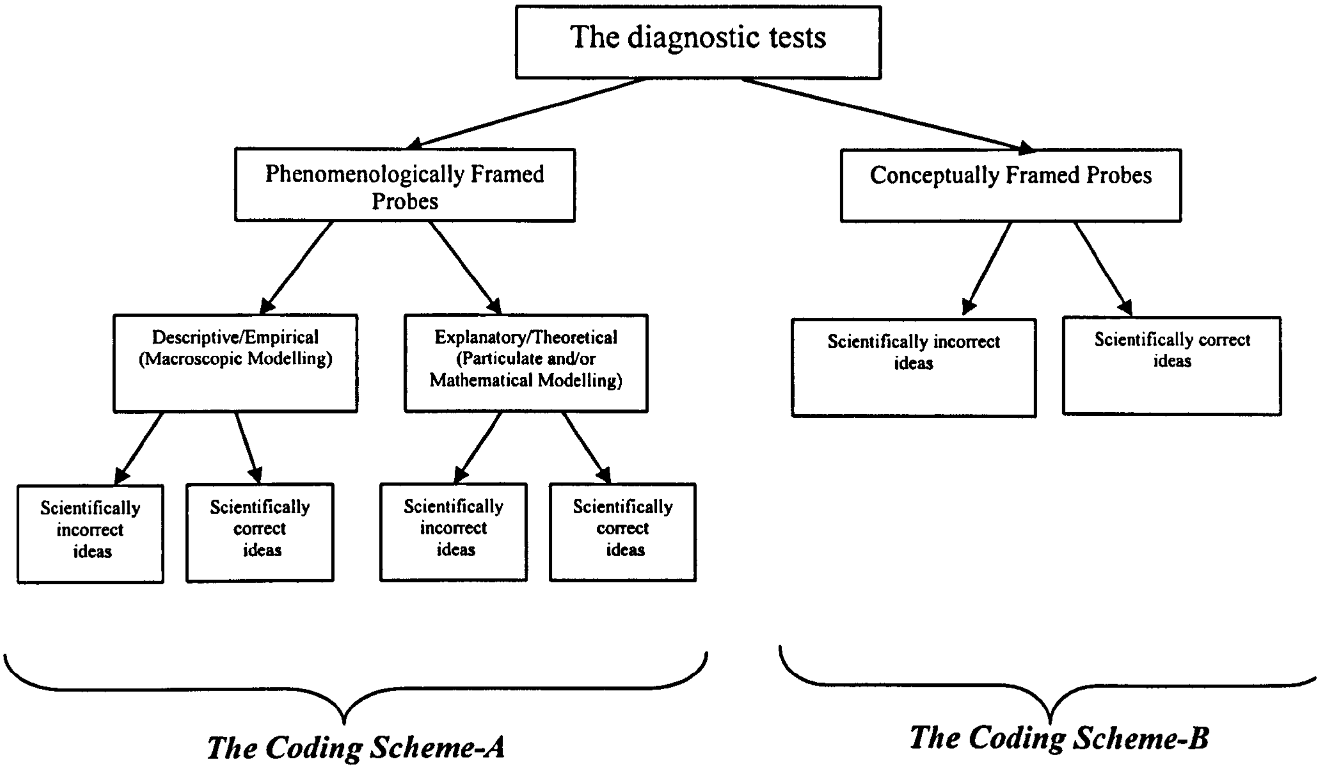

Figure 3.1 Conceptual framework for data analysis

3.7.1 The Coding Scheme-A

With respect to data analysis, when the research instruments were piloted opportunities to determine and develop an initial structure of analysis of data were gained. In order to analyse data it is necessary to follow some logical sequence: generating categories, organising and interpreting them, validating them, and finally exploring how the responses may be interpreted in terms of the categories. The first stage of analysis involved the development of a coding scheme for each probe. This was achieved by reviewing students' responses in interviews and on written probes, and by identifying common ideas and ways of explanation. The coding scheme was thus developed from students' responses rather than being based, for example, on normative science. Firstly, students' responses to the probe were read through and a note was made of frequently recurring responses. Then, coding categories were generated from such responses. These codes were re-applied to the data in the sample, and changes and modifications were made as appropriate. Eventually, the set of main coding categories were used for coding the whole sample. Three main categories of responses were identified and used in the reporting of results. These are:

(1) Descriptive/Empirical (Macroscopic Modelling),
(2) Explanatory/Theoretical (Particulate and/or Mathematical Modelling),
(3) All other responses (see Figure 3.2 and Section 4.1.1).

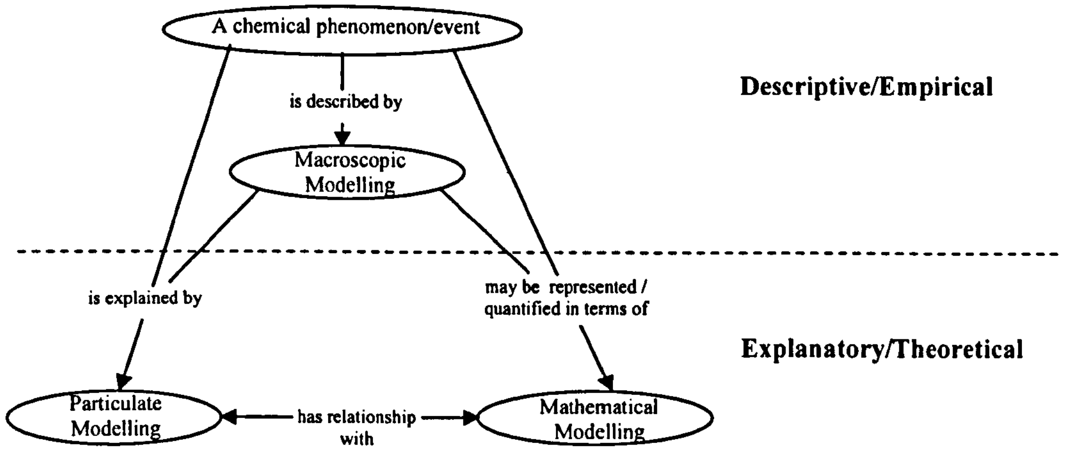

Figure 3.2 The relationship between chemical phenomena/events and theories/models (A framework for analysing students' explanations of chemical kinetics) (adapted from Logan, 1984; Johnstone, 1991; Tiberghien, 2000)

The category, termed *Descriptive/Empirical (Macroscopic modelling),* is descriptive in nature. This phrase refers to knowledge of what happens; interpreting the phenomenon in terms of what might be perceived (i.e. at a macroscopic, phenomenological level) but not referring to unseen entities and processes –such as interaction of particles/ molecules/ ions– or underlying mechanisms to account for the phenomenon. In some cases, students' responses are expressed mainly using everyday language or they include tautological restatements of available information in the task.

In order to clarify the coding scheme, it is worth illustrating it on a probe called the "rusty water pipe probe" (see Table 3.7). In the case of the rusty water pipe probe, responses in this category are based on explanations, which identify one or more key causal variables without any reference to underlying mechanism, or the explanation involves prototypical examples of everyday phenomena. These variables are observable or taken for granted. For example, heat and/or hot water was seen as a key factor for the phenomenon. As one of the school students put it "*The hot water pipe was destroyed by heat*". For this student, the structure of the pipe was changed or modified by the heat; however she did not mention a reaction between iron and oxygen/water. Here, the subject considers the form of cause and effect relationship; heat was seen as a key factor acting in rusting. In some cases, students had a preference for prototypical examples of everyday phenomena or metaphors; for instance, they considered rusting as something like decay. Here is an example:

> *Heat results in rust. Temperature destroys the structure of some substances. That is why we keep our foods in the fridge. Foods spoil very easily when left out at room temperature.* [Sa-D-15]

At this point it may be helpful to provide more detail about the meaning of some terms. For instance, the category, termed *Descriptive/Empirical (Macroscopic modelling)* does include statements/generalisations which some may call theoretical. However I am using the term *Descriptive/Empirical (Macroscopic modelling)* in this sense if responses do not involve an underlying mechanism and do not include some form of theoretical model or causal mechanism to account for the claim/statement. For instance, when a student argues: "*A rise in temperature increases reaction rate*", or "*Heat increases reaction rates*", I propose that these statements are "descriptive/empirical" (as discussed above) in that they do not involve a proposed mechanism for explaining the claim/statement. Scientific explanations are based on generalisations (laws) and theoretical models (theories) both of which share a common feature: they make claims which go beyond descriptive or empirical accounts of the phenomenon (Driver *et al.*, 1996). It is important to note that many laws (generalisations) are underpinned by theoretical models, however, from students' written responses, it would not be possible to judge whether the generalisation made is based on a theoretical model or it is just a tautological restatements of available information in the task. An example of such an explanation is:

> *The hot water pipe is warmer. Whilst, heat increases the reaction rate,* it [the hot water pipe] *rusts more quickly.* [Sb-D-26]

Data from interviews were used to find out what kind of justifications the students had used for their claims (see Section 3.7.3). Interviews with students revealed that in many cases students did not provide a theoretical model to justify their claims/generalisations. Again responses of this kind were placed in the *Descriptive/ Empirical (Macroscopic modelling)* category.

The category, termed *Explanatory/Theoretical (Particulate and/or Mathematical Modelling*[3]*)*, incorporates responses in which students use some form of theoretical

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[3] In this thesis, I will term these two modelling (Particulate and Mathematical Modelling) as Theoretical Modelling.

model or causal mechanism to account for the phenomenon/event. The causal mechanism proposed might involve a chain of events between variables or the evocation of formally defined theoretical constituents in chemistry. Explanation goes beyond the phenomenon by drawing upon theoretical entities that are not observable or directly measurable in the phenomenon itself. This category includes two subcategories: particulate modelling and mathematical modelling (which are forms of mental models expressed by an individual through speech or writing).

The subcategory termed *particulate modelling* incorporates those responses in which students use corpuscular models such as interaction of particles/ ions/ atoms/ molecules, or use the principles of the collision or transition-state model in their reasoning. The emphasis is on the microscopic processes taking place during the reaction and the relationships of such processes to the macroscopic behaviour of the reaction. For example, when a respondent says that:

> *Rusting is an oxidation reaction...The reaction rate increases with the rise of temperature...An increase in temperature increases the speed of molecules and also increases the kinetic energy of molecules. That increases the amount of substances overcome the activation energy barriers.* [UT-D-21]

From this excerpt, the respondent's explanation goes beyond descriptive accounts of the phenomenon by drawing upon theoretical entities within established chemical ideas. The respondent makes transformations from the phenomenological level of chemistry (i.e. observable changes in substances) to the sub-microscopic level, which explains changes in terms of the interactions between individual atoms, ions, and molecules.

The other subcategory, termed *mathematical modelling* is allocated to cases where justification involves algebra, diagrams, mathematical formulae or equations (e.g. $2Fe_{(s)} + O_{2\ (g)} \rightarrow 2FeO_{(s)}$). Mathematical modelling consists of physical properties (e.g. concentration, temperature) and mathematical functions represented in the form of an equation (e.g. reaction rate=k. $[A]^{m}$). Graphs can also be used to present equation relationships (e.g. the Maxwell-Boltzmann energy distribution). As an illustration, the student quoted below justified her answer based on mathematical formulae (i.e. the Arrhenius equation):

> *...In terms of the rate equation, reaction rate depends on rate constant which is a temperature dependent constant. The value of rate constant increases as temperature increases.* $k = A\,.e^{-Ea/RT}$ [UT-D-35]

Whilst, macroscopic modelling makes few claims about the nature of systems and has little predictive and explanatory power, particulate and mathematical modelling allow phenomena to be explained, quantified and predicted.

These two theoretical approaches ((a) particulate modelling and (b) mathematical modelling) are consistent with Johnstone's (1991) distinction between (a) sub-microscopic and (b) symbolic levels. However, there might be differences between what I mean by macroscopic modelling and what Johnstone considers as a macroscopic level. This category (Explanatory/Theoretical) is also similar to Tiberghien's (2000, p.29) description of the world of theories and models. However, the category, termed Descriptive/Empirical might be different from her description of the world of objects/events (that refers to all observable aspects of the material worlds) in that as discussed earlier, the Descriptive/Empirical category (macroscopic modelling) is not necessarily purely descriptive or observable; it may also include statements/ generalisations (e.g. "heat increases reaction rate" or "temperature increases reaction rate") which Johnstone and Tiberghien may call theoretical.

The category, termed *All other responses,* is allocated for incomprehensible responses or in cases where there is no response given in any part of the probe. In some cases, the total number of "subcategories" may exceed the total number of the participants, because some responses included characteristics of more than one subcategory; therefore they were coded into different subcategories. For example, if a student used particulate and mathematical modelling at the same time, it was coded twice.

This ideographic data analysis was followed by a nomothetic data analysis in order to find out to what extent students achieved a correct answer. Three digits were used for the coding scheme to code the responses. The first digit identifies the general groups, the second one identifies whether the response includes scientifically correct ideas ('1') or scientifically incorrect ideas ('2') and the third digit identifies the sub-categories. Students' answers to the probes were entered into SPSS (Statistical Package for Social Sciences) and analysed accordingly. An example of the outcome of an analysis is shown in Table 3.7.

Code	Category (Nature of response)	Example of response	SS *f* *(%)* (n=108)	UF *f* *(%)* (n=48)	UT *f* *(%)* (n=35)
1	**Descriptive/Empirical (Macroscopic Modelling)**		**57** ***52.8%***	**9** ***18.8%***	**3** ***8.6%***
1-1-1	Hot water/Heat as a key factor	Hot water destroys/tarnishes/wears out/ hazards/corrodes the water pipe.	9 8.3%	0	0
1-2-2	Cold as a key factor	For example, at underground, steel/iron gets rustier more quickly, because underground is cold. Therefore, the cold water pipe gets rustier than the hot water pipe	2 *1.9%*	*0*	*0*
1-2-3	Water vapour/moisture as a key factor	There would be more moisture/humid/water vapour on the hot water pipe; therefore it gets rustier than the cold water pipe. Temperature changes/differences makes more moisture on the hot water pipe.	17 *15.7%*	2 *4.1%*	1 *2.8%*
1-2-4	Explanation in terms of other macroscopic variables	Due to a higher temperature, the pipe expands and contracts that makes rust. Higher pressure inside of the hot water pipe results in more rust. When we stop to use hot water, the pipe suddenly gets colder and after a while when we start to use hot water, the pipe gets hotter again. Thus, that temperature change results in rust.	13 *12%*	1 *2%*	*0*
1-1-5	A rise in temperature increases reaction rate	A rise in temperature increases reaction rate. Heat increases the reaction rate	18 *16.7%*	6 *12.5%*	3 *8.6%*
2	**Explanatory/Theoretical (Particulate and/or Mathematical Modelling)**		**37** ***34.3%***	**35** ***72.9%***	**31** ***88.6%***
2-2-6	A rise in temperature increases the rate of endothermic reactions.	Oxidation/rusting is an endothermic reaction. Endothermic reactions occur faster at a higher temperature. $2Fe+O_2 + \text{Energy} \rightarrow 2FeO$ Oxidation/Rusting is an endothermic reaction, which needs energy to occur. Therefore, the hot water pipe gets rustier than the cold water pipe.	2 *1.9%*	8 *16.7%*	2 *5.7%*
2-2-7	Rust is formed inside of the pipe (misunderstood the question)	The solubility of gases increases/decreases with an increase in temperature. In the hot water (H_2O), H_3O^{+}, OH^{-}, O^{-2} ions moves more freely; therefore iron easily forms a compound with those [ions].	9 *8.3%*	3 *6.3%*	3 *8.6%*
2-1-8	Reasoning based on mathematical formulation	Explanation in terms of a rate equation and/or Arrhenius equation: In terms of the rate equation, reaction rate depends on rate constant which is a temperature dependent constant. The value of rate constant increases as temperature increases. $k = A.e^{-Ea/RT}$	4 *3.7%*	0	3 *8.6%*
2-1-9	A rise in temperature increases the rate of rusting/oxidation.	Iron reacts with oxygen faster at a higher temperature. $2Fe+O_2 \rightarrow 2FeO$ Iron reacts with water faster at a higher temperature. $2Fe+3H_2O \rightarrow Fe_2O_3 +3H_2$	16 *14.8%*	23 *48%*	14 *40%*
2-1-10	Explanation in terms of theories of kinetics (e.g. the collision and/or transition state model)	At higher temperature, molecules move faster. A rise in temperature increases the speed of molecules and increases the kinetic energy of molecules. The greater proportion of molecules will now have the activation energy for the reaction & so have sufficient energy when they collide.	6 *5.6%*	2 *4.2%*	11 *31.4%*
0	**All other responses**		**14** ***12.9%***	**4** ***8.3%***	**1** ***2.8%***
0-0-11	No answer		5 *4.7%*	2 *4.2%*	0
	Incomprehensible/Other		9 *8.3%*	2 *4.2%*	1 *2.9%*
TOTAL, f			**108** ***100%***	**48** ***100%***	**35** ***100%***

Notes: n= number of participants; f=frequency; %= percentage of participants.

In some cases, responses included characteristics of more than one subcategory; therefore they were coded into different subcategories. For example, if a student used particulate and mathematical modelling at the same time, it was coded twice (but it was coded only once in the Explanatory/Theoretical category). Therefore, the total number of "subcategories" may exceed the total number of the participants.

Table 3.7 A coding scheme for the "Rusty water pipe" probe

The developed coding scheme was applied to the other probes. After application of the coding scheme-A to the probes, it emerged that it would be more appropriate to use a different coding scheme for the conceptually framed probes. In order to clarify the reasons for this choice, it is worthwhile applying the coding scheme-A to a conceptually framed probe, for example to the "activation energy probe". An example of the outcome of such analysis is shown in Table 3.8. As Table 3.8 shows that none of the responses was placed in the *Descriptive/ Empirical (Macroscopic modelling)* category. Indeed, this result is not surprising, because the probe is conceptually framed and cueing was given, in that case the scientific concepts were introduced in the probe. Accordingly, students are more likely to respond to the probe by drawing upon scientific concepts and ideas (appropriately or inappropriately). It is therefore decided little to be gained by using coding scheme-A to the conceptually framed probes. Thus, a different coding scheme (termed the coding scheme-B) was developed for those probes.

The coding scheme-A was used for analysing five probes: the "De-scaler probe", the "vessel probe", the "rusty water pipe probe", the "nitrogen monoxide probe-C", and the "magnesium oxide probe".

Code	Category (Nature of response)	Example of response	SS *f* (n=108)	UF *f* (n=48)	UT *f* (n=35)
1	**Descriptive/Empirical (Macroscopic Modelling)**		**0**	**0**	**0**
2	**Explanatory/Theoretical (Particulate and/or Mathematical Modelling)**		**95** ***88%***	**44** ***91.7%***	**34** ***97.2%***
2-2-1	Activation energy is the kinetic energy of reactant molecules.	Activation energy is the kinetic energy of reactant molecules. Thus the second reaction occurs faster than the first one.	17 *15.7%*	4 *8.3%*	0
2-2-2	Activation energy is the kinetic energy of product molecules	Activation energy is the kinetic energy of product molecules. As a result the reaction with the higher activation energy occurs faster	3 *2.7%*	0	0
2-2-3	Activation energy is the [total] amount of energy released in a reaction	Activation energy is the energy released after a reaction. The second reaction is faster, because more energy is released. The faster a reaction, the more energy is released.	23 *21.3%*	5 *10.4%*	0
2-2-4	Activation energy is the maximum energy level in a reaction	Activation energy is the maximum energy state that substances can achieve.	12 *11.1%*	0	0
2-2-5	Responses including accepted ideas about activation energy but using those ideas inappropriately in the given situation.	Activation energy is a certain amount of energy that reactant substances must have to result in a reaction. ...There isn't any information about the concentrations; therefore we can't compare the reaction rates. Ea is the energy required for a reaction to occur. It can't be known how that [Ea] affects the reaction rate.	9 *8.3%*	3 *6.3%*	2 *5.7%*
2-1-6	Activation energy is the minimum energy required for the reaction to occur	Activation energy is the energy barrier that reactant particles must have to overcome for a reaction. Therefore the reaction with the lower activation energy occurs faster.	31 *28.7%*	32 *66.7%*	32 *91.4%*
0	**All other responses**		**13** ***12%***	**4** ***8.3%***	**1** ***2.8%***
0-0-7	No response		0	0	0
	Incomprehensible/Other		13 *12%*	4 *8.3%*	1 *2.8%*
		TOTAL, f	**108**	**48**	**35**

Notes: n = number of participants; f = frequency; % = percentage of participants. Percentages are shown in italics

***Table 3.8** Application of the coding scheme-A to the "Activation energy" probe*

3.7.2 The Coding Scheme-B

Conceptually framed probes involve eliciting students' knowledge about a concept or a scientific term, for example asking students what is understood about particular scientific concepts such as "rate of reaction", or "activation energy". The aim of those conceptually framed probes was to find out how well particular ideas that have been taught, have been understood by students. Therefore, it would be more appropriate first to evaluate the data against a set of normative criteria. Conceptually framed probes were analysed nomothetically and three main categories of responses were identified and used in the reporting results. These main categories are:

(1) Responses including mainly scientifically incorrect ideas about the topic,
(2) Responses including mainly scientifically accepted ideas about the topic,
(3) All other responses.

As mentioned earlier, in order to explore the nature of students' explanations and difficulties, an ideographic data analysis was needed. Therefore, this nomothetic data analysis (i.e. scientifically incorrect ideas and scientifically correct ideas) was followed by an ideographic data analysis (see, for example, responses in the codes 1-2-1 and 1-2-3 in Table 3.9). The coding scheme-B was applied on seven probes: the "reaction rate probe-A and B", the "activation energy probe", the "enthalpy probe", the "reaction rate-time probe", the "reaction mechanism probe", the "nitrogen monoxide probe-A-B-D" and the "catalysis probe". The students' responses to the activation energy probe are illustrated in Table 3.9 as an example for this coding scheme[4].

Code	Category (Nature of response)	Example of response	SS *f* (n=108)	UF *f* (n=48)	UT *f* (n=35)
1	**Responses including mainly scientifically incorrect ideas about the concept of activation energy**		**64** ***59%***	**12** ***25%***	**2** ***5.7%***
1-2-1	Activation energy is the kinetic energy of reactant molecules.	Activation energy is the kinetic energy of reactant molecules. Thus the second reaction occurs faster than the first one.	17 *15.7%*	4 *8.3%*	0
1-2-2	Activation energy is the kinetic energy of product molecules	Activation energy is the kinetic energy of product molecules. As a result the reaction with the higher activation energy occurs faster	3 *2.7%*	0	0
1-2-3	Activation energy is the [total] amount of energy released in a reaction	Activation energy is the energy released after a reaction. The second reaction is faster, because more energy is released. The faster a reaction, the more energy is released.	23 *21.3%*	5 *10.4%*	0
1-2-4	Activation energy is the maximum energy level in a reaction	Activation energy is the maximum energy state that substances can achieve.	12 *11.1%*	0	0
1-2-5	Responses including accepted ideas about activation energy but using those ideas inappropriately in the given situation.	Activation energy is a certain amount of energy that reactant substances must have to result in a reaction. ...There isn't any information about the concentrations; therefore we can't compare the reaction rates. Ea is the energy required for a reaction to occur. It can't be known how that [Ea] affects the reaction rate.	9 *8.3%*	3 *6.3%*	2 *5.7%*
2	**Responses including accepted ideas about activation energy and using those ideas appropriately in the given situation**		**31** ***28.7%***	**32** ***66.7%***	**32** ***91.4%***

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[4] Three digits were used for the coding scheme to code the responses. The first digit identifies the general groups, the second one identifies whether the response includes scientifically correct ideas ('1') or scientifically incorrect ideas ('2') and the third digit identifies the sub-categories.

2-1-6	Activation energy is the minimum energy required for the reaction to occur	Activation energy is the energy barrier that reactant particles must have to overcome for a reaction. Therefore the reaction with the lower activation energy occurs faster.	31 *28.7%*	32 *66.7%*	32 *91.4%*
0	**All other responses**		**13** ***12%***	**4** ***8.3%***	**1** ***2.8%***
0-0-7	No response		0	0	0
	Incomprehensible/Other		13 *12%*	4 *8.3%*	1 *2.8%*
		TOTAL, f	**108** **100%**	**48** **100%**	**35** **100%**

Notes: n = number of participants; f = frequency; % = percentage of participants. Percentages are shown in italics

Table 3.9 *A coding scheme for the "Activation energy" probe*

3.7.3 Analysis of interview data

The main aims of interviews were to obtain further information regarding students' ideas about chemical kinetics and to check for appropriate interpretation of the written responses. Most of the tape recorded interviews with students were transcribed into written form. These data were used to support the diagnostic tests data. Data also gave insight into how confident students were when responding to the probes.

In order to discover teachers' perceptions with regard to teaching and learning chemical kinetics, the interview was used as a research method. All the tape-recorded interviews were transcribed into written form. Data were qualitatively analysed: their perceptions on teaching and learning chemical kinetics were categorised by comparing the similarities and differences (see also Section 4.2).

In the text, the quotations taken from students' written responses and the transcripts were identified with the codes such as "Sa-D-13" or "UF-I-15". The code of each respondent/interviewee is placed at the end of each excerpt in brackets […]. In this code, first two letters 'Sa', 'Sb' and 'Sc' strand for secondary school students and 'UF' and 'UT' strand for university first year and university third year students respectively. The third letter 'D' and 'I' indicate the Diagnostic tests responses and Interview responses respectively and the number shows the student's number. The comments between brackets […] in the excerpts taken from the written responses and the interview transcripts aim to make the excerpts easier to understand. They are not the words of the students/interviewees. (…) in the excerpts indicates that transcript or written responses continues at a later point in a discussion or in the written response. This notation system will be used in the next chapters.

3.7.4 Disadvantages of using different coding schemes

One of the disadvantages of using different coding scheme is that it would be difficult to cross-tabulate students' responses across the probes to explore the consistency of students' ideas. However, avoiding that problem the probes testing the same idea were analysed by using the same coding scheme. For instance, the "rusty water pipe probe" (a phenomenologically framed probe) and the "nitrogen monoxide probe-C" (a conceptually framed probe) were designed to test the same ideas. Therefore, the same coding scheme (the coding scheme-A) was used for both probes in order to compare the students' explanations across these two tasks. In those cases, the reason for applying the coding scheme-A to the probes is that, as can be seen in Figure 3.1, the coding scheme-A is more ideographic and also includes the features of the coding scheme-B. Therefore, it enables me not only to compare which knowledge students use when they respond to the probes (descriptive/ empirical vs. theoretical/ explanatory), but also to assess their knowledge against the established scientific view (scientifically correct ideas vs. scientifically incorrect ideas).

3.8 VALIDITY AND RELIABILITY

Kirk and Miller (1986) describe the notions of objectivity, reliability and validity in the following way: "objectivity is the simultaneous realization of as much reliability and validity as possible. Reliability is the degree to which the finding is independent of accidental circumstance of the research, the validity is the degree to which the finding is interpreted in a correct way" (p.20). In order to ensure the validity and reliability in the research, piloting research instruments is essential. The pilot studies helped to find an accurate research instrument for achieving the research aim. During such studies a few Turkish chemistry teachers and lecturers checked the content validity of the probes against the curriculum.

The reliability of data analysis was examined in terms of the degree of consistency among different coders (i.e. inter coder reliability). In order to check reliability, a 10% sample responses (this sample was randomly selected) to two probes (a conceptually and a phenomenologically framed probes) was coded by two independent coders[5] and over 90% reliability was achieved. One main issue arose from this coding process. The

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[5] The second coder was a Turkish Ph.D. student in mathematics education.

second coder coded one of the student's response (to the rusty water pipe probe) which included a general statement ("...temperature increases rusting") to the explanatory/theoretical category (2-1-9). However, it was agreed that since the response does not include an underlying mechanism and do not include some form of theoretical model to account for the statement, it was coded in the descriptive/ empirical category (1-1-5).

3.9 SUMMARY

This chapter has considered the research design and methods used to collect data. It has also described how the research instruments were formulated and revised through the pilot studies and how data were analysed. The next chapter deals with conceptual analysis of chemical kinetics and teachers/lecturers' views on teaching and learning chemical kinetics.

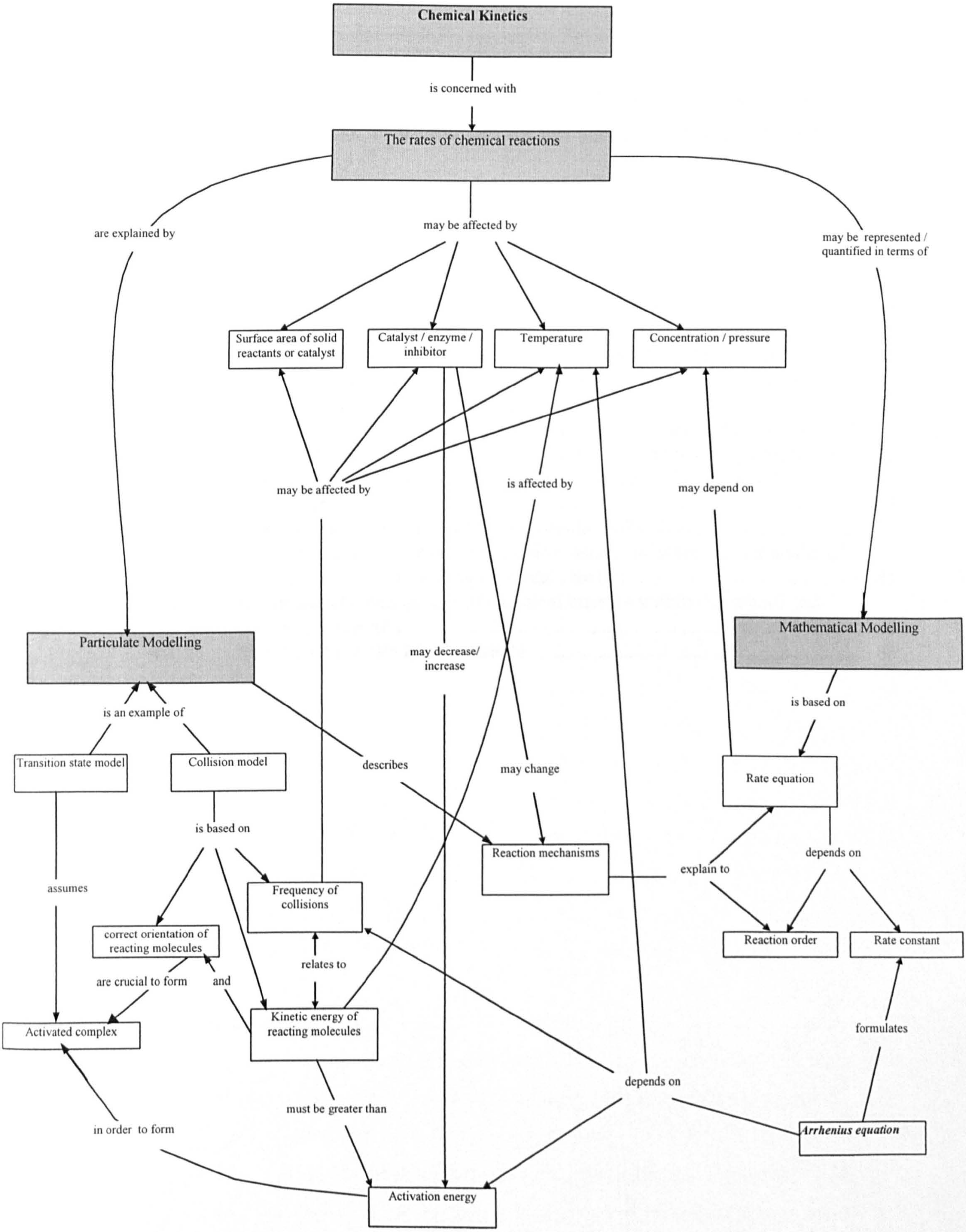

Figure 3.3 A concept map for chemical kinetics

CHAPTER 4

CONCEPTUAL ANALYSIS OF CHEMICAL KINETICS AND TEACHERS/LECTURERS' VIEWS ON TEACHING THE CONCEPT

CHAPTER 4

CONCEPTUAL ANALYSIS OF CHEMICAL KINETICS AND TEACHERS/LECTURERS' VIEWS ON TEACHING THE CONCEPT

4.0 INTRODUCTION

This study aims to evaluate secondary school and undergraduate students' conceptual understandings of chemical kinetics in the light of the aims of the Turkish chemistry curriculum. In order to address this aim, it is necessary (1) to analyse content structure of chemical kinetics and (2) to identify scientific knowledge taught at school and university. As discussed in Section 2.1.1 (page 10-11), it is important to analyse the content of chemical kinetics both in terms of current scientific understandings, and the curriculum content and structure. This conceptual analysis was used to identify the domain of interest of the study, and to design diagnostic instruments in order to probe students' understanding of the domain.

This chapter is structured into two sections. The first section describes how this conceptual analysis was carried out and how decisions were made on which aspects of chemical kinetics to investigate. The second section presents the data gathered from interviews with teachers and lecturers. It specifically concerns with teachers' views on the learning difficulties which students experience in chemical kinetics and possible solutions proposed by them to these difficulties.

4.1 APPROACH USED FOR CONCEPTUAL ANALYSIS

Conceptual analysis included identifying the key scientific ideas of the domain and exploring the extent to which the curriculum takes into account these key ideas. The approach used to carry out the conceptual analysis included the following steps:

- (i) Content analysis of chemical kinetics
- (ii) Identification of the key scientific ideas in chemical kinetics
- (iii) Analysis of the content area of chemical kinetics taught at school and university, and identification of the teaching objectives

(iii) Discussions with colleagues, teachers and lecturers about the validity of the conceptual analysis.

4.1.1 Content analysis of chemical kinetics

As reported in the literature review chapter (see Section 2.4, p.26), based on a conceptual analysis of chemical kinetics, Logan (1984) made a distinction between empirical and theoretical aspects of the domain[1]. The empirical aspect of chemical kinetics refers to the observable or experimentally accessible aspects of the chemical phenomena, whereas the theoretical aspect refers to theoretical models and theoretical entities within established chemical ideas. In view of that, the content structure of the domain suggests that it is premised on the idea that the rates of chemical reactions can be explained by a qualitative approach (Particulate Modelling) and may also be understood in terms of a quantitative approach (Mathematical Modelling): these two approaches are interconnected in some levels. The relationship between chemical phenomena and theories/models is shown in Figure 4.1. The aspects of Figures 4.1 and 3.3 were taken into consideration during content analysis of chemistry textbooks. For instance, at university level, the main emphasis of chemical kinetics courses seems to focus on the quantitative aspect of the subject.

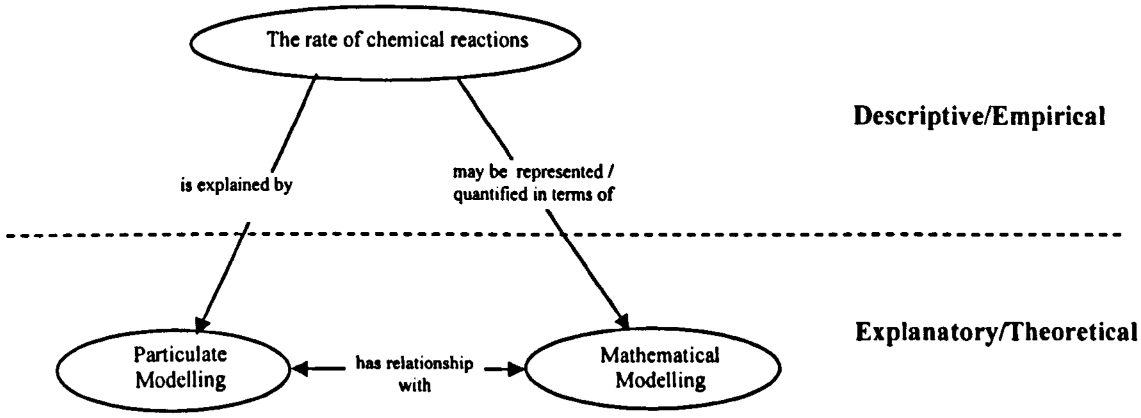

Figure 4.1 The relationship between chemical phenomena and theories/models (adapted from Logan, 1984; Johnstone, 1991; Tiberghien, 2000)

The content structure of chemical kinetics proposed a division into two sub-domains: (1) Descriptive/ Empirical (Macroscopic Modelling), and (2) Explanatory/ Theoretical

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[1] Tiberghien's (2000) distinction between the world of objects/events and the world of theories/models is similar to the Logan's distinction between empirical and theoretical aspects of a domain.

(Particulate and/or Mathematical Modelling). The first, at the macroscopic level, is the study of rates of reactions, e.g. what factors affect the rate of a reaction. The second sub-domain looks at the particulate and the mathematical levels. Here, the concern is with reaction mechanisms, the detailed pathways taken by atoms and molecules as a reaction proceeds and the notion of rate laws. These two sub-domains constitute the domain of chemical kinetics under which the field is conceptualised. By considering those, a hierarchy between them was sketched on a concept map (see Figure 4.1). Based on analyses of (i) the leading textbooks (i.e. school and university chemistry textbooks), (ii) the previous research on the content area, (iii) the school science curriculum, and (iv) analysis of the researcher's own knowledge about chemistry, a concept map for chemical kinetics was produced (see Figure 3.3) and key scientific ideas in chemical kinetics were identified (see Section 4.1.2 and Appendix 2). These analyses aimed at organising the key scientific ideas of the content and their relationships with each other. In addition, this concept map was used as a basis for identifying the main areas in the investigation. Figure 3.3 shows a structure of the domain, which constitute the main body of chemical kinetics. It was intended that the concept map would be useful in revealing and portraying gaps in students' understanding of chemical kinetics.

The content of the teaching materials was analysed in terms of the concept map. The assumption was to depict the nature of the scientific knowledge presented in the curriculum, and to identify the missing links between different concepts and form of representation. In order to achieve a full scientific understanding, students need to have some understanding of several modes of modelling. However, this is not often reflected in the curriculum. For instance, when I analysed chemistry textbooks with the help of Figures 3.2 and 3.3, in some areas of the domain there were such large gaps in the presentation that the students appear to have little possibility of understanding the relationships between different modes of representations without additional input from teachers. Emerging issues from content analysis of textbooks and students' notes was reported in the following chapters (e.g. see Sections 6.3 and 8.3)

In this study, students' understanding of chemical kinetics was investigated based on two sub-domains, each sub-divided into several sub-sections. These are:

(1) Descriptive/Empirical (Macroscopic Modelling)

The rate of any given reaction may be affected by the following factors:

(i) Concentrations or pressure of reactants
(ii) Temperature at which the reaction occurs or light of a particular wavelength
(iii) Surface area of solid reactants or a solid catalyst
(iv) Catalyst/enzyme/inhibitor

(2) Explanatory/Theoretical (Particulate and/or Mathematical Modelling)

It ought to be underlined that particulate modelling and mathematical modelling are not mutually exclusive, these two levels of modelling are closely interconnected in some levels and there is a strong link between them (see the concept map, in Figure 3.3).

Particulate Modelling
(i) Collision Model
(ii) Activation energy
(iii) Transition-state Model
(iv) Reaction mechanisms and the rate-determining step

Mathematical Modelling
(i) Rate equation (Rate laws)
(ii) Rate constant / Arrhenius equation
(iii) Reaction order

4.1.2 Identification of key scientific ideas which constitute the domain

In order to achieve a scientific understanding of the nature of a reaction system, students need to have some fundamental ideas in chemical kinetics. Consequently, twelve "key scientific ideas"[2] have been identified based on the conceptual analysis of chemical kinetics. They and their relations are described below.

1. ***Reaction rate:*** Reaction rate can be defined as the change in concentration of a particular reactant or product per unit of time. The rate of a reaction is commonly employed in three different forms: the average rate of reaction, the instantaneous rate of reaction, and the initial rate of reaction. The rate of a chemical reaction

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[2] These twelve scientific ideas will be termed the '*Key Scientific Ideas*' of the study.

may be affected by surface area of solid reactants, concentration of reactants (or pressure of gases), temperature (or light), and catalysts.

2. ***Concentrations or pressure of reactants:*** Increasing the concentrations of reactants increases the chance of collisions between reactant molecules. The concentration of a gas increases with its partial pressure. So, the rate of gaseous reactions can be increased by increasing the partial pressure of reactants. Increasing the concentration of a reactant normally causes an increase in the rate of a reaction; however, this is not the case for zero order reactions in which reaction rate is independent of the concentrations of reactants.
3. ***Temperature at which the reaction occurs:*** Increasing the temperature of a reaction mixture increases the kinetic energy of particles, which causes more collisions between particles per unit of time. Increasing temperature usually increases the rate of a reaction whether the reaction is exothermic or endothermic. Reaction rates increase with temperature because a higher temperature means a greater proportion of reactant molecules have enough energy to overcome the activation energy barrier per unit of time. A small increase in temperature may produce a large increase in the rate of a reaction, since there is a large increase in the proportion of molecules which possess the activation energy. For example, a small input of energy is usually required to initiate some reactions such as fuels and explosives which are exceedingly exothermic reactions.
4. ***Surface area of solid reactants or a solid catalyst:*** Where one of the reactants is a solid increasing the surface area of the solid increases the chance of interaction of reactant molecules. This increases the rate of reactions.
5. ***Catalysts:*** A catalyst is a substance that changes the rate of reactions without being used up after reaction. Catalysts do not affect the enthalpy change or equilibrium constant, though they affect the mechanism of the reaction. A catalyst lowers both the forward and reverse activation energies and it does not affect the yield of products. Enzymes are catalysts for many biological reactions.
6. ***Collision model*** describes reactions in terms of molecular collision. Collision between molecules does not always lead to reaction. For a collision to result in reaction the reactant molecules must be properly oriented and the colliding molecules must possess more than a certain minimum amount of energy called *activation energy*.

7. ***Activation energy:*** The minimum energy required to form an activated complex in a reaction.

8. ***Transition-state model:*** An important extension of collision model made by Henry Eyring focuses on the detail of a collision and the activated complex (Laidler & King, 1983). The transition-state model is concerned with what actually happens during a collision. It follows the energy and orientation of the reactant molecules as they collide and seeks an explanation of why such a small fraction of collisions results in reaction. The great contribution of this model, in respect to collision model, was not the provision of a more accurate calculus, but rather the establishment of a deeper relationship between thermodynamics and kinetics variables. The idea of the activated complex is the main core of this model, and this model is usually described in terms of an energy profile diagram in chemistry textbooks.

9. ***Reaction mechanisms and the rate-determining step:*** Most chemical reactions do not occur in one step but in several. The object of chemical kinetics is to understand the succession of steps that make up the mechanism of a chemical reaction at molecular level. The slow step of a reaction is the rate-determining step.

10. ***Rate equation (Rate law):*** The rate of a reaction can be described in terms of the disappearance of reactants and the formation of products in a unit of time. A rate law is an equation that relates the rate of a reaction to the concentrations of reactants and catalyst. The rate of a chemical reaction is expressed through an experimentally determined mathematical equation. Considering the hypothetical reaction below, this can be expressed for an elementary reaction:

    $$\mathrm{A} + 2\mathrm{B} \longrightarrow \mathrm{C}$$

    It could be written the rate equation in the form

    $$\text{Rate of reaction} = \text{k}.\ [\text{A}]^{m}.\ [\text{B}]^{n} = \frac{-d[A]}{dt} = \frac{-1}{2}\frac{d[B]}{dt} = \frac{d[C]}{dt}$$

    The exponents m and n must be determined experimentally and cannot be obtained simply by looking at the balanced equation.

11. ***Rate constant / Arrhenius equation:*** A rate constant is a proportionality constant that appears in the rate equation. The Arrhenius equation[3] explains the

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[3] The Arrhenius equation is presented to students at university level.

variations of rate constants for several elementary reactants using the relationship:

$k = A . e^{-Ea/RT}$

k: rate constant, A: pre-exponential factor, E_a: Activation energy, R: Universal gas constant, T: Temperature

12. ***Reaction order:*** The order of a reaction is the sum of concentration exponents in the rate equation, such as for the reaction above, the overall reaction order = m+n. The order of a reaction must be determined experimentally.

A series of written tasks involving concepts and phenomena in chemical kinetics were developed to probe students' understanding of each of these twelve key scientific ideas (see Chapter 3.3.2). It is expected that students should be able to grasp these key scientific ideas and their relationships with each other after completing their course in Grade 10 (see Appendix 2).

4.1.3 Analysis of the content area of chemical kinetics taught at school and university and identifying teaching objectives[4]

The concept of chemical kinetics is first taught to students in Grade 10 (ages 15-16) and further developed in the first year and third year of a five-year pre-service chemistry teacher-training course. The Turkish Education system and chemistry in the curriculum is summarised in Appendix 1. The course content of the participating schools and the university is also outlined in Appendix 1 (in section A1.2 and in Table A1.1)

The objectives of the course contents are broadly specified in the official documents. The Turkish chemistry curriculum specifies general teaching objectives for chemistry courses for each grade; however it does not include specific objectives for each topics, such as for chemical kinetics, or thermodynamics. The chemistry curriculum comprises only textbook-based syllabuses; there are no accompanied teacher guides or laboratory manuals. Since teaching objectives for the area of chemical kinetics were not specified, chemistry textbooks, and students' notes were analysed and teachers/lecturers were interviewed in order to specify the teaching objectives (see Appendix 2). That would

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[4] An objective of the curriculum may be defined as a statement of what students should gain as a result of learning and as an achievement which a student should be able to demonstrate.

allow me to evaluate students' understanding with respect to these objectives. Moreover, the purpose of the textbook analysis and students' notes was to explore the types of explanations (or representations) that have been provided in textbooks, and the ways in which the explanations are related to the scientific explanations. In addition, teachers and lecturers' written lesson plans were collected and analysed.

The results indicated that the school and university first year students follow the chemistry textbooks very closely, but that was not the case for university third year where the content and design of the course was determined by the lecturer. Therefore, university third year students' and the lecturer' notes were taken as a basis to identify teaching objectives for the university third year course. Appendix 2 shows the key scientific ideas and teaching objectives in the area of chemical kinetics at school and university levels.

4.1.4 Discussions with colleagues, teachers and lecturers about the validity of the conceptual analysis, the key scientific ideas and the teaching objectives

The scientific knowledge which is shared by the scientific community and by the educational system community would be different from each other in some levels. The types of explanations (or representations) that have been introduced in the curriculum may include simplifications of scientific explanations shared by scientific community. Since an existing curriculum is used as the basis for a conceptual analysis of the domain, the key scientific ideas identified and the conceptual analysis were discussed in detail with a lecturer in physical chemistry courses in order to determine whether aspects of the key scientific ideas were included correctly. In addition, during the pilot study and the main study, the concept map, the key scientific ideas and the teaching objectives identified were also discussed with secondary school teachers and chemistry lecturers who had taught the chemical kinetics unit in the participating institutions and accordingly appropriate modifications were made.

The next section discusses data gathered from interviews with teachers and lecturers and presents the findings emerged from these interviews. It is important to underline that the study is based mainly upon the written responses given by school and undergraduate students. Interviews with teachers/lecturers are used as a supplementary data. Therefore, it should be noted that interviews with teachers are part of the study, however relatively small part. That is an explanatory study, so that its findings are not intended to have the status of the main study.

4.2 ANALYSIS OF THE INTERVIEWS WITH TEACHERS AND LECTURERS

In order to determine their views and personal experiences on teaching chemical kinetics, three school teachers and two university lecturers who had taught chemical kinetics unit in the participating school/departments were interviewed. These semi-structured interviews (the interview schedule is presented in Appendix 4) were audio tape-recorded and transcribed into written form. Data gathered from these interviews were qualitatively analysed: their perceptions of students' learning difficulties were categorised by comparing the similarities and differences. Data were also used to explore their views on the sort of understanding they hope to instil in their students. In other words, the analysis of this data enabled me to identify the intended development of the subject within the school and university courses.

During interviews the sequence and structure of the chemistry curriculum were also discussed with teachers/lecturers. However, they were reluctant to talk about the sequence and the structure of chemical kinetics in the curriculum. They simply stated that they had taught and will teach chemical kinetics with the same structure identified in the curriculum/textbooks.

It should be noted that the lecturers who teach chemical kinetics to UF and UT were in different departments, one of which (L_1) was in the department of chemistry and the other (L_3) was in the department of education and there was a lack of co-ordination between them in terms of the design of course content.

4.2.1 Teachers/lecturers' views of their students' difficulties

The results of the discussion of teachers/lecturers' personal experience on their students' difficulties are reported below.

(i) Difficulties in interpreting visual representations

Visual representations (e.g. graphs and figures) play an important role in science teaching and learning. However, it is often reported that student have difficulties with interpreting these representations and grasping the underlying scientific knowledge expressed thought these visual models (e.g. Kozma, 2003). In the present study, two School Teachers (ST)[5] and one Lecturer (L_3) also argued that students had difficulties in interpreting graphs and failed to establish links between graph characteristics and theoretical models. As one of the lecturers put it:

> *I: ...Students have difficulties in interpreting the concentration vs. time graph. They can not see the slope of the concentration vs. time graph as the reaction rate.*
> R: What would be the reasons for that?
> *I: The reason would be lack of mathematical knowledge. Although, the relationships between the slope of the graph and the reaction rate were expressed during our teaching, it would be more helpful if chemistry content-related examples were practiced in their mathematics courses....Students' mathematical skills play an important role in comprehending kinetics. Students who lack the required mathematical knowledge, specifically the notion of rate of change, derivation and differentiation concepts, have difficulties in solving algorithmic problems in kinetics and I personally experienced that such students were unmotivated in chemical kinetics.* [L_3]

The lecturer argued that students' mathematical skills play an important role in comprehending chemical kinetics and on students' motivation. I agree the lecturer's suggestion (i.e. *...it would be more helpful if chemistry content-related examples were practiced in their mathematics courses*) has potential for improving students' understanding of mathematical aspects of chemical kinetics.

(ii) Memorising facts, concepts and formulae without conceptual understanding

Both teachers and lecturers argued that students memorise the concepts or mathematical formulae without understanding the ideas behind them. As one of the lecturers stated that:

> *They memorise the formulae; they know how to manipulate the data to solve the problems in terms of these formulae, whereas they have difficulties in interpreting a problem which requires them to explain the concepts underpinning the question.* [L_1]

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[5] ST_1, ST_2, and ST_3 refer to School Teachers and L_1, and L_3 refer to university first year and university third year Lecturers.
In the transcript, R and I stand for the researcher and the Interviewee respectively.

All of the teachers agreed that while the topic was not directly assessed in the Student Selection Examination (ÖSS), students were less motivated and less interested in chemical kinetics. As one of the teachers argues;

> *They memorise the definitions, concepts or mathematical equations in order to pass the exams. They memorise to pass their exams at school only.* [ST_2]

Consequently, assessment (ÖSS) has a powerful influence on what, and how, teachers teach chemistry at schools.

(iii) Lack of knowledge about the notion of catalysis at the sub-microscopic level

L_3 argued that his students had limited knowledge on the nature of the catalysis process. As he put it:

> *I: When we ask students how a catalyst affects on a reaction, they say that it lowers the activation energy of the reaction. However, when we ask how it does this, we could not get any response from them: they do not relate it with the mechanism of the reaction in some way; it remains mysterious to students.*
> **R**: What would be the reasons for students' lack of knowledge about the nature of catalysis?
> *I: I relate it to teaching at secondary school where the nature of the catalysis is taught in a simplistic way: students are taught that a catalyst lowers the activation energy without emphasising molecular aspects of the reaction. Accordingly, students are simply memorising this information. When they come to university, due to limited time and overloaded course content, it* [the concept of catalysis] *might have to be taught in a short period of time.* [L_3]

(iv) Lack of knowledge about the mechanism of decomposition reactions

L_3 stated that the students had difficulties in understanding the mechanism of decomposition reactions. He stated that the students can not imagine how a product is formed from an interaction or collision between the same kinds of molecules.

4.2.2 Teachers/lecturers' views on possible reasons and solutions for students' difficulties in understanding chemical kinetics

Teachers' and Lecturers' views on possible reasons and solutions for students' difficulties in understanding chemical kinetics were categorised as course-related, student-related and staff-related (after, Sozbilir, 2004).

(i) Course related

Textbooks and course content:

Although, school teachers and L_1 were satisfied by the chemistry textbooks, L_3 complained about the lack of resources and quality of textbooks written in Turkish. There are a limited number of physical chemistry textbooks. For example, though a translated version of physical chemistry textbook available (Atkins, 2001), only very few students had this book due to its cost. This leaves students and lectures in a disadvantaged position. As L_3 argued that:

> *Because of a lack of resources we can not give homework or research projects to students. When we do so, they come back to us for asking references. Since most of them lack foreign language skills, and there are limited resources available in Turkish, that makes the situation problematic.* [L_3]

All of the school teachers and lecturers tended to view syllabuses/textbooks as overloaded with content. Thus, students were inundated with too much information in a short period of time. There is some evidence to show that students are dissatisfied and unmotivated by overloaded course content (Sozbilir, 2004). Another issue raised by L_1 was that:

> *There are too many concepts to teach in a short period of time. ...It seems that at secondary school, students' engagement with the topic is varied. There is a big difference between different students' previous knowledge about the topic* [i.e. students' preconceptions]. *Accordingly, I need to teach the subject assuming that they had not been taught before* [at secondary school]. [L_1]

Due to overloaded course content, lecturers decided to cover a certain number of topics and leaving some others. For example, L_3 stated that "in some semester we need to teach the concept of chemical kinetics in a very short period of time or we do not teach the concept due to limited /insufficient time".

Practical work:

Data were collected in three classes from two different schools. Although students in two classes (around 30-35 students in each class) did experiments on chemical kinetics, students in the other school did not do experiments on the concept due to overcrowded class (more than 50 students in a classroom) and lack of resources. It is claimed that teachers in Turkish secondary schools usually prefer to teach chemistry with non-laboratory based instruction (Nakiboglu, 2003). As in any other developing country, because of inadequate laboratory facilities and the lack of financial resources, "chalk and talk" is the dominant teaching method. Due to overcrowded classes, demonstrations are common at schools. Consequently, it seems that the objectives of the curriculum in terms of practical work are highly constrained by the resources of schools and universities. As mentioned above two classes did experiments on chemical kinetics at the end of the course. The time devoted to the practical work was 3 hours. The school textbooks included five experiments on the factors affecting reaction rates; these are the nature of reactants, surface area of reactants, the temperature, the concentration of reactants and catalysts. Students were divided into groups of six or seven and each group designed one of the experiments in the textbook. In other words each group did only one experiment, however each group demonstrated their experiment to the students in other groups. The experiments were usually done at the end of the course, however one of the teachers stated that the following year students will do each experiment at the end of a particular concept. For example, the experiment about affect of temperature will be carried out after teaching the effect of temperature on reaction rates, rather than waiting until teaching all of the concepts in chemical kinetics. The reason for her decision was that she claimed that students were less motivated at the end of the topic. Another reason proposed was that it would be appropriate and easier to make links between the theoretical ideas and experiments.

Teachers and lecturers argued that classes with fewer students would provide a better laboratory environment for the students. As L_1 stated that:

> *At the university first year, classes are too crowded, that makes working in the laboratory so difficult. Students should start to do experiment by themselves in the first year that would prepare them for the next courses and that would give them confidence.* [L_1]

It is important to note that university first year and third year students did their experiments on chemical kinetics in a group of three or four students. The lecturer, as quoted above, urged that each student should do experiments by himself/herself. He also proposed that reducing the size of the classes might enhance students' learning, since different teaching methods could be applied, such as group work and group discussions.

Assessment:

All of the ST argued that since this subject was not assessed at the Student Selection Examination (ÖSS), students were less motivated and less interested in chemical kinetics. As emphasised earlier, the teachers argued that students simply memorise the definitions, concepts or mathematical equations in order to pass the exams instead of giving a good conceptual understanding. The teachers' claims are not surprising when I analysed the examination questions and questions in the textbooks which mainly test recalling facts about concepts, how to manipulate data to solve problems or students' mathematical skills. It seems that examination questions often centre on computational skills and recalling definitions rather than testing students' conceptual understanding. In other words, in some sense teachers do not test students' conceptual understandings, although they were aware of students' deficiencies in this area. Possibly there is no time and motivation to teach what is not in the textbooks and on the curriculum.

Secondary school students and undergraduates do not normally share similar goals or constraints. It seemed that when solving a question/problem, SS were more interested in achieving the correct answer in the problem rather than the reasoning behind it (why and how this has happened), possibly due to the assessment at the ÖSS or the assessment at school. For example, during administration of the diagnostic tests, the SS found the rusty water pipe probe (the probe required students to explain why the outside of the hot water pipe would rust more than the outside of the cold water pipe) a bit odd/different, because the answer (the answer seems obvious; because of higher temperature) was in the question, they were less interested in why and how these came about. It seems that assessment ends up driving the teaching: teachers want their students to succeed in an examination so they teach them how to answer the sorts of examination questions they are more likely to encounter at school or at the ÖSS. Indeed the interview with one of the school teacher indicated that not only students but also parents want teachers to design their teaching based on the ÖSS. Another reason for not using phenomenologically framed questions (both at school and university) would be that these questions can make it harder to assess students' level of understanding and it would take more time to score them.

(ii) Staff related

The chemistry textbook is the only guide for both students and school teachers. There were not teachers' guides, laboratory manuals or supplementary books for teachers, therefore teachers had responsibility for designing teaching and learning activities, and designing assessment questions. That makes inexperienced teachers anxious about teaching.

Both lecturers stated that because of shortage of lecturers, they have many hours of lessons including preparing teaching materials for the subject, grading papers and conduction research projects. As argued earlier, the lecturers who teach chemical kinetics to UF and UT were in different departments, and there was a lack of co-ordination between them in terms of the design of course content.

(iii) Students related

As argued earlier, teachers and lecturers stated that students tend to memorise the concepts and ideas without conceptualising them. Interview with teachers indicated that the topics not assessed in the ÖSS distracted students, and teachers had difficulties in motivating students on those topics. This may lead to underperformance among school students. Indeed chemical kinetics is one of the topics which is not directly assessed in the ÖSS. The teachers suggested that the structure of the ÖSS should be changed in that it should assess students' understanding of the all the topics taught at secondary school. In fact the exam only assesses their understanding of a small number of the chemistry topics taught at school. In parallel with this, the lecturer (L_1) also emphasised students' lack of knowledge about some chemistry topics. For instance, he argued that some students had limited knowledge of basic chemical kinetic ideas which are supposed to be learned at school. That makes a necessity for the lecturer to teach chemical kinetics at the very beginning, in other words assuming that the students have not taught the subject before. This may cause the lecturer not to cover other topics in the curriculum. Subsequently, the results revealed that both teachers and lecturers were not satisfied with the structure and nature of the ÖSS.

4.2.3 The intended development of chemical kinetics within the school and university curricula

As discussed earlier the objectives of the course contents are broadly specified in the official documents and in the teachers and lecturers' written lesson plans. Drawing upon the analysis of documentary evidence and analysis of the interviews with teachers/lecturers, the objectives of the school and university courses in the area of chemical kinetics were identified (see Appendix 2 and Table A1.1 in Appendix 1). From this analysis it emerges that the basic ideas and theories of chemical kinetics are introduced at school level. At school level these concepts are generally introduced at a qualitative level, but through university level the empirical framework of chemical kinetics (e.g. empirical techniques for measuring reaction rates) and the concepts which make up this empirical framework are introduced in more depth and explained mainly at a mathematical level. As Table A1.1 (in Appendix 1) shows the concepts which are introduced at school level have been developed at the university first year. The laboratory courses are given simultaneously with theoretical courses at the university first and third years. It is expected that students should be able to develop an understanding of the links between theoretical aspects of chemical kinetics and experiments. In other words, students are required to do experiments in their laboratory courses and expected to relate their theoretical ideas to empirical data. Nevertheless, an analysis of the university first year textbook shows that although students carried out an experiment on chemical kinetics in their laboratory course, the empirical framework of chemical kinetics is neglected in their theoretical course (e.g. see Mortimer, 1989). One of the main differences between school and university courses is that at school level, students are required to relate theoretical ideas to empirical data (mostly in classroom settings), however at university level students are given more opportunities to analyse empirical data which the students have gathered from experiments on chemical kinetics in their laboratory courses.

4.3 SUMMARY AND DISCUSSION

This chapter has presented a conceptual analysis of chemical kinetics and discussed data gathered from interviews with teachers and lecturers. Based on this conceptual analysis key scientific ideas in chemical kinetics were identified and the objectives of the curriculum were determined.

Chemical kinetics is repeatedly taught over a number of years within a variety of chemistry courses. However, particularly at university level, due to limited time and overloaded course content teachers/lecturers had problems in completing the course content. It is assumed that students have gained basic kinetic ideas at school; however the lecturer's (L_1) experience shows that this is not the case. As he argued "*... students' engagement with the topic is varied. There is a big difference between different students' previous knowledge about the topic* [i.e. students' preconceptions]. *Accordingly, I need to teach the subject assuming that they had not been taught before* [at secondary school]". Therefore, diversity of university first year students' engagement with the topic and their preconceptions about chemical kinetics should be acknowledged during design of the university curriculum. It seems that specifically at university level, there is a mismatch between the intended curriculum and teaching. Thus, it appears that there is a need for a carefully examination of the school and university curriculum and matching the curriculum to the needs of students. In particular, the co-ordination between the school and university curriculum needs more attention.

When teachers and lecturers were asked to express their students' learning difficulties and possible solution of these difficulties, the SS and L_1 did not give many specific learning difficulties. Rather they focused on more general difficulties the students came across, such as memorising concepts without understanding the underlying ideas behind them. However, L_3 gave more specific cases for students' learning difficulties, for example he said that "students had difficulties in interpreting the concentration vs. time graph", "students had limited knowledge on the nature of the catalysis process", "students had difficulties in understanding the mechanism of decomposition reactions". This might be due to his competence of pedagogical (content) knowledge. When I examined teachers and lecturers background information, it appeared that school teachers had their first degree in a chemistry education department, L_1 is a Professor in Biochemistry department and L_3 had a PhD in chemistry education. L_3 were more likely to aware of students' learning difficulties and more likely to reflect on his teaching. However, it was apparent that all of the teachers and lecturers mostly related students' lack of understanding in chemical kinetics to external factors, for example relating it to lack of resources or to the structure of the Student Selection Examination (ÖSS).

CHAPTER 5

STUDENTS' UNDERSTANDING OF THE REACTION RATE AND ITS RELATIONSHIPS WITH THE CONCENTRATIONS OR PRESSURE OF REACTANTS/PRODUCTS

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5.0 INTRODUCTION

This is the first of five chapters presenting the data gathered from diagnostic tests and interviews with students. The chapter presents students' responses concerning the reaction rate and its relationships with the concentrations or pressure of reactants/ products. Students' ideas about the relationships between reaction rates and concentration or pressure were elicited throughout their responses on five probes. The *Reaction rate probe*, the *Reaction rate-Time probe*, and the *Nitrogen Monoxide probe-B*[1] were conceptually framed and nomothetically analysed (see Section 3.7). The *De-scaler*, and the *Vessel* probes were more phenomenologically framed and ideographically analysed (see Section 3.7). The design of the probes and their relationships to the key scientific ideas in chemical kinetics is outlined in Section 3.3. As discussed in Sections 3.3.1 and 3.7, using a combination of different types of probes testing mainly the same ideas allowed me to investigate students' ideas in different contexts.

It should be noted that the reaction rate probe-B and the reaction rate-time probes asked students how reaction rate changes with time during a reaction, whereas the others asked how a change in the initial concentrations or pressure of reactants would affect reaction rates. The reaction rate probe-B and the reaction rate-time probes were designed to test the same idea which was how the rate of a reaction changes as the reaction progresses. Therefore, students' responses to these probes were cross-tabulated in order to explore how they use their knowledge in different probes (see Section 5.3). That also allowed me to explore the consistency of students' explanations across different educational levels.

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[1] Students' responses to the nitrogen monoxide probe-B are discussed in Chapter 9 (in Section 9.1.3).

Students' responses to each probe are discussed separately. This chapter also addresses emerging issues from the analysis of documentary evidence in terms of the notion of reaction rate and its relationships with the concentrations or pressure of reactants (see Section 5.6).

5.1 THE REACTION RATE PROBE

The aim of this probe was to investigate how students understand and model the concept of reaction rate. It included two parts: the *reaction rate probe-A* and the *reaction rate probe-B*. In the first part, students were asked to describe what they understand by the term "rate of reaction". The second part (the reaction rate probe-B) aimed to elicit students' knowledge about the relationships between reaction rate and time and/or concentrations of reactants. Each part of the probe is discussed separately.

5.1.1 THE REACTION RATE PROBE-A (Data analysis and results)

The probe was conceptually framed and was analysed nomothetically in order to identify whether students had produced answers that would be judged as correct within the established chemical ideas. Thus, the "coding scheme-B" (see Section 3.7), was applied to the dataset. The coding scheme had three main categories: (1) responses including mainly scientifically incorrect ideas about the concept of reaction rate, (2) responses including mainly scientifically accepted ideas about the concept of reaction rate, and (0) all other responses. Analysis of students' responses is summarised and illustrated in Table 5.1 and Figure 5.1. In the following sections those three main categories, and identified sub-categories, are discussed.

(1) Responses including mainly scientifically incorrect ideas about the concept of reaction rate

39% of the SS, 31% of the UF and 3% of the UT' responses included scientifically incorrect ideas about the concept of reaction rate (see Table 5.1). Those scientifically incorrect ideas were classified under three subcategories.

(1-2-1)[2] *Confusion between reaction rate and reaction time (Defining reaction rate as reaction time)*

Around 33% of the SS, 29% of the UF and 3% of the UT believed that reaction rate is the period of time taken for a reaction to occur. As quoted below students could not differentiate between "reaction rate" and "reaction time". While reaction time is a constant quantity for a reaction, the rate of a reaction is dynamic during a reaction. Here are some common examples from students' responses:

> *Substances react to form a new substance. Reaction rate is the time required for a reaction to be completed. Reaction could be too fast for some reactions and too slow for others. There are some factors affecting reaction rate. One of which is using a catalyst that increases or decreases the reaction rate without entering into a reaction.* [Sb-D-32]
>
> *Two different substances or elements react with each other to form products. Time period between beginning and at the end of the reaction is called reaction rate.* [UF-D-29]
>
> *The required time to form reactants is called reaction rate.* [UF-D-20]
>
> *The period of time that is required for a chemical reaction to occur. The faster a reaction proceeds, the faster a product forms.* [Sc-I-03]

Chemical kinetics is concerned with the rate of reactions which is a way of understanding how fast or how slow a reaction occurs. From a student's intuitive viewpoint, it might be logical to relate reaction rate to reaction time. Indeed, several students in this category mainly restated information provided in the probe (e.g. "Sabri's explanation is correct, the reaction rate is the period of time required for a reaction to occur") rather than providing further explanations.

As quoted below, in some instances, students agreed with both of the students' explanations displayed in the probe. They could not differentiate the correct and incorrect definition for the reaction rate term.

> *Reaction rate is the time required for a reaction to occur. In fact both of these students' answers can be accepted as a definition for reaction rate.* [UF-D-11]

---

[2] Three digits were used for the coding scheme to code the responses. The first digit identifies the general groups, the second one identifies whether the response includes scientifically correct ideas ('1') or scientifically incorrect ideas ('2') and the third digit identifies the sub-categories. This notation system will be used in this thesis.

> *The total time required for transforming all of the reactants into products is called reaction rate. Consequently, both of these students' ideas support each other.* [UF-D-24]

(1-2-2) Defining reaction rate as energy/heat

Three school students' responses were placed in the category. Two of them argued that "reaction rate is the energy or heat needed to initiate a reaction" and one stated that "reaction rate is equal to the formation energy of C [product]".

(1-2-3) Misapplication of a rate equation

Four SS and one UF described reaction rate based on a rate equation, however they were not able to recall the equation correctly. As quoted below, students confused reaction rate, enthalpy changes and equilibrium constant:

> *Reaction rate= ΔHproducts - ΔHreactans*
> *If rate of products is greater than reactants, reaction rate (ΔH) will be $\Delta H>0$. If rate of reactants is greater than products, reaction rate will be $\Delta H<0$. .... Reaction rate depends on temperature, and nature of the substances.* [Sa-D-02]
>
> *Reaction rate is the ratio of the concentrations of products to the concentrations of reactants.* [Sc-D-44]

This student's response (in the second excerpt) to the "nitrogen monoxide probe-B" and the "reaction rate–Time probe" revealed that he recalled a rate equation as "reaction rate=[C]/[[A].[B]". The student seems to confuse a rate equation with an equilibrium constant. Another two students in this category also formulated reaction rate and rate equation in the same manner.

(2) Responses including mainly scientifically accepted ideas about the concept of reaction rate

(2-1-4) Describing reaction rate in terms of some quantities per unit of time

This category incorporates those responses in which student defines the rate of a reaction as the rate of disappearance of reactants [A] or the rate of formation of products [C] either verbally or by using mathematical representations. The students described a range of different types of scientifically acceptable definitions for the concept of reaction rate. Here are some examples:

> *Reaction rate is the disappearance of [A]* [reactant] *or formation of [C]* [product] *in a period of time... Reaction rate= $-d[A]/dt=-d[B]/dt= d[C]/dt$* [UT-D-06]

> *Rate*= $\frac{\Delta[C]}{\Delta t}$; *Reaction rate explains how the concentration of C* [product] *changes with time.* [Sa-D-12]

> *Reaction rate= k. [C]; ...* [Reaction rate] *depends on temperature, concentrations, and catalysts.* [Sa-D-21]

31% of the SS, around half of the UF and almost all of the UT' responses encompassed scientifically correct ideas about the concept of reaction rate.

(0) All other responses

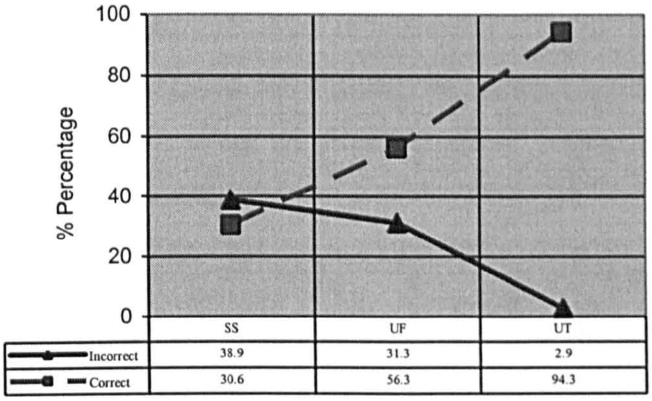
This category is allocated for incomprehensible responses or in cases where there is no response given in any part of the probe. 31% of the SS, 13% of the UF, and 3% of the UT' responses were placed in this category. Though many of these responses included scientifically correct ideas, they did not address the issue focused upon in this probe. For example, the following examples show how the students' responses are irrelevant to the idea tested in the probe: "The rate of a reaction depends on the nature of reactants, temperature, concentration, and catalysts" or "A slow reaction takes a long time and a fast reaction takes a short time".

Code	**Category (Nature of response)**	**Example of response**	**SS** *f* *(%)* **(n=108)**	**UF** *f* *(%)* **(n=48)**	**UT** *f* *(%)* **(n=35)**
1	**Responses including scientifically incorrect ideas about the concept of reaction rate**		**42** ***38.9%***	**15** ***31.3%***	**1** ***2.9%***
1-2-1	Confusion between reaction rate and reaction time	Reaction rate is the time required for a reaction to be completed.	35 *32.4%*	14 *29.2%*	1 *2.9%*
1-2-2	Defining reaction rate as energy/heat	Reaction rate is the amount of energy needed to initiate a reaction. Reaction rate is equal to the formation energy of products.	3 *2.8%*	*0*	*0*
1-2-3	Misapplication of a rate equation	Reaction rate is the ratio of the concentrations of products to the concentrations of reactants. Reaction rate=[C]/[[A].[B]	4 *3.7%*	1 *2.1%*	0
2	**Responses including scientifically accepted ideas about the concept of reaction rate**		**33** ***30.6%***	**27** ***56.3%***	**33** ***94.3%***
2-1-4	Describing reaction rate in terms of some quantities per unit of time	Rxn is the change in the amount of product or reactant over time Expressing the reactant/product concentration vs. time Reaction rate= -d [A]/dt=-d [B]/dt= d[C]/dt	33 *30.6%*	27 *56.3%*	33 *94.3%*
0	**All other responses**		**33** ***30.6%***	**6** ***12.5%***	**1** ***2.9%***
0-0-5	No answer		5 *4.6%*	0	0
	Incomprehensible/Other	A slow reaction takes a long time and a fast reaction takes a short time.	28 *25.9%*	6 *12.5%*	1 *2.9%*

		Increasing temperature would increase the rate of the reaction.			
TOTAL			**108** *100%*	**48** *100%*	**35** *100%*

Notes: n = number of participants; f = frequency; % = percentage of participants

Table 5.1 *A coding scheme for the reaction rate probe-A*



Uncodeable	30.6	12.5	2.9
Total %	100	100	100

Figure 5.1 *Percentage of responses to the reaction rate probe-A*

5.1.1.1 An overview of students' responses to the reaction rate probe-A

The results indicated that a considerable number of school (39%) and university first year students (31%) had scientifically incorrect ideas about the definition of reaction rate (see Figure 5.1). Most of those students confused reaction rate and reaction time. They defined the rate of a reaction as the time period required for a reaction to be completed. A few students defined it as a form of energy needed to initiate a reaction or others simply confused different forms of formulae in kinetics, thermodynamics and chemical equilibrium. During interviews, when students were asked what would be the units of reaction rate, several argued that it would be (moles/liter), or (second), rather than putting it in terms of some quantities per unit of time (e.g. moles/liter. second). Nonetheless, when they were prompted to define the units of rate in a different but more familiar context (e.g. they were asked what would be the units of rate of a car), they correctly defined it. For instance, they stated that rate of a car could be kilometres per second or meter per second. Drawing upon this information, I suggest teaching may start with first eliciting students' preconception about the notion of rate and then developing or connecting these ideas with the rate of a reaction.

A chi-square analysis[3] indicated that there was a statistically significant difference on the distribution of students' responses by different educational levels (χ^2=28.019, *df*=2, $p<0.01$) (see Table 5.2). An increase in responses including scientifically acceptable ideas was observed from school to university. 31% of the SS, around half of the UF and almost all of the UT had scientifically acceptable definition for the term reaction rate. Relatively high percentage of school students' responses (31%) were irrelevant to the idea tested in the probe.

	SS	**UF**	**UT**	***Total***
Incorrect	42	15	1	58
Correct	33	27	33	93
Total	75	42	34	151

**Statistically significant difference is observed:* $\chi^2=28.019$, *df=2*, $p<0.01$

Table 5.2 Chi-square test results for the reaction rate probe-A

5.1.2 THE REACTION RATE PROBE-B

The reaction rate probe-B aimed to investigate students' knowledge about the relationships between reaction rates and time/concentrations of reactants. Students were asked how the rate of a reaction changes as the reaction progresses. An expected answer would be: the higher the concentration of molecules, the greater the number of collisions in unit time and hence the faster the reaction. As reactants are consumed, their concentrations drop, collisions occur less frequently, and reaction rate decreases. However, this is not the case for zero order reactions in which reaction rate is independent of the concentrations of reactants, and accordingly reaction rate is constant during the reaction.

5.1.2.1 Data analysis and results

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[3] The statistical test Chi-square (χ^2) was used throughout this study.

The probe was conceptually framed; therefore the "coding scheme-B" (see Section 3.7), was applied to the dataset. As outlined earlier, the coding scheme had three main categories. The results indicated that a majority of responses for each educational level included scientifically incorrect ideas about how reaction rate changes during a reaction. Most of these students believed that the rate of a reaction increases/decreases or remains constant as the reaction progresses. Eight subcategories of responses were identified and used in the reporting of results. Seven mutually exclusive models were deduced from students' responses to the reaction rate probe-B. They are mutually exclusive in the sense that no written response has been coded as more than one model. The models represent different ways of thinking about the relationships between reaction rate and time/ concentration. The models and the data are illustrated in Figure 5.2. The models, described below, are illustrated by quotes from the written responses and the transcripts.

(1) Responses including mainly scientifically incorrect ideas about the idea tested in the probe

(1-2-1) The Increasing Model (IM):

According to this model the reaction is conceived to start slowly and occur faster thereafter. The students may use macroscopic or particulate or mathematical modelling for their justifications. For example, the first quotation given below includes inappropriate usage of mathematical formulae; the subject appears to confuse two different equations, an equilibrium constant and a rate equation:

> *Rxn* [reaction rate] $=k.\frac{[C]}{[A].[B]}$; *as the concentrations of reactants decreases, the concentration of products increases and as a result the reaction rate increases during the reaction time.* [UF-D-38]
>
> *Elements are formed slowly at the beginning of a reaction. During reaction time the formation of them rises and as a result the rate of the reaction increases.* [Sc-D-17]

15% of the SS, 13% of the UF and 11% of the UT used the Increasing Model.

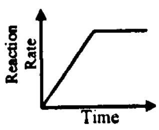
(1-2-2) The Increasing-Constant Model (ICM), in which reaction rate is zero at the beginning and gradually increases up to a maximum value, and remains constant at this value. 8% of the UF and 14% of the UT used the ICM. Most of them justified their responses by using theoretical models, but inappropriately. Some examples are given below.

> *Reaction rate would increase, because reaction rate is proportional to concentrations. As the concentration of product increases, reaction rate increases and after a while the rate* [of the reaction] *remains constant.* [UT-D-29]

> *Reaction rate increases until it reaches chemical equilibrium where the rate of reactions is constant.* [UF-D-22]

Similar conceptual difficulties (as seen in the second excerpt above) were reported by Hackling and Garnett (1985). For instance, they reported that students believe "The forward reaction rate increases with time from the mixing of the reactants until equilibrium is established".

In some cases, mechanical application of formulae was seen from students' explanations. For example;



> *According to the rate equation* $V=k.\ [C]$, *the concentration of C* [product] *increases, and as a result, the rate* [of the reaction] *rises. However, rising of the rate continues until equilibrium is established where the rate of the reaction is constant.* [UT-D-28]

The subject justified his answer by using a rate equation without a conceptual understanding or possibly he confused the graph with the concentration of products vs. time. The subject had also alternative conceptions about chemical equilibrium: he believed the reaction rate is constant at equilibrium. In fact, at equilibrium the forward and reverse reaction rates are equal.

(1-2-3) The Constant Model (CM)

This category includes respondents who argued that the reaction rate is constant as the reaction progresses. This model was common among school and university first year students, many of whom used what Viennot (1985) termed "*if* ... *then*" rule. She suggested that students tended to answer as if they had in mind a "conceptual structure" or a "way of reasoning" described by "IF (set of situations) THEN (features of response)" (ibid. 153). For instance, "*If* the temperature or concentration is changed, *then* the reaction rate would change, otherwise the reaction rate is constant during a reaction". Many of the students assumed that as long as certain factors (e.g. temperature, concentration or catalysts) were not altered, the reaction rate would remain constant or remain the same during a reaction.

> *The reaction rate does not change. There must be an effect from surroundings to alter the rate of a reaction. Those effects would be a change in temperature or using a catalyst. Those effects can increase or decrease the rate of reactions. Without these effects the rate of reactions does not change.* [Sb-D-32]

When I examined this student's response to the reaction rate probe-A, he stated that "*...Reaction rate is the time required for a reaction to proceed*". There might be a relationship between the student's definition of the reaction rate and how the reaction rate changes as time passes. This student conceives "*reaction rate*" as "*reaction time*". Therefore he says that reaction rate does not change, because he believes reaction rate is the reaction time. If nothing is changed, the reaction time (the reaction rate) will be the same. However, if some factors (i.e. an increase in temperature or adding a suitable catalyst) are altered, that results in a change in the reaction time (the reaction rate).

21% of the SS, 31% of the UF, and 14% of the UT used the Constant Model.

(1-2-4) The Increasing-Constant-Decreasing Model (ICDM):

The reaction is seen to start slowly and its rate increases up to a maximum value and at this level decreases gradually to zero when the limiting reactant is consumed. A small number of students, mainly undergraduates, used the ICDM. The following transcript and quotation have been selected to illustrate typical responses. The subject in the first excerpt used an anthropomorphic explanation (attributing of human characters to inanimate objects) in order to justify her ideas on the nature of a reaction system. In the transcript below, R and S stand for the researcher and the student respectively.

> R: What do you understand by the term reaction rate?
> *S: As I wrote here, it is the rate of formation of product, and when all of the products are consumed up, the reaction rate will end up.*
> R: How does the reaction rate change during time?
> *S: Since all of the condition is constant, when reactants are used up, the rate of the reaction will decrease, because the rate of the reaction depends on reactants. For example, when I am running, my energy level reaches a maximum level and then will decrease, when I get tired.*
> R: So at the beginning of a reaction is the reaction rate at a maximum level?
> *S: No, at first it starts slowly. Afterwards it reaches a maximum level and then decreases. Finally it stops*
> R: Can you explain it a bit more, why it follows this pattern?
> *S: When I am running, first I will run slowly and then faster and when I get tired I will run more slowly and stop.* [UF-I-02]

6% of the UF and 14% of the UT were placed in this category.

(1-2-5) The Decreasing Model (DM)

This model is mainly based on the idea that "a slow reaction takes a long time and a fast reaction takes a short time" or "reaction rate is inversely proportional to time" (also see the transcript given on page 106, in the Decreasing Model category). Here is an example;

> *If a reaction is fast, the reaction occurs in a short period of time, but if a reaction is slow the reaction occurs in a long period of time. The reaction rate is inversely proportional to time.* [Sa-D-19]

The subjects had a general picture of how *different reactions* tend to occur, however they did not explain how reaction rate changes during the course of *a reaction.*

(2) Responses including mainly scientifically accepted ideas about the idea tested in the probe

(2-1-6) The Scientific Model (SM):

This model reflects a close correspondence between students' ideas and the scientific model as used by a chemist. In this case, the rate of a reaction is described as being dynamic in nature. The relationships between the concentrations of reactants or products and the reaction rate were mainly described in terms of various theoretical models. The responses in this category encompassed both full understanding and understanding only some part of the specific idea tested in the probe. It was surprising that of the 191 students; only 3 university third year students had a full scientific understanding of the ideas tested in the probe. On the other hand, 9% of the SS, 31% of the UF, and 17% of the UT demonstrated incomplete (partial) understanding. Their explanations contained no misinformation, but the students made a general statement (i.e. rate of reactions decreases as reactions progress). Students tended to make over-generalisations of principles and ignoring some variables (i.e. the order of the reaction). Interviews revealed that they made the assumption that it was a first order reaction with respect to the reactants A and B (rate= k. [A]. [B]). They were aware that reaction rate decreases during reaction time, but they were not aware that this is not the case for a zero order reaction in which the reaction rate is constant.

> *Reaction rate decreases from the beginning to the end of the reaction. When a reaction proceeds, reactants will be consumed up, and the concentration of reactants will decrease. While the reaction rate is proportional to the concentration of reactants, the reaction rate will decrease.* [UF-D-05]

9% of the SS, 31% of the UF, and, perhaps surprisingly, only 26% university third year students used the scientific model.

(0) All other responses

This main category includes two subcategories.

(0-0-7) The Nature of Reactants Model (NoRM):

Though some of the responses seemed to include scientifically correct ideas about chemical kinetics, interviews revealed that those ideas were different from a chemist's view. Such students thought that reaction rates depend on the nature of reactants, nature of reactions or depend on some external factors (e.g. an increase in temperature). For example, these students stated that "*If reactants are in the gaseous phase, the reaction occurs faster and its rate increases*". The majority of the students in this category attempted to compare the rates of two different reactions rather than considering how the rate of a reaction changes during a reaction. For instance, they stated that "*Exothermic reactions occur faster than endothermic reactions*", or "*If temperature of the reaction is changed, or a catalys is used, the reactants react faster*". Here is another example:

> *The reaction rate either increases or decreases from the beginning until the end of a reaction. If temperature of the reaction is raised, the reaction rate will incresase or if temperature of the reaction is decreased, the reaction rate will decrease.* [Sc-D-05]

In these quotations above, the students compared the rates of two different reactions rather than considering how the reaction rate changes during a reaction. Interviews with students revealed that in some cases the probe was misunderstood by the students (i.e. they thought the question asked "how would a reaction rate be changed?"), in other cases they perceived the reaction rate as a static rather than dynamic in nature; hence they viewed the reaction rate as a constant quantity for each specific reaction. In other words, they were not aware of the differences between the instantaneous rate and the average rate for a reaction. What they meant by the reaction rate was actually the overall reaction rate. That may have led them to conclude that as long as certain factors (e.g.

temperature, pressure, catalysts, the initial concentration of recatants) were not altered, the reaction rate (the overall reaction rate) would not change.

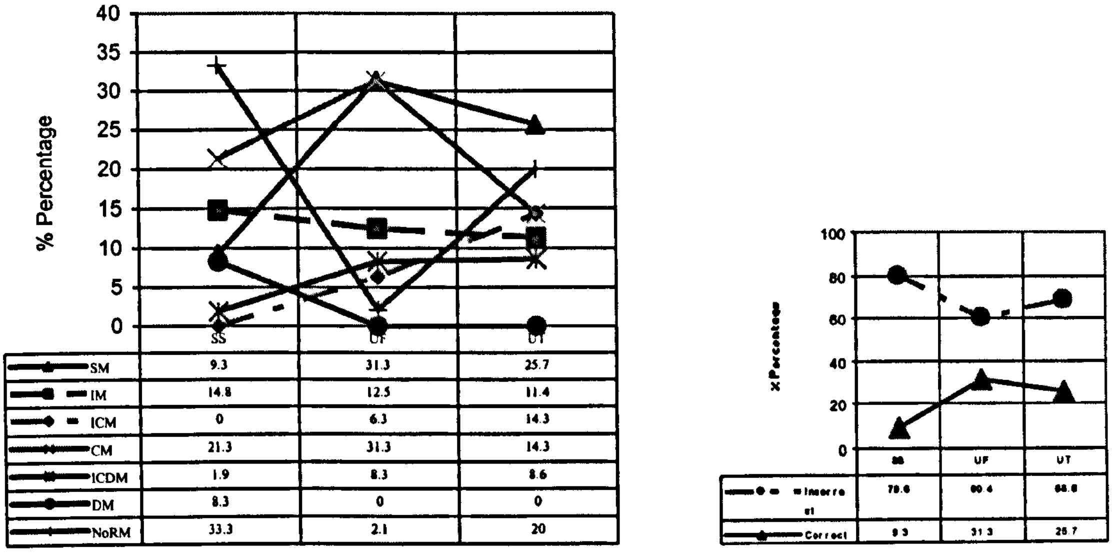
A few students misinterpreted a rate equation. As quoted below, the subject may have confused the reaction rate with the amount of reactants and products. The subject assumed that in terms of reactants reaction rate decreases, but in terms of products reaction rate increases.

> *Reaction rate*= $-\frac{d[A]}{t} = -\frac{d[B]}{t} = \frac{d[C]}{t}$ *... as the concentration of reactants decreases with time, the rate of the reaction will be decreasing until the reaction reaches an equilibrium where the reaction rate is constant quantity. However, based on this equation:* $\frac{d[C]}{t}$*, as the initial concentration of C is nil and as its concentration will be increasing with time, the rate of the formation of C will be increasing. At equilibrium* [reaction] *rates are equal.* [UT-D-07]

33% of the SS, 2% of the UF, and 20% of the UT were placed in this category.

(0-0-8) Uncodeable (U)

This category is allocated for responses not represented by any of the above categories or in cases where there is no response given in any part of the probe.



	SS	UF	UT
SM	9.3	31.3	25.7
IM	14.8	12.5	11.4
ICM	0	6.3	14.3
CM	21.3	31.3	14.3
ICDM	1.9	8.3	8.6
DM	8.3	0	0
NoRM	33.3	2.1	20

Uncodeable	11.1	8.3	5.7
Total %	100	100	100

Figure 5.2 The models used in the reaction rate probe-B

5.1.2.2 An overview of students' responses to the reaction rate probe-B

The results of the probe showed a low correct response rate: only 18% of the whole sample used the Scientific Model. A chi-square analysis showed that there was a statistically significant difference between school students and undergraduates (χ^2=12.208, *df*=2, *p*<0.01) in that the usage of the scientific model increased from school (9%) to university (31%-26%) (see Figure 5.2). University first year students (31%) performed better than university third year students (26%). Nevertheless, most students showed no evidence of having thought about the order of the reaction. Only a few university third year students mentioned reaction rates depend on reaction order: if a reaction is zeroth order, its rate is constant, and otherwise the rate of the reaction decreases during reaction time.

Despite teaching at school and university, many undergraduates did not provide a scientifically acceptable explanation about the nature of a reaction system. The main difficulties were as follows:

- The reaction is conceived to start slowly and occurs faster afterwards.
- Confusion between the rate of formation of products and the amount of products during a reaction. Since the amount of product increases as a reaction progresses, students may also conclude the rate of the reaction increases.
- As long as certain factors (e.g. temperature, concentration or catalysts) were not altered, the reaction rate would remain constant or remain the same during a reaction.

5.2 THE REACTION RATE-TIME PROBE

The purpose of the probe was the same as the "reaction rate probe-B"; however the context of the probe was different. This time, the probe presented students with experimental data; they had to assess the data and find out how the reaction rate changes with time. Students were asked to describe both textually and graphically, how the reaction rate changes during time. In addition, students were asked to justify their answers by helping the other students to understand the specific concepts.

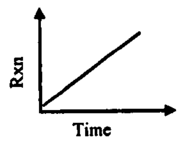
5.2.1 Data analysis and results

As being a conceptually framed probe, the "coding scheme-B", was applied to the reaction rate-time probe. The coding scheme had three main categories. Seven subcategories of responses were identified and used in the reporting of results. Six mutually exclusive models were deduced from students' responses to the reaction rate-time probe. They are mutually exclusive in the sense that no written response has been coded as more than one model. All of these models are the same as those identified in the "reaction rate probe-B". In other words, the responses share characteristics of the same models. Therefore, they were given the same name in order to compare individual students' responses across these two probes. Percentage of students' responses to the probe is illustrated in Figure 5.3.

(1) Responses including mainly scientifically incorrect ideas about the idea tested in the probe

(1-2-1) The Increasing Model (IM)

A main characteristic of this model is that the reaction is conceived to start slowly and its rate gradually increases thereafter. The students may use macroscopic or particulate or mathematical modelling for their justifications.



At the beginning of the reaction, reactant molecules are far away from each other; therefore the reaction rate is zero at the beginning. During time interaction of molecules increases and as a result the reaction rate increases. [Sc-I-04]

The concentration of A [reactant] *is decreasing, which means the rate of the reaction would increase.* [Sc-D-12]

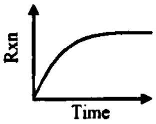
The second excerpt shows that the subject may have confused the reaction rate and the amount of product.

In some cases, mechanical application of formulae was seen from students' responses. For example, as quoted below, though the written formula was correct, the interpretation was not appropriate from a chemist's perspective, because calculus notation (derivative of the concentration of product with respect to time) was misinterpreted by the student.

Reaction rate$=\frac{d[product]}{dt}$*, while the concentration of product increases with time; the rate of the reaction will increase.* [UF-D-35]

This model was particularly common among school students (SS). 23% of the SS, 13% of the UF and 3% of the UT used the Increasing Model (IM).

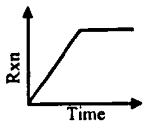
(1-2-2) The Increasing-Constant Model (ICM), in which reaction rate is zero at the beginning and gradually increases up to a maximum value, and remains constant at this value. This model has two sub-categories. One, ICM$_a$, involves responses in which whilst students' verbal justifications and reasoning are appropriate from a chemist's perspective, yet transferring that knowledge into a graphical form is different from a chemist's perspective (e.g. see the excerpt given below). This model (ICM$_a$) was common amongst undergraduates.



The reaction rate decreases because consumption of [A] is greater at the beginning; thereafter, it reduces. Since reaction rate is proportional to the concentrations of products, we can say that the reaction rate decreases during reaction time. [UT-D-16]

As quoted above and in many other cases, though the subject's justification and reasoning were correct, representation of those ideas on a graph was different from formal chemist's perspective. The reason might be that the student has conceptual difficulties in understanding that reaction rate is maximum at the beginning and is zero at the end of the reaction or they simply confuse it with the graph of the concentration of product vs. time.

The other sub-category, ICM$_b$, includes students who confuse the reaction rate with the amount of product. In other words ICM$_b$ includes both incorrect verbal justifications and graphical representation. This model (ICM$_b$) was common amongst school students.



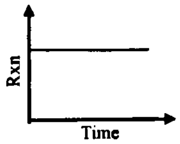
A [reactant] *is decreasing, that means product is formed, As A and B* [reactants] *are used up, the formation of C* [product] *increases and accordingly the reaction rate increases until all A and B are consumed where the reaction rate is constant.* [Sa-D-14]

This subject seems to confuse the reaction rate and the amount of product, as she says the reaction rate is constant at the end of the reaction. She might have thought that if the reaction rate is constant, no product is formed.

8% of the SS, 25% of the UF, and perhaps surprisingly, more than half of the UT (54%) used this model (ICM). Nonetheless, it should be noted that the majority of undergraduates' responses included characteristics of ICM_a.

(1-2-3) The Constant Model (CM)

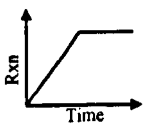
Students viewed the reaction rate as a constant quantity which remains the same as the reaction progresses. Hence, they stated reaction rate would remain constant during the reaction. This model was common among school students, many of whom used "*if... then*" rule (Viennot, 1985). For instance, "*If* the temperature or concentration is changed, *then* reaction rate will change, otherwise reaction rate is constant during a reaction". Many of the students assumed that as long as certain factors (e.g. temperature, concentration, catalysts) were not altered, reaction rate would remain constant during a reaction.

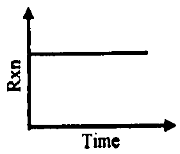


[A] and [B] decreases and [C] increases with time. The rate of the reaction would not change, because temperature has not been changed. [Sb-D-02]

The reaction rate is constant as time passes, because reaction rate does not depend on time. Time does not change reaction rate. [Sb-D-13]

It is worth underlining that the settings of the probe may affect students' reasoning. If a gaseous reaction or a heterogeneous reaction with the same concentration vs. time graph was used, some students might have used different models. For example, as quoted below, one of the school students first used the ICM (reaction rate increases up to a maximum value, and remains constant at this value), however during interviews when she realised this reaction occurs in the aqueous phase, she changed her answer with the Constant Model. Perhaps this feature of the probe was leading some students through the constant model.



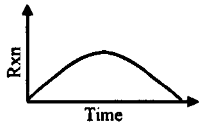


R- What would you say about the rate of this reaction?
S- *I did not realise they* [reactants and products] *were all in a liquid phase, I thought they were in the gas phase. If I knew that the reaction occurred in a liquid phase, I would have drawn like that* [referring the student (Pelin) who says the reaction rate is constant]
R- Can you explain this a bit more?
S- *Solids and liquids are not written in a rate equation, therefore the reaction rate depends on the rate constant which is constant.* [Sc-I-03]

19% of the SS, 6% of the UF and 6% of the UT used the Constant Model.

(1-2-4) The Increasing-Constant-Decreasing Model (ICDM)

The reaction is seen to start slowly and its rate increases up to a maximum value and at this level decreases gradually to zero when the limiting reactant is consumed.

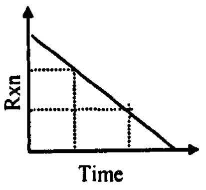


The rate of the reaction increases at the beginning of the reaction. When reactants are used up the reaction rate drops and at the end of the reaction, the rate is zero. [UF-D-36]

2% of the SS, 10% of the UF, and 9% of the UT used the ICDM.

(1-2-5) The Decreasing Model (DM)

This model is mainly based on the idea that "a slow reaction takes a long time and a fast reaction takes a short time" or "reaction rate is inversely proportional to time". The subjects had a general picture of how *different reactions* tend to occur, however they could not explain how reaction rate changes during the course of *a reaction*. While the relationship between reaction rate and time was graphically illustrated in a scientific way, the students' interpretations and rationale were different from that a chemist's perspective.



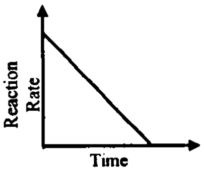
S- *Reaction rate is inversely proportional to time* [mentioning on the graph]. *A slow reaction takes a long time and that a fast reaction takes a short time.*
R- So, for this reaction what would you say about the reaction rate? How would it change during reaction time?
S- *If this reaction is fast, it takes less time, and if it is slow it takes more time to occur.*
R- How would the reaction rate change during this reaction?
S- [Repeating the answer given previously]. [Sc-I-02]

The discussion did not go beyond this point, the subject could not explain how the reaction rate changed during the reaction, rather he was talking about the situation for different reactions.

(2) Responses including mainly scientifically accepted ideas about the idea tested in the probe

(1-1-6) The Scientific Model (SM)

The rate of a reaction is described as being dynamic in nature. The relationship between the concentrations of reactants/products and reaction rate is described in terms of various models from established chemical perspectives. For instance, as quoted below, students may use mathematical modelling for their justifications (i.e. thinking of the reaction rate as the slope of the concentration vs. time graph). This category includes responses such as: "the reaction rate (Rxn) would decrease, because the higher the concentration of molecules, the greater the number of collisions in unit time and hence the faster the reaction. As reactants are consumed, their concentrations drop, collisions occur less frequently, and the reaction rate decreases" or "reaction rate is directly proportional to the concentrations of reactants, therefore the reaction rate would decrease". Here are some other examples:



> *The reaction rate depends on the concentrations of reactants, and as a result, the graph* [referring to the concentration of reactant vs. time graph] *shows that the gradient at any point along with the line will decrease. As the gradient is equal to reaction rate, as rate=d[C]/dt, this shows that reaction rate decreases as the reaction progresses.* [UF-I-05]

> *Reaction rate=k.[A]^m ...reaction rate is proportional to the concentrations of reactants. The concentrations of reactants decrease with time and as a result the rate of the reaction drops.* [UF-D-31]

It is surprising that of the 35 university third year students, only 9 (26%) used the scientific model, and that the university first year students (44%) had the highest percentage of using the scientific model.

(0) All other responses

This category is allocated for responses not represented by any of the above categories. 7% of the SS, 2% of the UF, and 5% of the UT were placed in this category.

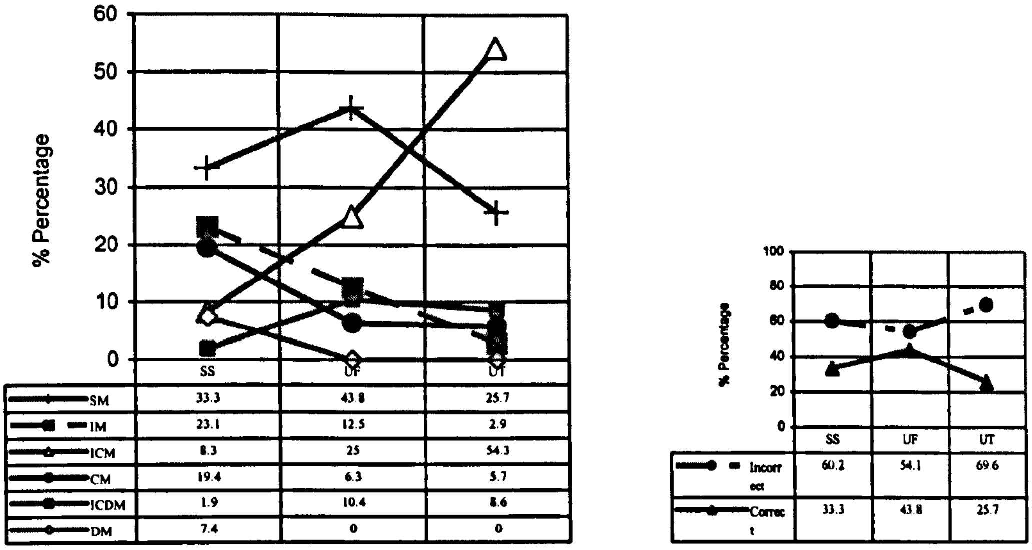
5.2.2 An overview of students' responses to the reaction rate-time probe

In contrast to the reaction rate probe-B, no statistically significant difference was found for the distribution of students' responses to the reaction rate-time probe by educational levels (χ^2=2.868, df=2, p>0.01) (see Table 5.3). Six models were deduced from students' responses to the reaction rate-time probe. A great number of students both secondary and university levels used conceptions not consistent with scientific perspectives and had conceptual difficulties in explaining how reaction rate changes as reaction progresses. Many conceptual difficulties identified in the "reaction rate probe-B" were also found in the students' responses to this probe. The idea that "reaction rate increases as the reaction progresses" (IM) or "reaction rate is constant" (CM) or "reaction rate increases up to a maximum value, and remains constant at this value" (ICM) were quite common among both school and undergraduate students. The students who gave the explanation that the rate of a reaction was constant (CM) could not anticipate that the reaction had a different rate at different stages of the reaction and that the reaction rate was dynamic, but rather believed that the reaction rate was static and had a constant quantity. Many students had difficulties in understanding that the reaction had the highest rate at the beginning of the reaction and the lowest rate at the end rather they thought the opposite. Indeed, similar to the results of the reaction rate probe-B, the reaction is conceived to start slowly. From a student's intuitive viewpoint, it would be logical to say that reaction rate increases as the reaction proceeds, due to his/her everyday life experience (e.g. a wood fire burns slowly at the beginning and goes faster thereafter).

As Figure 5.3 shows students' preference for the usage of ICM considerably increases from school to university. It should be emphasised that while the majority of the undergraduates used ICM_a, the school students mainly used ICM_b. In other words, whilst many undergraduates gave appropriate interpretations and rationale how reaction rate changes while the reaction progresses (particulate or mathematical modelling), they had difficulties in representing that knowledge symbolically –e.g. by representing it on a graph- (mathematical modelling). Research in other areas of science also shows that students have difficulties in making transformations within and across different representational forms (e.g. transforming a chemical equation into a corresponding graph) (Johnstone, 1991; Kozma, 2003).

Based on this nomothetic data analysis, when the percentage of students in different educational levels who provided a correct answer (i.e. using the Scientific Model) to the probe was graphed, a ∩-shaped performance curve (e.g. see Figure 5.3) was found from students' responses. 33% of the SS, 44% of the UF, and 26% of the UT used the 'scientific model' (SM). Perhaps interestingly the UF (44%) had the highest percentage of using the scientific model. In particular, whilst the undergraduates will be chemistry teachers, it is surprising that only 26% of the university third year students used the scientific model, while 69% used alternative models in their responses.

It is important to emphasise that as mentioned earlier (in the Constant Model section); students' ideas may depend to some extent on the format and contextual features of the probe presented (also see Section 5.3). For instance, if a gaseous reaction with the same concentration vs. time graph was used in the reaction rate-time probe, some students might have used different models. Further studies would be needed to shed more light on this issue



Uncodeable	6.5	2.1	4.7
Total %	100	100	100

***Figure 5.3** The models used in the reaction rate-time probe*

	SS	UF	UT	*Total*
Incorrect	65	21	25	116
Correct	36	26	9	66
Total	101	47	34	182

**No statistically significant difference is observed: χ^2=2.868, df=2, p>0.01)*

***Table 5.3** Chi-square test results for the reaction rate-time probe*

5.3 CONSISTENCY OF USE OF MODELS ACROSS DIFFERENT PROBES TESTING THE SAME IDEAS

This section investigates the consistency of individual students' responses to the *reaction rate probe-B* and the *reaction rate-time probe*. The second research question of this study was about finding out secondary school and university students' understandings of chemical kinetics and how their understandings change in relation to relevant teaching at secondary and university level. Another dimension of change may include the consistency of students' application of knowledge to a range of contexts. Therefore, in order to explore how students were reasoning, individual students' responses to the probes testing the same ideas were cross-tabulated. If students' reasoning is based on underlying reasoning patterns, consistent responses might be expected to the probes testing the same ideas.

Table 5.4 shows the pattern of individual students' responses to the reaction rate probe-B and the reaction rate-time probe. In the reaction rate probe-B, 173 students (91%) gave an answer consistent with the models identified; for the reaction rate-Time probe the figure was 182 (95%). However, only 60 (31%) used the same model in both probes and only 21 (11%) used the scientific model in both. Inspecting Table 5.4, it becomes evident that context plays a significant role in students' preference for the usage of these models. For example, of the 34 students used the scientific model in the reaction rate probe-B, only 21 used this model when answered the reaction rate-time probe. On the other hand, of the 66 student who answered the reaction rate-time probe in line with the scientific model, only 21 used this model when answering the reaction rate probe-B. Overall 60 students out of 191 (31.4% of the whole sample) used the same model in these two probes. These findings suggest that the students were influenced by contextual aspects of these two probes. This is in agreement with the findings of other researchers that students' reasoning is dependent on context (Engel Clough & Driver, 1986; diSessa, 1988; Palmer, 1997).

		The Reaction rate-Time Probe (n=191)							
		SM	IM	ICM	CM	ICDM	DM	Uncodeable	***Total***
The reaction rate Probe-B (n=191)	SM	**21**	3	6	1	2	0	1	***34***
	IM	7	**8**	9	2	0	0	0	***26***
	ICM	0	1	**7**	0	0	0	0	***8***
	CM	14	7	6	**12**	2	1	1	***43***
	ICDM	2	1	1	0	**5**	0	0	***9***
	DM	1	0	1	0	0	**7**	0	***9***
	NoRM	16	8	8	7	0	0	5	***44***
	Uncodeable	5	4	2	4	1	0	2	***18***
	Total	***66***	***32***	***40***	***26***	***10***	***8***	***9***	***191***

Table 5.4 *The pattern of students' responses (models) to the "Reaction rate probe-B" and the "Reaction rate-Time" probes*

Table 5.5 summarises the number of students using a model consistently in the two probes. Students were placed in this table if they used the same model in two probes (thereby indicating that they were not influenced by context). The results show that only 4.6% of the SS used the SM (scientific model) consistently across two probes, 20.8% of the UF and 17% of the UT did so. It seems that when attempting to answer closely related probes[4] on reaction rate, students did not use their scientific knowledge in a coherent way over these probes.

The percentage of students who used a particular model for two probes increased from school (24.1%) to university, yet the consistency of the university first year (41.6%) to third year (40%) students' responses was about the same. That supports the findings of other researchers that advanced science learner are better able to use their ideas appropriately in different contexts than novice learners. For instance, Palmer (1997) investigated students' reasoning about forces and found that younger students (15-16-year-olds) were influenced by contextual features such as speed, weight and position of moving object, the direction of motion and their own experience of the context. However, he found that older students (pre-service science teachers) were generally less affected by context and more consistent in their reasoning.

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[4] These two probes are relevant to each other from a chemist's point of view (i.e., the underlying chemistry is identical in both cases).

	SS *f (frequency)* (n=108)	**UF** *f* (n=48)	**UT** *f* (n=35)	***Total*** ***(n=191)***
SM	5 *4.6%*	10 *20.8%*	6 *17%*	***21*** ***(11%)***
IM	5 *4.6%*	3 *6.3%*	0	***8*** ***(4.2%)***
ICM	0	3 *6.3%*	4 *11.4%*	***7*** ***(3.7%)***
CM	9 *8.3%*	2 *4.2%*	1 *2.9%*	***12*** ***(6.3%)***
ICDM	0	2 *4.2%*	3 *6.3%*	***5*** ***(2.6%)***
DM	7 *6.5%*	0	0	***7*** ***(3.7%)***
Total	***26/108*** ***(24.1%)***	***20/48*** ***(41.6%)***	***14/35*** ***(40%)***	***60/191*** ***(31.4%)***

***Table 5.5** Consistency of individual students' responses to the "Reaction rate probe-B" and the "Reaction rate-Time" probes*

5.4 THE DE-SCALER PROBE

The probe, framed in terms of the use of domestic commercial De-scaling products, asked students to explain why a change in the initial concentration of reactant would affect the reaction rate. The results are presented below.

5.4.1 Data analysis and results

The probe was set in an everyday context where the language of chemical kinetics was not presented, however students were directed to interpret the phenomenon "in terms of particles". Accordingly, the analysis has been done using coding scheme-A (see Section 3.7), which has three main categories; (1) descriptive/empirical, (2) explanatory/ theoretical and (0) all other responses. These three main categories include five sub-categories. The results are summarised and illustrated in Table 5.6 and Figure 5.4.

(1) Descriptive/Empirical (Macroscopic Modelling)

(1-1-1) Explanations in terms of macroscopic features of the phenomenon

Responses in this category involve explanations in terms of macroscopic features of the phenomenon. In many cases, students used everyday terms or language to account for the phenomenon. For example, the following expressions were quite common amongst school students, but these types of expressions were practically absent by the end of secondary education:

> *Concentrated acid cleans / removes / melts / eats / destroys / burns / irritates more quickly limestone / limestone particles in the kettle.*
> *More concentrated acid removes more quickly limestone in the kettle, because it is stronger.*
> *More concentrated acid removes more quickly limestone in the kettle, because it is thicker.*

Terms like "dissolving/solubility" and "react/reaction" were not differentiated by many school students, and these terms were often used interchangeably. However, it should be noted that a feature of the probe may have led students to use the term "dissolving" in their responses. In Turkish, the term "De-scaler" is commonly called "limestone dissolver" in everyday language; therefore that might be one of the reasons in students' preference for the terms "dissolve/dissolving" instead of "react/reaction". In some instances, the objects of the macroscopic world (e.g. *strong acid* reacts more quickly with *limestone*) are treated as if they were *atoms* or *molecules* (the objects of the sub-microscopic world) (cf. Ben-Zvi *et al.*, 1986; Ahtee & Varjola, 1998). I suspect again language might be one of the problems here. Sometimes we may hear these types of expressions from trained chemists as well.

Many responses included *a general intuitive rule: "The more of A, the more of B"* (Stavy & Tirosh, 1996, p. 662)[5]. For instance, "*The more* concentrated an acid is, *the faster* it removes limestone in the kettle" or "*the more* concentrated an acid is, *the faster* it reacts to limestone in the kettle". Though those expressions or generalisations do not include incorrect ideas, yet they lack of underlying mechanism to account for the phenomenon.

65% of the SS, 46% of the UF and 6% of the UT' explanations offered fell into this category.

(2) Explanatory/ Theoretical (Particulate and/or Mathematical Modelling)

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[5] Stavy, Tsamir and Tirosh (2002) claim that students tend to react in similar ways to a wide variety of conceptually unrelated tasks which differ with regard to their content area and the required reasoning. They suggest that many students' responses, which the literature describes as alternative conceptions, could be interpreted as evolving from a small number of intuitive rules. They argue that many alternative conceptions, apparently related to specific scientific and mathematical concepts, are actually only applications of the rule "More A-More B" to such tasks.

Students in this category referred to sub-microscopic level of chemistry and they used the principles of various theoretical models in order to explain the phenomenon. The phenomenon was interpreted with reference to the properties or behaviour of posited entities, such as movement of acid molecules, rather than being grounded in the language of observations. In other words, explanations involved constructing some form of model or mechanisms to account for the phenomenon. The sub-categories are discussed below.

(2-2-3) Responses including scientifically incorrect ideas

A few students' explanations (7% SS, 4% UF and 3% UT) included scientifically incorrect ideas and some typical responses are given below:

> *There are more acid particles in Apex* [the more concentrated acid]; *therefore acid particles collide faster with each other and with limestone particles.* [Sb-D-13]

The interviews revealed that students believed that the speed of particles in the concentrated acid is higher; therefore they collide *faster* with each other and with limestone particles. Students had an idea that an increase in concentration increases the *speed of particles*. Furthermore, in many cases, students did not used the terms "react/reaction/the rate of reaction", but they used the terms "dissolve/dissolving/the rate of dissolving" instead. As pointed out earlier, the origin of this confusion may stem from meaning of the term De-scaler in Turkish language. A few students perceived the phenomenon as a dissolving process rather than an example of chemical reaction. As one of the students put it:

> *Acid is a solvent of substances... Increasing the amount of solvent increases dissolving..... 3% solution of acid is less effective than 5% solution of acid, because it has fewer acid particles. 5% solution of acid has more acid particles; therefore more particles will affect per same surface area. That will result in a faster dissolving. In other words, solubility of acids will increases with an increase in the amount of acids.* [Sa-D-22]

> *...There are more acid ions in the 5% acid solution; therefore more limestone particles will be dissolved per unit of time.* [Sa-D-23]

(2-1-3) Reasoning based on mathematical formulae or chemical equations (Mathematical Modelling)

This subcategory is allocated to cases where justification involves mathematical formulae or chemical equations (e.g. $CaCO_3 + 2HCl \rightarrow CaCl_2 + CO_2 + H_2O$). Several students justified their responses based on a rate equation. As one of the UT put it:

> *An increase in concentration raises the reaction rate: Rate of reaction is V=k. [A]. [B] When we increase the concentration of acid, the reaction between layer of limestone and acid will increase.* [UT-D-19]

3% of the SS, 19% of the UF, and 26% of the UT were placed in this category.

(2-1-4) Explanation in terms of theories of kinetics[6] (e.g. the collision and/or transition state model)

The respondents in this category provided scientifically acceptable ideas to account for the phenomenon. Students often drew upon the principles of the collision or transition state models to interpret the phenomenon. 19% of the SS, 33% of the UF, and 74% of the UT' responses were placed in this category and some common examples are given below:

> *Acid concentration is higher in the de-scaler with 5% acid solution. It contains more particles per same unit of volume; therefore more particles interact with limestone particles. Since reaction rate is defined as the change in concentration* [of reactants/products], *more product is formed per same unit of time.* [UT-D-07]

In some instances, students used particulate and mathematical modelling in tandem. 3 UF and 3 UT explained the macroscopic phenomenon using both particulate and mathematical modelling. Here are some examples:

> *Reaction rate is proportional to the concentration of reactants, Rxn=k. [A]. [B]. A higher concentration of reactants raises the probability of collisions between reactant molecules, which leads to an increase in the reaction rate. In other words, more substances will pass through the activation energy barrier* [per unit time]. [UT-D-21]

> $CaCO_3 + 2HCl \rightarrow CaCl_2 + CO_2 + H_2O$
> *There are more acid molecules in the concentrated de-scaler. Increasing percentage of acid molecules increases the probability of effective collisions between acid and limestone molecules.* [UT-D-13]

(0) All other responses

---

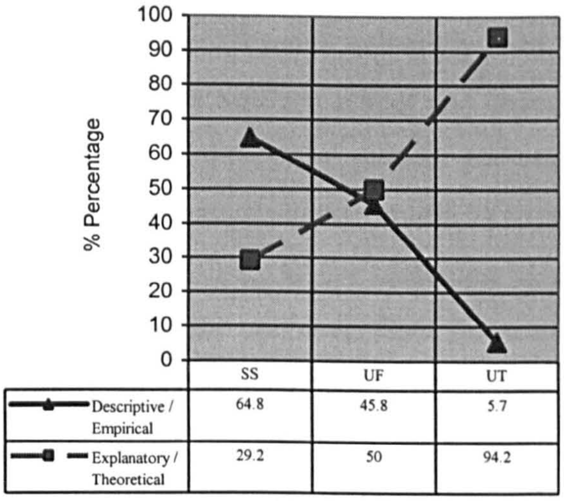
[6] It is important to note that explanations in the previous category (2-1-3) (mathematical modelling) are also embedded in theories of kinetics, but in mathematical or symbolic level.

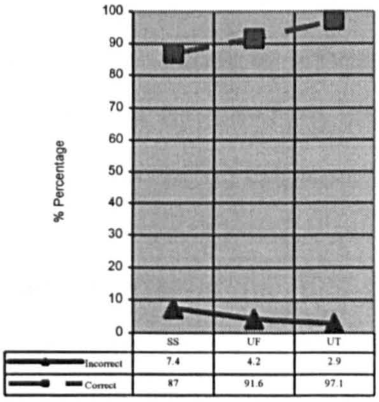
The category is allocated for incomprehensible responses or in cases where there is no response given in any part of the probe. 6% of the SS and 4% of the UF were placed in this category.

Code	Category (Nature of response)	Example of response	SS *f* *(%)* (n=108)	UF *f* *(%)* (n=48)	UT *f* *(%)* (n=35)
1	**Descriptive/Empirical (Macroscopic Modelling)**		**70** ***64.8%***	**22** ***45.8%***	**2** ***5.7%***
1-1-1	Explanations in terms of macroscopic features of the phenomenon	Using everyday language: Concentrated acid *cleans / removes / eats / destroys/ burns* more quickly limestone in the kettle. The more of A, the more of B: *The more* concentrated an acid is, *the faster* it reacts to limestone in the kettle	70 *64.8%*	22 *45.8%*	2 *5.7%*
2	**Explanatory/Theoretical (Particulate and/or Mathematical Modelling)**		**32** ***29.2%***	**24** ***50%***	**33** ***94.2%***
2-2-2	Scientifically incorrect ideas	A rise in the percentage of acid molecules increases the rate of dissolving There are more acid particles, which collide faster with each other and these particles have higher speed.	8 *7.4%*	2 *4.1%*	1 *2.9%*
2-1-3	Reasoning based on mathematical formulation	*Mathematical modelling*: RXN= k.[A].[B], reaction rate depends on the concentration of reactants. An increase in the concentration of reactants increases the rate of reaction.	3 *2.7%*	9 *18.9%*	9 *25.7%*
2-1-4	Explanation in terms of theories of kinetics (e.g. the collision and/or transition state model)	*Particulate modelling:* An increase in the concentration of the acid increases interactions between acid and limestone particles. There are more acid molecules in the concentrated de-scaler. Increasing percentage of acid molecules raises the probability of collisions between acid and limestone molecules.	21 *19.4%*	16 *33.3%*	26 *74.3%*
0	**All other responses**		**6** ***5.6%***	**2** ***4.2%***	**0**
0-0-5	No answer		4 3.7%	0	0
	Incomprehensible/Other		2 *1.9%*	2 *4.2%*	0
TOTAL			**108** ***100%***	**48** ***100%***	**35** ***100%***

Notes: In some cases, responses included characteristics of more than one subcategory; therefore they were coded into different subcategories. For example, if a student used particulate and mathematical modelling at the same time, it was coded twice, however it was coded only once in the Explanatory/Theoretical category. Therefore, the total number of respondents in "subcategories" may exceed the total number of the participants.

***Table 5.6** A coding scheme for the De-scaler probe*





Uncodeable	5.6	4.2	0
Total %	100	100	100

***Figure 5.4** Responses to the De-scaler probe*

5.4.2 An overview of students' responses to the de-scaler probe

Despite being directed to consider the phenomenon "in terms of particles", around two third of the SS and around half of the UF used explanations based on macroscopic properties. They did not use some forms of theoretical model or causal mechanism to account for the phenomenon (see Figure 5.4). Research in other areas of chemistry also indicates that students have difficulty in making transformations from the phenomenological level of chemistry (i.e. observable changes in substances) to the sub-microscopic level, which explains changes in terms of the interactions between individual atoms and molecules (Ben-Zvi & Gai, 1994; Roth & Reimann, 1998: Kozma, 2003).

	SS	UF	UT	*Total*
Descriptive/Empirical	70	22	2	94
Explanatory/Theoretical	32	24	33	89
Total	102	46	35	183

* *Statistically significant difference is observed:* $\chi^2=41.595, df=2, p<0.01$

***Table 5.7** Chi-square test results for the De-scaler probe*

The results indicated that the students following the curriculum made gradual progress from secondary school through university level. It was found that there is a statistically significant difference between school and undergraduate students' reasoning in that the reasoning based on theoretical models gradually increased from school to university (χ^2=41.595, *df*=2, *p*<0.01) (see Table 5.7). It was noticeable that by university level, students were more likely to use reasoning based on sub-microscopic or mathematical level. Almost all of the university third year students were able to use theoretical model appropriately in the phenomenon. However, around half (45.8%) of the first-year undergraduates did not refer any ideas concerning the dynamic nature of particles. Undergraduates' (particularly UT) responses were richer in the terminology and the range of justifications provided in that they used the principles of the collision or transition-state model more appropriately, frequently and confidently in their reasoning. Particulate modelling becomes increasingly popular as undergraduates move through the curriculum. Nevertheless, some students had difficulties in applying theoretical models in the given situations, for example some had the idea that "an increase in the concentration of reactants will accelerate the speed of particles".

A few students, mainly undergraduates, relied on mathematical formulae (e.g. the rate equation) and a functional vocabulary (e.g. reaction rate is directly proportional to the concentrations of reactants, thus increasing concentration of reactants increases the reaction rate) to describe the phenomenon. 6.3% of the first year and 8.3% of the third year undergraduates explained the macroscopic phenomenon using both particulate and mathematical modelling. Many of those were able to move between different levels of modelling and integrated one to the other to express their understanding of the chemical phenomenon.

5.5 THE VESSEL PROBE

The vessel probe was mainly designed to elicit students' understanding of the effect of pressure on gaseous reactions. In the probe, a reaction was set up in two closed containers under two different set of initial conditions and students were asked to explain in which set of conditions the reaction would occur faster. They were also asked to justify their answers by persuading the student(s) its correctness.

5.5.1 Data analysis and results

Though this was a conceptually framed probe, the coding scheme-A was applied to the dataset. Because, the De-scaler probe and the Vessel Probe were designed to test similar ideas, it was judged that using the same coding scheme would be beneficial in order to compare students' reasoning across those probes. The coding scheme-A has three main categories; (1) descriptive/empirical, (2) explanatory/theoretical and (0) all other responses. In the following sections those three main categories, and identified sub-categories, are discussed. Analysis of students' responses is summarised in Table 5.8.

(1) Descriptive/Empirical (Macroscopic Modelling)

The responses in this category are based on explanations, which identify one or more key variables without explaining underlying causal mechanism, or the justification involves analogical reasoning. It is worthwhile emphasising that students who justified their responses based on the ideal gas law formula (P.V=n. R.T) without referring to a theoretical model in chemical kinetics (e.g. referring to a rate equation, or referring to the collision model) were also placed in this category. Here is an example;

> *P.V.=n.R.T, so a drop in volume raises pressure. Therefore a reaction occurs faster in a smaller container.* [UF-D-21]

Around 61% of the SS, 38% of the UF, and 9% of the UT' responses included arguments in terms of macroscopic, observable features of the event.

(1-2-1) Explanations in terms of macroscopic features of the event (leads to wrong answer)

Temperature and/or the amount of reactants was seen as key variables. 21% of the SS, 17% of the UF, and 6% of the UT' responses were placed in this category. Most of the students argued that while temperature and the amount of reactants are the same, reaction rates will be the same for both cases. For example, many students proposed that "*The rates of reactions are the same because the same amount of reactants was used*". The subjects may recall some ideas taught at school in a mechanistic way. Here is another example:

> *....[T]he rate of these reactions are equal, because, though the volume of the second vessel is greater than the first one, temperature and the initial amount of*

> *A and B are equal for both cases. In other words, the rate of a reaction doesn't depend on volume; it depends on temperature and the amount of reactants.* [Sc-I-02]

The amount of substances, the number of moles and concentration were often not differentiated among school students and in some cases, these terms were used interchangeably (e.g. the rate of reactions are the same, because the concentration of reactants are the same for both cases). Students argued that pressure and the volume of a container do not affect reaction rates. They only recalled temperature, concentration and catalyst as factors affecting rates of reactions, but not the pressure for gaseous reactions.

(1-1-2) Explanations in terms of macroscopic features of the event (leads to correct answer)

40% of the SS, 21% of the UF, and 3% of the UT' responses were placed in this category and some typical examples are:

> *The first reaction* [reaction in the smaller vessel] *is faster, because the volume of the vessel is smaller.* [Sc-D-32]
>
> ....*The higher the concentration, the faster the reaction proceeds.* [Sa-D-08]

In many cases, students' responses involved a linear causal reasoning pattern. The interviews demonstrated that the majority of such students justify their responses based on the ideal gas law formula and on a rate equation.

> *The first reaction* [reaction in the smaller vessel] *is faster, because the volume of the vessel is smaller. A drop in volume increases pressure. An increase in pressure raises reaction rates.* [UF-D-17]

(2) Explanatory/ Theoretical (Particulate and/or Mathematical Modelling)

Respondents in this category provided explanations based on theoretical entities that are not directly observable in the event itself and provided an underlying mechanism for their claims. Around 29% of the SS, 63% of the UF, and 83% of the UT' explanations had the characteristics of this category. The subcategories are as follows.

(2-2-3) Using theoretical models inappropriately

Students had incorrect ideas about the relationships between volume change and temperature/the velocity of the molecules/kinetic energy. Some thought that an increase in pressure leads to increasing the temperature, the velocity or kinetic energy of molecules. Here are some examples:

> *I think reactions in the smaller vessel occur faster, because the number of reactant moles is equal in both vessels. However, molecules move faster in the smaller vessel (i.e. kinetic energy of molecules will increase).* [Sa-D-13]
>
> *When the volume is decreased, the velocity of gas molecules increases and their interactions with each other will increase. That reduces the reaction time and raises the reaction rate.* [UF-D-39]

In some instances, though students' explanations included some scientifically correct ideas, they could not apply them in the given situation:

> *The rates of reactions are the same. Because, there is same amount of A and B* [reactants] in both vessels. *Temperature is also the same (298 K), therefore kinetic energy will be the same. Thus, reaction rates will be the same for both cases.* [UT-D-10]
>
> *For a reaction to occur, the reacting particles must collide with a correct orientation. The number of moles and temperature are the same for both vessels. However, in the bigger container particles can move more easily and collide with each other in an appropriate orientation. Therefore the reaction occurs faster in the second vessel* [the bigger vessel]. [Sa-D-16]

As quoted below, one university first year student had incorrect ideas about the order of a reaction and he confused two different equations; an equilibrium constant and a rate equation:

> *I agree with Sibel. Important things here are the concentrations and order of the reactions. The order of the reaction with respect to [A], [B], [C], and [D] is zero.*
> *Rxn= k. [C].[D]/[A].[B] Decrease of the concentration of reactants and increase of the concentration of products will be equal; therefore rates of reactions will be the same.* [UF-D-38]

6% of the SS, 4% of the UF, 3% of the UT were placed in this category.

(2-1-4) Reasoning based on mathematical formulae or equations (Mathematical Modelling)

A number of students (8% SS, 21% UF, 29% UT) referred to a mathematical formula in their reasoning and their responses were accompanied by an arithmetic calculation. As quoted below, students made an assumption about the order of the reaction and wrote a rate equation based on this assumption;

> *The rate of a reaction is directly proportional to the concentration of reactants... Reaction rate=V= k. [A].[B]*

> *For 1.vessel, M=n/V=4/1=4M*
> *For 2. vessel, M=n/V=4/3M*
> *According to the rate equation, we can say that the reaction under first set of conditions is faster than the reaction under second set of conditions.* [UT-D-22]

(2-1-5) Explanation in terms of theories of kinetics (e.g. the collision and/or transition state model)

15% of the SS, 42% of the UF, and 57% of the UT were placed in this category and most of them justified their responses based on the principles of the collision model. Here are some examples:

> *Reaction in the smaller vessel will occur faster. Because, decreasing volume of the container increases pressure and frequency of collisions. Thus, the probability of a collision having sufficient energy for a reaction to occur also increases. Therefore, the first reaction* [in the smaller vessel] *occurs faster than the second one.* [UT-D-11]

> *The reaction under the first set of conditions is faster than the other reaction. Because the volume of the first vessel is smaller, the pressure will be higher than the second one. An increase in pressure pushes the molecules closer together so that they collide more often. This results in an increase in the reaction rate.* [UF-D-23]

(0) All other responses

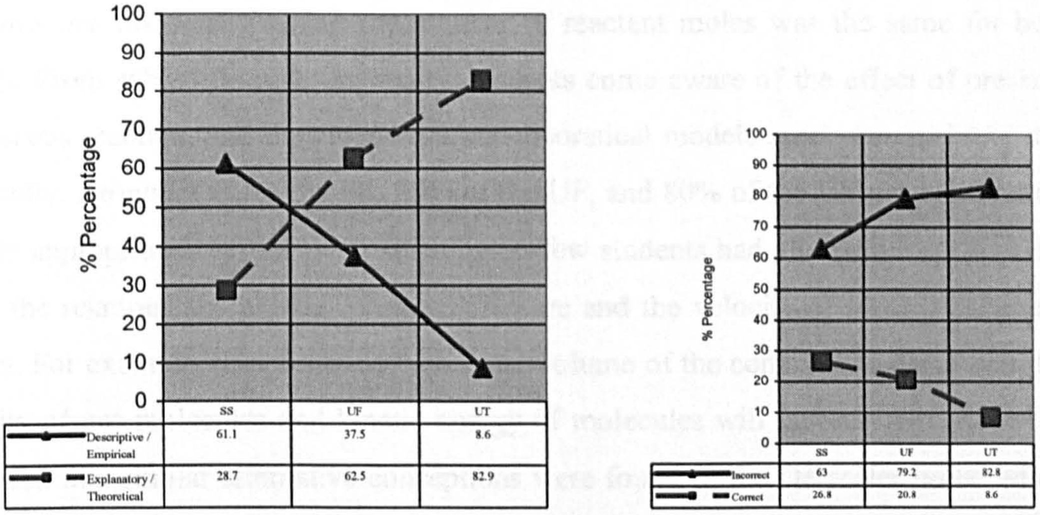
The category is allocated for incomprehensible responses or in cases where there is no response given in any part of the probe. 10% of the SS and 9% of the UT' responses were placed in this category.

Code	Category (Nature of response)	Example of response	SS *f* *(%)* (n=108)	UF *f* *(%)* (n=48)	UT *f* *(%)* (n=35)
1	**Descriptive/Empirical (Macroscopic Modelling)**		**66** ***61.1%***	**18** ***37.5%***	**3** ***8.6%***
1-2-1	Explanations in terms of macroscopic features of the event (leads to wrong answer)	The amount of reactants and/or temperature as key variables: E.g. reaction rates are the same, because the same amount of reactants is used. The volume of a container does not affect reaction rate.	23 *21.3%*	8 *16.6%*	2 *5.7%*
1-1-2	Explanations in terms of macroscopic features of the event (leads to correct answer)	Gaseous reactions occur faster in a small container. The higher the concentration of the reactants is, the faster the reaction proceeds.	43 *39.8%*	10 *20.8%*	1 *2.9%*
2	**Explanatory/Theoretical (Particulate and/or Mathematical Modelling)**		**31** ***28.7%***	**30** ***62.5%***	**29** ***82.9%***
2-2-3	Using theoretical models inappropriately	When the volume is decreased, the velocity of gas molecules increases and their interactions with each other will increase. That reduces the reaction time and raises the reaction rate.	6 *5.5%*	2 *4.1%*	1 *2.9%*

		Inappropriate usage of mathematical formulae: Rxn= k. [C].[D]/[A].[B] Decrease of the concentration of reactants and increase of the concentration of products are equal, therefore rates of reactions are the same.			
2-1-4	Reasoning based on mathematical formulae or equations	*Mathematical modelling*: The rate of a reaction is proportional to the concentrations/molarities of reactants For 1. Vessel MA=n/V=4M, MB=4M; Reaction rate= k.[A].[B]= k.4.4=16k For 2. Vessel MA=4/3, MB=4/3; Reaction rate = k. [A]. [B]=k.4/3. 4/3 =k 16/9k	9 *8.3%*	10 *20.8%*	10 *28.6%*
2-1-5	Explanation in terms of theories of kinetics (e.g. the collision and/or transition state model)	*Particulate modelling:* When the volume of the container is decreased, the frequency of collisions/effective collisions between reactants molecules will increase.	16 *14.8%*	20 *41.6%*	20 *57.1%*
0	**All other responses**		**11** ***10.2%***	**0** **0**	**3** ***8.6%***
0-0-6	No answer		0	0	0
	Incomprehensible/Other		11 *10.2%*	0	3 *8.6%*
		TOTAL	**108** ***100%***	**48** ***100%***	**35** ***100%***

Notes: The total number of respondents in "subcategories" may exceed the total number of the participants.

***Table 5.8** A coding scheme for the vessel probe*



Uncodeable	10.2	0	8.6
Total %	100	100	100

***Figure 5.5** Responses to the vessel probe*

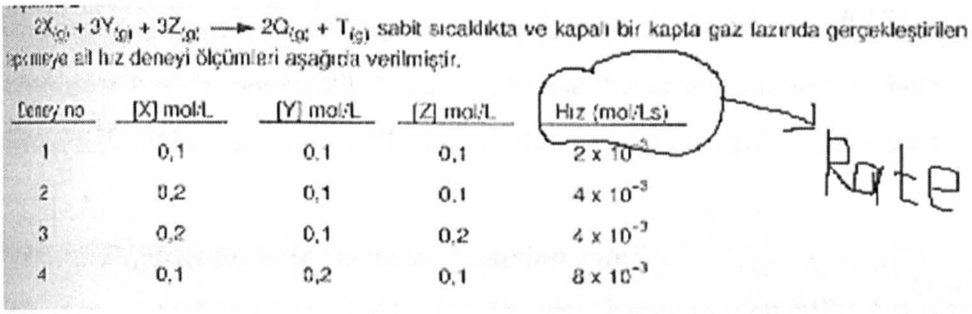
5.5.2 An overview of students' responses to the vessel probe

A chi-square analysis indicated that there was a statistically significant difference on the distribution of students' responses across educational levels ($\chi^2=36.713$, $df=2$, $p<0.01$). Similar to the results of the De-scaler probe, the results of the Vessel probe also revealed that the reasoning based on macroscopic properties decreased from school to university level, while the reasoning based on a theoretical model increased from school to university level (see Figure 5.5). School and university first year students tended to interpret the event drawing upon the macroscopic, observable features of the system (i.e. temperature, the amount of reactants, volume etc.). Many school students simply stated that "the first reaction is faster, because it occurs in a smaller container" by considering correlations between variables. Though most of the school students were aware of some factors affecting reaction rates (e.g. temperature, concentration, catalysts), a number of them did not accept volume or pressure as a factor affecting gaseous reactions rates. Several school students had lack of knowledge about some fundamental concepts in chemistry. For instance, the amount of substances, the number of moles and concentration were often not differentiated and in some cases, these terms were used interchangeably (e.g. *rates of reactions are the same, because the concentration of reactants are the same* [in fact the number of reactant moles was the same for both cases]). From school through university, students come aware of the effect of pressure on gaseous reaction, and they tended to use theoretical models more appropriately and frequently. Around 23% of the SS, 57% of the UF, and 80% of the UT used theoretical models appropriately in the given situation. A few students had alternative conceptions about the relationships between volume/pressure and the velocity of molecules/kinetic energy. For example, they believed "when the volume of the container is decreased, the velocity of gas molecules and kinetic energy of molecules will increase". It should be reminded that similar alternative conceptions were found in the De-scaler probe where students believed that "the velocity of particles in a concentrated solution will be higher than which of those in a dilute solution". Therefore, during teaching the effect of pressure on gaseous reactions, it should be emphasised that when pressure is increased or volume of the container is decreased, each particle collides more often: the particles do not sped up; they simply have less distance to each other.

It is worth underlining that interviews with students revealed that the settings of the probe may affect students' reasoning. For example, if a different reaction (e.g. $A_{(g)} + B_{(g)} \longrightarrow C_{(g)}$) was given with the same sets of data, students might have used different ideas. I suspect in that case the task would be more challenging and students may apply Le Chatelier's Principle to interpret the reaction rates. It would be interesting to investigate this issue in future studies in chemical kinetics.

5.6 EMERGING ISSUES FROM TEXTBOOK ANALYSIS IN THIS AREA OF KINETICS

The rate of a reaction is commonly expressed in three different forms: the average rate of reaction, the instantaneous rate of reaction, and the initial rate of reaction. Nevertheless, an analysis of school textbooks indicated that the differences between the notion of '*the initial rate*', '*the instantaneous rate*' and '*the average rate over a time interval*' are neglected. In most cases, only one term is used for the others, such as the 'initial rate' is termed as the 'average rate' or termed as the 'rate'. For instance, as presented in Tables 5.9 and 5.10, "initial rate" (in Turkish "Baslangic Hizi") is termed as "rate" (in Turkish "Hiz") in a question used in the school textbook (Kizildag & Dursun, 2000, p.103) and in the university laboratory book (Gurses & Bayrakceken, 1996, p.73). The question requires students to determine the rate law from ("initial") concentrations and ("initial") rates. Indeed, the results (students' responses to the reaction rate probe-B and the reaction rate-time probe) suggest that the students could not differentiate 'the instantaneous rate' and 'average rate'. They did not anticipate that a reaction may have different rate during a reaction, rather they tended to use the term reaction rate instead of average reaction rate, but actually what was meant was '*the instantaneous rate*'. The results revealed that students were more likely to compare two different reaction rates or to predict how a change in the initial concentration of reactant would affect the reaction rate, though they had limited knowledge about how the reaction rate changes from the beginning until the end of a reaction. One of the reasons might be that when comparing two different reactions rates, they are comparing the average rate (or comparing reaction time) of these reactions, however in the other case they need to appreciate the notion of instantaneous rate. The school textbook included the idea that the average rate of a reaction over a time interval can be calculated by dividing the change in concentration over that time period by the time interval, but did not include sufficient information about the notion of instantaneous rate. The idea that the instantaneous rate can be determined from a tangent line at the relevant instant of time on a graph of concentration versus time was emphasised at university level. It seems that at university level, the main emphasis was on the mathematical aspect of the reaction rate. The school textbook mainly emphasised on the initial and final state of a reaction, neglecting the process between these two states.



$2X_{(g)} + 3Y_{(g)} + 3Z_{(g)} \longrightarrow 2Q_{(g)} + T_{(g)}$ sabit sıcaklıkta ve kapalı bir kapta gaz fazında gerçekleştirilen
pkimeye ait hız deneyi ölçümleri aşağıda verilmiştir.

Deney no	[X] mol/L	[Y] mol/L	[Z] mol/L	Hız (mol/Ls)
1	0,1	0,1	0,1	2×10^{-3}
2	0,2	0,1	0,1	4×10^{-3}
3	0,2	0,1	0,2	4×10^{-3}
4	0,1	0,2	0,1	8×10^{-3}

Rate

***Table 5.9** An imprecise usage of a term in the school textbook: "initial rate" (Baslangic Hizi) is termed as "rate" (Hiz).*
Source: Kizildag & Dursun (2000, p.103)

	Deney I	Deney II	Deney III
C_{H_2} (mol/L)	0,10	0,20	0,20
C_{NO} (mol/L)	0,10	0,10	0,20
hız (mol/L s)	0,12	0,24	0,96

Rate

***Table 5.10** An imprecise usage of a term in the university laboratory book: "initial rate" (Baslangic Hizi) is termed as "rate" (Hiz).*
Source: (Gurses & Bayrakceken (1996, p.73)

The effect of pressure on gaseous reactions is neglected in the school chemistry textbook (Kizildag & Dursun, 2000, p.105-106). That might be one of the reasons that students argued that pressure and the volume of a container would not affect reaction rates. As discussed earlier students only recalled temperature, concentration, the nature of reactants and catalyst as factors affecting rates of reactions, but not the pressure for gaseous reactions.

5.7 SUMMARY AND DISCUSSION

One of the aims of this study was to explore the development of students' understanding of chemical kinetics in relation to relevant teaching at school and university level. This specifically involved investigating students' difficulties with specific concepts in chemical kinetics. In this chapter students' ideas about the relationships between the concentrations or pressure of reactants/products and rate of reactions have been discussed. The results showed that students often had scientifically incorrect ideas about chemical kinetics and did not frequently use theoretical models in their explanations as intended by the curriculum. The key findings are summarised and discussed below.

(i) Difficulties with the term "reaction rate"

The term "rate" is often used to describe the change in a quantity that occurs per unit of time. Students have experience of the term "rate" in their everyday lives (e.g. the rate of inflation, the rate of a car) or in their schooling (e.g. the rate of a reaction, the rate of dissolving). Nevertheless, drawing upon the results, several students had scientifically incorrect ideas about the definition of reaction rate. In other cases, they defined the term correctly, but could not apply this knowledge in a novel situation. It should be noted that there is a statistically significant difference between students in different educational levels ($\chi^2=28.019$, $df=2$, $p<0.01$). There was an increase in the number of students describing reaction rate as "a change in a quantity (e.g. the change in the concentration of the reactants) per unit of time" from school to university. However, a considerable number of students were not able to use those ideas in order to explain how the reaction rate would change during a reaction (this issue is also discussed in the next sub-sections). This might be the result of a straight memorisation of the definition of reaction rates. Indeed, the results revealed that, many school and university first year students confused the reaction rate and the amount of product (as seen in the ICM); or confused the reaction rate and reaction time (as seen in the CM). While reaction time is a constant quantity for a reaction, the rate of a reaction is dynamic during a reaction. With teaching at school and university level, students' assumptions about reaction rate move from the idea that "reaction rate is the period of time taken for a reaction to occur"; or believing that "reaction rate is the amount of product" to the scientifically acceptable ideas of reaction rates. Indeed, most of the university third year students defined reaction rate in terms of some quantities per unit of time. Some patterns emerge from students' responses. For example, it was found that there is a relationship between students' definition of the reaction rate and how the rate of the reaction changes with time. In addition, students who describe the rate of a reaction as the rate of formation of products often used the Increasing Model (IM) or the Increasing-Constant Model (ICM).

Partly following on from the point made in Section 5.5, the students had difficulties in differentiating the notion of "the initial rate", "the instantaneous rate" and "the average rate over the chosen time interval". One of the reasons would be that such concerns have little place in the curriculum. The results revealed that the word "reaction rate" was used differently in different contexts by students at different educational levels. In fact, when we (science educators) use terminology in kinetics, we make some assumptions (i.e. we also use the word in different meaning in different contexts), for example when we ask students "how a rise in temperature would affects the *reaction rate*", we assume that students understand what we are talking about (actually we are asking "how would a rise in temperature affects the *average reaction rate?*"), however we can not definitely be sure they really understand what we meant. Another example is that when we ask students "how would the *reaction rate* change during the reaction?" we actually mean "how would the *instantaneous rate* change during the reaction?" As science educators, we use the same term in different meaning in different contexts (i.e. in the examples given above, the reaction rate is used referring to the average reaction rate in one question and referring to the instantaneous rate in the other). My claim is that students' understanding of the notion of reaction rate and an appreciation of differences between these terms are essential for understanding other related concepts in kinetics. That would help students to predict how the reaction rate would change during a reaction or to understand "how" some factors may affect reaction rate. Otherwise students may form alternative conceptions. The point which is being made here is that during teaching the differences between these terms need to be acknowledged and that the teacher should monitor whether students understand the differences between these terms/concepts. This is one of the fundamental issues for teaching the notion of reaction rate.

(ii) Difficulties in explaining how reaction rate changes as the reaction progresses

The results of the "reaction rate probe-B" and the "reaction rate-time probe" indicated that at each educational level a significant number of students used scientifically incorrect ideas and had conceptual difficulties in explaining how the reaction rate changes during a reaction. Many students had difficulties in understanding that the reaction had the highest rate at the beginning of the reaction and the lowest rate at the end: rather they tended to think the opposite. The students' understanding might be constrained by the perceptual experiences from their daily lives or from the chemistry laboratory (Garnett *et al.*, 1995). For instance, the alternative conception mentioned above could have arisen from the observation in a chemistry laboratory that when during the reaction of magnesium with dilute acid, it usually takes some seconds for the surface oxide layer to dissolve before the surface of the metal is exposed to the dilute acid. Another reason for students' lack of knowledge or alternative conceptions would be that the approach used in the school textbook emphasised the initial and final state of a reaction, overlooked the dynamic nature of reaction system. In parallel with this, university courses mainly focused on mathematical aspects of the reaction system (e.g. see Section 5.6). The point which is being made here is that without being taught explicitly the nature of reaction system by referring to a particulate and/or mathematical model, students would have difficulties in understanding chemical kinetics. The results suggest that the dynamic nature of reaction system (during a reaction) should be more explicitly made in the design of teaching.

Another major difficulty the students experience was that while they provided appropriate explanation for the relationship between reaction rate and time in written or oral form, they failed to construct a symbolic representation for this relationship–e.g. by representing it on a graph (see the results of the reaction rate-time probe).

(iii) Consistency of individual student reasoning across different probes testing the same ideas

The "reaction rate probe-B" and the "reaction rate-time probe" were designed in such a way that they tested the same ideas in two different probes. The results suggest that there was some consistency in responses, but there were also some cases in which students' ideas were inconsistent. Generally speaking, there was little evidence showing that students offered explanations with a commitment to generalisability. Context (settings of the probes) apparently played a significant role in students' explanations of phenomena or events. For example, the interviews revealed that if a gaseous reaction with the same concentration vs. time graph was used in the reaction rate-time probe, some students might have used different models. Indeed, a student claimed that "if reactants are in the gas phase, the reaction rate will increase, but if reactants are in the liquid phase; reaction rate will be constant during the reaction, because solids and liquids are not written in a rate equation". The findings support the view that students' reasoning may significantly depending on the social and cultural contexts of questions and methods used (Palmer, 1997; Schoultz *et al.*, 2001; Ivarsson, Schoultz & Säljö, 2002).

(iv) Difficulties in providing appropriate explanation for the phenomenon/event

Many students had difficulties in providing appropriate explanation for the phenomenon/event. By "appropriate" I mean involving reference to particulate and/or mathematical modelling, both of which are introduced to these students in the curriculum. Many of them, particularly secondary school students, drew upon macroscopic modelling (which involves explanations in terms of macroscopic features of the phenomenon) when explaining the phenomenon/event in the de-scaler and the vessel probe. The students frequently used everyday life interpretations that were often tautologous– a generally unacceptable (or insufficient) mode of explanation in science. For instance, they may argue that "More concentrated acid removes more quickly limestone in the kettle, because it is stronger" or "...., because it is thicker".

It could be argued that the probes do not explicitly ask students for a scientific explanation, therefore students might legitimately give non scientific answers. However, one of the ideas tested through those probes was that whether students had an understanding of what constitutes a scientifically acceptable explanation and of scientific modes of thinking and talking (which is one of the objectives of the curriculum). The findings revealed that several students' explanations included characteristics of the macroscopic modelling rather than characteristics of theoretical models.

Drawing upon the De-scaler and the Vessel probes, a statistically significant difference was found between school and undergraduate students' reasoning in that the reasoning based on theoretical models gradually increased from school to university. Undergraduates' (particularly university third year students') responses were richer in the terminology and the range of justifications provided in that they used the principles of the collision or transition-state model more appropriately, frequently and confidently in their reasoning. Undergraduate students were more likely to use reasoning based on mathematical formulation. This result was not surprise since analysis of examination questions and questions in chemistry textbooks showed that overwhelmingly mathematical questions had been used to explore students' understanding of chemical kinetics. Nevertheless, some students tended to make over-generalisations of principles and ignoring some variables in a rate equation (i.e. order of the reaction) (also see Chapter 9, Section 9.1.3).

CHAPTER 6

STUDENTS' UNDERSTANDING OF THE EFFECT OF TEMPERATURE ON THE REACTION RATE

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6.0 INTRODUCTION

Two contextually different probes were designed to elicit students' ideas about the effect of temperature on the rate of a reaction. The *nitrogen monoxide probe-C* was framed in the language of chemical kinetics, whereas the *rusty water pipe probe* was framed in terms of the phenomenon of rusting where minimal contextual support was given within the probe. Using a combination of different types of probes testing the same ideas allowed me to explore how the contextual features of a probe affect students' ideas about the topic (see Sections 2.2 and 3.3.1). This chapter reports ideas used by students on these two probes, and describes how they change as a result of teaching. Each probe is discussed separately. The chapter also addresses emerging issues from the analysis of documentary evidence in this area of kinetics.

6.1 THE RUSTY WATER PIPE PROBE

The rusty water pipe probe which was framed in terms of the phenomenon of rusting aimed to elicit students' understanding of the effect of temperature on the reaction rate. Rusting was chosen because students would be familiar with the phenomenon in their everyday lives and the nature of rusting had been taught in primary and secondary schools. This probe was mainly designed to assess students' ability to deploy chemical knowledge and understanding to the given chemical phenomenon where the relevant concepts were not presented.

6.1.1 Data analysis and results

Since the probe was phenomenologically framed, coding scheme-A (see Section 3.7) was applied on the data set. The coding scheme consisted of three main categories: (1) Descriptive/ Empirical, (2) Explanatory/Theoretical, and (3) All other responses. These three main categories include eleven sub-categories. In the following sections those three main categories, and identified sub-categories, are discussed. Analysis of students' responses is summarised in Table 6.1.

(1) Descriptive/Empirical (Macroscopic Modelling)

Responses in this category are based on explanations, which identify one or more key causal variables without explaining underlying mechanisms to account for the phenomenon, or the justification involves prototypical examples of everyday phenomena. These variables are observable or taken for granted and explanations are mostly in the form of cause-and-effect relationships. For instance, students considered that rusting is caused by heat or by hot water. Explanations included re-description of the phenomenon or restatements of the information provided in the probe. The sub-categories are discussed below.

(1-1-1) Hot water/heat as a key factor

Heat and/or hot water was seen as a key factor for the phenomenon. Of the 108 secondary school students nine (8%) were placed into this category and some typical quotations are given below:

> *Hot water damages/wears out the water pipe.* [Sb-D-24]
>
> *The hot water pipe was destroyed by heat.* [Sb-D-06]

For these school students, the structure of the pipe was changed or modified by the heat or by hot water; however they did not mention a reaction between iron and oxygen/water. Some students seemed to treat rusting as physical changes in form or state (e.g. they suggested metal pipe wearing out) rather than as an example of a chemical reaction. Such students might have limited knowledge about the role of reactants (iron/water/oxygen) in rusting (cf. Hesse & Anderson, 1992). In some cases, students had a preference for prototypical examples of everyday phenomena or metaphors; for instance, they considered rusting as something like decay. Here is an example:

> *Heat results in rust. Temperature destroys the structure of some substances. That is why we keep our foods in the fridge. Foods spoil very easily when left out at room temperature.* [Sa-D-15]

(1-2-2) Cold as a key factor

Two school students did not agree with that the hot water pipe would get rustier than the cold water pipe; rather they thought the opposite. These students answered the probe by using reasoning developed from their everyday experiences. As one of the students expressed it:

> *In my opinion, the cold water pipe would get rustier than the hot water pipe. For example, at underground steel/iron gets rustier more quickly, because underground is cold. Therefore, the cold water pipe gets rustier than the hot water pipe.* [Sa-D-16]

The literature on school students' ideas about rusting as an example of chemical change also suggest that students consider "cold" or "coldness" as a necessary factor for rusting (e.g. see Scott *et al.*, 1994). One of the issues here is that the intuitive explanations which derived often very logically from students' observations and experiences in the natural world do not concur with accepted scientific theories. Accordingly, this different way of explanations (macroscopic modelling vs. theoretical modelling) should be addressed through teaching.

(1-2-3) Water vapour/moisture as a key factor

The water vapour was seen as a key factor by those students who were placed in this category. The students may use the term "reaction" without mentioning a reaction between iron and oxygen/water or underlying mechanism of rusting. 16% of the SS, 4% of the UF and 3 % of the UT were placed in this category and some typical responses are given below:

> *Little drops of water formed on the hot water pipe as a result of heat. That results in rust.* [Sc-D-42]
>
> *Due to heat, there would be more water vapour on the hot water pipe; therefore it gets rustier than the cold water pipe.* [Sc-D-48]
>
> *That temperature differences between inside and outside of the hot water pipe makes more moisture on the pipe. Therefore it gets rustier than the cold water pipe.* [Sb-D-18]

Here, explanations are in the form of cause-and-effect relationships. The students emphasised that more water vapour or moisture (in the air) collected (or condensed) on the hot water pipe than on the cold water pipe and accordingly that led to more rust.

(1-2-4) Explanations in terms of other macroscopic variables

Some students, mostly school students (12% SS and 2% UF), used explanations in terms of other macroscopic variables. They did not use the term "reaction" in their responses or did not mention the sub-microscopic processes taking place during rusting. The macroscopic variables were varied and included the followings:

> *Due to a higher temperature, the pipe expands and contracts that makes rust. Hot water makes the pipe softer.* [Sc-D-20]
>
> *Temperature differences between the inside and the outside of the hot water pipe causes more rust.* [Sb-D-09]
>
> *There might be less antirust paint on the hot water pipe.* [Sb-D-24]

In some cases, it was not clear from students' written responses whether rust is formed inside or outside of the pipe or through the pipe.

> *Temperature makes pressure* [A rise in temperature increases pressure]. *As a result of pressure, more rust is formed.* [Sb-D-15]

(1-1-5) A rise in temperature increases reaction rate

Responses in this category included accepted ideas but were less explicit than responses in the sub-category (2-1-9). Students in this category focused on the idea that an increase in temperature increases reaction rates without justification, whereas the students in the sub-category (2-1-9) describe the chemical reaction between iron and oxygen/water or justify their answers according to a chemical equation. 17% of the SS, 13% of the UF and 9% of the UT' responses were placed in this category.

> *...Temperature is one of the factors affecting reaction rate. A rise in temperature increases the rate of a reaction.* [Sc-D-06]
>
> *The hot water pipe is warmer. Whilst, heat increases the reaction rate, it* [the hot water pipe] *rusts more quickly.* [Sb-D-26]

It could be argued whether these statements are descriptive or theoretically embedded. Since there is no evidence from students' written responses explicitly showing that they are theoretically embedded, such responses were placed in the *Descriptive / Empirical (Macroscopic modelling)* category. These explanations might be a kind of tautological restatements of available information in the task.

(2) Explanatory/Theoretical (Particulate and/or Mathematical Modelling)

This category incorporates those responses in which students use some form of model or causal mechanism to account for the phenomenon. The causal mechanism proposed might involve a chain of events between variables or the evocation of formally defined theoretical constituents in chemistry. Explanation goes beyond descriptive accounts of the phenomenon by drawing on theoretical entities within established chemical ideas. The sub-categories are discussed below.

(2-2-6) A rise in temperature increases the rate of endothermic reactions

2% of the SS, 17% of the UF, and 6% of the UT' responses centred on the ideas that an increase in temperature increases the rate of endothermic reactions and that oxidation/rusting was seen as an endothermic reaction:

> *...Since the reaction is endothermic, an increase in temperature shifts the equilibrium towards the formation of products side. That means much reaction will be occurring and more rust will be formed.* [Sb-I-02]

This student (as quoted above) appears to inappropriately use Le Chatelier's principle.

> *...The reaction between the water pipe and oxygen from its surroundings is an endothermic reaction which needs energy to proceed. Due to a higher heat, it reacts easily with oxygen. Since the reaction rate is directly proportional to temperature, the hot water pipe will rust more than the cold water pipe.* [UF-D-05]
>
> *Oxidation is an endothermic reaction.* $2Fe + O_2 + Heat \rightarrow 2FeO$ *This reaction needs energy to occur; therefore, the hot water pipe gets rustier than the cold water pipe.* [UF-D-02]

It seemed that these students had alternative conceptions about some basic thermodynamic concepts. The underlying idea behind those responses was probably that heat/energy is needed to initiate an endothermic reaction, but it is not needed for an exothermic reaction. In other words, they may have thought an endothermic reaction cannot be spontaneous, as reported in earlier studies on students' ideas about thermodynamics (Johnstone *et al.*, 1977b; Sozbilir, 2001).

(2-2-7) Rust is formed inside the pipe (possibly misunderstood the question)

Some students (8% SS, 6% UF, and 9% UT) misunderstood the probe; they thought the inside of the pipe would get rusty. A few students reasoned that the solubility of gases increases or decreases with temperature. Here are some examples;

> *[...] temperature increases the reaction rate....Oxygen reacts with iron to form rust (iron oxide):* $Fe_{(s)} + 1/2O_{2(g)} \rightarrow FeO$ *(rust)*

> *As a result of decomposition of water $O_{2(g)}$ will be formed: $H_2O_{(g)} \rightarrow H_{2(g)} + O_{2(g)}$ An increase in temperature increases the number of evaporated water molecules. Thus more molecules* [$O_{2(g)}$] *reacts with iron to form FeO.... While the average kinetic energy of molecules increases with temperature, H_2O molecules move faster and reaction occurs faster.* [UF-D-41]

In this quotation above, though there are some scientifically correct ideas about chemical kinetics, the subject also have alternative conceptions in that she confuses decomposition of water ($H_2O_{(l)} \rightarrow H_{2(g)} + O_{2(g)}$) and evaporation ($H_2O_{(l)} = H_2O_{(g)}$). In fact, decomposition of water is a chemical change and requires much greater energy than evaporation.

> *Hot water increases the reaction between iron and water. Iron will get heat* [energy] *and will get rustier due to oxygen in the water. Solubility of gases decreases with temperature; therefore the solubility of oxygen will decrease and it will react with iron. Gases dissolve in cold water. Since there won't be evaporation, iron and water will not react so much, thus less rust would be formed.* [UF-D-23]

Again, this student above may confuse the solubility of gases and evaporation. The solubility of gases decreases with an increase in temperature, but this may not apply to the current situation, because volume remains constant ($P_1/T_1 = P_2/T_2$).

Three SS who had assumed that the cold water pipe would get more rusty than the hot water pipe, justified it by saying that "the solubility of gases decreases with temperature". As two school students put it:

> *Hot water may be a factor to increase the formation of Iron Oxide. However, my opinion is different. The solubility of gases decreases with temperature, there would be less oxygen in hot water than cold water. In other words, there would be less interaction between oxygen and* [the hot] *water pipe and less iron oxide would be formed. Therefore, the cold water pipe gets rustier than the hot water pipe.* [Sa-D-10]

> *I think the cold water pipe gets rustier, because more oxygen dissolves in the cold water.* [Sa-D-5]

(2-1-8) Reasoning based on mathematical formulation (Mathematical Modelling)

Mathematical Modelling consists of physical properties (e.g. concentration, temperature) and mathematical functions represented in the form of an equation (e.g. $Rxn = k.[A]^m$). Graphs can also be used to present equation relationships (e.g. Maxwell-Boltzmann distribution-Kinetic energy distribution). In some cases, students interpreted the phenomenon in terms of mathematical formulae (e.g. the Arrhenius equation). For example:

> *...In terms of the rate equation, reaction rate depends on the rate constant which is a temperature dependent constant. The value of the rate constant increases, as temperature is raised.* $k = A \,.e^{-Ea/RT}$ [UT-D-35]

4% of the SS and 9% of the UT justified their answers based on mathematical formulae or graphs. Interviews with students revealed that many students had conceptual difficulties on the mathematical relationship between reaction rate and temperature. This relationship was perceived being directly proportional (e.g. "*The reaction rate is directly proportional to temperature").* I suspect language might be one of the problems here. Another reasons might be that in the school textbook it is emphasised that "*the rate constant (k) depends on temperature, catalysts and the nature of reactions*" (Kizildag & Dursun, 2000, p.103) and since the rate of a reaction is proportional to the rate constant (k), the students may reach the conclusion that the rate of a reaction is directly proportional to temperature. It should be noted that the Arrhenius equation is presented to students at university level. University students are, therefore, more likely to conceptualise the mathematical relationships between temperature and reaction rate.

(2-1-9) A rise in temperature increases the rate of rusting/oxidation

As mentioned earlier the difference between the sub-category (1-1-5) and (2-1-9) is that the responses in the later category included the idea that iron combines with oxygen and/or water. 15% of the SS, 48% of the UF and 40% of the UT' responses were placed in this category. Some examples for these responses are given below:

> *Rust forms as a result of a chemical reaction between iron and oxygen. An iron-oxide compound is formed. The rate of the reaction increases with the rise of temperature. Temperature favours reactions between molecules.* [UF-D-37]

In some cases, it was not clear from students' written responses whether rust is formed inside or outside of the pipe.

> *The reaction between iron and water is:* $2Fe_{(s)} + 3H_2O_{(l)} \rightarrow Fe_2O_{3(s)} + 3H_{2\,(g)}$
> *The reason why more rust is formed on the hot water pipe is that an increase in temperature increases reaction rate.* [UF-D-15]

The distinction between sub-categories (2-1-9) and (2-1-10) is one of elaboration (as defined below). In category (2-1-10), the responses included more elaborated ideas about the usage of theoretical models. In the category (2-1-9), though students were aware of the reactions between iron and oxygen or water, yet they did not give details of this reaction in a sub-microscopic level. For example, as quoted above one of the undergraduates [UF-D-15] expressed the reaction between iron and water by means of a chemical equation and justified the answer by stating, "*an increase in temperature increases reaction rate*". However, the response does not involve any idea why a rise in temperature increases reaction rates or not involve underlying mechanisms to account for the phenomenon. On the other hand, the responses in category (2-1-10) included more elaborated ideas and included justification based mainly upon the principles of the collision or transition state model.

(2-1-10) Explanation in terms of theories of kinetics[1] (e.g. the collision and/or the transition state model)

This category incorporates those responses in which students use mainly the principles of the collision and/or transition state model in their reasoning. The emphasis is on the sub-microscopic processes taking place during the reaction (rusting/oxidation) and the relationship of such processes to the macroscopic behaviour of the reaction. Here is an example:

> *Rusting is an oxidation reaction...The reaction rate increases with the rise of temperature...An increase in temperature increases the speed of molecules and also increases the kinetic energy of molecules. That increases the amount of substances overcome the activation energy barriers* [per unit of time]. [UT-D-21]

6% of the SS, 4% of the UF, 31% of the UT' responses were placed in this category.

(0) All other responses

This category is allocated for incomprehensible responses or in cases where there is no response given in the probe. As shown in Table 6.1, 13% of the SS, 8% of the UF and 3% of the UT' responses were placed in this category.

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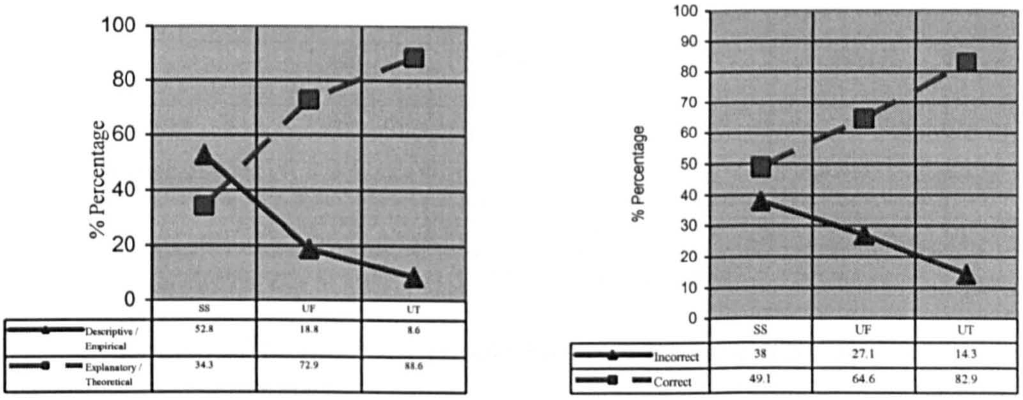
[1] It is important to note that explanations in the mathematical modelling category (2-1-8) are also embedded in theories of kinetics, but in mathematical or symbolic level. Moreover, responses in the category (2-1-9) might be embedded in the theories of kinetics. The differences between category (2-1-9) and (2-1-10) were discussed earlier.

Code	Category (Nature of response)	Example of response	SS *f* *(%)* (n=108)	UF *f* *(%)* (n=48)	UT *f* *(%)* (n=35)
1	**Descriptive/Empirical (Macroscopic Modelling)**		**57** ***52.8%***	**9** ***18.8%***	**3** ***8.6%***
1-1-1	Hot water/Heat as a key factor	Hot water destroys/tarnishes/wears out/ hazards/corrodes the water pipe.	9 *8.3%*	0	0
1-2-2	Cold as a key factor	For example, at underground, steel/iron gets rustier more quickly, because underground is cold. Therefore, the cold water pipe gets rustier than the hot water pipe	2 *1.9%*	*0*	*0*
1-2-3	Water vapour/moisture as a key factor	There would be more moisture/humid/water vapour on the hot water pipe; therefore it gets rustier than the cold water pipe. Temperature changes/differences makes more moisture on the hot water pipe.	17 *15.7%*	2 *4.1%*	1 *2.8%*
1-2-4	Explanation in terms of other macroscopic variables	Due to a higher temperature, the pipe expands and contracts that makes rust. Higher pressure inside of the hot water pipe results in more rust. When we stop to use hot water, the pipe suddenly gets colder and after a while when we start to use hot water, the pipe gets hotter again. Thus, that temperature change results in rust.	13 *12%*	1 *2%*	*0*
1-1-5	A rise in temperature increases reaction rate	A rise in temperature increases reaction rate. Heat increases the reaction rate	18 *16.7%*	6 *12.5%*	3 *8.6%*
2	**Explanatory/Theoretical (Particulate and/or Mathematical Modelling)**		**37** ***34.3%***	**35** ***72.9%***	**31** ***88.6%***
2-2-6	A rise in temperature increases the rate of endothermic reactions.	Oxidation/rusting is an endothermic reaction. Endothermic reactions occur faster at a higher temperature. $2Fe+O_2 + Energy \rightarrow 2FeO$ Oxidation is an endothermic reaction, which needs energy to occur. Therefore, the hot water pipe gets rustier than the cold water pipe.	2 *1.9%*	8 *16.7%*	2 *5.7%*
2-2-7	Rust is formed inside of the pipe (misunderstood the question)	The solubility of gases increases/decreases with an increase in temperature.	9 *8.3%*	3 *6.3%*	3 *8.6%*
2-1-8	Reasoning based on mathematical formulation	Explanation in terms of a rate equation and/or Arrhenius equation: In terms of the rate equation, reaction rate depends on rate constant which is a temperature dependent constant. The value of rate constant increases as temperature increases. $k = A .e^{-Ea/RT}$	4 *3.7%*	0	3 *8.6%*
2-1-9	A rise in temperature increases the rate of rusting/oxidation.	Iron reacts with oxygen faster at a higher temperature. $2Fe+ O_2 \rightarrow 2FeO$ Iron reacts with water faster at a higher temperature. $2Fe+3H_2O \rightarrow Fe_2O_3 +3H_2$	16 *14.8%*	23 *48%*	14 *40%*
2-1-10	Explanation in terms of theories of kinetics (e.g. the collision and/or transition state model)	At higher temperature, molecules move faster. A rise in temperature increases the speed of molecules and increases the kinetic energy of molecules. The greater proportion of molecules will now have the activation energy for the reaction & so have sufficient energy when they collide.	6 *5.6%*	2 *4.2%*	11 *31.4%*
0	**All other responses**		**14** ***13%***	**4** ***8.3%***	**1** ***2.9%***
0-0-11	No answer		5 *4.7%*	2 *4.2%*	0
	Incomprehensible/Other		9 *8.3%*	2 *4.2%*	1 *2.9%*
TOTAL			**108** ***100%***	**48** ***100%***	**35** ***100%***

Notes: n = number of participants; f = frequency; % = percentage of participants

In some cases, responses included characteristics of more than one subcategory; therefore they were coded into different subcategories and the total number of respondents in "subcategories" may exceed the total number of the participants.

Table 6.1 *A coding scheme for the rusty water pipe probe*



Uncodeable	13	8.3	2.9
Total %	100	100	100

Figure 6.1 *Percentage of responses to the rusty water pipe probe*

6.1.2 An overview of students' responses to the rusty water pipe probe

This section has reported students' ability to deploy chemical knowledge within a relevant context where the stimuli presented to students are an everyday chemical phenomenon rather than the concepts used in chemistry to explain it. The intention was to investigate in what way students analyse the phenomenon (descriptive/ empirical vs. explanatory/ theoretical) and to find out how appropriately they deploy their scientific knowledge and understanding when minimal contextual support is given within the probe. It was found that there is a statistically significant difference between school and undergraduate students' reasoning in that the reasoning based on theoretical models gradually increased from school to university level (χ^2=37.419, *df*=2, $p<0.01$) (see Table 6.2) and undergraduates' responses were more likely to have scientifically correct ideas. Around half of the school students interpreted the phenomenon in terms of its observable features and did not make links between chemical concepts and the chemical phenomenon (see Figure 6.1). Many school students did not invoke some scientific terms or principles such as atoms, molecules or the principles of the collision model in their explanations (even though they had been emphasised in the chemistry courses), a finding similar to that of Andersson (1986). Nevertheless, from school to university, there was, not surprisingly, a considerable progression in the number of students who justified their answers by referring to a theoretical model (see Figure 6.1). Around 24% of the SS, half of the UF, and 74% of the UT appropriately attributed a theoretical model to the phenomenon.

	SS	UF	UT	*Total*
Descriptive/Empirical	57	9	3	69
Explanatory/Theoretical	37	35	31	103
Total	94	44	34	172

* *Statistically significant difference is observed:* $\chi^2=37.419$, *df=2*, $p<0.01$

***Table 6.2** Chi-square test results for the rusty water pipe probe*

Many students appeared to focus on giving a correct answer rather than explaining the underlying reasoning. For instance, they stated that "a rise in temperature increases the reaction rate" or that "temperature is one of the factors affecting reaction rate; that is why the hot water pipe gets more rust". One of the reasons might be that the curriculum, classroom activities and assessment (including in the Student Selection Examination (ÖSS)) focused mainly on recalling definitions and algorithmic problems (see Chapter 4, textbook analysis[2]; students' notes; examination questions). Indeed, analysis of the examination questions revealed that many questions tested recalling facts about concepts or tested how to manipulate data to solve problems or tested students' mathematical skills. Phenomenologically framed questions were ignored in the examination questions. Furthermore, an analysis of the scientific knowledge presented in the curriculum (both school and undergraduate curriculum) indicates that in most cases, theoretical models are disconnected from chemical phenomena and everyday practices (also see Section 6.3).

6.2 THE NITROGEN MONOXIDE PROBE-C

The nitrogen monoxide probe, a conceptually framed probe, included four sub-questions, one of which (the nitrogen monoxide probe-C) asked students how a rise in temperature would affect the rate of the given reaction:

---

[2] The main emphasis of chemical kinetics courses seems to mainly focus on the quantitative aspect of the subject.

$$2NO_{(g)} \xrightarrow{Pt} N_{2(g)} + O_{2(g)} \quad \Delta H<0 \text{ (Exothermic).}$$

6.2.1 Data analysis and results

As discussed in Section 3.7, the same coding scheme was used for the probes testing the same ideas, in order to compare the students' responses across the probes. Therefore, although the probe was conceptually framed, the coding scheme-A was applied on the data set. The coding scheme-A encompassed three main categories: (1) descriptive/empirical, (2) explanatory/theoretical and (3) all other responses. These three main categories include seven sub-categories. In the following sections those three main categories, and identified sub-categories, are discussed. The responses are summarised and illustrated in Table 6.3, Figures 6.2 and 6.3.

(1) Descriptive/Empirical (Macroscopic Modelling)

This main category includes explanations which may involve a kind of tautological restatements of available information in the probe and do not involve an underlying mechanism for explaining the event. Around half of the SS, 17% of the UF, and 9% of the UT were placed in this category.

(1-1-1) A rise in temperature increases the rate of (exothermic) reactions

This category is mainly based on the idea that "an increase in temperature increases the reaction rate". Responses in this category included scientifically correct ideas but were descriptive in that they did not involve an underlying mechanism for explaining the claim. Some common responses are as follows:

> *A rise in temperature increases the rate of exothermic reactions.* [Sc-D-33]
>
> *An increase in temperature increases the reaction rate, because temperature is one of the factors affecting the rate of reactions.* [Sb-D-09]

Neither response was accompanied by a further explanation; therefore it was not easy to investigate the underlying ideas for their responses. Only one student used analogical reasoning to justify his answer.

> *...Temperature is always important... For example, when we cook an egg over lower flame/heat, it takes a longer period of time, but if we cook an egg over a higher flame, it takes less time to cook.* [Sc-D-31]

Around half of the SS, 17% of the UF and 9% of the UT were placed in this category.

(1-2-2) A rise in temperature decreases the rate of reactions

Two school students stated that an increase in temperature would decrease the reaction rate without justifying their answers.

(2) Explanatory/Theoretical (Particulate and/or Mathematical Modelling)

Students in this category justified their responses in terms of established chemical ideas and theoretical models. 35% of the SS, 75% of the UF, and 89% of the UT were placed in this category. The sub-categories are discussed below.

(2-2-3) A rise in temperature does not affect the rate of (exothermic) reactions

A few students (5% SS, 13% UF and 9% UT) argued that the rate of this reaction would not be affected by an increase in temperature. However, it should be noted that most of those students believed that a rise in temperature would increase the rate of endothermic reactions (e.g. see the first quotation below). The justifications for their answers were varied and some typical responses are given below.

> *Since the reaction gives out heat, increased temperature would not affect the reaction rate. However, if a reaction took heat* [from its surroundings]*; the reaction rate would increase with temperature. Because a rise in temperature increases the rate of a reaction that takes in heat.* [UF-D-17]
>
> *I don't think an increase in temperature would affect the rate of this reaction, because it is an exothermic reaction. While it gives off heat to its surroundings, temperature* [changes] *does not affect this reaction* [rate]. [UF-D-02]
>
> *This reaction is an exothermic reaction, which gives off heat to its surroundings. Therefore, an increase in temperature would not change the reaction rate.* [UT-D-29]

The underlying idea behind those responses was probably that exothermic reactions release energy; therefore they do not need energy to proceed and a rise in temperature would not affect the reaction rate. Students seemed to confuse the chemical kinetic concepts with thermodynamic concepts. Indeed, there is considerable evidence to show that students believe that endothermic reactions could not be spontaneous; however exothermic reactions could be spontaneous (e.g. Johnstone *et al.*, 1977b). Alternatively, the conceptual difficulties would arise due to a misapplication of Le Chatelier's principle.

In addition, a few students gave reasons based on mathematical formulae. As one of the UF put it:

> *In my opinion, a rise in temperature would not affect the* [reaction] *rate, because the* [reaction] *rate is independent of temperature.* [Reaction] *rate only depends on the rate constant and molarities.* [UF-D-4]

The student seemed to apply the formula (i.e. the rate equation) mechanically. Though she was aware that the reaction rate depends on the rate constant and concentrations, yet she was not aware that in the rate equation the temperature dependent quantity is the rate constant and that the reaction rate changes with a change in temperature because the rate constant will be affected.

(2-2-4) An increase in temperature decreases the rate of exothermic reactions (The misapplication of Le Chatelier's Principle)

A high percentage of students, mainly UF, (6% SS, 56% UF, 29% UT) argued that when temperature was increased, the rate of exothermic reactions would decrease, however the rate of endothermic reactions would increase with an increase in temperature. These conceptual difficulties arose because they tried to interpret the reaction rate and extent of the reaction by using Le Chatelier's principle and thus confused the concept of reaction rate and chemical equilibrium (cf. Hackling & Garnett, 1985; Banerjee, 1991; Quilez & Solaz, 1995). Some common explanations are of the following type:

> *Since the reaction is an exothermic reaction, an increase in temperature would affect opposite side and it decreases the reaction rate. The reaction gives out heat; therefore a rise in temperature would decrease the reaction rate.* [UF-D-03]
>
> *Because this reaction is an exothermic reaction, it will give off heat to its surroundings. If we give heat to system which gives off heat to its surroundings, we will be decreasing the rate of the reaction.* [UT-D-17]

The results revealed that the students had misapplied Le Chatelier's principle and they were not aware of the limitations on the use of the principle. Similar findings have been reported by Johnstone *et al.* (1977a); Banerjee (1991); Garnett *et al.* (1995) and Quilez & Solaz (1995).

(2-1-5) Reasoning based on mathematical formulation (Mathematical Modelling)

This category is allocated to cases where justification involves algebra or mathematical formulae (e.g. by using the Arrhenius equation). 4% of the SS and 23% of the UT' responses consist of mathematical functions represented in the form of an equation. For example:

> *$k = A.e^{-Ea/RT}$, $\ln k = \ln A - E_a/R.T$, if we give some value to T, we can see the value of k increases with T. As $V=k.[NO]^0$, the rate of the reaction would increase with an increase in the rate constant, k. In any case whether it is an endothermic or exothermic reaction, the rate of the reaction increases with an increase in temperature.* [UT-D-20]
>
> *In the rate equation the temperature dependent quantity is the rate constant (k), therefore an increase in temperature increases the reaction rate. $k \alpha T$.* [UT-D-07]

Interview with the student (UT-I-07) indicated that what she meant by ($k \alpha$ T) was that the rate constant is proportional to temperature (k= f(T)) and she was aware of the Arrhenius equation.

(2-1-6) Explanation in terms of theories of kinetics (e.g. the collision and/or transition state model)

This category incorporates those responses in which students appropriately use the principles of the collision model and/or transition state model in their reasoning. The emphasis is on the sub-microscopic processes taking place during the reaction and the relationship of such processes to the macroscopic behaviour of the reaction. 22% of the SS, 6% of the UF and 37% of the UT' responses were placed in this category and some typical examples are quoted below:

> *Whether the reaction is exothermic or endothermic, the kinetic energy of molecules, the frequency of collisions and the frequency of effective collisions increases with temperature.* [UF-D-34]
>
> *When the temperature is increased, the kinetic energy of molecules will increase and as a result the rate of the reaction will increase.* [Sb-D-12]

(0) All other responses

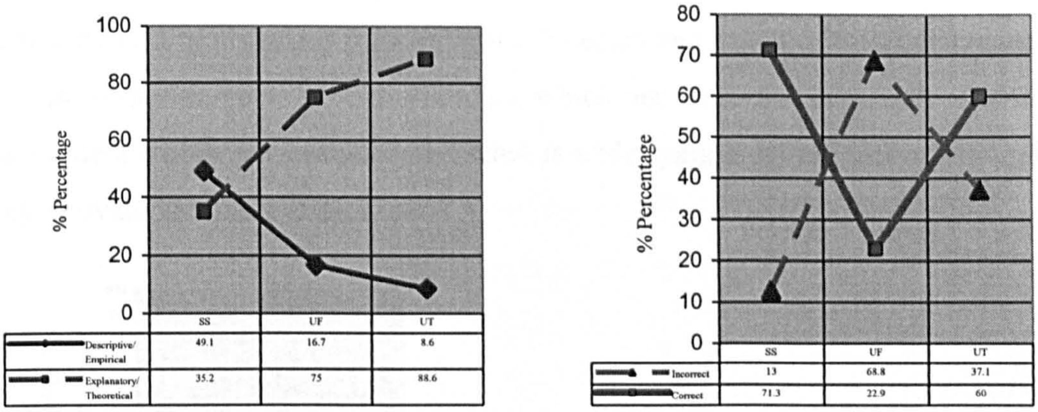
This category is allocated for incomprehensible responses or in cases where there is no response given in the probe. 16% of the SS, 8% of the UF and 3% of the UT' responses were placed in this category.

Code	Category (Nature of response)	Example of response	SS *f* % (n=108)	UF *f* % (n=48)	UT *f* % (n=35)
1	**Descriptive/Empirical (Macroscopic Modelling)**		**53** ***49.1%***	**8** ***16.7%***	**3** ***8.6%***
1-1-1	An increase in temperature increases reaction rate.	Temperature is one of the factors that affect the rate of reaction. An increase in temperature increases the rate of exothermic reactions. An increase in temperature increases both exothermic and endothermic reactions rate. Reaction rate always increases with increasing temperature.	50 *46.3%*	8 *16.6%*	3 *8.6%*
		Analogical Reasoning: An egg cooks faster over a higher flame.	1 *1%*	0	0
1-2-2	An increase in temperature decreases reaction rate.	An increase in temperature decreases reaction rate.	2 1.8%	0	0
2	**Explanatory/Theoretical (Particulate and/or Mathematical Modelling)**		**38** ***35.2%***	**36** ***75%***	**31** ***88.6%***
2-2-3	A rise in temperature does not affect the rate of (exothermic) reactions	This reaction is an exothermic reaction, which gives off heat to its surroundings. Therefore, an increase in temperature would not change the reaction rate. In my opinion, a rise in temperature would not affect the [reaction] rate, because the [reaction] rate is independent of temperature. [Reaction] rate only depends on the rate constant and molarities.	5 *4.6%*	6 *12.5%*	3 *8.6%*
2-2-4	An increase in temperature decreases exothermic reactions rate	Misapplication of Le Chatelier's Principle: An increase in temperature shifts the equilibrium to the reactants side. Therefore for exothermic reactions, reaction rate decreases with temperature. With the rise in temperature increases the rate of endothermic reactions rate, yet it decreases the rate of exothermic reactions.	6 *5.5%*	27 *56.3%*	10 *28.6%*
2-1-5	Reasoning based on mathematical formulation, Formal/Mathematical	*Mathematical Modelling:* Explanation in terms of rate equation, Arrhenius equation: $k=f(T)$ $k = A\ .e^{-Ea/RT}$	4 *3.7%*	0	8 *22.9%*
2-1-6	Explanation in terms of collision and/or transition state model	*Particulate Modelling:* When the temperature is increased, the kinetic energy of molecules will increase and as a result the rate of the reaction will increase.	24 *22.2%*	3 *6.3%*	13 *37.1%*
0	**All other responses**		**17** ***15.7%***	**4** ***8.3%***	**1** ***2.8%***
0-0-7	No response		3 *2.7%*	1 *2%*	0
	Incomprehensible		14 *12.9%*	3 *6.3%*	1 *2.8%*
TOTAL			**108** ***100%***	**48** ***100%***	**35** ***100%***

Table 6.3 A coding scheme for the nitrogen monoxide probe-C

6.2.2 An overview of students' responses to the nitrogen monoxide probe-C

The results indicated that there was a statistically significant difference between students' responses across different educational levels ($\chi^2=35.491$, $df=2$, $p<0.01$) in that undergraduates were more likely to use reasoning based on a theoretical model. Nonetheless, many of them, particularly UF, used theoretical models inappropriately in the given situation. The confusion between kinetic and thermodynamics was seen from students' responses. Furthermore, students confused kinetic concepts with chemical equilibrium. Such students attempted to apply general rules, such as Le Chatelier's Principle, to particular cases ignoring any conditions on its applications or ignoring its limitations.



Uncodeable	15.7	8.3	2.8
Total %	100	100	100

Figure 6.2 Percentage of responses to the nitrogen monoxide probe-C

When the students dealt with the probe, around 71% of the school and 60% of the university third year students' responses included correct ideas, only 23% of the university first year students' responses included correct ideas. When results (the correct answers) were graphed, a U-shaped performance curve appeared (see Figures 6.2 and 6.3). As students' responses were examined, it was apparent that school and undergraduate students' responses were different in that the reasoning based on macroscopic properties decreased from school to university level. Though the majority of the SS (71%) correctly predicted how a change would affect the reaction rates, they mainly justified their claims in terms of macroscopic modelling. By contrast, most of the undergraduates used various theoretical models in their responses. Interestingly, although majority of the university first year students gave explanations based on theoretical models, only a small number of them had achieved a correct answer. Perhaps surprisingly, only 6% of the UF used theoretical models appropriately. Nevertheless, the proportion of students which correctly used a theoretical model in their explanations significantly increased from university first year to third year.

The U-shaped change has variously thought to represent outcomes of teaching, performance, or development (Strauss & Stavy, 1982). For the current study it seemed that teaching had a negative effect on university first year students. It seems that the U-shaped performance is mainly a product of students' lack of knowledge about the appropriate use of Le Chatelier's principle. The U-shaped performance curve does not represent a natural or necessary pattern; rather it occurs as a result of misapplications of some rules, formulae, principles or variables which are embodied in a task. The drop and subsequent rise in performance and what is underlying it would inform designing teaching to overcome these difficulties.

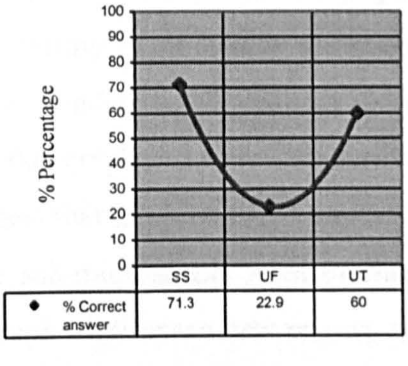


Figure 6.3 Percentage of correct answers to the nitrogen monoxide probe-C

6.3 EMERGING ISSUES FROM TEXTBOOK ANALYSIS IN THIS AREA OF KINETICS

Analysis of textbooks indicated that the effect of temperature on reaction rates is usually introduced on an energy vs. reaction coordinate graph (an energy profile diagram) (see Figure 6.4) and on the Maxwell-Boltzmann energy distribution graph (see Figure 6.5). The way in which each of these representations needs to be thought about is different: while the energy profile graph is a portrayal of "a single reaction" event, the Maxwell-Bolzmann energy distribution graph represents the distributions of the average energies of "many particles". Specifically, making links between these two visual representations or making transformations between them is a demanding process which students may find difficult to perform (cf. Bucat, 2004). Indeed, the school curriculum neglected to make links between or to specify the differences between these two graphical representations.

Though the Maxwell-Bolzmann energy distribution graph is conceptually demanding, the characteristics of the graph (i.e. explicit interpretations of the graph) and the reasons for its use are overlooked in the textbooks (e.g. see Kizildag & Dursun, 2000; p.107). In fact, it is questionable whether the Maxwell-Bolzmann energy distribution graph is at all necessary in elementary courses so as to introduce the effect of temperature on reaction rates. Instead, it might be more appropriate to introduce school students the effect of a change in temperature on reaction rates by using principles of the kinetic molecular theory, collision theory and of the transition state theory. That would be easier to be understood by school students and would be more efficient to use the teaching time. The point I am making here is that if the school curriculum aims to present the effect of temperature on reaction rates drawing upon the Maxwell-Bolzmann energy distribution graph, it is necessary that this graph needs explicit complementary verbal information (e.g. referring to the kinetic molecular theory and activation energy concept) in order to be easily understood by school students. The current approach used in the curriculum about this graph and verbal representation of it would be a challenge for school students. I suggest that more attention should be given to the interpretation of the graph in terms of the sub-microscopic level of chemistry. In addition, as mentioned in the preceding paragraph differences between an energy profile diagram and the Maxwell-Boltzmann energy distribution graph should be shown more clearly in the curriculum.

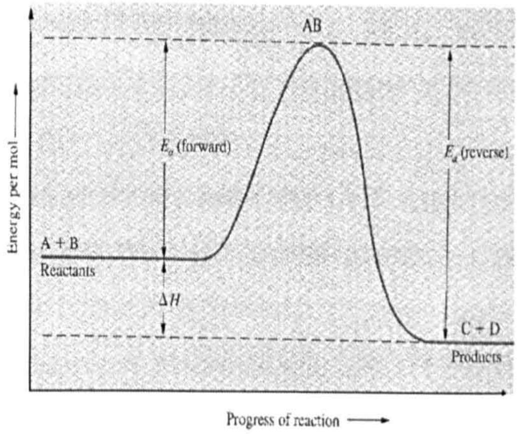


Figure 6.4 *An energy profile diagram for a reaction*

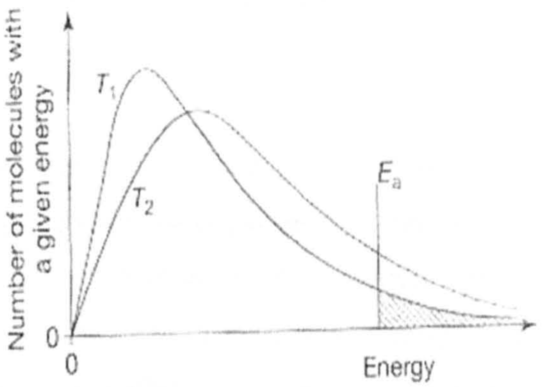


Figure 6.5 *Maxwell-Boltzmann energy distribution curves at different temperatures (T2>T1)*

6.4 SUMMARY AND DISCUSSION

In this chapter, students' ideas about the effect of a change in temperature on reaction rates have been presented. The key findings are discussed below.

(i) How do students' ideas change as a result of teaching?

Students' understanding of the effect of temperature on the reaction rate was elicited their responses upon two contextually different probes. One of the aims of the rusty water pipe probe was to find out in what way students analyse a phenomenon. The results indicated that many school students interpreted the phenomenon in terms of its observable features and that they did not make links or made incorrect links between chemical concepts and the phenomenon of rusting. From school to university, there was, not surprisingly, a considerable progression in the number of students who applied their chemistry knowledge to the phenomenon presented. Research in other areas of science (e.g. in physics, Savelsbergh *et al.*, 1998) also demonstrated that when novice problem solvers reasoned about a diagnostic question they did not use all the knowledge they had learned, because they failed to move between several domains that were often taught separately. More expert problem solvers differed from relative novices in the flexibility with which they can move and make links between different representations. It is important to emphasise that a huge gap was found between the objectives and outcomes of the chemistry curriculum. The curriculum required students to explain the phenomenon in terms of some fundamental models in kinetics, however many school students seemed to fail to do so. One of the reasons would be that the curriculum mostly focused on introducing facts, concepts, methods and processes; however those theoretical ideas are not linked with the physical phenomena and practices.

These results have possible implications for instructional practices. First, the results suggest that instructional practices should be designed to help (school) students to make the connection between theoretical models and chemical phenomena. Carefully designed classroom activities (i.e. chemistry experiments, labwork activities) and teaching can help students to make links between observable events/phenomena *and* various concepts and theories in science (Millar *et al.*, 1999; Tiberghien, 1999). In other words, chemistry teaching should be aimed at guiding students in understanding the links between them (Ben-Zvi & Gai, 1994; Bennett & Holman, 2002). Second, the context of the curriculum and the style of examination questions have possible influence on students' learning (Carson & Watson, 2002) and on students motivation (Bennett & Holman, 2002). For that reason, it would be helpful if teachers and curriculum designers were used both conceptually and phenomenologically framed questions for assessment of students' understanding rather than mainly focusing on algorithmic problems.

Based on a nomothetic data analysis, a U-shaped development was found from students' responses to the nitrogen monoxide probe-C. When students' responses were examined in an ideographic way, it was apparent that (similar to the rusty water pipe probe) many school students' responses included characteristics of macroscopic modelling. University students were more likely to use some form of theoretical model or causal mechanism to account for the event. Nevertheless, many university first year students used these theoretical models inappropriately. Indeed, a great number of students, particularly university first year students, drew upon Le Chatelier's principle and argued that "an increase in temperature decreases exothermic reactions rate". It seems that the students confused equilibrium with kinetic concepts or they simply misunderstood Le Chatelier's Principle. These findings are supported by studies in chemical equilibrium (e.g. Quilez & Solaz, 1995; van Driel & Gräber, 2002) which reveal that students regularly misapply Le Chatelier's principle in cases where its scope is limited. The present study showed that many students applied Le Chatelier's principle to dynamic systems (i.e. to kinetics). Therefore, during teaching, it should be emphasised that the application of Le Chatelier's principle to chemical kinetics is completely wrong.

Although, individual students' responses to these two probes were not compared in a systematic way, the general picture showed that students' ideas about the effect of temperature on reaction rate are not secure and depend to some extent on the format and contextual features of the probes presented. Subsequently, the results demonstrated that regardless of educational level, there was little evidence showing that students offered explanations with a commitment to generalisability across these two probes. Here is an example:

A student's response to the rusty water pipe probe:

> *....This is an oxidation reaction. A rise in temperature increases reaction rate. When temperature is raised, thermal motion of molecules will increase and they will reach the activation energy more quickly.* [UT-D-19]

The same student's response to the nitrogen monoxide probe-C:

> *Since this is an exothermic reaction, when we increase temperature, the reaction rate will decrease.* [UT-D-19]

Though this university third year student responds to the rusty water pipe probe with a generalised statement which is scientifically correct: "*A rise in temperature increases the reaction rate*", she makes a scientifically incorrect argument for the nitrogen monoxide probe-C.

(ii) Confusion between thermodynamic and kinetic factors in a reaction

Drawing upon these two probes, it was apparent that many students could not differentiate between ideas of reaction kinetics and thermodynamics. Indeed, many students thought that a rise in temperature does not affect exothermic reactions rate; however a rise in temperature increases endothermic reactions rates. The most common reasoning was that exothermic reactions release energy and occur spontaneously and faster, but endothermic reactions which require energy to progress; therefore endothermic reactions could not be spontaneous (cf. Johnstone *et al.*, 1977b), therefore a rise in temperature would increases the rate of endothermic reactions.

In a review paper on "teaching and learning chemical kinetics", Justi (2002) recommended a few research questions for future studies, one of which was:

> *How do students' understandings of chemical kinetics influence their learning of other related ideas, e.g. thermodynamics and chemical equilibrium?* (p. 307)

This current study may not be able to answer her proposed question, but in some sense, it would answer the question below:

> How do students' understandings of thermodynamics and chemical equilibrium influence their learning of chemical kinetics?

Consequently, as reported earlier students' lack of understanding in thermodynamics and chemical equilibrium significantly influences their ideas about chemical kinetics.

(iii) Overgeneralisation of the Arrhenius equation

Another, more subtle, point which seems to have been overlooked in textbooks is the overgeneralisation of the Arrhenius equation. At university level, the effect of temperature on reaction rates is explained based on the Arrhenius equation. Many undergraduates had an inclination to apply general statements and formulae (e.g. the Arrhenius equation) to every case regardless of the limitations on the use of principles. For instance, many students emphasised that for every reaction an increase in temperature increases the reaction rate. However, they were not aware that this is not the case for enzyme-catalysed reactions; the rate of these reactions will increase at first with increasing temperature, but then decreases beyond the optimum temperature for the enzyme since the enzyme is destroyed. Therefore, it would be helpful if the limitations on the use of the principle or the Arrhenius equation are expressed in *the university curriculum*.

CHAPTER 7

STUDENTS' UNDERSTANDING OF THE EFFECT OF SURFACE AREA OF A SOLID REACTANT ON THE REACTION RATE

CHAPTER 7

STUDENTS' UNDERSTANDING OF THE EFFECT OF SURFACE AREA OF A SOLID REACTANT ON THE REACTION RATE

7.0 INTRODUCTION

As Table 3.4 shows, students' ideas about the effect of surface area of solid reactants or a solid catalyst on reaction rates were elicited throughout their responses on two probes. These were the *magnesium oxide probe* and the *nitrogen monoxide probe-D*. Students' ideas about the effect of surface area of a solid catalyst on reaction rates were elicited in the nitrogen monoxide probe-D and the results are discussed in a different chapter, in Chapter 8 (in Section 8.2.2).

The magnesium oxide probe aimed to explore students' understandings of the relationship between reactant surface area and reaction rate for a heterogeneous reaction. The probe was set in a school science context and required students to explain whether granulated MgO or powdered MgO reacts with hydrochloric acid faster and give reasons for their answers.

This chapter reports ideas used by students on the magnesium oxide probe and addresses emerging issues from the analysis of documentary evidence in this area of kinetics.

7.1 THE MAGNESIUM OXIDE PROBE (Data analysis and results)

The magnesium oxide probe was framed in terms of a phenomenon where the language of chemical kinetics was used. Thus, coding scheme-A was applied to the data set (see Section 3.7). Three main categories were identified from students' responses: (1) descriptive/empirical, (2) explanatory/theoretical and (0) all other responses. These three main categories include seven sub-categories. In the following sections those three main categories with sub-categories are discussed. The responses are summarised and illustrated in Table 7.1, and Figure 7.1.

(1) Descriptive/Empirical (Macroscopic Modelling)

This category is descriptive in nature: in this form of reasoning, explanations are mainly based on casual relationships between some variables without any reference to underlying mechanisms. Students tend to consider causal relations between directly observable features of the phenomenon, or features which are taken for granted as existing in the material world (e.g. *the smaller the substances, the faster they react*). The students frequently used everyday life interpretations that were often tautologous – a generally unacceptable (or insufficient) mode of explanation in science – (e.g. *the reaction between MgO and HCl occurs faster, because smashing solid MgO is more difficult than smashing powdered MgO*) or referred to a prototypical example of an everyday phenomenon to describe the phenomenon (e.g. *powdered MgO reacts with hydrochloric acid faster than granulated MgO, because powdered sugar dissolves more quickly in water than granulated sugar does*). 54% of the SS, 27% of the UF, and 6% of the UT' explanations offered fell into this category.

(1-1-1) Observable features as a key factor (leads to right answer)

This category incorporates responses in which students used reasoning based on observable characteristics of the event. All respondents in this category (39% SS, 19% UF, and 6% UT) were aware that powdered MgO reacts faster with HCl than granulated MgO does, yet they did not provide any underlying mechanisms to account for their answers. As an illustration, the students quoted below were aware that physical features of reactants would affect reaction rates, however they simply describe behaviour of the phenomenon at the macroscopic level:

> *...Reactions rate is changed by physical features of substances. In some way, the reaction occurs faster with substances being ground into powder. However, the reaction for the substances in the solid state* [granulated MgO] *is slow, because they* [solid substances] *spread out slowly.* [Sa-D-05]
>
> *...I would tell these students that one of the factors affecting reaction rate is to grind solid substances. Therefore powdered MgO reacts with hydrochloric acid faster.* [Sa-D-21]

In some instances, students' explanations included taken for granted statements of how things are or how things work at the macroscopic level. For example, the following students' responses were tautologous;

> *Powdered MgO reacts with HCl more quickly, because it is in the form of powder.* [Sc-D-21]

> *...Second reaction, the reaction between MgO and HCl, occurs faster, because HCl affects quickly to the crushed form of solid.* [UF-D-03]

> *... Smashing solid MgO is more difficult than smashing powdered MgO. Therefore powdered MgO enters into the reaction faster* [than granulated MgO does]. [UF-D-28]

> *Powdered MgO reacts with HCl faster than granulated MgO, because small particles react faster than bigger particles.* [Sb-D-21]

Dissolving or the rate of solubility was seen as a key factor by some students. Everyday and scientific terms were often used interchangeably (e.g. melting, dissolving, reaction, the rate of solubility/reaction). A few students supposed that the substance first needed to dissolve in the solution before entering into the reaction. Here are some examples:

> *Powdered MgO reacts with hydrochloric acid faster than granulated magnesium oxide. Powdered MgO dissolves quickly. However granulated MgO dissolves slowly. Thus the reaction that includes powdered MgO occurs faster.* [Sa-D-17]

> *In order to enter into a reaction, solid substances need to dissolve. Since the powdered ones* [powdered MgO] *are in the form of powder, they quickly enter into a reaction. ....The solid substance first needs to dissolve, afterwards it reacts quickly. However, powdered substances dissolve quickly and as a result they more quickly enter into the reaction.* [Sb-D-08]

(1-1-2) Use of a prototypical example of everyday phenomenon to explain the phenomenon

The difference between the sub-category (1-1-1) and (1-1-2) was that students in the later category justified their answers "mainly" based upon prototypical examples of everyday phenomena. The examples used generally involved a physical change (the most common example was dissolving of caster sugar-sugar cubes in water) and occasionally involved a chemical change (e.g. a wood fire burns faster if the logs are chopped into smaller pieces). As one school student put it:

> *Powdered MgO reacts with HCl faster than granulated MgO does... For example, if we put some powdered sugar and sugar cubes into water, we can see that powdered sugar dissolves more quickly.* [Sa-D-02]

This quotation suggests that the student's interpretation of the phenomenon was not based on the application of particular theoretical models. Rather the student appears to be comparing the event under consideration to a prototypical example of everyday phenomenon. However, most of the prototypical examples, like the one quoted above, focused upon surface similarities between the event under consideration (surface/reaction area) and the prototypical example (dissolving of sugar). Mainly school students (14% SS, and 4% UF) justified their answers in terms of a prototypical example.

(1-2-3) Observable features as a key factor (leads to wrong answer)

1 SS and 2 UF argued that the rates of the reactions would be the same. Their justifications involved macroscopic variables of the given event, such as the amount of reactants or the number of moles of reactants. Two of these responses are given below:

> *The reaction rate is the same for both reactions. While the amount of substances and volume are the same, the rate of reactions will be the same. Physical features of substances (being a solid or powdered form) do not affect anything.* [UF-D-13]
>
> *The rates are the same. ...According to the reaction, 1 mol of MgO reacts with 2 moles of HCl. Since the same amount of substances was used, the reaction rates would be the same.* [UF-D-23]

(2) Explanatory/Theoretical (Particulate and/or Mathematical Modelling)

The second main category incorporates those responses in which students use some form of theoretical model or causal mechanisms to account for the phenomenon. Explanation goes beyond descriptive accounts of the phenomenon by drawing upon theoretical entities within established chemical ideas. The emphasis is on the microscopic processes taking place during the reaction and the relationship of such processes to the macroscopic behaviour of the reaction. The response may constitute cases where justification involves algebra or mathematical formulae (e.g. by using rate equation). It should be noted that the terms 'surface area' or 'reaction area' might be referred to everyday or scientific language. No matter how these terms were used, responses without an underlying mechanism for explaining the phenomenon were placed in the previous category – "Descriptive/Empirical" category (e.g. an increase in surface area increases reaction rate). 41% of the SS, 73% of the UF, and 94% of the UT' responses were placed in this category. The sub-categories are discussed below.

(2-2-4) Using theoretical models inappropriately (leads to wrong answer)

This category includes responses that suggest the student does not use theoretical models appropriately. The causal mechanism proposed involves either a chain of events between variables in verbal or in mathematical form. Furthermore, as quoted below, a few students presumed that the reaction rate is not affected by physical features of reactant substances. For example, while these two students (quoted below) can differentiate between the notion of solubility and reaction, they had scientifically incorrect ideas about the notion of reaction rates:

> *Serdar's opinion* [powdered MgO reacts with HCl faster than granulated MgO does] *is wrong......I would tell him not to confuse the concept of solutions/solubility with reactions. His idea is applicable for solution/solubility, but a reaction takes place here. ....The physical features of substances only affect the rate of dissolving, however there is a chemical reaction here and the reaction rate depends on molarities.* [UF-D-04]

This student seems to apply the formula (i.e. the rate equation) mechanically. In fact, evidence from interviews suggests that students who argued "the reaction rates for both cases would be the same" usually justified their answers based on a rate equation. For instance, one of the interviewees [UF-I-04] said that "reaction rate depends on the molarities of reactants. As the molarities are equal for both cases, we can say that reaction rates are the same". A few undergraduates also justified their answers based on mathematical formulae, but used the formulae inappropriately. Some examples are quoted below:

> *Reaction rate is constant, because the same amount* [of reactants] *is used. For example, once one of which proceeds in 10 minutes, the other proceeds in 20 minutes...*K_d *= Reactant/Product; Both reactions are the same, but in the first reaction a big pieces of MgO is used and that reacts with HCl slowly, yet all of it is converted into products. For the second reaction the surface of substrate is greater and as a result reaction occurs in a shorter period of time. But again all powdered MgO is converted into products.* [UT-D-14]

The subject seems to confuse the equilibrium constant and the rate equation. His notion of reaction rate is different from a chemist's perspective in that while he is aware that the period of time required for these reactions to occur is different; he states that the rates of these two reactions are the same. It seems that he has reached this conclusion based on an equilibrium constant formula. The student seems to simply memorise the formula without conceptual understanding and as a result fail to apply it in a given situation. As quoted below, another university third year student also appears to apply a rate equation mechanically.

> *Both reaction rates are the same, because the molarities of HCl are the same. ...First of all I would tell these students that due to greater surface area, the second reaction* [the reaction between powdered MgO and HCl] *occurs faster. In that case surface area does not affect the reaction rate, and it only helps the reaction to occur in a short period of time. The most important thing here is the*

> *concentration of HCl and while the concentration of HCl is equal, the reaction rates are the same.* [UT-D-26]

It appears that the source of the difficulty may partly come from the student's lack of knowledge about the notion of rate equation. Whilst he says "*The most important thing here is the concentration of HCl and while the concentration of HCl is equal, the reaction rates are the same*", it seems that he justifies his answer based on a rate equation. Indeed, when I examined this student's responses to the Vessel and to the Reaction rate probes, it revealed that he had often justified his answers based on a rate equation. For example, in the Vessel probe, he made an assumption for the order of the reaction (being a first order reaction) and stated that "*...based on the rate equation,* $k.[A]$*, the greater the concentration, the faster the reaction...*".

It should be noted that all students in this category were undergraduates (10% UF and 6% UT). While their responses were richer in the terminology and the range of justifications provided, they used those theoretical tools inappropriately in the given specific context.

(2-2-5) Using theoretical models inappropriately (combining with correct answer)

Though the students in this category (4% SS, 2% UF, and 6% UT) had reached a correct answer, their explanations included scientifically incorrect ideas. Such students mainly attempted to use principles of the collision theory in their reasoning, but they failed to apply fundamental kinetic ideas in the problem associated with the ideas. For example, as quoted below, they linked the macroscopic world to the world of theories and models, but incorrectly. As an illustration, the student quoted below (UT-D-02) believed that "molecules" of granulated MgO were more strongly bonded to each other than those of powdered ones.

> *To me powdered MgO reacts with HCl faster than granulated magnesium oxide does. Because its particles are far away from each other and HCl affects more easily to them. Do not endeavour too much. However, when MgO is in solid state, particles are more strongly bonded and HCl will spend more time to affect them, and bonds will be broken over a longer period of time. Molecules are more strongly bonded and are closer to each other in solid MgO than* [powdered MgO]. [UT-D-02]

(2-1-6) Using theoretical models appropriately

The responses include scientifically correct ideas about the relationship between reactant surface area and rate of a heterogeneous reaction. 37% of the SS, 60% of the UF, and 83% of the UT' responses were placed in this category and some examples are given below:

> *The powdered MgO has a greater surface area and will have the faster reaction rate. The effect of HCl on powdered MgO is more effective, because interactions between HCl and MgO molecules are increased. However, interaction between HCl and granulated MgO are limited as its surface area is smaller.* [UT-D-10]
>
> *The reaction is faster for the reaction with powdered magnesium oxide, because it has greater surface area for the reaction to occur. ...Increasing the surface area of MgO results in a higher number of reaction areas which raises interactions between reactants.* [UT-D-01]
>
> *The powdered MgO has a greater surface area. Increasing surface area increases interaction between reactant molecules. Thus powdered MgO reacts faster with HCl.* [UT-D25]

(0-0-7) All other responses

This category is allocated for incomprehensible responses or in cases where there is no response given in the probe. 5% of the SS' responses were placed in this category.

Code	Category (Nature of response)	Example of response	SS *f** *(%)* (n=108)	UF *f* % (n=48)	UT *f* % (n=35)
1	**Descriptive/Empirical (Macroscopic Modelling)**		**58** ***53.7%***	**13** ***27%***	**2** ***5.7%***
1-1-1	Observable features as a key factor (leads to right answer)	Powdered MgO reacts with HCl more quickly, because it is in the form of powder. I would tell these students that one of the factors affecting reaction rate is to grind solid substances. Therefore powdered MgO reacts with hydrochloric acid faster.	42 *38.9%*	9 *18.8%*	2 *5.7%*
1-1-2	Use of prototypical examples of everyday phenomena to explain the event	Powdered sugar dissolves faster than granulated sugar.	15 *13.9%*	2 *4.2%*	0
1-2-3	Observable features as a key factor (leads to wrong answer)	The reaction rate is the same for both reactions. Because the same amount of substances have been used.	1 *0.9%*	2 *4.2%*	0
2	**Explanatory/Theoretical (Particulate and/or Mathematical Modelling)**		**44** ***40.7%***	**35** ***72.9%***	**33** ***94.3%***
2-2-4	Using theoretical models inappropriately (leads to wrong answer)	The physical features of substances only affect the rate of dissolving, however there is a chemical reaction here and the reaction rate depends on molarities. ...K_d = Reactant/Product; Both reactions have the same rate.	0	5 *10.4%*	2 *5.7%*
2-2-5	Using theoretical models inappropriately (combining with correct answer)	Molecules are more strongly bonded and are closer to each other in granulated MgO than those of granulated ones.	4 *3.7%*	1 *2.1%*	2 *5.7%*

2-1-6	Using theoretical models appropriately (Increasing surface area/reaction area/interaction area increases reaction rate)	The powdered MgO has a greater surface area. Increasing surface area increases interaction between reactant molecules. Thus, powdered MgO reacts faster with HCl.	40 *37%*	29 *60.4%*	29 *82.9%*
0	**All other responses**		**6** ***5.5%***	**0**	**0**
0-0-7	No response		0	0	0
	Incomprehensible	The reaction with granulated MgO takes more time, because its mass is greater than the mass of powdered MgO.	6 *5.5%*	0	0
TOTAL			**108** ***100%***	**48** ***100%***	**35** ***100%***

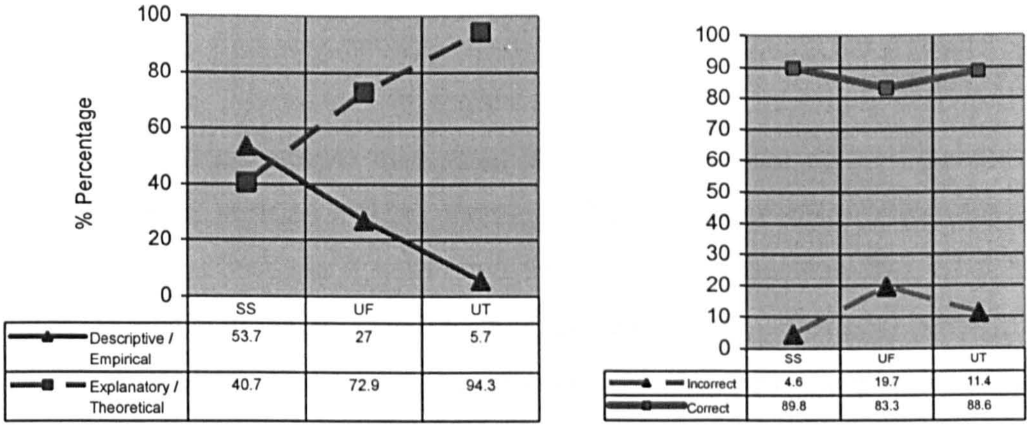
**f*, *n*= number of participants; %= percentage of participants

Table 7.1 A coding scheme for the magnesium oxide probe

7.1.1 An overview of students' responses to the magnesium oxide probe

In considering the overall picture of the students' responses, almost all of the students reached a correct prediction about the rates of these reactions. Based on an ideographic data analysis, it was apparent that around half of the school students' explanations included characteristics of macroscopic modelling (similar to the pattern of students' responses identified in the previous chapters) (see Figure 7.1). While students' usage of macroscopic modelling gradually decreases from school to university, their explanations based on theoretical modelling significantly increases from school to university ($\chi^2=32.693$, $df=2$, $p<0.01$). 37% of the SS, 60% of the UF, and most of the UF (83%) used theoretical models appropriately in the given situation.

Based on a nomothetic data analysis, no statistically significant difference was observed across different educational levels ($\chi^2=5.673$, $df=2$, $p>0.01$). However, it is interesting to note that more undergraduates' responses (20% UF and 11% UT) included scientifically incorrect ideas than those of school students (only around 5%). Such students often misapplied a mathematical formula.



Uncodeable	5.5	0	0
Total %	100	100	100

***Figure 7.1** Percentage of responses to the magnesium oxide probe*

7.2 EMERGING ISSUES FROM TEXTBOOK ANALYSIS IN THIS AREA OF KINETICS

In the school textbook, the effect of surface area of a solid reactant on reaction rates is explained by referring to prototypical examples of everyday phenomena, such as burning tree trunk or wood shavings. This is one of the areas that the textbook helps student to contextualise the content in terms of their own experience and knowledge. As noted in the preceding chapters, the curriculum rarely includes this approach which presents students opportunities to weave content and context together.

7.3 SUMMARY AND DISCUSSION

In this chapter, students' ideas about the effect of surface area on the reaction rate have been discussed. Students' responses on the magnesium oxide probe revealed some patterns in students reasoning. The key findings are discussed below.

(i) General pattern in students' responses

If a reaction involves a solid with a gas or liquid, the surface area of the solid affects the reaction rate. Indeed, the results revealed that majority of the students were aware that physical features of solid reactants would affect the reaction rates and such students mostly reached a correct answer. However, as discussed in the preceding section, many school and university first year students' responses presented mainly the characteristics of everyday language. Interviews with students revealed that they simply described the phenomenon at the macroscopic level (e.g. the smaller the size of the "granule" of reactant, the faster the reaction will be) and they did not need to explain further, because they thought this was obvious, it needed no further explanation. However, when they were asked to elaborate their answers, in many cases, they provided prototypical examples of an everyday phenomenon a common basis for further explanations or in other cases they made reference to scientific terms and models (e.g. referring to atoms, molecules, or the principles of collision theory). Drawing upon interview data, there was some evidence to show that students had various form of theoretical models, however they did not apply those to the given phenomenon instead they often used everyday ways of explanations in place of scientific ways of explanations. One of the reasons might be that such students did not know what constitutes a scientific explanation. Having an understanding of what constitutes a scientifically acceptable explanation and of scientific modes of thinking and talking is one of the most important objectives of the chemistry curriculum and this deserve attention during teaching.

The results showed that the students in the curriculum made gradual progress from secondary through university level. When students moved through the curriculum they were more likely to use reasoning based on theoretical models (χ^2, $p<0.01$). It was apparent that most of the university third year students were able to apply their chemistry concepts of the reaction area in the given situation associated with. A few students had lack of knowledge about the rate equation and chemical kinetics; they argued that "as the same amount of reactants was used in both cases, the rates of these two reactions would be the same, because the rate depends on the concentrations of reactants". This might be the result of a straight memorisation of statements or mathematical formulae without conceptual understanding.

(ii) Use of prototypical examples of everyday phenomena

In this study many students' responses presented mainly characteristics of everyday language or students justified their answers based upon prototypical examples of everyday phenomena. However, most of these examples focused upon surface similarities between the prototype and the target (concept), such as similarities between dissolving of sugar and the reaction between solid MgO and HCl. It has been posited that analogies and metaphors that focus on surface similarities may lead students away from the underlying scientific theories (Hesse & Anderson, 1992). Analogies, metaphors and prototypical examples of an everyday phenomenon can make abstract or new concepts more meaningful to students by connecting the new concepts with their existing knowledge and experiences. However, there is considerable evidence to show that some analogies can lead to confusion and misconceptions instead of the higher level of understanding that is desired (Glynn *et al.*, 1995). Therefore, the function of analogy and metaphor used in the curriculum should be addressed directly and its limitations should be considered. In addition, there should be an open communication between the teacher and the students when an analogy is used: the teacher should check whether students understand relationships between the analogy and the target concept (Thiele & Treagust, 1994).

CHAPTER 8

STUDENTS' UNDERSTANDING OF THE CONCEPTS OF ACTIVATION ENERGY AND CATALYSIS

CHAPTER 8

STUDENTS' UNDERSTANDING OF THE CONCEPTS OF ACTIVATION ENERGY AND CATALYSIS

8.0 INTRODUCTION

Students' understandings of the concepts of activation energy and catalysis were explored throughout their responses on four conceptually framed probes. These are the *Activation Energy*, the *Enthalpy*, the *Nitrogen Monoxide probe-D* and the *Catalysis* probes. All of those probes were conceptually framed and were analysed nomothetically in order to identify whether students had produced answers that would be judged as correct within the established chemical ideas.

This chapter is divided into four sections. The first section presents students' ideas about activation energy; the next section addresses students' ideas about the concept of catalysis, and the third one (Section 8.3) considers approaches used to introduce these concepts in the curriculum and it addresses emerging issues from textbook analysis and students' notes. Finally, the key findings are summarised in the last section.

8.1 STUDENTS' UNDERSTANDING OF THE CONCEPT OF ACTIVATION ENERGY

Two probes (the *Activation Energy*, and the *Enthalpy* probes) were designed to elicit students' understanding about the concept of activation energy. Mainly the same ideas were tested in those probes. The probes were designed to investigate students' ideas about the definition of activation energy and how they apply their ideas on different contexts (as discussed earlier in Chapter 3, by "context" I mean a situation in different settings in which different cueing is given). This section presents the analysis of these two probes and each probe is discussed separately.

8.1.1 THE ACTIVATION ENERGY PROBE

The aim of this probe was to investigate how students understand and model activation energy and relate it to reaction rates.

8.1.1.1 Data analysis and results

The probe was conceptually framed, and therefore was analysed nomothetically by using "coding scheme-B" (see section 3.7). The coding scheme consisted of three main categories: (1) responses including mainly scientifically incorrect ideas about the concept of activation energy, (2) responses including mainly scientifically accepted ideas about the concept of activation energy, and (0) all other responses. It ought to be noted that students who provided a scientifically correct definition of activation energy, but could not appropriately apply this knowledge to the given situation were placed in the first category (1). Students' responses to the probe is summarised in Table 8.1.

(1) Responses including mainly scientifically incorrect ideas about the concept of activation energy

59% of the SS, 25% of the UF and 6% of the UT' explanations included scientifically incorrect ideas about activation energy and its relationships with reaction rates (see Table 8.1). Those scientifically incorrect ideas were classified under five subcategories.

(1-2-1) Activation energy is the kinetic energy of reactant molecules

A number of students (16% SS and 8% UF) defined activation energy as the kinetic energy of reactant molecules. Many of those who viewed activation energy as the kinetic energy of reactant molecules reached a conclusion that the bigger the activation energy, the faster a reaction occurs. A typical example of this type of reasoning is provided in the following extracts:

> *...Activation energy is the kinetic energy of reactant molecules; therefore the second reaction (Ea=480 kJ) occurs faster than the first reaction (Ea=92 kJ) because its activation energy is higher.* [Sc-D-16]
>
> *Activation energy is the energy of reactant molecules. In other words, due to movement, reactant molecules have a certain amount of kinetic energy. Ea* [Activation energy] *is the energy of those molecules. ...The second reaction occurs faster, because it has a higher activation energy. An increase in Ea (in other words an increase in kinetic energy of molecules) increases collisions and increases the number of molecules that overcome the energy barrier. As a result the reaction rate rises.* [UF-D-34]

Although the student's response (in the second excerpt) includes some ideas of chemical kinetics (i.e. referring to theories of kinetics), the student could not use those ideas properly. One of the reasons might be that they could have learnt (or been taught) the concept by rote. It is important to note that the kinetic energy of reacting molecules might be equal to the activation energy of the reaction. A reaction occurs if the collision has enough energy to be either equal or greater than the activation energy and if the orientation of the collisions allows for correct bond formation. However, students seem to confuse these ideas. This might originate in the teacher's comments during teaching the concept of activation energy.

(1-2-2) Activation energy is the kinetic energy of product molecules

Three school students argued that "activation energy is the kinetic energy of product molecules and as a result the reaction with the higher activation energy occurs faster".

(1-2-3) Activation energy is the amount of energy released by a reaction

On several occasion students, mainly school students, showed confusion between activation energy and overall enthalpy changes. Students in this category defined activation energy as the amount of energy released by a reaction. 21% of the SS and 10% of the UF were placed in this category and some typical examples are given below:

> *Activation energy is the energy released after a reaction...The second reaction is faster, because more energy is released. The faster a reaction, the more energy is released.* [Sb-D-19]

When I examined this student's explanation to the "enthalpy probe", it appeared that she had a general idea that exothermic reactions occurs faster than endothermic reactions[1]. Here is her explanation to the "enthalpy probe":

> *I think the first reaction* [the exothermic reaction] *occurs faster, because exothermic reactions give out heat, but endothermic reactions take in heat. Of course giving heat out is easier; therefore those reactions* [exothermic reactions] *occur faster.* [Sb-D-19]

Students often used some scientific terms incorrectly, as in the excerpt below. The subject used the term activated complex inconsistently with scientific perspectives.

> *Activation energy is the energy released after a reaction...First reaction will proceed faster. Due to lower activation energy, the activated complex of this*

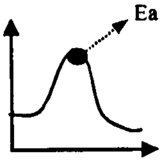
---

[1] The results of the enthalpy probe revealed that a high number of students believed that exothermic reactions occur faster than endothermic reaction (see Section 8.1.2, for detail)

> *reaction would be lower. Therefore there would be more molecules that overcome the activated complex. While the reaction rate depends on the number of molecules that overcome the activated complex, the first reaction will proceed faster.* [Sa-D-18]

(1-2-4) Activation energy is the maximum energy level in a reaction

11% of the school students stated that activation energy is the maximum energy that substances could have. From the interviews, it was apparent that such students attempted to define activation energy based on an energy profile diagram. When they were asked to define the meaning of activation energy, they could not give a correct definition for the activation energy and its relationships with reaction rates, rather as expressed in the quotation below, they interpreted activation energy as the highest point on the energy vs. reaction coordinate graph. The respondents had limited knowledge about the activation energy concept, for example, some simply stated that "activation energy is the peak of this diagram [the energy profile diagram]". Here is another example:



> S- *Activation energy is the maximum energy level that a substance can achieve*...[drawing a graph]...*On this graph the highest point is the threshold* [activation] *energy.*
> R- What would you say about the rates of these reactions?
> *S- I agree with Belma in that we cannot say anything about the rates of these reactions. There is not enough information given to do so.*
> R- What kind of information is needed to compare these reactions rates?
> *S- If the number of moles were given, we could compare the reactions rate.* [Sc-I-03]

One of the issues here is that without conceptualising the underlying ideas of a concept or of visual representation of that concept, students may interpret the representation based on surface features of it.

(1-2-5) Responses including accepted ideas about activation energy but using those ideas inappropriately in the given situation

A number of students (8% SS, 6% UF and 6% UT) had given a scientifically correct definition of activation energy, but some were not able to apply those ideas to the given situation associated with the ideas. For example:

> *Activation energy is a certain amount of energy that reactant substances must have to result in a reaction. ....There isn't any information about the concentrations; therefore we cannot compare the reaction rates. Ea is the energy required for a reaction to occur. It cannot be known how that* [Ea] *affects the reaction rate.* [UF-D-18]

> *Activation energy: Reacting substances must have to overcome the energy barrier in order for a reaction to proceed. ....Activation energy is the energy required for a reaction to take place. ...We can't say anything about these reactions rate*[s]. *....Activation energy does not affect a reaction rate.* [UT-D-26]

It should be emphasised that knowing a scientific word such as 'activation energy' does not necessarily mean that the student has a conceptual understanding of the concept. Indeed the results revealed that the students could not deploy that knowledge in the specific situation. The reason for not being able to apply the ideas in the problem could be that the students simply memorise the terms without understanding the ideas behind them. As a result they are not able to apply their knowledge to the problems they come across.

(2) Responses including mainly scientifically accepted ideas about the concept of activation energy

(2-1-6) Responses including accepted ideas about activation energy and using those ideas appropriately in the given situation

This category incorporates those responses which include accepted ideas about activation energy. The students in this category used those ideas appropriately in the given context. 29% of the SS, 66% of the UF and almost all of the UT (92%) responses were placed in this category and some typical examples are given below:

> *Activation energy is the energy barrier that reactant particles must have to overcome for a reaction. Therefore the reaction with the lower activation energy occurs faster.* [UT-D-11]

> *Activation energy is the minimum energy that reactant particles must have to result in a reaction. The first reaction occurs faster than the second reaction does, because the energy barrier for the first one is lower.* [UF-D-15]

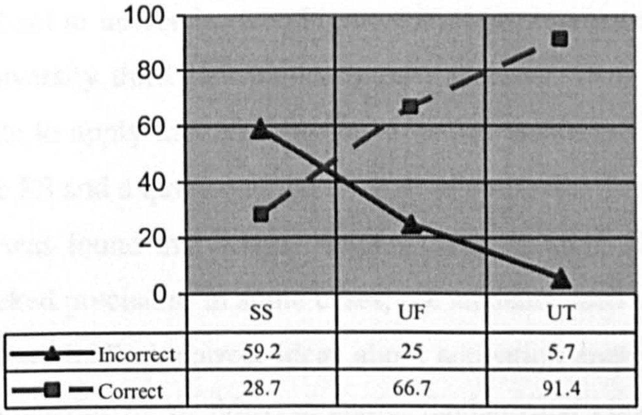
(0) All other responses

This category is allocated for incomprehensible responses or in cases where there is no response given in the probe. As shown in Table 8.1, 12% of the SS, 8% of the UF and 3% of the UT were placed in this category.

Code	Category (Nature of response)	Example of response	SS *f* *(%)* (n=108)	UF *f* *(%)* (n=48)	UT *f* *(%)* n=35)
1	**Responses including mainly scientifically incorrect ideas about the concept of activation energy**		**64** ***59.2***	**12** ***25%***	**2** ***5.7%***
1-2-1	Activation energy is the kinetic energy of reactant molecules.	Activation energy is the kinetic energy of reactant molecules. Thus the second reaction occurs faster than the first one.	17 *15.7%*	4 *8.3%*	0
1-2-2	Activation energy is the kinetic energy of product molecules	Activation energy is the kinetic energy of product molecules. As a result the reaction with the higher activation energy occurs faster	3 *2.7%*	0	0
1-2-3	Activation energy is the [total] amount of energy released in a reaction	Activation energy is the energy released after a reaction. The second reaction is faster, because more energy is released. The faster a reaction, the more energy is released.	23 *21.3%*	5 *10.4%*	0
1-2-4	Activation energy is the maximum energy level in a reaction	Activation energy is the maximum energy state that substances can achieve.	12 *11.1%*	0	0
1-2-5	Responses including accepted ideas about activation energy but using those ideas inappropriately in the given situation.	Activation energy is a certain amount of energy that reactant substances must have to result in a reaction. ...There isn't any information about the concentrations; therefore we cannot compare the reaction rates. Ea is the energy required for a reaction to occur. It cannot be known how that [Ea] affects the reaction rate.	9 *8.3%*	3 *6.3%*	2 *5.7%*
2	**Responses including accepted ideas about activation energy and using those ideas appropriately in the given situation**		**31** ***28.7%***	**32** ***66.7%***	**32** ***91.4%***
2-1-6	Activation energy is the minimum energy required for the reaction to occur	Activation energy is the energy barrier that reactant particles must have to overcome for a reaction. Therefore the reaction with the lower activation energy occurs faster.	31 *28.7%*	32 *66.7%*	32 *91.4%*
0	**All other responses**		**13** ***12%***	**4** ***8.3%***	**1** ***2.8%***
0-0-7	No response		0	0	0
	Incomprehensible/Other		13 *12%*	4 *8.3%*	1 *2.8%*
	TOTAL		**108** ***100%***	**48** ***100%***	**35** ***100%***

Notes: n = number of participants; f = frequency; % = percentage of participants

Table 8.1 A coding scheme for the activation energy probe



Uncodeable	12	8.3	2.8
Total %	100	100	100

Figure 8.1 Percentage of responses to the activation energy probe

8.1.1.2 An overview of students' responses to the activation energy probe

Students' understanding of the concept of activation energy and their ability to relate it to reaction rates were the focus of the probe. At school and university level, the concept of activation energy is mainly presented in a symbolic level (i.e. drawing upon an energy profile diagram) (see Figure 6.4) and also sub-microscopic level (i.e. referring to the transition state theory). That approach requires students to make links between particulate and mathematical modelling (see Figure 4.1, in Chapter 4). Nevertheless, the results revealed that a few school students had difficulties in interpreting an energy profile diagram for a reaction and associating it with theoretical models. Such students interpreted the diagram based on surface features of the diagram, such as they simply stated that "activation energy is the highest point on the diagram" or "activation energy is the peak of the energy profile diagram". It emerges that more attention should be given to the interpretation of symbolic representations of the concept and its relationships with the sub-microscopic level. Activation energy is one of the fundamental ideas in chemical kinetics and the results suggest that it is poorly understood by school students.

A chi-square analysis on the distribution of students' responses showed that there was a statistically significant difference by educational levels ($\chi^2=45.796$, $df=2$, $p<0.01$) in that an increase in responses including scientifically correct ideas was observed from school to university (see Figure 8.1). Many university first year students and almost all university third year students gave accepted ideas of activation energy and they were able to apply that ideas to the situation associated with; however, around two third of the SS and a quarter of the UF had scientifically incorrect ideas about activation energy. It was found that school students' explanations of the definition of activation energy lacked precision. In some cases, the students used both scientifically accurate ideas and scientifically incorrect ideas about activation energy. Many school students lacked the knowledge of, or failed to apply, fundamental kinetic ideas in the task associated with the ideas. Understanding the relationship between kinetic energy and activation energy was especially difficult for the students. As discussed earlier, when students were asked to define activation energy, many school students defined it as the kinetic energy of reactant/product molecules or defined it as the amount of energy released in a reaction. One of the reasons might be that the notion of activation energy is logically different from kinetic energy of molecules and perhaps demanding. Activation energy is the minimum *energy barrier* that reactant molecules must overcome to result in a reaction. Activation energy is equivalent *kinetic energy of reactant molecules*, but only under well defined conditions.

8.1.2 THE ENTHALPY PROBE

The probe aimed to investigate students' understandings of the concept of activation energy and enthalpy. It was also a conceptually framed probe and asked students whether they could compare rates of two different chemical reactions by using thermodynamic variables.

8.1.2.1 Data analysis and results

The enthalpy probe, a conceptually framed probe, was analysed nomothetically. Accordingly, the coding scheme-B was applied on the data set. In the following sections the main categories, and identified sub-categories, are discussed. The responses are summarised and illustrated in Table 8.2 and Figure 8.2.

(1) Responses including mainly scientifically incorrect ideas about kinetic and thermodynamic concepts

Responses in this category include scientifically incorrect ideas about kinetic and thermodynamic concepts. About the same percentage of students in all educational levels (57% SS, 58% UF, 60% UT) fell into this category. The subcategories are discussed below.

(1-2-1) Exothermic reactions occur faster

Around 32% of the SS, 25% of the UF and perhaps surprisingly 37% of the UT claimed that (at the same temperature) exothermic reactions occur faster than endothermic reactions Most of those students argued that (ii) exothermic reactions occur faster, because they do not need energy to proceed or argued that (iii) exothermic reactions occur faster because they have a lower activation energy. Nevertheless, a number of students did not provide (i) any further explanation for their answers. These subcategories are discussed below in more detail.

(i) No further explanation is provided

15% of the SS, 4% of the UF and 6% of the UF did not provide any further explanation for their answers. As one of the school students put it:

> *From my point of view, the first reaction is faster, because exothermic reactions are faster than endothermic reactions.* [Sa-D-23]

Neither response in this subcategory was accompanied by a further explanation; therefore it was not easy to investigate the underlying ideas for their responses. In some instances, students' reasoning was tautologous, such as they stated "the exothermic reaction is faster, because it is exothermic".

(ii) Exothermic reactions occur faster, because they do not need energy to proceed/occur

The students had a general view that exothermic reactions occur faster than endothermic reactions. The most common reasoning was that exothermic reactions release/give off energy and occur spontaneously and faster, but endothermic reactions require energy to proceed; therefore endothermic reactions could not be spontaneous (cf. Johnstone *et al.*, 1977b), and they take place slowly. Mainly undergraduates' responses (11% SS, 21% UF, and 32% UT) were placed in this category and some of the typical quotations are given below.

> *...The exothermic reaction occurs faster, because the reaction gives off energy after the reaction. But the endothermic reaction needs to get energy for the reaction* [to proceed]. [Sb-D-13]
>
> *The first reaction* [the exothermic reaction] *occurs faster, because exothermic reactions do not require energy* [to proceed], *they occur spontaneously. However, endothermic reactions need a certain amount of energy to progress; therefore an endothermic reaction cannot occur spontaneously.* [UT-D-01]

The respondents argued that if a reaction releases energy, it is a spontaneous reaction, but if energy is needed from the outside to stimulate a reaction, it cannot be a spontaneous reaction (cf. Sozbilir, 2001). They seem to confuse the rate of a reaction with the spontaneous occurrence of a reaction.

(iii) Exothermic reactions have a lower activation energy

A few of the school students (6%) either did not understand exothermic and endothermic reactions or did not understand the notion of activation energy and overall enthalpy changes. Such students believed that the exothermic reaction would occur faster, because exothermic reactions had a lower activation energy:

> *The lower the enthalpy change, the faster the reaction will proceed.* [Sa-D-06]
>
> *The exothermic reaction occurs faster, because its energy barrier is lower.* [Sc-D-34]

As quoted above/below students sometimes simply confused the concept of activation energy and overall enthalpy changes:

> *Reaction 1, $\Delta H=Ea(fwd)-Ea(rev)$* [Ea(fwd) refers to the forward activation energy, Ea(rev) refers to the reverse activation energy]*; Reaction 2, $\Delta H=Ea(fwd)-Ea(rev)$. The lower the activation energy, the faster the reaction will proceed. The higher the activation energy, the slower the reaction will proceed. As shown above* [in the equation] *the Ea of the exothermic reaction is lower than the Ea of the endothermic reaction; therefore the first reaction* [the exothermic reaction] *occurs faster.* [Sa-D-27]

(1-2-2) Endothermic reactions occur faster

Several students argued that endothermic reactions occur faster than exothermic reactions. The most common reasoning was that endothermic reactions take energy from their surroundings, but in exothermic reactions energy is given out; therefore endothermic reactions occur faster than exothermic reactions. As one of the students put it:

> *None of those opinions are correct, because endothermic reactions occur faster. Endothermic reactions take heat* [energy] *from its surroundings.... Since an increase in temperature raises reaction rate, the second reaction* [endothermic reaction] *occurs faster.* [UF-D-43]

The student seems to think that endothermic reactions absorb heat/energy from their surroundings; therefore they have got more heat/energy than exothermic reactions. Thus, the student concludes that the endothermic reaction occurs faster than the exothermic reaction. 15% of the SS, 19% of the UF, and 9% of the UT' responses were placed in this category. Of those one of the school students believed that endothermic reactions have a lower activation energy:

> *The activation energy of exothermic reactions is higher; therefore the first reaction will proceed slower. As the second reaction absorbing energy, its Ea is lower and as a result it will proceed faster.* [Sc-D-17]

(1-2-3) At lower temperatures exothermic reactions occur faster, however at higher temperatures endothermic reactions occur faster

3 university first year students' responses centred on the idea that if the system temperature is low, exothermic reactions occur faster, otherwise endothermic reactions occur faster. It was not clear from students' responses what the criterion for the low and high temperature was. I suspect those students attempted to apply Le Chatelier's principle to the present situation.

(1-2-4) At the same temperature rates of endothermic and exothermic reactions are equal

System temperature was seen as a key factor by some students (10% of the SS, 8% of the UF and 14% of the UF). They argued that at the same temperature, rates of both exothermic and endothermic reactions would be equal. Here are some examples:

> *Since the temperature is the same, both for exothermic and endothermic reactions, the reactions rate would be the same.* [UF-D-39]
>
> *As both reactions take place at the same temperature, kinetic energy of reacting molecules would be equal. Thus, the number of collisions and the number of effective collisions would be the same; therefore the rate of reactions would be the same.* [UF-D-34]

In the second quotation, while the respondent was aware of the kinetic energy and dynamic interaction between molecules, she did not anticipate the idea that these two reactions might have different activation energies.

(2) Responses including mainly scientifically accepted ideas about kinetic and thermodynamic concepts

(2-1-5)Rates of reactions cannot be compared by using information provided in the probe

31% of the SS, 38% of the UF, and 34% of the UT stated that not enough information was given in the probe to compare rates of these reactions. They argued that if some other variables/quantities were given, it would be possible to compare the rate of these reactions. The subcategories are as follows:

(i) No further explanation is provided

18% of the SS, 23% of the UF and 9% of the UT simply stated that it is not possible to compare rates of these reactions, because there is not enough information given in the question. None of these responses was accompanied by an explanation; therefore it is not possible to draw a conclusion for those responses.

(ii) Concentrations of reactants are needed

Some students' responses (3% of the SS, 11% of the UF, and 9% of the UT) centred on the idea that the higher the concentration of reactants, the faster the reaction. Those students attempted to justify their answers based on a rate equation. Nevertheless, most of them did not consider the rate constant of a reaction or they simply assumed that at the same temperature, the rate constant of these reactions would be equal (cf. Sozbilir, 2001). In fact, temperature is not the only factor that alters the rate constant. The results reflect a lack of understanding of the rate constant, its significance and the variables affecting it. Of those only one school student stated that if the concentration vs. time graph was given for the reactions, it would be possible to compare rates of the reactions.

(iii) Concentrations of reactants and the rate constants are needed

A few students (5% of the SS, 2% of the UF, and 3% of the UT) tried to answer the probe by considering (some) variables in a rate equation.

> *....So as to comment on these reactions rates, reaction steps, concentrations, and rate constants are needed.* [UT-D-20]
>
> *...In order to say something about these reactions rate, we need to know concentrations and the rate constant (k) of these reactions. Rate=* $[B]/\Delta t$*; we need to know how long a reaction proceed.* [Sa-D-21]

(iv) The activation energy of these reactions is needed

Only 5% of the SS, 2% of the UF and 14% of the UT argued that if the activation energy of these reactions was given, it would be possible to predict the faster/slower reaction.

(0) All other responses

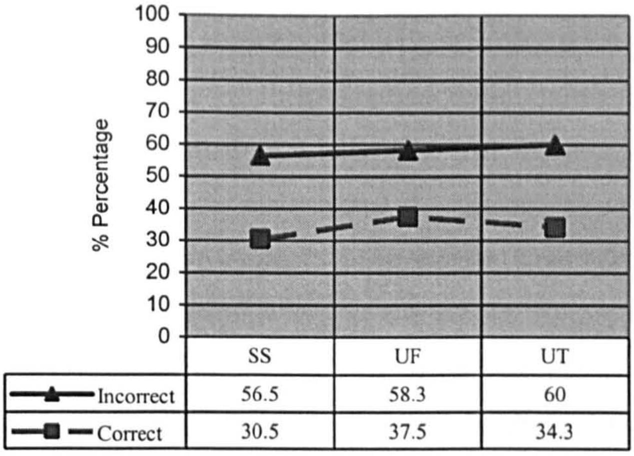
This category is allocated for incomprehensible responses or in cases where there is no response given in the probe. As shown in Table 8.2, 13% of the SS, 4% of the UF and 6% of the UT' responses were placed in this category.

Code	Category (Nature of response)	Example of response	SS *f* *(%)* (n=108)	UF *f* *(%)* (n=48)	UT *f* *(%)* (n=35)
1	**Responses including mainly scientifically incorrect ideas about kinetic and thermodynamic concepts**		**61** ***56.5%***	**28** ***58.3%***	**21** ***60%***
1-2-1	Exothermic reactions occur faster	(i) No further explanation is provided (e.g. the first reaction occurs faster, because it is an exothermic reaction)	16 *14.8%*	2 *4%*	2 *5.7%*
		(ii) Exothermic reactions occur faster, because they do not need energy to proceed/occur. (e.g. The exothermic reaction occurs faster, because the reaction releases energy after the reaction. But endothermic reactions need to get energy for a reaction.)	12 *11%*	10 *20.8%*	11 *31.4%*
		(iii) Exothermic reactions have a lower activation energy. (e.g. The exothermic reaction will proceed faster, because exothermic reactions have a lower activation energy)	6 *5.5%*	0	0
1-2-2	Endothermic reactions occur faster	An increase in heat increases reaction rates. As the endothermic reaction take heat from its surroundings, it occurs faster.	16 *14.8%*	9 *18.8%*	3 *8.6%*
1-2-3	At lower temperatures exothermic reactions occur faster, however at higher temperatures endothermic reactions occur faster.	If the system temperature is low the exothermic reaction will proceed faster, it the system temperature is high the endothermic reaction will proceed faster.	0	3 *6.3%*	0
1-2-4	At the same temperature rates of endothermic and exothermic reactions are equal	As both reactions take place at the same temperature, kinetic energy of them is equal. Thus the number of collisions and the number of effective collisions would be the same; therefore the rate of reactions would be the same.	11 *10%*	4 *8.3%*	5 *14.3%*
2	**Responses including mainly scientifically accepted ideas about kinetic and thermodynamic concepts**		**33** ***30.5%***	**18** ***37.5%***	**12** ***34.3%***
2-1-5	Rates of reactions cannot be compared by using information provided in the probe	(i) No further explanation is provided (e.g. It is not possible to compare the rate of these reactions, because there is not enough information given in the question)	19 *17.6%*	11 *22.9%*	3 *8.6%*
		(ii) Concentrations of reactants are needed (e.g. The higher the concentration of reactants, the faster the reaction)	3 *2.7%*	5 *10.4%*	3 *8.6%*
		(iii) Concentrations of reactants and the rate constants are needed (e.g. In order to say something about these reactions rate, we need to know concentrations and the rate constant (k) of these reactions. Rate= [B]/ Δ t; we need to know how long a reaction proceed)	5 *4.6%*	1 *2%*	1 *2.8%*
		(iv) The activation energy of these reactions is needed (e.g. If the activation energy of these reactions is given, it would be possible to predict the faster/slower reaction)	5 *4.6%*	1 *2%*	5 *14.3%*
0	**All other responses**		**14** ***13%***	**2** ***4.2%***	**2** ***5.7%***
0-0-6	No response		2 *2%*	0	0
	Incomprehensible/Other		12 *11%*	2 *4.2%*	2 *5.7%*
TOTAL			**108** ***100%***	**48** ***100%***	**35** ***100%***

Table 8.2 A coding scheme for the enthalpy probe

8.1.2.2 An overview of students' responses to the enthalpy probe

In contrast with the results of the "activation energy probe", no statistically significant difference was found for the distribution of students' responses to the enthalpy probe across different educational levels (χ^2=0.216, *df*=2, *p*>0.01). The results showed that students made trivial progress from school to university level (see Figure 8.2). Around 31% of SS, 38% of the UF, and 34% of the UT stated that the rate of these reaction could not be compared by using the given information, however many gave no further explanation to justify their answers. In many cases, students attempted to answer the probe based on a rate equation, however they often forgot to consider some variables in the rate equation (i.e. the rate constant or the activation energy of the reaction; some students assumed that at the same temperature the rate constant of those reaction are equal). Many students at both secondary and university levels used conceptions not consistent with scientific perspectives and had conceptual difficulties in kinetic and thermodynamic ideas. For example, the expressions "exothermic reactions occur faster", or "at the same temperature the rates of exothermic and endothermic reactions are equal" were quite common amongst students' responses. Nearly half of the students in all levels (46% SS, 44% UF, and 46% UT) argued that exothermic reactions occur faster or that endothermic reactions occur faster. Surprisingly, the proportion did not change much from school to university. A few students argued that exothermic reactions have a lower activation energy than endothermic reactions and that is why those reactions occur faster. Consequently, several students had limited knowledge or scientifically incorrect ideas about endothermic/exothermic reactions. The results suggested that students did not make a clear distinction between kinetic (e.g. activation energy) and thermodynamic ideas (e.g. enthalpy changes) and tried to use thermodynamic ideas to explain the kinetic of a reaction. This is about inappropriately attributing a relationship between thermodynamic and kinetic factors. These results are also supported by Thomas and Schwenz (1998) and Sozbilir (2001)'s studies.



Uncodeable	13	4.2	5.7
Total %	100	100	100

Figure 8.2 Percentage of responses to the enthalpy probe

8.1.3 SUMMARY OF THE MAIN POINTS ARISING FROM STUDENTS' RESPONSES TO THE ACTIVATION ENERGY AND THE ENTHALPY PROBES

Mainly the same ideas were being tested in the activation energy and enthalpy probes. In this section, the key findings are summarised and discussed.

(i) *General patterns in students' responses and conceptual difficulties that students experienced*

The results suggested that students were more likely to give a correct answer to the activation energy probe than to the enthalpy probe. For the activation energy probe, a significant progression was observed from school to university, whereas for the enthalpy probe the trend did not change much from school to university.

Many students lacked the knowledge of, or failed to apply, fundamental kinetic ideas (i.e. activation energy) in the problem associated with the ideas. A majority of school students had alternative conceptions about activation energy and its relationships with reaction rates. For instance, some students confused the activation energy with the total enthalpy change of the reaction (de Vos & Verdonk, 1986). Nevertheless, from school to university, there was a considerable progression in the number of students who had scientifically correct conceptions about activation energy. However, the majority of the university third year students had scientifically correct ideas about activation energy, only a small number of them applied their knowledge in the "enthalpy probe". As outlined earlier, confusion of kinetics and thermodynamics was a major source of students' difficulties. In many cases the students used thermodynamic data such as the enthalpy value of a reaction to compare the rates of two different reactions which are related to kinetics. Around half of the whole sample's explanations included the view that exothermic reactions occur faster or endothermic reactions occur faster. During interviews, many students were able to talk about the concept of activation energy and enthalpy (i.e. using these ideas consistent with scientific perspectives); however this knowledge was not transferred to the problems posed in the *enthalpy* probe by a significant number of students. Research in other areas of science (e.g. in physics, Savelsbergh *et al.*, 1998) also demonstrate that when novice problem solvers reasoned about a diagnostic question they did not use all the knowledge they had learned or they could not use theoretical tools appropriately.

(ii) Consistency of students' ideas across these two probes

The activation energy and the enthalpy probes were designed to investigate students' understanding of activation energy and to investigate how appropriately students deploy scientific knowledge and understanding within different contexts. If students' reasoning is based on underlying reasoning patterns, consistent responses might be expected to the probes testing the same idea. However, it is found that context plays a significant role in students' reasoning. For example;

A student's response to the Activation energy probe:

> *Activation energy is the energy required for a reaction to proceed... The reaction with lower activation energy occurs faster, because reactants would reach the required energy for a reaction more quickly and as a result the reaction takes place faster.* [UF-D-39]

The same student's response to the Enthalpy probe:

> *Since the temperature is the same, both for exothermic and endothermic reactions, the reactions rate would be the same.* [UF-D-39]

While the student correctly defined the term activation energy and was able to apply her knowledge to the "activation energy probe"; she could not use that knowledge in a situation in different setting (i.e. in the "enthalpy probe"). This might be the result of a straight memorisation of the concepts. Drawing upon the analysis of these two probes, it was evident that students' responses depended on the probe being used. This suggest that when cueing is given, in this case the information given in the activation energy probe (or in this case during an interview), students are more likely to identify accepted ideas.

(iii) Approaches to probing conceptual understanding

The results have possible implications for research on probing conceptual understanding and assessment. The students' reasoning to these two probes seems to be context-dependent; in other words, the social and cultural contexts of probes are significant in influencing the responses that students give (Palmer, 1997; Schoultz *et al.*, 2001). This suggests that it would be beneficial if students' conceptual understanding of a particular domain elicited in different contexts and/or by using different research instruments (e.g. diagnostic tests, interviews). Teaching can then be planned so as to address these conceptual difficulties that students experience.

8.2 STUDENTS' UNDERSTANDING OF THE CONCEPT OF CATALYSIS

This section reports students' ideas about the role of catalysts in chemical reactions and reaction mechanisms. Students' ideas about the concept of catalysis were elicited throughout their responses on two probes: the *catalysis probe* and the *nitrogen monoxide probe-D*. Each probe is discussed separately.

8.2.1 THE CATALYSIS PROBE (Data analysis and results)

The catalysis probe was designed for probing students' knowledge of the effect of catalysts on (A) a reaction rate, (B) the activation energy of a reaction, (C) the yield of products, (D) mechanisms of the reaction and on (E) a reaction pathway. The probe was conceptually framed and was analysed nomothetically by using the coding scheme-B (see Section 3.7). Analysis of students' responses is summarised and illustrated in Tables 8.3, 8.4, 8.5, 8.6, and 8.7.

8.2.1.1 The effect of a catalyst on reaction rate and on the activation energy of a reaction

Analysis of the data indicated that most of the school students and almost all of the undergraduates were aware that a catalyst increases the rate of a reaction by lowering the activation energy of the reaction (see Tables 8.3 and 8.4). However, a few students stated that a catalyst would not affect the rate. Here is an example:

> *A catalyst does not affect the reaction rate, because this reaction occurs in the liquid phase. We do not write liquids or solids in a rate equation, therefore usage of a catalyst will not affect the reaction rate.* [Sc-D-03]

Code	**Category (Nature of response)**	**Example of response**	**SS *f* *(%)* (n=108)**	**UF *f* *(%)* (n=48)**	**UT *f* *(%)* (n=35)**
1	**Responses including mainly scientifically incorrect ideas about the idea tested in the probe**		**13** ***12%***	**0**	**0**
1-2-1	A catalyst *does not affect or does not change* the rate of a reaction	A catalyst does not affect the reaction rate, because this reaction occurs in the liquid phase. We do not write liquids or solids in a rate equation, therefore usage of a catalyst will not affect the reaction rate	13 *12%*	0	0
2	**Responses including mainly scientifically accepted ideas about the idea tested in the probe**		**85** ***78.7%***	**47** ***98%***	**35** ***100%***
2-1-2	A catalyst *increases/decreases* the rate of a reaction	A catalyst lowers activation energy of a reaction, as a result the reaction proceeds faster.	85 *78.7%*	47 *98%*	35 *100%*
0-0-3	**All other responses**	No response or Incomprehensible responses	**10** ***9.3%***	**1** ***2%***	**0**
TOTAL			**108** ***100%***	**48** ***100%***	**35** ***100%***

Table 8.3 A coding scheme for the catalysis probe-A (How would a catalyst affect the rate of a reaction?)

Code	**Category (Nature of response)**	**Example of response**	**SS *f* *(%)* (n=108)**	**UF *f* *(%)* (n=48)**	**UT *f* *(%)* (n=35)**
1	**Responses including mainly scientifically incorrect ideas about the idea tested in the probe**		**19** ***17.6%***	**5** ***10.4%***	**0**
1-2-1	A catalyst *increases* the activation energy of a reaction	A catalyst gives energy to a reaction, therefore it increases activation energy	10 *9.3%*	2 *4.2%*	0
1-2-2	A catalyst *does not affect or does not change* the activation energy of a reaction	A catalyst only increases the rate of a reaction; it has no effect upon the activation energy	9 *8.3%*	3 *6.3%*	0
2	**Responses including mainly scientifically accepted ideas about the idea tested in the probe**		**78** ***72.2%***	**41** ***85.4%***	**35** ***100%***
2-1-3	A catalyst *decreases* the activation energy of a reaction	A catalyst increases the rate of a reaction by lowering activation energy of the reaction	78 *72.2%*	*41* *85.4%*	35 *100%*
0-0-4	**All other responses**	No response or Incomprehensible responses	**11** ***10%***	**2** ***4.2%***	**0**
TOTAL			**108** ***100%***	**48** ***100%***	**35** ***100%***

***Table 8.4** A coding scheme for the catalysis probe-B*
(How would a catalyst affect the activation energy of a reaction?)

8.2.1.2 The effect of a catalyst on the yield of products

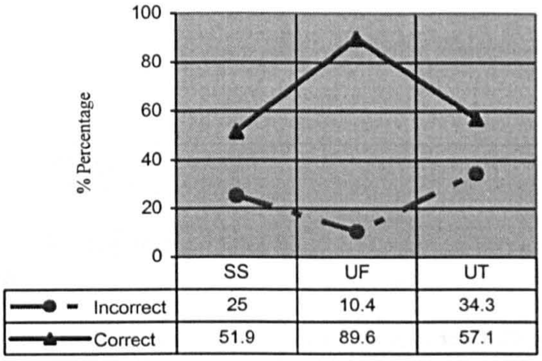
The results revealed that many students (23% SS, 8% UF and 34% UT) believed that a catalyst would increase the yield of the products (see Table 8.5) (cf. Johnstone *et al.*, 1977a). The majority of their justifications included that "the yield of the product would increase; because a catalyst provides an alternative reaction path with reduced activation energy. Therefore, more molecules would pass through the energy barrier and as a result more products would be formed". Hackling & Garnett (1985) argue that students do not anticipate that a catalyst lowers both the forward and reverse activation energies; rather they believed that a catalyst just reduces the forward activation energy and as a result they may reach the conclusion that the catalyst favours the yield of the product. Although, a one-way reaction was given in the probe, students may have used similar underlying ideas and accordingly concluded that a catalyst increases the yield of products.

A ∩-shaped performance curve was found from students' responses to the probe (see Figure 8.3). Several students (52% SS, 90% UF, and 57% UT) argued that a catalyst would not affect the yield of the product; however most of those did not provide further explanation. Only a few justified (appropriately or inappropriately) their answers; some examples are that "the catalyst will not affect the yield, because it is not used up during the reaction", "the catalyst starts/ignites a reaction and unchanged at the end of the reaction, therefore it would not affect the yield of products".

Code	**Category** **(Nature of response)**	**Example of response**	**SS** ***f*** ***(%)*** **(n=108)**	**UF** ***f*** ***(%)*** **(n=48)**	**UT** ***f*** ***(%)*** **(n=35)**
1	**Responses including mainly scientifically incorrect ideas about the idea tested in the probe**		**27** ***25%***	**5** ***10.4%***	**12** ***34.3%***
1-2-1	A catalyst *increases* the yield of products	A catalyst reduces the activation energy. As a result, more particles will have energy greater than the activation energy. That leads to higher percentage of products.	25 *23.1%*	4 *8.3%*	12 *34.3%*
1-2-2	A catalyst *decreases* the yield of products	No further explanation	2 *1.9%*	*1* *2.1%*	0
2	**Responses including mainly scientifically accepted ideas about the idea tested in the probe**		**56** ***51.9%***	**43** ***89.6%***	**20** ***57.1%***

2-1-3	A catalyst *does not affect or does not change* the yield of products	No further explanation or Insufficient details	55 *50.9%*	38 *79.1%*	18 *51.4%*
		The catalyst will not affect the yield, because it is not used up during the reaction.	1 *0.9%*	5 *10.4%*	2 *5.7%*
0-0-4	**All other responses**	No response or Incomprehensible responses	**25** ***23.1%***	**0**	**3** ***8.6%***
		TOTAL	**108** ***100%***	**48** ***100%***	**35** ***100%***

***Table 8.5** A coding scheme for the catalysis probe-C*
(How would a catalyst affect the yield of products?)



Uncodeable	23.1	0	8.6
Total %	100	100	100

***Figure 8.3** Percentage of responses to the catalysis probe-C*

8.2.1.3 The effect of a catalyst on mechanisms of a reaction

While most of the students were aware that a catalyst increases the reaction rate by lowering the activation energy of the reaction, majority of those had limited knowledge about how it affects the mechanisms of the reaction and how it works (see Table 8.6). Indeed, several students (56% SS, 79% UF, and 60% UT) stated that the catalyst would not affect/change the mechanisms of the reaction. As one of the UF (and a few others provided similar justification for their answers) stated that:

> *A catalyst will not change the reaction step, because it does not react with the reactants during the reaction. If an uncatalysed reaction occurs in 2 steps, with a catalyst it also occurs in two steps.* [UF-D-45]

No statistically significant difference was found across educational levels (χ^2=8.468, *df*=2, *p*>0.01), however, it was surprising that the majority of the UF (79%) and around two third of the UT had scientifically incorrect ideas about the mechanism of a catalysed reaction. Though 18% of the SS, 10% of the UF and 34% of the UT argued that a catalyst would change the mechanism of the reaction, most of them did not provide further explanation for their answers. Only a few students -mainly the undergraduates- expressed that "catalysed and uncatalysed reactions have completely different mechanism that the catalyst reacts with one or more of the reactants and accordingly a series of reactions take place, during which the catalyst is consumed and regenerated. Thus, the catalysed reaction occurs in more then one step".

Code	Category (Nature of response)	Example of response	SS *f* *(%)* (n=108)	UF *f* *(%)* (n=48)	UT *f* *(%)* (n=35)
1	**Responses including mainly scientifically incorrect ideas about the idea tested in the probe**		**60** ***55.5%***	**38** ***79.1%***	**21** ***60%***
1-2-1	A catalyst *does not affect or does not change* the mechanisms of a reaction	A catalyst will not change the reaction step, because it does not react with the reactants during the reaction.	60 *55.5%*	*38* *79.1%*	21 *60%*
2	**Responses including mainly scientifically accepted ideas about the idea tested in the probe**		**19** ***17.6%***	**5** ***10.4%***	**12** ***34.3%***
2-1-2	A catalyst *changes* the mechanisms of a reaction	The catalyst reacts with one or more of the reactants. Thus, the catalysed reaction occurs in more then one step	19 *17.6%*	5 *10.4%*	12 *34.3%*
0-0-3	**All other responses**	No response or Incomprehensible responses	**29** ***26.9%***	**5** ***10.4%***	**2** ***5.7%***
TOTAL			**108** ***100%***	**48** ***100%***	**35** ***100%***

***Table 8.6** A coding scheme for the catalysis probe-D*
(How would a catalyst affect mechanisms of the reaction?)

8.2.1.4 Drawing a reaction pathway for a catalysed reaction

When students were asked to draw a reaction pathway for a catalysed reaction, most of them drew a graph with lower activation energy (see Table 8.7). Nevertheless, most of these graphs had one transition state showing that the catalysed reaction also occurs in one step[2]. Only 2% of the UF, and 20% of the UT' drawings and explanations indicated that a catalysed reaction occurs in two or more steps[3]. 15% of the SS and 9% of the UF drew the incorrect representations shown in Figure 8.4 to reflect an energy profile for a catalysed reaction.

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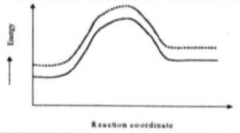
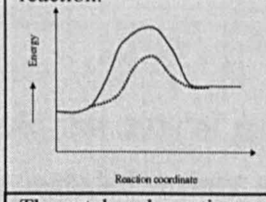
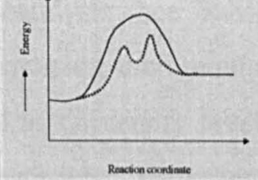
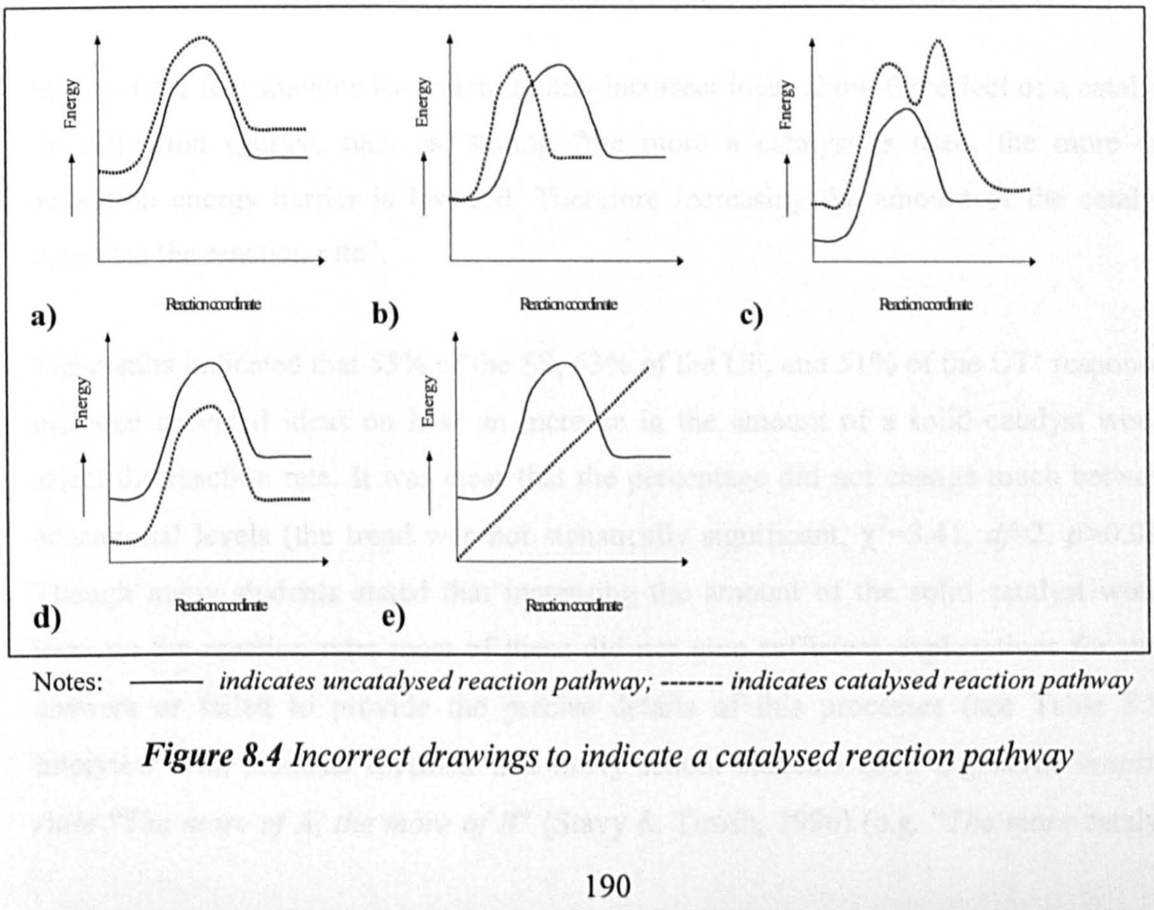
[2] It might be argued that this is an incorrect representation (Haim, 1989, p.935); however since textbooks and/or students' notes used this graph as a basis, a student's response which includes that kind of representations was justified as being correct.

[3] Scientifically correct representations

Code	Category	Example of response	SS *f* *(%)* (n=108)	UF *f* *(%)* (n=48)	UT *f* *(%)* (n=35)
1-2-1	**Incorrect drawings**	See also Figure 8.4. A catalyst gives energy to a reaction, therefore it increases the activation energy of the reaction 	16 *14.8%*	*4* *8.3%*	0
2-1-2	**Correct drawings**	A catalyst decreases the activation energy of the reaction. 	84 *77.8%*	34 *71%*	26 *74.3%*
		The catalysed reaction occurs in more than one step 	0	1 *2.1%*	7 *20%*
0-0-3	**All other responses**	No response or Incomprehensible responses	8 *7.4%*	4 *8.3%*	2 *5.7%*
		TOTAL	**108** ***100%***	**48** ***100%***	**35** ***100%***

Notes: —— *indicates uncatalysed reaction pathway; ------- indicates catalysed reaction pathway*

Table 8.7 *A coding scheme for the catalysis probe-E*
(Please draw a pathway for a catalysed reaction)



Notes: —— *indicates uncatalysed reaction pathway; ------- indicates catalysed reaction pathway*

Figure 8.4 *Incorrect drawings to indicate a catalysed reaction pathway*

8.2.2 THE NITROGEN MONOXIDE PROBE-D (Data analysis and results)

The nitrogen monoxide probe-D (a conceptually framed probe) was designed to elicit students' understanding of heterogeneous catalysis. The students were asked how an increase in the amount of a solid catalyst would affect the reaction rate. The surface area of a solid catalyst is important to the reaction rates. Because reaction occurs at the surface of the catalyst, the rate increases with increasing surface area or increasing the amount of the catalyst.

The results showed that 29% of the SS, 27% of the UF, and around half of the UT (49%) responses included mainly scientifically incorrect ideas about the concept of (heterogeneous) catalysis (see Table 8.8). Surprisingly, the number of students who believed that "increasing the amount of the catalyst would not affect the reaction rate" rises from school to university level. The responses below are some examples for the students in this category: increasing the amount of the catalyst would not change the reaction rate "because it is not a variable of rate equation/expression"; "...because a catalyst does not affect zero order reactions"; "...because a catalyst just starts/ignites a reaction, just a small amount of it would be enough to do that". Here is another example:

> *Normally a catalyst raises the reaction rate; however this is a zero order reaction. In that case a catalyst doesn't change the reaction rate.* [Sc-D-17]

Moreover, a few students had scientifically incorrect ideas about the effect of a catalyst on activation energy; such as, stating "the more a catalyst is used, the more the activation energy barrier is lowered. Therefore increasing the amount of the catalyst increases the reaction rate".

The results indicated that 55% of the SS, 63% of the UF, and 51% of the UT' responses included accepted ideas on how an increase in the amount of a solid catalyst would affect the reaction rate. It was clear that the percentage did not change much between educational levels (the trend was not statistically significant, $\chi^2=3.41$, *df*=2, $p>0.01$). Though many students stated that increasing the amount of the solid catalyst would increase the reaction rate; most of these did not give sufficient explanations for their answers or failed to provide the precise details of this processes (see Table 8.8). Interview with students revealed that many school students used a *general intuitive rule: "The more of A, the more of B*" (Stavy & Tirosh, 1996) (e.g. "*The more* catalyst we use, *the faster* the reaction occurs") and they could not give a mechanism to account for this process. Nevertheless, when students move through the curriculum, they provided more elaborated ideas on the catalysis process. Here is an example:

> *Increasing the amount of the catalyst raises both exothermic and endothermic reactions rates, because a catalyst plays an important role in interactions between reactants. It enables reactants to interact in a proper orientations and it enables them to form intermediates with weaker covalent bonds. Those effects will result in a rise in the reaction rate.* [UT-D-05]

Code	Category (Nature of response)	Example of response	SS *f* *(%)* (n=108)	UF *f* *(%)* (n=48)	UT *f* *(%)* (n=35)
1	**Responses including mainly scientifically incorrect ideas about the idea tested in the probe**		**32** ***29.6%***	**13** ***27.1%***	**17** ***48.6%***
1-2-1	Increasing the amount of the catalyst *does not affect* the reaction rate	Increasing the amount of the catalyst does not affect reaction rate, because catalyst just starts/ignites a reaction, just a small amount of it would be enough to do that.	17 *15.7%*	8 *16.7%*	15 *42.9%*
1-2-2	Increasing the amount of the catalyst *decreases* the reaction rate	No further explanation.	6 *5.5%*	0	0
		Inappropriate reasoning : It decreases the reaction rate, because a solid catalyst is used. The reaction between a solid and gas is difficult. If a gas catalyst was used, increasing the amount of the catalyst would increase the reaction rate.	5 *4.6%*	1 *2.1%*	0
1-2-3	Increasing the amount of the catalyst *increases* the reaction rate	Inappropriate reasoning: The more catalyst is used, the more the activation energy barrier is lowered.	4 *3.7%*	4 *8.3%*	2 *5.7%*
2	**Responses including mainly scientifically accepted ideas about the idea tested in the probe**		**59** ***54.6%***	**30** ***62.5%***	**18** ***51.4%***
2-1-4	Increasing the amount of the catalyst *increases* the reaction rate	No further explanation.	52 *48.1%*	21 *43.8%*	6 *17.1%*
		Appropriate reasoning: The surface of a solid catalyst is important to the reaction rate. The reaction occurs on the surface of the solid catalyst, therefore rate increases with increasing the amount of solid catalyst.	7 *6.5%*	9 *18.8%*	12 *34.3%*
0	**All other responses**		**17** ***15.7%***	**5** ***10.4%***	**0**
0-0-5	No response or Incomprehensible responses	Increasing the amount of the catalyst affects the rate of reaction.	17 *15.7%*	5 *10.4%*	0
TOTAL			**108** ***100%***	**48** ***100%***	**35** ***100%***

***Table 8.8** A coding scheme for the nitrogen monoxide probe-D*
(How would increasing the amount of the catalyst affect the reaction rate?)

It is important to note that although several students in response to the "magnesium oxide probe" (as discussed in Chapter 7) explained the effect of surface area of "solid reactants" on reaction rates by referring to the various theories in kinetics, few such students applied those ideas to the "nitrogen monoxide probe-D" which aimed to investigate students' ideas about the effect of surface area of a solid catalyst on reaction rates. One of the reasons might be that students were not aware that the reaction occurs on the solid catalyst. Alternatively the students might be influenced by contextual aspects of these two probes.

8.2.3 SUMMARY OF THE MAIN POINTS ARISING FROM THE CATALYSIS PROBE AND THE NITROGEN MONOXIDE PROBE-D

One of the purposes of the study was to explore the development of students' understandings of the concept of catalysis in the context of the aims of the curriculum in Turkey. Although most of the students were aware that an appropriate catalyst increases the rate of a reaction by lowering the activation energy of the reaction, they had limited knowledge about the process of catalysis (i.e. how a catalyst affects the course of a chemical process and mechanisms of a reaction). Interviews with students revealed that some school students believed that a catalyst is something abstract (e.g. a form of energy) or regarded as a mysterious object. Therefore, during teaching, it should be emphasized that a catalyst is a substance: heat and light might assist in achieving a reaction or increase reaction rates, but they cannot be catalysts. The results revealed that a great number of students stated that the catalyst would not change the mechanism of the reaction; accordingly the catalysed and uncatalysed reactions proceed via the same mechanisms. Furthermore, several students argued that catalysts result in the formation of a higher percentage of products (Johnstone *et al.*, 1977a). It was somewhat surprising to see that most of the future chemistry teachers did not hold the scientific view of the role of a catalyst in a chemical reaction.

In the next section, some possible reasons for students' lack of knowledge and difficulties about the notion of catalysis are discussed.

8.3 EMERGING ISSUES FROM TEXTBOOK ANALYSIS AND STUDENTS' NOTES

The concepts of catalysis and chemical kinetics have been regarded as a difficult topic area for students to understand (Logan, 1984; Justi, 2002). Part of the difficulty rests with the nature and complex structure of the domain (Logan, 1984), but more seems to stem from the ways by which the concept of catalysis is customarily taught. The results show that the students following the curriculum have made no substantial progress in understanding how a catalyst affects the course of a chemical process, and the mechanisms of chemical reactions. A number of issues have been identified that appeared to serve as barriers to such students in developing more appropriate ideas about the notion of catalysis. Firstly, the results concerning students' difficulties and lack of knowledge may result from a purely macroscopic approach (in some case with symbolic representations) for teaching the concept of catalysis. It seems that the curriculum concentrated on the macroscopic and the mathematical level, neglecting the particulate level. For instance, high school chemistry textbooks (e.g. Kizildag & Dursun, 2000) simply state that a catalyst provides a new pathway for a reaction, one with a lower activation energy. School textbooks did not explicitly or implicitly present how a catalyst affects the mechanism of a reaction, nor did they explain the nature of the catalysis process. The effect of a catalyst on a reaction is usually mentioned on the diagram shown in Figure 8.5. Although that was not the case for undergraduate textbooks (Mortimer, 1989; Atkins, 2001), analysis of the undergraduate students' notes indicated that in classrooms settings, the effect of catalysts on reaction rates was also mentioned on that diagram. Such diagrams do not depict "the most important feature of catalyzed reaction, namely, that they involve sequences of several activated complexes and intermediates" (Haim, 1989, p.936). Such diagrams, which do not provide sufficient evidence for the mechanism of a reaction, can give students the impressions that the catalysed and uncatalysed reactions proceed via the same mechanism (a one-step mechanism). Indeed, these diagrams and representations might be one of the reasons for students' lack of knowledge, and for their commitments to alternative conceptions about the role of catalysts in chemical reactions.

It could be argued that whether these kinds of diagrams should be used as curricular models or not. Rather than discussing the correctness of these representations[4], we need to focus on the crucial questions: what are our teaching goals, and is it feasible to achieve these teaching goals by means of our teaching tools/approach? If our teaching goals are to teach the chemical process of catalysis, and to teach this notion in a consistent way, then the current approach in the curriculum has limitations. I propose that there should be consistency between different forms of representations and that

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[4] I suggest that kind of representations would be a curricular model, a simplified version of any consensus or historical model, since the nature, scope and limitations of the model/representation were acknowledged.

there should not be mismatches between them. At least the limitation of the models needs to be acknowledged. For example, the nature of catalysis process would be explained at the sub-microscopic and also at the symbolic level, but if there is a mismatch between them that may lead to misconceptions. In fact, there is a mismatch between different forms of representations. For example, equations for the catalysed and uncatalysed reactions would be as follows:

The equation for without a catalyst:

$$A + B \longrightarrow AB$$

The equations for a catalysed reaction would be as follows: (C indicates a catalyst).

Step 1: $A + C \longrightarrow AC$

Step 2: $AC + B \longrightarrow AB + C$

Overall: $A + B \xrightarrow{C} AB$

The catalyst C gets involved, initiating a sequence of reactions and yet is regenerated. From this equation the catalaysed reaction occurs in two steps, however in terms of the energy profile graph (see Figure 8.5) both the catalysed and uncatalysed reactions occur in one step. Therefore, these two forms of representations would not map onto each other and would be a mismatch between them.

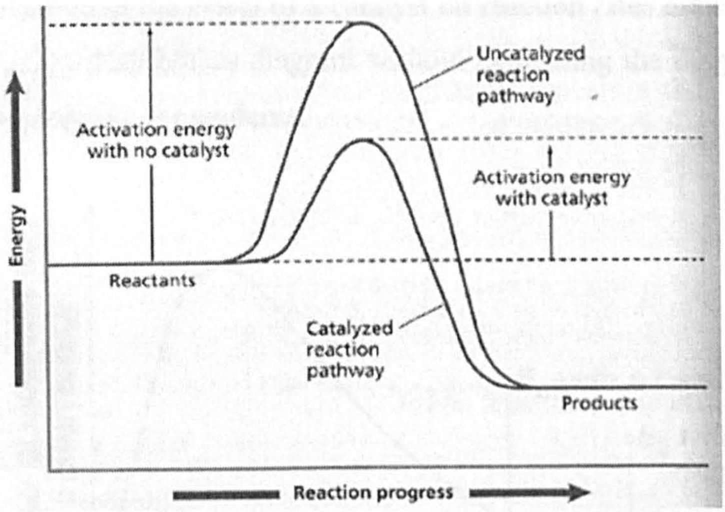

Figure 8.5 An energy profile for a catalysed and uncatalysed reaction

Students' responses to the catalysis and the nitrogen monoxide probe-D revealed that many students believed that a catalyst did not react with any of the reactants or products. One of the reasons for that would be scientifically imprecise definition of the catalyst used in the school textbook, which defines catalysts as "…a substance that changes reaction rate without entering into the reaction" (in Turkish: "Kendisi tepkimeye girmedigi halde, tepkime hizini degistiren maddelere, katalizor denir.") (Kizildag & Dursun, 2000, p.108). This kind of scientifically imprecise statements can promote alternative conceptions about the mechanism of catalysis. Therefore, a more comprehensible definition for a catalyst would be that a catalyst is a substance that works by changing the mechanism of a reaction in that it actually reacts with the one or more of the reactants present or adsorbs reactant molecules (cf. van Driel and de Vos, 1989, in Justi, 2002). It should be emphasized that a catalyst affects the rate constant and the activation energy of the reaction.

Another issue emerged from textbook analysis was that two diagrams commonly used to account for the effect of catalysts on reaction rates: (1) the reaction profile for a catalysed and an uncatalysed reaction refers to "single particle events" (see Figure 8.5), and (2) the Maxwell-Boltzmann energy distribution graph refers to the average energy of "many particles" (see Figure 8.6). Understanding of these representations is conceptually demanding in that it requires students to understand characteristics of each graph and to make links between them. Since one of the graphs shows single particle event and the other shows many particles events, developing an understanding of links between them involve is likely to be difficult for students. Consequently, just illustrating the effect of a catalyst on reaction rates drawing on the Maxwell-Boltzmann energy distribution diagram without explaining the diagram qualitatively would not be appropriate for students.

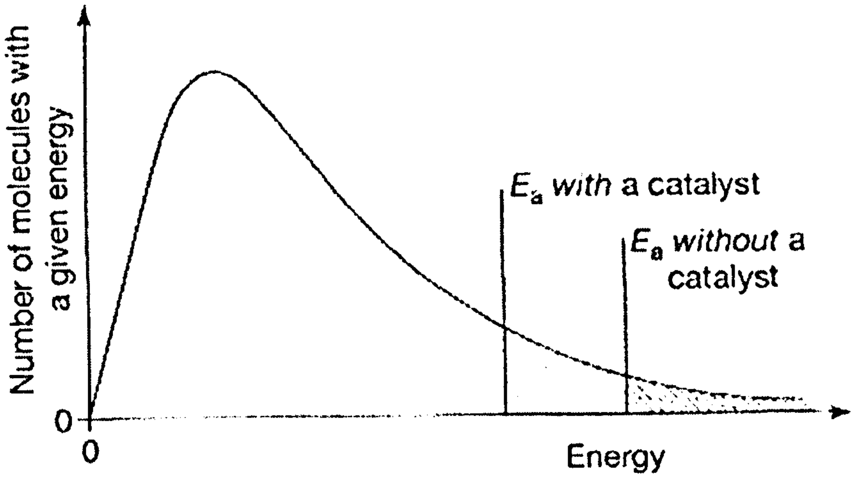

***Figure 8.6** Maxwell-Boltzmann energy distribution curve showing the effect of a catalyst*

The results indicated that several students (23% SS, 8% UF and 34% UT) believed that a catalyst would increase the yield of the product. It seems that mainly SS and UT have this alternative conception. Furthermore, a ∩-shaped performance curve was found from students' responses to the probe in that the UF (89.6%) had the highest percentage rate for the correct answers (see Figure 8.3). One of the reasons would be the way of teaching during their course. For example, an analysis of textbooks indicated that the effect of catalysts on reaction rates is introduced on the Maxwell-Boltzmann energy distribution (see Figure 8.6) both in the school chemistry textbook and in the physical chemistry textbook (for UT), but not in general chemistry textbook (for UF). That representation can give students the impression that with a catalyst more product is formed, since the shaded area for the catalysed reaction is greater that the area for the uncatalysed reaction. As discussed earlier (in Section 8.1.1.2) there was some evidence showing that students tend to interpret diagrams such as energy profile diagrams based on surface features of the diagrams. Another issue on the representation of the concept is that while the Maxwell-Boltzmann energy distribution is conceptually demanding, important characteristics of the graph (i.e. explicit interpretations of the graph) are overlooked in the textbooks. It emerges that more attention should be given to the interpretation of symbolic representations of the concept and its relationships with the sub-microscopic level. In fact, it is questionable whether the Maxwell-Boltzmann energy distribution diagram (i.e. in a graphical format) is at all necessary in elementary courses to introduce both the effect of catalysis on reaction rates and the effect of temperature on reaction rates (see also Section 6.3).

Based on his analysis of A-level chemistry syllabuses (in England, Wales and Northern Ireland), Logan (1984) argues that since mechanisms of catalysis, whether heterogeneous or homogenous, have little in common and A-level students (age 16+) do not have facilities and time to do any experiments whose results might suggest a probable mechanism of any catalysed reaction, "it does seem strange that this aspect [mechanisms of catalysis] should be so heavily emphasised" (ibid. 21). In an attempt to provide a more comprehensive approach to introduction of catalysis, he argues that it would be more appropriate to encourage (A-level) students to learn how the reaction rate may depend on the amount of catalyst –on its concentration- for homogenous catalysis or depend on its surface area for heterogeneous catalysis. However, I would argue that in order to achieve these objectives, it is necessary to emphasise the mechanisms of catalysis. Van Driel & De Vos (1989, in Justi, 2002) and Haim (1989) also propose that it is necessary to emphasise the impact of catalysts on reaction mechanisms. Indeed, Van Driel & De Vos designed a teaching unit in catalysis based on these premises and implemented it on 15-16 years old students. They found that although most students had difficulties in understanding the complexity of catalysis processes, the students usually understood the idea that a catalyst is a substance that actually reacts with one or more of the reactants present.

Neither school nor university first year textbooks explained how enzymes affect a reaction rate at the sub-microscopic or symbolic levels, rather they simply stated that enzymes would affect reaction rates. However, the effects of enzymes on reaction rates displayed in school Biology textbooks. It would be helpful if the chemistry and biology teachers established ways to display kinetic knowledge across domains.

Drawing upon the results of the study, I propose an alternative representation for teaching the notion of catalysis. This is presented in Appendix 5.

8.4 SUMMARY AND DISCUSSION

In this chapter, students' understandings of the concepts of activation energy and catalysis have been presented. The key findings are discussed below. This section is mainly focused on emerging issues on the concept of catalysis, issues related to the activation energy concept are mainly discussed earlier in Section 8.1.3.

(i) General patterns in students' responses

The results indicate that whilst most of the students were aware of that a catalyst is a substance that increases the rates of a reaction by reducing the activation energy of the reaction; many of the precise details of this process remain a mystery to the students. The results revealed that students following the curriculum have made no substantial progress in understanding how a catalyst affects the course of a chemical process, and the mechanisms of catalysed reactions. For instance many of the students stated that the catalyst would not change the mechanism of the reaction; accordingly the catalysed and uncatalysed reactions are thought to proceed via the same mechanisms. It was somewhat surprising to see that most of the future chemistry teachers did not hold the scientific view of the role of a catalyst in a chemical reaction. As discussed earlier, one of the reasons for students' lack of knowledge or having scientifically incorrect ideas about the notion of catalysis would be the approach used in the curriculum which is somewhat lacking in explanatory power[5] and has possible source of alternative conceptions (i.e. the symbolic representation of the concept, see Figure 8.5). In particular, mismatches between different forms of representations were identified. I propose that there should be consistency between different forms of models used and limitations of the models needs to be acknowledged. Symbolic representations should not be used for the sake of visual representation; they should be supported with complementary information in verbal (e.g. by teacher talk) and/or written form. The approach for the design of a modeling activity would be to specify in details and to justify, the science knowledge to be taught, to analyse the knowledge that is actually taught and to assess students' understanding of that knowledge.

(ii) Instruction and the nature of practical work

Among the difficulties the students had experienced, I found that a major one was connecting their macroscopic modeling of chemical phenomena to theories and models in chemical kinetics (which involve particulate and/or mathematical modelling), probably because they lacked a mechanism to explain this process. The experiments presented in the school textbook and in the university first year laboratory book seem to be designed just for showing to students that a catalyst affects or increases the rate of reactions. The links between the concepts and observable or empirical aspects of the experiments were not specified or ignored in the curriculum[6]. Without being explicitly introduced the relationships between concepts and the aspects of the experiments, students would have conceptual difficulties in making links between them. I propose that the instructional activities should rather be designed to stimulate students' understanding of the nature of the catalysis process in the following areas: how a catalytic reaction takes place, how the reaction rate may depend on the amount of a catalyst, how a catalyst affects the yield of the products, and how the reaction mechanism is affected in the presence of a catalyst. In other words, since the students had difficulties in understanding of the role of catalyst in a chemical reaction and failed to move between the world of objects/events (that refers to all observable aspects of the

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[5] As being argued in the proceeding section, the approach used in the school textbook had some limitations; such as it lacked the notion of reaction mechanism for a catalysed reaction and the detailed pathways taken by atoms and molecules as a reaction proceeds in the presence and absence of a catalyst.

[6] I do not have any evidence of what kind of support provided by the teacher during carrying out the experiments or of the nature of the practical work (e.g. the nature of the discourse between students and teachers or between students and students).

material worlds) and the world of theories/models, instructional activities should be designed to support and to mediate students' conceptualisation of the interrelationships between these two worlds (cf. Tiberghien, 1999).

CHAPTER 9

STUDENTS' UNDERSTANDING OF RATE EQUATIONS AND REACTION MECHANISMS

CHAPTER 9

STUDENTS' UNDERSTANDING OF RATE EQUATIONS AND REACTION MECHANISMS

9.0 INTRODUCTION

This chapter is structured into two distinct sections. The first section reports the analysis of students' responses to the *nitrogen monoxide probe-A* and *B* which were designed to probe students' ideas about the existence of relationships between empirical data and rate equations. The second section (section 9.2) presents students' responses to the *reaction mechanism probe* that was designed to elicit their understanding of reaction mechanisms and the rate-determining step. Each section also addresses emerging issues from the analysis of documentary evidence in these areas of kinetics. All of the probes reported in this chapter were conceptually framed and were analysed nomothetically by using the coding scheme-B.

9.1 STUDENTS' UNDERSTANDING OF THE REACTION ORDER AND RATE EQUATIONS

This section reports students' responses on the nitrogen monoxide probe-A and B. The first part of the probe (the nitrogen monoxide probe-A) aims to explore students' ideas about the reaction order and how they understand the existence of relationships between empirical data and rate equations. The probe presented students with data; they had to assess the data and argue how the data supports the scientists' conclusion about the reaction order. The probe assesses students' ability to interpret diagrams representing empirical data. So as to answer the probe students need to link the graph characteristics with theoretical models. The second part of the probe (the nitrogen monoxide probe-B) aims to investigate students' ideas of the variables in a rate equation.

9.1.1 THE NITROGEN MONOXIDE PROBE-A (Data analysis and results)

The probe was conceptually framed and accordingly the analysis was done by using "coding scheme-B" (see Section 3.7), which had three main categories: (1) responses including mainly scientifically incorrect ideas about the idea tested in the probe, (2) responses including mainly scientifically accepted about the idea tested in the probe, and (0) all other responses. In the following sections those three main categories, and identified sub-categories, are discussed. Analysis of students' responses is summarised and illustrated in Tables 9.1 and Figure 9.1.

(1) Responses including mainly scientifically incorrect ideas about the idea tested in the probe

The respondents in this category often interpreted the presented graph based on surface features of the graph without referring to any theoretical model (e.g. see category (1-2-1) and (1-2-2) below). However, it is not possible to answer this probe properly at a descriptive/empirical level. The subcategories are discussed below.

(1-2-1) Interpreting the graph based on directly observable features of the probe

The respondents simply described what they see on the graph or in the probe. In other words restated or rephrased the information provided in the probe. 36% of the SS, 8% of the UF and 9% of the UT' responses were placed in this category and some typical responses are: "*the concentration of the NO decreases; therefore the reaction rate is zero order*", "*the experiment shows that this is a zero order reaction*", "*the reaction order is the difference between the number of reactants and products moles. While the number of moles does not change during the reaction, it would be a zero order reaction*". In some instances, students' reasoning was tautologous (e.g. "*the scientists proved that the reaction was zero order*").

(1-2-2) Since the concentration of NO is zero at the end of the reaction, it is a zero order reaction

The difference between the sub-category (1-2-1) and (1-2-2) was that students in the later category also justified their answers on the observable features of the event, however they argued that if all of the reactants were used up during the reaction, the reaction order would be zero.

> *All of NO* [reactant] *is used up, and at the end of the reaction the concentration of NO is zero. Therefore the reaction is zero order with respect to NO.* [UF-D-29]

32% of the SS, 25% of the UF, and 11% of the UT were placed in this category.

(1-2-3) It is not a zero order reaction

2 school students disagreed about the reaction order. The interviews showed that the students believed that this reaction was second order with respect to NO. Those students had a general view that the concentrations of reactants in the rate equation have exponents equal to the stoichiometric coefficients of the reactants in the balanced equation for the reaction. They assumed that the rate equation for the decomposition of NO

$$2NO \rightarrow N_2 + O_2 \text{ ; } Rate = k.[NO]^2$$

has an exponent of 2 on [NO], which means the reaction is second order with respect to NO. The students were not aware that the order of a reaction must be determined experimentally. If a chemical reaction occurs in one step, the concentrations of reactants in the rate equation have exponents equal to the coefficients of the reactants in the balanced equation for the reaction. However that is not the case for the given reaction which is a catalysed reaction and occurs in more than one step.

(2) Responses including mainly scientifically accepted ideas about the idea tested in the probe

(2-1-4) Explanation in terms of theories of kinetics

The respondents in this category used theoretical models appropriately in the given situation. Most of the students justified their responses based on a mathematical model (e.g. thinking of the reaction rate as the slope of the concentration of reactants vs. time graph; since the slope of the graph is constant at any point, they assume that the reaction is independent of NO concentration). 3% of the SS, 38% of the UF and 60% of the UT responses were placed in this category and some typical quotations are given below:

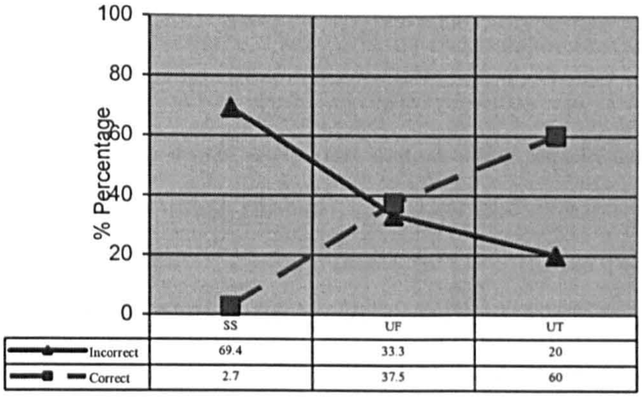
> *The scientists have got a linear graph and they saw that the concentration of nitrogen monoxide decreases proportionally against time; in other words they see the slope of the graph is constant. As a result they reached the conclusion that this reaction is zero order with respect to NO.* [UF-D-03]
>
> *The consumption of nitrogen monoxide per unit time is constant; consequently the reaction rate is constant. Therefore, we can say that this is a zero order reaction and the reaction rate only depends on the rate constant.* [UT-D-20]

(0) All other responses

This category is allocated for incomprehensible responses or in cases where there is no response given in the probe. A high percentage of the students (27% SS, 29% UF and 20% UT) were placed in this category.

Code	**Category** **(Nature of response)**	**Example of response**	**SS** ***f*** ***(%)*** **(n=108)**	**UF** ***f*** ***(%)*** **(n=48)**	**UT** ***f*** ***(%)*** **(n=35)**
1	**Responses including mainly scientifically incorrect ideas about the idea tested in the probe**		**75** ***69.4%***	**16** ***33.3%***	**7** ***20%***
1-2-1	Interpreting the graph based directly on the observable features of the event/probe.	The concentration of the NO decreases; therefore the reaction rate is zero order. The reaction order is the difference between the number of reactants and products moles. While the number of moles does not change during the reaction, it would be a zero order reaction.	39 *36.1%*	4 *8.3%*	3 *8.6%*
1-2-2	Since the concentration of NO is zero at the end of the reaction, it is a zero order reaction.	All of NO [reactant] is used and at the end the concentration of NO is zero. Therefore the reaction is zero order with respect to NO.	35 *32.4%*	12 *25%*	4 *11.4%*
1-2-3	It is not a zero order reaction.	It is not a zero order reaction; rather it is a second order with respect to NO. The concentrations of reactants in the rate equation have exponents equal to the stoichiometric coefficients of the reactants in the balanced equation for the reaction.	2 *1.8%*	0	0
2	**Responses including mainly scientifically accepted ideas about the idea tested in the probe**		**3** ***2.7%***	**18** ***37.5%***	**21** ***60%***
2-1-4	Explanation in terms of theories of kinetics	Mathematical Modelling : The reaction rate is the slope of the concentration vs. time graph. As the slope of the graph is constant, we can conclude that this reaction is a zero order reaction with respect to NO. For a zero order reaction, the concentration vs. time graph is linear. Otherwise the graph is parabolic.	3 *2.7%*	18 *37.5%*	21 *60%*
0	**All other responses**		**29** ***26.9%***	**14** ***29.2%***	**7** ***20%***
0-0-5	No answer		9 *8.3%*	5 *10.4%*	4 *11.4%*
	Incomprehensible/Other		20 *18.5%*	9 *18.7%*	3 *8.6%*
TOTAL			**108** ***100%***	**48** ***100%***	**35** ***100%***

Table 9.1 A coding scheme for the nitrogen monoxide probe-A



Uncodeable	26.9	29.2	20
Total %	100	100	100

Figure 9.1 *Percentage of responses to the nitrogen monoxide probe-A*

9.1.1.1 An overview of students' responses to the nitrogen monoxide probe-A

The probe examines students' ability to connect empirical data with scientific theories. It is important to emphasise that so as to answer the probe students need to use some form of theoretical model, such as the notion of rate law, the concept of derivation, or the rate of change; without referring to some of these ideas, it would be difficult to answer the probe. A rate equation is a kind of equation which might be conceptually demanding for students in that it describes not only a relationship between two quantities, but also how a quantity changes over time. By using a rate equation, one can calculate the change in reaction rate over time. Subsequently, without reference to a theoretical model, it is difficult to achieve a correct answer. Indeed, the results showed that students who used a macroscopic model could not produce a correct answer (see Table 9.1).

Analysis of the written responses showed that many students did not attempt to answer the probe or their explanations were incomprehensible. The results in the interviews showed that students were not confident to give explanation for this probe. Understanding and applying the notion of rate law was likely to be problematic for many beginning chemistry students.

A chi-square analysis indicated that there was a statistically significant difference on the distribution of students' responses by different educational levels (χ^2=60.927, *df*=2,

$p<0.01$). An increase in responses including scientifically acceptable idea was observed from school to university. Only 3% of the school students, 38% of the UF, and 60% of the UT used theoretical models appropriately in the given situation. Though many (school) students were able to use a rate equation for other settings (i.e. when responding to the other probes), yet they had difficulty in applying the notion of rate equation and the rate of change into a more complex problem. One of the reasons would be that they did not grasp the meaning of reaction rate or they had limited knowledge of the concept of derivation; the rate of change. This probe was about implication of the definition of reaction rate and of the rate law. As discussed earlier so as to answer the probe students need to have an understanding of the notion of instantaneous rate or the average rate over the chosen time intervals.

9.1.2 THE NITROGEN MONOXIDE PROBE-B (Data analysis and results)

The nitrogen monoxide probe included four sub-questions, one of which (the nitrogen monoxide probe-B) asked students how an increase in the initial concentration of the reactant [NO] would affect the rate of the given reaction (the decomposition of nitrogen monoxide on a platinum surface). The probe assessed students' competence in manipulating variables in a rate equation. The coding scheme-B was applied on the data set. In the following sections the main categories, and identified sub-categories, are discussed. The responses are summarised in Table 9.2.

(1) Responses including mainly scientifically incorrect ideas about the idea tested in the probe

66% of the SS, 50% of the UF and 31% of the UT' explanations included scientifically incorrect ideas about the effect of concentration on reaction rates. Those scientifically incorrect ideas were classified under three subcategories.

(1-2-1) Increasing the concentration of NO increases the reaction rate

The respondents in this category (25% SS, 25% UF and 11% UT) appeared to ignore some relevant variables in the rate equation (i.e. the reaction order) or to use superficial generalisation of rules (i.e. the more concentrated the reactants are, the faster the reaction). Some other examples are given below:

> *Increasing the concentration of reactants increases the reaction rate.* [Sa-D-04]

> *The more concentrated the reactants are, the greater the reaction rate.* [Sb-D-08]

Interviews with students revealed that many students had a general view that the concentrations of reactants in a rate equation have exponents equal to the stoichiometric coefficients of the reactants in the balanced equation for the reaction. Despite being told that it was a zero order reaction with respect to nitrogen monoxide, the students assumed the rate equation as Rate=k.[NO] or as Rate=k. $[NO]^2$.

(1-2-2) An increase in the concentration of NO decreases the reaction rate

The students in this category (16% SS, and 8% UF) argued that since the concentration of reactant [NO] was increased, the reaction rate would decrease. Few students justified their answers mainly based upon prototypical examples of everyday phenomena. For example, one of the school students stated that:

> *When we put less sugar into water it dissolves faster. However, when we put more sugar into water it dissolves slower. Therefore increasing the concentration of NO decreases the reaction rate*". [Sa-D-02]

It seems that the student has difficulties in understanding the notion of rate of change. As argued in the "reaction rate probe-A" (see Section 5.1.1), the students might have thought that reaction rate is the period of time taken for a reaction to occur and they may have confused reaction rate with time for the reaction to complete. It appears that students could not differentiate between "reaction rate" and "reaction time". Here is another example:

> *When we add more NO, the reaction needs more time to proceed. Thus, the reaction rate will decrease.* [Sb-D-03]

(1-2-3) Misapplication of the theoretical models

The students seem to ignore some relevant variables in a rate equation (e.g. they did not consider the presence of the solid catalyst or the order of the reaction). The justifications for their answers were varied and some typical responses are given below

> *With more concentrated reactants, more collisions take place between reactant particles. Thus, the reaction rate increases.* [UT-D-14]

> *Since the rate of a reaction is directly proportional to the concentrations of reactants, increasing the concentration of NO increases the reaction rate.* [UF-D-14]

5 SS, 2 UF and 3 UT stated that reaction rate is directly proportional to the concentrations of reactants; therefore an increase in the concentration of NO will increase the reaction rate. However, this is not the case for this reaction, which is zero order with respect to NO. The rate is independent of the reactant concentration.

In some cases, students treated the reaction as an equilibrium reaction and attempted to apply Le Chatelier's Principle to the given reaction (10 SS, 1 UF and 1 UT). As two of the students put it:

> *When we increase the concentration of NO, the reaction needs to re-establish equilibrium. Thus, the forward reaction produces more products and the reaction rate increases.* [UF-D-35]

> R: How would an increase in the concentration of nitrogen monoxide affect this reaction rate?
> I: *When we increase the concentration of nitrogen monoxide, the reaction rate will increase. Increasing the concentration favors formation of products that will increase the rate of the reaction.*
> R: The rate increases?
> I: *Yes...*
> R: What about the order of the reaction? In that case it is zero order with respect to nitrogen monoxide. Does it matter whether it is a zero order or first order reaction?
> I: *No...*
> R: Are you saying that increasing the concentration of reactants increases the reaction rate whether it is a zero order or a first order reaction?
> I: *Yes.* [Sc-D-03]

Furthermore, misapplication of a rate equation was found from students' responses (4 SS, 1 UF, and 2 UF). For example;

> *Reaction rate=$[N_2].[O_2]/[NO]^2$; thus an increase in the concentration of NO decreases the reaction rate.* [Sa-D-09]

> *Rxn =k.$[N_2].[O_2]$, when we increase the concentration of NO, the concentration of N_2 and O_2 will increase, as a result the reaction rate will increase.* [Sa-D-20]

(2) Responses including mainly scientifically accepted ideas about the idea tested in the probe

(2-1-4) Explanation in terms of theories of kinetics

The students in this category (13% SS, 46% UF and 69% UT) were able to apply theoretical models appropriately in the given situation. They usually justified their responses based on a rate equation. Here are some common quotations:

Increasing the concentration of NO does not affect the reaction rate. In terms of the rate equation Rxn=k. $[NO]^{0}=k$*, the rate is independent of the concentration.* [Sa-D-05]

This reaction is zero order with respect to NO. For a zero order reaction, reaction rate only depends on the rate constant (k), therefore an increase in the concentration of NO does not affect the reaction rate. [UF-D-13]

(0) All other responses

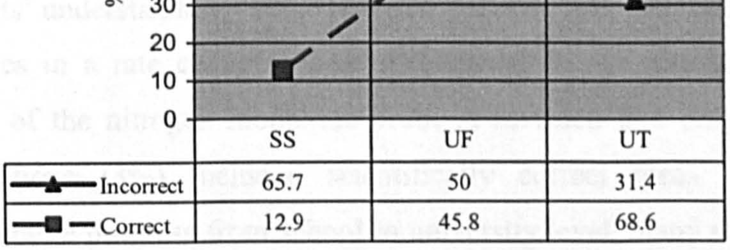
This category is allocated for incomprehensible responses or in cases where there is no response given in the probe. 21% of the SS, and 4% of the UF' responses were placed in this category.

Code	Category (Nature of response)	Example of response	SS *f* *(%)* (n=108)	UF *f* *(%)* (n=48)	UT *f* *(%)* (n=35)
1	**Responses including mainly scientifically incorrect ideas about the idea tested in the probe**		**71** ***65.7%***	**24** ***50%***	**11** ***31.4%***
1-2-1	Increasing the concentration of NO increases the reaction rate	Superficial generalization of rules. (Ignoring some relevant variables): The more concentrated the reactants are the greater the reaction rate. The reaction rate is proportional to the concentrations of reactants.	27 *25%*	12 *25%*	4 *11.4%*
1-2-2	An increase in the concentration of NO decreases the reaction rate	When we add more NO, the reaction needs more time to proceed. Thus the reaction rate decreases.	17 *15.7%*	4 *8.3%*	0
1-2-3	Misapplication of the theoretical models.	With more concentrated reactants, more collisions take place between reactant particles. Thus, the reaction rate increases. Misapplication of the Le Chatelier's Principle: When we increase the concentration of NO, the reaction needs to re-establish equilibrium. Thus, the forward reaction produces more products and the reaction rate increases.	27 *25%*	8 *16.7%*	7 *20%*
2	**Responses including mainly scientifically accepted ideas about the idea tested in the probe**		**14** ***12.9%***	**22** ***45.8%***	**24** ***68.6%***
2-1-4	Explanation in terms of theories of kinetics	The reaction rate is not affected by the changes in the concentration of NO. Because, the reaction is a zero order reaction and its rate only depends on the rate constant.	14 *12.9%*	22 *45.8%*	24 *68.6%*
0	**All other responses**		**23** ***21.3%***	**2** ***4.1%***	**0**
0-0-5	No answer		2 *1.8%*	2 *4.1%*	0
	Incomprehensible/Other	Since reaction rate depends on the amount of substances, the reaction occurs in a longer period of time. The reaction is a zero order reaction.	21 *19.4%*	0	0
TOTAL			**108** ***100%***	**48** ***100%***	**35** ***100%***

***Table 9.2** A coding scheme for the nitrogen monoxide probe-B*

9.1.2.1 An overview of students' responses to the nitrogen monoxide probe-B

The responses to the nitrogen monoxide probe-B indicated that students made significant progress from school to university (see Table 9.2) (χ^2=32.919, *df*=2, *p*<0.01). However, majority of the school students (66%), half of the UF and around a third of the UT' responses included scientifically incorrect ideas about the relationships between the concentrations of reactants and the reaction rate (see Figure 9.2). In many cases, the students attempted to answer the probe based on a rate equation, however they had forgotten to consider some variables in the rate equation (i.e. the reaction order). A few students argued that there is a linear relationship between concentration of reactants and reaction rate; they did not anticipate the order of the reaction or the role of the solid catalyst. Accordingly, they expected a higher rate from increasing concentration of reactants. Indeed, the interviews showed that although the students were reminded that this reaction is zero order with respect to NO, most of them assumed that is a second order reaction with respect of NO. Such students had a general view that the concentrations of reactants in the rate equation have exponents equal to the stoichiometric coefficients of the reactants in the balanced equation for the reaction.



Uncodeable	21.3	4.1	0
Total %	100	100	100

***Figure 9.2** Percentage of responses to the nitrogen monoxide probe-B*

9.1.3 EMERGING ISSUES FROM TEXTBOOK ANALYSIS IN THIS AREA OF KINETICS

In the school textbook (Kizildag & Dursun, 2000) the rate of a reaction is defined as the rate of change of concentration of a particular reactant or product.

$$A_{(g)} + B_{(g)} \rightarrow C_{(g)} + D_{(g)}$$

The rate of the reaction is given by

$$\text{Rate of formation of C} = \frac{change.in.concentration.of.C}{time.taken} = \frac{\Delta[C]}{\Delta t}$$

This equation gives the average rate over time interval Δt. If the time interval is very short, the equation gives the instantaneous rate-that is, the rate at a particular instant of time. However, the school textbook does not introduce the notion of instantaneous rate. As discussed in section 5.6 the approach used in the school textbook neglected the differences between the notion of 'the initial rate', 'the instantaneous rate' and 'the average rate over the chosen time interval'. School students has practiced on some written questions so as to determine the order of a reaction by comparing initial rates for several experiments in which different initial concentrations are used. It should be noted that the notion of instantaneous rate is implicitly introduced to students at university level. In addition, university first year and third year students did an experiment in order to find out order of a reaction and the rate equation (see Appendix 1, in Table A1.1). They determined the order of a reaction by graphical plotting of the data for the experiment.

9.1.4 SUMMARY AND DISCUSSION

Students' understandings of the notion of rate law and their competence in manipulating variables in a rate equation were investigated in the nitrogen monoxide probe. The results of the nitrogen monoxide probe-A revealed that only a few school students' explanations (3%) included scientifically correct ideas. Though students made considerable progress from school to university level, many students had difficulties in interpreting the experimental data. One of the reasons might be that students had limited knowledge about the slope of a graph and the notion of reaction rate. The absolute value of rate at any time (the instantaneous rate) can be found from the tangent at any point on the curve (from the concentration-time graph), as it has the magnitude of the gradient but opposite sign. However that idea (graphical method for determining reaction rate and reaction order) is introduced to students at university level. That would be one of the reasons for significant progress from university first year.

Chemical kinetics is the study of reaction rates, how reaction rates change under varying conditions, therefore it involves controlling variables. Hence changes in any of the variables will result in changes within the reaction rate which may be predicted by using the rate equation or by using the notion of rate law. Therefore, the learner has to consider several variables in a rate equation. Though many (school) students were able to use a rate equation for other settings (i.e. when responding to the other probes), yet they had difficulty in applying the notion of rate equation and the rate of change into a more complex problem. One of the reasons would be that students tended to consider only one factor/variable as possible influencing the phenomenon, such as concentration of reactants was seen as a factor influencing rate of reaction; however other possible influential factors (e.g. the rate constant, the reaction order, surface area of the solid catalyst) were overlooked. Research in other areas of science has also shown that pupils and students had difficulties in controlling variables (e.g. in thermodynamics, Rozier & Viennot, 1991). The nitrogen monoxide probe-B assessed students' competence in manipulating variables in a rate equation. The results revealed that the students had a general view that the concentrations of reactants in the rate equation have exponents equal to the stoichiometric coefficients of the reactants in the balanced equation for the reaction. This reasoning works only if the reaction occurs in one step (i.e. elementary reactions). The students were not aware that the relation between rate and concentration and the order of a reaction must be determined experimentally. These facts deserve attention during teaching.

Furthermore, many students used a common reasoning: "the more concentrated the reactants are the greater the reaction rate" or "increasing the concentration of reactants increases the reaction rate" without referring the reaction order, or probably without being aware of it. Such cases can be considered as overgeneralisations of a *general intuitive rule: "The more of A, the more of B"* (Stavy & Tirosh, 1996). However, the use of this rule decreased with teaching; undergraduates were more likely to consider the variables in a rate equation. Perhaps surprisingly, only a few school students' responses (14%) included an accepted answer. Most of the students who had an accepted answer was justified their answers based on a mathematical model (i.e. referring to a rate equation). None of these students gave a qualitative reasoning (particulate modelling).

Nevertheless, so as to explain *why* increasing the concentrations of reactants does not affect the rate of zero order reactions, students need to have an understanding of some mechanism of how a solid catalyst works in a chemical reaction. This kind of reasoning may be considered too demanding, however without referring to the sub-microscopic properties (including the notion of heterogeneous catalysis), it would not be possible to explain properly *how* an increase in the concentrations of reactants does not affect the rate of zero order reactions. Indeed, as one of the university third year students argued:

> *With more concentrated reactants, more collisions take place between reactant particles. Thus, the reaction rate increases.* [UT-D-14]

Though the statement is correct for most of the reactions, it does not apply to the given reaction which was a zero order reaction taking place on a solid catalyst. None of the students who justified their answers at the sub-microscopic level could reach a correct answer. One of the reasons would be that they did not consider the surface area of the catalyst and the role of the solid catalyst in the reaction system. The point which is being made here is that the links between the notion of heterogeneous catalysis and zero order reactions are important and these links should be made explicitly during teaching. The results of the magnesium monoxide probe revealed that the majority of the students were aware that in the case of heterogeneous systems (see Chapter 7), the area of contact between the reacting substances influences the reaction rate, however such students did not use that knowledge in the nitrogen monoxide probe-B and D (also see Section 8.2.1), probably because they lacked a mechanism to explain a heterogeneous catalysis process. Therefore, during teaching connections between the idea of surface area and a heterogeneous catalysis system need more attention.

9.2 STUDENTS' UNDERSTANDING OF REACTION MECHANISMS AND THE RATE-DETERMINING STEP

The reaction mechanism probe aimed to investigate students' understanding of reaction mechanisms and the rate-determining step. The probe was conceptually framed and set in a school science context. The probe presented students with data; they had to assess the data which were presented on a graph and find out a possible mechanism for the reaction. The probe examined students' ability to establish relationships between empirical data and scientific theories. The probe is conceptually demanding in that it requires students to understand characteristics of the presented graph and to link them with theoretical models. The cognitive process involves understanding the visual representations and transferring them into symbolic representations. This is a demanding process which the students found difficult to perform.

9.2.1 THE REACTION MECHANISM PROBE (Data analysis and results)

The "coding scheme-B" was applied on the data set. The students' responses are summarised and illustrated in Table 9.3 and Figure 9.3.

Before presenting analysis of the probe, it is worth underlining that this reaction probably proceeds via formation of J, followed by consumption of J and formation of the final product, Q:

$$X \longrightarrow J \text{ (fast)}$$
$$J \longrightarrow Q \text{ (slow)}$$

From this proposed mechanism[1] the second step, the formation of Q step, is the rate-determining step. In some cases, students provided a correct reaction mechanism, but with an incorrect prediction of the rate-determining step or with incorrect ideas about the intermediates (e.g. "J" was seen as a catalyst or the activated complex). Such responses were placed in the first category (1- responses including mainly scientifically incorrect ideas).

(1) Responses including mainly scientifically incorrect ideas about reaction mechanisms and the rate-determining step

A considerable number of students (69% SS, 40% UF and 49% UT) had scientifically incorrect ideas about the mechanism of the reaction or about the rate-determining step. Those scientifically incorrect ideas were classified under three subcategories.

(1-2-1) The reaction occur in one step

The students (24% SS, 25% UF, and 9% UT) argued that this reaction would occur in one step. A high number of the students assumed "J" as a catalyst or assumed "J" as the activated complex.

> $X \xrightarrow{J} Q$, *this reaction occurs in one step. The concentration of "J" is the same at the beginning and at the end of the reaction; therefore it should be a catalyst.* [UF-D-21]

---

[1] It should be underlined that a mechanism can never be proven to be correct. It can only be consistent with all available data.

(1-2-2) The reaction occurs in two steps (without providing a possible reaction mechanism)

A few students (6% SS, and 6% UT) argued that the reaction occurs in two steps; however they did not provide any reaction mechanisms. "J" was seen as a catalyst or the activated complex.

(1-2-3) The reaction occurs in two steps (responses including incorrect ideas about the rate-determining step)

Though many students (39% SS, 15% UF, and 34% UT) gave an acceptable mechanism for the reaction, they had scientifically incorrect ideas about the rate-determining step or had scientifically incorrect idea about the intermediates. The students assumed the first step as the slowest step. As found in the students' responses to the "Reaction rate-Time Probe" (see Section 5.2), many students conceived the reaction to start slowly and occur faster thereafter. Students may have used the same notions for this consecutive reaction. They may have thought that in a consecutive reaction, the first reaction occurs slowly and the following reactions occur faster thereafter.

> *This is a two step reaction and the slowest step (the first step) is the rate-determining step:*
> $X \longrightarrow J$ *(slow)*
> $J \longrightarrow Q$ *(fast)* [Sb-D-13]

Most of the students in this category stated that the first reaction (the slow reaction) is the rate-determining step. Expressions "the second reaction is the rate determining step", "J is a catalyst" and "J is the activated complex" were also found among students' responses.

(2) Responses including mainly accepted ideas about the reaction mechanisms

(2-1-4) The reaction occurs in two steps (with an acceptable reaction mechanism)

The respondents in this category provided an acceptable reaction mechanism for the reaction. 13% of the SS, 58% of the UF, and 49% of the UT' responses were placed in this category and some common examples are given below:

> *The reaction occurs in two steps:*
> $X \longrightarrow J$ *(fast)*
> $J \longrightarrow Q$ *(slow), and the second step is the slowest, because according to the graph consumption of [X] in unit time and formation of [J] in unit time is faster.*

> *J is a intermediate product. The rate of production of J is greater than the rate of its consumption. ....The slowest reaction determines the reaction rate; in that case the second step is the rate-determining step.* [UT-D-20]
>
> *I think this reaction occurs in two steps. On the first reaction X → J; X is converted to J and this is the fastest step, because the concentration of X decreases in a short period of time and J is formed. In the second step, J is converted to Q : J → Q....The second step is the rate-determining step.* [UF-D-15]

A few students (7% SS, 2% UF, and 3% UT) stated that "the reaction occurs in two steps" but did not justify their responses or did not provide any information about the rate-determining step. Responses of this kind were also placed in this category.

(0) All other responses

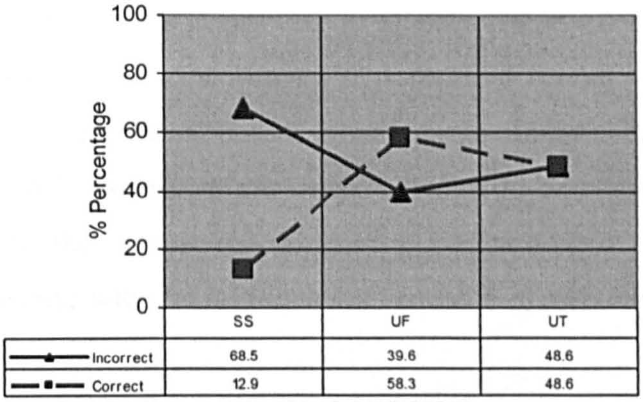
This category is allocated for incomprehensible responses or in cases where there is no response given in the probe. 19% of the SS, 2% of the UF, and 3% of the UT' responses were placed in this category and an example is given below:

> *Step 1: X ⟶ J (exothermic)*
> *Step2: J ⟶ Q (endothermic), and the first reaction occurs faster, because exothermic reactions occur faster than endothermic reactions.* [Sa-D-23]

Code	**Category (Nature of response)**	**Example of response**	**SS** ***f*** ***(%)*** **(n=108)**	**UF** ***f*** ***(%)*** **(n=48)**	**UT** ***f*** ***(%)*** **(n=35)**
1	**Responses including mainly scientifically incorrect ideas about reaction mechanisms and the rate-determining step**		**74** ***68.5%***	**19** ***39.6%***	**17** ***48.6%***
1-2-1	The reaction occurs in one step	No further explanation	9 *8.3%*	1 *2.1%*	0
		J is a catalyst. $X \xrightarrow{J} Q$	11 *10.1%*	7 *14.6%*	2 *5.7%*
		J is the activated complex. $X \longrightarrow Q$	6 *5.5%*	4 *8.3%*	1 *2.9%*
1-2-2	The reaction occurs in two steps	J is a catalyst.	4 *3.7%*	0	0
		J is the activated complex	2 *1.9%*	0	2 *5.7%*
1-2-3	The reaction occurs in two steps: Step 1: $X \longrightarrow J$ (slow) Step 2: $J \longrightarrow Q$ (fast)	The first step is the rate determining step	37 *34.3%*	4 *8.3%*	10 *28.6%*
		The second step is the rate determining step	1 0.9%	3 *6.3%*	0
		J is a catalyst.	4 *3.7%*	0	0
		J is the activated complex	0	0	2 *5.7%*
2	**Responses including mainly accepted ideas of reaction mechanisms**		**14** ***12.9%***	**28** ***58.3%***	**17** **48.6%**
2-1-4	The reaction occurs in two steps	No further explanation	7 *6.5%*	1 *2.1%*	1 *2.9%*
		Step 1: $X \longrightarrow J$ (fast)	7	27	16

		Step 2: $J \longrightarrow Q$ (slow), and the second step is the rate-determining step	*6.5%*	*56.3%*	*45.7%*
0	**All other responses**		**20** ***18.5%***	**1** ***2.1%***	**1** ***2.9%***
0-0-5	No answer		3 *2.7%*	0	0
	Incomprehensible/Other	Step 1: $X \longrightarrow J$ (exothermic) Step 2: $J \longrightarrow Q$ (endothermic), and the first reaction occurs faster, because exothermic reactions occur faster than endothermic reactions	17 *15.7%*	1 *2.1%*	1 *2.9%*
		TOTAL	**108** ***100%***	**48** ***100%***	**35** ***100%***

***Table 9.3** A coding scheme for the reaction mechanism probe*



Uncodeable	18.5	2.1	2.9
Total %	100	100	100

***Figure 9.3** Percentage of responses to the reaction mechanism probe*

9.2.1.1 An overview of students' responses to the reaction mechanism probe

Drawing upon the results, it was found that there was a statistically significant difference between school and undergraduate students' explanations (χ^2=29.971, *df*=2, *p*<0.01) in that the undergraduates were more likely to provide an accepted answer. However, still the percentage of those undergraduates was low, around 50%. Generally speaking, students, specifically school students, had difficulties in interpreting the graph. Though many students thought that the reaction occurs in two steps, they had scientifically incorrect ideas on the intermediates. For example, J, an intermediate, was seen as a catalyst or the activated complex. Many of them (39% of the SS, 15% of the UF, and 34% of the UT) saw the first reaction (X→J) as a slow reaction. They may have thought that in a consecutive reaction, the first reaction occurs slowly and the following reactions occur faster or possibly the context of the probe (alternative answers used in the probe) may have influenced students' responses. Other probes in this study confirm that students conceive reactions to start slowly and proceed faster thereafter.

9.2.2 EMERGING ISSUES FROM TEXTBOOK ANALYSIS IN THIS AREA OF KINETICS

The notions of reaction mechanisms and the rate-determining step are very briefly mentioned in the school textbook. It is expressed that the slowest step in a reaction mechanism is called the rate-determining step. However, the underlying ideas are not specified in the textbook. Those ideas are mentioned in detail at university level. One of the important issues in this area of kinetics is that teachers and textbook authors should emphasise that the mechanism of a reaction cannot be observed directly, however a mechanism can be proposed, based on experimental data. A mechanism can never be proven to be correct. It can only be shown to be consistent with all available data. In addition, the underlying ideas for the notion of rate-determining step and its relationships with the rate equation should be shown more clearly in the curriculum.

9.2.2 SUMMARY AND DISCUSSION

Comparing with the results of the other probes in the diagnostic tests, a relatively low percentage of students achieved a correct answer for the probes presented in this chapter. Specifically many school students found it difficult to answer the "nitrogen monoxide probe-A" and the "reaction mechanism probe", both of which aimed to investigate students' ability to interpret empirical data which was presented in a graphical representation. One of the reasons would be that the students generally had difficulties in interpreting empirical data and graphical representation. Therefore, it would be useful if students' understanding of the reaction order, reaction mechanisms and the rate-determining step were also elicited in different contexts.

The next chapter, Chapter 10, summarises the key findings of the study and discusses their implications for teaching and learning chemical kinetics.

CHAPTER 10

DISCUSSION, CONCLUSIONS AND IMPLICATIONS

CHAPTER 10

DISCUSSION, CONCLUSIONS AND IMPLICATIONS

10.0 INTRODUCTION

In this final chapter, findings related to the purpose of the study and the research questions are reviewed. The chapter is divided into three sections. The first section discusses the key findings relating to the research questions. The second section provides a methodological critique of the study, and the final section identifies some areas suitable for further research.

Aims and research questions

The study set out to evaluate secondary school and undergraduate students' conceptual understandings of chemical kinetics in the light of the aims of the Turkish chemistry curriculum. The research questions of this study, introduced in Chapter 1, are as follows:

(1) What kind of development is intended in the subject of chemical kinetics within the school and university curricula, in Turkey?

(2) What are secondary school and university students' understandings of chemical kinetics and how do they change in relation to relevant teaching at school and university level? This specifically involves finding out;

   (i) What kind of conceptual difficulties do students experience in chemical kinetics?
   (ii) How well do students understand and use chemical kinetics in a range of contexts?

(3) What are the implications for the effective teaching of chemical kinetics at school and university level?

10.1 SUMMARY OF FINDINGS

This section summarises the key findings relating to the research aim and questions. This section is structured into three sub-sections. Section 10.1.1 relates to the first research question. Section 10.1.2 summarises the answers which this study provides to the second research question by addressing some patterns identified from students' responses, and Section 10.1.3 considers some possible implications drawn from this research study for teaching and learning chemical kinetics

10.1.1 THE OBJECTIVES OF THE CURRICULUM

As discussed in Section 4.1.3 the objectives of the course contents are broadly specified in the official documents and in the teachers and lecturers' written lesson plans. Since the chemistry curriculum mainly consist of textbook-based syllabuses, determining teaching objectives, setting appropriate teaching situations, and assessing students' learning is left to the teachers/lecturers (see Section 10.1.3.3).

The Turkish chemistry curriculum introduces basic ideas and theories of chemical kinetics at school level. It is expected that school students should be able to have an understanding of the dynamic nature of the reaction system in terms of some fundamental models in kinetics (e.g. the collision model and the transition-state model) (see also Section 4.2.3). In addition, school students should be able to use their knowledge of chemical kinetics so as to propose solutions to problems involving basic concepts and processes in kinetics, and to analyse simple experimental data on kinetics. At university first year those ideas are reinforced and developed (e.g. the Arrhenius equation is introduced and the temperature dependence of reaction rates is explained on the Arrhenius parameters), and more emphasis is given to practical work on chemical kinetics. However, the empirical aspect of chemical kinetics is not explicitly introduced in their theoretical courses. At the university third year, the main emphasis is on the empirical framework of chemical kinetics (e.g. empirical techniques for measuring reaction rates) and the concepts underpinning this empirical framework are introduced in more depth and explained mainly at a mathematical level (e.g. accounting for integrated rate laws). It is expected that students should be able to develop an understanding of the links between theoretical aspects of chemical kinetics and experimental data, and to evaluate information and evidence gathered from experiments.

The objectives of the curriculum are summarised in Appendices 1 and 2. Briefly, what the curriculum aims to achieve are as follows:

It is expected that students should be able to:

(i) develop an understanding of the dynamic nature of the reaction system

(ii) describe the rate of a chemical reaction in terms of some fundamental models in kinetics (e.g. the collision model and the transition-state model)

(iii) explain the factors that affect the rate of a chemical reaction and use some theoretical models in kinetics to give explanations

(iv) use their scientific knowledge of chemical kinetics in novel contexts

(v) develop an understanding of the link between theory and experiment; and develop an understanding of the nature of scientific enquiry

(vi) be aware of the relevance of the notion of chemical kinetics to society and other areas of chemistry

These teaching objectives run across school and university levels. The results indicated that the content of the chemistry courses included a variety of information and contexts in order to accomplish the objectives of the curriculum in terms of items (i)-(iv), however it seems that specifically at university level, the main emphasis of chemical kinetics courses appears to be on the mathematical aspect of the subject. The relationships between different forms of representations (i.e. macroscopic, particulate and mathematical modelling) are not explicitly specified in the curriculum. A very limited contextualised situations or problems (i.e. phenomenologically framed problems) are constructed in the textbooks and in the examinations papers.

Analysis of the curriculum and interviews with teachers/lecturers revealed that the objectives of the curriculum in terms of (v) were highly constrained by the resources of school and universities. Specifically, there were few possibilities for school students to do practical work on chemical kinetics.

The objectives of the curriculum in terms of (vi) were neglected both in the school and university curriculum. It appears that the Turkish chemistry curriculum is ignoring the significance and relevance of scientific concepts with connection to students' lives and to current technological development, and social issues. As outlined above, in some areas of the domain there was a mismatch between the objectives of the curriculum, the kinds of teaching which occurred, and the outcomes of the curriculum.

10.1.2 STUDENTS' UNDERSTANDINGS AS A RESULT OF FOLLOWING THE CURRICULUM

This section summarises answers to the second research question which is concerned with school and university students' understandings of chemical kinetics, and to find out how they change or develop in response to teaching at school and university. I found development in the forms of justification used across the educational levels, with school students tending to justify their claims by simple prototypical examples, or by drawing upon taken for granted everyday knowledge, or by tautological restatements of available information in the tasks. By contrast, undergraduates were more likely to use some forms of theoretical model or causal mechanism to account for phenomena/events. The results revealed that school students did not frequently use theoretical models, and in many cases such modelling was not used as intended by the curriculum.

Another dimension of change in students' explanations was the changes in the conceptual content of explanations offered by students (e.g. see Section 10.1.2.4). The following subsections describe the major conceptual difficulties in coming to understand the concept of chemical kinetics. These difficulties have been identified with a view of the structure of the subject matter, and an analysis of students' ideas on the key scientific ideas in chemical kinetics. The results indicated that a considerable number of (third year) pre-service chemistry teachers still had scientifically incorrect ideas in chemical kinetics, even though this concept had been covered many times. In many instances, school and university students showed similar conceptual difficulties and alternative conceptions.

One of the aims of the study was to find out how effective the Turkish chemistry curriculum had been in meeting its aims in terms of students' learning of chemical kinetics. As summarised in the preceding section, the university curriculum assumes that the basic ideas and theories of kinetics are already introduced at secondary school and to some extent understood. However, there is no evidence from this study to suggest that this assumption is valid. Analysis of the school students' responses to the diagnostic tests and interviews with lecturers revealed that school students had limited knowledge about chemical kinetics. As one of the lecturers (L_1) pointed out that in contrast to the intended curriculum, he had to teach the subject assuming that the undergraduates had not been taught at secondary school, because he experienced a big difference amongst students' preconceptions about the topic. Thus, due to limited time and overloaded course content, the lecturer might teach the intended course content in a short period of time or may cover a certain number of topics and leaving some others. Similar to the university first year curriculum, the university third year curriculum assumes the qualitative aspects of chemical kinetics are already introduced at UF and to some extent understood. Thus the main focus of university third year courses is on the mathematical and empirical aspects of the topic. Again, there is no convincing evidence to suggest that this assumption is valid. The results of the study suggest that many university first year students had scientifically incorrect ideas about chemical kinetics. It appears that there is a need for a carefully examination of the school and university curriculum and matching the curriculum to the needs of students (see Sections 10.1.3.4 and -5). Particularly the co-ordination between them and the progression which is intended across educational levels need more attention. In conclusion, the Turkish chemistry curriculum in the area of chemical kinetics is not fulfilling its intentions, and the assumptions about progression on which it is based are not justified. The following subsections summarise areas of the curriculum that are not well-understood by students. This could be because they are not taught at all, or very poorly. Alternatively, difficulties could arise due to the characteristics of students' reasoning.

10.1.2.1 Changes in the nature of explanations offered by students

In a broad sense, the students following the curriculum made progress from secondary through university level. This progression was different in different areas in chemical kinetics. However, the general picture was that relatively more school students than university students justified their answers on descriptive grounds (i.e. at a macroscopic, phenomenological level) and did not provide appropriate explanations for the phenomenon/event. By "appropriate" I mean involving reference to particulate and/or mathematical modelling, both of which are introduced to these students in the curriculum. There was a decline in the use of macroscopic modelling with teaching; university students were more likely to use reasoning based on a sub-microscopic or mathematical level. The distinction between school and undergraduate students' responses was one of elaboration (both in terms of the nature of the knowledge and the explanation used: epistemological differences between different way of knowing). One of the distinctions was related to the epistemological assumptions made: on the one hand, school students gave reasoning drawing upon taken for granted everyday knowledge. For example, such students might respond to the "rusty water pipe probe" by stating that "Heat destroys substances" or "Hot water destroys/wears out/tarnishes the water pipe". On the other hand, undergraduates provided explanations based upon theoretical entities and models within established chemical ideas. For instance, such students might argue that "An increase in temperature increases the speed of molecules and also increases the kinetic energy of molecules. That increases the amount of substances overcome the activation energy barriers". Rather than working from scientific ways of reasoning (i.e. referring to the principles of the collision model or the transition state model), school students tended to use simple prototypical examples or everyday ways of reasoning (i.e. by using the characteristics of the macroscopic modelling) for justifying their answers (e.g. see Section 6.1). In this respect, progression in learning involves changes in existing modes of thinking or developing new modes of thinking, and having an understanding of scientific modes of thinking and talking.

The results showed that though both school and university students were more likely to give a correct answer to how a change in the reaction conditions (e.g. increasing concentration, temperature, the surface area or using a catalyst) would influence the reaction rate, yet they had difficulties in providing explanations about the dynamic nature of the reaction system. For instance, a considerable number of school and university students had scientifically incorrect ideas about how reaction rate changes from the beginning until the end of a reaction. As discussed in Chapter 5, only a small number of students (both at school and university level) used conceptions consistent with scientific perspectives in order to explain how reaction rate changes as a reaction progresses. One of the reasons for students' lack of knowledge or alternative conceptions would be that the approach used in the curriculum emphasised the *initial* and *final state* of a reaction, neglecting *the process* between these two states.

As discussed earlier, the context of the probes was framed in terms of the objectives of the secondary school chemistry curriculum which expects students to interpret a chemical phenomenon/event in terms of theories of kinetics. However, in contrast to that a significant number of students did not use (or incorrectly used) a theoretical model when explaining the dynamic nature of a chemical phenomenon/event instead using a macroscopic model. This study indicated that school students and pre-service chemistry teachers possess generally low-level of conceptual understanding of chemical kinetics. Many pre-service chemistry teachers seem to start their professions with limited conceptual understanding of the key scientific ideas in chemical kinetics.

10.1.2.2 The effect of context on students' responses

The second research question was about finding out secondary school and university students' understandings of chemical kinetics and how their understandings change in relation to relevant teaching at school and university. Another dimension of change may include the consistency of students' application of knowledge to a range of contexts. In this study, a limited number of comparisons was made in order to investigate how students use their ideas across different probes. In order to explore consistency of explanations, individual students' responses to the probes testing the same ideas were cross-tabulated. If students' reasoning is based on underlying reasoning patterns, consistent responses might be expected to these probes. The results revealed that consistency of students' ideas (both scientifically correct and incorrect ideas) increased from school to university (e.g. see Section 5.3 and Table 5.5). Nevertheless, there was little evidence showing that students offered explanations with a commitment to generalisability. Their responses appeared to be influenced by contextual features of the probes; however undergraduates' responses were generally less affected by context. These findings on the consistency of students' responses across tasks are in agreement with previous studies (Engel Clough & Driver, 1986; diSessa, 1988; Fischbein, Stavy & Ma-Naim, 1989), which reported that students' conceptions identified by different probing tasks do not necessarily agree with each other and that the expression of a particular conception by students depends to some extent on the format and contextual features of the tasks. It is possible that the nature of the task is not the only contextual factor which influences students' conceptions. Students might have been influenced by their own experience of the context (i.e. an unfamiliar context would be demanding both procedurally and conceptually). It thus appears that in many cases students are in fact unable to generalize their conceptions of chemical kinetics. This inconsistency of students' conceptions across specific tasks creates a necessity for research to describe and explain the variation of students' conceptions and ways of reasoning (Palmer, 1997). On the basis of this information, teachers can promote awareness of strategies for generalising thinking by engaging their students in activities that require reflection.

Thus, teachers and curriculum designers would provide students with opportunities to develop metacognitive skills.

It is important to note that generally speaking, students were more likely to use theoretical models in order to answer conceptually framed probes; however they tended to draw upon macroscopic modelling when interpreting phenomenologically framed probes. When cueing is given, students are more likely to use scientific terms and theoretical models in their explanations. The results suggest that the setting of a probe can affect students' approach to explanations. Thus, in order to assess students' understanding of a specific content area, careful consideration of the probe is needed and it is necessary to investigate their ideas in a range of contexts.

10.1.2.3 Difficulties in interpreting symbolic representations or making transformations within and across different representational forms

Chemical kinetics is one of the areas in chemistry where several different visual representations are used, such as energy profile graphs for catalysed and uncatalysed reactions, or the Maxwell-Boltzmann energy distribution diagram and so on. However, this study revealed that students often had difficulties with interpreting various graphical representations used in the textbooks (e.g. see Section 8.3) and grasping the underlying scientific knowledge expressed through these visual models (e.g. see Chapter 9). One of the reasons would be that the approaches used in the curriculum neglected the connections between different forms of representation. For instance, it did not provide explicit complementary verbal information for each of the graphical representations (see Sections 6.3 and 8.3). More attention should be given to the interpretation of symbolic representations of the concept and its relationships with the sub-microscopic or mathematical levels. Symbolic representations should be supported with complementary information in verbal (e.g. by teacher talk) and/or in written form.

Furthermore, students appeared to have difficulties in moving within and across different representational forms. For instance, while they provided appropriate explanation for the relationship between reaction rate and time in written or oral form, they failed to construct a symbolic representation for this relationship–e.g. by representing it on a graph (see the results of the "reaction rate-time probe", in Chapter 5). Curriculum analysis revealed that the approaches used in the curriculum neglected relationships between different forms of representations. Duval (1995, in Tiberghien, 2000, p.31) claimed that "*when students change registers to make explicit their ideas (for example, when they transfer ideas from algebraic register to a graphical register or linguistic register in written or oral form), this process in itself plays a role in helping them to construct meaning from the underlying idea*". Thus giving students opportunities to transform their knowledge within and across different representational forms may help them to understand the relationships between different representational forms and improve their understanding of the particular concepts.

10.1.2.4 Patterns of progression in students' responses: the U-shaped and the ∩-shaped performance curves

Based on a nomothetic data analysis, when the percentage of students in different educational levels who provided a correct answer to a probe was graphed, in some cases a U-shaped performance curve (e.g. see Figure 6.3) or a ∩-shaped performance curve (e.g. see Figure 8.3) was found from students' responses. For instance, a U-shaped development (Strauss & Stavy, 1982) was found from students' responses to the "nitrogen monoxide probe-C" (see Figures 6.2 and 6.3). While around 71% of the school and 60% of the university third year students' responses included correct ideas, only 23% of the university first year students' responses included correct ideas. In order to find out the nature of students' explanations and the nature of students' difficulties, an ideographic data analysis was carried out. The results indicated that students' responses were different in nature at different educational levels. While school students reached a correct answer mainly based on macroscopic modelling (e.g. they simply argue that "temperature increases reaction rate"), university students were more likely to use some form of theoretical model or causal mechanism to account for the event, nevertheless in most cases UF could not use them appropriately. For instance, such students applied Le Chatelier's Principle to explain the effect of temperature on the reaction rate (cf. Quilez & Solaz, 1995). Here is an example: "*Since the reaction is an exothermic reaction, an increase in temperature would affect opposite side and it decreases the reaction rate. The reaction gives out heat; therefore a rise in temperature would decrease the reaction rate*". It seems that here the U-shaped performance is a product of students' lack of knowledge about the appropriate use of Le Chatelier's principle. One of the reasons would be that students learn the principle by heart and try to apply it without understanding. In particular, an increase in the concentration of reactants or an increase in temperature to the reaction system often cause problems, because they often try to interpret the problem in terms of Le Chatelier's principle.

Based on a nomothetic data analysis, a ∩-shaped performance curve was found from students' responses to some probes (such as responses to the "reaction rate-time probe", and the "catalysis probe-C"). For example, analysis of the "catalysis probe-C" indicated that several students (52% SS, 90% UF, and 57% UT) argued that a catalyst would not affect the yield of the product (see Figure 8.3); however most of those did not provide further explanation (they simply stated that "a catalyst has no affect on the yield" without justifying the reasons behind their ideas). Almost all of the UF gave a correct answer but perhaps interestingly, the percentage of such students considerably decreased from university first year to third year. Some would ask what would be the reasons. As discussed in Section 8.3, one of the reasons for this might stem from the visual representations used in the school and in the university third year textbooks. Such students might have misinterpreted the Maxwell-Boltzmann energy distribution graph showing the effect of a catalyst (see Figure 8.6). Another possible reason was that though the majority of the UF reached a correct answer, yet data from interviews revealed that many of those used an incorrect justification for their answers. For instance, interviews with students revealed that university first year students often confuse kinetic concepts with equilibrium concepts. They seem to answer this question based on ideas learned in chemical equilibrium lessons. For instance, they argued that "this reaction is a zero-order reaction and in terms of the rate equation, reaction rate depends on rate constant, k. A catalyst does not affect rate constant, k". It seems that students confuse the rate constant, k, with the equilibrium constant, capital K (which is a thermodynamic quantity and depends on the overall stoichiometry of the reaction). As emphasised in the textbook "A catalyst does not affect the value of equilibrium constant, K", students seems to simply memorise this and to apply this knowledge into the given situation. The results suggest that such students have limited knowledge of both kinetic and equilibrium concepts.

It ought to be underlined that the findings suggest that the U-shaped or ∩-shaped performance curve does not represent a natural or necessary pattern; rather it occurs as a result of misapplications of some rules, formulae, principles or variables which are embodied in a task; that is it is task/context specific. The drop and subsequent rise in performance (or the other way round) and what is underlying it would inform designing teaching to overcome these difficulties. Perhaps, those patterns are inevitable when students do not conceptualise the domain. Students may need some time in order to understand, apply and reflect their knowledge and understandings in this area. In that respect, revisiting concepts in the curriculum over a period of time and within closely related concepts would help students' understanding.

10.1.2.5 Confusion between chemical equilibrium and kinetics: Misapplication of Le Chatelier's principle

The results suggested that students often confused equilibrium with kinetic concepts. For instance, many school and undergraduate students applied Le Chatelier's Principle to explain the rate of a reaction. Here, they confused equilibrium with kinetic concepts or they simply misunderstood Le Chatelier's Principle. Indeed, there is considerable evidence in studies on chemical equilibrium showing that students frequently misapply Le Chatelier's principle in cases where its scope is limited (Quilez & Solaz, 1995). In an attempt to overcome these difficulties, various suggestions have been made. For example, Le Chatelier's principle has been considered inappropriate for teaching in schools and elementary courses (De Heer, 1957; Gold & Gold, 1985) except its historical setting (Allsop & George, 1984). Nevertheless, analysis of school chemistry textbooks (e.g. Kizildag & Dursun, 2000) shows that changes in chemical equilibrium are usually studied from a semi-quantitative perspective, which is, in many countries, still dominated by the use of Le Chatelier's principle (van Driel & Gräber, 2002). De Heer (1957) suggests to replace Le Chatelier's principle in elementary courses by a small number of rules each of which has a limited range of applicability and is less ambiguous, which may be ultimately justified on thermodynamic grounds (see the following paragraph). Moreover, Allsop & George (1984) and Quilez & Solaz (1995) have argued that the Le Chatelier's qualitative statements[1] are vague and ambiguous and suggested the replacement of the principle by the use of chemical equilibrium law (Allsop & George, 1984) and by the alternative use of van't Hoff's laws on equilibrium (Gold & Gold, 1985; Kemp, 1987).

There are at least two opinions on the usage of Le Chatelier's Principle at elementary courses. (1) Replacing it by other approaches, for example Quilez & Solaz (1995)

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[1] Le Chatelier's Principle assumes that if one or more of the factors that affect the position of a chemical equilibrium are altered, then the equilibrium shift to reduce (oppose) the effect of the change.

suggest to replace Le Chatelier's Principle by a small number of rules, one of such rules may be formulated as: The addition of some amount of one of the substances of a chemical system at equilibrium leads to a subsequent decrease of the concentration (or partial pressure) of this substance, and vice versa. Alternatively (2) not to study of Le Chatelier's principle in the way it is traditionally taught. In other words, being aware of students' difficulties with Le Chatelier's principle and designing instructional strategies to avoid these difficulties. Unfortunately, many of the suggested approaches presented above have not been tested in actual classroom settings (van Driel & Gräber, 2002). Thus, the effectiveness of these approaches is not known yet. Therefore, in the case of teaching chemical kinetics, the most promising procedure seems to emphasise that the application of Le Chatelier's principle to dynamic systems (i.e. chemical kinetics) is completely wrong, be aware of that alternative conceptions and plan instructional strategies accordingly.

10.1.2.6 Inappropriately attributing relationships between concepts of thermodynamics and kinetics

A number of cases were noted in the study where students inappropriately attributed a relationship between thermodynamic and kinetic factors or where they lacked knowledge of fundamental thermodynamic concepts. Students often did not make a clear distinction between kinetic (e.g. activation energy) and thermodynamic factors (e.g. enthalpy change, Gibbs free energy, or spontaneity) and attempted to use thermodynamic ideas to explain the rates of reactions. For instance, students' responses to the "enthalpy probe" (see Section 8.1.2) showed that a highly significant number of school and undergraduate students (nearly half of the whole sample) argued that exothermic reactions occur faster or that endothermic reactions occur faster. Surprisingly, the proportion did not change much from school to university. These results are striking, in that half of the prospective chemistry teachers had alternative conceptions about some fundamental concepts in thermodynamics and kinetics. It is intuitively plausible that they will pass those scientifically incorrect ideas on to their students.

On the one hand thermodynamics is about how stable things are in one state versus another, on the other hand kinetics is about how quickly or slowly species react and is about the progress of a chemical reaction. From a student's intuitive viewpoint, it is possible to confuse thermodynamic quantities like Gibbs free energy with kinetics ones like activation energy. One of the reasons might be that these concepts are often taught separately and that the relationships or the differences between them are not specified in the curriculum. I suggest that it might be helpful to emphasise the distinctions between these concepts and to treat some of the components together (see also Section 10.1.3.5).

In short, findings of the study suggest that students' lack of understanding in thermodynamics and chemical equilibrium significantly influences their ideas about chemical kinetics. Therefore, their relationships to kinetic arguments should be made clearly in the curriculum and during teaching.

10.1.2.7 Memorising facts, concepts and processes, without underpinning conceptual understanding

This study investigated two related but different types of understanding in chemical kinetics. These are (1) expressing scientific knowledge (e.g. recalling facts, concepts, methods and processes) and (2) using this knowledge in different contexts. Driver and Erickson (1983) claimed that students may develop scientific knowledge as a result of instruction and other experiences; however they may not necessarily relate these to actual phenomena. For that reason, the probes targeted both students' scientific knowledge about the topic and how they apply this knowledge in a novel situation. Generally speaking, although students displayed scientific knowledge of concepts, terms, formulae and principles, they did not use that knowledge in a novel situation or they used it inappropriately. For instance, while several students correctly defined the term "reaction rate", a relatively small proportion of such students used this knowledge to interpret how the reaction rate would change during a reaction (see Section 5.8 and Chapter 5). There were similar findings in the "activation energy" and the "enthalpy" probes. Again many students failed to apply fundamental kinetic ideas (e.g. the notion of activation energy) to the probe presented (see the "enthalpy" probe, in Section 8.1.2). This might be as a result of a straight memorisation of the concepts and principles or possibly another reason might be that the concepts were taught or learnt by rote. The implication of this finding is that instructional practices should be designed to provide students with opportunities to develop their ideas, to apply and to reflect their knowledge and understanding in a wide range of context in a supportive environment.

Applying mathematical formulae mechanically

Logan (1996) argues that chemical kinetics has an unusually complex structure in that it interprets and reports experimental data in terms of essentially empirical parameters. The concepts which are needed for this empirical framework and their use in the treatment of data on the progress of chemical reactions are the scope of chemical kinetics. Nevertheless, the results indicated that students had conceptual difficulties in interpreting empirical data in terms of theories and concepts in chemical kinetics (e.g. see Section 9.1). Students tended to use mathematical formulae mechanically when answering the probes. For instance, on several occasions they attempted to answer the probes based on a rate equation; however they had forgotten to consider some variables in the rate equation (e.g. the reaction order or the concentration of catalyst).

Lack of knowledge about basic ideas in chemistry

This study indicated that a number of school and university first year students lacked some basic ideas in chemistry and had difficulty differentiating concepts, such as the amount of substances, the number of moles and concentration. In addition, differentiation between heat, energy and temperature constituted considerable difficulty for the students and in some cases, these terms were used interchangeably. The results suggest a need to review the instructional practices, because students' understanding of these concepts is the key to many other related concepts.

In the next section, the educational significance of the study is discussed in the light of the literature review.

10.1.3 CONCLUSIONS AND EDUCATIONAL IMPLICATIONS

This section addresses the third research question. It focuses on ways of teaching chemical kinetics which aim to avoid or overcome the learning difficulties (or lack of knowledge) described in this study. Some possible implications for planning the curriculum and teaching are proposed in the light of the results of the study.

Educational significance of the findings

As discussed in Chapter 2, because chemical kinetics is one of the most fundamental concepts in chemistry, it is regularly taught in both school and university courses in most countries. Nevertheless, relatively little empirical research has been carried out on students' ideas of chemical kinetics. In particular, this empirical study is the first in the Turkish literature exploring the development of students' understanding of chemical kinetics in the context of the aims of the school and university curriculum (Cakmakci, 2005). In addition, this study is the first in the chemistry education literature exploring the development of students' understanding of chemical kinetics from school to university (Pfundt & Duit, 2004). Accordingly, the findings of the study would make a contribution to Turkish chemistry education, as well as being of broad interest internationally. Replication studies and planned cross-country studies, such as the study undertaken by Saglam (2003) on Turkish and British students' ideas about electromagnetism, suggested that, though there may be variations from individual to individual, there are common patterns in conceptual difficulties which appear in group of students as a whole irrespective of differences in their educational system, curricula and cultural background. As a result, the information produced from the present study can be drawn upon by other teachers, textbook writers, and curriculum designers in other countries in planning more effective teaching activities in the area of chemical kinetics. For example, explicit teaching of the key ideas of chemical kinetics and more emphasis on students' conceptual difficulties in specific areas that are reported in the thesis can improve students' understanding of chemical kinetics.

This study has drawn upon qualitative and quantitative data on students' ideas of chemical kinetics. The qualitative nature of data facilitated to describe the underlying ideas of students' explanations with regard to chemical kinetics. The quantitative nature of data assisted to determine the incidence of particular ideas and the significance of any changes between different educational levels. The quantitative data was particularly useful to supplement and extend the qualitative data analysis. Probably the most striking conclusion to be made from the quantitative data presented was that in some areas of chemical kinetics, the proportion of students who had scientifically incorrect ideas about the domain was quite high, and did not change much from school to university (e.g. see section 8.1.2). In particular, this data is an extension of existing knowledge about students' difficulties in this field.

10.1.3.1 A framework for analysing students' explanations of chemical kinetics

Different ways of explanation: Descriptive/Empirical vs. Explanatory/Theoretical

In this thesis I propose a framework for analysing students' explanations of chemical kinetics which might be extended to other areas of the chemistry curriculum (see Figure 10.1 and Section 3.7.1). Although the framework was developed based on a specific area of chemistry, I believe that it has possible implications for planning teaching in other areas of chemistry as well (though further studies would be needed to shed more light on this claim). The proposed framework was developed on the basis of a conceptual analysis of chemical kinetics and students' ways of explanation about chemical kinetics. Such an approach allows the analysis of the scientific knowledge and the students' knowledge (in the area of chemical kinetics) from the same point of view. That would allow us (if necessary) to design teaching so as to close the gaps between these two views. The pictorial representation given in Figure 10.1 would permit the organisation of the various considerations which need to be taken into account during teaching. Elaborating students' conceptions both at the level of content and of establishing links between the world of phenomena/event and the world of theoretical models (i.e. integrating content and context or developing an understanding of links between theories and experiments) has potential for improving students' conceptual understanding in chemistry. I do not claim that one level of modelling is better than another (indeed each of these modes of modelling would be appropriate at different times for various aspects of chemistry/daily life); rather, my claim is that the learning demands for each of these modes of modelling and for the relationships between them should be acknowledged and dealt with directly during teaching (if the teaching objectives aim to do so).

The proposed framework would guide teachers to analyse students' explanations. That would enable teachers to achieve a better understanding of the nature of their students' explanations and difficulties, and to design effective teaching activities/strategies accordingly. I suggest that good teaching is based on an ongoing dialogue between the teacher and students, in which both parties are able to understand the other's point of view (Scott, 1998). The proposed framework would provide a potent tool not only for designing teaching in terms of different modes of modelling and their interactions with each other but also for improving the teacher's understanding and approaches to teaching in this field. Questions, such as "what kind of reasoning/modeling do we aim for students?", or "what kind of instruction would help students to achieve the teaching objectives?" would guide teachers to consider different aspects of the ways of explanations. I suggest that an analysis of the differences between everyday and scientific modes of thinking and knowing (i.e. learning demands (Leach & Scott, 2002)) in different areas of science can be useful for designing teaching, identifying new learning aims, and suggesting how specific knowledge can effectively be made available to students.

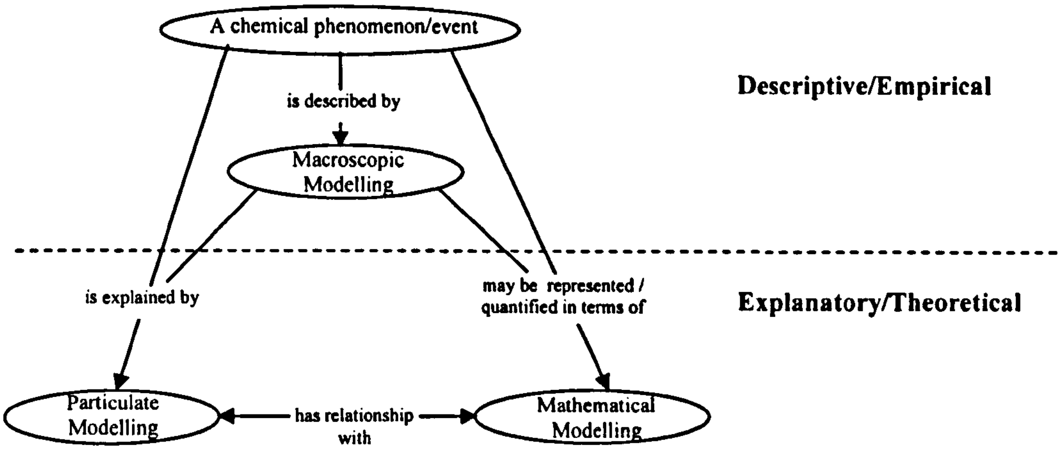

Figure 10.1 The relationship between chemical phenomena/events[2] *and theories/models (A proposed framework for analysing students' explanations of chemical kinetics)*[3]

Drawing upon interview data, there was some evidence to show that students had various form of theoretical models, however they did not apply those to the given phenomenon instead they often used everyday ways of explanations in place of scientific ways of explanations. Interviews with such students revealed that they seemed to think that their answers which described the phenomenon at the macroscopic level (e.g. the smaller the size of the "granules" of reactant, the faster the reaction will be) were obvious and they did not need to explain further. One of the reasons might be that such students did not know what constitutes a scientific explanation. I suggest that the curriculum should aim to introduce students not only to chemical concepts and theories, but also introduce them to have an understanding of what constitutes a scientifically acceptable explanation and of scientific modes of thinking and talking.

10.1.3.2 Teaching about (multiple) representations rather than just by (multiple) representations

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[2] This phenomenon or event can/should be chosen from a range of contexts, from school science context (i.e. an experiment in the lab) to controversial issues (e.g. the depletion of ozone layer that is a current issue in chemistry/the environment would be used to discuss the action of a homogeneous catalyst). In other words, it may include social, economical, environmental, technological or industrial applications of chemistry in order to integrate the content and context or to demonstrate the role of concepts for the life of individual and society.

[3] The framework is adapted from Logan, 1984; Johnstone, 1991; Tiberghien, 2000.

One of the purposes of the study was to explore the development of students' understandings of chemical kinetics in the context of the aims of the curriculum. The results showed that in some areas in chemical kinetics, students made substantial progress, but in some other areas (e.g. how a catalyst affects the course of a chemical process, and the mechanisms of chemical reactions) they made no substantial progress. Among the difficulties the students had experienced, I found that a major one was connecting their macroscopic modeling of chemical phenomena to theories and models in chemical kinetics. Many of them, particularly secondary school students, drew upon macroscopic modelling when explaining the phenomenon/event. This research also shows that the students had difficulties in making transformations within and across different representational forms (e.g. while the students provide appropriate explanation for the relationship between reaction rate and time in written or oral form, they fail to construct a symbolic representation for this relationship). Research in other areas of science also shows that students have difficulties in making transformations within and across different representational forms (Kozma, 2003).

Since the students could not appropriately transform ideas within and across different types of representations, the curriculum should guide students to use multiple, linked representations in the context of collaborative activities (Kozma, 2003; Wu, 2003). My claim is that all these three levels of modelling (see Figure 10.1) and their relationships with each other are necessary for achieving a full scientific understanding of chemical kinetics. Supporting and mediating students' conceptualisations of the interrelationships between these three levels of modelling have potential for improving their conceptual understandings of chemical kinetics. As social and discursive interaction constitutes the process of meaning making (Mortimer & Scott, 2003), the teacher's role should be supporting and mediating students' conceptualisation of the relationships between macroscopic, particulate and mathematical modelling. As Johnstone (1982) expressed it "trained chemists jump freely from level to level in a series of mental gymnastics" (p.377). The ability to pass confidently between these models should be an important goal for pre-service chemistry teachers to ensure that they will not pass conceptual difficulties and scientifically incorrect ideas on to their students. In addition, teachers need some explicit knowledge of the significance of these different modes of representations (Erduran & Duschl, 2004), and require a range of pedagogical strategies in order to make these links explicit in teaching. Chemists do it tacitly: teachers need to have explicit knowledge to draw upon and to employ this in planning their teaching and their interactions with students.

An analysis of the scientific knowledge presented in the curriculum indicates that although the nature of these three models is generally presented clearly, the links between them are not explicitly specified. In most cases, theoretical models are disconnected from physical/chemical phenomena and practices. The results suggest that it would be helpful if the relationships between these three levels of modelling was clearly expressed in the curriculum and students were given explicit teaching and support in moving between them. At this point a pedagogical question would arise: how to interconnect the multiple representations and use them in combination in order to help students to accomplish cognitive goals. Therefore, the idea of teaching about multiple representations rather than just by multiple representations (van Someren *et al.*, 1998) should be the focus of pre-service and in-service chemistry teacher-training programmes.

10.1.3.3 Explicitly specifying content-specific teaching objectives

The Turkish school chemistry curriculum only includes a wide variety of general teaching objectives, topics of subject area and subtitles of each topic (MEB, 2004). These objectives were intended to delineate the overall domain of chemistry (see Chapter 4). Thus, determining teaching objectives is left to the teachers who need to translate general teaching objectives of chemistry into specific (or general) teaching objectives of chemical kinetics. In other words, content specific objectives derived from general curriculum objectives. Thus different teachers may end up with different teaching objectives in a specific area of chemistry. Interviews with teachers and lecturers indicated that they had some teaching objectives about chemical kinetics in their minds, however in most cases these were more general objectives. Since classroom instruction is intended to help students to achieve (specified) teaching objectives, it is reasonable for teachers to consider all important aspects and components of the domain, to specify their teaching objectives and to design teaching accordingly in the way, for example, Leach and Scott (2002) did so for some domains in the school curriculum. That would also help them to decide what to assess in terms of students' understanding. I propose that it could be more appropriate (1) to specify general objectives of the chemistry course, (2) to specify teaching objectives of chemical kinetics, and (3) to consider approaches and teaching tools in order to achieve these objectives. It would be better to move from unclear and ambiguous general objectives towards content specific objectives and designing teaching accordingly. For example:

General teaching objectives *may include* (overall goals):

1) Social and ethical issues.
2) Social and ethical responsibility of chemists.
3) The level of scientific/chemical literacy.
4) Risk assessment (risks and benefits) and so on.

For instance for the "concept of catalysis", content specific teaching objectives (specific goals) may include:

1) To *open up students' own ideas* about catalysts and catalysis
2) To *emphasise* the idea that:
   - enzymes and catalysts are important for industry and for our daily lives
   - a catalyst is a *substance* that would be a solid, liquid or a gas.
3) To *build on* the ideas that:
   - a reaction occurs if the collision has enough energy to be either equal or greater than the activation energy and if the orientation of the collisions allows for correct bond formation.
   - a catalyst accelerates a reaction by altering the mechanism so that the activation energy is lowered.
4) To *draw attention to, and to emphasise*, the ideas that:
   - a catalyst is a substance that works by changing the mechanism of the reaction
   - the reaction rate may depend on the amount of catalyst –on its concentration- for homogenous catalysis or depend on its surface area for heterogeneous catalysis
   - when catalysts and reactants are in the same phase, the reaction proceeds through an intermediate species.
   - in reversible reactions a catalyst reduces both forward and reverse activation energies equally; as a result it speeds up both forward and reverse reactions and cannot increase the final equilibrium yield, but it gets to the final equilibrium state faster.
5) To *introduce, and support the development of*, the ideas that:
   - the principles of catalysis process can be used to explain the effect of enzymes on reaction rates (e.g. these ideas can be used in the biology lessons to explain the effect of enzymes on reaction rates, such as comparing heterogeneous catalysis to the catalytic action of enzymes)
6) To *draw attention to*;
   - the nature, scope and limitations of models (i.e. teachers should be aware of the limitations of models that they introduce to students).
7) To *teach*;
   - students how to reason in a coherent way and to show them the limits of each level of explanation/representation.

It is important to note that there is no written national curriculum available for universities and that the school chemistry curriculum comprises only textbook-based syllabuses. There are not teachers' guides, laboratory manuals or supplementary books for teachers, therefore teachers had responsibility for designing teaching and learning activities, and designing assessment questions. That would make inexperienced teachers anxious to engage with teaching. I believe that the Ministry of Education should provide teachers supplementary books and that now is time for researchers to write practical books for teachers about teaching and learning different chemistry topics. For example the Royal Society of Chemistry's chemical science network (RSC, 2005) has been developing materials to support the school and university curriculum. That would be a model for Turkey.

It could be argued that greater specification of the objectives of the curriculum may constrain teachers' freedom and creativity. However, the key assumption behind this specification is that identifying content specific teaching objectives can be a model for those teachers who want to design their teaching drawing upon these objectives. In other words, teachers are given freedom to choose the proposed model or their own models.

10.1.3.4 Sequencing the curriculum

As Appendix 1 shows, chemical kinetics is introduced to school and university first year students after teaching thermodynamics and the concept of chemical equilibrium is taught after chemical kinetics. However, chemical kinetics is introduced to university third year students after teaching thermodynamics and chemical equilibrium. Interviews with teachers and lecturers revealed that they thought this structure is appropriate and works well.

School students follow a common science curriculum, which is developed and approved by the Ministry of National Education. However, there is no national or centralised curriculum for universities. Universities need to follow very similar coursework which is suggested by the Higher Education Council of Turkey (YÖK). In some sense, lecturers define the content and structure of courses. As argued in Section 10.1.2, the university curriculum assumes that the basic ideas and theories of kinetics are already being introduced at school level and to some extent understood. Thus, the university first year curriculum aims to develop and introduce those ideas in more depth. However, the evidence shows that school students come to university with very limited knowledge of chemical kinetics. The lecturer who taught chemical kinetics to the UF argued that there is a huge difference amongst students' preconceptions about chemical kinetics. Accordingly, the lecturer had to teach the subject assuming that they had not been taught at school. The findings suggest that lecturers may need to take into account this diversity of students' engagement with the topic at school. It is important not to overestimate students' prior knowledge of chemical kinetics. The results suggest that specifically the structure of the university curriculum needs to be designed on the basis of students' needs. The curriculum should be designed with the co-operation of chemistry lecturers across different educational levels. Other issues about structuring the curriculum are discussed in the following sections.

10.1.3.5 Close reference to related concepts

As outlined in Sections 10.1.2.4 and 10.1.2.5 the students did not make a clear distinction between kinetic and thermodynamic ideas and tried to use thermodynamic ideas to explain the kinetic of a reaction: in some cases they confused the concept of reaction rate and chemical equilibria. One of the reasons would be that these concepts were often taught separately (e.g. some concepts in kinetics and thermodynamics such as activation energy, enthalpy, spontaneity, entropy, free energy, the notion of exothermic and endothermic reactions) and links between those concepts were not specified or ignored in the curriculum (as observed by Viennot (2001) in other contexts). Thus, students failed to move between several concepts/domains. Without being explicitly introduced the relationships between some concepts in kinetics and thermodynamics, students would have conceptual difficulties in moving between them. As argued in Chapter 6, students also had similar conceptual difficulties in some concepts in kinetics and chemical equilibria.

Understanding of chemical kinetics requires an integrated conceptual understanding of some fundamental ideas: the particulate nature of matter, the kinetic molecular theory and dynamic aspects of chemical reactions (Justi, 2002). I believe it would be useful to treat closely related concepts of chemistry together. In other words, during teaching the teacher (and the curriculum) should help students to move back and forth in order to make links between different concepts introduced to them through teaching. For example, making link between the half life for a first-order reaction and radioactive decay[4] (e.g. giving examples of dating the remains of living things) would help students to appreciate the contribution of the concept/chemistry to the society and to see the relevance of chemical kinetics to other studies in chemistry. The teacher, therefore, should encourage students to bring together knowledge of different areas of chemistry and to relate to each other. In conclusion, the instructional strategies need to put more emphasis on how concepts are interconnected so that students will understand the links between them.

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[4] In fact this link is neglected in the curriculum.

10.1.3.6 Teaching chemistry in context

Integrating content and context

Establishing links between the world of object/events and the world of theories/models (Linjse *et al.*, 1990; Tiberghien, 2000) was particularly challenging for the school students. Thus presenting opportunities to weave content and context together, and expressing the importance and relevance of content to their lives and to current technological development would help students to understand the relationships between the content and context (Mahaffy, 2004). A perceived benefit of a context based approach is the fact that lower achiever students can see the relevance of content to their lives/the material world.

At this point it is useful to consider the nature of practical work. Research (e.g. Tiberghien, 1999) suggest that it is possible to improve students' learning about a particular area in science in carefully planned situations where student are given the opportunity to discuss, reflect and consider alternative situations. Learning would take place in such a dynamic social environment if students are provided with support as they struggled to understand the scientific point of view (Harrison *et al.*, 1999). Developing an understanding of links between concepts, theories and experiments should be one of the aims of the chemistry curriculum. The current study revealed that the objectives of the curriculum in terms of practical work were highly constrained by the resources of schools and universities.

Assessing chemistry in context

It is found that many students appeared to focus on giving a correct answer by mainly drawing upon macroscopic modelling rather than explaining the reasoning behind it (i.e. drew upon theoretical models). One of the reasons might be that the school curriculum, classroom activities and assessment focused mainly on recalling definitions and algorithmic problems and phenomenologically framed questions (context-based problems) were ignored in the examination questions (including in the Student Selection Examination (ÖSS)). This is important because the nature of assessment (i.e. the style of examination questions) affects students' approach to learning. Assessment would facilitate or discourage critical and conceptual thinking (Pushkin, 1998).

Furthermore, an analysis of the scientific knowledge presented in the curriculum indicates that in most cases, theoretical models are disconnected from chemical phenomena and everyday practices. That could be one of the reasons why school students had difficulties in deploying their chemical knowledge and understanding within a familiar context/phenomenon. From school to university, there was a considerable progression in the number of students who justified their answers by referring to a theoretical model. Undergraduates were more likely to attribute a theoretical model to the phenomenon. These results have possible implications for instructional practices. Chemistry education aims to introduce students not only to the abstract concepts involved but also the ways in which they can apply these to various situations, some in a laboratory settings and some in the material world. Thus, providing more opportunity to practice using context-based problems would help students to relate chemical principles to everyday life and the natural phenomena (as suggested by Holman & Pilling (2003), in thermodynamics). One of the claims for context-based approaches is that using everyday context as starting points and of employing a wide range of activities in lessons can stimulate students' motivation in chemistry (Ramsden, 1997).

10.1.3.7 Using ICT in facilitating students' understanding of chemical kinetics

The results of the study suggest that many students' conceptual difficulties in chemical kinetics stem from inadequate or inaccurate models of the molecular world. With respect to representations, computers can be used to assist students' understanding of the process of chemical reactions at the sub-microscopic level (Lynch, 1997; Reid *et al.*, 2000). For instance, simulations of processes which are impossible to experience in the school environment (e.g. simulation of industrial processes), simulations of the behaviour of specific models (e.g. pathways taken by atoms and molecules as a reaction proceeds in the presence and absence of a catalyst), or animations that portray reaction mechanisms at the sub-microscopic level would be used. Indeed, there is considerable evidence to show that using multimedia and multiple external representations can improve students' conceptual understanding in chemistry (Wu, 2003; Ardac & Akaygun, 2004) and can stimulate students' motivation and interest in chemistry (Tasker, 2000). For example, Mayer (2003) argues that the combined use of text and animated graphics make the information more memorable by helping learners encode this information in both visual and verbal forms and integrate these forms in long-term memory.

10.1.3.8 Not to overestimate teachers/lecturers subject matter knowledge and especially their pedagogical content knowledge

There is convincing evidence to show that both teachers' subject matter knowledge (SMK) and teachers' pedagogical knowledge are crucial to good science teaching and student understanding (de Jong *et al.*, 2002). The results of the study revealed that in some areas of kinetics pre-service chemistry teachers had similar conceptual difficulties to those of secondary school students. Drawing upon these findings, I have proposed some suggestions some of which were discussed in previous sections. When we look at these suggestions, in most cases, roles of the teacher/lecturer and their pedagogical content knowledge (PCK)[5] are crucially important. Do teachers/lecturers have sufficient pedagogical content knowledge to transform the findings of the study into classroom practice?

I am sceptical whether teachers and particularly lecturers have sufficient pedagogical skill to make this transformation. In Turkey, prospective chemistry teachers follow courses, similar to the British PGCE course, in order to become a school chemistry teacher. However, university lecturers (in common with the other countries' educational systems) do not need to take any courses or seminars on pedagogy. My concern is that we, as researchers, sometimes overestimate lecturers' pedagogical content knowledge. Lecturers are experts in chemistry, however the study of an academic discipline may not provide them the kind of understanding they need to effectively transform their academic knowledge into instructional practice (Geddis, 1993; de Jong *et al.*, 2002). Knowing about chemistry and knowing how to teach chemistry are inextricably linked. Only a combination of both SMK and an understanding of the nature of effective teaching and learning can enable teachers to teach effectively (Kyriacou, 1997). My claim is that university lecturers may need to participate in specific courses, seminars or workshops on pedagogical skill (1) in order to be aware of potentially relevant research findings, (2) to use these findings to improve their classroom practice, (3) to critically

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[5] Pedagogical content knowledge concerns the transformation of several types of knowledge for teaching a specified content area (Shulman, 1987). Those include subject matter knowledge, pedagogical knowledge (e.g. classroom management, educational aims), and knowledge about context (school, students).

reflect upon and evaluate their own teaching, and (4) to be able to do good science teaching. Consequently, sufficient guidance should be given to teachers/lecturers in order to transform findings from research into their classroom practice. Indeed, I agree with the view that successful reform of chemistry teacher/lecturer education relies on the co-operation of chemistry teacher educators, chemistry teachers/lecturers and researchers (de Jong *et al.*, 2002; Gilbert *et al.*, 2004).

My second claim is that pre-service chemistry teacher programmes should not only focus on how to teach science/chemistry (in a broad sense), but also focus on how to teach a specific content area in chemistry (i.e. content specific teaching skills). In other words, these programmes should be more focused on enhancing teachers' pedagogical content knowledge (e.g. common difficulties faced by students in their learning of the particular subject matter under consideration and strategies for avoiding these difficulties) rather than merely enhancing their pedagogical knowledge (e.g. being audible, managing students and activities or having an understanding of some educational theories) or merely enhancing their subject matter knowledge. Prospective teachers need to learn not just how to teach but rather how to teach "electrochemistry" or how to teach "chemical kinetics or thermodynamics". As Lederman *et al.* (1994, in de Jong *et al.*, 2002, p.378) point out "the development of PCK among preservice science teachers is promoted by the constant use of SMK in teaching situations".

10.2 A CRITICAL REFLECTION ON THE STUDY

In this section, a methodological critique of the study and how that could be addressed in future research are discussed.

In order to seek answers to the first research question which is concerned with the intended development of chemical kinetics within school and university curricula, an approach consisting of analysis of the curriculum, and interviews with teachers/lecturers was employed. Since written content-specific teaching objectives were not available for the school and university courses, the objectives of the chemistry curriculum in the area of chemical kinetics were identified from conceptual analysis of the curriculum, students' notes and interviews with teachers/lecturers. Though this methodological option was successful, it would have been helpful to do interviews with the school chemistry curriculum designers in order to investigate what kind of teaching objectives they aimed to achieve. However, time and procedural constraints did not allow me to do so. Another point is that evidence of the implemented curriculum and of the nature of teaching can be obtained from systematic observation of lessons. One of the limitations of the study was that it was not possible to observe lessons to gather information about what went on inside the classroom (in Millar's (1989) term *inside the 'black box'*), because of time/budget restrictions on overseas data collection. Data about the implemented curriculum were obtained through an analysis of students' notes and interviews with teachers/lecturers (see Section 3.2.1.1).

In order to seek answers to the second research question (which is concerned with the outcomes of the curriculum for chemical kinetics in terms of students' learning at school and university levels), an approach consisting of written diagnostic questions, and interviews was employed. I believe this methodological option was highly successful. It is, however, acknowledged that several factors would enhance or constraint students' learning. I did not have sufficient evidence about what went on inside the classroom. Therefore, there were limited data available to explore the possible sources of students' lack of knowledge or conceptual difficulties about chemical kinetics.

There were a number of constraints on sampling in this study. Three classes of schools were selected to represent a mixture of socioeconomic areas and to cover different students' profile. Nevertheless, due to time constraints, only one university was selected for the study. It is, however, judged to be a typical university in Turkey. On the basis of the Student Selection Examination (ÖSS) results, it was about an average university. Consequently, due to this small sample and this purposive sampling strategy (Cohen *et al.*, 2000), the limitations of such data and the results should be regarded and recommendations made on the basis of findings from the study must be treated as tentative. Therefore, the implementation of such recommendations should be evaluated. Nevertheless, it should be acknowledged that the findings of the study gave insights into the ways in which school and university students conceptualise chemical kinetics in typical chemistry classes in Turkey.

Because little research has previously been conducted on students' understanding of chemical kinetics, it was not possible to use previously designed diagnostic questions. I have designed most of the probes; therefore, piloting the research instruments was crucially important for this study. Accordingly, two pilot studies were carried out and these studies helped me to improve the research instruments. Most of the probes worked reasonably well at the main study. Nonetheless, a number of students found it difficult to understand the content of some of the probes. For example, interviews with students revealed that in some cases the "reaction rate probe-B" was misunderstood by some students. They thought the question asked "how would a reaction rate be changed?" In fact the probe asked "*How does the rate of the reaction change from the beginning until the end of the reaction? Please explain your answer as fully as you can!*" Therefore, wording of the probe could be improved. In addition, many school students found it difficult to answer the "nitrogen monoxide probe-A" and the "reaction mechanism probe", both of which aimed to investigate students' ability to interpret empirical data which was presented on a graph. One of the reasons is possibly that the students generally had difficulties in interpreting empirical data and graphical representation. Therefore, it would be necessary to elicit students' understanding of reaction order, rate equations and reaction mechanisms also in different contexts. Further research would be needed to shed more light on these aspects of kinetics.

As discussed in Chapter 5 in Turkish, the term "De-scaler" is commonly called "limestone dissolver" in everyday language; therefore that might be one of the reasons in students' preference for the terms "dissolve/dissolving" instead of "react/reaction" in response to the De-scaler probe. That may not be a problem for using the probe in other languages and countries; however it might be useful to elicit Turkish students' understanding of the effect of concentration on reaction rates in a different context.

The "enthalpy probe" asked students whether they could compare rates of two different chemical reactions by using some thermodynamic variables. They were asked to consider "these two reactions, occurring at the same temperature". Wording of this probe could be altered in the future studies. It should be emphasised to "consider these two reactions, occurring at the same *initial* temperature".

In this study, two different coding schemes were used. The rationale for using these coding schemes is discussed in Section 3.7. In a broader sense, phenomenologically framed probes were analysed in an ideographic way by using coding scheme-A, yet conceptually framed probes were analysed nomothetically by using coding scheme-B (see Figure 3.1). One of the disadvantages of using different coding scheme was that it is difficult to cross-tabulate students' responses across different probes to explore the consistency of students' ideas. To avoid that problem the probes testing the same ideas were analysed by using the same coding scheme. It is important to note that if a study aims to investigate individual students' explanations across several probes; in that case these two different coding schemes would be problematic or may not work.

Students' written responses were entered into SPSS and analysed accordingly. That enabled me to interpret and compare students' responses more easily. It would have been helpful to use computer assisted qualitative data analysis software, such as NVivo or MAXqda, in order to analyse data gathered from interviews. By using such software it would be possible to save a great amount of time that otherwise would be spend on mechanical task. Nevertheless, due to funding constraints, analysis of transcripts was done manually.

10.3 ISSUES FOR FURTHER RESEARCH

This cross-sectional study has investigated the development of Turkish students' understanding of chemical kinetics, following relevant teaching, from upper secondary to university level. It is important to acknowledge that the study provided relative strength and weaknesses of the education system in the area of chemical kinetics; however it also raised serious questions and suggested some areas suitable for further inquiry. For instance, as emphasised earlier, the methodological approach used did not allow me to investigate in depth why the curriculum was not being effective in certain areas of kinetic. As emphasised in the preceding section, it would have been desirable to do observation during teaching chemical kinetics; however, it was impossible, due to constraints on time and budget. Thus, in order to address possible sources of students' lack of knowledge or conceptual difficulties about chemical kinetics and to investigate what are favourable conditions for conceptual understanding of chemical kinetics, an ethnographic and observational research is needed.

The main focus of the study was to investigate the development of Turkish students' understanding of chemical kinetics as a result of teaching. One dimension of development or change is students' attitudes to chemistry and their views on the nature of science and scientific enquiry. That would be a direction for future research.

Drawing on the results of the study and on the data in the literature, designing a teaching unit in chemical kinetics, implementing it with secondary and/or university students, and assessing the effectiveness of this teaching unit would be considered for further research. As a result, the designed materials, and the results and experience gained from the research can be disseminated to other teachers of chemistry, who are interested improving their teaching.

The results of the study revealed that students' (lack of) understanding in thermodynamics and chemical equilibrium significantly influences their ideas about chemical kinetics. Therefore, considering interrelationships between these domains and designing/implementing/evaluating these combined teaching units would be also considered for future research. In other areas of science, there are some research studies on teaching and learning sequences (see, for example, *the International Journal of Science Education*, 2004, Special Issue on teaching-learning sequences); however I have not come across any research paper which focuses on designing and evaluating teaching sequences for several closely related topics.

It is important to acknowledge that in this study, a purposive sampling strategy was used to select schools/universities and students. Drawing upon the findings of the study a more standardised diagnostic test (e.g. two-tier diagnostic questions, or multiple choice questions) could be designed in order to evaluate and investigate students' understanding of chemical kinetics in a larger sample by using a random sampling strategy or potentially this test would be used by teachers in order to diagnose their students' understandings and to monitor students' learning.

In Turkey, there is an extensive body of research on students' ideas on various science domains; by contrast there is a limited number of studies on the development of students' ideas across different educational levels (Cakmakci, 2005). It would be beneficial to assess the new Turkish primary science curriculum (which is going to be implemented in September 2005) by using a longitudinal or cross-sectional design.

A study that clarifies whether the results of the study are applicable to the other countries chemistry curricula would be needed.

APPENDICES

A1.1 The Turkish education system and chemistry in the curriculum

The Turkish education system can be considered as comprising of three main components; eight years compulsory primary education, between ages 6-14 (Grades 1-8); three years of secondary education, between ages 14-17 (Grades 9-11); and higher education (colleges and universities), from age 17 and upwards. Both primary and secondary education is free of charge in public schools; however the higher education is not. As the demand for higher education far exceeds the places available at the higher institutions, those who graduated from secondary schools are required to sit for a nation-wide examination, named the Student Selection Examination (ÖSS) in order to continue their higher education. Just to exemplify, around 20% of the applicants to the ÖSS were placed in universities in 2002 (ÖSYM, 2003). This also included some two-year vocational colleges.

In Turkey, formal chemistry courses, which take three years, start with secondary education (Grades 9-11, ages 14-17). School students follow a common science curriculum, which is developed and approved by the Ministry of National Education. However, there is no national or centralised curriculum for universities. Universities are partly controlled by the Higher Education Council of Turkey (YÖK). Universities need to follow very similar coursework which is suggested by the YÖK.

A1.2 The course content of the participating schools and university

In the secondary school (Grades 9-11), chemistry is taught as a separate subject. In the first year (Grade 9), matter and its properties, separating of matter, elements, compounds and atomic structure, periodic table and the chemical bonding are taught. In the second year (Grade10) gases, chemical reactions, liquids and solids, radioactivity, chemical reactions and energy, chemical reaction rates (chemical kinetics), chemical equilibrium, solubility equilibrium, acids and bases are taught. Oxidation and reduction reactions, the chemical bonding, basic organic chemistry including hydrocarbons, alcohol and ethers, aldehydes and ketones, carboxylic acids, esters, carbohydrates, aromatic ammonium derivatives and aromatic compounds are introduced in the final year (Grade 11) of the secondary school chemistry curriculum (MEB, 2004).

In Turkey the concept of chemical kinetics is introduced at upper secondary level and further developed at university level. All school students who participated in this study majored in mathematics and science. The concept of chemical kinetics is first taught to students in Grade 10 (ages 15-16). Chemical kinetics is taught again in detail in the first year in a general chemistry course and in the third year in a physical chemistry course in a five-year pre-service chemistry teacher-training course. Furthermore, the first year and third year pre-service chemistry teachers do experiments on chemical kinetics in their laboratory courses. Table A1.1 shows the course content of the participating institutions in the area of chemical kinetics.

General chemistry is taught as a two-semester course in the first year of a pre-service chemistry teacher training programme. Matter and energy, chemical equations, atomic structure, periodic table, radioactivity, chemical bonds, the properties of gases, liquids and solids, mixtures and solutions, chemical thermodynamics, chemical kinetics, chemical equilibrium, and acids and bases are introduced in the first year of the university curriculum. A general chemistry laboratory course is usually compatible with the theoretical course.

Physical chemistry typically is taught as a two-semester course in the third year of the university. Topics generally include gases and kinetic theory of gases, classical thermodynamics (the first law, the second and third laws), chemical equilibrium and chemical kinetics. A physical chemistry laboratory course is given simultaneously with the theoretical course.

		Content
Grade 10	**Chemical Kinetics** *(About four-week unit on chemical kinetics (3 chemistry lessons per week, each lesson takes 45 minutes))*	1. Rates of chemical reactions 2. Measuring reaction rates 3. Collision theory 4. Activation energy 5. Enthalpies of reactions 6. Potential energy diagrams 7. Reaction mechanism, rate equation and rate order 8. Factors affecting reaction rate (i) The nature of reactants (ii) Effect of concentration on reaction rate (iii) Effect of temperature on reaction rate (iv) Effect of surface area on reaction rate (v) Effect of catalysts on reaction rate 9. Practical work: Five different experiments on factors that may affect reaction rates (as mentioned above *in item 8*) Suggested textbook: Kizildag, G., & Dursun, M. F. (2000). *Kimya: Lise 2 (Chemistry: Lycee 2).* Istanbul: Milli Egitim Basimevi.
University first year	**General Chemistry Course** *(About 6 chemistry lessons on chemical kinetics)*	1. Reaction rates 2. Dependence of rate on concentration 3. Elementary reactions; Collision and Transition State Theories 4. The rate law and Reaction mechanisms 5. Rate equations and temperature 6. Catalysis Suggested textbook: Mortimer, E. (1989). *Modern University Chemistry (in Turkish)* (T. Altinata, Trans.). Istanbul: Caglayan Kitabevi.
	General Chemistry Laboratory Course *(Two hours per week)*	Catalytic decomposition of hydrogen peroxide $2H_2O_{2\,(l)} \xrightarrow{HI} H_2O_{(l)} + O_{2\,(g)}$ Carrying out the experiment so as to find out the rate equation. Measuring the rate of evolution of oxygen provides a method of studying the rate of this reaction. Students also practice the effect of increasing concentration of the catalyst on the reaction rate. Suggested book: Alkan, M., Gurses, A., Bayrakceken, S., & Demir, Y. (1996). *Deneysel Kimya (Experimental Chemistry).* Erzurum: Kultur ve Egitim Vakfi Yayinlari.
University third year	**Physical Chemistry Course** *(About 4-6 chemistry lessons on chemical kinetics)*	1. Empirical chemical kinetics: Experimental determination of rate 2. The rates of reactions and the rate laws 3. Integrated rate laws 4. The temperature dependence of reaction rates 5. Accounting for the rate laws 6. Reaction mechanisms 7. Catalysis Suggested textbook: Atkins, P. W. (2001). *Fizikokimya (Physical Chemistry)* (S. Yildiz, H. Yilmaz & E. Kilic, Trans.). Ankara: Bilim Yayincilik.
	Physical Chemistry Laboratory Course *(Four hours per week)*	$2I^- + S_2O_8^{2-} \longrightarrow I_2 + 2SO_4^{2-}$ Carrying out an experiment in order to find out order of the reaction and the rate equation. Students determine the order of the reaction by graphical plotting of the data for the experiment. Suggested book: Gurses, A., & Bayrakceken, S. (1996). *Deneysel Fizikokimya (Experimental Physical Chemistry).* Erzurum: Ataturk Universitesi Yayin No:807.

Table A1.1 The course content of the participating schools and university in the area of chemical kinetics

Appendix 2 The content area of chemical kinetics taught in secondary school and *university*[1] courses in Turkey[2]

Area (The Key Scientific Ideas)	It is expected that students should be able to:
1. The rate of chemical reactions $A + B \longrightarrow C + D$ r = rate of disappearance of reactants r = rate of formation of products $r = -\frac{\Delta[A]}{\Delta t}$	1.1 describe reaction rate in terms of some quantity (reactant or product) per unit of time 1.2 show awareness of the importance of reaction rates for industry 1.3 discuss situations in which the rate of a reaction can be controlled 1.4 recall the factors that affect the rate of a chemical reaction and use collision model to give simple explanations 1.5 describe simple experimental techniques for measuring reaction rates 1.6 ***have an understanding of experimental techniques for measuring reaction rates and using rate laws in order to analyse the experimental data***
2. Concentration / Pressure	2.1 describe qualitatively, in terms of collision model, the effect of concentration changes on the rate of a reaction 2.2 describe the role of pressure on reaction rate for gaseous reactions 2.3 predict how a change in concentration (pressure of gases) affects the rate of a chemical reaction for different order reactions 2.4 describe the effect of concentration / pressure on the rate of a reaction in terms of a rate equation
3. Temperature	3.1 describe the role of temperature on the reaction rate 3.2 describe qualitatively, using the Maxwell-Boltzmann energy distribution, the effect of temperature changes on the rate of a reaction 3.3 predict the affect of temperature on endothermic and exothermic reactions 3.4 ***recall the role of temperature in the Arrhenius equation***[3] 3.5 ***recall the qualitative effect of temperature on the rate constant of a reaction***
4. Surface area of solid reactants or a solid catalyst	4.1 describe how and why surface area affect heterogeneous reactions rates 4.2 describe qualitatively, in terms of collision model, the effect of surface area on the rate of a heterogeneous reaction

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[1] In this section, university is termed as a four-year pre-service chemistry teacher-training course

[2] Based on an analysis of school science curriculum (MEB, 2002), chemistry textbooks, students' notes and interviews with teachers/lecturers, these teaching goals were identified.

[3] ***The italic statements used in this section are related to university level***

5. Catalyst	5.1	explain what is meant by a catalyst, inhibitor and enzyme
	5.2	show awareness of the importance of catalysts and enzymes for industry
	5.3	account for the role of catalysts in reactions
	5.4	explain that, in the presence of a catalyst, a reaction proceeds via a different route
	5.5	sketch and label the energy profile of a reaction and show how a catalyst affects the profile
	5.6	describe the relationship between catalyst and activation energy
	5.7	anticipate that to increase the efficiency of a solid catalyst the surface area should be as large as possible in order to increase the number of active sites available.
	5.8	***outline a model to explain homogenous and heterogeneous catalysis in terms of the formation of intermediates***
	5.9	***evaluate the advantages and disadvantages of using enzymes to bring about chemical reactions.***
6. Collision model 7. Activation energy	6.1	demonstrate an awareness of that reactions are the result of collisions between reactant particles
	6.2	show awareness that collision between molecules does not always lead to reaction
	6.3	identify the factors that affect the magnitude of activation energy
	6.4	describe the relationship between activation energy and the rate of a reaction
	6.5	aware of that sufficient kinetic energy and favourable geometry are required for successful collisions
	6.6	describe the factors which increase the frequency of collisions
	6.7	describe elementary reactions in terms of collision model
	6.8	describe how collision model can be used to explain changes in reaction rate
	7.1	describe the notion of activation energy
8. Transition-state model	8.1	describe how transition-state model can be used to explain changes in reaction rate
	8.2	explain qualitatively, using the Maxwell-Boltzmann energy distribution and enthalpy profile diagrams, what is meant by the term activation energy
	8.3	draw and label potential energy diagrams for both exothermic and endothermic reactions, including activated complex, activation energy, and enthalpy changes
	8.4	compare and contrast the potential energy diagrams for a catalysed and uncatalysed reaction in terms of reaction mechanism and activation energy
	8.5	construct and interpret an energy diagram showing the progress of an exothermic/endothermic reaction

9. Reaction mechanisms / Rate-determining step	9.1 identify reactant, product, catalyst and reaction intermediate from a given reaction mechanism 9.2 suggest mechanisms from analysis of the concentration of the reactant and product 9.3 describe a reaction mechanism as the series of steps that results in the overall reaction 9.4 explain what is meant by rate-determining step 9.5 predict the rate expression in terms of proposed mechanisms 9.6 deduce the dependence of total rate on the rate determining step 9.7 ***account for the rate laws for more complex reactions***
10. Rate equation (rate laws) The rate of a reaction is function of the rate constant, concentration of reactants and reaction order $aA \longrightarrow bB$ $r \alpha k.[A]^m$ $r = k.[A]^m = -\frac{1}{a}\frac{d[A]}{dt} = \frac{1}{b}\frac{d[B]}{dt}$	10.1 write a rate expression for a given reaction 10.2 deduce how reaction rate varies with, rate constant (k), reactant concentration ([A]), and reaction order (m) 10.3 use mathematical skills in the analysis of given experiment data and evaluate rate constant 10.4 describe how rate expressions are related to reaction mechanisms 10.5 ***evaluate activation energy by using two rate constant data at two different temperature***
11. Rate constant, ***Arrhenius equation*** $k = A.e^{-Ea/RT}$ • ***A : pre-exponential factor (a constant with different values for different reaction) same unit as k :*** ***1st order reaction: s^{-1}*** ***2nd order reaction: $M^{-1} s^{-1}$*** • ***E_a: Activation energy (a constant which is different for different reactions) kJ mol^{-1}*** ***R : Gas constant, J K^{-1} M^{-1}*** • ***T : Temperature, K***	11.1 recall that reaction rate is proportional to the rate constant. 11.2 calculate rate constants from experimental data 11.3 deduce that reaction rates generally increase very rapidly as the temperature increases 11.4 ***describe the relationship between variables in the Arrhenius equation*** 11.5 ***use the Arrhenius equation to evaluate the rate constant***

12. Reaction order $A \longrightarrow B$ $r = k.[A]^m = -\frac{d[A]}{dt}$ ***Order*** ***Rate law*** ***Integrated rate equation*** $m = 0$ $r = k$ $[A]_t = -kt + [A]_0$ $m = 1$ $r = k.[A]$ $\ln[A]_t = -kt + \ln[A]_0$ $m = 2$ $r = k.[A]^2$ $\frac{1}{[A]_t} = kt + \frac{1}{[A]_0}$	12.1 predict how the reaction rate varies with reaction order 12.2 determine the reaction order graphically 12.3 interpret given experiment data and predict reaction order for an elementary reaction 12.4 use experimental data to find out the order of a zero, first, and second order reaction 12.5 use given data to calculate half-life for a reaction 12.6 ***account for integrated rate laws*** 12.7 ***use mathematical skill and write the integrated rate for zero, first and second order reactions*** 12.8 ***determine the order of a reaction by graphical plotting of the data for the experiment.***

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A STUDY ON STUDENTS' IDEAS OF "REACTION RATE"

Dear Students;

This study aims to investigate students' ideas of "reaction rate". This test will not affect your marks in any way. It will be most helpful to this study if you would write as much as you can for each question. Thank you for participation in this study.

Gültekin Çakmakçı

This test takes 50 minutes to complete.

Name/Surname:..

Department/Class:...

Reaction rate:

Consider a reaction where two chemicals 'A' and 'B' react to form 'C'

$$A + B \longrightarrow C$$

Halil, a student in the class, says: "The reaction rate is the rate of formation of 'C' and it increases during time"

His friend *Sabri* disagrees: "No, the rate of reaction shows the period of time that is required for a reaction to occur"

The students are having some problems!
Answer question (a) and (b) to help the boys to understand!

a) Explain in your own words what you understand by the term **"rate of reaction"**.

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b) How does the rate of the reaction change from the beginning until the end of the reaction? Please explain your answer as fully as you can!

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Rusty water pipe:

When a house was newly built both the hot and the cold water pipes in the kitchen were shiny. After a while, the **outside of these pipes** had become dull and rusty (covered with a thin, brown coating). The outside of the hot water pipe was more rusty than the outside of the cold water pipe.

Explain why the **outside** of the hot water pipe was **more rusty** than the **outside** of the cold water pipe. Please give as much detail as you can!

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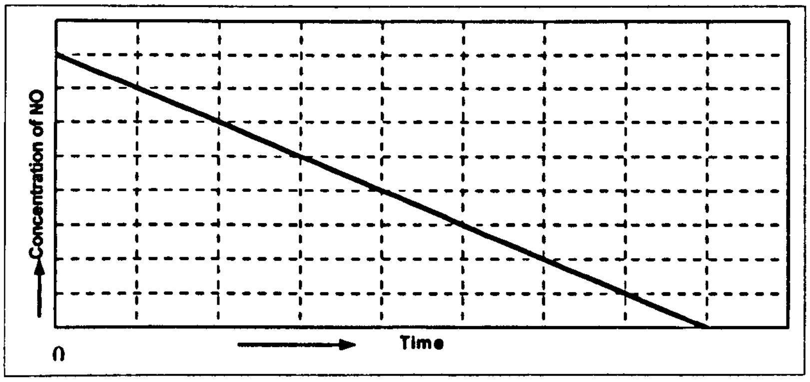
Nitrogen monoxide:

Some scientists did an experiment to find out the order of the reaction below:

$$2NO_{(g)} \xrightarrow{Pt} N_{2(g)} + O_{2(g)} \qquad \Delta H < 0 \textbf{ (Exothermic)}$$

They measured the concentration of nitrogen monoxide (NO) regularly over time.

The graph below shows how the **concentration of NO** changes as time passes.



After interpreting the graph, the scientists concluded that the reaction is **zero order** with respect to 'NO' and thus the rate expression for the reaction is: $\mathbf{r_{NO} = k\,[NO]^0 = k}$

a) How do you think the graph supports their conclusions? Explain your answer as fully as you can.

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Explain how the following conditions would affect the reaction rate. **Please give reasons for your answer.**

b) Increasing initial concentration of nitrogen monoxide

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c) Increasing temperature of the reaction

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d) Increasing the amount of the solid catalyst (Pt, Platinum)

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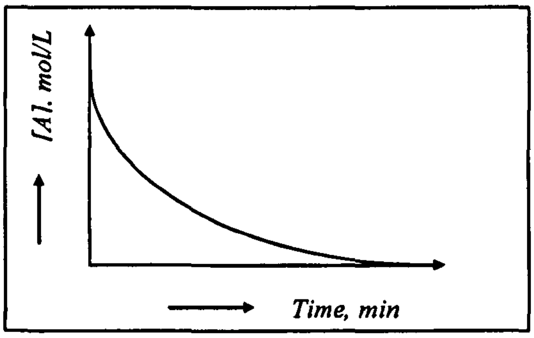
Reaction rate-Time:

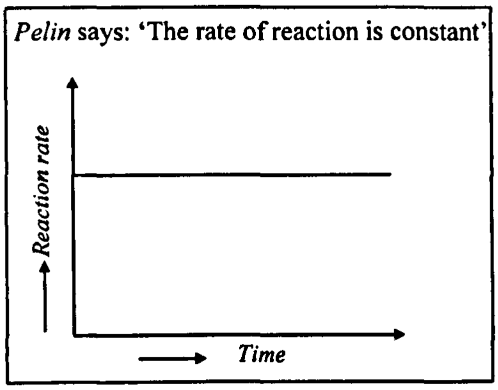
Consider a reaction where two chemicals 'A' and 'B' react to form 'C'

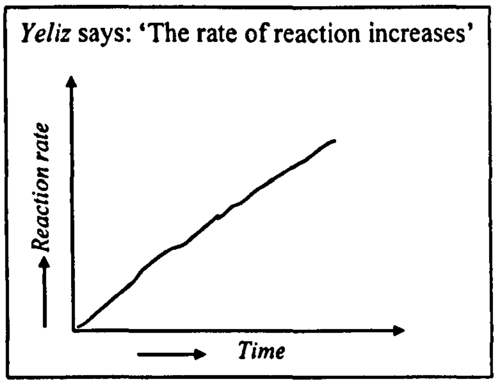
$$A_{(aq)} + B_{(aq)} \longrightarrow C_{(aq)}$$

The teacher drew a graph showing how **the concentration of A** changes with **time.**

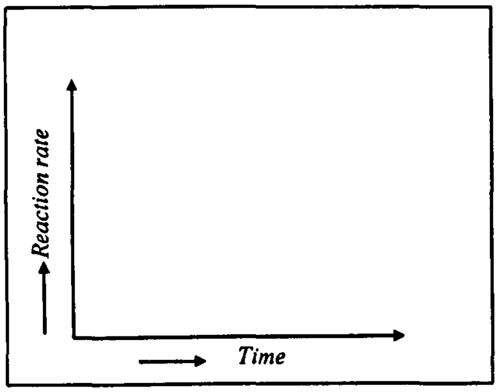


The teacher asks *Pelin* and *Yeliz* to use the graph to draw a graph for the reaction rate against time.





a) What is your opinion? Make a drawing to show the rate of reaction against time.



b) What would you say to convince the girl(s) that your answer is correct? Give as much detail as you can!

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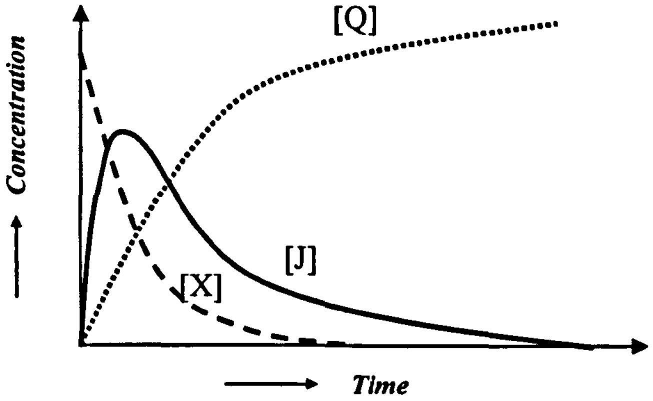
Reaction mechanisms:

Some scientists did an experiment to discover the mechanism of the decomposition of element X to element Q:

$$X \longrightarrow Q$$

They measured **the concentration** of the substances involved in the reaction and created the graph below.



Four students are analysing this graph and trying to find out the mechanisms of the reaction.

Ahmet says: "The reaction occurs in one step, and 'J' is the activated complex. $X \longrightarrow Q$"

Erhan disagrees: "No, the reaction occurs in two steps and the reaction mechanism is:

Step 1: $X \longrightarrow J$ (slow)

Step 2: $J \longrightarrow Q$ (fast), and the first step is the rate determining step"

Cem says: "Yes, I do agree with Erhan about the mechanism of the reaction, however the rate determining step is the second step"

Tarik says: "No, the reaction occurs in one step and 'J' is a catalyst. $X \xrightarrow{J} Q$"

The students have some problems!
Answer question (a) and (b) to help the boys to understand!

a) In how many steps do you think the reaction occurs? Please write down the possible reaction mechanisms and give reasons for your answer.

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b) If you think the reaction occurs in more than one step, which step has highest rate and which step is the rate determining step? Explain your answer as fully as you can.

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A STUDY ON STUDENTS' IDEAS OF "REACTION RATE"

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Gültekin Çakmakçı

This test takes 50 minutes to complete.

Name/Surname:..

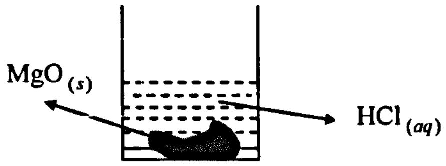
Department/Class:...

Magnesium oxide:

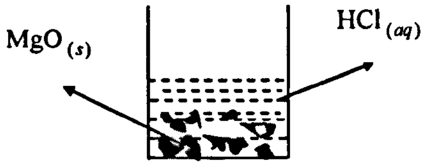
Two students are doing an experiment with equal amounts of magnesium oxide and hydrochloric acid.

Please follow what they are doing and then give your ideas.

1. ***Tolga*** puts 100 ml, 1M HCl into the beaker
2. Afterwards, he put 10 g **granulated** Magnesium oxide into the beaker.



1. ***Serdar*** puts 100 ml, 1M HCl into the beaker
2. Afterwards, he put 10 g **powdered** Magnesium oxide into the beaker.



The reaction between magnesium oxide with hydrochloric acid as follows:

$$MgO_{(s)} + 2\,HCl_{(aq)} \longrightarrow MgCl_{2(aq)} + H_2O_{(l)}$$

Serdar now thinks that "powdered magnesium oxide reacts with hydrochloric acid **faster** than granulated magnesium oxide does"

His friend, *Tolga* disagrees: "No, both reaction rates are **the same,** because we both used the same amounts of HCl and MgO"

a) What is your opinion?

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b) What would you say to convince the boy(s) that your answer is correct? Give as much detail as you can!

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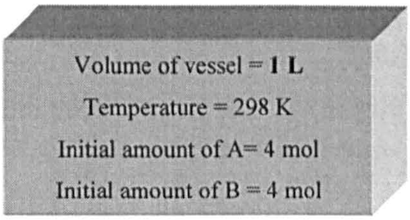
Vessel:

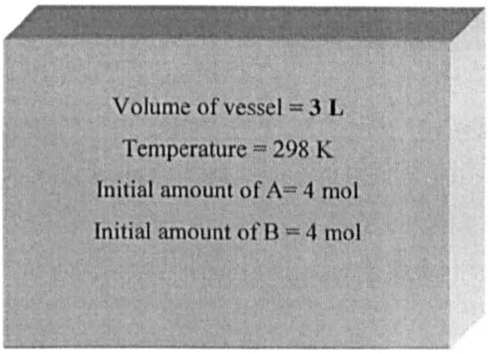
The following **gaseous reaction** occurs at room temperature (298 K):

$$A_{(g)} + B_{(g)} \longrightarrow C_{(g)} + D_{(g)}$$

The reaction is set up under two different sets of initial conditions:



First set of conditions



Second set of conditions

Tuba, a student in class, says: "The reaction under first set of conditions is **faster** than the reaction under second set of conditions"

Her friend *Sibel* disagrees: "No, the rates of reactions are **the same** because the same amount of reactants was used in both reactions"

a) What is your opinion?

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b) What would you say to convince the girl(s) that your answer is correct? Give as much detail as you can!

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De-scaler:

Serap's mother usually used *Tudor* brand kettle de-scaler, which contains a 3% solution of acid. However this time her husband went shopping, and he bought a different kettle de-scaler called *Apex*, containing a 5% solution of acid. When Serap's mother used the new kettle de-scaler for removing limestone collected in the kettle she realised that the new de-scaler *Apex* removed the limestone faster than *Tudor* did.

Why did it take less time to remove limestone in the kettle with concentrated kettle de-scaler (*Apex*)? Explain your answer as fully as you can in terms of particles.

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Activation Energy:

Consider these two reactions that have different activation energies (E_a) occurring at **the same temperature**;

Reaction 1: $Y_{(aq)} + P_{(aq)} \longrightarrow C_{(aq)}$ $E_a = 92\ \text{kJ}$

Reaction 2: $T_{(aq)} + V_{(aq)} \longrightarrow Z_{(aq)}$ $E_a = 480\ \text{kJ}$

Some students are discussing the meaning of activation energy and the relationship between activation energy and the rates of the reactions.

Zeynep says: "Activation energy is the kinetic energy of the reactant molecules. Thus the second reaction occurs faster than the first one"

Belma disagrees: "No, activation energy is the total amount of energy released in a reaction. Thus there is not enough information for comparing the rates of these reactions"

The students are having some problems!
Answer question (a) and (b) to help the girl(s) to understand!

a) Explain in your own words what you understand by the term "**activation energy**".

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b) Which reaction do you think is **likely to be faster**? Please explain your answer as fully as you can.

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Catalysis:

Consider a reaction where two chemicals 'A' and 'B' react to form 'C'.

$$A_{(aq)} + B_{(aq)} \longrightarrow C_{(aq)} \qquad \Delta H > 0 \text{ (Endothermic)}$$

Some students in the class are discussing how a catalyst would affect this reaction.

Ali says: "The catalyst changes the mechanism of the reaction in such a way that the activation energy of the reaction decreases"

Okan disagrees: "No, the catalyst just decreases the activation energy of the reaction without affecting on reaction mechanism"

Selim says: "With catalysts, more product is formed"

Ali and *Okan* disagree: "No, the catalyst does not affect the yield of 'C'"

The students are having some problems!

Answer question (a), (b) and (c) to help the boys to understand!

a) Explain **how** a catalyst affects (1) **the rate of reaction,** (2) **activation energy,** (3) **the yield of product** and (4) **mechanisms of the reaction**? Please give reasons for your answer.

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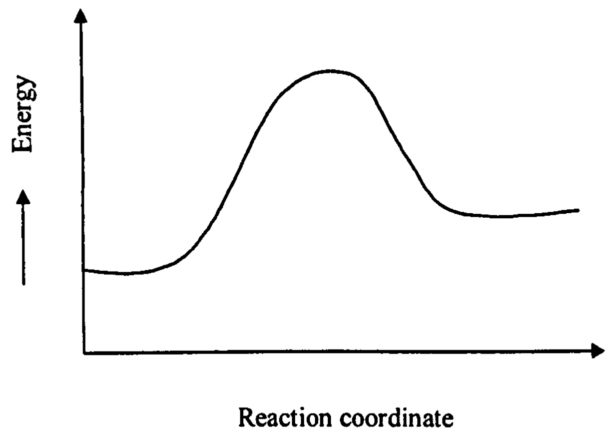
b) This graph shows a pathway for uncatalysed reaction. Mark on the graph a second line to indicate the reaction pathway with a catalyst.



c) Please explain your drawing

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Enthalpy:

Consider these two reactions, occuring at **the same temperature**;

Reaction 1: $C_{(g)} + P_{(g)} \longrightarrow B_{(g)}$ $\Delta H < 0$ **(Exothermic)**

Reaction 2: $G_{(g)} + V_{(g)} \longrightarrow Q_{(g)}$ $\Delta H > 0$ **(Endothermic)**

On the basis of this information some students are comparing the rates of these two reactions.

Serap says: “Reaction 1 is faster, because exothermic reactions occur faster than endothermic reactions”

Mine says: “The rates of these reactions are the same, because they occur at the same temperature”

Burcu disagrees: “No, it is not possible to compare the rates of these reactions, because there is not enough information given in the question”

The students are having some problems!
Answer the question below to help the girls to understand!

a) What is your opinion about the rates of these two reactions? Please **explain your answer** as fully as you can!

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Appendix 4 Teacher/lecturer Interview Schedule

(i) Background information

1- Could you please give some brief details about yourself?

(ii) The sequence of the curriculum [Stimulus materials: chemistry topics written on cards]

2- How many hours are devoted to present chemical kinetics in the curriculum?
  - Do you think this time is enough for this subject? [*Why you need more or less than this?]*

3- What kind of resources do you typically use in a chemical kinetics lesson?

4- Do you teach chemical kinetics in the same order as that is suggested by textbook or the curriculum? Could you please sequence the topics on the cards that you usually follow in a chemistry course?
  - Do you think the sequence of the textbook/curriculum is appropriate for chemical kinetics? (too early, just right, too late?)
  - For example, what should students' earliest experience and knowledge of chemical kinetics be? What should a prerequisite for conceptual understanding of chemical kinetics be considered?

(iii) Students' mistakes/learning difficulties in chemical kinetics [Stimulus materials: concepts in chemical kinetics written on cards]

5- Do you think the content of chemical kinetics is sequenced appropriately in the textbook/curriculum? Could you please sequence these cards according in the order that you usually follow in chemical kinetics lessons?

6- In the light of your experience, which part (based on the cards) of the chemical kinetics is the most important and needs more attention? Why?
  - *Do you think the textbook/curriculum give enough attention to those parts that you mentioned as being the most important part of chemical kinetics?*
  - *Do you think the textbook gives the content of chemical kinetics satisfactorily? What kind of deficiencies does the textbook/curriculum have in chemical kinetics?*

7- Which aspects / parts of chemical kinetics do students find difficult? (Based on the cards). Why are those difficult? [*Proposed solutions? Is chemical kinetics too abstract for the students you teach? Or do you feel that any aspects of chemical kinetics are conceptually too demanding for your students/for this level?]*

8- What kinds of mistakes/difficulties do students commonly make in chemical kinetics? [*Referring to the cards, mainly which area?]*

9- What do you think makes it hard for students to understand these aspects/parts of chemical kinetics in chemistry/physical chemistry? [*Learning difficulties: e.g. factors related to students/content/course/teaching methods/staff*].
  - How do you normally deal with these difficulties that students have?

10- (Structure of the lesson) When teaching chemical kinetics do students/you do any practical work/experiments/demonstrations? *How does practical work affect (would practical work affect) students' understanding of chemical kinetics?*

(iv) Assessment / Development

11- While you are teaching how do you find out whether students are learning?

- *[keeping track.*
- *Is there anything that can be done to improve the result of your work?*]

12-Talking about exam questions & questions in the textbooks [Stimulus materials: exam questions and/or questions in the textbook]

The enclosed examination questions are ones I have picked out from this [last] years course booklet. Could you tell me through these what you hope to learn about a student's understanding from each one?

- What mathematics knowledge are the students likely to need in your course? And what do they already know?
- Can poor maths ability hold back a student's chemical kinetics learning? *[How would you deal with a student with such a problem]*
- [Reactions to national testing and its impact on practice] Does the Student Selection Examination (ÖSS) affect your assessment / exam questions? How/why? [*school teachers only*]
- Do you think that students should have a realisation of the application of chemical kinetics in the natural world, outside the laboratory?
- What do you think the curriculum requires to make this a reality?

13- In the light of your experience, what is the relationship between the intended development of the subject of chemical kinetics in the curriculum and actual development of students' understanding? Do you feel that the levels of in the curriculum match your experience of the development of students' understanding?

14- What changes would you make to the textbook/curriculum? How would you change the science curriculum / chemistry textbook?

15- What do you think could be done to help students understand chemical kinetics better? Which of these is the most important for better understanding in chemical kinetics?

Appendix 5 A proposed representation for teaching the concept of catalysis

Drawing upon the results, I have proposed an alternative representation for teaching the notion of catalysis. However, it should be pointed out that the proposed approach is conceptually demanding. It requires students to make connections within and across different representational forms; therefore the role of the teacher as a mediator is crucial.

It is evident from the foregoing discussion (in Section 8.3) that many improvements to textbooks and teaching are desirable. If the objective for teaching is to teach the actual process of catalysis, the current approach in the school textbooks had limitations. Therefore, an alternative approach for teaching the concept of catalysis is proposed. The alternative representation for teaching the concept of catalysis is presented in Table A5.1.

It is claimed that much of the meaning-making in science classrooms is achieved not only through talk (by teacher and students) but also through various images, and visual representations (Kress *et al.*, 2002). Understanding and conceptually integrating multiple representations play a crucial role in teaching and learning scientific concepts. Accordingly, by attempting to provide a more comprehensible approach for teaching the concept of (homogenous) catalysis, it might be more fruitful to teach the role of a catalyst in reaction mechanisms on the diagram shown in Table A5.1, by making clear that a catalyst is a substance that works by changing the mechanism of the reaction in that it actually reacts with the one or more of the reactants/products. The figure with the reaction mechanisms below may help students to understand the role of catalysts in chemical reactions. Writing a catalyst in the chemical equation may help students to understand that a catalyst enters into the reaction; however at the end of the reaction it undergoes no permanent change. For example, the depletion of ozone in the stratosphere by chlorine atoms can be illustrated the action of a homogeneous catalyst. This example is chosen since the depletion of ozone layer is a current issue in chemistry/the environment (Ebbing & Gammon, 1999) and it includes social and economical issues. Kotz & Treichel (1996) argue one of the reasons for studying chemistry as:

> *You will be called on to make many decisions in your life for your own and for the good of those in your community-your local community or the global community. An understanding of science in general and chemistry in particular can only help in these decisions.* (p.14)

It is important to note that the proposed multiple representation of the action of a homogeneous catalyst is conceptually demanding. It requires students to make links between multiple representations; therefore the role of the teacher as a mediator is crucial. Critically, this role involves helping students to move between different forms of representations.

Different modes of representations

The current issue: Depletion of the Ozone Layer

Ozone (O_3) normally presents in the ozone in the stratosphere and provides protection against biological destructive, short-wave-length ultraviolet radiation from the sun. Higher levels of radiation resulting from the depletion of the ozone layer have been linked with increases in skin cancers and cataracts. The depletion of ozone in the stratosphere is believed to result from the Cl-catalysed decomposition of O_3. Chlorine atoms in the stratosphere originate from the decomposition of chlorofluorocarbons (CFCs), such as $CClF_3$ and CCl_2F_2. At one time, CFCs were used widely as refrigerants, solvents for degreasing, spray-can propellants, and blowing agents for making plastic foams. Usage of CFSs is banned in many nations, in fact its use is spreading to Third World countries, such as the nations of Africa and many South America, and its availability has a profound effect on their economies.

The equation for **without a catalyst:**

$$O_{3(g)} + O\bullet_{(g)} \longrightarrow 2\,O_{2(g)}$$

The equations for **a catalysed reaction are given below** (Cl atom is the catalyst for this reaction). The mechanism can be divided into two steps:

Step 1: Cl atom reacts with ozone to form ClO and O_2

$$Cl\bullet_{(g)} + O_{3(g)} \longrightarrow ClO\bullet_{(g)} + O_{2(g)}$$

Step 2: ClO reacts with O atoms to produce Cl and O_2

$$ClO_{(g)} + O\bullet_{(g)} \longrightarrow Cl\bullet_{(g)} + O_{2(g)}$$

Overall: $O_{3(g)} + O_{(g)} \xrightarrow{Cl\bullet} 2\,O_{2(g)}$

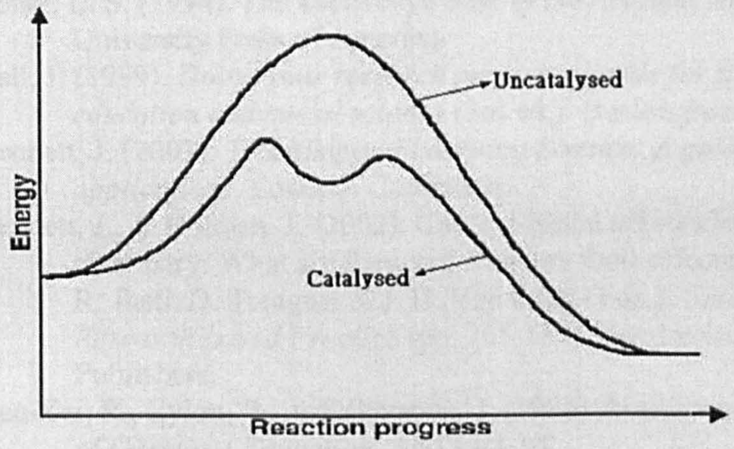

***Table A5.1** A multiple representation of the action of a homogeneous catalyst*

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