Impact of Process Safety Management Performance and Human Error on Off-Site Risk - A Comparative Study

Volume I - Thesis

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by

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Summary

The research described in this thesis provides a comparative study of the impact of Process Safety Management System (PSMS) performance and Human Error rates on off-site risk from two major hazards sites in Malaysia. One of the sites was built and run by a multinational company until a few years ago while the other was built and run by a local company since its inception. The sites handle bulk quantities of ammonia for downstream distribution. The study considers:

- the assessment of the sites PSMS performance using a structured audit technique
- the assessment of human error potential from ammonia road-tanker filling operations
- assessing the impact of site PSMS and human error potential on off-site risk from the sites
- investigating the possibility of linking the assessment of site PSMS performance with human error potential

Results of Quantitative Risk Assessment (QRA) conducted on the two sites showed a significant difference in terms of individual and societal risk when site specific PSMS performance and human error potential are taken into consideration. The use of site specific Management Factor (MF) and site specific Human Error Probabilities (HEPs) produces a significant impact on the results of the off-site risk as compared to estimates of risk based only on generic failure rates. This finding emphasized the need to consider explicitly the contribution of site specific PSMS performance and human error potential in major hazard risk assessment especially in developing countries like Malaysia where there exists significant differences on these factors between locally owned and multinational sites. The approach to link the results of the site specific PSMS performance audit with the assessment of human error potential was found to be inadequate to describe all the influences which will be exerted on the reliability of individual tasks involving human error potential.

Synopsis

The research described in this thesis provides a comparative study of the impact of Process Safety Management System (PSMS) performance and Human Error rates on off-site risk from two major hazards sites in Malaysia. One of the sites was built and run by a multinational company until a few years ago while the other was built and run by a local company since its inception. The sites handle bulk quantities of ammonia for downstream distribution. The study considers:

- the assessment of site safety management performance using a structured audit technique
- the assessment of human error potential from ammonia road-tanker filling operations
- assessing the impact of site specific safety management performance and human error potential on off-site risk from the sites
- investigating the possibility of linking the assessment of site specific safety management performance and human error potential

The Process Safety Management Systems (PSMS) at three major hazard sites were assessed using a structured audit technique called PRIMA. Two of the sites which are ammonia bulk terminals provided the venue for the case studies. The other site, a compound fertiliser plant which uses ammonia, was also audited to provide an additional PSMS comparison. The assessments involved site inspection, interviewing the management and workforce, observing the execution of hazardous tasks, verifying documents and analysing accident records. The results of the audit are presented in the form of management control loops which highlight the strengths and weaknesses of key elements of the PSMS for each site. A quantitative output in the form of a Modification Factor (MF) for each site is also determined. This factor is used to modify generic failure rates used for Quantitative Risk Assessment (QRA) in order to include site specific PSMS standard in the risk assessment. The audit assessments show that the three sites have different PSMS performance as defined by the PRIMA technique. Site A was assessed to have a Poor MF, Site B has an Average MF, while Site C has a Good MF. The study indicated a difference of about a factor of 10 in term of the PRIMA Modification Factor between the two extreme sites. This finding emphasised the need to consider explicitly the contribution of site specific management performance in major hazard risk assessment.

As the control of human error is an important aspect in process safety management a specific study on this subject was also conducted in an attempt to explore its relationship with the PSMS performance for each site. For this purpose ammonia filling operations at Site A and Site B were assessed, based on physical inspections of the filling system, interviews with the operators, analysing work procedures and observation of critical tasks with the help of video taping. A human error analysis technique, SLIM was used for the analysis, which identified a number of critical tasks that provide major contributions to human error potential in ammonia filling operations. The analysis also yields a quantitative output in the form of Human Error Probabilities (HEPs), based on the analysis of Performance Influencing Factors (PIFs) on these critical tasks. The tasks to connect and disconnect flexible hoses, and setting the target filling weight for the road tanker were found among the most critical to human error.

Quantitative Risk Assessment (QRA) was carried out on the two sites to determine the off-site risk from ammonia loading operations to a road tanker in the form of individual risk and societal risk. Information required for the QRA was gathered through the examination of plant layout, piping and instrumentation diagrams, physical plant inspections, analysis of the local weather and a determination of the population distributions. Two types of QRA approach were conducted. The first one used representative failure sets to study the impact of site specific PSMS performance on off-site risk. Initially a baseline QRA was conducted on each site using generic failure rates. Then the PRIMA Modification Factors (MF) were used to produce site specific failure rates which provide an explicit measure of the PSMS performance.

The second approach used fault tree modelling to decompose the failure events so as to include the human actions in carrying out the loading operation. The human error rates in the form of HEPs from a SLIM assessment were used as an input for the QRA. This approach models the effect of the site specific PIFs on human error rates. Additional runs were then conducted using nominal HEP values from THERP and HEART databases to compare the off-site risk results using these values which represent generic human error rates. A number of sensitivity runs were also conducted using HEPs derived from SLIM using different sets of calibration points to analyse the impact of selecting the different calibration points which represent one of the main uncertainties of using the technique.

Results from these two different approaches highlight the effect of PSMS performance and human error on off-site risk. The effect of considering site specific PSMS performance in conducting the QRA increases the off-site risk distance to a specified individual risk level of 10E-06 by a factor of 2 and 1.2 for Site A and Site B respectively, while the effect of considering individual human error contributions increases the off-site risk distance to a specified individual risk level of 10E-06 by a factor of about 1.2 and 1 for Site A and Site B respectively. The results show that both approaches predict similar effects for the influence of site specific PSMS performance and the site specific human error rates on off-site risk. The results also suggest that despite its global approach, the PRIMA technique is capable of predicting the effect of site specific organisational characteristics on QRA results, in a manner which is comparable to the more detailed approach of using fault tree modelling.

The study found that the site specific PSMS performance provided significant influence on off-site risk at the two major hazard sites. This suggested the need to consider explicitly its influences, especially in developing countries like Malaysia where there exist significant difference in PSMS performances, for example between locally owned and multinational sites. The PSMS laid down by the multinational company was found to have provided a positive contribution to PSMS performance for the sites under study. It also provided positive contributions in managing human error through better training, the retention of experienced personnel and good

operating procedures. However it is interesting to note that the influence of individual human errors on QRA is complex, because while human error increases system failure rates, people also provided mechanisms for recovery in the event of hardware failures.

The study also found that the PRIMA audit approach, the human error analysis technique SLIM and the QRA tool RISKAT were all suitable to be used for a developing country like Malaysia, with only minor modifications. It also found that QRA requires good site specific weather data as this strongly influences the outcome of the risk results, especially for toxic materials. It therefore stressed the need to develop good weather data which is quite scarce in developing countries.

An analysis was also made to link the results of the PRIMA audit with the assessment of human error. The aim was to utilise valuable information gathered through the structured audit technique for the quantification of site specific human error potential. However it was found that the PRIMA audit information can only assess performance at global or organisational level, and is inadequate to describe all the PIFs which will have an effect on the reliability of individual tasks which involve human error.

Finally the research has involved the application of knowledge from three distinct types of subject areas i.e. Safety Management Systems, Human Error Analysis and Quantitative Risk Assessment. It has explored the overlapping boundaries of the contributions between system hardware failures, human error and safety management on off-site risk. The comparative study conducted on two major hazard installations provided a means to investigate the interplay between them in a real world situation. The fact that the two sites under investigation were in a developing country, like Malaysia, provides further dimensions to the research.

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Moral support from my family has been instrumental in completing the research and they deserve my deepest love and gratitude. For my wife Ibah for her patience and perseverance. For my three children Juriana, Ilyana and Izzaty for keeping the house lively with their antics and I hoped they have enjoyed their stay here in Sheffield and made many new friends along the way.

Finally in the world full of uncertainty man could only at best explore what has been harmoniously designed by the Creator and stumbled along the way evidences of His greatness. While we can plan to anticipate the future as in the case of risk assessment, He is the only One who could turn the plan into a reality.

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List of Abbreviations

AIChE	American Institute of Chemical Engineers
APJ	Absolute Probability Judgement
CIMAH	Control of Industrial Major Hazards
EEM	External Error Mode
EPC	Error Producing Condition
FMEA	Failure Mode and Effects Analysis
FTA	Fault Tree Analysis
DOSH	Department of Occupational Health and Safety, Malaysia
HAZOP	Hazard and Operability Study
HEA	Human Error Analysis
HEP	Human Error Probability
HEART	Human Error Assessment and Reduction Technique
HRMS	Human Reliabilty Management System
HSE	Health and Safety Executives, U.K.
HTA	Hierarchical Task Analysis
IChemE	The Institution of Chemical Engineers, U.K.
IMAS	Influence Modelling and Assessment System
MCS	Minimum Cut Set
MF	Modification Factor
MHI	Major Hazard Installation
MORT	Management Oversight Risk Tree
NPP	Nuclear Power Plant
OSHA	Occupational Safety and Health Act, Malaysia
PEM	Psychological Error Mode
PIF	Performance Influencing Factor
PHEA	Predictive Human Error Analysis
PREI	Potential Risk Exposure Index
PRIMA	Process Risk Management Audit
PSMS	Process Safety Management Audit
QRA	Quantitative Risk Assessment
RISKAT	Risk Assessment Technique
SAM	System Action Management

SLI	Success Likelihood Index
SLIM	Success Likelihood Index Methodology
SPEAR	System for Predictive Error Analysis and Reduction
SRK	Skill, Rule and Knowledge
THERP	Technique for Human Error Rate Prediction
WPAM	Work Process Analysis Method

Chapter 1

Introduction

1.1 Research Topic

Impact of Process Safety Management System and Human Error on Off-Site Risk - A Comparative Study.

1.2 Background

As Malaysia moves rapidly towards industrialization there will be growing numbers of large chemicals, petrochemicals and petroleum processing plants known as Major Hazard Installation (MHI) being built in the country. This rapid growth unfortunately will bring about a very significant increase in the number of people, including both workers and members of the public who will be subjected to risk from major accidents arising from the plants operation. Major accidents of this nature have taken place all over the world such as at Flixborough, U. K (28 people killed) Bhopal, India (2000 people killed) and Mexico City, Mexico (500 people killed) as mentioned by Cox (1991). In Malaysia itself a number of similar incidents have also occurred, such as at Sungai Buluh, Selangor (23 people killed) (MHLG 1992) and Perlabuhan Klang, Selangor (13 killed) (MHLG 1994).

The Department of Occupational Safety and Health (DOSH) of Malaysia which was formerly known as The Factories and Machinery Department (FMD) of Malaysia is currently given the responsibility to regulate the operations of MHI in the country with the overall objective of ensuring an acceptable risk exposure to workers and the public at large from the plants' operation. One of the means to carry out the responsibility is by conducting process safety risk assessments on such plants. Risk assessment can systematically assess and measure the level of risk arising from the plant operations. The risk measures obtained then could be compared to a set of criteria to ensure that there is an acceptable level to the workers and member of the public in the vicinity. If the risk is found to be at unacceptable level a number of decisions has to be made. In the case of a new installation a strong advise would be given to the planning authorities to not allow the plant to be built at the present site, that would mean they have to look for a more suitable site, failing which it would not be allowed to built at all. As for existing installations order will be given to carry out modifications and providing better mitigative measures with the aim of reducing present risk to an acceptable level and at the same time giving advice to the planning authorities to stop further development intended for human occupation within the unacceptable risk zones.

So proper utilization of risk assessment results is very important for MHI in Malaysia in ensuring workers and public safety from the plants' operation. Underestimating the risk will put human lives and limbs at risk while an overestimates will deprive investors of suitable locations to locate their plants, resulting in loss of much needed investment and job opportunities in the country. Balancing both aspects has never been easy even in industrialized countries in Europe and the U.S. While risk assessment result is only one of the criteria in making the final decision, efforts to make the technique more accurate and transparent to the decision makers is always worth pursuing.

Traditionally, Quantitative Risk Assessment (QRA) was developed on a hardware and engineering based approach but lately human factors consideration are seen as at least an equally important determinant of risk. It is important issues to consider the extent to which human error is included and how organisational structure and management style affects the risk from specific plant (Hurst, 1989). In the hardware only approach of conducting QRA the issue of human factors is only being considered implicitly, i.e. by assuming the plant is manned and operated to so-called ‘industry standard’ which is supposed to be monitored by a regulatory body in a particular area.

In reality though the so called 'industry standard' may vary significantly as the enforcement activity and procedures differ. Most of the times it fails to differentiate the contribution of human factors both from human error and from the management style point of view.

Hence there exists an immediate need to consider human factors, i.e. the human error and the organisational and management factors in QRA. Currently there are few techniques has been developed to incorporate safety management system (PSMS) into QRA. Their application is at the moment mainly restricted to the U. K and some (on an experimental basis) in Europe (Hurst et al., 1993). The question whether they are applicable to developing countries which have different safety cultures is left unanswered. At the same time human error has been incorporated in fault trees for consequences analysis on an ad-hoc basis. There is no formal procedure as yet to fully incorporate it into QRA. Human error is likely to represent a major contribution to root causes of failures in process plant operations in developing countries thus attempts to analyse its contribution to QRA in an explicit manner on would be worthwhile. Finally, if the contribution of both human error and safety management system to QRA is found to differ significantly between two major hazards installations in developing countries like Malaysia, it could provide further evidence that the assumption that all MHI is operated and manned to the so called "industry standard" is not true. It would also serve as a means to validate whatever PSMS quantification technique is being used, this time in a different system climate of a developing country.

Under present circumstances the abovementioned area of research will only be made possible using a number of proven techniques that are currently available for QRA, PSMS quantification and human error analysis and quantification. Unfortunately most of the techniques are not in the public domain so the proposed research has to rely on cooperation from the proprietor of those techniques.

The University of Sheffield and HSE have been collaborating with each other in a number of research projects and postgraduate courses for a number of years. A memorandum of understanding exists between the two parties that allows researchers from The University to have some access to HSE facilities. Such an arrangement has made it possible to use two HSE in-house tools namely RISKAT and PRIMA for research purposes. Similarly a private consultant that has links with the University has agreed to allow the use of its proprietary human reliability quantification technique called SLIM for the research.

1.3 Problem Statement

The quantification of risk from major hazard installations using generic failure rate does not explicitly take into account the different performance of Process Safety Management System (PSMS) which exists at such plants. Since in reality there exist differences in PSMS performances between major hazard installations especially in developing countries like Malaysia, such an approach will result inaccurate quantification of risk of a particular installation. This will lead to inaccurate input made available to the decision makers (for example on siting issues for land use planning). More detrimental is the failures to identify weakness in a major installation's PSMS components that provide major contributions to the overall level of risks of the installation. If such components could be identified and expressed in a more explicit manner, there exist opportunities to focus on their improvements which in turn could significantly reduce the level of risk from a major hazard installation.

1.4 Research Goals

The overall goal of this research could be divided into two i.e.;

a) To compare the contribution of site specific PSMS performance on QRA of two MHI in Malaysia that handled similarly hazardous material but with significantly different style of management.

b) To compare the contribution of human error on off-site risk from a similarly hazardous operation carried out at both sites. For this purpose the off-site risk from ammonia loading operation to a road tanker will be assessed through the inclusion of Human Error Probability (HEP) in the analysis of the system failures.

c) To provide a linkage between the assessment of PSMS performance and Human Error potentials through site auditing. Such linkage will allow the site specific organisational characteristics that influence both factors to be assessed together in a single audit.

1.5 Research Objectives

There are several objectives to be met in order to achieve the overall goal of the proposed research. They are given as follows;

a) To test whether the existing technique developed in U.K. to quantify PSMS performance namely PRIMA is suitable for use in developing countries such as Malaysia by carrying out such an audit on two MHI in that country that handled similar types of hazardous materials.

b) To test whether the existing tool developed in the U.K. to conduct QRA namely RISKAT could be successfully used in developing countries like Malaysia.

c) To find out whether PSMS quality determined by PRIMA provides significant contributions to risk as being quantified using RISKAT on the two MHI.

d) To compare the difference of impact of PSMS on QRA that might arise from different style of management at the two MHI.

e) To test whether the human error quantification technique developed in the U. K namely SLIM could be used in developing countries like Malaysia by quantifying human error on a hazardous activity being carried out at the two MHI.

f) To compare the difference in results of human error quantification using SLIM on one of the most hazardous activity carried out, i.e. loading and unloading of hazardous materials at both MHI.

1.6 Hypotheses

1. There exists significant differences in the contributions of PSMS performance on QRA of two MHI in Malaysia that handles similarly hazardous material but with different style of management as quantified using the Management Factor technique.

2. There exists significant differences in Human Error Probabilities (HEPs) in the process of carrying out a similar hazardous operational activity between the two MHI as quantified by an established human error quantification technique.

3. The off-site risk level of MHI that has a better PSMS performance is lower as compared to the other MHI as determined plant wide using the Management Factor technique.

4. There exist a linkage between site specific PSMS performance and Human Error Probabilities that could be assessed through a same site audit that allowed their impact to off-site risk to be assessed together.

1.7 Conceptual Assumptions

Objectives set in the previous section could only be achieved by making a number of conceptual assumptions concerning a number of important factors that will influence its implementation. These assumptions are given as follows;

a) The three techniques selected to conduct the research namely PRIMA, SLIM and RISKAT represent proven and reliable techniques that have been adequately tested in a developed country, i.e. in the U.K.

b) Sufficient information and data are available to provide inputs to carry out Human Error quantification using SLIM, PSMS audit using PRIMA and to carry out QRA using RISKAT.

c) The two MHI selected for the research in a way represent the cross section of such installations in Malaysia as far as PSMS is concerned, i.e. one is managed by a multinational company while the other is managed by a local company.

d) The process systems at both MHI are quite similar and almost at the same level of technology even though the capacity and manning level might differ significantly .

e) Both MHI ammonia loading system are quite similar and almost at the same level of technology even though the capacity and manning level might differ significantly .

f) Both MHI has been built in the last ten years and has been continuously operated in the last ten years. This ensures that they were not subjected to a nationwide siting policy that has only been introduced lately with regards to land use planning.

g) Both MHI are not subjected to changes of ownership for the last three years. This ensures a continuous management style that has reached a maturity stage.

1.8 Research Method

The research is essentially a comparative study of two major hazard sites in Malaysia. As such the method adopted to conduct the study consisted of field work to collect the necessary information and data, and the analysis of data using established techniques for Process Safety Management System (PSMS), Human Error Analysis (HEA) and Quantitative Risk Assessment (QRA). The selection of specific techniques to analyse these subject areas will be discussed in Chapter 3. The techniques that have been selected for the analysis of each subject areas as follows;

- PSMS performance - PRIMA (Hurst et al, 1996)
- Human Error Analysis - SLIM (Embrey et al, 1984)
- Quantitative Risk Assessment - RISKAT (Nussey et al, 1993)

Baseline analysis will be conducted for each subject area that will serve as the reference points for comparisons. A number of sensitivity analysis will also be conducted to evaluate the effect of changing certain input parameters in an attempt to better understand the source of uncertainties. Results from the analysis for each of the subject areas will be compared within each site using the sensitivity analysis. They will also be compared between the two sites to look for evidence or indications as to how the site specific PSMS performance and Human Error influence the quantification off-site risk at the two sites. This evidence will provide some answer on problem statements that provided the foundation of the research.

1.9 The Thesis

This thesis is made up of eight chapters which when combined provide some evidences on what is the impact of PSMS and Human Error on off-site risk from MHI. The analysis is made possible using data and information collected during field audits and the use of a number of established techniques made available by a number of organisations. It also explores the possibility of linking the assessment for site specific PSMS performance and Human Error using a combined audit. A brief description of each chapter is given as follows;

1.9.1 Chapter 2 - Literature Review

Chapter 1 started with the current status of major hazard control in developed countries especially in Europe which is currently at the forefront in this area. It then focuses to the developing countries, Malaysia in particular where it is just at the infancy stage despite rapid growth in the production, handling and utilisation of large quantities of hazardous materials. Major problems that currently beset the control of major hazards are then discussed. The issue of using risk assessment as a predictive tool for decision making especially in land use planning is then discussed. One of the main issues in risk assessment, especially in its quantification process are uncertainties arising from the use of generic failure rate. In the real world the each major hazard sites is managed in a different way and operated by different groups of people so the application of a generic failure rate for QRA may not be appropriate. The chapter then reviews the management influence on risk, focusing specifically on PSMS. Critical review on the current approaches to incorporate management aspect into risk, their application and problems are presented. The influence of human error to risk especially for a quantitative assessment is then discussed. Current techniques in assessing human errors in the form of HEP are described, commenting on their strengths, shortcomings and applications. The discussion on QRA methodology then follows. It goes on to describe the Modification Factor approach to incorporate site specific management performance in the quantification of risk. Methods of incorporating human error in the quantification of risk then follow. The use of Human Error Probability (HEP) for risk quantification using fault tree decomposition is reviewed. The literature review managed to identify a number of 'gaps' that existed in the current effort to address the impact of management and human error to risk. They include the question of whether the current techniques of assessing site specific management factors and human error that have been developed for Europe are applicable in developing countries. Another gap is that since management factors include human activity, there must be common ground that links them with human error in influencing the risk from major hazard sites. These two gaps set the research direction for the thesis.

1.9.2 Chapter 3 - Research Methodology

This chapter describes the methodology in conducting the research. It starts by describing a comparative approach to assess the influence of management system specifically PSMS and human error on three major hazard sites in Malaysia. Selection of the three sites was made based on a number of criteria that would facilitate the objective to compare and contrast management influences on off-site risk between the sites. For comparing the influence of human error a similar hazardous activity needed to be selected which was undertaken at two sites under study. Based on the number of criteria being set the ammonia loading operation to road tanker activity was selected for comparison. As only two sites carry out this activity, comparison will be made between these two sites.

The selection of techniques for analysis is described next. For PSMS the PRIMA audit (Hurst et al, 1996) was selected to assess site specific PSMS performance in the form of a quantitative measure called Management Factor at the three sites. As for the human error the SLIM technique (Embrey, 1984) was used. As for the QRA the RISKAT software (Nussey et al, 1993) was chosen.

After identifying the sites and selecting appropriate techniques for analysis a field study will be conducted in Malaysia to collect necessary information and data for the their input. The field study is expected to last about 15 weeks in total for the two sites. The first part of the field study concerns conducting PSMS audit using PRIMA. The audit will involve site inspections, interviews with management and operators, reviewing relevant documents and making judgement on the performance of PSMS components. The second part involved the study of human error on ammonia road tanker loading operations. This study involved task observation with the help of video tape, talk through and walk through exercises with the operator, reviewing operating procedures, inspecting safety protection equipment, and analysing the task sequence with process systems available on-site. The last part of the study is collecting information for QRA from ammonia road tanker loading operation. This involved site inspection, detailed examination of piping and instrumentation diagram (PI&D), physical inspections on ammonia storage tank's equipment and piping, process safety fittings and traffic movement within the site. For off-site risk meteorological data, population distribution and ground conditions surrounding the sites will need to be collected. Information gathered from the field study will then be used to analyse the three major components of the research i.e. PSMS, Human Error and QRA. Result of the analysis is expected to indicate the influence of PSMS and human Error on off-site risk. It is also expected to clear up possible links between safety management and human error. While practical experiences in conducting the PSMS audit and Human Error will allow some findings to be made on the 'suitability' of PRIMA and SLIM technique usage in developing countries like Malaysia.

1.9.3 Chapter 4 - PSMS Audit on 3 Major Hazard Sites

Chapter 4 described the auditing of Process Safety Management Systems (PSMS) at three major hazard sites in Malaysia. The audits were conducted using a PSMS audit tool called PRIMA. The audits were carried out to fulfill a number of objectives which include the suitability and effectiveness of PRIMA, which was developed in Europe, to be use in developing countries like Malaysia. It is used to assess the PSMS on the three major hazard sites and to identify their strengths and weaknesses using the concept of management control as provided in PRIMA and to compare the differences in PSMS between the sites. A quantitative output from PRIMA known as a Modification Factor has been determined for each site to modify generic failure rates for Quantitative Risk Assessment (QRA). In general PRIMA was found to be a useful tool to assess the PSMS at major hazard sites in Malaysia. The structured questionnaires were comprehensive enough to draw out relevant information for a critical assessment of the PSMS. This information can be combined with a thorough site inspection and document verification to obtain a view of the overall situation of the site's PSMS and can be represented in the form of a control loop. The control loop enabled the state of the PSMS on each site to be summarised in a simple diagrammatic form that highlighted its strength and weaknesses. Key areas of strengths and weaknesses of the PSMS of each site will be briefly discussed. The study also identified some problems and shortcomings of PRIMA as an auditing tool for major hazard sites in developing countries like Malaysia. This included the need to provide adequate training for the assessors, the need to translate the questions to local language, and to balance the requirements for written document with the complexity of the process and size of sites under review.

1.9.4 Chapter 5 - Human Error Analysis on Ammonia Loading Operation

The control of human error is an important element in process safety since various studies have shown that it is one of the largest single contributors to accidents. This chapter describes predictive human error analysis on ammonia filling operation to road tanker at two ammonia bulk terminals in Malaysia. The first part of the study involved a qualitative approach using the Hierarchical Task Analysis (HTA). This approach is used to identify critical tasks in ammonia loading operations and their associated Performance Influencing Factors (PIFs), predict human errors and their consequences and finally provide appropriate error reduction strategies. The second part of the study involved the human error quantification analysis. Critical tasks identified in the qualitative analysis were quantified using the SLIM technique that generated Human Error Probabilities (HEPs) for each task. The probability figures were used to rank the critical tasks as well as input to QRA. The study has identified a number of task induced human errors in ammonia filling operations that could be reduced by proper management control. Findings from the study also indicated that the site specific PSMS performance exerts significant influence on the way human error contributed to accidents in carrying out a hazardous operation.

1.9.5 Chapter 6 - Quantifying Off -Site Risk from Ammonia Loading Operation

This chapter involved the process to estimate public risk arising from Site A and Site B operation in handling bulk quantities of toxic gas i.e. anhydrous ammonia. Result of the risk estimates is to be compared with a specified public risk criteria in this case will be the probability of fatality to an individual (individual risk) and to the public (societal risk). The chapter started by putting down the objectives of conducting the QRA which includes;

- to estimate off-site risk to members of the public surrounding the site
- to estimate the impact of site specific PSMS performance to off-site risk using PRIMA Modification Factors

- to compare the risk estimates found on Site A with Site B to identify the key management contributions

It then described the approach taken to conduct the QRA for the study;

- identifying potential leaks and major releases from fractures of process pipelines and vessel
- estimating the frequency (failure rate) of the Top Event which was associated with major releases using fault tree analysis
- modifying the generic failure rate with site specific Management Factors (MF) as obtained from PRIMA audits
- incorporating key human failure rate in the form of Human Error Probability (HEP) together with equipment failure rate in fault tree analysis

The analytical technique used for the analysis includes Fault Tree Analysis using Fault Tree Manager (AEA, 1994) computer code - for event frequency estimation, RISKAT Computer Code for QRA which facilitates the calculation for release rates, gas dispersion analysis, hazard ranges and fatality probability (Hurst et al, 1989) and the PRIMA Audit technique to calculate the Modification Factor for generic failure rate.

The chapter describes significant findings based on the experience of conducting the QRA as well as results of the analysis. They includes;

- The site specific weather data is one the most dominant factors influencing the off-site risk level at the two sites.
- QRA runs using FTA that takes into consideration the hardware failures and HEPs showed a lower off-site risk value as compared those which only consider hardware failures.
- Site specific PSMS performance provides significant impact on off-site risk at the two sites. PRIMA Modification Factor can be used as a means to explicitly consider the of effect site specific management influences.

1.9.6 Chapter 7 - Using PRIMA as an integrated audit for PSMS and HEA

This chapter described an analysis that looked into the possibility of integrating PSMS audit and Human Error Analysis using the PRIMA technique. The analysis looked at some common attributes that essentials for both PSMS Audit and HEA, mainly in the form of some organisational factors such as procedures, training, stress, communication and feedback, and hardware factors such as operator/equipment interfaces, personal protective equipment (PPE) and process safety system. As the existing PRIMA Audit questionnaires assessed these attributes, its findings could be used not only to assess site specific PSMS performance but also to assess the influence of site specific PIFs for HEA. Results of the analysis found that the PRIMA audit questionnaires were found to be able to address a number of areas that provided basic information to determine the overall or 'global' PIFs, at least for the four common PIFs under consideration. However it is less rigourous as compared to the dedicated PIF analysis such that has been carried out in Chapter 5. However for the purpose of quantification using the SLIM technique, such information is adequate to assist in assigning appropriate weighting of the overall PIFs influence on each site. Further investigation is needed to look at the existing PRIMA Audit structure to find out whether it is capable to accommodate other components of HEA.

The attempt to link the PSMS audit results with HEPs analysis found difficulties as the audit could only assess the site specific PIFs at the management (global) level. As PIFs influenced differently for a different task a global assessment of PIFs was found to be inadequate.

1.9.7 Chapter 8 - Findings, Conclusions and Suggestions for Further Work

The last chapter summarised major findings and conclusions found from the study as well as suggested further work that could be useful to support the outcomes of the research. This chapter started with the discussion on the overall findings from the study. Discussions on these findings on specific subjects are put under main headings on PSMS Audit, Human Error Analysis and QRA. The discussion highlights significant findings from results of the analysis of each subject as well as from the practical experience in carrying out the analysis. The PSMS audit technique PRIMA was found to be useful in providing a structured and efficient means to assess site specific PSMS performance. The PRIMA audit results showed a significant difference in site specific PSMS performances which between the good and the worst site showed a difference of about a factor of ten. However a number of shortcomings were identified and were suggestions provided to make the technique more compatible with developing countries' situation. The Human Error Analysis using SLIM technique was found to be capable in identifying the critical tasks that heavily influenced by human error, and to quantify the probabilities of human error that could lead to major releases of ammonia. RISKAT was found to be quite effective in conducting QRA for off-site risk from major releases of ammonia. The QRA results showed site specific PSMS performance as being quantified using PRIMA technique exerts strong influence on off-site risk on each site under study. This finding supports the need to consider site specific PSMS performance in conducting QRA. The results also indicate that Human Error in the form of HEPs provided considerable influences on risk results.

Conclusions derived from the study are centered around the main objective of the study that is to compare and contrast the management and human error influence on off-site risk between the two sites that has a quite different PSMS system and performance. Finding from the study found that both factors provided significant influences on off-site risks for the two sites. This finding supports the need to consider the two factors explicitly when conducting QRA for off-site risk at major hazard sites. Other conclusion related to the suitability of a number assessment technique that are primarily developed for usage in the developed countries performed in a developing country environment. The PRIMA technique used to determine the PSMS performance, the SLIM technique used to analyse Human Error and The RISKAT computer code used to conduct the QRA which were develop primarily for usage in the European theatre was found equally suitable to be used in a developing country like Malaysia, albeit with some modifications. Finally the attempt to integrate PSMS and HEA audit through PIF from the PRIMA audit is only partly successful at the global level PIFs

Suggestions for further work include conducting a similar study on major hazard sites in other developing countries. If time and resources permit more major hazard sites should be studied in order to compare findings from this study that was based only on two sites. The application of other techniques for PSMS audits, Human Error Analysis and QRA should be considered if other techniques are made available. Finally a suitable framework should be developed to integrate the assessment of site specific PSMS performance and Human Error as both aspects are related to each other in some way. Such a framework will allow the interaction between the two and how they influence the off-site risk be established.

Chapter 2

Literature Review

2.1 Introduction

Essentially the proposed research is expected to cover three distinct subject areas, namely PSMS, HEA and QRA, each of which on its own is a very comprehensive subject. So the literature review will not attempt to discuss each subject in its entirety, but to highlight the links that exist between them, the gaps that still exist and the future direction of research areas as indicated by various researchers. This chapter mainly provides critical reviews of the current situation which deals with PSMS, HEA and QRA with the emphasis on the incorporation of management and human error influences to risk assessment. Such review aims to set the scenario of the proposed research and show the direction for its implementation.

2.2 Current Situation on Major Hazards Control in Malaysia

Malaysia has a fairly comprehensive regulatory system to ensure safety and health at work places. Through The Factories and Machinery Act 1967 (FMD, 1967) and the new Occupational Safety and Health Act 1994 (DOSH, 1994) which is based on the U.K Health and Safety At Work etc Act (HASEWA) (HSE, 1974) the safety and health of workers at work being regulated throughout the country. There are many regulations made under both Acts, which provide detailed requirements on specific areas such as boilers and pressure vessels, competency of persons in charge and the registration of places of work, just to name a few. For hazardous installations such as petroleum, petrochemicals and chemical plants specific regulations called The Control of Industrial Major Accidents Regulations (DOSH, 1995) which is based on the U.K CIMAH Regulations (HSE, 1995) is currently in place. Similar to the CIMAH Regulations a new major hazard installation is required to present a safety case or a safety report to the authority, i.e. DOSH before given the approval to operate. However the Malaysian CIMAH Regulations require the owner of such installations to consult a competent person or a competent company which is authorised by the authority in the preparation of the safety case. This requirement is to ensure that the owner or the operator of a major hazard installation will be given proper assessment of their sites by a responsible expert, especially those run by small time operators.

One aspect of regulatory activity which is quite unique to Malaysia as compared to other countries like the U.K, is direct involvement of the authority in ensuring the safety at potentially hazardous plant and equipment, such as boilers, reactors, distillation towers and other pressure vessels. This is being carried out by reviewing the design, checking the fabrications, conducting hydrotest, witnessing commissioning and carrying out annual inspections on each vessel for 'fitness for purpose'. Such a system ensures to a certain extent the integrity of such vessels on the aspect of design, fabrication, operation and maintenance. Records showed that such an inspection system has contributed to low incidents of overpressure, explosions and loss of containment of these hazardous vessels especially those operated by small and medium size operators (DOSH, 1996).

However there are other areas which are not regulated in such an explicit manner, yet could significantly contribute to the overall risk from a major hazard installation. Areas like safety management system, operator's skill and qualifications, the control of human error and the overall system reliability still much left to the operators to implement. This situation to a certain extent resulted in different systems being adopted by each MHI operator with different end results. Those who have adopted a good system will benefit from good PSMS performance while those who have not will suffer from low PSMS performance. Similarly from human error point of view MHI operator which implement an effective human error reduction strategy will benefit from low incident rate that contributed to human error while those who do not.

2.3 The Application of QRA for Major Hazards Control

The unfortunate events resulting from major hazards incidents that occurred around the world have prompted the need for an effective control system. The major accidents that have took place in Saveso, Flixborough, Bhopal and Mexico City, and Piper Alpha has increased the public awareness which in turn have put pressures on various governments to provide legislative measures to prevent such accident from taking place.

In Europe, the EC Directive (CEC, 1982) provided the basis for such legislation. The Directive requires that safety studies of major hazards have to be carried out. In some European countries like the Netherlands the safety studies must include quantified risk estimates (Jensen, 1992). Other countries like Germany do not use probabilistic method, instead rely on consequence analysis to assess safety distance and protective measures (Pasman, 1995). The Health and Safety Executives (HSE) in the U.K uses tolerability criteria of risk for land planning purposes (HSE, 1989). They have used QRA in a number of studies involving major hazard sites such as Canvey Island (HSE, 1978). They also carried out studies on the transportation of hazardous goods by rail, road and water that involved QRA (Purdy, 1993). After the Piper Alpha incident, Safety Cases for off-shore installations became compulsory in Norway, The U.K and The Netherlands (Jensen, 1992). In the U.K. for example the HSE use quantitative risk estimates to advise the Local Planning Authorities on planning permission (HSE, 1989). Other European countries like Portugal and Greece do not specify specific requirements for QRA (CEC, 1995).

The control of Major Hazards in the U.S. takes effect through a number of separate legislation such as the OSHA's Process Safety Management of Highly Hazardous Materials (OSHA, 1993) and the DOE's Nuclear Safety Analysis Report (DOE, 1992). Both regulations, while they do not specify specifics requirements for QRA, require adequate analysis be carried out to reflect the level of risk at the facility under consideration (Deshotels et al, 1995).

In Australia, the New South Wales Government included the use of risk assessment criteria as guidelines for land use safety planning (DOP, 1990). Quantitative risk assessment criteria covering cumulative risk levels for individual fatality, injuries, property damage and accident propagation are provided by the guidelines. Results of the risk analysis is assessed against the criteria to assist the decision making process for land use safety planning (Schubach, 1995).

Meanwhile in Malaysia the major hazard control is provided by specific legislation called The Control of Industrial Major Accidents Regulations (DOSH, 1995). The regulations requires 'top tier' major hazard installations (MHI) identified through the type and quantity of hazardous materials to prepare safety cases demonstrating their safe use. This included the use of quantitative measures where appropriate.

2.4 Current Approaches of QRA

QRA is a methodology for assessing and improving the safety of a technology. The methodology entails the construction of possible chains of events called ‘event tree’ which lead to unwanted consequences or working backward, constructing chains of faults called ‘fault tree’ in search for accident precursors. The risks are quantified by calculating an estimate of probability of these event or fault sequences and combining this with an estimate of consequences (Tweeddle, 1992).

This method was introduced as an alternative to deterministic methods which have been the basis of most safety criteria in the past, for example the use of a single criterion and the fail-safe principle. The weakness of a deterministic approach is that it adopts conservative assumptions, and consequently focuses on worst case accident scenarios which provide an unrealistic picture of the safety system and give little evidence on the relative ranking of safety improvements (Bayer, 1991).

The American Institute of Chemical Engineers (AIChE, 1989) described ten components of QRA. They are;

1. QRA Definition: deciding on study goal and objectives
2. System Description: compiling of all technical and human information needed for the analysis
3. Hazard Identification: identifying hazards that could arise from the system using techniques such as HAZOP, FMEA, Fault Trees and Event Trees.
4. Incident Enumeration: identifying and tabulating of all events or incidents without regard to their importance or to the initiating event
5. Selection: selecting significant incidents and identifying incidents outcome
6. QRA model construction: selecting appropriate consequence models and their integration to the overall algorithm to produce risk estimates for the system under study
7. Consequence estimation: the methodology used to determine the potential for damage or harm from specific incident
8. Likelihood estimation: estimating the frequency or probability of occurrence of an incident
9. Risk estimation: combines the consequences and likelihood of all incident outcomes from all selected incidents to provide a measure of risk
10. Utilisation of risk estimates: utilising results from risk analysis for decision making

For large plant with complex process and technology the execution of QRA components that has been described above becomes tedious and time consuming. Hence there a need to develop computerized methods to accelerate the derivation of risk estimates needed for decision making. As the outcome a number of computer codes were developed in an attempt to address the problem such as SAFETI and RISKAT.

RISKAT (Nussey et al, 1993) was developed by HSE initially for major toxic hazards and later was refined and extended to flammable hazards. As it is not commercially available its use is restricted within HSE and some other research institutions. SAFETI (DNV, 1994) was developed by Technica Ltd. for the Dutch Government and later was commercialised and used by quite a number of organization throughout the world. There are other software being developed for the same purposes but they are either not as complete as these two or have not matured yet to gain wide acceptance.

The procedure which is used by RISKAT to calculate risk from major hazards can be broken down into a number of steps (Pape and Nussey, 1985);

i. Analysis of the major hazard plant, its control and safety system, and operational procedures so that a representative number of hypothetical releases with the potential to affect workers and the neighbouring populations can be identified.

ii. For each hypothetical release the chance that such an event will occur in a given time period is determined either from historical failure statistics (so-called generic failure rate data) or by synthesis from basic component failure rate data using well-established techniques such as fault tree analysis.

iii. For each release case, estimates are made of the rate of release of hazardous material and duration of the release.

iv. For toxic, and certain type of flammable releases, calculations are made of the atmospheric dispersion of hazardous material in various weather conditions. For flammable releases the chance of immediate ignition at the source is also considered. Delayed ignition is treated in terms of predicted concentration level within a drifting cloud or plume of flammable material and the likelihood of an ignition source being encountered.

v. These dispersion, explosion and flammable calculations enable the spatial and temporal variations in the effects, for example toxic gas concentration, thermal radiation, extent of fire zone and overpressure of the hazards to be mapped out.

RISKAT in essence calculates the chance of a hypothetical individual receiving at least a specified criterion dose of the toxic material, a specified dose of thermal radiation, or a specified level of overpressure at a particular location (Nussey et al, 1993). These doses in principle can be converted into probabilities of fatality or some specified level of injury. One of the common methods uses for this purposes is the 'probit' relationship (Finney, 1971). The probit relationship links dose with probability of death or some other level of injury which allowes the level of risk to an individual of receiving at least the specified dose be calculated and known as 'individual risk'. If such risk estimates takes into account the number of people in the surrounding areas that could be affected by an incident the risk measure is called 'societal risk' (IChemE, 1995). The societal risk normally presented by a probability in any one year, F, of an event affecting at least a certain number, N, of people forming the FN curve.

Risk quantification exercises require significant amounts of data. So ideally when applying QRA to a specific operation, a specific data base for the study must be created from new and existing data bases. The types of data bases required include equipment failure rate, human error, toxicity, ignition, external event, meteorology, and location specific data of the nearby population (AIChE, 1989). These data could be obtained from a number of sources such as from existing data banks, from plant experience, using predictive techniques, and from expert opinion (Skelton, 1997). In the U.K. the National Centre of System Reliability (NCSR, 1990) is the largest reliability data bank which contains failure rates for various failure modes, time dependencies of failure rate and the predicted effect of preventive maintenance or condition monitoring. For accident and incident data the MHIDAS maintained by AEA Technology U.K. (previously Safety and Reliability Directorate) and FACT maintained by TNO Division of Technology Society, The Netherlands provided major hazard incident data. In the U.S. the WASH 1400 Report (US Nuclear Reliability Centre) and NPRD 91 Database (Reliability Analysis Center, New York) provided reliability data that could be useful for chemical and process industries.

However the application of such data may not be representative to developing countries as they are mostly obtained from developed countries which have different operating conditions, level of inspection and maintenance, and operator skill and experience. So ideally a comprehensive country specific data base would be the best sources of data. While the accuracy of the QRA may not be significantly affected for certain data bases like the failure rate, the effect of not using local weather data could be severe, for example for toxic releases (Marshall et al, 1995).

The strength of QRA lies in its ability to decompose complex systems and extrapolate failure rates derived from historical operating data on the component parts such as vessels and pipework. Experience has shown that QRA methodology is well suited for identifying safety improvements in plant design and operations, for regulatory compliance, as well as for general safety purposes such as land siting and environmental impact statements. The technique has been used extensively in the aerospace, electronics, nuclear and chemical process industries to quantify the likelihood of either a specific incident of event of a sequence of event (Cox et al, 1992)

There are a number of weaknesses in the current approach of QRA. They can be divided into technical limitations and management limitations (AIChE, 1989). The technical limitations is mainly due to the many sources of uncertainty at all stages of the risk assessment process. They include incomplete enumeration of incidents, improper selection of incidents, unavailability of required data, and uncertainty in consequences and frequency modelling. Management limitations include lack of resources (personnel, time and tool) and inadequate skill to perform the analysis.

Another apparent weakness of the current approach of QRA is that it only addresses the 'hardware' component of the process system such as vessels and pipework while assuming the 'software' aspects such as human error and organisational and management factors of at an 'average industry standard' (Jeremy and Hurst, 1992). Then the utilisation of generic failure rate for hardware failures are assumed to implicitly include the contributions of the software aspects. Given the scenarios of MHI which consists of a wide range of different process with different technology, and with different organisational and management style and quality, the implicit approach is not satisfactory. In some cases the use of generic failure rate data could give misleading risk estimates (Smith, 1994). Despite the weaknesses associated with QRA, its numerical approach of evaluating risk could lead to better understanding of the system particularly through the enumeration of incident scenarios, hazard identification, and human response to emergencies, allowing the benefit of risk reduction strategies for example to be measured (Allum et al, 1993).

2.5 The influence of PSMS on QRA

According to Hurst (1989), Quantitative Risk Assessment (QRA) has traditionally been developed on a hardware or engineering based approach but increasingly human factors consideration are seen as at least equally important determinants of risk. It is an important issue to consider the extent to which human error are included and how organisational structure and management style affects the risk from specific plant. Kuo (1994) is of the opinion that the identification of hazard for risk analysis and reduction tends to be seen as an engineering task, but for the effective treatment of safety there is a need for the incorporation of the PSMS. More often than not the roles of management and human error in safety are often not fully understood (Tweeddle, 1992). Hence there is a need to address the effects of PSMS in risk analysis as well as to measure the human error contribution on the overall risk arising from hazardous plant operations. If an effective method could be established to relate human error to PSMS, and PSMS to risk analysis, it would allow more accurate assessment of risk from a hazardous plant to be carried out.

There have been a number of attempts to look at managerial influence on safety. A study by Suokas (1988) identified eight characteristics of companies having low incident rates, one which relates directly to management commitment to safety. Whaley and Lihou (1988) mentioned two techniques namely MORT and Statement Analysis that can be used to identify the contribution that management made to an accident or the current standard of management structure within the organization. Ratcliffe (1993) described STATAS, an in-house technique developed by HSE to assess safety management systems by systematically looking into the management activities and in particular evaluating the effectiveness of management control loop.

Phang (1994) in her survey of safety audit techniques found out that a number of techniques did provide some means to evaluate safety management system effectiveness in qualitative form. Most of these technique like ISRS, SHARP, CHASE and LETSA are looking at some important factors in PSMS such as health and safety policy, management structure, management of hazardous substances and training at various levels of depth. ISRS for example provides a systematic analysis of a safety management plan at a particular installation. The principal objective is loss control on an existing plant by the identification of critical deficiencies in all elements of the health and safety plan. A points system is used to evaluate each safety element.

2.6 The quantification of PSMS influences

As QRA gained considerable acceptance by the regulators and the operators the need to look at the possibility of quantifying the management influence arose when the industry started to query the application of generic failure rate to all plant and companies despite management differences when carrying out the QRA. It is common that for a consideration of the QRA, plant hardware and the performance of its PSMS be kept quite separate because while the interlocking between them is well appreciated it is not well understood (Hurst, 1993). As a result in the last few years there has been growing interest to measure or quantify the quality of an organisational PSMS and its effect on the outcome of QRA being carried out. In the U.K a number of audit systems have been developed in an attempt to analyse how management and organisational factors contribute to accidents or incidents.

The MANAGER audit technique (Pitblado et al, 1990) was the early solution to this problem and was based on consideration of major causes of accident where system failure had occurred. It is based on audit questions that have been developed under major causal categories, experience and data gathered from various sources. The quantification process was developed from a combination of the auditor's evaluation, and a risk modifications formula derived from both expert judgement and an examination of the ranges of failure rates of component. The technique concentrates on four main areas of sociotechnical influences that influence safety management i.e. system norms, pressures, resources and communication. It is based on a review of the role of safety management to actual accident causation within the chemical process industry. The technique attempts to provide both a qualitative overview of site safety management and an indication of quantitative modification to generic failure frequencies (Williams and Hurst, 1992). The strength of this technique is in its investigative approach which could provide a snapshot of the performance of SMS and provide an organized set of recommendations given reasonable time and resources. It weaknesses lay on the fact that equal weighting given to each question, the nature of the quantification process and the uncertainty whether all relevant areas are covered. The results of applying MANAGER have produced findings indicating that PSMS influences could reduce risk estimates based on generic failure rate data.

The quantitative technique developed by Health and Safety Laboratory of HSE which hereafter is called PRIMA, is based on an audit system with a demonstrable statistical and theoretical basis to quantify the quality of PSMS at a plant and link this into the QRA being carried out (CEC, 1995). The statistical basis is based on an analysis of reported incidents involving failure of fixed pipework and vessels on chemical and major hazard plants. A 3-Dimensional classification scheme was developed which classifies direct causes, underlying causes and failures of preventive mechanisms. This scheme provided an objective quantitative model on which to base a PSMS audit which emphasized loss-of-containment accidents as opposed to occupational accidents. The theoretical basis is based on the Sociotechnical Pyramid Model of the effects of PSMS, and the general climate within which it operates on failure rates. It explores increasingly remote system failures through engineering reliability to organization and management, communication and control and system climate. This theoretical model is based on authoritative texts on chemical plant risk management, conventional organization and management theory, and management of quality and consideration of major accidents and system failures (Hurst, 1991). PRIMA have been used by HSE Factory Inspectors to audit PSMS and to quantify it for QRA on a number chemical plants in the U.K. It is also being used on a trial basis by a number of European countries under EEC funding (CEC, 1995).

The University of Surrey, Department of Psychology developed the so-called Management Factor Technique which evaluate the contribution of human and social factors to hazardous occurrences in the chemical and petrochemical industry. The technique essentially consists of questions developed using expert judgement and review of incidents, which relate to management factor contributions. An assessor would visit a plant and make a rating on each of the questions for that plant. This rating would be multiplied by weighting coefficients, reflecting the relative importance of the questions, prior to calculating the final management factor (Bellamy, 1990).

The management factors determined by an audit technique such as PRIMA or MANAGER could be used to provide input into QRA in three areas;

a) Modification of generic failure rate.

b) Modification of release parameter.

c) Modification of impact on the population.

From the literature it appears that the first area, i.e. the modification of generic failure rate seems to be favoured by current researchers to include the MF in QRA. Hurst (1989) described two approaches in modifying the generic failure rate. They are;

i) The implicit approach

This approach assumes that the installation is manned at least to the average standard that is supposed to be monitored by regulatory agencies. QRA is then carried out on hardware only using generic failure rate data which incorporates component failure rate from all causes 'including' human error. The advantages of this approach is that difficult judgements about issues of adequacy of management do not need to be quantified , it is easy to appreciate and not open to criticism for arbitrariness.

Nevertheless the implicit approach is 'conservative' since failures rates are taken from the generic failure rate probably less than the average plant standard. A refinement to this approach could be made by the use of engineering judgement to modify the generic failure rate to the condition found at the plant. Assessors might include an adjustment to failure rate to allow for some deviation from 'average' of the overall quality of the safety management at the installations.

ii) Modification of Risk.

In this approach the 'hardware only' QRA is used to calculate the 'average' risk for a site given details of chemical inventories and hardware data using generic failure rates. The risk figure is then 'modified' in a formal way on the basis of a site specific audit to take account of wider issues. Essentially this formalizes the method of using engineering judgement. This method improves the 'transparency' of QRA by making the assumptions in the method explicit and thus enables a broader consistency of approach to be adopted. It also allows the cost and benefits of improvement to be quantified, across a wider range of influencing factors rather just hardware failures. Its weakness is that the level of judgement depends on the experience of the assessor which could lead to inconsistency and be open to criticism. Nevertheless according to Hurst (1991) some of the weaknesses of the modification of risk method could be overcome by using the 3-Dimensional classification scheme as described earlier.

By combining the statistical basis and the theoretical model, a comprehensive question set could be developed to cover the main underlying causes of failures and failures of management control system. Hence a distinction could be made between an operating error which is a direct cause of failure leading to loss of containment, and a safety management failure which may be both underlying cause of a failure or failure of a potential preventive mechanism.

While the quantification of PSMS has been carried out on quite a number of installations using various techniques such as PRIMA and MANAGER, very few comparisons have been made to validate whether these techniques could really differentiate the influence of PSMS performance on two similar plant. Jeremy and Hurst (1992) conducted a study in this direction by comparing the management effectiveness of two technically similar major hazard site using MANAGER. The sites selected operated practically identical plant, possessed similar toxic inventories, had high daily throughputs and required the highest level of product quality control at all times. The comparative study was aimed to make unqualified prediction of the computed Management Factor (MF) difference that might be observed between the two sites. Findings from the study has shown that the technique was able to predict an overall difference by about a factor of two in relation to the safety management performance and this was found to be highly compatible with observed safety performance. This suggests that it may be possible in the future to discriminate between the safety management effects of individual organisations in relation to assessment of MHI. They have suggested that similar studies be conducted in order to support the finding.

2.7 The Contribution of Human Error to Risk

The contribution of human error to accidents has been realized way back in the 60s. Kriliss (1962) found out from his investigation that almost seventy percent of plane crashes in the USAF over a period of time was due to human error. In the nuclear industry, empirical and analytical studies have shown that human error contributes significantly to accident at nuclear power plants (Barnes, 1990). The Health and Safety Executives (HSE, 1989) in their publication on Human Factors has indicated that as many as 90% of workplace accidents in the U.K had a contribution from human factors. Gano (1987) found out based on studies by United States BWR utilities and INRO, that 36% of root causes of incidents are due to human error. Even root causes categories under procedural and equipment failures have human contribution. Hurst (1993), in a study on causal contribution of safety management failures based on an extensive database and pipework failure, found out that the contribution of human failures from operation and maintenance activities is between 25% to 30% of the overall causes of failures. The many examples has prompted Watson and Oakes (1988) to conclude that human reliability and its quantification is a central and important aspect of reliability and risk assessment.

Since risk assessment is now widely being used to assess the potential hazards posed by MHI, any attempt to evaluate the contribution of human error would increase the transparency of such assessment and provide valuable information on the means of how to minimise it. In this respect, a distinction could be made between operating error which is a direct cause of failure leading to loss of containment, and a safety management failure which may be both an underlying cause of failure or the failure of a potential preventive mechanism.

According to Watson and Oakes (1988) the term "human error" is used to cover many different situations and events, including error of management decision, design and maintenance, and most particularly operators. The Kennedy Report (1979) described the interplay of a large number of managerial, organizational and regulatory root causes in the Three Mile Island Incident. Kletz (1985) has also provided numerous case studies which illustrate the ways which human error at various levels of an organization can give rise to a major disaster. Recent disasters including Bhopal, Chernobyl and Piper Alpha, have showed the importance of managerial and organizational factors in accident causation (Pate-Cornell, 1992).

Accidents and major losses in chemical process industries seldom arise from a single human factor or component failure (AIChE, 1994). Most of the time it is a combination of some triggering events (hardware or human) coupled with pre-existing conditions such as design error, maintenance failures or hardware deficiencies. Therefore it is important to distinguish between active and latent errors of failures. An active human error has an immediate effect in that it either directly causes a hazardous state of the system or is the direct initiator of a chain of event which rapidly leads to the undesirable state. The latent failures on the other hand can occur at the level of engineering design or management policy.

The degree of which a system i.e. ammonia loading operation is vulnerable to human error is one of the principal determining factors in deciding the level of analysis required (Kirwan, 1994). If the system critically depends on human reliability for safe operation, and which involves potentially large losses e.g. in term of lives, then a full investigation of human contribution to the level of risk is justifiable. Perrow (1984) defined three factors which can be considered in setting the scope for HEA i.e. complexity, interactiveness and coupling. According to him a system which is complex, highly interactive and tightly coupled will require an intensive risk analysis and in turn needs an in- depth HEA.

2.8 Qualitative Analysis of Human Error

Early human reliability methodologies were dominated by behavioural psychology, and measurements were taken of simple stimulus or response tasks to the exclusion of higher level decision making and problem solving tasks and out of context of the overall system. The behaviourist view of human as a mechanism (or a machine) fitted in with the way in which the human component was modelled in most system reliability assessments as being described by Hagen and May (1981). Here human error is treated as a factor in system reliability and needs to be seen as a process itself. Probability data on required task performance were feed into conventional fault tree analysis in the same way as hardware component failure probabilities. Then whether this error could be recovered, and if it cannot be recovered what would be the consequences that will affect the overall system reliability are considered.

Looking from a system context, human error could be defined as a failure of the part of a human to perform a presented act (or the performance of a prohibited act) within specified limits of accuracy, sequence, or time, which could result in damaged equipment and property, or disruption of scheduled operation (Hagen and Mays, 1991). While Park (1981) defined it as the probability of error free performance within a specific period of time. Both of the descriptions are essentially looking at a human error from human factors engineering or ergonomics perspective. This approach is concerned with the 'external' mode of human error (External Error Mode - EEM), such as error of omission, error of commission and extraneous error (Swain and Guttman, 1983). It could be easily applied to the technological system such as NPP and offshore installations despite lack of a sound theoretical model (Kirwan, 1994).

Rasmussen (1986) challenged the behaviourist thinking. He reviewed a large number of incidents and accidents reported from nuclear power plant, chemical plant and aviation industry and made the observation that 'operator error' only makes sense when they were classified in term of the mental operations being utilized in the task. His resulting model called Skill, Rule, and Knowledge (SRK) based model of 'cognitive' control has become a market standard within the system reliability community in assessing work place reliability (Cox and Tait, 1991). Norman (1988) highlights two fundamental categories of error; slips and mistakes. Slips are results of automatic and routine action under subconscious control, while mistakes are results from conscious deliberation. Although a number of cognitive models have been developed, Rasmussen's is probably the only model that has achieved wide spread acceptance (Kirwan, 1994). This approach goes beyond the EEM and look further at the 'internal' mode of human error which is known as Psychological Error Mode (PEM). Human error taxonomy based on this approach has been proposed by HSE (1989) which comprised of 5 types of human error namely; misperception, mistake priorities, attentional lapse, mistake action and willfulness, and finally violation and sabotage.

Reason (1990) extended the SRK framework to form the basis of a generic error modelling system (GEMS). The system provides a conceptual framework within which to locate the origins of basic types of human error. It integrates two different areas of error research; slips and lapses in actions deviate from current intentions and mistakes, in which action may run according to plan but where the plan is inadequate in some way.

However, concern for the reliability of specific systems (more generally the management of safety) requires the error to be classified and explained in the context of the work process. This approach has been suggested by Meiser (1971) and Rasmussen (1986). Such context dependent taxonomies have to consider the role and the interplay of task, technological and organizational as well as individual process. Mapping taxonomies of error onto the work process opens up the possibility that error may be usefully reviewed in different ways in relation to different aspect of work, i.e. design of system implementation, operation, management and maintenance. In this context human error is viewed as a sociotechnical process rather than as an individual psychological process. This requires the study on the interrelation of task, individual, organisation and technology which contributes to human error.

The various approaches attempting to deal with human error analysis that have been described above could be adequately summarised by AIChE (1994) to be made up of;

1. Traditional Safety Engineering
2. Human Factors Engineering/Ergonomics
3. Cognitive System Engineering
4. Sociotechnical Systems

Traditional engineering approaches look at the individual factors that could give rise to accidents and so give emphasis to the selection of people, together with motivational and disciplinary emphasis.

Human factors engineering/ergonomics approach emphasizes the mismatch between human capabilities and system demands as being the main source of human error so the primary remedy is to ensure that the design of the system takes into account the physical and mental characteristics of the human.

The cognitive system engineering approach is rooted in the applied psychology branch of knowledge which took the current view that individuals were purposeful in that their actions were influenced by future goals and objectives, instead of merely a passive black box that is analogous to an engineering component. This approach is applicable in particular to activities such as planning and handling abnormal situations.

The last approach is the sociotechnical systems perspective which arose from the realization that human performance at the operational level cannot be considered in isolation from the culture, social factors and management policies that exist in an organization. This approach is mainly concerned with the implications of management and policy on system safety, quality and productivity.

Currently a number of methods exist to conduct qualitative human error analysis. This includes THERP, Human Error HAZOP, SRK, SHERPA, GEMS, Murphy Diagrams, and HRMS (Kirwan, 1994). Each of the technique at the very least should be able to identify the EEM as it is a necessary step to integrate the human error element into QRA. Each of the method has its own strengths and weaknesses.

THERP (Swain and Guttman) for example is the simplest method yet capable to identify a high proportion of human error. Its weakness lies with the fact that this methodology lacks rigourous structure and is not capable of considering the underlying psychological mechanism. At the other end the HRMS technique (Kirwan, 1990) is a fully computerised system which allows the complete task of assessing human reliability to be accomplished through its task analysis module, human error identification module, task classification module, cognitive error analysis sub-module and human error analysis sub-module. However this technique is quite new and still not available in the public domain. As such there is not enough practical application to show its effectiveness.

In between the two classes of techniques that has been described above lies the System for Predictive Error Analysis and Reduction (SPEAR) technique. The SPEAR framework was developed as one of the methodologies for analysing and reducing risks arising from human error in chemical process industries (Embrey et al, 1994). It is based on an earlier computerised framework called SHERPA which has been developed for the same purposes (Embrey et al, 1986). The framework was developed in order to provide a logical and consistent structure to allow users to easily apply specific technique for human error analysis such as task analysis and predictive error analysis. SPEAR represents an integrated set of techniques for identifying tasks where human error could occur with severe consequences. It goes on with the process of identifying specific errors and their consequences within the task. The framework also facilitates the development of cost-effective methods for reducing the probability of these error. In the area of risk assessment the framework could be used to identify a critical task with high risk potential which subsequently could be used as input for QRA.

Phase 1 of SPEAR is made up of a screening process. Its purpose is to identify the human interaction with a process system which in the event of error occur could result in significant risk. The screening process ensure that all possible sources of risk on a site are identified. Decisions could be made with regard to whether the risks constitutes a serious threat that warrants detailed analysis. By focusing on operator involvement on high risk system of the plant, the amount of effort required to apply other techniques such as task analysis, which form the SPEAR framework could be reduced. The screening process uses a number of scoring systems that are used to rank a particular task based on its intrinsic hazard, intrinsic vulnerability and the frequency of operator involvement.

Detailed Predictive Error Analysis made up Phase 2 of the SPEAR system. The process evaluates errors that could arise in the subset of tasks that have been identified by the screening process. The evaluation is carried out in three stages. The first stage is the Hierarchical Task Analysis (HTA) which describes in detail the structure of tasks and the plans which determine the order in which the task step is performed. The second stage is the Predictive Human Error Analysis (PHEA) where each of the task steps identified in the task analysis is evaluated for its error potential. The last stage of Phase 2 is the Consequence Analysis which specifies possible consequences from errors that have been identified in term of the severity of the consequence and the frequency that it could happen.

The final phase of SPEAR is Error Management Control Analysis. The first stage of Phase 3 involves the evaluation of the factors which determine the probability of error known as Performance Influencing Factors (PIFs). These factors such the quality of training, procedures, and human-machine interfaces, most of the time are dependent on the performance of site specific safety management systems for their effectiveness. The PIF analysis allows factors that exert strong influences in the realisation of an error to be systematically identified and their current situation assessed. The analysis is then extended to look at the weaknesses or shortcomings of the present safety management systems that created the site's PIFs situation. Based on this information appropriate error reduction strategies could be developed, which made up the Stage 2 of Phase 3. The Phase 3 determines cost-effectiveness of various error reduction strategies that have been developed in Stage 2. Finally the most cost effective reduction strategies that has been identified are implemented on site and their effectiveness is verified over time.

2.9 Quantification of Human Error

Safety and Reliability Directorate (SRD) in its publication on Human Reliability Assessor Guide (Humphreys, 1988) described eight techniques for determining human reliability;

1. Absolute Probability Judgement (APJ)
2. Paired Comparison (PC)
3. Technique Empirica Stimo Operation (TESEO)
4. Technique for Human Error Rate Prediction (THERP)
5. Human Error Assessment and Reduction Technique (HEART)
6. Influence Diagram Approach (IDA)
7. Success Likelihood Index Method (SLIM)
8. Human Cognitive Reliability Method (HCR)

The abovementioned techniques could be grouped into basically four main categories as follows;

1. Analytical Decomposition Methods - e.g. THERP and HEART
2. Time-Reliability Curve Approaches - e.g. HCR
3. Expert Judgement Based Methods - e.g. APJ
4. Scaling Techniques - e.g. PC and SLIM

Analytical Decomposition Methods break the task down to the task step level for example open valve, press button etc. It assigns Human Error Probabilities (HEPs) to each task element from a data bank. Then the HEPs are modified to take into account the Performance Influencing Factors (PIFs) and the dependence between task steps. Finally the overall probability of error is synthesised from constituent probabilities using the event tree. THERP (Swain and Guttman, 1983) is one of the techniques that fall under this category which basically comprise of a database of human error HEPs and PIFs such as stress which could affect human performance. These factors can then be used to alter the basic human error probabilities in the database, using an event tree modelling approach and a dependency model. HEART (Williams, 1986); was developed based on a literature review on human factors and experimental evidences of various parameters that affect human performances. A set of generic error probabilities for different types of tasks is defined for quantification purposes. The task under consideration need to be defined under one of the generic error provided. Then the Error Producing Conditions (EPCs) which is similiar to PIFs, that could influence the task need to be identified. For each of the EPC evident, the generic HEP need to be multiplied by the EPC multiplier provided, which will yield the final HEP. A set of practical error reduction strategies are also provided by the technique.

The Time-Reliability Curve approaches are based on the assumption that the probability that the operator will not perform a required function is primarily dependent on the time available after the onset of the signal for action. HCR is one of the technique which use this approach where its correlation is a set of time-reliability curves whose shape is determined by the type of information processing associated with the task being performed. It encompassed three types of information processing; skill-based, rule based and knowledge-based processing.

As the name suggested the Expert Judgement based methods use experts to generate human probabilities directly. It may occur in various forms, from the single expert assessor, to the use of a larger group of individuals who may work together, or whose estimates may be mathematical aggregated. As one of such techniques APJ requires experts, and these expert must firstly have substantive expertise, i.e. they must know in-depth the area that they are being asked to assess. Secondly the experts must have normative expertise, i.e. they must be familiar with probability calculus, as otherwise they will not be able to express their expertise coherently in quantitative form.

The scaling technique originates from the theory of decision analysis. It is essentially a technique of defining preferences amongst a set of items, in this case human error task. SLIM is one of the technique which fall under this category. It defines preferences which represent the relative likelihood of the errors, as a function of various factors that can affect human performance which is known as the Performance Influencing Factor (PIF). This includes for example level of training, quality of the procedures, time available, quality of the operator interface, etc. It creates a relative scale representing the likelihood of errors, called the Success Likelihood Index (SLI). This index can be "calibrated" to generate human error probabilities using a logarithmic relationship based on experimental data and relative scaling of error likelihood from the comparison of different experts.

Roafaat and Abduoni (1987) developed an expert system on human reliability analysis which is modelled on three previously listed techniques i.e. THERP, SLIM and APJ. The main intention of developing an expert system in this area was to reduce the dependence on the human factors and ergonomic analyst judgement required in the current method and technique. Although the system was primarily designed for nuclear and process plant, it can be adapted for other industrial and occupational situations.

Analysis of human performance and estimation of human error probabilities require supporting quantitative data. These data could be obtained through the following methods (AIChE, 1994);

1) Laboratory studies.

2) Task simulators.

3) Operational observations.

Time measures of human performance could be obtained using instrumentation which includes reaction time and task duration. Meanwhile frequency data are produced by counting numbers of operator responses, errors, output and events. Data collected from relevant operating experience or from relevant industrial experiment would be ideal to be used (Kirwan, 1994). In the absence of such data, subjective or operator based judgement have been used and a variety of psychometric techniques employed (Gertman et al, 1994).

2.10 Current Approaches to Incorporate Organisational Factors and Human Error into QRA

Realising that organisational factors and human error plays a significant role on risk from hazardous installations many researchers have proposed a number of approaches in trying to include their impact in risk assessment. Many of them are geared towards the nuclear industry where the application of risk assessment in the form of Probabilistic Risk Assessment are well established. However some of these approaches could be extended to other industries with certain adjustment. A number of these approaches is rooted in the chemical process industries especially in Europe where the application of risk assessment in the form of Quantitative Risk Assessment (QRA) has gained considerable acceptance from the owner, practitioner and regulators (CEC, 1995). Reviews of some of the prominent approaches to incorporate organisational and human error in risk assessment will be deliberated in the following paragraphs.

2.10.1 The Work Process Analysis Model (WPAM)

The Work Process Analysis Model (WPAM) (Davoudian et al, 1994), as the name suggested uses the work process in the nuclear industry as its foundation. In a typical nuclear power plant, the plant work processes are created by working units formed according to their technical specialisation. This may include units of operations, maintenance, instrumentation and control, and health physics. The coordination between these working units is made by a series of information based decision processes which are developed to facilitate the accomplishment of the overall tasks. There are a number of organisational factors which influence the success of achieving these tasks. The bottom layer of these organisational factors is made up of the plant specific culture such as organisational culture, ownership, and safety culture. The next layer is made up of factors such as decision making, communication, administrative knowledge and human resource allocation. The link between the two layers is achieved by taking into consideration that any one or more of the organisational factors can influence the quality and efficiency of a given work process in the format of 'many to many mapping'. In turn this will affect the personnel and/or equipment performance.

The model attempted to incorporate the impact of organisational factors on nuclear power plant safety by accounting for the dependence of these factors introduced among probabilistic safety assessment parameters. WPAM framework is geared towards capturing the common-cause effect of organisational factor on NPP. It considers not only organisational common cause failures of similar systems but also between dissimilar systems or components.

The strength of WPAM is that it concentrates on capturing the common-cause effect of organisational factors on nuclear power plant safety. It goes beyond conventional common-cause failure analysis since it considers common-cause failures of the organisation of similar and dissimilar systems or components or both. Such an approach allows the common effect of organisational factors to be considered rather than a mere recalculation of independent event probabilities.

As for the shortcomings, WPAM currently only considers a steady-state scenario, for example a pre-accident operation. A dynamic situation, for example the operator action during a transient are not analysed. Secondly the analysis is only shown the usage within the framework of the corrective maintenance work process. It is claimed however that with some modifications, the model could be made applicable to other work processes, for example testing work processes (e.g. surveillance testing, in-service testing).

2.10.2 The Onion Model

Modarres et al (1992) proposed a framework which can depict the elements of plant safety in a hierarchical manner. The framework is made up of two structures. The first structure is called diamond trees which describes the functional hierarchy of plant safety, including the role of operator and plant management. The second structure is called the organisational field model which describes the behavioural aspect of the organisation related to the management and operation of the plant.

The diamond tree is a structured top-down, success oriented tree that can describe a plant functional hierarchy and its operation. The functional hierarchy shows how the function of the system influences and fulfil a system objective. The development of a diamond trees involves firstly identifying the plant's principal objective in this case would be plant safety. Secondly, identifying the plant's function that must be met in order to achieve that objective. These functions then will be examined in detail which will describe the plant in term of its functional requirement for operation. By developing the tree further the relationships between hardware components and the plant function which they support can be identified and shown in the form of success tree or success path. These relationship provide a basis to identify aspects of the plant operation which are essential to safety. The complete tree then will be able to show the relationships between human activities and hardware performance. This is achieved by recognising the fact that human actions affecting the hardware performance and the same affecting the quality of various activities under plant programme such as maintenance activities. And since the plant programme are implemented and monitored by the management some form of relationship could be established between the plant hardware and human activities within the plant.

The Organisation Field Model (Onion Model) is used to consider the informal factors or element of safety within the organisation that cannot be adequately represented by the Diamond Tree structure. Factors such as morals, attitude, and knowledge of the plant personnel. The model looks at a site organisation for example at nuclear power plant as a series of concentric layers (englobing fields) of organisational levels that mutually interact with each other while maintaining their identity at each level. This organisation field model is developed from research in management, organisation, and human factors which structure attempts to depict generic factors that influence a worker's reliability and productivity.

The proposed framework could be used for qualitative assessment of how different factors influence plant and personnel. The framework shows how various elements interact with each other and shows the paths from a given factor to safety which provides a qualitative explanation of the influence of that factor. The framework also can be used as the underlying model for quantitative assessment of the organisational factors influence. In principle by using appropriate quantitative measures of safety the effect of various organisational factors and characteristics of the system of interest could be calculated. However the need to define measures of influence and develop method of estimation is not an easy task. For this purpose the author proposed converting the entire framework into a digraph representation and measure the propagating degree of influence through the model using special mathematical rules such as Mason's rule from Signal Graph Theory.

The strength of the proposed framework is that it uses two separate models, i.e. the diamond trees and the organisation field model. The diamond model depicts a fairly accurate representation of the formal elements of safety in hierarchical form while the later deals with psychological side of the organisation. Combining the two models yield a useful framework that could provide qualitative and quantitative assessment of organisational influences on safety.

Its weakness lies in the lack of application for chemical process industries. The author only mentioned it uses for assessment and integration of safety performance indicator in NPP but did not elaborate its effectiveness. A case study to show the actual application of such a framework for a qualitative or quantitative assessment would be very useful. For qualitative assessment the framework is unable to show the dynamics of organisational influences. As for a quantitative assessment the measures of influence are not defined and the method for estimation was not mentioned. Only the method to propagate this influence from basic elements to the higher level of organisation was described, i.e. using Mason's Rule.

2.10.3 Incorporation of Organisational Factors into Human Reliability Analysis in PRA

Moeni and Orvis (1993) proposed a systematic approach to incorporate organisational factors into human reliability estimates for probabilistic risk assessment so it could be applied to safety culture improvement and integrate risk management. It uses the decision trees, expert judgement, empirical data on human error and information collected on organisational factors (OFs) in the form of ratings. The dependence between multiple operators' actions in an accident scenario due to common factors rooted at the organisational level is also being addressed.

The determination of human error probability of a specific task requires the assessment of a number of important Performance Shaping Factors (PSFs) that influence the likelihood of error being committed by human attempting carrying out or completing the task. Traditionally the PSFs being used are those that directly influence the outcome of specific task such as the quality of training, operating procedures, time stress and man-machine interface. Hence a logical extension of the PSF concepts would be the inclusion of organisational influences as higher influences that may affect several of the specific or low level influences that are currently being used. In addition other organisational factors that can directly influence personnel performance such as motivation and attitude are also introduced. By calibrating PSFs for organisational factors (OFs) empirically the probability of an accident or incident of an NPP could be calculated under one organisational situation. Any changes to the plant organisational situation will affect OFs (for worse or better) which in turn will alter the probability of that accident taking place. This will allow comparison to be made on a failure probability of an event at the same NPP under a different organisational situation or with another NPP which may under different organisational situation. The authors explained the application of such an approach by using an example to determine the reliability of control room operating crew in a typical NPP.

The strength of the proposed model is its ability to breakdown the organisation into various departments of work processes such as training, licensing, maintenance and etc. This way the organisational factor that influences safety can be rooted at specific departments. The model also uses five groups of organisational factors that have been identified through extensive research on past safety related incidents on NPP in the U.S. It uses a decision tree technique to estimate HEPs under identified categories of human factors. The technique allowed the influence of organisational factors to be assessed, rated, and weighted using well established technique such as BARs and weight of evidence.

The shortcoming of this technique is that the casual model developed must be adequate to depict the relevant department and identify the category of influencing factor within an organisation. Another shortcoming is the need to provide anchor points as starting point for the subsequent estimation of weight of evidence for other influencing factors. Lastly the 5 groups of organisational factors used is based on NPP historical data (incident assessment) which will be significantly different in non-nuclear application such as in the petrochemicals industry.

2.10.4 Model of Accident Causation using Hierarchical Influence Network (MACHINE)

Embrey (1992) proposed a generic model of accident causation which combine human errors, hardware failures and external event called MACHINE. This model attempts to approximate accident causation involving three levels of human errors, i.e. active error and two levels of latent error, one from operational and another from organisational. It describes the interrelationships between management influences, immediate causes and operational errors which can be used for organisational auditing, monitoring and system design. The influences are in the form of 'many to many mapping' or 'many to many pattern of influence' that has been described by other researcher (Davoudian, 1993).

While their relationship looks complex certain generic features can be deduced based on large number of accidents that has been analysed. It is claimed that this model could be easily extended to accommodate additional influences and levels so that it constituted a comprehensive generic model of accident causation. An example of the application of the technique for accident analysis is given using a generic model of accident causation. The first level of influences represents typical factors such as performance of training and time pressure which provide direct effects on the likelihood of occurrence of the immediate causes. The second level of influences represent typical policy level factors which determine the likelihood that the first level influences will be negative or positive, for example the policy to ensure feedback from operational experience will be of use as input for future training. Using the Influence Diagram technique the probability of influences between the second and first level could be established based on the concept of weight of evidence. This concept requires the assessment of weight of evidence of the lower level factors influencing the higher level influencing factor in term of probability. These probability values could be obtained using techniques such Absolute Probability Judgement and SLIM.

One of the potential applications of the model is that it could be used as a basis for a safety auditing tool since it could show various levels of influences that actually determine the likelihood of an accident. Another application area of the model would be for a quantitative risk assessment where it could capture the effects of a network of influences. In fact the model could be used to incorporate directly the effects of management and organisational variables in the quantification of both human and hardware failures.

As for its implementation the model needs to use a suitable elicitation technique to capture from individuals in the organisation the detailed structures of influences that could results or have resulted in accidents. For this purpose the information made available from accident investigation and near-miss occurrences could be used. In addition some form of representation of influence is required which need to be compatible with the generic model. To fulfill these requirements the Influence Modeling and Assessment System (IMAS) (Embrey et al, 1984) is used. It has an added advantage of being able to quantify the effects of various influences that have been identified. IMAS was originally developed as a method to elicit the diagnostic models held by NPP operator when responding to emergencies. An interactive computer program was used to elicit the diagnostic model which depicts the model as a network comprising of three entities;

(a) Event - occurrences that are causally connected to other events or nodes in the network

(b) Linkages - pattern of connections between events that are causally related

(c) Indicators - information sources which can be directly observed by the operator, which indicate states or events which cannot be assessed directly.

The IMAS structure can be readily applied to the MACHINE accident causation influence network. The nodes in IMAS represent the states that influence other states as opposed to events that causally lead to other events in MACHINE. This in turn influences the likelihood of events active or latent error of hardware failures. The Influence Diagram methodology could be used to quantify these influences. And as these influence links are probabilistic in nature the outcomes could be easily incorporated into probabilistic risk assessment.

The strength of MACHINE is that the model is supposed to be generic in nature since it is based on information gathered from analysis of real accident or near-miss occurrences. It is fairly comprehensive and captures various levels of influence that actually determine the likelihood of an accidents. Its structure also lends itself to quantification using techniques such as Influence Diagram which use an approach based on balance of evidence as opposed to the use of absolute judgement of a particular error.

Shortcoming of the approach lies on the need to tailor the generic model for a specific system under consideration. The elicitation technique to capture detailed structures of influences need information from teams of individuals at all level in the organisation. Data from incident and near miss investigation could be used as a starting point. This will be well and good for an organisation which have a good safety management system in placed backed by adequate resources, i.e. trained and experienced personnel. But in an organisation with poor PSMS, information from individuals and data from accident and near misses investigation, may not be adequate to identify the actual structures of influences needed to modify the generic model. This will result in wrong representation of site specific structures of influences by the model. The IMAS tool use for eliciting and representing the influence structures also does not attempt to capture every interrelationship but only those needed for the purpose in hand. It mean that the model is not generic in a true sense as it needs to be modified every time for different uses. Field validations also need to be conducted to check whether the provisional influencing factors assigned to the model are truly generic in nature or if the factors varies within different industries. Finally the error probability calculated as shown in the case study is at global level which includes active, latent and recovery errors. The application to assess human influences on hardware failures which normally involve influences of low level tasks was not illustrated.

2.10.5 System-Action-Management (SAM) Approach

Pate-Cornell and Murphy (1994) proposed the SAM approach which provides the link between probabilities of system failures to human and management factors. Its objective is to improve probabilistic risk analysis (PRA) as a tool for managing and reducing risk. The important feature of this model is that the management factor affects the physical system only through human decisions and actions. It uses PRA as a starting point to simplify the subsequent human and organisational analysis. The PRA will provide the guidance to search for the pertinent human and organisational factors. Variables from each of the model will lead to a study of the specific parts of the processes that affect it. SAM was claimed to offer an analytical approach for modelling the risk associated with a specific system as the structure of human and management effects on risk can be described by a simple set of equations. The application of the technique was illustrated in three case studies of failures of three diverse systems, i.e. operation and fire risk on-board offshore platforms, the management of heat shield of the NASA space shuttle orbiter, and the root of patient risks in anesthesia. Despite the diversity of the system under study some common traits were found which could be useful in designing risk management strategies for a complex system. For example they found too much emphasis is often put on technical rather than organisational risk mitigation measures and found that operators are generally predictable, competent, and well intentioned than normally perceived.

The proposed model was an extension of previous work carried out by Pate-Cornell and Bea (1992). They presented a methodology to link the PRA input to decisions and errors during design, construction and operation phases of offshore platforms. They assessed the contribution of different types of error scenarios to the overall probability of platform failures. According to them a large fraction of these errors are attributed to errors and bad decisions rooted in the organisation, based on accident analysis of well-known incidents such as Piper Alpha platform. Such errors and bad decisions may affect the PRA inputs but not accounted in an explicit manner, eventhough they might be included implicitly in performance statistics and expert opinion. Bad decisions may involve errors of reasoning, excessive risk taking, or unwarranted optimism. Thus organisational errors encompass some of the classical human error and other factors, such as communication and incentive problems that give significant contribution to the probability of a system failure. These organisational errors could be linked to a system reliability through PRA which is designed to provide information for amongst others for the setting of priorities among different types of measures at improving system reliability that includes organisational means.

Key organisational elements of system reliability includes individual skills, information (collection, communication, and learning), resource constraints (budget set by corporate goals), and the reward system (job appraisal, wage increases, incentives, etc.). In turn these factors are rooted in the structure, the procedures, and the culture of an organisation which contributed to safety of the site operation.

They proposed a taxonomy of operator error which can relate the individual decisions to organisational features such as information and reward systems. The taxonomy made fundamental decision between gross errors that taking place in unambiguous situations and error of judgement which occurred under uncertainty. Gross error involved mostly information problems which are caused by a temporary or permanent lack of knowledge, and misunderstanding of a situation. This error can also caused by human physical and psychological limitations for example when working under an unusual environment such as on an offshore oil platform.

Errors of judgement concerned with issues of incentives, preferences, and rationality. These errors cannot be easily defined by a violation of a fixed norm (a deterministic truth). Hence the authors used an approach based on "bounded rationality" where people generally respond to the reward system and use, to certain extent available information even when it is incomplete. Violation of this rational represent one of the key sources of errors of judgement.

Strengths of this approach are that it looks at errors rooted at organisational level through error of actions and decisions which some of them go beyond the traditional approach of human error. The division of error to gross error and error of judgement make it much easier to find their root at the organisational level. This in turn provides the linkage for variables in risk analysis to some organisational factors and assess the effect of errors (occurrence and consequences) on system performance. Hence it may be possible to reduce the base rate of errors and increase the rate of error detection by organisational changes, such as improving learning mechanisms or improving of scheduling to reduce time pressures. Using offshore platforms as case study the approach was shown to be able to compare different approaches to risk management. It was also able to highlight the contribution of low-severity error which provides significant contribution to system failure. This type of error normally hidden by the emphasis to look at high severity error which is often the visible trigger of an incident.

Weaknesses of such an approach lies firstly on the highly simplified representation of a complex installation such as the offshore platform in order to elicit human error and provides their linkages to the organisational level. While such a global approach will facilitate the elicitation process it may miss the linkage of certain low level tasks which may not follow such global representation. Secondly on the use of expert opinions in the form of an absolute judgement for all human error data. While it is quite straight forward for gross error, to assign values for error of judgement (under uncertainty) need a more robust approach. This is especially true as not much statistics are available on error of judgement or exist for comparison. A bounded value of such errors probably necessary to check the range of uncertainty. Thirdly the approach did not address the way to detangle human and organisational error which made up the generic hardware failure rate used in the analysis. Finally the approach was only tested on off-shore platforms which have specific and well defined structure for decision making. It remains to be seen how it would cope with other industries where decision making structure is less clear and more complicated. Or in a situation where the operator does not have much say (e.g. due to lack of expertise) at the design and construction stages as often found in the developing countries.

2.10.6 The PRIMA Audit

Health and Safety Laboratory of HSE, U.K has developed a technique to quantify site specific PSMS performance. The technique is based on an audit system with a demonstrable statistical and theoretical basis to quantify the performance of PSMS at a plant and link this into the QRA being carried out (Hurst, 1993). The statistical basis is taken from an analysis of reported incidents involving failure of fixed pipework and vessels on chemical and major hazard plants. A 3-Dimensional classification scheme was developed which classify direct cause, underlying cause and failure of preventive mechanism. This scheme provided an objective quantitative model on which to base a PSMS audit which emphasized loss-of-containment accidents as opposed to occupational accidents. The theoretical basis is based on the Sociotechnical Pyramid Model of the effects of PSMS, and the general climate within which it operates on failure rates. It explores increasingly remote system failures through engineering reliability to organization and management, communication and control and system climate. This theoretical model is based on authoritative texts on chemical plant risk management, conventional organization and management theory, and management of quality and consideration of major accidents and system failures (Hurst, 1991). The technique has been used by HSE Factory Inspectors to audit PSMS and to quantify it for QRA of a number chemical plant in the U.K . It is also being used on a trial basis by a number of European countries under EEC funding (Hurst et al, 1993) .

Experience gathered from audit trials in the U.K and other European Countries has led to further development of the technique, primarily revising the question set and the judgement for various anchor points (CEC, 1995). The final audit version is then called PRIMA (Process RIsk Management Audit). PRIMA is an audit tool for the quantitative assessment of PSMS performance. The technique was initially developed to incorporate site specific safety management system quality into quantitative risk assessment. Since then it has undergone further development including on the audit materials, primarily the question sets and anchor points. Training audit has been conducted in the U.K and the audit version produced following the audit and used in field trials at a number of European countries was referred to as PRIMA.

PRIMA consists of eight key audit areas namely;

- Hazard review of design (DES/HAZ)
- Human factor review of maintenance (MAINT/HF)
- Checking/Supervision of maintenance tasks (MAINT/CHECK)
- Routine inspection and maintenance (MAINT/ROUT)
- Human factors review of operations (OP/HF)
- Checking/supervision of construction/installation (CON/CHECK)
- Hazard review of operations (OP/HAZ)
- Checking/supervision of operations (OP/CHECK)

The following tools are available to assist the auditor in carrying the audit;

- A model of an ideal PSMS defined by the control and monitoring loops
- A set of four key themes within each audit area
- A question set
- An audit manual
- A calculation method to generate the modification factors

Strengths of PRIMA;

- The technique was developed based on sound theoretical and statistical basis. However the loss of containment data base needed updating.

- The audit questionnaires set is comprehensive and do cover the necessary areas for PSMS audit. In fact some of the information made available from the questionnaire could be used for other purposes for example to carry out human error analysis

- The use of management control loop provides an effective way to represent PSMS situation for each site

- The technique provides a quantitative output in the form of PRIMA Modification Factor that can be used to modify generic failure rate for QRA

Weaknesses of PRIMA;

- Need a thorough site inspection and document verifications in order to make sound judgment for the PSMS performance

- Too much emphasis on written documents which may not be appropriate to smaller site with simple process

- The time required to complete the whole audit exercises is quite significant.

2.11 Conclusions

The literature review has shown the emergence of QRA as a decision making tool for Major Hazard control in some developed countries (Pasman, 1995) and to certain extent in few developing countries (ILO, 1992). The contribution of QRA does not lie squarely on the number that they produce but through the process itself which is capable of systematically identifying, assessing and estimating the risk from major hazard sites (AIChE, 1989). Such an exercise provides valuable information that could be used to assist the decision making process by the operator and the regulator alike (McQuaid, 1995 and Bayer et al, 1991).

However each major hazard site possesses specific organisational characteristics that shaped their ability to manage risk associated with its operation. The existence of effective operating procedures, the availability of skill and experience of the operator, the effectiveness of inspection and maintenance system, and not least the management commitment influence the ability of a particular site in controlling risk. These factors were found to be important contributors to risk beside the hardware integrity (Purdy and Wasilewski, 1994). As human and management systems are part of a site organisation, understanding their influence to QRA could provide a means to reduce the risk, and improving the transparency and accuracy of the risk estimate.

Existing research on the influence organisational factors to QRA is still at the development and validation stages. In the U.S the research mostly concentrated on nuclear industry (Davoudian et al, 1994) while in Europe is more prominent in the chemical process industries (CEC, 1995). The situation in developing countries is more or less uncharted for (Basri, 1996), even though this is the place where the organisational differences are more pronounced due to side by side existence of local and multinational major hazard sites. Any attempt to address this situation is considered timely as risk reduction effort through organisational changes require less resources which is of major concern in developing countries (ILO, 1992).

Chapter 3

Research Methodology

3.1 Introduction

The proposed research is essentially a comparative study on the influence of PSMS on risk from major accidents of two MHI in Malaysia which handles similarly hazardous material but with a significant difference in safety management performance. The comparative study will be carried out using the established technique of QRA and the PSMS quantification. Further attempts would then be made to compare the result of human error quantification on one of the main components in PSMS, that is human error with one of the hazardous operational activities being carried out at both installations. The main goal is to compare and contrast the differences on the level of risk and human error probability that might arise due to the different style of PSMS existing at the installations.

3.2 Research Background.

Malaysia as a fast developing country has successfully moved from agriculture based industry to manufacturing and processing industries. Discovery of gas and petroleum reserves in the last decade has seen many large petroleum, chemical and petrochemical plants being built throughout the country. At the same time small and medium size downstream industries started to be established. While the large upstream industries mainly belong to multinational or nationalized companies, the downstream industries see the mixture of such companies as well as those who are owned by small local operators.

Different types of ownership mean the possibility of a different approach in managing the day to day running of the plants. Their differences to a certain extent will filter down to safety management system of individual plant. This unique scenario represents an excellent opportunity to evaluate the impact of safety management performance which might arise from the different management style in such plants on the overall risk from its operations. It is expected that the plant which is owned by a multinational will be operated by the parent's company management style to a large extent and this includes the safety management aspect. While the locally owned company is managed by a management style that is peculiar to small Malaysian companies with very little influences from developed countries. Any little influences that exist probably in the form of following the operational and maintenance procedures and guidelines as laid down by the process hardware suppliers which mostly come from developed countries.

Similarly the scenario also offers good opportunity to explore and investigate the contribution specific component of safety management i.e. human reliability to both the safety management quality and plant overall risk. The plant owned by the multinational is expected to benefit from the parent's company expertise and experience with regards to human error. Necessary steps to reduce human error such as achieving task pre-conditions and carrying out task analysis on critical activities should have been taken. As for the locally managed plant, typically very little consideration is given on the aspect of reducing human error. Whatever steps taken toward that probably will be by trial and error basis.

3.3 Regulatory Framework.

As been described in Chapter 2, Malaysia has adequate regulatory system to ensure safety and health at work places. The Factories and Machinery Act 1967 (FMD, 1967) and the new Occupational Safety and Health Act 1994 (DOSH, 1994) which is based on the U.K Health and Safety At Work Act etc (HASEWA), provide the minimum standard of safety and health for workers at work places throughout the country. The regulations made under both Acts, provided detail requirements on diverse areas such as the registration of place of work, competency of persons in charge and inspection of dangerous machinery such as lift, boilers and pressure vessels.

The Control of Industrial Major Accidents, which is based on the U.K CIMAH regulations is currently in place to control hazardous installations such chemicals, petroleum, and petrochemicals plants. These regulations are similar to CIMAH where the major hazards installation existing and new, is required to present a safety case or safety report to the authority before be given the approval to operate. The Malaysian regulations however, require the owner of such installations to consult a competent person or competent companies which are approved by the authority in the preparation of safety cases to ensure that the owner or the operator of a major hazards installation will be given proper assessment by an expert, especially those run by small time operators.

DOSH of Malaysia has direct involvement in ensuring the safety of potentially hazardous hardware like boilers, reactors, distillation towers and other pressure vessels. This is carried out by reviewing the design, checking the fabrications, conducting hydrostatic tests, witnessing commissioning and carrying out annual inspection on each vessel for 'fitness of purpose'. This direct involvement ensured to a certain extent the integrity of such in vessel at the design and fabrication stages, and continue through its operation and maintenance cycle. It will be interesting to find out whether this sort of arrangement benefits the PSMS of both MHI under investigation especially in auditing the design integrity and maintenance aspect of pressure systems.

Still there are other areas that are not regulated thoroughly, yet that could contribute significantly to the overall risk of the installations. The operator's qualifications and skill, accident statistics monitoring system, management of human error and the overall system reliability still much left to the operators to implement as long as it meets the minimum general requirements of safety and health. The situation resulted in different systems being adopted by each MHI. This has resulted in different quality of PSMS performance and human error management at different sites.

3.4 Overview of Methodology

The method employed to conduct the research will be based on field study which consisted of observations, interviews, site inspections and documents review to be conducted on two MHI in Malaysia. Field studies on two sites which have different style of plant management system will be conducted to assess the site specific PSMS performance contribution to QRA. One of the installations is owned by an established multinational company and managed according to a modern big corporation style of management. While the other installations selected is owned by a family business and managed as a family run organization. However both installations are expected to handle or process similarly hazardous material i.e. toxic gas such ammonia eventhough the capacity and size may be different. Such an arrangement is expected to be able to provide a common background as far as the hazardous material is concerned, allowing the effect of different management style to PSMS and eventually the results of QRA to be properly investigated.

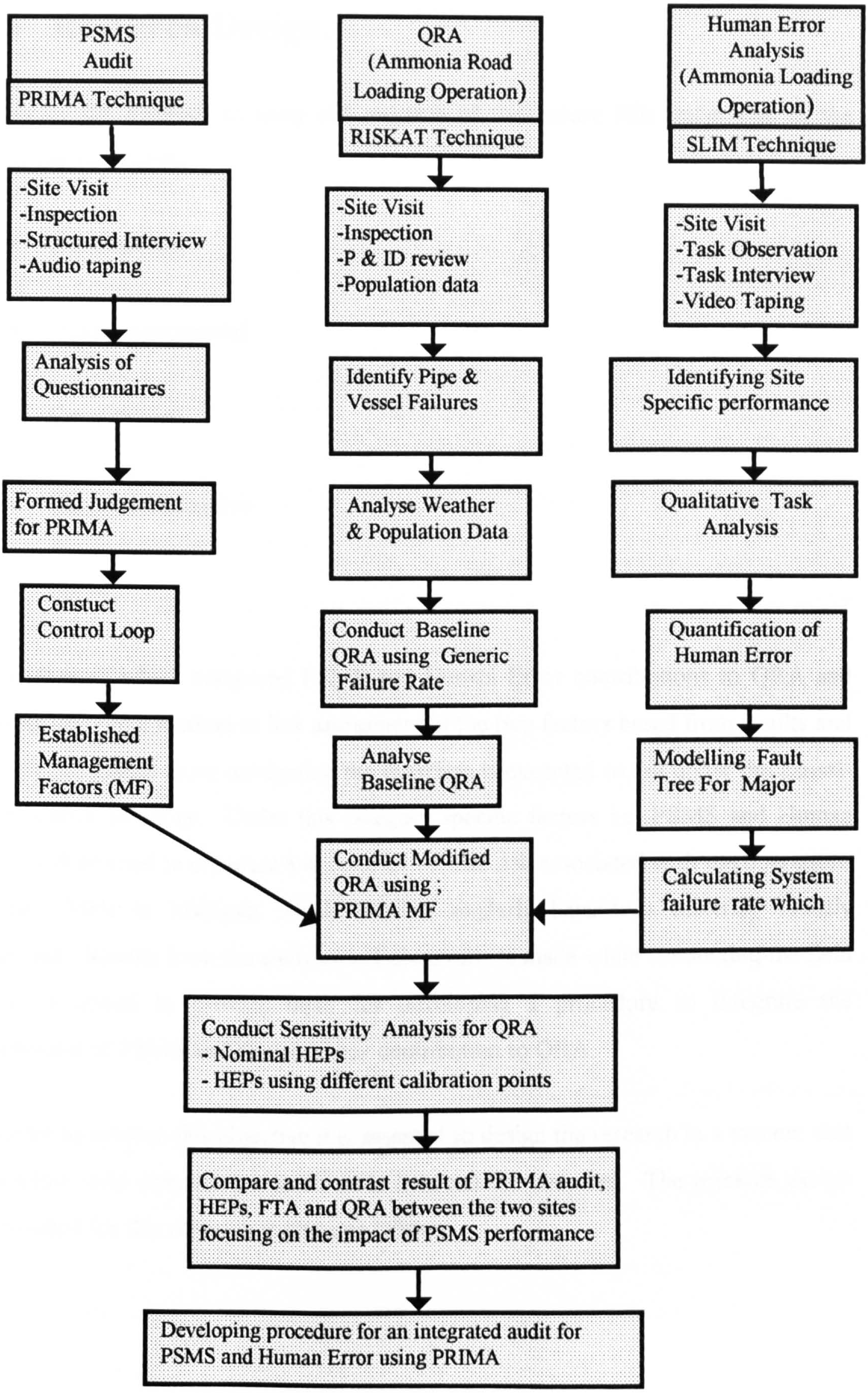
The second factor that will be assessed is the human error on one of the activities that it is expected to provide the highest risk contributor in the plant operations. This activity will be identified during the baseline QRA assessment and supported by historical data on the plant failures. As this aspect is not adequately or explicitly covered by the current legislation in Malaysia, it will be interesting to explore their effect on both the safety management system and the overall risk level of the installation. It is envisaged that human error for this research is approached in a system context. In this approach human error will be treated as part of the overall system reliability. As one of the factors in system reliability, human error is expected to be seen as a process itself rather than of causation-kind effect and recovery. This approach requires the identification of antecedent conditions that could lead to human error. The next step is to determine whether this error could be recovered, and if it cannot be recovered what would be the consequence that will effect the overall system reliability. To fulfill this objective a similarly highly hazardous task will be selected in both plant operations, for example task or activity of loading and unloading of highly flammable or highly toxic material. Analysis on human error in carrying out two almost identical hazardous tasks at different site would allow comparison to be made on its effect on PSMS and eventually on results of QRA.

Results from the analysis of PSMS and Human Error on the two MHI will be compared and contrasted. These compare and contrast approach is expected to highlight differences and similarities on important factors of PSMS and Human Error that contributed to the outcome of QRA between the two plants. Factors that provide significant contributions to the plant's QRA then will be scrutinised to look for effective mean to reduce their impact to the overall risk level on both MHI. Findings from this research on means to reduce the off-site risk then could probably extend to other MHI in Malaysia.

Further results from the research coupled with experiences gathered while carrying out the PSMS audit and Human Error analysis will be used to develop a procedure to link the effect of PSMS and Human Error on QRA. This procedure will allow a unified approach to assess the impact of the quality of PSMS and the state of human error in a particular MHI plant through a common site audit. The interplay between human factors, organisational structure and management is expected to be clearly defined, analysed and assessed in a systematic manner.

An overview of the research methodology could be represented by a flow chart as shown in Figure 3.1

Figure 3.1 Research Methodology Flowchart



3.5 Research Design.

In theory the methods to carry out research of this nature falls under one of the following categories;

- Experimental
- Quasi-experimental
- Correlational
- Causal-comparative
- Survey

This research which compared PSMS and Human Error contributions to QRA and coming up with a method to link assessment of the two factors based from results and knowledge gained from conducting the exercises is expected to fall under the causal-comparative category. Under this category specific factors i.e. PSMS and Human Error will be used to compare and contrast off-site risk associated with the operations of two MHI in Malaysia which handled similarly hazardous material, namely ammonia. Results from the analysis and observations made while conducting the field study is hoped to provide input for developing a procedure to integrate the assessment of PSMS and Human Error contribution to QRA.

In order to achieve this objective it is essential to design the research in a manner that will allow valid comparisons to be made between the two sites. The research design formulated for this research is given as follows;

3.5.1 Selection of the MHI for comparison

As the main goal of the research is to compare and contrast, the proper selection of MHI is of a paramount importance. Statistical representation is not critical since the study looked at specific factors i.e. PSMS and Human Error in great details rather than looking at basic correlation between many samples. The two MHI selected should have the following characteristics;

- A major hazard installation as defined in the Malaysian regulations in the control of major accident.
- Different type of ownership, i.e. one installation belongs to an established multinational, preferably a European concern, which have been exposed to some form of major accident control legislation through the European Community (EC) directives. The other installation to be fully locally owned preferably 'family run' type of ownership
- Different style of plant's management, i.e. it is anticipated that the multinational installation being selected will be managed in accordance with that be practiced at their plant in developed countries. The locally owned installation selected may or may not follow strictly to any particular management style as practiced by the multinational. Certain degree of influence by the process hardware supplier is to be expected.
- Different plant's operator recruitment policy, training procedures and work incentives, i.e. it is expected that the multinational company provides more comprehensive training and better work incentives while possessing an effective recruitment policy as compared to the local one.
- Operating an almost similarly plant, process same level of technology but plant capacity or through-put could differ significantly.
- Sited in an industrial estate but at different locations.
- Built or constructed in the last ten years and have been operated ever since. These factors are important to ensure that they have existed well before any

legislation in place with regard to major hazard control, especially on siting issues.

- Have fairly adequate records on accident statistics, maintenance, repairs, inspection and training of personnel especially the plant's operator.
- Management willingness to provide information, to allow safety audit and human reliability assessment to be carried out on site over a significant duration. This factor is extremely important to ensure the success of the proposed research

3.5.2 Selecting an operational activity for Human Error Analysis

The activity selected for Human Error analysis should be made available at both MHI. It is decided the activity should be a hazardous operational activity that forms part and parcel of the plants' normal operation. Operational activity is selected against other plant's activity such as maintenance and repairs since it represents the highest contributor to failures of vessels and pipework as reported by an analysis conducted by HSE (Hurst, 1991). The activity will be selected based on the following criteria;

- It should be one of the highest risk contributors as determined by the baseline QRA.
- Involve a number of tasks that require human involvement
- Has set of established procedures
- It requires a fairly high degree of skill for execution
- Operators has been adequately trained to carry out the activity
- Historical data has shown that such activity is one of the highest contributor of process plant failures.

3.5.3 Selection of techniques for analysis

A number of techniques will be employed to conduct the research. For this purposes it is necessary to select appropriate techniques for a specific purpose from an array of techniques currently available in public domain. Criteria of selection differ depending on types of applications but academic endeavour over commercial interest would be the prime consideration. Full discussions on the selection of various technique is given as follows;

a) PSMS auditing technique

There are a number of techniques currently available to audit PSMS. Some of the techniques such as MORT and CHASE only provide qualitative results while others as ISRS, MANAGER and PRIMA provide mean to convert qualitative results to quantitative ones. As the research is aimed towards QRA it would be necessary to select only those techniques that are capable of giving quantitative results. After conducting thorough evaluations from available literature it was found that the PRIMA (Hurst et al, 1996) is the most appropriate technique that could fulfill the research objectives. Main reasons for selecting this technique are;

- it was developed based on a sound management theory i.e. the Sociotechnical management theory.
- the quantitative part of the technique is based on a good set of historical data of vessels and pipework failures.
- it allows the analysis of contributing underlying causes of failures which include human factors
- has been successfully tested for field applications by a number of research bodies in the U.K and to lesser extent in Europe.

b) QRA Technique

Conducting full QRA on medium size MHI requires a lot of resources and time consuming if done manually. To ensure completeness large numbers of credible scenarios would be required to be analysed and quantified. So there is a need to use a computer code to carry out numerous runs for the analysis. Currently there are a number of QRA computer codes available but almost all are proprietary software, hence accessibility is of prime importance. At the end the available choice is between two software namely RISKAT developed by HSE (Nussey et al, 1993) and SAFETI developed by TECHNICA Ltd. (Technica, 1994). Evaluation made based on available literature showed very little to separate between the two. Finally RISKAT was chosen due to the following reasons;

- it is more user-friendly as it utilised the Window operating environment
- allowed faster sensitivity analysis to be carried out
- usage of 'toxic load' which is more realistic for land use planning (Fairhurst et al 1993)

c) Human Error Quantification Techniques

There are quite a number of techniques currently available for the prediction of human error. They fall under three broad category as follows;

- Analytical Decomposition Methods - e.g. THERP and HEART
- Time-Reliability Curve Approaches - e.g. HCR
- Expert Judgement based Methods - e.g. APJ
- Scaling Technique - e.g. PC and SLIM

Some of the techniques such as THERP (Swain and Guttman,1983) and HEART (Williams, 1986) are in public domain while others like SLIM (Embrey, 1984) and JHEDI are propriety owned. Selecting one appropriate technique for this research based upon available literature proved to be quite difficult. Validation exercises that have been conducted by a number of researchers such as Humphreys (1988) and Kirwan (1988) provided some guidelines. Finally the SLIM technique was selected for use for the following reasons;

- the technique capable to assess Human Error Probability (HEP) at system, sub-system and task levels

- accessibility to technique and owner could provide training
- fairly accurate technique
- maturity - has been in existence and used for quite sometime in the chemical process industry
- fairly high degree of acceptability by the regulatory bodies, the scientific community and HRA assessor
- available as computer code that would speed up the analysis and permit greater degree of sensitivity analysis to be carried out.

3.6 Research Procedures

The research procedures are described in the following paragraph. Step by step description of the procedures is given as follows;

3.6.1 Analysing the background of MHI in Malaysia.

The first step is to study and analyse the background of MHI in Malaysia. Such an analysis is important in order to understand the earlier development, current status and future direction of the industry. The previous and current regulatory framework that governs safety and health aspects and land siting policy in Malaysia would be scrutinised. Information made available by such analysis would be valuable in setting up the research direction and boundary. For example in the absence of regulatory requirement for minimum level of plant's operator basic qualifications it would be difficult to consider such factor as a major aspect in human reliability. Another example is that the absence of comprehensive siting policy in Malaysia until recently, created a situation where one major hazard installation is allowed to be built nearer to populated area as compared to another installation.

The Malaysian government policy to attract foreign investment has resulted many multinational companies to invest in the country by building up large petroleum, petrochemical and chemical installations. Each multinational company will then bring in together their management's skill and system for the plant's operation. Some of these companies formed joint ventures with locals that sometimes resulted in a different style of management. Then there are local companies, most often family run business which run small and medium scale major hazard installations such as LPG bottling plants, ammonia bulking plants for the rubber industry and chlorine bottling plants for the water treatment. These mixtures of plant's management style, would affect the safety management system of the plant to certain extent and this could provide a fertile ground to investigate the 'management factor' influence on overall risk.

Similarly the absence of any form of curriculum be it at the national or state level for plant operator's basic theoretical knowledge and skill has resulted in a quite big difference in terms of the operator's skill operating major hazard installations eventhough for those using hardware of the same technology. There are instance where due to the requirement to provide job opportunities to people surrounding a newly built major hazard installation, the company has to recruit locals who were mainly with fishing or agricultural skill to operate a highly sophisticated process. In such situation the local operator will be given an ad-hoc 'crash' training programme that sometimes involved short attachment with a foreign installation followed by supervision of on-site training. Since it is done on an ad-hoc basis by each company it would be interesting to find out whether the skill they have acquired is appropriate and how they contributed to human reliability in each plant or installation. Also how further training, incentives, safety and quality management on-site contributes to human reliability especially on hazardous tasks or activities.

3.6.2 Selecting two MHI in Malaysia for comparative study

The second step involving the selection of two major hazard installations where a full scale analysis of QRA, PSMS audit and Human Error analysis will be carried out. As the research does not intend to prove statistical significance but to compare and contrast, their selections do not require strict procedures to ensure randomness and representativeness. In fact a certain degree of familiarisation is desirable to ensure their selection fulfills the objective of research. Basically the two major hazard installations selected should have the characteristics as described earlier in Section 3.5.1.

3.6.3 Conducting baseline QRA

Conducting 'baseline' QRA on both installations will serve two purposes. One is to determine the risk level on both plants using generic failure rate without considering the impact of PSMS. Second is to determine which activity within the plant that represent one of the highest risk contributor to the overall plants risk level. This activity then will be considered to be subjected to human reliability analysis.

The QRA will be conducted using RISKAT software which was developed by HSE. Necessary input for the analysis would be made available through physical inspection, examining records and procedures, interviewing personnel and site observations. Further input such as weather information, population density, site-map, PI&D diagram could be made available prior to the actual analysis. Some of the input requires expert judgement to be made.

Necessary steps will be taken to ensure those input data to RISKAT are compatible since it was being developed basically for use in the U.K. Certain input like the weather data, site-map grid and population density from Malaysia probably need to be modified to make it compatible with RISKAT. Another factor that needs to be considered is on various built models that being utilized by the software for consequences analysis. For example it is necessary to check whether the heavy than air gas dispersion model utilized by RISKAT is suitable to be used in a humid climate like in Malaysia.

As it is required to compare the QRA results of the two MHI a consistent approach in conducting the analysis is needed. For this purpose a checklist will be developed to ensure similar type of questions asked, same type of documents searched and similar assumptions being made in the process of carrying out the analysis. In the event of expert judgement needing to be made a cautious approach will be taken to prevent bias toward a particular MHI.

3.6.4 Quantification of PSMS performance

An established audit technique called PRIMA (Hurst et al, 1996) will be used to conduct PSMS audits on both major hazard installations that have been selected. The aims of this audit is to determine or 'measure' management factor that is associated with the performance site specific PSMS. The PRIMA audit checklist is quite comprehensive and requires the participation of both workers, supervisors and managers. To ensure some degree of accuracy, it is essential the auditor be familiar with the philosophy, concept and technique of auditing system selected and have some experience conducting safety management audit.

The PRIMA audit technique utilises formal questions set covering nineteen functions within an overall safety management system. Based on the extensive analysis on vessels and pipework failures eight combinations of functions were identified as major contributors. The research will attempt to cover the eight combinations namely;

- Design/Hazop (DES/HAZ),
- Maintenance/Human Factor (MAINT/HF)
- Maintenance/Checking (MAINT/CHEC)
- Maintenance/Routine (MAINT/ROUT)
- Operation/Human Factor (OP/HF)
- Operation/Hazop (CON/CHEC)
- Operation/Checking (OP/HAZ)
- Construction/Checking (OP/CHEC)

The audit will involve conducting interviews with senior managers, line managers, supervisors, operators and tradesman. Relevant company documents will be reviewed and critical documented procedures will be checked upon. However it would be very difficult to interview everyone involved in the activities under scrutiny. Instead a sampling technique will be used to look at 'horizontal' and 'vertical' slices of the site's organisation that ensure that opinion will be obtained from a cross section of personnel on each site.

The horizontal slice involved carrying out formal interviews with managers, who have influences and have duties in the areas of forming and implementing policy in relation to the activities under consideration which include establishing organisational arrangements and managing the relevant system and procedures. The vertical slice involved interviewing those individuals in the chain of command who are responsible for delivery of engineering reliability and operator competence including foreman, operators and technicians.

A number of visits to each MHI are expected to be carried out to complete the audit process. The availability of subjects for interviews especially the senior managers make it difficult to really estimate the actual duration of the auditing process. Similarly looking for the right documents for review will be another factors to be considered. Also the observations of some critical activities against written procedures may not take place at certain periods of time. So comprehensive planning is necessary to ensure the audit's success for example by fixing appointment for interviews, looking at the plant's works schedule and informing in advance the type of information needed to be reviewed.

3.6.5 Modification of generic failure rate

A Management Factor (MF) obtained from safety management audit from each installation will be used to modify the generic failures rate. The use of modified failure rate will be better able to reflect the actual performance of safety management system as compared to using the implicit approach. PRIMA provides the option to use the audit results to modify generic failure rate used in QRA. This will be done by directly modifying failure rates using three types of information: the audit ratings; weights for each area; and a scaling factor based on range and distribution of loss containment accidents and incidents.

3.6.6 Conducting QRA using modified generic failure rate

This step requires QRA to be conducted on both installations using modified generic failure rates that have been determined as in Section 3.6.5 using the same QRA assessment tool RISKAT. Other inputs needed for the analysis such as weather data, population density and system hardware together with various assumptions made will remain the same. This will ensure that all the other factors remain constant except the modified generic failure rate is used for analysis. A number of sensitivity analyses will be conducted to evaluate the effect of a number of input parameters

3.6.7 Comparing QRA results between the two MHI

The next step is analysing and comparing results of QRA conducted on both installations. The QRA results are expected to be in the form of individual risk, societal risk and some critical hazard ranges. The effect of different management factor value (MF) between the two installations is expected to be reflected in the QRA results. This comparison will show how QRA is going to be affected by management factors at both installations. Results obtained from this analysis will be used to test two hypothesis that have been set earlier, i.e.;

- PSMS does affect QRA results
- MHI with better PSMS performance has lower off- site risk

3.6.8 Selecting an activity in normal operation for Human Error Analysis

This step represents an attempt to investigate the effect of human error on PSMS and the overall risk from major hazard installations. To achieve this objective it is necessary firstly to select a hazardous task or an activity in the plant where a critical assessment on the aspect of human error could be carried out. This approach is expected to provide a 'snap shot' on the state of human error management of the entire plant since it is not possible to conduct a complete assessment on all major task or activities. Concentrating on only one activity will reduce task diversity, differences in preventive mechanism and the level of hardware technology as well as operator's skill requirement to carry out such activity safely and efficiently. It will also make the investigation and the following analysis more manageable within the scope and time available to conduct the research. Providing common background for the selected activity for both installations will minimise the influence from other variables that are not directly related to human error.

3.6.9 Conducting Human Error analysis

The next step is to conduct human error assessment on the selected activity using an established human error predicting technique SLIM at both MHI. The emphasis again is familiarisation on the usage of the technique especially on its concept, approach and methodology. This step is expected to be given a lot of attention due to lack of exposure in conducting such assessment. Adequate training will be sought from the technique's proprietor. Expert advice from human error specialist probably needs to be sought to ensure completeness of assessment.

Once again close cooperation from the plant's management is essential, especially from the operators which carry out the designated task. A briefing session will be carried out to the supervisors and operators involved to prevent undue stress working under close observations. Similar to the QRA analysis a checklist will be developed to ensure consistency in carrying out this human error analysis on both MHI.

3.6.10 Comparing Human Error Analysis results.

This step involves the analysis of results on human error analysis for both installations. Due to significant differences in areas like operational procedures, maintenance standard, operator's knowledge and skill, work incentives and motivation as well as management control, it is expected the level of human reliability between the two plants will be different on the activity under consideration. Judgement is then needed to be made to estimate whether results from analysis on specific task or activity could represent the overall standard of human error for both installations. Findings from this exercises will be used to support the hypothesis that has been set earlier i.e.;

- Human error does contribute to the risk level of an MHI.
- The MHI managed according to multinational style have smaller human error probability in one of the activity under investigation i.e. loading and unloading operation compared to the locally managed one.

3.6.11 Analysing the contribution of PSMS performance and Human Error to off-site risk

In this step the contribution of human error and PSMS and the overall plant risk level will be investigated. The contribution of two human factors areas in PSMS auditing namely OP/HF and MAINT/HF will provide a good starting point to investigate a possible correlation between PSMS and Human error. However the two factors only represent a portion of a complex interaction between the two. While human error has significant contributions to PSMS it also has direct contribution to QRA on its own.

One possible approach is to further decompose the interplay of human error at managerial, organisational and operational level as described by the Kennedy Report (1979) and quantifying human reliability as part of the system's overall reliability as proposed by Cox (1991) and Embrey (1992). Specific attempts will be made to link the contribution of human reliability with the site specific PSMS. Results of the PRIMA audit and Human Error analysis as well as experienced in conducting both exercises at the two sites will be scrutinised in order to look for possible linkage.

3.6.12 Developing a procedure to link the analysis of PSMS and Human Error

The final step is looking at the possibility of linking the assessment of PSMS and Human Error at a particular site. This represents an initial attempt to follow through suggestions made by Reason (1989) for an integrated approach to analyse accidents and human error, as the root causes do not appear to belong exclusively to any one domain i.e. hardware, software or liveware. Information and data gathered from the field study will be used together with extensive literature reviewed to come up with some form of procedure.

3.7 Conclusion

The research involved the application of knowledge from three distinct types of subject i.e. Safety Management System, Human Error and Risk Assessment. It attempts to explore at overlapping boundaries of contributions between system hardware, human error and safety management on risk. The comparative study conducted on two major hazard installations provides a means to investigate the interplay between them in a real situation. The fact that the two sites under investigation were in Malaysia provides additional dimension to the study. While there have been many attempts to look at it from developed countries' perspectives (mainly in the nuclear industry) this study is believed the first one to address the situation prevailing in developing countries.

Process Safety Management Audits on Three Major Hazard Sites in Malaysia

4.1 Introduction

The majority of MHI in Malaysia were built after the discovery of large quantities of gas and petroleum in the eighties. They comprise mainly of gas processing plants, petroleum refineries, petrochemical complexes and some related downstream chemical plants. These MHI are operated by large companies, either belonging to multinationals or large national corporations. Having significant experience in dealing with hazardous operations these companies normally have good PSMS installed on site. They have proper safety organisations and adequate resources in place to manage the risk associated with the sites' operations (Nanyan, 1987).

However there are also small numbers of MHI which are operated by small companies, mainly locals. These sites operate simple processes such as chemical blending operations, bulking and bottling operations of chemicals and petroleum products. The sites PSMS is characterised by lack of effective organisation and inadequate resources to effectively manage risk that arised from the sites operation (DOSH, 1994.)

4.2 The PRIMA Audit

PRIMA is an audit tool for the assessment of PSMS performance (Hurst et al, 1996). The technique was initially developed to incorporate site specific safety management system quality into quantitative risk assessment. Since then it has undergone further development including on the audit materials, primarily the question sets and anchor points. Trail audits have been conducted in the U.K and the audit version produced following the audit and used in field trials at a number of European countries was referred to as PRIMA (Hurst, 1996).

PRIMA was developed from a number of concepts, research studies and classification schemes which include analysis of loss of containment accidents, a sociotechnical model of accident causation, a control and monitoring loop model of safety management and audit themes. It consists of eight key audit areas namely;

- Hazard review of design (DES/HAZ)
- Human factor review of maintenance (MAINT/HF)
- Checking/Supervision of maintenance tasks (MAINT/CHEC)
- Routine inspection and maintenance (MAINT/ROUT)
- Human factors review of operations (OP/HF)
- Checking/supervision of construction/installation (CON/CHEC)
- Hazard review of operations (OP/HAZ)
- Checking/supervision of operations (OP/CHEC)

The following tools have been developed for PRIMA which could be used to assist the auditor in carrying out the audit;

- A model of an ideal PSMS defined by the control and monitoring loops
- A set of four key themes within each audit area
- A question set
- An audit manual
- A calculation method to generate the modification factors

As the PRIMA technique was developed primarily based on the European experiences, this study set out to see if it could work in developing countries like

Malaysia. The existence of multinational and small local companies operating MHI in such countries allows analysis to be carried out to compare and contrast the PSMS management performance between the two. Strengths and weaknesses in the application of the technique could also be identified from a developing country perspective.

4.3 Conducting PRIMA audits in Malaysia

As the PRIMA audit technique is quite new to Malaysia a significant amount of groundwork needed to be carried out to ensure a reasonable degree of audit standard achieved as what the technique is intended for (Basri, 1996). As an example training sessions had to be conducted to familiarise the Malaysian auditors with the theoretical and practical aspects of its application. The following steps were taken as groundwork to the audit;

4.3.1 Conducting training for the Malaysian audit team

The auditors were made up of three DOSH Inspectors with Major Hazards auditing experience between three to eight years. The training was conducted by the author and lasted for about two weeks. It covered the theoretical aspects of the technique and practical aspects of its application. The theoretical aspects include explaining the sociotechnical approach used to develop PRIMA and the statistical background that provided the weightings for the Modification Factor used for the quantification of PSMS performance. The practical aspects covered previous experience conducting the audit by a number of researchers in the U.K. and Europe (Hurst et al, 1996). Due to time constraint no specific pilot audit was conducted, however a considerable time was allocated for practice on the first day of the actual audit at Site A.

4.3.2 Providing keywords to PRIMA audit questionnaires

The existing audit questionnaires were found to be quite lengthy and were judged not suitable to be asked in their entirety in a country where English is not the first language. It was felt necessary to simplify the questionnaires by providing keywords for each question and posing them using simpler sentences. This arrangement helped both the auditors and the interviewee to focus quickly on the gist of the questions using short sentences. For the category of personnel like fitters and operators a translation to Malay, the local language was found to be necessary. A sample of keyword for the audit questionnaires is shown in Appendix 1.

4.3.3 Preparing a structured answer sheets.

The requirements to conduct the horizontal and vertical slices during the audit meant that responses from a number of personnel for similar questions need to be noted down to assist in the forming of audit judgement. As the existing questionnaires lack space for this purposes a structured answer sheet was developed to facilitate the process. This arrangement facilitated quick cross references to be made between responses from various personnel on a particular question and assisted the judgement making process. It also allowed each member of the audit team to note down the answers given by an interviewee systematically and facilitate the comparison of notes between team members when making judgement on a particular key issue. A sample of the answer sheets made for audit questionnaires is shown in Appendix 2.

4.3.3 Selecting MHI for PRIMA audits

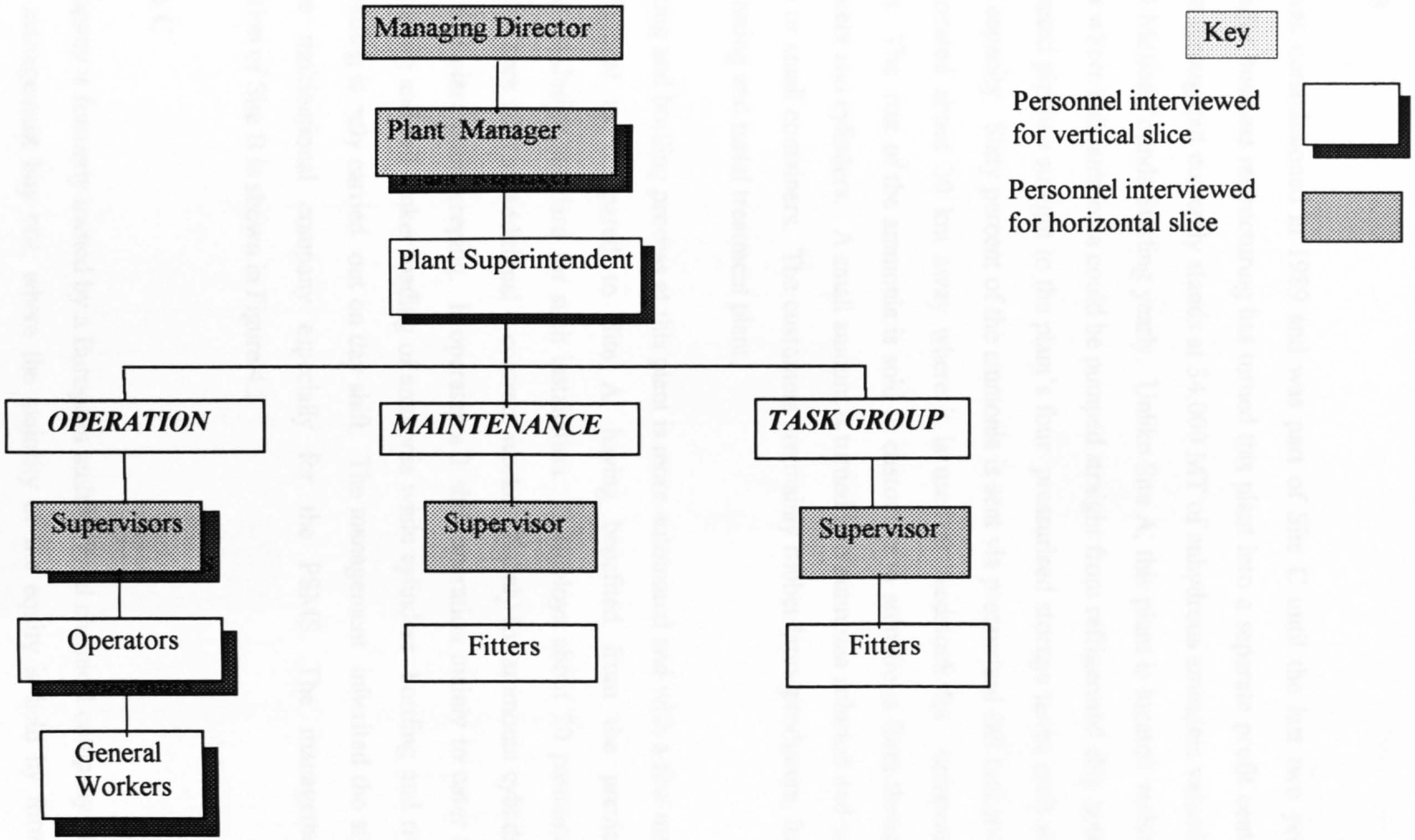
Three MHI sites were selected for the audits. Two of the sites handle ammonia for downstream distribution while the other uses ammonia as feedstock to make compound fertilizers. The main risk from the three sites is from toxic releases of ammonia gas. Such similarity provides common background as far as the type of risk is concerned. This allowed the comparison of PSMS performance to be made on more equal basis. A brief description of each site is given as follows:

i) Site A

Site A is an anhydrous ammonia bulk terminal which has an annual throughput of about 12,000 metric tonnes per year with sales value close to 4 Million Pounds Sterling. It basically runs ammonia bulking and bottling activities and has been in operation since 1985. Ammonia is brought into the terminal via low pressure refrigerated ships from producers and pumped into onshore pressurised storage tanks through a dedicated pipeline running along the berthing jetty. The two 225 metric tons (MT) capacity storage tanks near the jetty area serve as holding tanks where the whole load of the ship could be discharged in one go. The ammonia is then transferred on demand using road tankers to two 125 MT storage tanks at the bottling plant located about three kilometers from the jetty. At this location the bulk ammonia is filled into smaller skid tanks, cylinders and dedicated road tankers to be sent then to customers throughout Malaysia and the neighbouring countries like Singapore, Indonesia and Sri Lanka. Customers consist mainly of rubber latex processing factories where ammonia is used as an anti coagulant agent, electricity generating plants where it is used for anti-pollution treatment, and food manufacturing plants where it used to provide the protein chain for food additives.

The bottling and bulking process is fairly straight forward using simple technology and a high degree of manual operations. The plant was designed and constructed with minimum automation and process control. There are about twenty process workers and five office staffs headed by a Plant Manager. The plant operates only during the day, except for ammonia unloading from the ship which may be carried out at night depending on the availability of time for berthing at the Tanjung Bruas Port jetty. The management style adopted by the sites could be described as typical of a family owned local companies. Organisation chart for Site A is shown on Figure 4.1.

Figure 4.1 Organisation Chart for Site A



ii) Site B

Site B was commissioned in 1989 and was part of Site C until the last two years where major business restructuring has turned this plant into a separate profit centre. The plant throughput currently stands at 34,000 MT of anhydrous ammonia valued at about 10 Million Pounds Sterling yearly. Unlike Site A, this plant is located within a port area where bulk ammonia could be pumped straight from refrigerated ship tanker via dedicated pipeline straight to the plant's four pressurised storage tanks each with 125 MT capacity. Sixty percent of the ammonia is sent via pressurised rail tankers to Site C located about 30 km away where it is used as feedstock for compound fertilisers. The rest of the ammonia is sold to customers in anhydrous form through road tankers and cylinders. A small amount is turned into ammonia solution and sold in drums or small containers. The customers are mainly rubber latex producers, food manufacturing and metal treatment plant.

The bulking and bottling process at this plant is more automated and with a few more safety features as compared to Site A, having benefited from the previous multinational design standard for such installation. It employs about 20 permanent process workers with an additional 6 contract workers mainly for ammonia cylinders stacking and plant housekeeping. It operates a 3 shift operation mainly to cater for ship unloading and rail tanker loading of ammonia while cylinders bottling and road tanker loading is only carried out on day shift. The management inherited the style from the multinational company especially for the PSMS. The management organisation of Site B is shown in Figure 4.2.

iii) Site C

This company is formerly owned by a European multinational chemical company until a local management buy out, where the majority of the equity is held by former employees of the company in November 1994. The company started operation in September 1966 as the first compound fertiliser plant in Malaysia that used the ICI process technology at that time. Now the plant is fully managed by locals but still

Figure 4.2 Organisation Chart for Site B

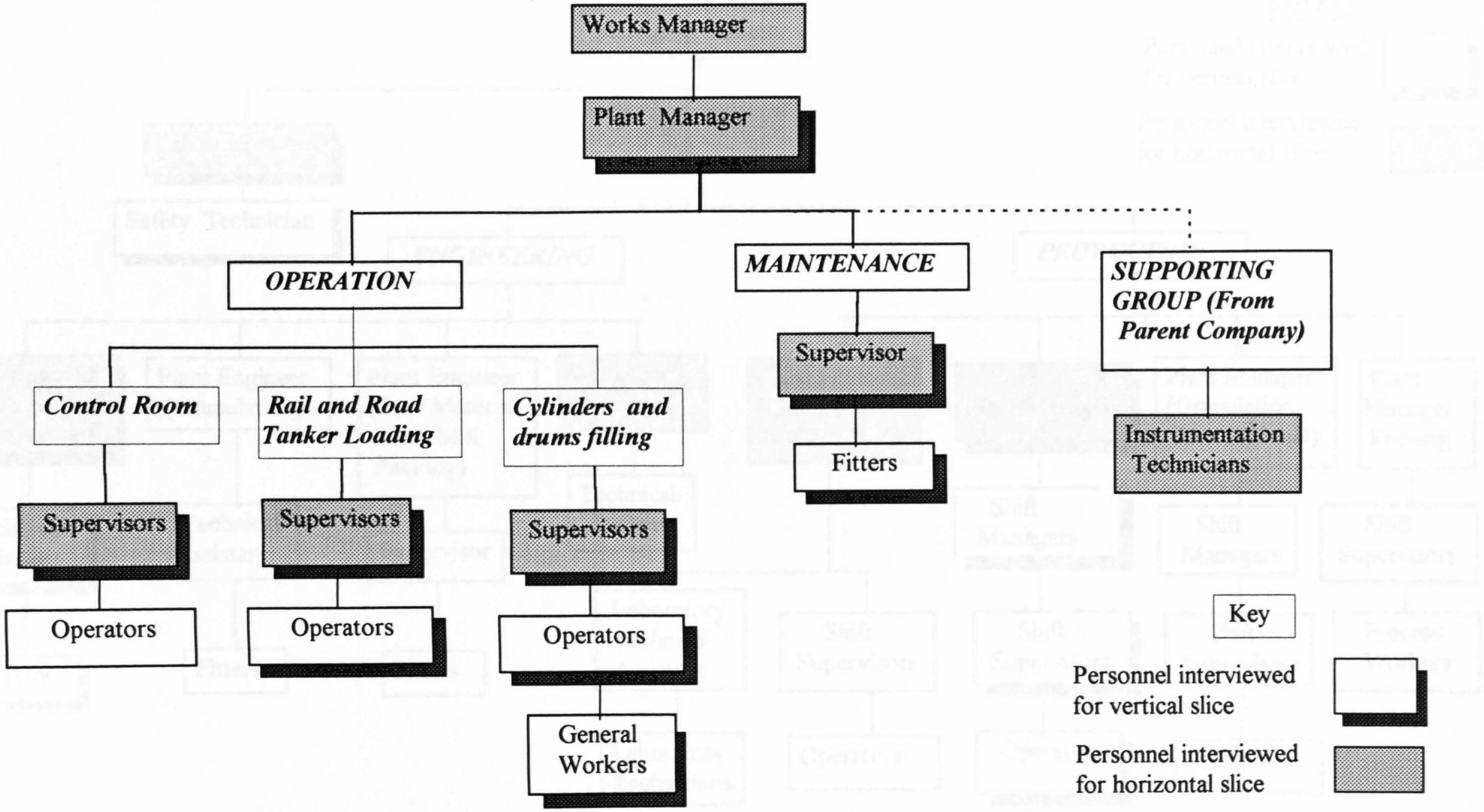


Figure 4. 3 Organisation Chart for Site C

follows very closely the safety management style inherited from the previous multinational owner. The works currently consists of the following plants on its site;

- A nitric acid plant with production capacity of 75000 MT per year
- A granulation plant with production capacity of 240000 MT per year
- A paraquat and gramoxonne plant with production capacity of 2400 MT and 10 million litres per year respectively
- A packing plant with large storage facility

The operation of each plant is headed by a Plant Manager supported by the so called engineering groups each headed by a senior engineer which basically provides maintenance services for respective plants on site. The works is headed by a Works Manager who reports to the Managing Director. Safety Department is not under the Works Manager and is headed by a Safety Manager who reports direct to the Managing Director. The works employs 316 permanent staff and working 24 hours per day, 7 days per week on 3 shifts.

Ammonia that is used as feedstock for the nitric acid plant is supplied by its sister company Site B at Port Klang by pressurised rail tanker each with 50 MT capacity. The liquid ammonia is then stored in a pressurised 600 MT sphere which is semi-refrigerated. The nitric acid is then converted into ammonium nitrate which is then mixed with other compounds to make the fertilisers. The fertiliser plant uses almost 20 years old ICI technology but the level of automation and process control is considered adequate with minimum upgrading. The current management style especially the PSMS still largely follows the system that has been set by the former multinational owner. The management organisation of Site C is shown in Figure 4.3.

4.3.4 Pre-Audit Plant Familiarisation

The three MHI sites selected are registered work places under the OSHA, and DOSH have kept records of each site which includes hazardous inventory, process layout, critical vessels and piping diagram, accident records, up to date safety and health inspection records, management organisation charts and emergency response plan. Such information provided valuable background knowledge for the pre-audit plant familiarisation. This did shorten the time required for the actual site familiarisation. So more time could be spent on the interview, task observation and assessing procedures and safe system of work.

4.4 Conducting PRIMA Audits

After the background works had been completed the actual audit was then conducted. A consistent approach was taken to ensure each site being audited in the same manner. For each site the following audit steps were taken;

4.4.1 Management Briefing

This briefing was to explain to the management the purposes and objective of the audit. It would be an academic exercise in nature and any shortcoming and possible violation occupational safety and health law discovered would not result in legal action. This was essential as the audit team consisted of enforcement officers from DOSH. The site management was asked to give a short briefing on the current PSMS organisation and issues, and activities carried out at the site. This was to ensure that the audit would take into consideration the latest site situation. The management and worker representatives were told in advance on the scope of the audit, level of personnel likely to be interviewed and documents to be verified.

In essence the briefing was trying to convince the management and workers that the audit was intended for research purposes aiming to evaluate the effectiveness of the site PSMS. This briefing also provided essential safety and security arrangements that needed to be adhered to by the audit team.

4.4.2 Plant Familiarisation

This step represents the actual site visit to familiarise the audit team with the plant process layout, activities carried out on site, means of communication, safe system of work installed, the usage of work procedures and permit to work, and wearing of personal protective equipment when carrying out hazardous tasks. It is one of the most important steps in the audit as it gives a snapshot of the site activities and the current situation of the PSMS installed on-site. Sufficient time needed to be allocated for this purposes especially for a large site. The pre-audit plant familiarisation was found to be a big help.

4.4.3 Conducting Interview

The interview was conducted using the PRIMA questionnaires set which has been improved to facilitate the process in view of the local situation as mentioned in section 4.3.2 previously. The PRIMA audit manual was constantly referred to throughout the exercises to ensure consistency with the technique approach and requirements.

As it would not be practical to interview all workers, only a number of them were selected for interview. The selection is made based on the site work organisation and was made as such to represent the so called 'horizontal slice' and 'vertical slice' of the organisation as suggested by PRIMA audit manual. The horizontal slice involved carrying out formal interviews with managers who have influence and duties in the areas of forming and implementing policy in relation to the activities under scrutiny for example establishing organisational arrangements and managing the relevant systems and procedures. For the vertical slice individuals in the chain of command who are responsible to deliver engineering reliability and operator competence that included shift managers, supervisors, operators and technicians were interviewed.

For the vertical slice the same sets of questions were asked to the shift manager, supervisors, operators and general workers who belongs to the same department e.g. the operation or maintenance department. The purpose is to get a cross section view right from the shift manager to shop floor workers on a particular issue. Conflicting answers between this group of interviewees indicated problems with the site PSMS which needed to be analysed in detail. As an example the shift manager feels very strongly the need to adhere strictly to operating procedures, but the shop floor operators think otherwise as the procedures are poorly written to assist them in carrying out the operations. This vertical slice approach was able to highlight conflicts within a department in trying to adhere to the PSMS installed on site.

As for the horizontal slice a number of similar questions were asked to the group of personnel who are responsible in the areas of forming and implementing policy in different departments. For example questions on the implementation of permit to work system were asked to the operation manager and to the maintenance manager. As both of them were implementing the same permit to work system e.g. for the maintenance crew to check certain operational equipment, the answers obtained from the two managers were able to highlight whether there existed conflicts in the use of work permit system between the two departments. This horizontal slice approach is able to highlight the inter departmental problems and conflicts in trying to adhere to the PSMS installed on site.

The selection of personnel to be interviewed was also made in such a way it represented the best representation of each site's PSMS. At the top of the site management hierarchy the Managing Director or the Works Manager was interviewed. The vertical slice is made up of personnel from the Operation Department because it has the largest hierarchy on site and they performed critical tasks that were judged would give significant impact on off-site risk. For the horizontal slice purpose personnel from other department such as the Maintenance, the Technical Services and Safety personnel were interviewed depending on the arrangement of the PSMS organisation available on site.

Personnel interviewed for the vertical and horizontal slice for each site is shown in the respective organisation chart in Figure 4.1, Figure 4.2 and Figure 4.3. To ensure frank answers made available especially from the lower rank personnel all the interviews were conducted in a closed room without interference from the management. Where permission was granted, both from the management and the individual, the interviews were recorded using audio tape to assist the audit team. The interview process was found to take the largest portion of the audit time. However it was essential as it provides the insight of the site PSMS performance from the policy maker down to the shop floor operator. It also identified areas of conflict between workers and management that impact on the site PSMS.

4.4.3 Document verifications

The types of document verified were those relate to the successful implementation of the site's PSMS. This includes safety policy and organisation, operating procedures, maintenance procedures and records, permit to work system, accident and near miss records and result of previous internal or external safety audits done at the site. The verification exercises served two purposes. First to confirm that written documents referred to during the interview exist and those who require them can have easy access. Secondly to assess the 'quality' of the document itself in term of depth of coverage, usefulness of content and the ease of use to the intended target group for example the shop floor operator. Given the nature of the audit it would not be possible to verify all documents so priority was given to those associated with high risk activities and those found to be a source of conflict or concern by workers and management during the interviews.

4.4.4 Site inspection

Site inspection carried out differed from site familiarisation in terms of details. For the site inspection the conditions of plant housekeeping, critical vessels and pipework, safety systems installed and personal protective equipment provided on site were inspected in detail. Observation of critical tasks carried out on site also included checking whether it followed the correct procedures, to identify possible violations and to estimate the duration taken to complete critical tasks such as loading of ammonia to road tanker. The time required to complete a critical task gave some indication of time pressure to carry out the task given the production target set by the management. Another important area was inspecting the availability of work procedures on site, the implementation of permit to work system, the operator/hardware interfaces, and the effectiveness of communication within department and between departments. We found this step of the audit is very important in order to make sound judgement of a site PSMS performance because it revealed what actually happened on the ground. A certain degree of bias was detected for example due to operator consciousness when work under observation. Audit team member knowledge and experience in chemical process plant inspection plays a very important role at this stage.

4.4.5 Formed Judgement

Culminating the PRIMA audit exercise was making judgement on the site PSMS performance. Judgements were made based on the information gathered from all the steps described above. The judgement formed for each key audit area is translated into PRIMA management control loops. For this purpose the audit team had to sit down together shifting through answers from questionnaires, refer to related documents, recall site observations and inspections' findings. At all times the process had to refer to the various anchor points that made up the PRIMA audit control loop as shown in Figure 4.4. Our experience shown that this is the most difficult part of the audit and adequate time needs to be set aside. Sometimes further verifications were required from workers and management on areas of conflict. Additional verifications were sometimes needed of important document such as operating procedures and accident records. At times additional inspections on plant condition and extra tasks observation needed to be carried out to bridge missing information needed to make sound judgements. However by closely referred to the audit manual, the ideal model of a PSMS control loop and the definition of anchor points provided as shown in Figure 4.5, a reasonable judgement was reached between the audit team members. Management control loops for each key audit areas were drawn up at the end of this judgement making exercise.

4.4.6 Post-audit management briefing

This post audit briefing is aimed to let the management and worker representatives know the results of the PRIMA audit. The briefing was broad in nature and mainly outlined the key strengths and weaknesses of the PSMS. The management control loops of the eight audit key areas were shown and explained to them. Some suggestions for improvement were given. Great care had to be taken in making the presentation as not to create issues that could be exploited by other parties to jeopardise the site's industrial relations.

Figure 4.4 - PRIMA Audit Anchoring Control Loop

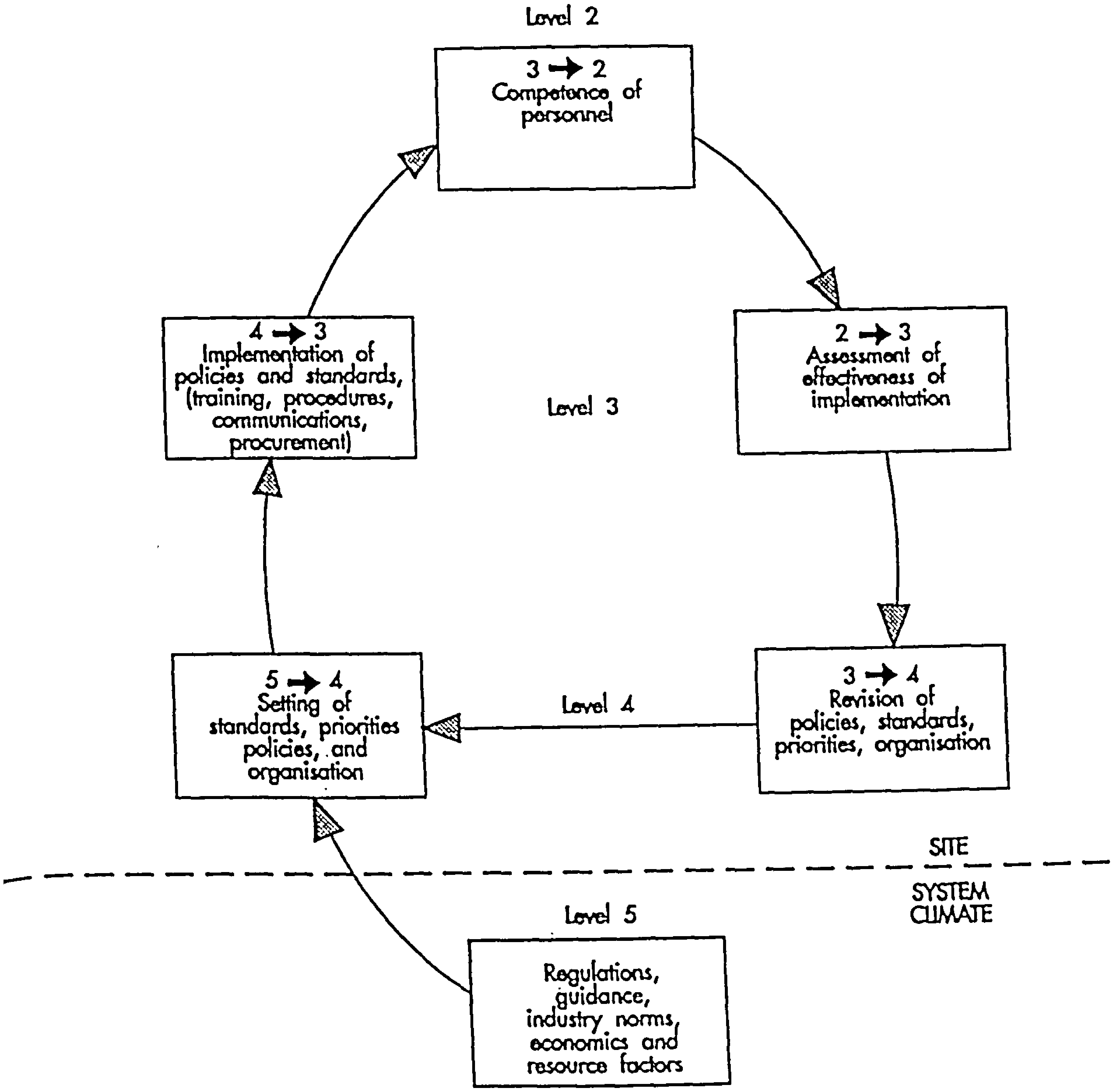


Figure 4.5 Definition of Anchor Points for Control Loop

1. GOOD

- PSMS fully represented by Control and Monitoring Loop diagram
- Little evidence of weaknesses within any of the key elements
- The system components (boxes) and links (arrows) are in place
- The components and links are actively used
- There is complete integrity within the loop
- There is a continuous process for improvement

2. AVERAGE

- On the whole the PSMS is represented by the diagram
- Some evidence of weaknesses within the system components or links
- The components are in place and are normally used
- Incomplete integrity of the loop (system not used or used incorrectly)
- Process of continuous improvement contains weaknesses

3. POOR

- The PSMS rarely matched the Control Loop diagram
- Evidence of major weaknesses and absences of system components
- Not all system components and links are in place
- Ad hoc system may be used
- There is no integrity of the loop
- Process of continuous improvement absent or have major weakness

4.4.7 Audits Duration

The time needed to conduct the PRIMA audit for each site varies primarily due to the size of site under review. However from our experience the learning curve from the first site audit will cut short the time required to do the next audit. This was especially true when the audit team is relatively new to the technique. A summary of the duration taken to carry out various stages of the audit activities for each site are given in Table 4. 1.

4.5 PRIMA Audit Results

Discussion on PRIMA audits results for the 3 sites are made based on the PSMS control loops constructed from the audit team judgement for the eight key audit areas. In making the judgement, findings from the audit team members were discussed and summarised for each key audit area, as samples shown in Appendix 2. Detailed discussion of the results are given as follows;

4.5.1 PSMS Control Loops for the 3 Sites

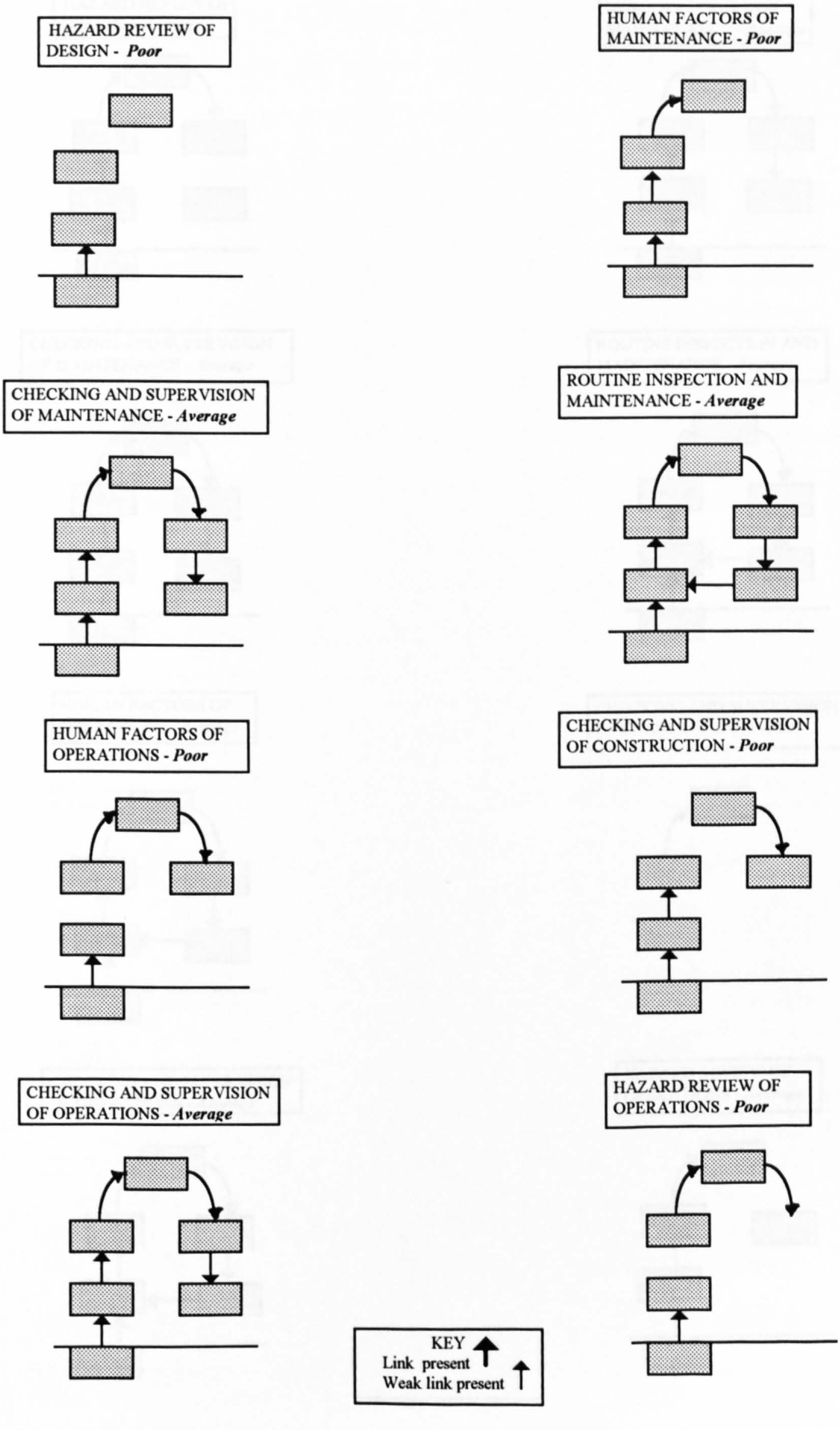
The PRIMA management control loops of all key audit areas for the three sites are shown in Figure 4.6 to Figure 4.8. The construction of the control loops for the three sites were made based on PRIMA PSMS Anchoring Control Loop shown in Figure 4.4 and the definition of anchor points for control loop as shown in Figure 4.5. These diagrammatical presentations are made of boxes and arrows that show the linkages. The existence of boxes means that there is evidence that the PSMS components under review (such as the monitoring and assessment of control system) are in place. The arrow line indicates the link between two PSMS components and the frequency of usage of the two. A thick arrow line indicates that there is evidence of strong linkages between the two PSMS components under review, i.e. it is regularly being used. A thin arrow line indicates a weak link, i.e. that they are only occasionally being used. The advantage of representing the state of PSMS components in diagrammatical form is that it captures the performance of the site PSMS in a simple format that is easy to understand.

Table 4.1. PSMS Audit activities and duration

Activities	Site A (no.of days)	Site B (no.of days)	Site C (no.of days)
1. Management briefing and plant familiarisation	1	1	1
2. Conducting audit interview on PSMS for vertical and horizontal slices based on PRIMA questionnaires	7 (9 personnel interviewed)	6 (9 personnel interviewed)	8 (13 personnel interviewed)
3. Verification of document related to PSMS	1	1	1
4. Physical inspection on safety, operation and maintenance system installed on site.	1	1	2
5. Discussing on preliminary findings of the audit interview with other team members with the aid of answer sheets and tape recorders	2	2	2
6. Forming initial judgement on PSMS control loop based on results of the interviews, document verifications and plant inspections	1	1	2
7. Presentation of the preliminary audit finding to the plant management	1	1	1
TOTAL DAYS SPENT	15 days	14 days	17 days

A quick glance at the control loop diagram will tell the strengths and weaknesses of a site's PSMS that could assist in decision making. A site management could use the control loops to assess the state of the site's PSMS, identify problem areas and then implement a strategy to improve them using available resources. For a regulatory agency like DOSH the weaknesses of a site PSMS component as identified from the control loop will be the area that needs closer attention and the site management will be asked to give top priority to improve them within a specified period.

Figure 4.6 PRIMA Control Loops for Site A



HAZARD REVIEW OF DESIGN - *Poor*

HUMAN FACTORS OF MAINTENANCE - *Poor*

CHECKING AND SUPERVISION OF MAINTENANCE - *Average*

ROUTINE INSPECTION AND MAINTENANCE - *Average*

HUMAN FACTORS OF OPERATIONS - *Poor*

CHECKING AND SUPERVISION OF CONSTRUCTION - *Poor*

CHECKING AND SUPERVISION OF OPERATIONS - *Average*

HAZARD REVIEW OF OPERATIONS - *Poor*

Figure 4.7 PRIMA Control Loops for Site B

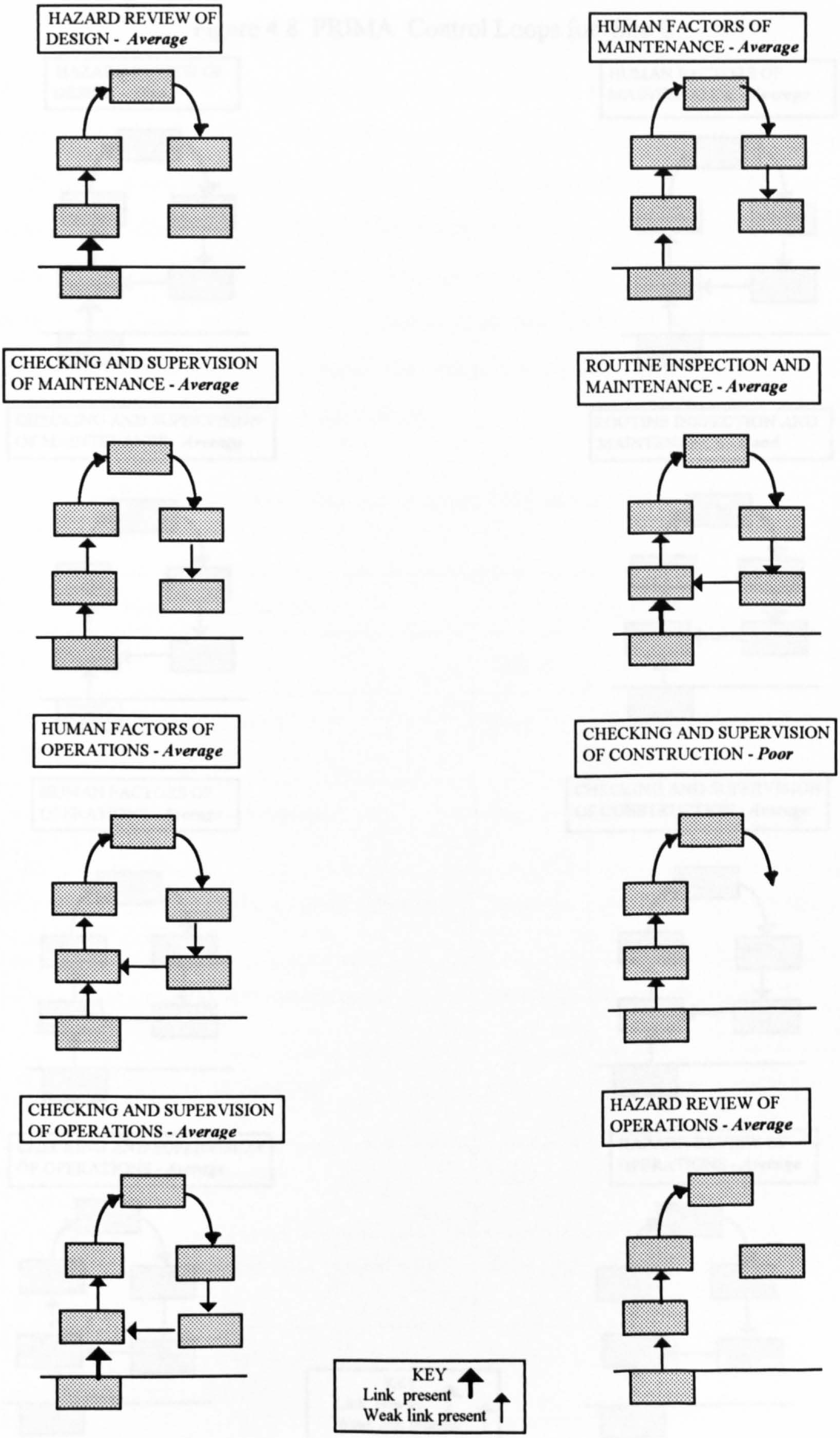
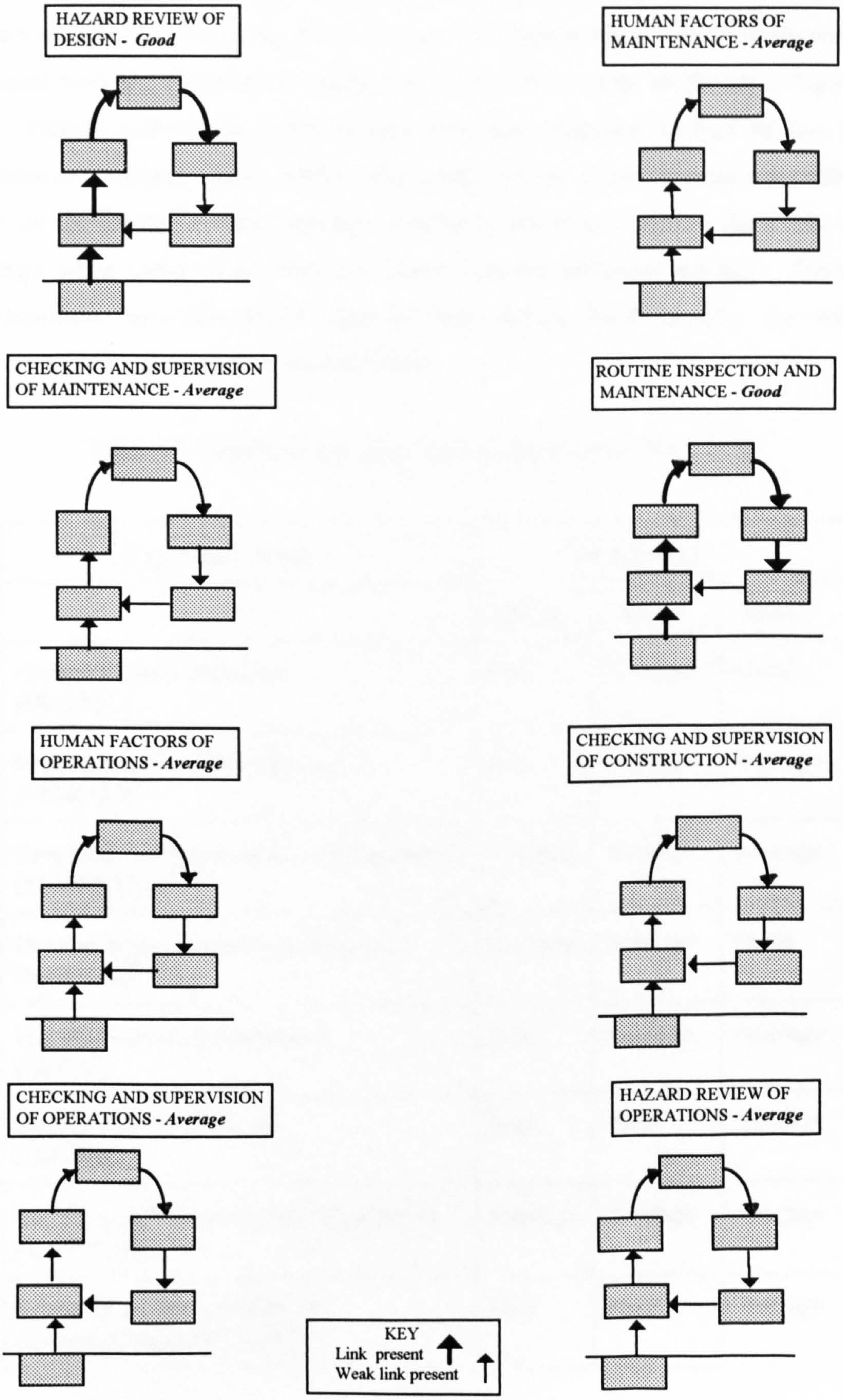


Figure 4.8 PRIMA Control Loops for Site C



4.5.2 Summary of PSMS Audit Results for the 3 Sites

The summary of PRIMA audit results on eight key audit areas for all the sites is shown in Table 4.2. The rating Poor, Average and Good in PRIMA audit rating were assessed from the definition of anchor points for control loops as shown in Figure 4.2. PRIMA audit derived these ratings were from statistical analysis of loss of containment incidents (Hurst, 1994). The rating Poor in a simple term means that they are below the industrial average, Average means about equal to the industrial average while Good means they are better than the industrial average. Closer examinations show that Site A fared the worst among the three sites, i.e. with highest number of key audit areas rated Poor .

Table 4.2 Results of Key Audit Areas Judgement for the 3 Sites

Key Audit Areas	**Judgement**		
	Site A	Site B	Site C
Hazard Review of Design (DES/HAZ)	Poor	Average	Good
Human Factors of Maintenance (MAINT/HF)	Poor	Average	Average
Checking and Supervision of Maintenance (MAINT/CHEC)	Average	Average	Average
Routine Inspection and maintenance (MAINT/ROUT)	Average	Average	Good
Human Factors of Operations (OP/HF)	Poor	Average	Average
Hazard Review of Design (OP/HAZ)	Poor	Poor	Average
Checking and Supervision of Operations (OP/CHEC)	Average	Average	Average
Checking and Supervision of Construction(CON/CHEC)	Poor	Poor	Average

Site B has more key audit area components which were judged to be average. Only two key audit areas were judged to be poor. Site C was judged to have the best PSMS performance among the three sites. Two of its key audit areas were judged to be good while the rest were judged to be average.

Discussions on results of PRIMA audit for each site is presented below. The discussions are centred around the strengths and weaknesses of the PSMS components.

i) Site A

Site A was found to have the weakest PSMS. The site overall PSMS was judged to be Poor. For key audit areas namely OP/HF, OP/HAZ, CON/CHEC, DES/HAZ and MAINT/HF were rated poor. These audit areas are concerned with hazard reviews, checking and supervision and the control of human factor in design, construction, operation and maintenance. Typical of a small time operator in Malaysia they have little knowledge and experience in all those areas. The design and construction of the plant for example will be left entirely to foreign companies with very little input from the operator especially for hazard review of design and safety checking and supervision during construction. The control of human factors using specific approach is unheard of. Minimum effort is given to proper documentation such as written procedures, permit to work system and emergency response plan. The site strength lies in the less formal structure of the management organisation that allows effective communication between the managers and workers. It also allows the implementation of 'multi-skilling' where supervisors and workers' duty are rotated i.e. from maintenance to production vice-versa over a three months period.

ii) Site B

Even though Site A and Site B carry out a similar process i.e. handling of bulk quantities of ammonia their PSMS performances is quite different. Only two key audit areas at Site B i.e. CON/CHEC and OP/HAZ were judged to be Poor while the rest are considered to be of Average. Evidence from the audit finding indicated that the main reason the two audit areas are poor is the business restructuring exercise which turned Site B (originally part of Site A) into an independent business entity. This resulted in loss of experienced personnel which used to be sourced from Site A such as safety inspector, HAZOP reviewer and instrumentation technicians. However as far as safety system and safety organisation are concerned Site B undoubtedly has benefited from the good PSMS laid down by the previous multinational owner. The Site overall PSMS were judged to be Average.

iii) Site C

The best among the three sites, none of Site C key audit areas were rated poor. In fact two areas i.e. DES/HAZ and MAINT/ROUT were rated good while the rest rated as average. This site was built and run by a well-known European multinational chemical company for nearly twenty-five years. Even though it has been bought by a local company recently the new owner has retained the PSMS laid down by the previous owner. The site retained most of the experienced technical staff and shop floor operators. Safety related documents such as operating and maintenance procedures, permit to work, emergency planning, process and instrumentation diagrams are available and updated quite regularly. However there are a number of potential problems that could degrade the PSMS in the near future that includes downsizing of the workforce that will reduce the number of experienced operators and maintenance personnel in the near future.

4.5.3 Comparison of PSMS audit results between Sites

By examining the PRIMA audit results of the three sites the following comparisons could be made;

- Site A was found to have the weakest PSMS, while site C was the best among the three sites.
- Even though they belong to the same owner the PSMS at Site B is weaker to Site C. On closer examination of the audit results it was found Site B used to rely on maintenance specialist support from Site C. However, recent

management restructuring turned the site into an independent business entity which deprived Site C from having competent personnel to provide specialist maintenance support for them.

- Site B and Site C had benefited from good PSMS laid down by the previous multinational owner .
- Lack of written PSMS document is the most glaring difference between Site A and Site C. The strong emphasis on written documentation by PRIMA audit make the difference more obvious
- Apparent weakness in managing human error at all sites. While there has been some form of control method (e.g. ergonomic consideration for control panel layout to manage human factors) they were ad-hoc and not systematic
- Weaknesses in communication and feedback (level 3) were apparent at all sites, reinforcing the need for better communication within the organisation. This area was found to be a low priority in each site PSMS as it needs adequate resources to implement with low immediate returns as compared to production improvements.

4.6 PRIMA Modification Factors.

Ratings made on judgement of various key audit areas at each site provides a quantitative output called PRIMA Modification Factor. The factor can be used to calculate a failure rate which explicitly includes the assessed PSMS performance. A summary of ratings judged for various key audit areas for the three sites is shown in Table 4.2.

These qualitative ratings made during PRIMA audit are converted into a quantitative scale using findings from statistical analysis of a failure rate data database that covers some vessels and pipes (Hurst et al, 1994). The failure rate data is found to be lognormally distributed and to vary by about ± an order of magnitude. An analysis of loss of containment data reported through the HSE Reporting of Incidents, Diseases and Dangerous Occurrence Regulations (RIDDOR) (HSE, 1985) also indicated that a variance of one order of magnitude between the best and worst performing sites. This finding is supported by other researchers such as Taylor (Taylor, 1994) who found that incident rates of similar equipment could vary by a factor of 100. Based on these findings PRIMA scaling factor, x(i), used a value of ± 1 order of magnitude from median (2 orders of magnitude overall). This means that the use of generic failure rates (in lognormal scale) referred to an Average site as rated using PRIMA will have a zero rating in relation to a Poor site which has higher failure rate than average, and a Good site that will have lower failure rate than average. The formula used to calculate the factor is given as follows;

$$\text{Logfail}_{SMS} = \text{Logfail}_G + \sum_{i}^{i=8} a(i)x(i) \text{ .... equation (1)}$$

where;

Logfail_{SMS} is the(-$\log_{10}$) failure rate adjusted by the Modification Factor

Logfail_G is the(-$\log_{10}$) unmodified generic failure rate

a(i) is the weighting for each audit area

x(i) is the scaling factor; where Good = 1, Average = 0, and Poor = -1

$\sum a(i).x(i)$ is the (-Log_{10}) of the Modification Factor

A sample calculation is shown in Table 4.3. The calculation referred to rating for key audit areas for Site A as given in Table 4.2 and their associated weighted based on pipework failure in Table 4.4.

Table 4.3 Sample Calculation for Site A

Key Audit Areas	PRIMA Rating	Pipework Weighting a(i)	Scaling Factor x(i)	a(i)x(i)
Hazard Review of Design (DES/HAZ)	Poor	0. 25	–1	–0.25
Human Factor of Maintenance (MAINT/HF)	Poor	0.15	–1	–0.15
Checking and Supervision of Maintenance (MAINT/CHEC)	Average	0.13	0	0
Routine Inspection and Maintenance (MAINT/ROUT)	Average	0.10	0	0
Human Factors of Operations (OP/HF)	Poor	0.11	–1	–0.11
Hazard Review of Design (OP/HAZ)	Poor	0	–1	0
Checking and Supervision of Operations(OP/CHEC)	Average	0.02	0	0
Checking and Supervision of Construction (CON/CHEC)	Poor	0.08	–1	–0.08
$-\text{Log}_{10}$ Modification Factor (MF) = $\Sigma a(i)x(i)$ =				–0.59

Table 4.4 - Data base for weights (Bellamy, et al, 1989)

Audit Areas	Data base for weights (%), a(i)		
	Pipework	Vessels	Hoses
Hazard Review of Design (DES/HAZ)	25	29	19
Human Factor of Maintenance (MAINT/HF)	15	6	0
Checking and Supervision of Maintenance (MAINT/CHEC)	13	4	2
Routine Inspection and Maintenance (MAINT/ROUT)	10	11	15
Human Factors of Operations (OP/HF)	11	24	35
Hazard Review of Operations (OP/HAZ)	0	5	9
Checking and supervision of construction (CON/CHEC)	8	2	6
Checking and Supervision of Operations (OP/CHECK)	2	2	10

Assume a generic pipework guillotine failure rate (Logfail $_{SMS}$) of $1\text{x}10^{-7}$ /m /year,

Substituting values of a(i) and x(i) from Table 4.3 into equation (1);

$$\text{Logfail}_{SMS} = \text{Logfail}_G + \sum_{i}^{i=8} a(i)x(i) \quad \ldots\ldots\ldots \quad \text{equation (1)}$$

$$= 7 + [\,0.25 \times (-1)\,] + [\,0.15 \times (-1)\,] + [\,0.13 \times (0)\,] + [0.1 \times (0)] + [0.11\times (-1)] + [(0 \times (-1)] + [0.02 \times (0)] + [0.008 \times (-1)]$$

$$= 6.41$$

Modified failure rate = anti Log_{10} (-6.41)

= $\underline{4\text{x}10^{-7}\ \text{/m /year}}$

Alternatively;

From Table 4.3 we get,

$$-\text{Log}_{10}\,\text{Modification Factor (MF)} = \Sigma a(i)x(i) = -0.59$$

$$-\text{Log}_{10}\,\text{MF} = -0.59$$

$$\text{MF} = \text{anti Log}_{10}\,0.59$$

$$\text{MF} = 4$$

Assume a generic pipework guillotine failure rate (Logfail $_{SMS}$) of $1\text{x}10^{-7}$ /m /year

Then the corrected failure rate (Logfail_G) becomes;

Modified failure rate = generic failure rate x MF

$= 1\text{x}10^{-7}\text{x}\,4$

$= \underline{4\text{x}10^{-7}\ \text{/m /year}}$

Similar calculations were carried out using weightings from pipework, vessels and hoses data bases. Multiplying generic failure rate for specific component (e.g. a transfer hose) with the appropriate MF (in this case MF based on weightings from hose data base) yielded the modified failure rate for the component. The modified failure rate then is used as input for failure frequency in the QRA.

Results of PRIMA Modification Factors (MF) calculations for Site A, Site B and Site C are shown in Table 4.5. The calculations were made using three different sources of loss of containment data base as shown in Table 4.4. They show a difference of about a factor of ten between the worst site, i.e. Site A and the best site, i.e. Site C. This emphasises the need to consider site specific PSMS performance when carrying out the QRA for a major hazard site.

Table 4.5 Results of PRIMA Modification Factor Calculations

Data base for weighting	Site A	Site B	Site C
Pipework	4.0	1.2	0.45
Vessels	4.6	1.2	0.44
Hoses/Arms	4.9	1.4	0.46

4.7 Strengths and Shortcomings of PRIMA

Throughout the whole audit exercise we have identified a number of strengths and weaknesses of the technique. They will be discussed as follows;

4.7.1 Strengths

- The technique was developed based on sound theoretical and statistical basis. However the loss of containment data base needs updating.
- The audit questionnaires set is comprehensive and covers the necessary areas for PSMS audit. In fact some of the information made available from the questionnaires could be used for other purposes for example to carry out human error analysis.
- The use of management control loop provides an effective way to represent PSMS situation for each site.

- The technique provides a quantitative output in the form of PRIMA Modification Factor that can be used to modify generic failure rate for QRA.

4.7.2 Shortcomings

- Needs a thorough site inspection and document verifications in order to make sound judgement on the PSMS performance.
- Too much emphasis on written documents which may not be appropriate to the smaller site with a simple process.
- The questionnaires do not address explicitly the aspect of on-site and off-site emergency response plans which are crucial for major hazard sites PSMS.
- The need to rephrase the questionnaires in simple English or to translate it to the local language so they could be easily understood by lower rank personnel such as shop floor operators and fitters.
- The time required to complete the whole audit exercise is quite long i.e. from 14 days for a smallest site (Site A) to 17 days for the largest site (Site C).

4.8 Recommendation to improve PRIMA

Based on the experience in conducting PRIMA audit at the three sites the following recommendations are suggested to improve the technique. For easy discussion they are divided into headings as follows;

4.8.1 The Methodology

- There is a need to update the database used to determine the weights used to calculate the PRIMA Modification Factors. Ideally it should base on quite a large database of loss of containment from developing countries to reflect the design, construction, operation and maintenance standards of such countries.

- PSMS at Major Hazard site should include an effective on-site and off-site emergency response plan. PRIMA audit questionnaires currently do not address this factor explicitly.

4.8.2 The Audit Tools

- There are a number of overlapping questions in the questionnaires set, which need to be streamlined.

- As mentioned previously the questionnaires could be simplified by defining key words and build the question around it using simple sentences. This will be of a big help in countries where English is not the first language. At the extreme translation to local language might be necessary especially for lower rank personnel such as the shop floor operators and fitters.

- There is a need to develop computerised versions of the questionnaires with facilities to store answers for the questionnaires as well as findings from site inspection and document verifications. This will speed up the process of making judgement for the management control loops.

4.8.3 The Usage of PRIMA Audit

- A thorough site inspection and document review are essential in order to be able to make sound judgement on management control loop. Hence adequate time must be set aside for this purpose especially for larger sites.

- The technique places a very strong emphasis on written documentation. While this is essential for a large site with complex processes it is probably not totally applicable for a small site with simple process. Adequacy on written documentation should reflect the specific need of a particular site.

4.9 Conclusion

The PRIMA audits conducted on three major hazard sites in Malaysia is believed to be the first attempt to apply the technique outside Europe where it was originated. The technique was found to be suitable for use, albeit with some minor modifications. This could pave the way for further use in other developing countries where PSMS audit could become a useful tool to assist in the control risk from major hazard sites. The PRIMA Modification Factor made available from this technique can be used to modify the generic failure rate used for QRA. It will allow the performance of site specific PSMS to be considered in an explicit manner. Such factor is very pertinent in developing countries where there exist significant differences in PSMS performance, for example between multinationals and small local operators. The modified QRA result that takes into account a site specific PSMS quality will greatly assist the decision making process, for example for land-use planning to ensure the safety of workers and the public at large from risk of major hazard sites. Underestimating the risk will put human lives and limb at risk while an overestimate will deprive investors of suitable location to built their plant, resulting the loss of much needed investment and much needed job opportunity for a developing country like Malaysia.

Chapter 5

Conducting Human Error Analysis On Road Tanker Loading Operations

5.1 Introduction

Controlling the risk from major hazard sites requires the assessment of potential risk from the sites using a suitable approach such the Quantitative Risk Assessment (QRA). Such an assessment will identify, evaluate and quantify risks associated with the site operation from possible failures of the plant hardware such as process vessels and piping. Of late the assessment has been extended to 'software' failures that include human, management and organisational failures (Tweeddle, 1992). This is due to the fact that human error contributes to the high percentage causes of failures at chemical process plants (HSE, 1989). The analysis of human error will provide a better description of the human contribution to risk and identify ways to reduce them (Gertman, 1994).

5.2 Human Error Analysis

The quest to study human performance has lead to the analysis of human error. The foundations of human error analysis were basic research conducted in the experimental psychology and the behavioural sciences. It provides the taxonomies of behaviour, task analysis techniques, psychometric techniques, and the quantification of human error (Gertman, 1994). Many of the techniques have gathered data and provided mechanisms for estimating failure probabilities from these basic disciplines. In the last decade the number of quantification techniques has grown considerably, but none has universal acceptance (AChIE, 1988). It is left to the analyst's discretion to decide which technique to be used, eventhough a number of reviews and validation exercises (Humphrey, 1988 and Kirwan, 1988) could provide some guidelines.

5.2.1 Description of ammonia bulk terminals

The selection of ammonia bulk terminals for the study was made based on two main reasons. Firstly, the risk from major toxic gas release such as ammonia is time dependent and could reach wider population that makes it a critical input in land used planning. Secondly ammonia is used very widely in the rubber and fertiliser industries in Malaysia. Also ammonia bulking activities in Malaysia is currently being carried out by both big multinational and small local operators using about the same level of hardware technology. The last reason provides a unique scenario to explore and compare the influences of management and organisational on human error.

Full description of the two sites selected for the human error analysis was given in Chapter 4. Specific description of each site which focus on human factors is given below;

i) Site A

In brief Site A is an ammonia bulk terminal which has an annual throughput of about 12000 metric tonnes (MT) per year. It basically runs ammonia bulking and bottling activities and has been in operation since 1985. At this location the liquid ammonia is filled into road tanker, skid tanks and cylinders for downstream distribution. The bulking and bottling process is fairly straight forward using low technology and with a high degree of manual operations.

The plant was built loosely based on Japanese technology but most of the critical vessels e.g. storage tanks and piping system were fabricated locally. It is totally owned by a local company with a management and organisational style typical of a Malaysian medium size industry. The Managing Director is the main shareholder of the company and responsible for the overall control of the company. As he also runs a number of other companies the day to day running of the plant is carried out by the Plant Manager. During the audit period the Plant Manager had just resigned so his responsibility was taken by the existing plant engineer who will eventually take over the vacant post.

There are three main work sections at the sites, divided by the types of work that each carries out. The operation section carries out the ammonia loading from and to the road tanker, filling of ammonia cylinders and skid tanks and filling the liquid ammonia solution (aqueous ammonia) into plastic containers and drums. The maintenance section carries out inspections on the integrity of oncoming empty cylinders, drums, skid tanks and their associated fittings to ensure that they are in good condition for filling. They are also carry out scheduled and breakdown maintenance of the plant equipment and conduct pressure testing on cylinders and ammonia transfer hose at specific intervals. The Task Group is involved with ship tanker loading of ammonia to the holding tanks at the jetty and transporting the ammonia to Site A by road tankers. Currently the two sections i.e. operation and maintenance work only on day shift, while the Task Group has to work in shifts during the unloading of ammonia from ship. Workers in each section will be rotated to other section every three months or so. According to management such a system promotes 'multi-skilling' among the workers, reduces boredom and automatically rotates the workers to work night shifts for ship tanker unloading when they are assigned to the Special Task section.

The workforce of this plant mainly consists of able men in their late twenties. They were recruited fresh from school most with SPM qualification (an equivalent to the U.K. 'O' Level qualification). They were given on the job training that involved the attachment to senior workers or supervisor, learning the trade through observation and gradual hands-on involvement with a particular task. The attachment is made to all main work departments of the site i.e. operation, maintenance and special tasks. No fixed time period is set for a trainee attachment to a particular section. It depends on the ability of each trainee in learning the trade of a section. The emphasis is to carry out a particular task efficiently and safely. The trainee progress is assessed by the section supervisor and the plant manager through observation and interview. No written evaluations are carried out.

ii) Site B

Site B is another bulking terminal with an annual throughput of about 34,000 MT. The plant was commissioned in 1989 and served mainly as an import terminal for a large compound fertiliser plant located about 30 km inland. Liquid ammonia is discharged through dedicated pipeline straight from the ship tanker to the site's four storage tanks each with 125 MT capacity. Sixty percent of this load is immediately transferred to the fertiliser plant using pressurised rail tankers. The remaining ammonia is stored on-site and filled into road tankers, skid tanks and cylinders for downstream distribution. A small amount of ammonia is turned into ammonia solution (aqueous ammonia) and sold in drums and small containers.

The plant was designed, built and run by a European multinational until a local management buy out about two years ago. The process is basically similar to Site A and uses about the same level of technology. The difference mainly lies on the level of process automation and capacity which is slightly higher than Site B.

The management still inherited the style set by the previous multinational owner especially on site organisation, work division, production management and safety management. Under the new local management the site is put under the overall control of a Works Manager who are stationed at the company's Chlor-Alkali Plant located about 300 km away. Day to day running of the site is under the responsibility of the Plant Manager. He has the overall responsibility on the site personnel, production, safety and administration. He is authorised to spend a certain amount of money for the site expenditure but needs approval of the Works Manager on works that involve large sums of money such as major repairs, modifications or replacement of system of equipment which require large capital outlay. The Works Manager oversees the site through fortnightly visits and reports posted to him every week.

Training for new workers is conducted through the on the job method where they learn through observation and hands-on involvement under the supervision of experienced workers and supervisors. For new workers and outside contractors there are compulsory safety and emergency training. The basic training lasted about six months. The plant manager and supervisor assess whether they are ready to do certain jobs through observations and interview. After the basic training the workers are assigned to specific task i.e. operations, maintenance or services that becomes their long term career with the company. While this approach promotes worker specialisation it was found that it also created discontent among them. Over the year workers from the operations department i.e. the operator have a better chance of promotion as compared to their maintenance counterparts. They could rise to the post of Shift Manager while the maintenance could only move up to fill few maintenance supervisor posts. The low turnover of workers aggravates the situation. Post employment training is only given to those ranking as supervisors and on courses mainly related to quality and productivity and occasionally on health and safety.

5.2.3 Data collection for Human Error analysis

The observational technique was the main method used for data collection in this study. This technique was selected because it is able to collect physical task performance data, to capture social interaction and represent major environmental influences such as noise, light and interruptions (Kirwan, et al 1992). It also is suitable to be used in 'natural environment' as the field study, instead of a controlled and constrained environment as in a task simulator. Using this technique data is obtained by directly observing the activity or behaviour under study (Drury, 1990). The written notes made during the observation process were supplemented by audio-visual recording and verbal description from the operator of the decision processes taking place. Further clarification on critical points was made from reviewing relevant documents such the operating procedures. The activity associated with data collection that has been carried out at the two sites is shown in Table 5.1

5.4 Qualitative Analysis of Human Error

Qualitative human error analysis represents one of the most important aspect in assessing and reducing the human contribution to risk (AChIE, 1988). Such an analysis allows the identification of critical tasks that are greatly influenced by human error and the identification of performance influencing factors that influence such risks. It is also capable of predicting the specific errors associated with tasks or task steps and identify the means by which these errors could be prevented and recovered before they have negative consequences to risk. The scope and detail of this type of analysis depend on the objectives of conducting such analysis. For the purposes of this research the qualitative human error analysis have involved the following;

- Selection of hazardous tasks
- Task Analysis
- Performance Influencing Factor Analysis (PIF)
- Predictive Human Error Analysis (PHEA)
- Consequences Analysis
- Error Reduction/Recovery Analysis

5.4.1 Selecting a hazardous activity for PHEA

As the objective of the study is to compare and contrast possible human error at the two sites it is important to select a task that is similar in nature carried out at both sites. The following criteria was used for the selection;

- a hazardous task that could lead to major releases of ammonia
- high degree of human/operator involvement
- using about the same level of hardware/technology
- regularly conducted
- not a new task that has only recently been introduced
- not too complex which requires large resources for analysis
- historical data indicating that the task could lead to major releases of ammonia
- support from some form of ranking assessment

Table 5.1 Human error analysis activities and duration

Activities	**Site A (no. of days)**	**Site B (no. of days)**
1. Critical observation of high risk activities with high proportion of human involvement for selection purposes using TEACHER screening criteria	1.5	2
2. Observing step by step operation of the selected activities i.e. loading of ammonia to road tanker	1	1
3. Interviewing the operator, supervisors and plant engineer on ammonia loading activity	0.5	0.5
4. Analysing the written job procedure for ammonia loading with the aid of flow chart and PI&D	0.5	0.5
5. Videotaping the entire ammonia loading to road tanker activity assisted by verbal description of decision making process by the operator	1	1
6. Conducting preliminary task analysis	1	1
7. Checking and observing Performance Influencing Factors(PIFs) associated with road tanker loading	1	1
8. Discussing with the plant engineer and supervisor on the outcome of the preliminary task analysis and modifying them after obtaining further clarification on specific issues	1	1
TOTAL DAYS SPENT	7.5	8

There are a number of separate activities that are carried out at both sites that could result in the release of ammonia. These included bottling operation, ship unloading operations, rail tanker loading operation, and, road tanker loading and unloading operation. However for comparison purposes only one activity needs to be selected for the Human Error Analysis. The method used for the selection is SPEAR the screening technique that was put forward (Embrey et al, 1994).

The SPEAR screening process allows the identification of human involvement in a process which could yield to significant sources of risk if errors take place. A detailed discussion of this technique is given in Chapter 3. The process is important to identify all sources of risk on the plant and to reduce the amount of effort in applying other techniques by focusing on risks arising from operator involvement. The site visit allowed the development of an inventory of tasks with significant human involvement in the various areas of the plant and rating the associated hazard potential.

The three stages of screening process that have been carried out at Site A and Site B are:

- development of an inventory of operator tasks
- identification of a subset of critical task with risk potential
- prioritisation of the critical tasks on the basis of consequences

These three factors were assessed using a series of questions to produce an index in each case. The three indexes were then combined to give an overall index called the Potential Risk Exposure Index (PREI). Detailed calculation of this index is given in Appendix 3.

The result of PREI calculations for main activities at Site A is shown in Table 5.2. The ammonia loading activity to road tanker is ranked first with a PREI value of 0.88, followed closely second by the activity of filling ammonia into cylinders and drums with a PREI value of 0.81. The result of PREI calculations for main activities at Site B is shown in Table 5.3. The ammonia loading activity to road tanker is ranked first with a PREI value of 0.81. The calculations showed that the ammonia loading activity is with the highest PREI, suggesting that detailed analysis of the activity should be given the top priority. The use of the PREI was found to be useful in selecting critical activity that has high risk exposure to human error. The alternative approach like in the Dow Index looking at the potential risk solely from process point of view i.e. quantity of hazardous material, reactivity, temperature and pressure tends not to be able to assess the impact of human (operator) involvement to risk in a particular activity.

Discussion with the management and operators at the two sites also indicated this operation is quite critical and could lead to major release. In fact there has been major release at Site A during the loading operations of a lorry mounted tanker (FMD, 1992). In this incident about 1 metric ton of ammonia escaped from a skid tank during filling operation due to bursting of filling hose. The resulting ammonia travelled downwind more than a kilometre injuring about forty people living in the surrounding areas.

Table 5.2. Results of SPEAR Screening Analysis for Activities on Site A

Activity	**Intrinsic Hazards**	**Nature of Interaction**	**Frequency**	**Potential Risk Index (PREI) Score and Ranking**	
	IHS	**IVS**	**IFS**	**PREI Score**	**PREI Ranking**
1. Ammonia Bulk Storage Loading and unloading	1	0.43	0.8	**0.74**	**3**
2. Road Tanker/Skid Tanks Loading	1	0.64	1	**0.88**	**1**
3. Cylinders and drums filling	1	0.43	1	**0.81**	**2**
4. Aqueous solutions filling	0.5	0.07	1	**0.52**	**5**
5. Cylinders and drum checking, stacking and loading	0.75	0.14	1	**0.63**	**4**

IHS - Intrinsic Hazard Score = (S-2)/4

IVS - Intrinsic Vulnerability Score = (S-7)/14

IFS - Index of Frequency Score = (S-1)/5

PREI - Potential Risk Index = (IHS +IVS +IFS)/3

Figure 5. 3. Results of SPEAR Screening Analysis for Activities on Site B

Tasks	**Intrinsic Hazards**	**Nature of Interaction**	**Frequency**	**Potential Risk Index (PREI) Score and Ranking**	
	IHS	**IVS**	**IFS**	**PREI Score**	**PREI Ranking**
1. Ammonia Bulk Storage Loading and unloading	1	0.43	0.8	**0.74**	**3**
2. Rail Tanker Loading	1	0.57	0.8	**0.79**	**2**
3. Road Tanker/Skid Tanks Loading	1	0.64	0.8	**0.81**	**1**
4. Cylinders and drums filling	1	0.36	1	**0.79**	**2**
5. Aqueous solutions filling	0.5	0.07	1	**0.52**	**5**
6. Cylinders and drum checking, stacking and loading	0.75	0.14	1	**0.63**	**4**

IHS - Intrinsic Hazard Score = (S-2)/4

IFS - Index of Frequency Score = (S-1)/5

IVS - Intrinsic Vulnerability Score = (S-7)/14

PREI - Potential Risk Index = (IHS +IVS +IFS)/3

Analysis of historical data on loss of containment of hazardous materials by a number of researchers also indicated that the loading operations of road tanker represent one of the main causes of loss of containment (HSE, 1989 and Embrey et al, 1994).

Using the SPEAR screening method the road tanker filling operation at both sites was found to be the activity where the risk is heavily influenced by human error. This is further supported by judgement made by the auditor based on information gathered through task observations, interview of personnel, reviewing operating procedures and accident records on each site and findings from other studies that has been mentioned above.

5.4.2 Brief description of road tanker filling operation

The system of filling ammonia to road tanker for downstream distribution at both sites is almost identical. Detailed steps for the road tanker loading operation for the two sites is given in operating procedures described in Appendix 4. Basically liquid ammonia from the storage tank is pumped into the road tanker through a flexible hose connection at the filling bay. The back pressure developed during pumping operation is discharged back to the storage tank through the vapour return line. The filling continues until it reaches the target filling weight that has been pre-set based on the allowable ullage of the particular size of a road tanker. The road tanker is then disconnected from the filling bay, checked and sent to the customer after filling the necessary document.

Even though Site B was designed and equipped with Chiksan hard loading arm for top loading it could not be used as intended due to the different configuration of the current road tanker valve inlet that is designed for bottom loading. So additional flexible hoses had to be fixed to the end of Chiksan arm to accommodate the bottom loading.

Similarly even though both sites adopted the same system for road tanker filling there is some differences in term of operating procedures, safety system and the hardware being utilised. The differences were determined through analysis of site operating procedures, interview of operators, task observation on site and from video taping.

5.4.3 Task Analysis

After selecting an activity where risk is subjected to high degree of human error, the next step is to carry out detailed analysis on the activity, using a technique called task analysis. The objective of task analysis conducted in this study is to provide a systematic and comprehensive description of the task structure and provide insights into how error arises from tasks associated with ammonia loading operations to road tanker. The type of task analysis used for the study is called Hierarchical task Analysis (HTA) which has been widely applied in the industries (Kirwan et al, 1992).

HTA represents a wide approach to task analysis where the analyst needs to establish the sequence of various subtasks to be carried out to meet a system's goal. For this study the technique is used to produce a hierarchy of 'operations' which refer to tasks that need to be carried out by the operator within a system, i.e. ammonia road tanker loading operation, and 'plans' which refer to statements of conditions which are necessary to undertake the operations. Hence HTA provides an effective means to describe how work should be organised in order to meet a system's goal of loading ammonia to road tanker.

Using this approach the overall objective of the task under consideration i.e. loading of ammonia to road tanker was broken down to the level that could have direct implication on failures of a system or sub-system which eventually could lead to major releases of ammonia. This was carried out by successively describing the task of loading of ammonia to road tanker in increasing detail to the desired level. A plan is produced at each level that described how the steps or functions at each level were to be executed. The HTA provided a complete, structured, and detailed description for example of what the operator actually does during each of the loading sub-tasks being considered. With its structured hierarchical format HTA has considerable advantage over a sequential task description. The structured format also provided important input in managing human error such as for the improvement of training and operating procedures.

In order to concentrate on tasks that could lead to off-site risk there is a need to make further selection between the tasks that made up the ammonia loading activity. This would reduce the amount of analysis needed to address human error that posed little significance to off-site risk from the operation. For this purpose the SPEAR screening process was applied again to identify the critical tasks that involve human error that could lead to the releases of a large amount of ammonia.

Results of the second screening analysis on tasks that made up the ammonia loading activity is shown in Table 5.5 for Site A. The analysis identified the task of filling the ammonia road tanker with a PREI ranking of 0.88 as most critical in terms of the contribution of human error to off-site risk from ammonia loading operations. This is followed by the task of disconnecting road tanker from plant with a PREI ranking of 0.83. The task of connecting road tanker is third with a PREI ranking of 0.59. These three tasks will be subjected to detailed PHEA analysis as they are subjected to high degree of human error that could result in major releases of ammonia at Site A.

Results of the second screening analysis on tasks that made up the ammonia loading activity is shown in Table 5.6 for Site B. The analysis identified the task of filling the ammonia road tanker and disconnecting tanker from plant, both with a PREI ranking of 0.79 as the most critical in terms of the contribution of human error to off-site risk from ammonia loading operations. This is followed by the task of preparing the road tanker from plant with a PREI ranking of 0.55. Similarly only these three tasks will be subjected to detailed PHEA analysis as they are subjected to high degree of human error which could result in major releases of ammonia at Site B.

Details of HTA conducted for Site A and Site B is shown in Appendix 4. The analyses were conducted only on three subtasks that have been identified as high risk tasks that could lead to major release of ammonia at the two sites. Results from the analysis were able to indicate critical tasks that are likely to contribute to failures due to human error. As an example the task analysis revealed greater risk of ammonia release from overfilling of road tanker at Site A. This is mainly due to poor procedures to determine the ammonia road tanker filling weight has been reached.

Table 5.5 Results of Screening Analysis for Ammonia Loading Operation - Site A

Tasks	**Intrinsic Hazards**	**Nature of Interaction**	**Frequency**	**Potential Risk Index (PREI) Score and Ranking**	
	IHS	**IVS**	**IFS**	**PREI Score**	**PREI Ranking**
1. Prepare Plant	0.5	0.21	0.8	**0.50**	**5**
2. Prepare Road Tanker	0.5	0.28	1	**0.59**	**3**
3. Filling of Road Tanker	1	0.64	1	**0.88**	**1**
4. Monitor Transfer	0.25	0	1	**0.42**	**6**
5. Decouple Road Tanker	1	0.5	1	**0.83**	**2**
6. Final Checks	0.5	0.07	1	**0.52**	**4**

IHS - Intrinsic Hazard Score = (S-2)/4

IFS - Index of Frequency Score = (S-1)/5

IVS - Intrinsic Vulnerability Score = (S-7)/14

PREI - Potential Risk Index = (IHS +IVS +IFS)/3

Table 5. 6. Results of Screening Analysis for Ammonia Loading Operation - Site B

Tasks	**Intrinsic Hazards**	**Nature of Interaction**	**Frequency**	**Potential Risk Index (PREI) Score and Ranking**	
	IHS	**IVS**	**IFS**	**PREI Score**	**PREI Ranking**
1. Prepare Plant	0.25	0.21	0.8	**0.42**	**4**
2. Prepare Road Tanker	0.5	0.35	0.8	**0.55**	**2**
3. Filling of Road Tanker	1	0.57	0.8	**0.79**	**1**
4. Monitor Transfer	0.25	0.07	0.8	**0.37**	**5**
5. Decouple Road Tanker	1	0.57	0.8	**0.79**	**1**
6. Final Checks	0.5	0.07	0.8	**0.47**	**3**

IHS - Intrinsic Hazard Score = (S-2)/4   IFS - Index of Frequency Score = (S-1)/5

IVS - Intrinsic Vulnerability Score = (S-7)/14   PREI - Potential Risk Index = (IHS +IVS +IFS)/3

The road tanker ammonia loading bay is not fitted with a weighbridge. Hence the loading bay cannot be fitted with weight trip system and the operator has to rely on observing the road tanker content gauge to ensure the tanker is not being overfilled. This situation could easily lead to human error as the operator may not be around throughout the filling duration.

The HTA results are also used to highlight major differences on the task loading of ammonia to road tanker between the two sites through its structured step by step format. Discussion of the differences between the two sites and how they influences human error on each site is presented in Table 5.7.

5.4.4 Predictive Human Error Analysis (PHEA)

This analysis involved the prediction of specific errors associated with tasks or task steps in a systematic manner. The process involved two stages. The first stage was to determine the planning error, i.e. error associated with incorrect planning being followed, e.g. filling the road tanker without establishing its empty weight or decoupling loading hose during pumping operation. The second stage involved the analysis of operation errors. This analysis systematically identified External Error Mode (EEM) that could occur while conducting a task or task steps. The EEM considered for operation errors of the study are action errors, checking error, retrieval error, transmission or communication error, and finally the selection error. The EEM category used was as suggested by SPEAR (Embrey, 1994) as shown in Table 5.8.

Table 5.7 - The main differences in ammonia road tanker loading operation between Site A and Site B as identified through HTA

TASK	SITE A	SITE B	Differences and how they influence Human Error
1.PREPARE PLANT	Plant status is established manually i.e. through physical check on gauges and instruments	Plant status is established mainly using process control display	The use of better control system at Site B reduces human error in establishing plant status, especially when the tasks involved reading some of the gauges at height and under hot sun as in Site A
	Opening of valves is done manually by the same operator that will be conducting the loading operations	Valves opening at plant site are actuated remotely by the control room operator. This information is then need to be communicated to the loading operator.	High potential of human error during manual activation of valves at Site A, especially as the valves are poorly marked Error in communicating information Site B on valves status from control room to the loading operator
2. PREPARE ROAD TANKER	Road tankers are owned by Site A and driven by drivers who are permanent staff of the company	All road tankers belong to customer or transport contractors driven by their own drivers	Some customer drivers might not be familiar with ammonia loading operation at Site B. Cannot react properly during emergency, and a higher chances of hose pull away by road tanker driven away while filling operation is in progress
	The filling bay is not equipped with weighbridge.	The filling bay is equipped with weighbridge and weight trip alarm and pump cut-off	Over reliance on the operator to ensure the tanker is not overfilled at Site A.
3. COUPLE TANKER TO PLANT	The task of connecting flexible hose system from plant to road tanker is carried out by the loading operators.	The task of connecting flexible hose system from plant to road tanker is carried out by the maintenance crew under the supervision of the loading operator.	Some delay at Site B, as it has to wait for the maintenance crew to for connection. However such arrangement increases the chances of proper connection being made from job specialist.

	No proper leak test being conducted to ensure joint integrity prior to the ammonia pumping to road tanker	Leak test is included in the operating procedures for ammonia loading	Connection errors at Site A, could not be detected and recovered earlier. Large ammonia leaks could only be detected during pumping which may be difficult to recover in time
4. MONITOR TRANSFER	The operator has too be vigilance towards the end of the filling operation in order to prevent overfilling	The weight trip system will cut off pumping automatically at pre determined levels and sound the alarm to alert the operator	The chance of road tanker overfilling is higher at Site A, especially the operator has to remain vigilance near the road tanker under the hot sun. However in the event of weight trip system failures it will take longer time to notice and recovery begins
5.DECOUPLE TANKER FROM PLANT	Depressurisation and removal of remaining ammonia inside only involved the flexible connecting hoses.	Both Chiksan arm and flexible hoses need to be fully depressurised and vent out to scrubber to free it from remaining ammonia.	Improper use of Chiksan arm at site B which need flexible hoses attachment for filling connection make the task of depressurising and venting more difficult to be executed successfully
	After the completion of filling operation the plant is isolated manually	The plant isolation after loading operation is made by control room operation	The manual operation to isolate plant at Site A is more likely to be subjected to human error as its involved closing of manually valves with poor marking in the open under hot sun.
6. FINAL CHECKS	After road tanker loading the new plant status e.g. stock tank levels, pressure and temperature is established through manual checking	The new plant status is established by updating information at the control room display	The manual operation to isolate plant and established new plant status at Site A is more likely to be subjected to human error as its involved reading some of the gauges at height and under hot sun. However remote checks at Site B could suffer from operator's lack of attention as he is not in immediate danger from ammonia release.

Table 5.8 - EEM Category used for PHEA

Error Category	Error Mode
Action	Action omitted Action incomplete Action in wrong direction Action too much/too little
Checking	Check omitted Check incomplete Right check on wrong object
Retrieval	Information not obtained Wrong information obtained Information retrieval incomplete
Selection	Selection omitted Wrong selection made

The consequences analysis was then carried out on human error that has been identified. In this analysis the consequences of all predicted errors were considered. This reduced the chance of discounting certain errors from quantitative analysis before considering its consequences. Errors with low probability of manifestation but with high consequences are important contributor in risk analysis. Both immediate and long term consequences were considered which related to two types of failure i.e. active failures and latent failures. The one that has immediate consequences to personnel, plant or process is called active failure. While latent failures are those actions or decisions that generate vulnerable conditions which, in combination of with subsequent operating errors or operational conditions, give rise to accidents.

Two types of ratings were included in the consequences analysis. The first rating was for the severity of the consequences, while the second is for the likelihood that the error will occur and will lead to the consequences (i.e. will not be recovered). In both cases the rating uses the classification of 'high', 'medium', and 'low'. The consequences severity reflects the effects of error on personnel, plant, process or environment. The classification scheme suggested by Embrey (Embrey et al, 1994) for consequences of error is used with slight modification to reflect the ammonia loading operations under study, as given in Table 5.9. and Table 5.10. A similar approach to this classification scheme was also proposed recently (Moore 1997). Results of the consequences analysis have made it possible to identify critical tasks that are most likely to initiate major releases of ammonia with off-site consequences.

Table 5.9 - Classification scheme for the severity of consequences of error

Severity of Consequences	Personal injury	Ammonia Releases
HIGH	Loss Time Accident (LTA), Hospitalisation, Fatality	Large releases of Ammonia
MEDIUM	Exposure to ammonia which cause minor injury	Significant release of ammonia
LOW	Irritation only	Not more than slight release of ammonia

Table 5.10 - Classification scheme for the frequency of consequences of error

Frequency of Consequences	Time period within which an error occurs
HIGH	6 months
MEDIUM	2 years
LOW	5 years

Detailed PHEA for the two sites is shown in Appendix 5. The results identified a set of critical tasks that are heavily influenced by human error. These critical tasks were made up of a number of sub-tasks that were predicted could lead to major consequences (severity and frequency) and low means of recovery as shown in Table 5.11 and Table 5.12 respectively. The judgement high, medium and low were made based on SPEAR classifications scheme where information was available. In the absence of such information expert judgement of the auditor was used.

Table 5.11 Critical tasks that are strongly influenced by human error at Site A as identified through PHEA.

System Goal	Type of Error (Planning Error)	Consequences	
		Frequency (F)	Severity (S)
Loading ammonia to road tanker	Incorrect plan executed.	Low	High
	Inappropriate plan executed.	High	Medium
Tasks	**Type of Error (Operation error)**	**Consequences**	
		Frequency (F)	**Severity (S)**
2.1 Drive tanker to weighbridge.	Action too much	Medium	High
2.3 Chock front and rear wheel .	Action omitted	High	Medium
2.4 Ensure the tanker is empty	Check omitted.	Medium	High
2.6 Established ammonia filling weight.	Action omitted	Low	High
3.1 and 5.1, Operators put on PPE	Action omitted.	Low	High
3.4 Connect liquid filling hose to tanker's liquid inlet valve.	Action omitted.	Low	High
3.9 Ensure there is no leaks.	Check omitted.	High	High
3.10 Rectify leaks	Action omitted.	High	High

Table 5.11 shows that the influence of human error on system goals and tasks that could lead to major releases of ammonia on Site A. The errors consisted of two types of error i.e. planning error and operation error.

The planning errors identified through the PHEA at Site A include two critical planning errors. First is the planning error where the incorrect plan executed. The correct plan requires the weight of ammonia remaining in the incoming road tanker to be established before filling. This is to ensure that the tanker will not be filled exceeding the permissible ullage level based on the tanker volumetric capacity that could lead to catastrophic failure of the tanker. Such a failure would result in large releases of ammonia with high severity high off-site risk. As the existing procedures to establish the tanker empty weight at Sight A is poor, the frequency of such error to taking place is expected to be high.

The second planning error is associated with the execution of an appropriate plan. The written procedures for road tanker loading at Site A did not include the requirement for leak test to ensure connection integrity of flexible loading hoses. In the absence of such written requirement the frequency of such error taking place is judged to be high. Without leak testing to check its integrity, the connections might fail under pumping pressure which could lead to major ammonia releases with high severity off-site risk.

There are a number of operation errors that have been identified through the PHEA. Under this category of error there are several tasks that were found to be under strong influence of human error. The EEM error types are mainly under action error i.e. action omitted. The tasks that have been identified using the consequences (frequency and severity) included driving the road tanker, putting chocks to road tanker wheels, establishing the permissible ammonia filling weight, wearing PPE and connecting and disconnecting flexible loading hoses to road tanker. The tasks selected were judged to have at least one of the consequence component, i.e. frequency or severity, in high category.

Table 5.12 Critical tasks that are strongly influenced by human error at Site B as identified through PHEA

System Goal	Type of Error	Consequences	
	(Planning Error)	Frequency (F)	Severity (S)
To load Ammonia to road tanker.	Incorrect plan executed.	Low	High
	Plan pre-condition ignored	Low	High
Tasks	Type of Error	Consequences	
	(Operation Error)	Frequency (F)	Severity (S)
2.1 Drive road tanker to loading bay	Operation too much / too little.	Low	High
2.2 Establish tanker empty weight	Action omitted	Low	High
2.2.8 Place 4 chocks to front and rear wheels to prevent tanker movement.	Action omitted.	Low	Medium
2.2.9 Deduce tanker filling weight	Action omitted.	Low	High
3.1 and 5.1 Operator dons appropriate PPE	Operation omitted.	Low	Medium
3.2 and 5.2 Ensure that maintenance crew and driver wear appropriate PPE	Check omitted.	Low	Medium
3.5 Connect Chiksan arms and flexible hoses to tanker.	Operation omitted	Low	High
3.6 Do leak test on joint to ensure connection integrity.	Operation omitted.	Low	High
3.7 Set weight trip setting	Operation omitted.	Low	High
3.9 Ensure there are no leaks.	Check omitted	Low	High
3.10 Rectify leaks	Action omitted	Low	High

Table 5.12 shows the influence of human error on system goal and tasks that could lead to major releases of ammonia on Site B. Similarly the errors consisted of two types of error i.e. planning error and operation error.

The planning errors identified through the PHEA at Site B included two critical planning errors. First is the planning error where incorrect plan executed. The plan for ammonia loading to road tanker requires the incoming tanker empty weight to be determined in order to check for remaining ammonia inside before filling. This is important especially since Site A uses the contractor or customer tankers for downstream distribution. If this step of the loading plan is omitted, either voluntary or by mistakes, the ammonia remaining will not be accounted for in establishing the filling weight. This could result in wrong setting of weight trip system and could lead to the overfilling of the road tanker.

The second planning error identified is where the plan pre-conditions are ignored. The existing operating procedure calls for the services of maintenance crew to connect and disconnect the road tanker to plant using the Chiksan arms and flexible hoses. From the observation and interview this has caused considerable delay in loading the ammonia especially for urgent shipment. There are chances that in the event the maintenance crew is not available, the operator under delivery pressures may decide to carry the connection, which is not a difficult task, all by himself. Given lack of training and experience in carrying out the task the connection made may not be secure and could fail under pumping pressures, resulting major ammonia releases.

The PHEA also identified a number of critical operation errors that could be committed in carrying out the road tanker loading operations at Site B. Similarly the consequence's criteria based on frequency and severity was used to identify tasks that are strongly influenced by human error. Tasks that has been identified included establishing road tanker empty weight, deduce the correct filling weight, connecting and disconnecting road tanker to plant, putting wheel chocks to prevent hose pull away and the wearing of PPE for the operators, drivers and maintenance crew.

As can be seen from the analysis, by using simple criteria of consequences, i.e. that made up of frequency and severity, tasks that are under strong influence of human error could be identified. The consequences approach was found to be appropriate for the research as the study is looking at major releases of ammonia with high consequences that could give rise to off-site risk. The limitation of such an approach is lack of transparency in making judgement as to what should fall under the low, high and medium scale for both the frequency and severity. Site specific incident and near miss records could be used to support the judgement, but unfortunately they were not sufficient for both sites under study.

5.4.5 Implementing human error reduction strategies through PSMS

One objective of the research is to link the human error to site specific PSMS. It is important to assess whether the so-called human error that could arise in executing certain tasks is actually rooted in management weaknesses. However as the relationship between human error and PSMS has many facets, a straight forward relationship is always difficult to realise. In this study such a relationship is established using the error reduction strategies and the PSMS components that will be involved in the implementation of such strategies. As can be seen from Table 5.13 and Table 5.14, the PHEA could be extended to include strategies to reduce the impact of human error on tasks that made up the ammonia road tanker loading operation.

Such inclusions will be able to serve two purposes. First as important source of information on relevant strategies on how the human error influence on certain task could be reduced or minimised. Second providing the linkage to the site specific PSMS on means to implement the recommended error reduction strategies. When using PRIMA technique for PSMS evaluation such linkages could be directed further to include the relevant key audit areas and the control loop audit levels. The analysis shown in both tables is carried out only on tasks that under strong influence of human error using PHEA for Site A and Site B as shown in Table 5.13 and Table 5.14 respectively.

Table 5.13 shows the analysis that depicts human errors, their possible consequences, the recommended error reduction strategies and the relevant PSMS components that need to be addressed for successful implementations on Site A. For example the planning error of not including leak test requirement in operating procedures (inappropriate plan executed), could be overcome by including the requirement. The failure to include such requirement was found to be rooted to the PSMS failure to set a good safety standard, in this case to check the integrity of connection joints.

Referring the situation to PRIMA audit technique such failure falls under OP/CHECK key audit areas. Looking further into the PRIMA control loop the reduction strategy recommended lies in Level 4 → 3 of the loop which represents the items on communication, control and feedback. The operational errors could be analysed in the same manner. For example for the task of placing wheel chocks to road tanker (task number 2.3), the error reduction strategy recommended is the formalisation of additional checks to reduce the operator's error in placing the wheel chocks at road tanker wheels. Such recommendation falls under PRIMA key audit areas of OP/HF and at level 2 → 3 in the PRIMA control loop. It requires exercising greater control on adhering to the written procedures through additional checks by the driver and occasional spot checks by the supervisor.

The analysis that shows human errors, their possible consequences, the recommended error reduction strategies and the relevant PSMS components that need to be addressed for successful implementations on Site B is shown in Table 5.14. As an example the planning error of operator failing to establish the quantity of ammonia remain inside the tanker prior to filling (incorrect plan executed), could be overcome by proper training and strict adherence to operating procedures. Referring the situation to PRIMA audit technique the recommended error reduction falls under OP/CHECK key audit areas. Within the PRIMA control loop the reduction strategy recommended lies in Level 2 → 3 of the loop under the component of communication, control and feedback. The recommendations involved exercising greater control on adhering to operating procedures through observations and spot checks.

Table 5.13 Implementing error reduction strategy through PSMS on tasks that are strongly influenced by human error at Site A

System Goal	Error Type (Planning Error)	Description	Consequences	Error Reduction Strategy	PSMS Implementation
Loading of ammonia to road tanker.	Incorrect plan executed.	Filling operation carried out without establishing the amount of ammonia remained inside the tank	Overfilling of road tanker could result in catastrophic failures resulting to major releases of ammonia	Training and strictly follow the procedures.	Key audit Area - OP/CHECK. PRIMA Control Loop - Level 2 → 3 Exercise greater control on adhering to written operating procedures through observation and spot checks. Monitor effectiveness of the procedures and get feedback through operator input and observation
	Inappropriate plan executed.	The loading procedure did not include the requirement for leak test	Connection joints integrity cannot be ascertained, leaks might develop under pumping pressures	To include steps for leak testing for connection joints prior to ammonia pumping to road tanker	Key audit Area - OP/CHECK. PRIMA Control Loop- Level 4 → 3 Setting up a good safety standard to ensure the written procedures include adequate requirements for testing after completion of hazardous tasks.

Task	Error Type (Operation Error)	Description	Consequences	Error Reduction Strategy	PSMS Implementation
2.1 Drive tanker to weighbridge.	Action too much	Tanker is driven too fast in site compound.	Tanker meets accident with other vehicles or hitting plant piping, resulting in releases of ammonia	Provide systematic vehicle movement inside the plant and enforce speed limit.	Key audit Area - OP/HF. PRIMA Control Loop Level 5 →**4** Provide traffic movement plan within the site with maximum speed limit. Level 2 →3 Exercise greater control in adhering to the written plan through observation and spot checks. Monitor effectiveness of the plan and get feedback through operator input and observation
2.3 Chock front and rear wheel .	Action omitted	Operator omits to place the wheel chocks. Tanker could be driven away during filling resulting in hose pull-away and ammonia leaks	Tanker could be driven away with transfer hose still attached to it resulting in releases of ammonia	Checks by driver and spot checks by the supervisor.	Key audit Area - OP/CHECK Level 2 →3 Exercise greater control in adhering to the written procedures through observation and spot checks by third party. e.g. driver

2.4 Ensure the tanker is empty	Check omitted.	Operator failed to establish that the tanker is empty before filling. Tanker could be overfilled during filling	Tanker overfilled resulting rupture of tanker and major releases of ammonia	Enforce strictly the filling procedures.	Key Audit Areas - OP/CHECK Level 2 →3 Exercise greater control on adhering to the written procedures through observation and spot checks by supervisor or plant manager.
2.6 Established ammonia filling weight.	Action omitted	Operator omits to establish target filling weight, e.g tare weight of different model of tanker.	Wrong target weight being establish resulting overfilling	Provide checklist and training .	Key Audit Areas -OP/CHECK Level 4 →3 Formalise the use of checklist to ensure strict adherence of procedures in critical tasks.
3.1 and 5.1 Operators put on PPE	Action omitted.	Operator omits to put on PPE	Operator is not protected in the event of ammonia releases and cannot take mitigative actions	Check the suitability of PPE in used for local conditions. Strict enforcement on wearing of PPE	Key Audit Areas -OP/CHECK Level 2 →3 Exercise greater control on adhering to the written procedures through observation and spot checks by supervisor and plant manager. Get feedback from the operator on the suitability of PPE in used.
3.4 Connect liquid filling hose to tanker's liquid inlet valve.	Action omitted.	Operator omits to connect liquid filling hose to tanker's liquid inlet valve.	Major ammonia releases when pumping commences	Checklist and counter check by 2nd. operator	Key Audit Areas -OP/HF Level 4 →3 Formalised the use of checklist to ensure strict adherence of procedures in critical tasks.

3.9 Ensure there is no leaks.	Check omitted.	Operator failed to check for leaks.	Leaks might develop and release significant amount of ammonia	Incorporate written leak check procedure.	Key audit Area - OP/CHECK. PRIMA Control Loop- Level 4 →3 Setting up a good safety standard to ensure the written procedures include adequate requirements for testing after the completion of hazardous tasks.
3.10 Rectify leaks	Action omitted.	Operator omits to rectify leaks.	Small leaks could escalate and make it difficult to repair as ammonia vapour cloud developed	Incorporate proper procedure to rectify leaks. Provide equipment to check for leaks.	Key Audit Areas -OP/HF PRIMA Control Loop - Level 4 →3 Setting up a good safety standard to ensure the written procedures include proper method to rectify leaks Level 2 →3. Providing quality of job support to the operator i.e. proper tool to rectify leaks

Table 5.14. Implementing error reduction strategy through PSMS on tasks that are strongly influenced by human error at Site B

Task	Error Type (Planning Error)	Description	Consequences	Error Reduction Strategy	PSMS Implementation
To load ammonia to road tanker.	Incorrect plan executed.	Filling operation carried out without establishing the amount of ammonia remaining inside the tank	Overfilling of road tanker that could led to catastrophic failures resulting in major releases of ammonia	Training and strictly follow the procedures.	Key audit Area - OP/CHECK. PRIMA Control Loop - Level 2 → 3 Exercise greater control in adhering to written operating procedures through observation and spot checks. Monitor effectiveness of the procedures and get feedback through operator input and observation
	Plan pre-condition ignored	The operator has to carry out connection and disconnection of tanker for urgent shipment as the maintenance crew is not available.	As the operator does not have the skill and hand on experience, he might do improper connection and resulting leaks during filling	Gradually train the operators to carry out connection and disconnection procedures under the supervision of the maintenance crew until they are competent to do by themselves as practised at Site A	Key audit Area - OP/HF Level 3 → 2 Broaden the scope of work of the operators through formalised training until they are competent to carry out tasks that formed part and parcel of a system operation.

Task	Error Type (Operation Error)	Description	Consequences	Error Reduction Strategy	PSMS Implementation
2.1 Drive road tanker to loading bay	Operation too much / too little.	Road tanker is driven too fast in plant compound.	Meet accident with other vehicles or hit plant piping or cylinder storage area.	Provide systematic vehicle movement inside the plant and enforce speed limit.	Key audit Area - OP/HF Level 2 →3 Exercise greater control in adhering to the written plan through observation and spot checks.
2.2 Establish tanker empty weight	Action omitted	Operator omits to establish tanker weight prior to filling (empty weight)	Operator set wrong target weight and consequently sets wrong alarm and tripping weight.	Provide checklist that laid out all steps required to establish tanker empty weight	Key audit Area - OP/HF Level 4 →3 Setting up a good safety standard to ensure that suitable checklist made available to enhance the effectiveness of operating procedures
2.2.8 Place 4 chocks to front and rear wheels to prevent tanker movement.	Action omitted.	Operator omits to place wheel chocks.	Tanker can be driven away during filling resulting hose pull away and initiating ammonia release.	Training.	Key audit Area - OP/HF Level 2 →**3** Exercise greater control in adhering to the written procedures through and spot checks by third party. e.g. driver
2.2.9 Deduce tanker filling weight	Action omitted.	Operator omits to establish tanker filling weight.	Operator may set wrong target filling weight, could resulted in overfilling.	Provide checklist with simple table that will helped the operator to deduce tanker filling weight	Key Audit Areas -OP/CHECK Level 4 →3 Formalise the use of checklist and to ensure strict adherence of procedures in critical tasks.

3.1 and 5.1 Operator dons appropriate PPE (gas hood with air supply)	Operation omitted.	Operator failed to put on gas hood with air supply.	Exposure to ammonia leaks and under worst circumstances incapacitated and unable to take mitigative action.	Training and strict enforcement on wearing of PPE	Key Audit Areas -OP/CHECK Level 2 → 3 Exercise greater control in adhering to the written procedures through observation and spot checks by supervisor and plant manager. Get feedback from the operator on the suitability of PPE in used.
3.2 and 5.2 Ensure that maintenance crew and driver wear appropriate PPE (gas masks with face shield).	Check omitted.	Operator failed to check maintenance crew and driver failed to wear gas masks with face shield	Gas masks fail to protect them and they cannot take appropriate mitigative action in the event of gas leaks.	Training and strict enforcement on wearing of PPE, especially for contractor's drivers	Key Audit Areas -OP/CHECK Level 2 → 3 Exercise greater control in adhering to the written procedures through observation and spot checks by supervisor and plant manager. Get feedback from the maintenance crew and driver on the suitability of PPE in used.
3.5 Connect Chiksan arms and flexible hoses to tanker.	Operation omitted.	Maintenance crew omit to connect flexible hose to tanker.	Major ammonia releases when pumping commences	Counter check by operator before transfer commences.	Key Audit Areas -OP/HF Level 4 → 3 Include checklist in the operating procedures and counter checks by the operator.
3.6 Do leak test on joint to ensure connection integrity.	Operation omitted.	Maintenance crew omit to carry out leak test under time pressure.	Integrity of joint is not known, might leak when transfer commences.	Training /Checklist.	Key Audit Areas - OP/HF Level 2 → 3 Assessing the connection integrity through monitoring and feedback from leak tests

3.7 Set weight trip setting	Operation omitted.	Operator omits to set trip setting at weight indicator.	Filling operations would not be automatically trip, no alarm sounded and could result in overfilling.	Checklist with simple calculation table to assist the operator sets the trip weight setting.	Key Audit Areas - OP/CHECK Level 4 → 3 Formalised the use of checklist and tables to assist successful completion of critical tasks.
3.9 Ensure there are no leaks.	Check omitted	Operator omits checking for leaks.	Leaks might develop and release significant amount of ammonia.	Spot checks by supervisor during filling	Key Audit Areas - OP/CHECK Level 2 → 3 Exercise greater control in adhering to the written procedures through observation and spot checks by supervisor and plant manager
3.10 Rectify leaks	Action omitted	Operator omits to rectify leaks.	Leaks escalated and release significant amount of ammonia.	Spot checks by supervisor during filling	Key Audit Areas - OP/HF Level 2 → 3 Exercise greater control in adhering to the written procedures through observation and spot checks by supervisor and plant manager
5.3 Depressurised the Chiksan arms by draining remaining ammonia to the catchpot.	Operation omitted.	Operator omits to depressurise Chiksan arm and flexible hoses	Ammonia remains inside Chiksan arm and flexible hoses that could result in ammonia release during disconnection.	Use appropriate checklist for disconnection and counter checks by maintenance crew	Key Audit Areas - OP/HF Level 4 → 3 Include checklist in the operating procedures and counter checks by the maintenance crew.

Task number 3.7, i.e. setting weight trips on road tanker weighbridge is an example of a task that could be subjected to operation error. The omission to set the weight trip system could result in overfilling of road tanker. The recommended error reduction strategy calls for formalising of the use of checklist and reference tables to assist the operator. Such recommendation falls under the PRIMA audit area of OP/CHECK. It lies in Level 4 → 3 of the PRIMA control loop under the component of communication, control and feedback.

The explanation above showed that PHEA results may not only be useful to identify tasks that under strong influence of human error and to recommend appropriate error reduction strategies, but also to determine the PSMS safety components that are associated with their implementation. If PRIMA technique is used to assess the site specific PSMS performance the analysis could be extended further to identify the key audit areas and control loop levels associated with the recommended error reduction strategies. This enables the site management to evaluate such recommendations in greater detail and assessing the resources required for their implementation. In a way this approach provides one means to integrate the analysis of human error and PSMS.

5.4.6 Performance Influence Factor (PIF) Analysis

This step involved the evaluation of factors associated with a task which could influence the likelihood of errors identified in Step 5.4.2 and 5.2.3. These factors are called Performance Influencing Factors (PIFs). These factors to a large extent are determined by the effectiveness of the management policy in controlling human error. These include quality of procedures, effectiveness of training, and implementing the use of PPE for hazardous tasks. For example results from PSMS audit using PRIMA technique in Chapter 4 have found that Site B inherited quality operating procedures from the previous multinational owner, but the site lacked experience personnel to review and update the procedures as new changes are made. These could result in errors made by the operators who are not aware of the changes, which in some situations could lead to accidental releases of ammonia. This illustrated that the quality of PIFs at the operational level, in this case outdated operating procedures, provided an indication of the effectiveness of management policy in controlling human error.

The relevant PIFs associated with ammonia loading operations at the two sites were identified using a classification as suggested by AIChE (AIChE, 1994). These PIFs were identified by assessing information made available to the auditors from interviews of workers and managers, review of documents, tasks observation with the help of video taping, physical inspections of the site process, vessels and piping and evaluation of factors that affect the operating environment such as heat, humidity and noise. However such detailed classification was found could be grouped under four main PIFs associated with ammonia loading operations, i.e. experience and training, procedures, stress and feedback. The grouping allowed detailed analysis to be carry out for human error quantification at the later stage.

Findings of this assessment for the Site A and Site B are shown in Appendix 6. Such qualitative analysis provided important information on the status of site specific PIFs and theirs influences on human error. As an example for PIF on operating experience, the majority of operators at Site A have less than five years of experience due to high workforce turnover. Whereas for Site B the majority of the operator have more than ten years experience working with ammonia related facilities. Better pay and long term job security from a multinational organisation has resulted in low workforce turnover, enable Site A to retain it experienced operators. The availability of experienced operators to carry out hazardous tasks such as ammonia road tanker loading will reduce the chance of human error.

In terms of job aids and procedures, Site A was found to be lacking. The majority of the tasks performed on site are without written procedures. Procedures that are available for certain tasks like ammonia road tanker loading operation were poorly written and inadequate. Site B however inherited a good set of operating procedures and job aids from the previous multinational owner and they are well written and regularly being used. The usage of good operating procedures in carrying out hazardous tasks will reduce the chances of human error and increase the likelihood of successfully completing the tasks.

The summary PIFs analysis in Appendix 6 for the four PIFs under consideration is shown in Table 5.15. The analysis provides site specific assessment on the current situation of main PIFs that are judged to exert strong influence on human error. However the assessment only provided for the overall PIFs situation at the organisational level (or global level) of each site. Apart from identifying strengths and weaknesses of management control, the results of the assessment are used to assign weighting of each PIFs for human error quantification later.

Table 5.15 Summary of findings from PIFs analysis at Site A and Site B

PIFs	Site A	Site B
1. Experience and Training	The majority of operators have less than 5 years working experience. High turnover of operators due to lower salary and hazardous working conditions as compared to other factories surrounding the site, e.g. electronic factories. Training programme was not properly developed and implemented. Only received ad hoc training in the form of work attachment with senior operators and very limited chances for continuous training. The adoption of multi-skilling provides work flexibility and allowed better promotion chances as all workers are capable to carry out most of the tasks associated with ammonia loading operations. This particular PIF at Site A is assessed to be average and could impart quite strong influences on human error.	Operators have long working experience and the majority have more than 10 years of working experience. Low operator turnover due to job security from an established company. Training programme was based on job specialisation as set by previous multinational company followed good in house standards. Adequate pre -employment training, with some opportunity for continuous training. However the job specialisation while providing specialised skill has created inflexibility in the utilisation of manpower and fewer chances for promotion for the non-operators (i.e. maintenance crew). This particular PIF at Site B is assessed to be good with little influences on human error.

2. Procedures	Procedures and job aid are minimum and only available for road tanker and ship loading operations. Developed based on limited operating experience and manuals of the equipment supplier. Description is not detailed enough, instructions and diagrams are not clear and lack compatibility with the actual task that needs to be carried out. Procedures are updated only as the outcome of serious incidents This particular PIF at Site A is assessed to be poor and could impart strong influences on human error.	Procedures and job aids are adequate. Developed based on good standards laid down by previous multinational owner. Level of descriptions, clarity of instruction and compatibility with operational experience is good. However updating exercise has fallen behind the stipulated schedule under the present management. This particular PIF at Site B is assessed to be good with moderate influences on human error.
3. Stress	The road tanker loading operation is not complicated but with high level of perceived danger and suddenness onset of event (e.g. from sudden releases of ammonia) that provides enough stress to keep the operator alert. On average three road tanker loading are made daily, besides other loading for skid tanks mounted lorry and these posed fairly high time stress. As the loading bay is in the open the operators are subjected to hot tropical sun and high humidity which exerts high physical work stress. The ammonia loading operation is mostly carry out in day time and that reduces the stress from working at night. This particular PIF was assessed to be poor and could impose strong influences on human error.	Similarly the road tanker loading operation is fairly straight forward but with high level of perceived danger and suddenness onset of event (e.g. from sudden releases of ammonia) that provided enough stress to keep the operator alert. Time pressure for unloading is low at this site as on average only two shipments are made per week. Stress from physical work environment which mainly from hot tropical sun and high humidity is moderate as the loading operations carried out under solar canopy of the loading bay. Low number of ammonia loading eliminates the need to carry out loading at night. This particular PIF was assessed to be average with moderate influences on human error.

4. Feedback	Plant and equipment layout are satisfactory but manual control could only provide minimum recovery. No central control room but rely on a number control panels located near the place where a major activity takes place, e.g. the road tanker loading bay. Remote operation is limited to emergency stop button that shut down all site operation. Critical information on plant status has to be gathered manually, some which located at heights and in the open and this could lead to human error. Labelling and identification scheme for equipment, valves and piping is inadequate. Emergency alarms limited to gas leaks and fire only. This particular PIF was assessed to be poor and could impose strong influence on human error.	Good plant and equipment layout provide good interface and facilitate adequate feedback to the operators. A central control room provides critical information on the plant status and allowed remote operation of major process equipment and valves that provide certain degree of recovery in the event of failures due to human error. Identification, display and grouping of critical process information is satisfactory and compatible with user expectation. Labelling and identification scheme for equipment, valves and piping is adequate. Emergency alarms available for gas leaks, fire and evacuation. This particular PIF at Site B is assessed to be good with small influence on human error.

For individual task steps they have to be analysed in more detailed as each PIFs influenced specific errors in different manner and with varying degree of influence depending on the nature of the task. As an example, one of the PIF under consideration, i.e. procedures exert strong influence on the success of executing the task to vent-off the ammonia filling lines after loading. However the same PIF only has marginal influence on the task of putting the road tanker wheel chocks. For this reason a more focused application of information from the PIFs assessment, together with other relevant data collected by the auditors is needed to assess the influence of the PIFs under consideration for each task. That is one of the main reason why for quantification purposes it is not feasible to assess all PIFs associated with task under consideration, instead only those with significant influences are considered. Details of the quantitative analysis for the two sites are described in the following section.

5.5 Quantitative Analysis of Human Error

Quantification of human errors is central and important aspect of risk assessment (Humphrey et al, 1988). In this study it is used to contribute to an evaluation of overall risk for comparison with quantitative risk criteria. It also provided a means to determine the relative contribution of different sources of system failures that could be used to prioritise the allocation of limited resources in order to minimise risk. Due to its importance a fairly large number of techniques exist. However, only a small number of the techniques have been used in practices, mainly in the nuclear industry. A much smaller number has been used in the chemical process industries (AIChE, 1994). The SLIM technique is used for quantification of human error in this study (Embrey et al, 1984).

5.5.1 The SLIM technique

The Success Likelihood Index Method (SLIM)(Embrey, 1984) was initially developed for the nuclear industry but has subsequently been used for the other industries such as chemical and transportation. The technique can be applied to tasks at any level of details, i.e. whole tasks, subtasks, task steps down to individual error associated with task steps. Full description of the technique is given in Chapter 3. The basis of SLIM technique is that the probability of error at any level of task is a function of Performance Influencing Factors (PIFs) in the situation. The PIFs which have direct influences on error such as the quality of procedures, the level of training, and the degree of feedback is used to numerically rate the tasks. The combined ratings of PIFs influence on each task yields an index called the Success Likelihood Index (SLI). Using a general relationship between SLI and a task with known error probability the task error under consideration could then be converted to a quantitative measure known as Human Error Probability (HEP). The SLIM software provided by the Human Reliability Associates was used for the quantification. It consists of two modules. The first module called SLIM is used to analyse the likelihood of success of a set of task based on the evaluation and contributions of important PIFs that could affect the human reliability in performing the tasks. The second module, called SARAH (Systematic Approach to the Reliability Assessment of Humans) is used to calibrate the relative success likelihood's, in order to generate absolute HEPs.

5.5.3 Determining HEPs for ammonia road tanker loading tasks at the two sites using SLIM technique

The main application of the quantification of human error in the form of HEPs for this study is as input to failure model of ammonia road tanker loading operation. This study used Fault Tree Analysis (FTA) to depict the failure models that show the contribution of both hardware failures and human errors to the overall system failure, i.e. loading of ammonia to road tanker. Human errors reduce the likelihood of success to accomplish the tasks associated with road tanker loading operation. HEPs in conducting the tasks that have been identified from FTA for each site are quantified using the SLIM technique. The FTA which depicts the critical tasks that made up the failure model of ammonia road tanker loading operations for the two sites is shown in Appendix 14. Incidentally some of the tasks identified using the FTA were also predicted to be under strong influence of human error as indicated from PHEA results in Section 5.4.3.

Steps taken in using SLIM procedure for this analysis are;

- Definition of situation and subsets
- Elicitation of PIFs
- Rating of the tasks on the PIFs
- Elicitation of ideal points and calculations
- Weighting procedure
- Calculation of the Success Likelihood Index (SLI)
- Converting the SLI to probabilities
- Sensitivity Analysis

5.5.3.1 Definition of situations and subsets

This task involved carefully defining the situations to be evaluated in this case ammonia road tanker loading operation, by getting as much information as possible regarding the characteristics of the tasks, the individual (operator) who performed the tasks, and other factors that influenced the likelihood of success. In ammonia loading operation the situation involved the execution of several tasks by human, i.e. the operators which required interfacing with the hardware. For this study such information is gathered through observations, interviews, studying operating procedures and video taping of the ammonia loading operation.

5.5.3.2 Select the relevant PIFs

A data base developed within each site on the predetermined PIFs associated with particular categories of tasks would be the ideal information for deciding the relevant PIFs to be used in the analysis. However as such information was not readily available, the relevant PIFs were selected from judgement made based on information gathered through interview of workers and management, task observation, physical inspection and document reviewed. As each task is under the influence of many PIFs only those which were judged to have direct and major influences on errors in performing the task were selected (AChEI, 1994).

Using this approach four PIFs were selected for the quantification purposes. They are;

- Experience
- Procedures
- Stress
- Feedback

The four PIFs belong to operational level factors that have a direct effect on probability of errors occurring. Management level factors such as the effect of policies on training and equipment design was not included even though they have indirect impact to the likelihood of error, as they determine the quality of operational level PIFs mentioned above. This was due to the difficulties in making judgement on the degree of influence of each factor, and they may have multiple influences on all the operational level PIFs that have been identified. Brief definitions for each PIFs selected for quantification purposes is given in Table 5.16.

Figure 5.16. Description of PIFs selected for human error quantification

PIFs	Description
1. Experience	Represent the importance of an operator experience and training on the success of a particular task. This factor represents the importance of an operator experience and training on the success of a particular task. It is a combination of relevant training given to the operator and the length of time of which the operator work for a particular task. While the training provides the essential knowledge on how to carry a task safely and efficiently, the length of time of the operator has been carrying out the task allowed an in depth familiarisation in carry out such task. Such familiarisation allowed the operator to understand the specific characteristics of the hardware and its interfaces under various operating conditions.
2. Procedures	Represent the importance of written procedures and job aids in assisting the operator to successfully carry out a particular task. It concerns with the availability of good procedure in term of depth, coverage and practicality, in ensuring success of a task e.g. depressurising ammonia filling line
3. Feedback	Represent the amount of information (if any), being relayed back to the operator during a task, which indicates that he is in the error mode. For example, the pressure indicator on the supply line gives the operator information on pressure inside the line, and this represents important feedback during disconnection procedures.
4. Stress	Represent the effect of operator stress on the success of a task. It is considered that there is an optimum stress level and the ideal point has been set at 6. The range of 1 to 6 represents an increasing level of stress that is beneficial to the success of the task. The stress level represents the operator perception of risk, i.e. if the operator perceived that a task is potentially dangerous to his welfare he is more likely to take considerable care. Once the optimum level of stress has been exceeded, however, there is possibility of panic and the thus the range between 6 to 9 represents an increasing chance of error due to panic.

5.5.3.3 Rate PIFs Selected

The next step is to rate PIFs on tasks under consideration which in this case would be the tasks that need to be carried out for loading operation of ammonia to road tanker. SLIM technique provided a numerical rating on a scale of 1 to 9. The end of the scale normally represent the best or worst PIF conditions. For example a highly experienced operator will have an optimal value of 9, while a novice is represented by the worst scale of 1. However, other PIFs like Stress possessed a different optimal value. For Stress it was judged that certain level of stress was necessary to keep the operator alert. The stress would rise from perceived danger of a particular task for example during decoupling of transfer hose after filling which might still have remains of ammonia inside it. As such the scale rating of 6 would best represent the optimum value for this PIF. However too much stress, e.g. from sudden escaped of large ammonia cloud due to ruptured loading hose during filling, will pose too much stress and increased the tendency of the operator to make errors. In such situation stress would be at the worst with a 9 rating on the scale. Closer attention was given during the analysis due to the fact that the same rating value could have a different significance to a successful execution of a task under considerations. Rating of PIFs for tasks under consideration for Site A and Site B is shown in Table 5.17 and Table 5.18 respectively.

Table 5.17 Results of SLI Analysis for Site A

Base Event No.	SLIM Task No	Description of Base Events	Performance Shaping Factor (PIF)				SLI	Remarks on PIFs rating
			E	P	S	F		
HL121b HL121b	T5	Driver moves tanker while filling operation is in progress	6	2	7	5	0.69	The site owns the ammonia road tanker and the drivers are permanent workers. Hence the drivers are quite experience and familiar with the filling operations. However this situation has reduced the urgency to provide good procedures that could minimise the chance for the driver to drive away the tanker, i.e. the procedure of handing over the tanker ignition key to the filling operator for safe keeping.
HL122b HV122b	T8	Operator failed to put on wheel chocks on tanker	7	2	4	5	0.51	The loading bay for tanker is wide and flat and is not marked. This reduces the tendency the tanker to roll and make the placement of wheel chocks seem not that critical than it actually is. The absence of a comprehensive procedure and lack of enforcement on this task is apparent.
HL1411b	T11	Operator failed to open tanker inlet valves	7	3	4	4	0.49	Lack of procedures and the use of ball valve without rising stem or clear marker reduces feedback to the operator
HL1421	T12	Operator failed to open tanker outlet valves	7	2	5	4	0.49	The tanker outlet valve similar in nature to the tanker inlet valve except for its size. No label or tagging is provided and couple with lack of simplified line diagrams reduce the feedback to the operator.

HL15b HV15b	T16	Operator disconnect filling hose from tanker while filling operation is still in progress	7	6	7	6	0.7	Procedures available for disconnecting hose after filling. Stress is near optimum as the task is perceived as one of the most hazardous beside the task to connect hoses. Feedback is also quite good as the will be escaping ammonia as the line being cracked opened
HL211b	T8	Remote operator failed to isolate leak in the event of release	7	4	8	5	0.56	The site does not have a proper control room. However emergency stop buttons to stop filling operation by pneumatically controlled valves are located at three different locations. In the event of leak other operator, e.g. remote operator could press any of these buttons to cease the operation.
HL221b	T1	Local operator failed to isolate leak	7	3	8	5	0.71	Stress is high as the local operator may be exposed to ammonia. The type PPE available is the form of cartridge type gas mask which only suitable for short duration of ammonia exposure. Previous incident of unsuccessful attempt to isolate a major release of ammonia increase the perceived danger of such task by the operator
HV1411b	T13	Operator failed to closed plant vapour return valve	7	2	5	4	0.51	Assume the PIFs for opening line valves and tanker valves are similar. Lack of marking or tagging as well as line diagram reduce feedback.
PL12112b	T12	Operator failed to open liquid line valves	8	6	6	4	0.72	Similar to T12-assume the opening and closing of liquid valves under similar rating of PIFs.

PL14b PV14b	T3	Operator commences filling without connecting plant to tanker	8	6	6	7	0.81	Feedback is high as the actual connection is carried out by experienced maintenance crew under the watchful eyes of the operator
PV1212b	T12	Operator failed to open vapour line valves	8	6	6	4	0.72	Assume the PIF for opening liquid line valves and vapour line valves are similar
TL2211b TV2211b	T9	Operator failed to establish tanker empty weigh	8	6	5	4	0.67	Feedback is low as the operator alone establish the tanker empty weight which might still have remain of ammonia inside
TL2112b TV2212b	T10	Operator read gross weight of different tanker and uses the values to set the target filling weight	8	6	5	4	0.67	Since there are difference sizes of road tankers comes for filling, the operator has to refer the actual tare weight of each tanker using a small table manually. As this is a one man operation no feedback existed apart from his experience differentiating the various type of tanker
TL2121b TV2221b	T6	Operator set wrong filling weight that could result to overfilling of road tanker	8	6	5	4	0.67	Similar to T9 and T10 the operator has to manually set the filling weight without being checked by others

Table 5.18 Results of SLI Analysis for Site B

Base Event No	SLIM Task No	Description of Base Events	Performance Shaping Factor (PIF)				SLI	Remarks on PIFs rating
			E	P	S	F		
HL121b HL121b	T5	Driver moves tanker while filling operation is in progress	5	6	6	6	0.69	The practice of using outside contractor tanker with limited experience in handling ammonia. No specific briefing or training being given apart from general safety and health and emergency action. The driver does not involved at all during the actual filling process
HL122b HV122b	T8	Operator failed to put on wheel chocks on tanker	8	4	6	5	0.69	Simple task that has optimum stress as the loading bay is narrow and elevated. Unless accurately positioned the tanker will tend to move forward or backward which increase the awareness on the need to place the wheel chocks.
HL1411b	T11	Operator failed to open tanker inlet valves	8	6	6	4	0.72	The use of ball valve without rising stem or clear marker reduces feedback to the operator
HL1421	T11	Operator failed to open tanker outlet valves	8	6	6	4	0.72	The tanker outlet valve is similar in nature to the tanker inlet valve
HL15b HV15b	T16	Operator disconnect filling hose from tanker while filling operation is still in progress	8	7	6	8	0.88	Good procedures available for disconnecting hose after filling. Feedback also good as there will be ammonia escaping as the line being cracked opened
HL211b	T1	Control room operator failed to isolate leak in the event of release	8	6	7	7	0.76	Control room operators are of the rank of supervisor with good operating experience. The control room is air-conditioned, fully enclosed but with excellent view to the loading bay
HL221b	T2	Local operator failed to isolate leak	8	6	8	7	0.71	Stress is high as the local operator may be exposed to ammonia. But the availability of good PPE located nearby e.g. air supply hood would enable the operator to successfully isolate the leak

HV1411b	T12	Operator failed to closed plant vapour return valve	8	6	6	4	0.72	Assume the PIFs for opening line valves and tanker valves is similar
PL12112b	T12	Operator failed to open liquid line valves	8	6	6	4	0.72	Similar to T12 - assume the opening and closing of liquid valves under similar rating of PIFs
PL14b PV14b	T3	Operator commences filling without connecting plant to tanker	8	6	6	7	0.81	Feedback is high as the actual connection is carried out by experienced maintenance crew under the watchful eyes of the operator
PV1212b	T12	Operator failed to open vapour line valves	8	6	6	4	0.72	Assume the PIFs for opening liquid line valves and vapour line valves are similar
TL2211b TV2211b	T9	Operator failed to establish tanker empty weigh	8	6	5	4	0.67	Feedback is low as the operator alone establish the tanker empty weight and the contractor tanker might still have remain of ammonia inside
TL2112b TV2212b	T10	Operator read gross weight of different tanker and uses the values to set the target filling weight	8	6	5	4	0.67	Since there are difference sizes of road tankers comes for filling, the operator has to refer the actual tare weight of each tanker using a small table manually. As this is a one man operation no feedback existed apart from his experience differentiating the various type of tanker
TL2121b TV2221b	T6	Operator set wrong trip weight that will automatically stop the filling operation to prevent overfill	8	6	5	4	0.67	Similar to T9 and T10 the lone operator has to manually set the tripping weight without being checked by others

5.5.3.4 Assigning weight to selected PIFs

The step concerned with evaluating how much emphasis is to be given to each of the PIF in relation to its effect on the likelihood of success. The weight represents the relative influence that each PIF exerts on all the tasks being evaluated. It could be done based on the analyst's experience or error theory (AChIE, 1994). The assignment of weight is not mandatory in SLIM. The technique assumes that all PIFs are of equal importance in their contribution to the overall likelihood of success if the weights are not used. For this study attempt was made to assign the weight for each PIFs based on the qualitative assessment made previously as shown in Table 5.19.

Table 5.19 - Weighting assigned to PIF

PIFs	Weight
1. Experience	0.4
2. Procedures	0.2
3. Stress	0.2
4. Feedback	0.2

Given limited information available to support the judgement made, a sensitivity analysis was carried out using equal weight to all the PIFs (or not assigning weight) to see the difference on results of HEPs. It was found that the use of weighted and unweighted PIFs only introduced small differences in the HEPs values as shown in Table 5.22 and Table 5.23.

5.5.5 Calculating the Success Likelihood Indices (SLI)

Based on rating and weight assigned to each task, the SLI were calculated using the following expressions;

$$SLI_j = \sum W_i \cdot R_{ij}$$

Where;

SLI_j = the SLI for task j (j= no. of tasks)
W_i = normalised importance weight for the i PIF
R_{ij} = Scaled rating of Task j on the i th PIF

Results of SLI calculation using the SLIM software is shown in Table 5.17 and Table 5.18 for Site A and Site B respectively.

5.5.6 Converting The SLI into Probability

As the SLI only represent a measure of the likelihood that the operations to carry out a task is successful relative to one another, some forms of conversion need to be carried out to turn it into probability of failure, i.e. in the form of Human Error Probability (HEP). To transform into HEP, the SLI scale was calibrated for each task under consideration. For this purposes the relationship between SLI and HEP followed a log-linear relationship (Embrey et al, 1984) in the form of;

$$\text{Log (HEP)} = a\text{SLI} + b \text{ .... equation (1)}$$

Where a and b are constants

Embrey et al, (1984) provides some theoretical justification and gives experimental data to support the validity of this relationship in SLIM's context. Such relationship also provided by other researcher such as Pontecrovo (1965) and Comer, et al (1984). The two constants a and b was calculated using two tasks with known SLI and Error Probabilities, referred to as the calibration points. Two simultaneous equations were produced using the two calibration points from equation (1) to calculate the value for the constants. By substituting the values of these constants to equation (1), a general calibration equation for converting SLIs values to HEPs is made. The SLI values for the remaining tasks were then converted to HEPs using this formula. The SLIM computer code calculates these HEPs and converts them to HEPs values automatically.

The selection of two calibration points for conversion was found to be quite difficult. Embrey (1984) suggested three ways of getting these data, i.e. the use of data made available from simulator, using data made available from other similar analysis that has been conducted by other analyst or using absolute probability judgement (Comer et al, 1984). However it was found that data from simulator available in the literature are mainly on simple and basic tasks (Kirwan et al, 1990) which did not adequately represent the actual tasks under consideration. The use of published data from other analysts was also found not that feasible because either they originated from the nuclear industry or they utilised PIFs that did not match the PIFs selected for the current analysis. Finally the absolute probability judgement method was used for calibration points that takes into consideration on site specific situation such the influence of relevant PIFs, the process safety system installed, and accident records. HEPs values derived using these calibration points served as baseline values for QRA. Additional analysis using calibration points taken from study on chlorine loading operation (HSE, 1989) was also conducted to check the difference in HEPs values arising from the use of different set of calibration points. The report is used as reference as it was conducted on similar loading operation, but for different chemical, i.e. chlorine. Summary of the calibration points used for the SLIM analysis is shown in Table 5.20.

Table 5. 20 Calibration points used for SLI calculations using SLIM

Source of information	Tasks with known HEPs used as calibration points	HEPs Site A	HEPs Site B
Auditor Judgement (APJ)	1. Operator omits to check pressure gauge is zero prior to disconnecting filling hoses (upper calibration point)	5E-03	1E-03
	2. Operator omits to check line valve stuck (lower calibration point)	5E-02	1E-02
HSE(1989)	1. Operator omit to connect filling hoses to road tanker (upper calibration point) 2. Operator conducts leak test incorrectly (lower calibration point)	1E-04 3E-01	1E-04 3E-01

As can be seen from the table the HEP values on similar tasks were judged differently for the two sites. These were made to reflect the site specific PIFs situation obtained from PIFs analysis conducted in Section 5, that influence human error on each site. To provide some measure of confidence, the HEP values judged by the auditor were compared with nominal HEPs on similar or equivalent tasks from two human error databases, i.e. THERP (Swain and Guttman, 1983) and HEART (Williams, 1986). The comparison showed that the HEPs values on tasks used for calibration points as judged by the auditor lies within the uncertainty bounds of nominal HEPs from the two data bases as shown in Table 5.21.

Table 5.21. HEPs value used for calibration points for SLI calculations using SLIM

Tasks with known HEPs used as calibration points	Auditor Judgement		THERP Database	HEART Database
	HEPs Site A	HEPs Site B	Nominal HEP	Nominal HEP
1. Operator omits to check pressure gauge is zero prior to disconnecting filling hoses (upper calibration point)	5E-03	1E-03	0.001 LB = 0.0033 UB = 0.003	0.07 LB = 0.008 UB = 0.009
2. Operator omits to check line valve stuck (lower calibration point)	5E-02	1E-02	0.01 LB = 0.0017 UB = 0.015	0.09 LB = 0.06 UB = 0.009

Where; UB - Upper Boundary, LB - Lower Boundary

The calibration points taken from HSE study (HSE, 1989) were made using expert judgement made by the auditors who prepares the report then. If these values are adopted then Site A and Site B will be using the same HEPs values of for calibration points despite being subjected to different degree of PIFs influence. This highlight major drawback of adopting known HEPs values from other site analysis, as each site may be under different influences of PIFs. Even under similar PIFs influences, the degree of influences may vary. The effect of using three calibration points instead of two to increase regression accuracy as suggested by Kirwan (1994) was also explored through another analysis using three calibration points. Results of these conversions are shown in Figure 5.18 for Site A and Figure 5.19 for Site B respectively.

Table 5.22 Results of Human Error Probabilities (HEPs) calculations using SLIM for Site A

Base Event No.	Description	Baseline run using 2 calibration points from APJ	Sensitivity runs using calibration points obtained from APJ but (i) weighted (ii) same calibration points as Site B (iii) 3 calibration points			Sensitivity runs using calibration points from other data bases (iv) HSE Report (HSE, 1989) (v) HEART (Williams, 1986) (vi)THERP (Swain&Guttman, 1984)		
		HEPs from APJ-Equal Weight	(i)HEPs using APJ-Weighted	(ii)HEPs using APJ-Same Calibration Points	(iii)HEPs using APJ-(3P)	(iv)HEPs using HSE Report	(v)HEPs using HEART	(vi)HEPs using THERP
HL121b	Drivers moves tanker while filling operation is in progress	1.8E-02	2.6E-02	3.6E-03	2E-02	4.3E-02	2E-02	3E-03
HL122b	Operator failed to put on wheel chocks.	2.6E-02	2.2E-02	5.3E-03	2.7E-02	8.9E-02	2E-02	3E-03
HL14111b	Operator failed to open tanker inlet valve .	1.8E-02	2.6E-02	3.6E-03	2E-02	4.3E-02	2E-02	8E-03
HL14121b	Operator failed to open tanker vapour outlet valve.	1.8E-02	2.6E-02	3.6E-03	2E-02	4.3E-02	2E-02	8E-03
HL15b	Operator disconnect liquid hose while filling operation is in progress.	3.9E-04	9.7E-04	4.1E-05	4.3E-07	3E-05	3E-03	1E-03
HL21b	Operator failed to isolate leak.	7.3E-03	1.5E-02	1E-03	1.6E-02	3.8E-03	2E-02	8E-03

HV121b	Driver moves tanker while filling operation is in progress.	1.8E-02	2.6E-02	3.6E-03	2E-02	4.3E-02	2E-02	3E-03
HV122b	Operator failed to put wheel chocks	2.6e-02	2.2e-02	5.3E-03	2.7E-02	8.9E-02	2E-02	3E-03
HV1411b	Operator failed to closed plant vapour return	1.8E-02	2.6E-02	3.6E-03	2E-02	4.3E-02	2E-02	8E-03
HV15b	Operator disconnect hose while filling operation is in progress	3.9E-04	9.7E-04	3.6E-03	2E-02	3E-05	3E-03	1E-03
PL1212b	Operator failed to open liquid line valves	1.8E-02	2.6E-02	3.6E-03	2E-02	4.3E-02	2E-02	3E-03
PL14b	Operator commences filling without connecting filling hose to tanker	2.6E-03	5E-03	1.5E-04	4.3E-03	1E-04	3E-03	3E-03
PL211b	Remote operator failed to isolate leak	1.8E-03	9.7E-03	2.8E-04	9.7E-03	3.4E-03	3E-03	1E-03
PL221b	Local operator failed to isolate leak	1.4E-02	1.5E-02	1E-03	1.6E-02	3.8E-03	2E-02	8E-03
PV122b	Operator failed to open vapour return piping valves	1.8E-02	2.6e-02	3.6E-03	2E-02	4.3E-02	2E-02	3E-03
PV14b	Operator commences filling without properly connecting vapour return hose to tanker	2.6E-03	5E-03	1.5E-04	4.3E-03	1E-04	3E-03	3E-03
TL2112b	Operator read wrong tanker gross weight	5.3 E -02	3.3E-03	5.3E-03	2.7E-02	8.9E-02	2E-02	3E-03

TL2121b	Operator failed to monitor tanker's content gauge	5.3 E -04	5E-04	5.3E-04	4.3E-03	1.1E-03	2E-02	1E-03
TL2211b	Operator failed to establish tanker empty weigh	5.3 E -02	3.3E-03	5.3E-03	2.7E-02	8.9E-02	3E-03	3E-03
TV2211b	Operator failed to established tanker empty weight	5.3 E -02	3.3E-03	5.3E-03	2.7E-02	8.9E-02	3E-03	3E-03
TV2212b	Operator read wrong tanker gross weight	5.3 E -02	3.3E-03	5.3E-03	2.7E-02	8.9E-02	2E-02	1E-02
TV2221b	Operator failed to monitor tanker content gauge	5.3 E -04	5E-04	5.3E-04	4.3E-03	1.1E-03	2E-02	1E-03

Table 5.23 Results of Human Error Probabilities (HEPs) using SLIM calculations for Site B

Tasks/Base Event No.	Description of tasks	Baseline run using 2 calibration points from APJ	Sensitivity runs using calibration points (c.p) obtained from APJ but (i) weighted (ii) 3 calibration points		Sensitivity runs using calibration points (c.p) from other data bases (iii) HSE Report (HSE, 1989) (iv) HEART (Williams, 1986) (v) THERP (Swain&Guttman, 1984)		
		HEPs using APJ- Equal Weight	(i)HEPs using APJ-weighted	(ii)HEPs using APJ(3P)	(iii)HEPs using HSE(1989)	(iv)HEPs using HEART	(v)HEPs using THERP
HL121b	Drivers moves tanker while filling operation is in progress.	1E-03	5.2E-03	1.2E-03	5E-03	2E-02	3E-03
HL122b	Operator failed to put on wheel chocks.	1E-03	1E-03	1.2E-03	5E-03	2E-02	3E-03
HL14111b	Operator failed to open tanker inlet valve .	5.8E-04	5.8E-04	7.2E-04	1.9E-03	2E-02	8E-03
HL14121b	Operator failed to open tanker vapour outlet valve.	5.8E-04	5.8E-04	7.2E-04	1.9E-03	2E-02	8E-03
HL15b	Operator failed to connect hose to plant liquid filling line.	3.7E-05	3.7E-05	2.6E-04	1.4E-04	3E-03	3E-03
HL21b	Operator failed to isolate leak.	1.1E-03	4.6E-04	1.3E-03	2.3E-03	2E-02	8E-03

HV121b	Driver moves tanker while filling operation is in progress	1E-03	5E-03	1.2E-03	5E-03	2E-02	3E-03
HV122b	Operator failed to put wheel chocks	1E-03	1E-03	1.2E-03	5E-03	2E-02	3E-03
HV1411b	Operator failed to closed plant vapour return	5.8E-04	5.8E-04	7.2E-04	1.4E-05	2E-02	8E-03
HV15b	Operator disconnect hose while filling operation is in progress	3.7E-05	3.7E-05	7.2E-04	1E-04	3E-03	3E-03
PL1212b	Operator failed to open liquid line valves	5.8E-04	5.8E-04	7.2E-04	1.9E-03	2E-02	8E-03
PL14b	Operator commences filling without connecting plant to tanker	1.9E-04	1.9E-04	2.6E-04	1E--04	3E-03	3E-03
PL211b	Control room operator failed to isolate leak	4.6E-04	4.6E-04	5.8E-04	4.8E-04	3E-03	1E-03
PL221b	Local operator failed to isolate leak	1.1E-03	1.1E-03	1.3E-03	2.3E-03	2E-02	8E-03
PV122b	Operator failed to open vapour return piping valves	5.8E-04	5.8E-04	7.2E-04	1.9E-03	2E-02	3E-03
PV14b	Operator commences filling without connecting vapour return hose to tanker	1.9E-04	1.9E-04	2.6E-04	1E-04	3E-03	3E-03

TL2112b	Operator read wrong tanker gross weight	1.4E-03	1.4E-03	1.6E-03	8.9E-03	2E-02	1E-02
TL2121b	Operator set wrong trip weight - over maximum ullage	1.4E-03	1.4E-03	1.6E-03	8.9E-03	3E-03	1E-02
TL2211b	Operator failed to establish tanker empty weigh	1.4E-03	1.4E-03	1.6E-03	8.9E-03	3E-03	3E-03
TV2211b	Operator failed to weigh tanker empty weight	1.4E-03	1.4E-03	1.6E-03	8.9E-03	3E-03	3E-03
TV2212b	Operator read wrong tanker gross weight	1.4E-04	1.4E-03	1.6E-03	8.9E-03	2E-02	1E-02
TV2221b	Operator set wrong trip weigh above maximum	1.4E-04	1.4E-03	1.6E-03	8.9E-03	3E-03	1E-02

Results of HEPs calculations for Site A are shown in Table 5.22. The results showed the differences of HEP values obtained using 6 different calibration points for each tasks under consideration. For example the HEP for task No HL121b, i.e. driver moves tanker while filling operation is in progress could range from the highest value of 4.3E-02, using calibration points from HSE report (HSE, 1989) to the lowest value of 3E-03, using calibration points from THERP nominal data (Swain and Guttman, 1984), a difference of about a factor of 10. Given large uncertainties associated with data base use for human error and risk assessment the difference shown by this analysis is very reasonable. The effect of using weighted and unweighted PIFs for the task is also small. The HEP value for this task using equal weight for PIFs is 1.8E-02 and when using weighted PIFs from Table 5.22 is 2.6E-02, a difference about a factor 2. Using the APJ with two calibration points the HEP value the task under consideration is 1.8E-02, while when using three calibration points is 3.6E-03, a difference of about a factor of 5. This small difference shows that the use of three calibration points over two calibration points in calculating the HEPs is not as significant as suggested by Kirwan (1994).

Table 5.23 shows the results of HEPs calculations for Site B. Similarly the results showed the differences of HEP values obtained using 6 different calibration points for each tasks under consideration. The HEP for task No HL121b i.e. driver moves tanker while filling operation is in progress range from the highest value of 2E-02, using calibration points from HEART nominal data (Williams, 1986) to the lowest value of 1E-03, using calibration points from using the APJ, a difference of about a factor of 10. The difference shown by this analysis is considered acceptable given large uncertainties associated with data base use for human error and risk assessment (Hurst et al, 1992). The effect of using weighted and unweighted PIFs showed for the task is also small. The HEP value for this task using equal weight for PIFs is 1E-03 and when using weighted PIFs from Table 5.23 is 5.2E-03, a difference of about a factor 5. The analysis also shows small difference using the auditor judgement of APJ with two calibration points the HEP value the task under consideration is 1E-03, while when using three calibration points is 1.2E-03, a difference of about a factor of 5. This shows that the effect of using three calibration points over two calibrations points in calculating the HEPs is also not that significant.

The HEP value of the task No. HL21b, i.e. operator failed to isolate leak for Site A is 7.3E-03 (Table 22 column 3) and for Site B is 1.3E-03 (Table 23 column 3), a difference of about a factor of 7. The result showed that PIFs at Site A provided greater influence in reducing the likelihood of success in executing the task as compared to Site B. A similar trend also exists for other tasks under consideration. For example comparing HEPs results calculated using unweighted calibration points made through APJ in column 3 in Table 22 and Table 23 showed that HEPs values of similar tasks at Site A are higher than Site B. Their differences ranged from a factor of about 30 for task No. HL4111b and to a factor of about 7 for task No.HL21b. Even when comparing the HEPs values obtained using the same calibration points for the two sites, (i.e. Site A-Table 22. Column 3 and Site B-Table 23. Column 5), the trend persists but with much smaller margin of differences. Based on these results it could be concluded in this study that Site A is subjected to higher HEPs as compared to Site B in ammonia road tanker loading operation.

5.6 Conclusions

Results from the qualitative human error analysis for the two sites has indicated the following;

- The Hierarchical Task Analysis (HTA) has revealed that Site B has a better work plan to successfully undertake the task of ammonia road tanker loading operation as compared to Site A. The work plan and procedures in place are appropriate and comprehensive which could reduce the chances of the operator making planning errors. The usage of specialist, i.e. maintenance crew to carry out the connection and disconnection of filling hoses also reduce the chances of operational errors. Error recovery is enhanced by better process safety hardware, e.g. the use of weight trip system to prevent overfilling of road tanker and the presence of independent checks by the maintenance crew of certain critical tasks such as the venting-off the filling line prior to disconnection. However the use of maintenance crew at Site B to carry out the filling hose connection and disconnection increases the duration of filling as compared to Site A due to waiting period for their availability. Inadequate hardware design consideration at Site B also has resulted the need to modify the Chiksan arm for bottom loading to road tanker by adding flexible hose connection. That arrangement makes the task to vent-off the remaining of ammonia prior disconnection more difficult and hazardous which defeats the very purpose of installing the Chiksan arms.

- Results from the PHEA conducted showed that use of consequences i.e. severity and frequency provides a simple and effective mean to predict tasks that are under strong influence of human error. However lack of site specific information on the two attributes, e.g. from accidents or near miss records forced the use of expert judgement which at best lacks transparency. For both sites tasks associated with the connection and disconnection of filling hoses, the establishment of correct filling weight to prevent overfilling and the on-site movement of road tanker which could resulted to collisions and hose pull away has been identified as those likely to fail to be accomplished due to human errors. The analysis also allowed appropriate recommendations to be made to reduce the impact of human error on the critical tasks that have been identified. The implementation of recommendations being made were then referred to the site PSMS. Using PRIMA technique the relevant key audit areas and the control loop levels within the PSMS could be determined. This enables the appropriate error reduction strategies and the resources needed for their implementation to be identified in a systematic manner. This approach also indicated one possible mean to integrate human error with PSMS.

- Results of PIFs analysis at the two sites have systematically identified the relevant PIFs at the organisational level (global level) that would influence human errors on tasks that made up the ammonia loading operations. As it is not practical to consider the influences of all PIFs that has been identified, only four were assessed in detail. This detailed assessment showed that they are all more likely to increase the chances of human error in carrying out tasks associated with ammonia road tanker loading operation at Site A as compared to Site B.

The primary objective of conducting quantitative analyses was to calculate HEPs for input to failure analysis of the ammonia road tanker loading operation. However analysing the HEPs results using SLIM technique the yield the following conclusions;

- Proper selection of PIFs is important as they provided the basis for determining the HEPs values. This can only be achieved through proper qualitative analysis. The study found the need for a thorough qualitative analysis prior to human error quantification exercises.

- Selecting appropriate calibration points in SLIM was found to be one of the main difficulties of the quantification exercises. Proper selection is needed as they influence the outcome of HEPs values for all tasks under consideration. Lacking reliable data the points were selected using absolute judgement technique. Sensitivity runs using calibration points obtained from other HEPs quantification exercises showed the maximum difference is about a factor 30. Taking into consideration large differences normally associated with human error data base such difference is quite acceptable.

- Results of HEPs calculated using SLIM techniques showed that Site A has higher value of HEPs as compared to Site B for identical tasks. This finding suggested that in ammonia road tanker loading operation Site A is subjected to higher influence of human error as compared to Site B.

Quantifying Off-Site Risk from Road Tanker Loading Operations

6.1 Introduction

Risk associated with ammonia bulking operation would be major releases of ammonia that could affect the surrounding population. In the event of a major release cloud of ammonia could travel over a long distance in the downwind direction. People engulfed by the could be expose to various concentrations of ammonia. The amount of ammonia concentration exposed and the duration of exposure is known as 'toxic load' (Nussey et al, 1990). Above a certain level of toxic load people could get injured from ammonia exposure. A very high level of toxic load could result in fatality. Consequences from such releases could be considered in term of possible 'injury' or 'fatality' to an individual or the population due to exposure of certain amount of toxic load of ammonia.

6.1.1 Objectives of conducting the QRA

The main objective of conducting the risk assessment exercise for this study is to determine the off-site risk posed by road tanker loading activity at two major hazard sites using two different approaches, i.e. the representative failure sets and the fault tree modelling. Results of individual risk and societal risk obtained using the two approaches were compared. The impact of site specific PSMS performance was analysed. This is done by modifying the generic failure rate with the site specific Management Factor or MF. The Management Factor is determined through the PSMS audit that has been conducted as being described in Chapter 4. A number of sensitivity analysis were also conducted to compare among others the effect of different values of Human Error Probabilities (HEPs) to the system failures. The

HEPs values quantified using the SLIM technique were compared to those obtained using nominal values of generic databases from other technique such as HEART and THERP. This provides the mean to evaluate the effect of so-called 'generic human error' (comparable to generic hardware failure rate) on the system failure rate and eventually the off-site risk values from ammonia loading operation. Sensitivity analysis using different HEPs values from SLIM technique is also carried out. The primary aim is to address the main weaknesses on the usage of such technique, i.e. the selection of calibration points to convert the Successful Likelihood Index (SLI) into HEPs (Kirwan, 1994). For this purpose two sets of calibration points were derived. The first set is derived using Absolute Probabilistic Judgement (APJ) values based on site specific situation. The second set of values is obtained from existing HSE Report (HSE, 1989) on risk assessment of a similar activity. The flow chart of QRA conducted for this study is shown in Figure 6.1.

The other objective is to compare the off-site risk posed by the two sites in carrying out a similar activity, i.e. the loading of ammonia to road tanker. Using the same failure scenarios at both sites their off-site risks were calculated. Since the level of technology for this activity is almost identical at both sites, differences in off-site risk values between the two sites will reflect to some degree the influences of site specific PSMS performance and Human Error performance influences. Along the same line of argument the contribution of human error to the overall system off-site risk was compared between the two sites. Since the two sites belong to two different types of ownership (one locally owned while the other ex-multinational) the results could provide some insight into the influence of site specific ownership on process safety management system performance and on the control of human error. Admittedly the off-site risk results from the two sites under consideration could not be taken statistically to represent the prevailing situation in Malaysia. However if the contribution from site specific PSMS and Human Error found in the study is significant, it could highlight the need to consider the two factors in detailed when using QRA as a tool for decision making, e.g. for land-use planning.

Figure 6.1. QRA Methodology Flow Chart

6.1.2 Types of ammonia releases that can lead to off-site risk

Ammonia is comparatively less toxic than other bulk gases use in the industry such as chlorine, so can only be harmful to the people at high toxic load (Nussey et al, 1990). This suggested that off-site risk could only be realised from considerable releases of ammonia. At the ammonia bulking installations under study releases of this nature were considered possible from significant loss of containment of pipework and storage tanks. As for the pipework and hoses, large containment loss would most likely arise from guillotine failures or complete rupture of piping. Such releases could also result from human error. For example the operator may fail to connect the liquid transfer hose but continue pumping the ammonia that could lead to a full bore spillage (error of omission). The operator might also inadvertently disconnect the filling hoses while the loading operation is in progress resulting in a release (error of commission). In the case of storage tanks such releases could arise from rupture of the tanks. Ruptures below the tank liquid level resulted to liquid releases. Ruptures above the tank liquid level gave vapour releases. For a same size of rupture hole liquid releases will have a higher release rate compared to vapour releases due to the higher mass density of liquid ammonia.

6.1.3 Events that could lead to ammonia releases

After identifying the type of releases that could most likely lead to off-site risk the next step is to identify the events that could cause such releases. Theoretically they are many events that could lead to such releases. As it is not practical to consider all possible events only credible events associated with the actual site under consideration were evaluated. There are many methods available for such evaluations such Fault Trees, FMEA, HAZOP and Expert Judgement. Two different techniques were used for the evaluation.

The first evaluation was made using Expert Judgement method. This technique was used as the system under consideration, i.e. road tanker loading operation is quite simple. Results of hierarchical task analysis (HTA) conducted for the Human Error Analysis was also used to identify human error that could lead to large releases of ammonia. The audit team that analysed the system also had considerable experience in the design, operation and conducting accident investigation of similar systems. In addition the team also spent considerable time at each site to observe and inspect the system.

The second method is Fault Tree modelling. Using this method the chain of sub-events that could lead to major releases of ammonia were constructed top down in a hierarchical manner until it reached the so-called base events. These base events represent a series of components or actions that could initiate the top event, i.e. major releases of ammonia. The next step is to determine the frequency of such events taking place. For components or hardware failures these values were obtained from historical data. As for the human error these values were obtained from historical data or evaluated in the form of human error probabilities (HEPs). These HEPs value were calculated using a number of techniques such as THERP, HEART or SLIM. Failure frequencies or failure probabilities were assigned to each of the base components or actions. Using mathematical manipulation these values were combined and calculated following the hierarchical path upward right to the top event. The failure probability of the top event, e.g. the probability of liquid hose guillotine failure is then determined. This probability value represents the chances of failure per demand, e.g. the probability of guillotine failure of liquid hose per loading. The value is then converted to frequencies by multiplying it with the number of events taking place over a duration of interest, for example the number of loading takes place per year.

6.1.4 Quantifying risk from ammonia releases

By combining the consequences of failures and the probability or frequency of failure of an event the risk from such event was determined. For individual risk, the risk measure is presented in the chances of fatality over a duration of interest, e.g. frequency of death in one million years. Another form of measures is the societal risk that described the frequency in which a certain number of population will be affected by the injury or fatal consequences of an event. The latter risk measure takes into account the population distribution density surrounding a site that could be affected by major ammonia releases.

A comprehensive risk assessment needs to consider the consequences of a number events under various influences of actual site conditions. This includes the site layout, surrounding population, and the prevailing meteorological conditions besides the actual physical system under consideration. Such number of contributions and the possible combination of variables require the representation of a fairly complex consequence modeling. Such model needs to be worked out using a computer for efficiency. For this study the HSE risk assessment computer code RISKAT is used.

6.1.5 Criteria to assess the impact of risk

For toxic materials such ammonia, RISKAT assessment criterion is based on 'toxic load' (Pape and Nussey, 1985). This criteria is a combination of gas concentration and exposure time referred to as 'dose'. For the land planning purposes the toxic load criteria in RISKAT used the HSE 'dangerous dose' criteria which could resulted in severe distress to almost everyone exposed, a substantial fraction requiring medical attention, some of those seriously injured requiring prolong treatment, and highly susceptible people possibly being killed (HSE, 1989). The broad criterion is set to avoid spurious impression on accuracy such as normally implied by the use of probit relationship, e.g. the use of single criteria such as lethality (Turner and Fairhurst, 1989). This approach also allowed greater flexibility, particularly when faced with poor quality data, when compared with probit expression of mortality data only (Fairhurst and Turner, 1993). Such criteria is adopted for this study.

6.2 Description of Ammonia Bulking Operations

The bulk of ammonia usage in Malaysia is as feedstock for compound fertiliser. In the rubber industry ammonia is used as anti-coagulant agent for rubber latex. As there is no ammonia producing plant in West Malaysia where the majority of the rubber plantation situated, it has to be imported using semi-refrigerated tanker from East Malaysia and Sumatera, Indonesia. The anhydrous ammonia imported is a by product of urea production from the synthesis of natural gas which is abundant in the two areas.

6.2.1 Site A

Site A is an anhydrous ammonia bulk terminal that has an annual throughput of about 12,000 MT per year and has been in operation since 1985. Ammonia is brought into the terminal via low pressure refrigerated ships from producers and pumped into onshore pressurised storage tanks via a dedicated pipeline running along the berthing jetty. The two 225 MT capacity storage tanks near the jetty area serve as holding tanks where the whole load of the ship could be discharged at one go. The ammonia is then transferred on demand using road tankers to two 125 MT storage tanks at the bottling plant located about three kilometres away from the jetty. At this location the bulk ammonia is filled into smaller skid tanks, cylinders and dedicated road tankers to be sent to customers.

The plant was designed and constructed loosely based on design standard of the U.K. multinational that built Site B but with minimum automation and process control. The plant operates only during the day, except for ammonia unloading from the ship which may be carried out at night depending on the availability of time for berthing at the Tanjung Bruas Port jetty. This terminal is a dedicated ammonia bulking located near the jetty. They are equipped with facilities for road tankers, skid tanks and cylinders filling.

The bottling and bulking process is fairly straight forward using simple technology with high degree of manual operations. The simplified line diagram for road tanker loading is shown as Figure A7.1 in Appendix 7. The empty road tanker arrived at the site will be physically check for fitness of purposes. The target filling weigh is then determined by the capacity of the road tanker and the permissible ullage. The tanker is then connected to the plant's liquid and vapour return line using flexible transfer hoses. Liquid ammonia is pumped from the storage tank into the road tanker under the watchful eyes of the operators. Once the target filling weigh is reached the pump is stopped. The remaining ammonia inside the flexible transfer hoses is vented to the scrubber before being disconnected. The road tanker is once again checked for abnormalities and allowed to drive-off after the relevant paper work has been completed.

6.2.2 Site B

Site B is also an ammonia bulk terminal but with a larger throughput of about 34000 MT per annum and was the ammonia loading terminal for a compound fertiliser plant i.e. Site C, until the last two years where major business restructuring has turned this plant into an independent profit centre. The management style is inherited from the mutltinational company especially for the PSMS.

Unlike Site A this plant is located within the port area where bulk ammonia could be pumped from refrigerated ship tanker via dedicated pipeline straight to the plant's four pressurised storage tanks each with 125 MT capacity. Sixty percent of the ammonia is shipped to Site C by pressurised rail tankers to be used as feedstock for compound fertiliser. The remaining ammonia is filled into road tankers, skid tanks and cylinders for downstream distribution mostly for anti-coagulant agent for rubber latex.

The bulking and bottling process at this plant is more automated and with a few more safety features as compared to Site A, having benefited from its U.K multinational parent company design standard for such installations. It operates a 3 shifts system, mainly to cater for ship unloading and rail tanker loading of ammonia while cylinders bottling and road tanker loading is only carried out on the day shift.

The bottling and bulking process is very similar to Site A but with a higher degree of process automation. The rail tanker loading is equipped with a number of process safety systems such as wheel interlocks which prevent the rail tanker from moving while loading is in operation. The road tanker loading bay is not fitted with wheel interlocks nor barriers that could reduce the chance of connection failures due to hose pull-away. Even though it is equipped with Chiksan arm top loading, the arrangement is not compatible with the current fleet of road tankers that require bottom loading. So additional flexible hoses need to be fitted to the end of the Chiksan arm to facilitate the loading operations.

The simplified line diagram of road tanker loading operation is shown in Figure A7.2 in Appendix 7. The empty road tanker arriving at the site will be physically checked for fitness of purpose. The tanker is then driven to a dedicated filling bay equipped with a weighbridge fitted with weigh trip system. The tanker is weighed to determine its empty weight. The target filling weight is set by calculating capacity of the road tanker and the permissible league. The alarm for the weigh trip system is set at 10% below the target filling weight. The tanker is then connected to the plant's liquid and vapour return line using flexible transfer hoses attached to the end of the Chiksan arms. Liquid ammonia is then pumped from the storage tank into the road tanker under the supervision of the operator. Once the trip weigh is reached the pump is automatically stopped and the tripped alarm sounded. The operator then needs to reset the alarm to allow the pumping to proceed until the target filling weight is reached. After the pumping stops ammonia remaining inside the Chiksan arm and flexible transfer hoses is vented to a catchpot before the hoses are disconnected from the road tanker. The tanker is once again checked for abnormalities and allowed to drive off after the relevant paper work has been completed.

6.3 Collecting Data for QRA on The Two Sites

The main effort in conducting QRA on the two major hazard sites involved the collection and gathering of site specific information such as plant layout, major vessels and piping data, safety system installed, failure rate data base, population data, meteorological data and frequency of road loading operations. For this purpose a variety of tasks have been carried out which include site inspections, interviewing workers and management, observing the road tanker loading operations, visiting populated areas surrounding the sites, visiting a number of Government agencies for population data, site maps and meteorological data. Such activities consumed bulk of the field study that span over almost 6 weeks duration for the two sites. The population data and meteorological data then were modified to fit into the requirements of the QRA computer code RISKAT.

The ammonia release scenarios of selected incidents were quantified using established source models which estimate the discharge rate and extent of flash and evaporation from a liquid pool. RISKAT incorporates two types of computer code developed within the HSE to calculate discharge rates. A computer code called VOGLE is used to calculate discharge rate from liquid releases, and COPTERA is the computer code used to calculate 2-phase flow. The source term output is then converted to concentration fields downwind using an appropriate dispersion model. Two type of gas dispersion models are incorporated in RISKAT. The first model is called DENZ which deals with instantaneous or 'puff' type dispersion. The other is called CRUNCH which models the continuous dispersion of heavier than air gases. Both models are able to predict the gases downwind concentration at given distances. The dispersion's calculations rely heavily on the weather data input such as the prevailing wind speed and wind direction as well as the atmospheric stability.

6.3.1 Collecting Malaysian weather data

Weather data is essential in conducting a realistic quantitative risk assessment. The dispersion modelling part of the consequence calculations requires specification of wind speed and atmospheric stability. The impact calculations also require directional frequencies for each combination of wind speed and stability used. The atmospheric stability classification emphasised the importance of utilising data on wind direction fluctuation and wind-inclination fluctuation. The Pasquill-Gifford (Gifford, 1975) classification is used for this purposes

A number of combinations of wind speed and stability are selected for the dispersion modelling. The combination number generally is six which can adequately reflect the full range of observed variations of the wind speed and atmospheric stability. It is not practical nor computationally efficient to consider every combination observed. These combinations are grouped into representative weather classes that together cover all the conditions observed. The classes chosen must be sufficiently different to produce significant variations in dispersion modelling results. The conditions most likely to give rise to large effect distances must not be grouped with those leading to shorter effect distance.

The collection of weather data in Malaysia is carried out by the Meteorological Department of Malaysia (MDM). The Department only monitors weather data at major airports for civil aviation purposes. The data consists of basic information on wind speeds, wind directions, and atmospheric stability classes monitored on a daily basis. Only at few locations does this data go back for the last fifteen years. For RISKAT this data need to be analysed further into stability classes.

Risk assessment conducted in Malaysia currently used stability classes that are based on assessors own judgement made based on limited local weather data. Some even used much simplified dispersion model which does not take into account the effect of atmospheric stability. Such approaches are not satisfactory because they are neither consistent nor representative of the real conditions. So the author through the good office of his employer, Department of Occupational Safety and Health (DOSH) of Malaysia initiated the request for the analyses of stability classes from the Meteorological Services Department of Malaysia (MSD, 1996). Such analysis would not only be useful for the author's current research but also for future used by the public, e.g. for consequences analysis in emergency planning. The format for the required stability classes was given to them and they were requested to analyse the last 10 years weather data.

However due to cost and other job priorities the MSD only managed to analyse weather data from one airport, i.e. Alor Star in the format requested. It gives for the first time the stability classes information derived from the actual data rather than based on individual estimates. The analysed weather data for this airport is shown in Appendix 8. Summary of the 10 year data is shown in Table 6.1. This data is used as input for RISKAT runs in this study. Even though it is not the actual data for the two sites, in the author's opinion it is a better representation of Malaysian weather data as compared to individual estimates or the use of available data from developed countries. Furthermore the airport and the two sites under study are located on the west coast of Peninsular Malaysia and are subjected to almost the same weather pattern especially the direction of the wind blows. From the month of March to September the wind blows north-easterly from the Malacca Straits while the rest of the year the wind predominantly blows south-westerly from the South China Sea.

As shown in Table 6.1 atmospheric stability category A and B dominate the day time with a combined contribution of about 92% of the day time stability classes. Referring to atmospheric stability classification in Appendix 9, such situation reflects very unstable conditions normally associated with warm and sunny weather with light wind and cloudless skies. The rate of change of temperature with height known as 'lapse rate' is high in the atmosphere. Thus any gas releases in this type of weather will be quickly diluted due to strong mixing with air and dispersed upward following the rise of warm air from the ground. As a result the toxic gas cloud that being released is quickly diluted and would not travel over a very long distance downwind. The area under toxic concentration will not be large and in a populated area less number of people will be put at risk.

During the night however the situation is reversed. Almost 98% of the conditions fall under F weather category. This category indicates calm or stable weather where there is strong cooling of the ground. There exists inversion of atmospheric temperature. In this condition very little or negative upward movement of air exists. A gas cloud releases in this condition cannot readily dispersed upward and will travel over a long distance downwind. For a toxic gas cloud this means a greater area will be engulfed by lethal toxic concentration due to the lack of dilution and dispersion in the atmosphere. In a populated area this means more people will be put at risk.

Table 6.1 Meteorological Data for Alor Star Airport, Malaysia (MSD, 1996) (Combination of 10 years normalised data)

Directional Sector	**Day time Data (0700-1900)**						
	A 1 m/s	**A 2 m/s**	**B 3 m/s**	**D 5 m/s**	**D 7 m/s**	**F m/s**	**TOTAL**
N	7.35	4.12	1.09	0.26	0.00	0.00	12.82
NNE	2.19	3.83	1.42	0.37	0.00	0.00	7.82
NE	1.95	5.82	4.60	1.62	0.03	0.00	14.02
ENE	1.54	2.82	2.68	1.27	0.02	0.00	8.33
E	1.87	2.17	0.39	0.19	0.00	0.00	4.62
ESE	1.03	1.51	0.15	0.01	0.01	0.00	2.72
SE	0.87	1.72	0.28	0.03	0.00	0.00	2.91
SSE	0.68	1.79	0.37	0.07	0.00	0.00	2.92
S	0.96	2.44	1.06	0.30	0.01	0.00	4.77
SSW	0.59	1.43	0.96	0.31	0.01	0.00	3.31
SW	0.90	2.54	2.19	0.61	0.02	0.00	6.27
WSW	1.02	3.62	3.50	1.14	0.04	0.00	9.32
W	1.64	4.77	3.72	1.07	0.03	0.00	11..22
WNW	0.83	1.95	0.86	0.23	0.01	0.00	3.89
NW	0.76	1.36	0.41	0.08	0.00	0.00	2.61
NNW	0.89	1.29	0.23	0.04	0.00	0.00	2.46
TOTAL	**25.09**	**43.19**	**23.92**	**7.61**	**0.19**	**0.00**	**100.00**

Directional Sector	**Night time Data (0700-1900)**						
	A 1 m/s	**A 2 m/s**	**B 3 m/s**	**D 5 m/s**	**D 7 m/s**	**F m/s**	**TOTAL**
N	0.00	0.00	0.00	0.28	0.00	18.05	18.33
NNE	0.00	0.00	0.00	0.00	0.00	13.14	13.14
NE	0.00	0.00	0.00	0.05	0.00	26. 29	26.34
ENE	0.00	0.00	0.00	0.24	0.00	9.50	9.74
E	0.00	0.00	0.00	0.03	0.00	3.49	3.52
ESE	0.00	0.00	0.00	0.00	0.00	4.00	4.00
SE	0.00	0.00	0.00	0.16	0.00	4.33	4.49
SSE	0.00	0.00	0.00	0.15	0.00	3.17	3.32
S	0.00	0.00	0.00	0.10	0.00	2.65	2.75
SSW	0.00	0.00	0.00	0.10	0.02	0.73	0.85
SW	0.00	0.00	0.00	0.17	0.00	1.03	1.10
WSW	0.00	0.00	0.00	0.16	0.00	1.33	1.49
W	0.00	0.00	0.00	0.26	0.03	2.31	2.60
WNW	0.00	0.00	0.00	0.06	0.00	2.13	2.19
NW	0.00	0.00	0.00	0.08	0.00	2.93	3.01
NNW	0.00	0.00	0.00	0.00	0.00	3.04	3.04
TOTAL	**0.00**	**0.00**	**0.00**	**1.84**	**0.05**	**98.10**	**100.00**

6.3.2 Determining population density surrounding the sites

Population distribution is required for assessing the impact of the site's off-site risk on people who lives nearby. Toxic releases have the potential to affect large area so it is necessary to analyse population distribution quite a distance away from the source of releases. The impact of the off-site risk could be assessed based on the individual risk distance or risk contour that could reach the populated area. Alternatively it could be assessed of using Societal Risk in the form Frequency-Number (F-N) curve which gives the frequency of events causing N or more fatalities, injuries or exposure (AIChE, 1989).

For this study the population density for the two sites was obtained from the Statistical Department of Malaysia (SDM). It is based on the 1991 nation-wide survey on population density (SDM, 1991). The population density map for a particular district was mapped based on the total number of people surveyed within a defined area. The population density for the two sites used for this study is shown in Appendix 10. The population density map is capable of giving an indication of areas where it is densely populated but not the type of dwelling, i.e. whether it is residential, industrial or commercial. For the latter purposes the data needs to be referred to the Ordnance Map of the two sites. These maps were obtained from the Land Surveying Department of Malaysia (LSDM, 1992). By comparing information on the two maps the population distribution surrounding the sites in term of density and type were established. However RISKAT is only capable of dealing with four different types of population density namely urban, commercial, rural and special area. So the population density range categories needed to be regrouped to fit into RISKAT requirements.

6.3.3 Selecting Hardware Generic Failure Rate

One of the main sources of uncertainty to beset the QRA is the lack of robust data for the hardware failure rate. While there has been some progress in establishing hardware data banks in developed countries, very little is available in developing countries like Malaysia. As such the QRA practitioner in the country resorts to various data banks or literature available world wide. Large multinational companies are resort to in-house data banks when carrying the QRA.

This situation posed difficulties for a regulating agency like DOSH in Malaysia in interpreting the risk results for decision making. It is not practical to standardise the use of hardware failure rate since none of the data banks is truly generic and could be appropriately applicable at all sites. Given different operating conditions, maintenance standard and operators skill in developing countries, imposing the use of a single data bank will be counter productive. Instead DOSH maintained a set of internal data that is used as guidelines to review the all the QRA submitted to them (DOSH, 1996). The QRA proponent will be required to provide satisfactory explanation if there is large discrepancy between the hardware failure rate used by them when compared to this internal data. The data also is used by DOSH when conducting its own QRA for regulatory and advisory purposes, e.g. advising the local authority on land use planning matters.

The internal data was established with the help of an established foreign consultant which has wide experiences worldwide in the area of risk and environmental impact assessment. This data is used as the baseline data for local application and will be reviewed regularly to incorporate local factors as the information made available, e.g. through operating experience and accident data. So the DOSH internal data as shown in Appendix 11 is the primary source for generic hardware failures used in the analysis. In the absence of specific hardware data from the list data from HSE (HSE, 1989) is used. In the event particular data is not available from both list the handbook on process safety to (Lees, 1990) is referred. When available the DOSH data is always used even though there is different data available in HSE data base and the reference handbook. This approach will provide some consistency in the selection of generic hardware failures.

6.3.4 Determining Human Error Probabilities (HEPs)

The HEPs is required as input to the QRA being conducted. The modelling of failure scenarios using Fault Tree Analysis (FTA) include human error components in the form of External Error Mode (EEM). As described in Chapter 4, the SLIM technique was used to determine the HEPs. A number of sensitivity calculations have been made to address uncertainty from calibration points selected to convert the SLI to HEPs. HEPs calculated in the sensitivity runs were also be used as input for the QRA sensitivity runs. These sensitivity runs show the range of error in QRA results that contributed to the usage of different calibration points in calculating the HEPs. Table 5.17 and Table 5.18 from Chapter 5 show the summary of HEPs values calculated using SLIM technique that will be used for the QRA runs using FTA approach for Site A and Site B respectively.

Nominal HEPs values from THERP (Swain and Guttmans, 1983) data base and HEART (Williams, 1986) data base were also used as input to the FTA. The purpose as mentioned in Chapter 5 is to provide the equivalent of the generic hardware failure rate in determining the system failures. These two sets of HEPs also were used as input to the FTA and eventually for the QRA. Results of the QRA run using HEPs obtained through this method could provide some indication of the effect of considering Performance Shaping Factor (PSFs) in determining the HEPs. Sets of nominal HEPs values obtained from the THERP data base and those obtained from HEART data base are shown in Appendix 12.

6.4 Conducting QRA on the Two Sites

The QRA exercises made up the final stages of the research after the PSMS Audits and Human Error Analysis. Results obtained from first two analysis were used as input to the QRA. This provided a mean to assess the influence of site specific PSMS performance and Human Error on off site risk from the two sites. The main goal, objectives, and approaches taken to conduct the QRA on the two sites is given in the following paragraphs;

6.4.1 Goal and objectives of conducting the QRA

The goal of the study is to estimate public risk arising from the handling of bulk quantities of toxic gas, i.e. anhydrous ammonia at the two sites. Results of the risk estimates are to be compared with a specified public risk criteria which in this case will be the probability of fatality to individual (individual risk) and to the public (societal risk).

The specific objectives of the study are;

- to estimate off-site risk to members of the public surrounding the site
- to estimate the impact of site specific PSMS performance to off-site risk using PRIMA Modification Factors
- to compare the risk estimates found on Site A with Site B
- to identify the key management contributions

As the main objective of the study is to estimate off-site risk to the public, the general approach in this study will be to identify credible scenarios that could lead to major releases and to calculate their impact. Localised incidents which could lead to small releases would not be considered, as they are not expected to create off-site risk.

The following approach is used for this study;

- identifying potential leaks and major releases from fractures of process pipelines and vessels
- estimating the frequency of the Top Event which is associated with major releases using fault tree analysis
- incorporating human failure rates in the form of Human Error Probabilities (HEPs) together with equipment failure rates in fault tree analysis

The analytical techniques used for the analysis are;

- Fault Tree Analysis using Fault Tree Manager computer code - for event frequency estimation and minimum cut set importance (AEA, 1994)
- RISKAT Computer Code - for release rates, gas dispersion analysis, hazard ranges and fatality probability (Hurst et al, 1989)
- PRIMA Audit technique - to calculate Modification Factor for generic failure rate (CEC, 1995)
- SLIM Computer Code - to calculate Human Error Probability (HEPs)

6.4.2 Approaches taken to conduct QRA

The quantitative risk assessment conducted for both sites is carried out using two methods. The first method based on engineering judgement and expansive list of failures of critical components mainly vessels, piping, transfer hoses and their associated fittings. This implies some selections as incidents that considered to small to give consequences to off-site risk are ignored. The remaining incidents were analysed and were grouped together if they give similar consequences. A single cumulative frequency will be used to represent all the failure cases in that group. For example several liquid leaks can be grouped together, and several vapour leaks placed in another group.

The second method used Fault Tree technique to decompose failure of the top event to a series of basic events that eventually lead to hardware and human failures. Generic failure rates are used for hardware failures, e.g. pipework or vessels rupture. Human Error Probabilities (HEPs) derived from SLIM technique are used as input for human failures contribution. Using a computer code (Fault Tree Manager) the failure probabilities of the base events were combined using Boolean algebra mathematical rules to yield the overall failure probability of the top event.

For the consequences analysis of toxic releases specific source and dispersion models within RISKAT were utilised. These models provided quantitative information on source rates (release rate) and dispersion of vapour clouds to specific concentration levels of interest. Effect models were then used to convert the incident-specific results into effect on people in terms of injury or deaths or dangerous dose which combines the two (Nussey et al, 1993). The facility to include mitigating factors such as sheltering and evacuation, which in real life can reduce the magnitude of the effects of such incidents provides by RISKAT were also being utilised.

In both approaches the process of collecting on-site information to identify credible failure scenarios that could lead to off-site risk at each site involved the following activities;

1. Management briefing
2. Site visit for plant familiarisation
3. Reviewing documents
    - plant layout and PI&D,
    - operating procedures
    - maintenance schedules
    - accident and near miss reports
    - emergency response plan
4. Critical observation on ammonia bulking process with emphasis on the road tanker loading operations
5. Conducting physical inspection on the plant conditions with specific emphasis on flexible filling hose, piping, storage tanks and road tanker
6. Interviewing the manager, supervisors and operators on road tanker loading process
7. Conducting walk through and talk through exercises with the operator on ammonia loading process to road tanker.

Table 6.2. Duration taken to collect on-site information for QRA

Activities	Site A (no. of days)	Site B (no. of days)
1. Management briefing and deciding on the QRA boundary	0.5	0.5
2. Detailed understanding on the plant layout, process and critical equipment	1	1
3. Reviewing documents such as operating procedures, permits to work, maintenance procedures and emergency procedures	1	1.5
4. Critical observation of ammonia loading of road tanker on-site	0.5	0.5
5. Conducting physical inspection on critical plant items such as road tanker, plant piping and flexible hoses	1	1
6. Interviewing managers, supervisors and operators on the ammonia loading activity	0.5	0.5
7. Walk through exercise with the operator on road tanker loading activities	0.5	0.5
8. Identifying credible failure scenarios that could lead to major releases of ammonia	1	1
9. Visiting the plant surrounding area to assess the impact on population in the event of a major ammonia releases	1	1
TOTAL DAYS SPENT	7	7.5

8. Visiting the areas surrounding the plant to identify inhibited buildings, busy roads, open spaces, ground roughness, and estimate distance between them and the site

9. Discussion session to make final judgement on credible scenarios.

6.4.3 Conducting QRA Using Representative Failures Approach

The representative failures approach is one of the method of conducting the QRA. In this approach the credible failure scenarios are identified using expert judgement. As the name implies it requires adequate knowledge and experience of the system under consideration on the part of the assessor. A simple system which consists of a few storage tanks and piping runs would also make it easier to apply the technique.

It is considered appropriate to use this approach for the QRA in this study for the following reasons:

- the system under study, i.e. loading of ammonia to road tanker for the two sites is fairly simple and independent from the rest of plant operations.
- the ammonia loading operation involved only a small number of personnel at each site.
- the team that assessed and conducted the QRA has considerable knowledge and experience in the operation of similar system.
- the assessor team spent considerable time to in carrying out site inspection, reviewing PI&D and safety documents, observing the operations and interviewing the operator.
- only failure scenarios that could lead to off-site risk are considered which eliminates to need to consider small releases.
- results of the Hierarchical Task Analysis performed on the ammonia loading activities were also referred to in identifying the credible failure scenarios.

- results of QRA will be used mainly to for comparison between the two sites and not to meet specific risk criteria for decision making

The process of identifying and selecting the credible failure scenarios that could lead to off-site risk at each site involved the activities as shown in Table 6.2.

The representative failure set that has been identified using expert judgement that could lead to off-site risk for the two sites is shown in Table 6.3 respectively. As can be seen from the table failures from ammonia storage tanks on-site are not considered. Results of on-site inspection revealed that these tanks are located quite a distance from traffic movement. So the possibility of them being hit by moving vehicles are remote. Secondly these tanks are fixed and so not subjected to fatigue loading from road abuse unlike the road tankers. The tanks are also fitted with additional safety features such as non-return valves, excess flow valves and adequately sized pressure relief valves. The steel plate construction with sufficient notch toughness properties also greatly reduced the possibility of fast fracture. While it will be essential to analyse these tank failures in overall risk assessment for the site, it was judged not to be within the risk assessment boundary of road tanker loading operation.

Input data used for conducting the QRA using the representative failures set approach for the two sites is shown in Appendix 12. As shown in Table A12.1 and for Table A12.2 the releases scenarios for hoses and piping are based on full-bore releases due to guillotine failures. As for the road tanker the failure scenarios assumed shell ruptures equivalent to 100 mm (4 inches) diameter for the two sites. Ruptures below and above the liquid line were considered. The frequencies of failures for vessels, pipework and hoses were taken from DOSH failure rate data as shown in Appendix 11. These failure frequencies were then converted to failure probabilities by dividing them with the total number of ammonia loading operations take place in a year for each site. As these figures vary slightly every year depending on customers demand an average number is used for the analysis. The average number of ammonia loading to road tanker for Site A is taken as 480 per year, while for Site B the number is taken as 96 per year.

Table 6.3. Representative Failure Set selected for two sites

Credible Failure Scenarios	Justification for selection
1. Guillotine failures of flexible liquid filling hose	This hose could easily ruptured in guillotine fashion due to hose pull away, strength degradation, hit by moving vehicle, and overpressure. This type of failure also included those due to human errors, i.e. failure to properly connect prior filling and disconnecting the hose while filling operation is still in progress.
2. Guillotine failure of flexible vapour return hose	Similarly liquid filling hose guillotine failures could be due to hose pull away, impact loading, strength degradation and overpressure.
3. Guillotine failures of liquid filling line	The plant piping arrangement at the two sites made this type of failures quite credible. The most likely probably due to impact loading from moving vehicles such as lorry and other road tanker as well as strength degradation of piping.
4. Guillotine failures of vapour return line	Similarly the plant piping arrangement at the two sites made guillotine failures of vapour return lines possible. It could be due to impact loading from moving vehicles such as lorry and other road tanker and strength degradation of piping
5. Rupture of road tanker below liquid line	There is a lot of vehicle movement within the site, e.g. fork lift, lorry carrying ammonia cylinder and skid tanks. Poor traffic arrangement within both sites would make failures due to impact loading feasible. However slow movement of vehicles within the site would not result in collision that could completely rupture the road tanker. Fast fracture from ammonia induced stress corrosion cracking is considered not to be significant due to the material approved the road tanker construction has to meet notch-toughness requirements set by approved design code by DOSH
6. Rupture of road tanker above liquid line	Apart from failures due to impact loading from collision as described above, the road tanker could also fail from loss of strength due to corrosion or fatigue. As internal inspection only conducted every 5 years it is quite likely weakening of the tanker integrity left undetected. However this type of failures is more likely to have resulted in hole-type failures rather than catastrophic rupture of the road tanker.

6.4.4 Conducting QRA Using Fault Tree Modelling

In this approach the failure scenarios identified using the representative set approach were modelled in more detail using the fault tree analysis. By decomposing the failure scenarios farther the base events that could contribute to the failure of the top event could be identified. These base events were made up of hardware failure and human errors.

For the purpose of the study, hardware failure base events are made up of component failures due to physical defects. As an example a faulty content gauge is considered a hardware failure even though it may be due human error in fixing or calibrating the gauge.

Base events that were considered as human error are those which failures are due to human activities. The type of human error considered are those which fall under the External Error Mode or EEM. This type of error only deal with error of commission or error of omission (Swain and Guttman, 1983). As an example failure to connect filling hose to tanker by the operator is considered as human error. The study does not attempt to look at psychological reason why the operator failed to connect the hose. This type of human error fall under the Psychological Error Mode or PEM (Rasmussen et al, 1983). For example the underlying reason why the operator failed to connect the hose may be due to memory lapse or mental block. The main reason for not attempting to look at the PEM is that lack of reliable data on this type of error. Other reasons included lack of expertise on the part of the assessment team. Both reasons would increase the level of uncertainty in the study, which did not justify their inclusion.

In essence the modelling of the failure scenarios using the FTA was to identify the influence of human and hardware failures to the overall system failures. The main objective is to measure the contribution of both types of error that could lead to large releases of ammonia which capable of creating off-site risk to the surrounding population.

Fault tree diagrams for site A are shown in Appendix 14. Diagrams A14.1 shows the fault tree for system failure (guillotine failures) due to both hardware failures and human error failures. Diagrams A14.2 shows the fault tree for system failures due to hardware failures only. These diagrams provide the basis to compare the contribution of human error to the overall system failures.

Fault tree diagrams for site B are shown in Appendix 14. Diagram 14A.3 shows the fault tree system failures of Site B from base events which are made up of hardware failures and human error. The top-down decomposition of base events showed similarity with fault tree for Site A. This is due to the fact that the tasks involved in the ammonia loading activity at both sites are very similar. Despite being designed and built by a multinational company the level of automation and safety system installed for this site is not much higher than Site A. The main difference lies in the road tanker weighing system which uses a weighbridge equipped with a weight trip system. This provides an additional safety feature to the system in preventing overfilling. Diagram 14A.4 shows the system fault tree due to base events from hardware failures only. The human error contribution to the overall system failure could be assessed by comparing results of the two fault trees.

Input for QRA using this approach are comprised of generic failure rate and HEPs for hardware and human activities as identified in the fault trees. The baseline QRA used HEPs values derived using SLIM technique as described in Chapter 5. QRA sensitivity runs used nominal HEPs values as provided by THERP and HEART data bases. This nominal data is based on 'average' industrial condition which did not subject a worker to unusual degree of discomfort and that is fairly representative of the NPP industry (Swain and Guttman, 1983). This input is shown in Appendix 15. Table A15.1 shows the input data for Site A while Table A15.2 shows the input data for Site B. The generic failure rates for hardware such as valves and gauges are taken from the DOSH failure rate data as shown in Appendix 11. For Human Error different HEPs values generated using different calibration points provide additional run for the sensitivity analysis. These analysis were carried out to address one the inherent weaknesses of SLIM technique, i.e. the selection of appropriate calibration points to generate the HEPs (Kirwan, 1994). This aspect has been described in detailed in Chapter 5.

6.5 Results of Fault Tree Analysis (FTA)

Results of fault tree analysis using FTM software for Site A are shown in Table 6.4. while Table 6.5 shows the result of fault tree analysis for Site B. The Minimum Cut Set (MCS) importance analysis for the two sites is shown in Appendix 16. The base events contribution and some suggestions for error reduction for the two sites is shown in Appendix 17.

Discussion of the results is given in the following paragraph. The discussion is broken into two parts. The first part will describe results between various base lines and sensitivity runs for a particular site. The second part will compare results of the fault tree analysis between the two sites. This is to compare and contrast the risk components between the two sites.

Analysis of results for both sites will be discussed at the system level, i.e. for the overall system failure from road tanker loading operations, and at sub-system level, i.e. the major failure components that contributed to the overall system failure.

Analysis at the system level provides some insight into the probability values of system failure from the application of HEPs values derived from three different sources i.e, SLIM, HEART and THERP. It also provides comparison on sensitivity runs using HEPs values derived from different calibration points from the SLIM technique.

The analysis of sub-system failures results identifies important base events and the MCS that acted as the highest contributor to the overall system failure. By analysing the underlying mechanism why the base event failure took place, certain suggestions could be made to reduce their probability of failure.

6.5.1 FTA Results for Site A

Discussions on system failure rates are based on FTA results shown in Table 6.4, Appendix 16 and Appendix 17.

1. FTA using the HEART and THERP nominal human failure rate data yields higher overall system failure rate as compared to those assessed using SLIM technique for the human failure rate. This suggested that the site specific PIFs that are the major determinant of HEPs should be taken into consideration in determining the system failure rate.

2. Results of FTA using PIFs with equal weight and assessed weight in SLIM analysis show a difference by a factor of 2 for Site A. This small difference suggested at least in the case study that the contribution of weighting on PIFs are not that significant, contrary to finding by Zimolong (1992).

3. FTA using hardware only data gives higher system failure rate as compared to those being decomposed further to hardware and human error components. It appears that the presence of human activities provided the recovery in the case of hardware failure.

4. Minimum Cut Set (MCS) analysis of Site A fault trees shows 3 MCSs provided the highest contributions to the system failures. The 3 MCS made up to more than 96% of the contribution to the system failures as shown in Table A16.1 in Appendix 16. Referring the fault trees for Site A in Diagram A14.1 show that the base events that made up these MCSs belong to the sub-system failures of flexible hoses. The results indicate that a considerable risk reduction to the overall system failures could be realised by improving the safety measures of this sub-system. One of the measures is installing a barrier with interlock to prevent road tanker pull away.

Table 6.4. Results of Fault Tree Runs for Site A

Description of Fault Tree Runs	Probability/ Frequency (per year)	System Failures (R)	Liquid Hose (HL)	Vapour Hose (HV)	Liquid Piping (PL)	Vapour Return Piping (PV)	Tanker Liquid Side (TL)	Tanker Vapour Side (TV)
1. HEPs from SLIM - using APJ Calibration Points	Probability	8.22E-04	5.77E-04	2.67E-04	3.56E-08	1.38E-06	9.89E-08	1.12E-06
	Frequency (per year)	3.95E-01	2.48E-01	1.28E-01	1.71E-05	6.62E-04	4.75E-05	5.38E-04
2. HEPs from HEART Nominal Data	Probability	1.26E-03	8.28E-04	4.29E-04	2.35E-08	1.66E-07	9.34E-08	3.23E-06
	Frequency (per year)	6.04E-01	3.98E-01	2.06E-01	1.13E-05	7.96E-05	4.48E-05	1.55E-04
3. HEPs from THERP Nominal Data	Probability	2.09E-04	1.36E-04	7.23E-05	2.41E-08	4.82E-08	5.09E-08	2.19E-07
	Frequency (per year)	1.0E-01	6.53E-02	3.47E-02	1.16E-05	2.31E-05	2.44E-05	1.05E-04
4. HEPs from SLIM - using Hays Calibration Points	Probability	5.25E-01	3.43E-04	1.79E-04	2.25E-09	9.69E-07	1.67E-07	2.53E-06
	Frequency (per year)	2.5E-01	1.65E-01	8.59E-02	1.08E-06	4.65E-04	8.01E-05	1.21E-03
5. HEPs from SLIM - using APJ calibration points as B	Probability	1.12E-05	7.32E-06	3.71E-06	1.53E-10	3.84E-09	5.19E-08	1.54E-07
	Frequency (per year)	5.37E-05	3.51E-03	1.78E-03	7.34E-08	1.84E-06	2.49E-05	7.39E-05
7.Hardware Only Data	Probability	1.81E-04	4.1E-05	1.22E-04	1.15E-06	4.62E-06	3.7E-07	1.19E-05
	Frequency (per year)	8.69E-02	1.97E-02	5.85E-02	5.52E-04	2.22E-04	1.78E-04	5.71E-05

5. At the component level the failure rates of flexible hoses failures were found to be much higher than tanker and piping failures. Analysing the tree further showed that guillotine failures of hoses that could release ammonia from the road tanker could be not easily isolated by hardware or human intervention. Operator failures to isolate such releases could arise from the need to manually shut-off the road tanker valves in the event of guillotine failures of the hoses. Such action would be likely to have a low degree of success as the operator would need to work inside the ammonia cloud. Wearing inadequate PPE like gas mask without air supply, the operator would most likely abandon the task when he comes under threat of large releases of ammonia from guillotine failures of the hoses.

6. Base events contribution in term of importance is shown in Appendix 17. One of the highest contributors for the system failure is base event no. HL21b which represents the operator failure in isolating possible leak from guillotine failure of the flexible liquid hose. This failure scenario would be from the release of ammonia from tanker to the atmosphere (reversed flow) when the tank is filled after some time. If the hose failure takes place ammonia from the tanker will flow outward. Note that road tanker could not be fitted with non-return valve as it is supposed to receive and to deliver ammonia via the same valves system. The same base event also provided the highest contribution of system failure for the rest of the sensitivity runs. This provides valuable information when attempting to reduce the off-site risk from the system based on hardware and management deficiencies that exist at Site A. For example from a design point of view putting separate valves on road tankers for the delivery and receiving, with the latter fitted with non-return valves. In the event of guillotine failure of flexible liquid hose the non-return valve could prevent ammonia releases from the road tanker being filled. From the human error point of view further analysis could provide more insight on how and why the operator fail to isolate such releases in the event of hose failures. The audit interview and site observation revealed that the main reason could

be due to the operator failing to wear the necessary PPE in hot working environment. From safety management point of view lack of comprehensive emergency procedures or insufficient emergency drills makes the operator not adequately prepared when facing with the actual event.

7. Several tasks could be decomposed further to include more sub-components of human error but this was not done because of the need to stay within the boundary of External Error Mode (EEM). Treating the human error further, i.e. analysing the Psychological Error Mode (PEM) would introduce more uncertainty to the analysis as explained earlier.

6.5.2 FTA Results for Site B

Results of system and sub-system failure rates for Site B calculated using FTM are shown in Table 6.5.

1. FTA using the HEART and THERP nominal human failure rate data yields higher overall system failure rate as compared to those assessed using SLIM technique.

2. FTA using hardware only data gives lower system failure rate as compared to those being decomposed further to hardware and human error components. It appears the presence of human activities increases the likelihood of failure. This finding reinforced the need to consider the impact of human error in conducting the QRA.

3. At the component level the failure rate of flexible hoses is much higher than road tanker and piping failures. Analysing the tree further showed that guillotine failures of hose are difficult to isolate by hardware or human intervention. This is due to the likelihood that the operator would have to work within a large cloud of ammonia in order to be able to isolate the leak. However the operator at Site B is provided with gas mask with air breathing line which maintains a positive pressure. Such and arrangement will allow, more time for the operator to manually shut off the tanker outlet valves.

Table 6.5. Results of Fault Tree Runs for Site B

Description	Probability/ Frequency (per year)	System Failures (R)	Liquid Hose (HL)	Vapour Hose (HV)	Liquid Piping (PL)	Vapour Return Piping (PV)	Tanker Liquid Side (TL)	Tanker Vapour Side (TV)
1. HEPs from SLIM - using APJ Calibration Points	Probability	2.3E-06	1.34E-06	7.29E-07	1.03E-10	4.26E-10	8.82E-08	9.29E-08
	Frequency (per year)	2.21E-04	2.12E-06	6.99E-05	9.89E-9	4.08E-08	8.46E-06	8.91E-06
2. HEPs from HEART Nominal Data	Probability	1.34E-03	8.7E-04	4.71E-04	6.16E-08	4.70E-07	1.16E-07	7.08E-07
	Frequency (per year)	1.28E-01	8.25E-02	4.52E-02	5.91E-06	4.51E-05	1.11E-05	6.79E-05
3. HEPs from THERP Nominal Data	Probability	2.44E-04	1.54E-04	8.97E-05	2.46E-04	9.04E-08	1.32E-07	1.04E-06
	Frequency (per year)	2.34E-02	1.48E-02	8.61E-03	2.36E-06	8.68E-06	1.26E-05	9.9E-05
4. HEPs from using Hay's Calibration Points	Probability	1.56E-05	9.42E-06	5.17E-06	1.17E-10	2.36E-09	1.43E-07	1.26E-06
	Frequency (per year)	1.49E-03	9.04E-04	4.96E-04	1.12E-08	2.29E-07	1.37E-05	1.21E-04
5. HEPs from SLIM - using APJ Calibration Points(weighted)	Probability	4.45E-06	2.32E-06	1.95E-06	2.07E-10	7.95E-10	8.89E-08	1.04E-07
	Frequency (per year)	4.27E-04	2.22E-04	1.87E-04	1.98E-08	7.63E-08	8.53E-06	9.98E-06
6.Hardware Only Data - without considering HEPs	Probability	4.5E-05	1.58E-05	2.08E-05	5.05E-07	7.38E-07	4.09E-07	6.75E-06
	Frequency (per year)	4.32E-03	1.51E-03	1.99E-03	4.85E-05	7.08E-05	3.92E-05	6.48E-04

4. Similarly Minimum Cut Set (MCS) analysis of Site B fault trees in Table A16.2 in Appendix 16 showed 3 MCSs that provided the highest contributions to the system failures. As shown in Appendix 16 the 3 MCS made up more than 96% contribution to the system failures. Referring to the fault trees for Site B in diagram A14.3 showed that the base events that made up these MCSs belong to the sub-system failures of flexible hoses. The results also suggested that a considerable risk reduction to the overall system failures could be realised by improving the safety measures of this sub-system, such as installing barrier with interlock to prevent road tanker pull away.

5. The base event contribution in term of importance to system failure for Site B as calculated using the FTM software is shown in Appendix 17. Similar to the Site A scenario the highest contributor for the system failure is base event No. HV21b which represents the human activity of isolating possible leak from guillotine failure of the flexible liquid hose. Such failure would result in reverse flow of ammonia from the road tanker to the atmosphere via the ruptured flexible hose that would be difficult to isolate.

6. The need to limit to External Error Mode (EEM) when comparing the importance of base events prevented several tasks being decomposed further to include more sub-components. Treating the human error further into the Psychological Error Mode (PEM) such as 'memory lapse' would introduce more uncertainty and make the comparison between the two sites more difficult.

6.5.3 Comparing FTA Results between Site A and Site B

Comparison of FTA results between the two sites provides some indication of the difference in terms of the probability of failures in road tanker loading operations. For comparison purposes results of the fault tree runs for both sites are summarised in Table 6.6. Comparing the baseline FTA in Table 6.6, failure probability of ammonia loading of road tanker at Site A is shown to be higher than Site B by about a factor about 360. The difference in system failures in term of frequency per year for Site A is much higher as this site carry out four times more road tanker loading as compared to Site B. Taking into consideration that the error factor in the generic hardware failure rate of vessels and pipeworks is about by a factor of an order of magnitude (Hurst et al, 1992) and HEPs which about is about a factor of 3 (Swain and Guttman, 1997) this difference is quite significant.

The two sites possess the same level of hardware technology so far as ammonia loading operations to road tanker is concerned. Site B, despite having a more sophisticated safety system for the rest of the bulking operation, e.g. for rail tanker and cylinder filling, has a road tanker loading system equipped with only basic safety system. The only major difference in safety systems is the used of a weighbridge equipped with a weight trip alarm that could reduce the likelihood of overfilling. Comparison of failure probability due to hardware contribution only (as shown in item no.4 in Table 6.6) shows a very small difference, i.e. of only 0.04. So factors that created these large differences in the likelihood of the ammonia road tanker system failures must have been contributed by the non-hardware items, i.e. PSMS performance or Human Error or both.

So it could be concluded that from the hardware failure contribution point of view there is not much difference between the two sites. However the HEP values for base event at Site B for are lower than Site A. This reduces the human error contribution to the overall system failures. The HEPs values in turn are heavily influenced by site specific PIFs and such procedures, stress, experience and training. As these factors are prominently featured in the assessment of site specific PSMS performance they may be deduced to have significant influence on system failures.

2. At the two sites the probabilities of flexible hoses failure provide the highest contributor to the overall system failures. This is due to the fact that hardware failure rate of flexible hoses from historical data base is higher as compared to piping and road tanker. The underlying cause of hose failures is because they are of inferior construction material which make them more susceptible to rupture due human error, e.g. and tanker pull-away and due to strength degradation.

Table 6. 6. Comparison of FTA Results Between Site A and Site B

Description of Fault Tree Runs	Probability of System failure	Site A	Site B	Differences (Ratio of probability of system failures - Site A over Site B)
1. FTA using HEPs from SLIM	Probability (per demand)	8.22E-04	2.30E-06	360
	Frequency (per year)	3.95E-01	2.21E-04	1780
2. FTA using HEPs from THERP nominal data base	Probability (per demand)	2.09E-04	2.44E-04	0.85
	Frequency (per year)	1.00E-01	2.34E-02	0.04
3. FTA using HEPs from HEART nominal data base	Probability (per demand)	1.26E-03	1.34E-03	0.94
	Frequency (per year)	6.04E-01	1.28E-01	4.72
4. FTA using Hardware only data (not using HEPs)	Probability (per demand)	1.81E-04	4.5E-05	0.04
	Frequency (per year)	8.69E-02	4.32E-03	0.2

6.6 Results of Quantitative Risk Assessment (QRA)

As the main objective of conducting the QRA is to determine and compare the off-site risk from ammonia loading operations at the two sites, the QRA results need to be discussed in full. To fulfil that objective, the discussion of the results is broken into two parts. The first part will discuss QRA results between the base line run and sensitivity runs for a particular site. The second part will compare results of the QRA between the two sites. The aim is to explain the QRA results and to highlight significant differences in off-site risk between the two installations.

Two types of QRA were conducted for both sites. The first run used the representative set of failure scenarios approach. The failures set were selected based on judgement of credible scenarios that could lead to off-site risks. As the toxic load for ammonia is for land planning purposes is fairly high, i.e. 3.76E-08 ppm^2 min (Nussey et al, 1993) only guillotine failures of flexible loading hoses and piping, and large ruptures of road tanker are considered for the analysis.

The second RISKAT run for the Site QRA used Fault Tree Modelling. In this approach major releases of ammonia that could lead to off-site risk were modelled using the top-down approach. Using Fault Tree Analysis the top event was decomposed down to the base events that could trigger the event. The base events identified are made of hardware failures such as line valves sticking open, and human error failures such as the operator failing to close road tanker valves. Hardware failures values for base events were obtained from generic failure rate data from various sources. The main source of data will be the Malaysian DOSH failure rate database that provides most of the failure rate values. In the absence of certain failure rate from this data, failure rate values from other sources such as the U.K. HSE and SRD Data bank are used. As for the human error failures the SLIM technique is used to generate the failure probabilities in the form of the HEPs.

The combined hardware and human error probabilities for the base events are then analysed in the fault tree using the Fault Tree Manager software. This analysis yields the top event and the sub-event failure probabilities per loading. The probabilities then could be converted to failure frequencies by multiplying them with the number of ammonia loading in a given time period, for example in a year. These failure frequencies are then used to quantify the individual risk from ammonia loading of road tanker. As the HEPs for the base events were derived in different ways using SLIM technique, the RISKAT analysis is also used to calculate their results for comparison. Also comparison is made using nominal HEPs values from THERP and HEART data base.

6.6.1 Discussions on QRA Results for Site A

Two types of QRA were conducted for Site A, one using the representative failure approach while another using the fault tree modelling. Result of QRA runs using RISKAT software for Site A are shown in Table 6.7. The discussions of the QRA results for each type of the analysis are given in the following paragraphs.

6.6.1.1 Results of QRA using representative failure set approach

QRA results for Site A using the representative failure is shown under item No.1 in Table 6.7. Discussion on the results is given as follows;

- Baseline QRA (Run No.A1) using generic failure rate, i.e. without Modification Factor show a maximum distance 200 metres to the individual risk values of 10E-06. This indicates the off-site risk to public did go beyond the site's boundary which is approximately about 70 metres from the loading bay and will affect a number of factories that surround the site. However the distance still falls short of nearest public dwelling which the nearest located approximately 500 metres from the source of releases. At 10E-07 individual risk level the contour reached the maximum distance of about 470 metres. This distance still fell short of the populated area where there are ‘sensitive people’ i.e. children and elderly that would be susceptible at that individual risk level. The nearest school is located about 1.5 kilometres away from this site.

Table 6.7. Results of QRA runs for Site A

File No.	QRA Runs No.	Scenarios	Failures Rate	Individual Risk Distance (metres)		
				10E-05	10E-06	10E-07
1. QRA Using Representative Failures Approach						
Jotekr2	A1	Baseline QRA of Site A using 6 credible scenarios for off-site risk	Generic failure rates of vessel, pipework, hoses	80	200	470
Jotekr2a	A2	Modified QRA of Site A using Poor Modification Factor (MF)	Modified failure rates of vessel, pipework, hoses	100	400	630
2. QRA Using Fault Tree Analysis (FTA) Approach						
Tekapja1	A4	QRA by FTA of Site A using generic failure rates and HEPs from SLIM	HEPs from SLIM using APJ Calibration Points with equal weight for PIFs	270	400	630
Tektherp1	A5	QRA by FTA of Site A using generic failure rates and HEPs from THERP	Nominal HEPs from THERP Data base	230	350	570
Tekheart1	A6	QRA by FTA of Site A using generic failure rates HEART Nominal Data	Nominal HEPs from HEART Data base	270	400	640

.... Table 6.7. Results of QRA runs for Site A

Tekhard1	A7	QRA by FTA (Hardware Only) of Site B	Using Hardware Data Only	320	530	800
3. **QRA Sensitivity Runs Using Fault Tree Analysis (FTA) Approach**						
Tekhaya1	A8	QRA by FTA of Site A using generic failure rates and HEPs from SLIM	HEPs from SLIM using Hay's Calibration Points with equal weight for PIFs	280	460	700
Tk3apja1	A9	QRA by FTA of Site A using generic failure rates and HEPs from SLIM	HEPs from SLIM using APJ with 3 Calibration Points	280	440	690
Tkapjaw1	A10	QRA by FTA of Site A using generic failure rates and HEPs from SLIM with U.K. weather data	HEPs from SLIM using APJ Calibration Points	700	1200	2500

- Modifying the failure rate using PRIMA Poor Modification Factor for hoses, piping and vessel yields a different set of individual risk values (Run No.A2). As the site's PSMS performance was judged to be Poor, the QRA results using this modification represent the 'true' off-site risk values which have taken into consideration of site specific PSMS performance influence. The 10E-05 individual risk level distance increased by about 20 metres to 100 metres. The 10E-06 individual risk level increased by about 200 metres to 400m.

  This means that using the generic failure rate, i.e. not taking into consideration the site specific PSMS performance the individual risk distance at 10E-06 risk level will be underpredicted by a factor of two. The 10E-07 individual risk distance is reaching 630 metres that still fell short of the distance to school located about 1.5 km away.

- Result for Societal Risk for Site A is shown in Table 6.14. The baseline QRA (Run no. A1) shows a value of F=30E-06, N=20. This suggested that there is thirty times in a million years risk that ammonia release from Site A will lead to exposure of dangerous dose to 20 or more persons (Nussey et al, 1993). The number of persons involved is depended on the population density surrounding the site. Societal risk for the Modified QRA using Poor MF (Run No.A2) shows an increase in frequency (F) by about a factor of 2. As this is supposed to be the actual risk value for Site B after taking into consideration site specific MF, the use of generic failure rate resulted in an underprediction of off-site risk by a factor of two from the societal risk point of view.

- The relevant authorities in Malaysia do not use societal risk as the criteria for the acceptance of the off-site risk measures in the decision making. One country to use such criteria for land planning purpose is the Netherlands Government (Pasman, 1995). However the criteria used in the Netherlands is based on the frequency of fatality (F) as opposed to the dangerous dose produced by RISKAT. As such no direct comparison could be made between the Site A societal risk and the Netherlands societal risk acceptance criteria.

6.6.1.2 QRA Results Using Fault Tree Modelling

The results of the RISKAT run for Site A are shown in Table 6.7. Discussion on results using this approach is given as follows;

- Baseline QRA runs using HEPs generated from SLIM using APJ calibration points showed that the 10E-06 level extended to 400 metres from the loading position of the road tanker. For Site A this means that the a number of factories surrounding the site will be affected. As the site is located within a light industrial area such level is considered to meet the off-site risk criteria. The 10E-07 risk level which is the criteria for sensitive population, e.g. the school children and elderly extended to about 630 metres, well away from the nearest population centre located about 1.5 kilometre away from the site.

- QRA sensitivity runs using nominal HEPs values from THERP (Run No.A5) and HEART (Run No.A6) data bases show about the same distance covered by the 10E-06 risk level as compared to baseline QRA runs, i.e. by about 100 metres. It appears to suggest that the use of nominal HEPs values without taking into considerations the site specific PIFs do not really affect the off-site QRA result for Site A.

- When considering the system failure due to hardware only, i.e. omitting the human error components, the QRA results (Run No.A7) also show much longer individual risk distance. For the 10E-06 risk level the difference is about 130 metres as compared to the base line QRA runs. This suggested that the use of hardware only data resulted in overprediction of off-site risk by more than 30% . It appears that the introduction of human error components into the Fault Tree Analysis gave lower failure probability. It could be that human, i.e. the operator provided some form of recovery from hardware failures.

- A QRA sensitivity run using HEPs value derived from SLIM technique using APJ calibration points obtained from an HSE study (Run No.A8) showed slight difference with the baseline QRA results. At 10E-06 level the individual risk distance is 460 metres as compared to 400 metres for the baseline run, a difference of about 60 metres or about 11%. This suggested that the calibration points selected using APJ method by the auditor for the base line QRA was not far out from those judged by the experts conducting a similar study (HSE, 1989c).

- A QRA sensitivity run using three APJ calibration points (Run No.A9) was conducted to check whether the use of more calibration points would make the HEPs value more reliable as compared to the minimum two calibration points suggested by Kirwan (1994). Results showed for Site A the difference is quite small. At the 10E-06 and 10E-07 risk level the difference is only about 10% respectively. At least for Site A the use of three calibration points did not really result in significant difference to the off-site risk.

- The final QRA sensitivity run (Run No.A10) was to investigate the effect of using different weather data. As ammonia dispersion is influenced by weather conditions such as wind speed and atmospheric stability it would be of interest to see its effect on off-site risk of Site A. For this purpose the U.K weather data taken at Portsmouth weather station have been utilised. QRA results using this weather data showed a big difference as compared to the baseline QRA using Malaysian weather data. The distance to the 10E-05 risk level differs by a wide margin of almost 400 metres. The 10E-06 risk level differs by nearly 800 metres or by a factor of 2. The difference to 10E-07 risk level distance is even higher, about 1800 metres or about a factor of 3. Analysing the stability category of the two sets of weather data showed that the Malaysian weather data were dominated by Class A and B which indicates very unstable weather conditions with high lapse rate which could disperse the ammonia rapidly into the upper atmosphere (Marshall et al, 1995). This is the reason why the baseline QRA show insignificant risk level beyond the 750 metres distance as shown in Table 6.8. While the U.K. weather tends to be equally divided in term of weather class stability. The day time is dominated by Class A to D categories weather which promotes rapid dispersion of ammonia. However during the night Class E to G weather category prevails which represent calm weather where an ammonia cloud could travel over long distance before natural process of mixing with air reduces its lethal concentration. As RISKAT apportioned this weather conditions to average the daytime and night time weather probability the calm weather under Class E to G category slows down the upward dispersion of the gas and makes it linger close to the ground at much further distance.

- Table 6.8 showed that the individual risk distance using the U.K weather data exceeds the 2 km. The result of this sensitivity run showed the importance of using site specific weather data. Using another country weather data in the absence of local data might result in a significantly wrong estimate of off-site risk distance.

- Societal Risk results for Site A using FTA modelling are shown in Table 6.9. The baseline QRA (Run No. A4) shows a value of F=150E-06, N=20. This suggested that a prediction of fifteen incidents in a hundred thousand years that ammonia releases from Site A will lead to dangerous dose exposure that will affect 20 persons or more.

Table 6.8. Results of QRA runs at various distances for Site A

Runs No.	Scenarios	Failure Rate	Individual Risk Level (10E-06) at various distance (metres)								
			100	200	300	500	750	1000	1500	2000	3000
1. QRA Using Representative Failures Approach											
A1	Baseline QRA of Site A using 6 credible scenarios for off-site risk	Generic failure rate	2	1	0.8	0.06	0	0	0	0	0
A2	Modified QRA of Site A using Poor MF	MF failure rate for vessel, pipework, hoses	10	4	3	0.02	0.005	0	0	0	0
2. QRA Using Fault Tree Analysis (FTA) Approach											
A4	QRA by FTA of Site A using generic failure rates and HEPs from SLIM	Using APJ calibration points with equal weight for PIFs	12922	84.95	3.65	0.35	0.04	0	0	0	0
A5	QRA by FTA using generic failure rates and HEPs from THERP	Nominal HEPs from THERP Data base	3404	23.74	1.88	0.18	0.02	0	0	0	0

……… Table 6.8. Results of QRA runs at various distances for Site A

A6	QRA by FTA using generic failure rates and HEPs from HEART	HEART Nominal Data for HEPs	2075	132.8	3.44	0.33	0.04	0	0	0	0
A7	QRA by FTA using generic failure rates (Hardware Only)	Using Hardware using generic failure rates only	1156	31.59	13.83	1.32	0.16	0	0	0	0
3. **QRA Sensitivity Runs Using Fault Tree Modelling Approach**											
A8	QRA by FTA of Site A using generic failure rates and HEPs from SLIM	SLIM Data using Hay's Calibration Points with equal weight for PIFs	8612	61.69	6.15	0.59	0.07	0	0	0	0
A9	QRA by FTA of Site A using generic failure rates and HEPs from SLIM	SLIM Data using APJ with 3 Calibration Points	18144	122.54	5.19	0.49	0.06	0	0	0	0
A10	QRA by FTA of Site A using generic failure rates and HEPs from SLIM using with U.K. weather data	SLIM Data using APJ Calibration Points equal weight for PIFs	9873	2495	1005	555.23	5.27	3.14	0.16	0.13	0.08

Table 6.9. Results of QRA Runs for Societal Risk - Site A

File No.	RISKAT Runs No.	Scenarios	Failure Rate	Societal Risk
				F-Frequency, N= Fatalities
1. QRA Using Representative Failures Approach				
Jotekr2	A1	Baseline QRA of Site A using 6 credible scenarios for off-site risk	Generic failure rate - No Modification Factor (MF)	F=30E-06, N=20
Jotekr2a	A2	Modified QRA of Site A using Poor Modification Factor (MF)	Poor MF for failure rate of vessels, pipework, and hoses	F=150E-06, N-20
2. QRA Using Fault Tree Modelling Approach				
Tekapja1	A4	QRA by FTA of Site A using generic failure rates and HEPs from SLIM	HEPs from SLIM using APJ Calibration Points with equal weight for PIFs	F=15000E-06, N=20

6.6.2. Discussion on QRA Results for Site B

Two types of QRA were conducted for Site B, one used the representative failure approach while another using the fault tree modelling. Results of QRA run using RISKAT software for Site A are shown in Table 6.10. The discussions of the QRA results for each type of the analysis are given in the following paragraphs.

6.6.2.1 QRA Results Using Representative Failure Approach

Results of RISKAT runs on Site B using this approach indicate the following;

- As the PSMS performance of Site B was assessed to be Average, the QRA result (Run No.B1) using the generic failure rate, i.e. without Modification Factor is considered to be representative of the 'true' values. This baseline QRA using generic failure rate show a maximum distance 290 metres to the individual risk values of 10E-06. It indicates that the acceptable level of off-site risk to public did go beyond the site boundary which is approximately about 50 metres from the loading bay. This level of risk will cover the adjacent public road as well as a portioned of the Animal Feedmill factory next door. However the level of risk did not go beyond the industrial estate to the populated area that are located about 2 km away.

  At 10E-07 individual risk level the contour almost reached a half kilometre distance. However this distance still fell short of the populated area as the nearest housing estate where there are children and elderly is about 3 km from the site.

- Modification of failure rates using Good Modification Factor (Run No.B2) for hoses, piping and vessels showed a decrease in the individual risk contour distance as compared to the generic or unmodified failure rate. For the 10E-06 individual risk level the contour distance is reduced by about 190 as compared to analysis using unmodified failure rate. This means that if the Site PSMS were assessed to fall under the Good category the 10E-06 risk level will be by almost a factor of 2. The result shows the need to consider site specific PSMS performance as each site may have different performance even though they belong to the same company as in the case of Site B and Site C.

- Table 6.12 shows the results of Societal Risk for Site B. The baseline QRA (Run No. B1) shows a value of F=70E-06, N=30. This suggested that there would be seventy incidents in a million years that ammonia releases from Site B will lead to a dangerous dose exposure that will affect 30 persons or more. The number of persons involved is depended on the population density surrounding the site.

- Societal risk for the Modified QRA using Poor MF (Run No. B2) shows an increase in frequency (F) by about a factor of 2. As this supposed to be the actual risk value for Site B after taking into consideration site specific MF, the use of generic failure rate resulted an underprediction off-site risk by a factor of two from the societal risk point of view.

6.6.2.2 QRA Results Using Fault Tree Modelling

Results of the RISKAT run using the approach is given in Table 6.10. Discussion of the results is given as follows;

- Baseline QRA run (Run No. B4) using HEPs generated from SLIM using APJ calibration points shows that the 10E-06 individual risk distance level extended to 270 metres from the loading position of the road tanker. For Site B this means that the next door installation, i.e. the animal feedmill will be affected. As the site is located within the port industrial area such level is considered to meet the off-site risk criteria.

  The 10E-07 risk level which is the criteria for sensitive population, e.g. the school children and elderly extended to about half a kilometre well away from the nearest population located about 3 kilometres away from the site risk.

Table 6.10. Results of QRA runs for Site B

QRA File No.	QRA Run No	Scenarios	Failures Rate	Individual Risk Distance (metres)		
				10E-05	10E-06	1E- 07
1. QRA Using Representative Failures Approach						
Joamr2	B1	Baseline QRA using 6 credible scenarios for off-site risk	Generic failure rate for vessels, pipework, and hoses	40	260	480
Joamr2b	B3	Modified QRA Good MF	Modified failure rate of vessels, pipework, hoses	At Source	70	200
.2. QRA Using Fault Tree Analysis (FTA) Approach						
Amapja1	B4	QRA by FTA using generic failure rates and HEPs from SLIM	HEPs from SLIM using APJ calibration points with equal weight for PIFs	140	275	450
Amtherp1	B5	QRA by FTA using generic failure rates and HEPs from THERP	Nominal HEPs from THERP Data base	280	380	500

..........Table 6.10. Results of QRA runs for Site B

Amheart1	B6	QRA by FTA using generic failure rates and HEPs from HEART	Nominal HEPs from HEART Data base	330	410	490
Amhard1	B7	QRA by FTA (Hardware Only)	Using generic failure rates - without considering HEPs	240	400	600
3. **QRA Sensitivity Runs Using Fault Tree Analysis (FTA) Approach**						
Amhaya1	B8	QRA by FTA using generic failure rates and HEPs from SLIM	HEPs from SLIM using HSE(1989) calibration points with equal weight for PIFs	200	310	500
Am3apja1	B9	QRA by FTA using generic failure rates and HEPs from SLIM	HEPs from SLIM using APJ with 3 calibration points	140	280	450
Amapjaw1	B10	QRA by FTA using generic failure rates and HEPs from SLIM with U.K. weather data	HEPs from SLIM using APJ calibration points with equal weight for PIFs	150	500	1250

- QRA runs using nominal HEPs values from THERP (Run No. B5) and HEART (Run No. B6) data bases show much longer distance covered by the 10E-06 individual risk level as compared to baseline QRA runs, i.e. by about 100 metres or 40%. This indicates that the HEPs value has considerable influence on the QRA results. It also suggests that the use of nominal HEPs values without taking into considerations the site specific PIFs would overpredict the off-site QRA result.

- When considering the system failure due to hardware only, i.e. leaving the human error components, the QRA results (Run No. B7) also show much longer individual risk distances. For the 10E-06 risk level the difference is about 120 metres as compared to the base line QRA runs. This suggests that the use of hardware only data resulted an overprediction of off-site risk by about 45%. It appears that the introduction of human component into the Fault Tree Modelling improved the failure probability. One possible explanation would be that human, i.e. the operator provided some form of recovery in the event of hardware failures.

- A QRA sensitivity run (Run No. B8) using HEPs value derived from SLIM techniques using APJ calibration points obtained from an HSE study (HSE, 1989c) showed some difference with the baseline QRA results. At 10E-06 level the individual risk distance is 310 metres as compared to 270 metres for the baseline runs, a difference of about 40 metres or about 13%. This suggests that the calibration points judged using APJ method for the base line QRA was not far out from those judged by the experts conducting the HSE study.

- A QRA sensitivity run using three APJ calibration points (Run No. B9) was conducted to check whether the use of more calibration points would make the HEPs value as derived from SLIM more reliable as compared to the minimum two calibration points as suggested by Kirwan (1994). Results showed for Site B the difference is quite small. At the 10E-06 risk level the difference is only about 10 metres or a mere 2%. As for Site A the use of three calibration points did not really result in significant difference to the off-site risk for Site B.

- The final QRA sensitivity run was to investigate the effect of using different weather data (Run No. B10). As ammonia dispersion is influenced by weather conditions such as wind speed and atmospheric stability it would be of interest to its effect on off-site risk of Site B. As for Site A the U.K weather data within RISKAT taken at Portsmouth weather station have been utilised. QRA results using this weather data show a very significant difference as compared to the baseline QRA using Malaysian weather data. While the distance to the 10E-05 risk level differs only by about 7%, the 10E-06 risk level differs by 275 metres or a factor of 2. The difference to 10E-07 risk level distance is even higher which is about 750 metres or about by a factor of 8. These differences are comparable to that of Site A. This showed a consistent impact of using the U.K. weather data for the two sites. As discussed earlier the Malaysian weather data were dominated by Class A and B which indicates very unstable weather conditions with high lapse rate that could disperse the ammonia rapidly into the upper atmosphere. That explained why the baseline QRA show insignificant risk level beyond the 750 metres distance as shown in Table 6.11. The U.K. weather tends to be equally represented in term of weather class stability. Class A to D dominated the day time weather categories which promote rapid dispersion of ammonia. During the night calm weather persists, i.e. Class E to G weather category, where ammonia cloud could travel over a long distance before natural process of mixing with air reduces its toxic concentration. Table 6.18 showed that the 10E-06 individual risk distance using the U.K weather data could reached 1 km from the release point. Result of this sensitivity run once again showed the importance of using site specific weather data. Using another country weather data especially with a significant climate difference, e.g. between tropical and temperate climate, will resulted in a very significant difference in off-site risk distance.

Table 6.11. Results of QRA runs at various distances for Site B

File . No.	Scenarios	Failure Rate	Individual Risk Level (10E-06) at Various Distance (Metres)								
			100	200	300	500	750	1000	1500	2000	3000
1. QRA Using Representative Failures Approach											
B1	Baseline QRA using 6 credible scenarios for off-site risk	Generic failure rate	9.93	6.35	1.71	0.78	0.01	0	0	0	0
B3	Modified QRA using Good MF	Modified failure rate of vessels, pipework, hoses	0.34	0.23	0.10	0.04	0	0	0	0	0
2. QRA Using Fault Tree Modelling Approach											
B4	QRA by FTA using generic failure rates and HEPs from SLIM	SLIM Data using APJ Calibration Points with equal weight for PIFs	20.16	3.18	0.71	0.06	0.01	0	0	0	0
B5	QRA by FTA using generic failure rates and HEPs from using THERP Nominal Data	HEPs from THERP Data base	1345	159	5.32	0.09	0.01	0	0	0	0

...Table 6.11. Results of QRA runs at various distances for Site B

B6	QRA by FTA using generic failure rates and HEPs from HEART Nominal Data	HEPs from HEART Data base	7576	891	25.4	0.08	0.01	0	0	0	0
B7	QRA by FTA (Hardware Only) of Site B	Using generic failure rate only	154.62	22.86	3.86	0.29	0.03	0	0	0	0
3. **QRA Sensitivity Runs Using Fait Tree Modelling Approach**											
B8	QRA by FTA using generic failure rates and HEPs from SLIM	HEPs from SLIM using HSE (1989) Calibration Points with equal weight for PIFs	85.22	11.13	1.32	0.10	0.01	0	0	0	0
B9	QRA by FTA of using generic failure rates and HEPs from SLIM	HEPs from SLIM using APJ with 3 calibration points	22	3.5	0.2	0.06	0.005	0	0	0	0
B10	QRA by FTA using generic failure rates and HEPs from SLIM with U.K. weather data	HEPs from SLIM using APJ calibration points with equal weight for PIFs	11.44	6.57	2.44	1.04	0.57	0.29	0.03	0.02	0.01

Table 6.12. Results of QRA for Societal Risk Site B

File No.	RISKAT Runs No.	Scenarios	Failure Rate	Societal Risk
				F-Frequency, N= Fatalities
1. QRA Using Representative Failures Approach				
Joamr2	B1	Baseline QRA using 6 credible scenarios for off-site risk	Generic failure rate - No Modification Factor (MF)	F=7E-06, N=30
Joamr2b	B3	Modified QRA using Good Modification Factor (MF)	Modified failure rate of vessel, pipework, and hoses	F=2.4E-06, N=30
2. QRA Using Fault Tree Modelling Approach				
Amapja1	B4	QRA by FTA using generic failure rates and HEPs from SLIM	HEPs from SLIM using APJ calibration points for PIFs	F=23E-06, N=30

- Societal risk results for Site B using FTA modelling is shown in Table 6.12. The baseline QRA (Run no. B4) shows a value of F=2.3E-03, N=30. This suggests that there would be 23 incidents in ten thousand years that ammonia releases from Site B will lead exposure to dangerous dose affecting persons or more. Comparing this figure with baseline QRA using representative failures approach (Run no.B1) of 70E-06 shows a difference of about a factor of about 30.

6.6.3 Comparison of QRA Results Between The Two Sites

The main objective of comparing the results of various QRA runs between the two sites is to identify their differences and similarities. As the two sites carry out the same type of activity, i.e. road tanker loading operations using basically the same level technology, it would be useful to identify factors that influence the QRA results. Some of these factors may be link to the site PSMS. Assessing the interaction of these factors with site specific PSMS performance would provide some understanding on how PSMS influences the off-site risk from major hazard installations. QRA results for Site A as shown in Table 6.7 and for Site B as shown in Table 6.10 are referred to for the discussion.

6.6.3.1 QRA Using Representative Failures Approach

- The QRA results using generic failure rates for both sites showed a varying degree of differences between the two as shown in run No. A1 and B1 respectively. At the individual risk level of 10E-05 the off site of Site A reached a distance of about 80 m as compared 40 m to Site B, a difference of about a factor of 2. At these distances the risk would not extend outside the two site's plant boundary. For the 10E-06 and 10E-07 individual risk level distances, the difference is just about 23% and 2% respectively. The results suggest that the off-site risk posed by the two sites is about the same when unmodified generic failure rate data being utilised in the analysis.

- The PRIMA Audit results show that Site B PSMS performance fall under the Average category so the generic failure rates need not to be modified as they represent the failure rate of an average plant. However the PRIMA Audit results show that Site A PSMS performance fall under Poor category hence a Poor Management Factor (MF) should be applied to the generic failure rate. The QRA results of the two scenarios (Run No.A2 for Site A and Run No.B1 for Site B) would represent the 'true' off-site risk level, i.e. after considering the site specific PSMS performance. Analysing the QRA results between the two shows a significant difference. At individual risk levels of 10E-05, 10E-06 and 10E-07 the risk values of Site A are higher than Site B by about 60%, 35% and 23% respectively. These results suggest that the off-site risk from ammonia road tanker loading operations posed by Site A is higher than Site B. Given an almost similar level of hardware technology, the factor that influences the QRA results would be the site specific PSMA performance. The results provide a positive indication on the need to consider the influence of site specific PSMS performance to the off-site risk.

6.6.3.2 QRA Using Fault Tree Modelling

Analysing the QRA results for Site A and Site B using this approach yields a number of important findings. QRA results for Site A as shown in Table 6.7 and for Site B as shown in Table 6.10 are referred to for the discussion.

- Comparing the base line runs for the two sites shows that the overall individual risk level distance for Site A (Run No.A4) is higher than Site B (Run No.B4). The risk values of Site A are higher than Site B in term of individual risk level at 10E-05, 10E-06 and 10E-07 by about 90%, 30% and 30% respectively. These results suggest that off-site risk from Site A is slightly higher than Site B. As mentioned earlier given the same type of activity conducted at the two sites and the use of almost similar hardware technology these results pointed out to possible differences in the level of HEPs. The HEPs values are largely influenced by site specific PIFs such the quality of operating procedures, experience and training which also factors that influence the site specific PSMS performance. As such some indirect conclusion could be made that site specific PSMS did influence the off-site risk.

- The QRA runs using nominal HEPs from THERP and HEART data bases show small differences between the two sites. Using THERP data base rate (Run No.A5 and B5) the difference in individual risk level at 10E-05, 10E-06 and 10E-07 is only 21%, 8% and 12% respectively. As for the HEART data base rate (Run No.A6 and B6) the difference in individual risk level at 10E-05, 10E-06 and 10E-07 is only 18%, 2% and 23% respectively. Since the same values of HEPs are used for both sites the differences in the off-site risk would be most likely contributed by the generic failure rate.

- Comparing the QRA runs using fault trees that only consider hardware failures showed similar trend. The QRA results show the off-site risk from Site A is higher than Site B. The difference in individual risk level at 10E-05, 1E-06 and 1E-07 is about 28%, 25% and 33% respectively.

- The final runs using the baseline QRA but with U.K. weather data also indicate that Site A off-site risk is higher than Site B. In fact this QRA run provides the biggest difference on the individual risk level distance. At individual risk level of 10E-05, 10E-06 and 10E-07 the risk value of Site A is higher than Site B by about 80%, 58%, and 50% respectively. The results support the need to give priority in developing more accurate site specific or country specific weather data as its impact on off-site risk is more pronounced.

6.6.4 Summary of the impact of PSMS performance and Human Error to QRA results

The impact of site specific PSMS performance and Human Error on QRA results for the two sites are shown in Table 6.13. In order to make a consistent comparison only the risk measures of 10E-06 individual risk level distance will be utilised. Discussion on the results is given as follows;

Table 6.13. Effect of PSMS Performance and Human Error on QRA Results for Site A and Site B

Description of Analysis	Risk Measures	Site A	Differences (Factor)		Site B	Differences (Factor)
Effect of site specific PSMS Performance on QRA						
1. **QRA without the Effect of Safety Management Performance** (Baseline QRA by Representative Failure Set - using Generic failure rate, i.e. which did not takes into consideration the site specific PSMS Performance)	Individual Risk to (10E-06) Distance	200 m	**2**		260 m	**1.2**
2. **QRA with the Effect of Poor Safety Management Performance** (QRA by Representative Failure Sets - using PRIMA Modification Factor which takes into consideration the site specific PSMS Performance)	Individual Risk to (10E-06) Distance	400 m			310 m	
Effect of site specific Human Error potentials on QRA						
3. **QRA with the Effect of Human Error using Fault Tree Analysis** (Baseline QRA with Nominal HEPs i.e. generic HEPs) derived from THERP Database)	Individual Risk to (10E-06) Distance	230 m	**1.2**		280 m	**1**
4. **QRA with the Effect of Human Error using Fault Tree Analysis** (QRA with HEPs derived from SLIM Technique which takes into consideration the site specific Human Error potentials)	Individual Risk to (10E-06) Distance	270 m			275 m	
Effect of considering Human Error components in Fault Tree analysis for QRA						
5. **QRA without` the Effect of Human Error using Fault Tree Analysis** (Hardware only QRA using Fault Tree Analysis without considering the Human Error components)	Individual Risk to (10E-06) Distance	320 m	**0.8**		240 m	**1.2**
6. **QRA with the Effect of Human Error using Fault Tree Analysis with Human Error components** (Baseline QRA with HEPs derived from SLIM Technique)	Individual Risk to (10E-06) Distance	270 m			275 m	

6.6.4.1 The impact of PSMS performance on QRA results

The analysis No.1 and 2 in Table 6.13 showed that the difference of QRA results when the site specific PSMS performance is taken into consideration is by about a factor of 2 for Site A. The difference of Management Factor (MF) of about a factor of 4 for generic failure rate of pipework for Site A (Table 4.5, page 104 in Chapter 4) is translated into a difference of a factor of 2 in the QRA results.

As for Site B the difference of the QRA results is about a factor of 1.2. The difference of Management Factor of about a factor of 1.2 for generic failure rate of pipework for Site B (Table 4.5, in Chapter 4) seems to be directly translated into the actual difference in the QRA results.

6.6.4.2 The impact of Human Error on QRA results

The impact of Human Error in the form of HEPs on QRA could be made by comparing results as shown in analysis No.3 and No.4 in Table 6.13. For Site A the analysis that did not take into consideration of Human Error in carrying out the ammonia road tanker loading operation provided higher off-site risk than the one that does, by a factor of about 1.2. The result implies that Human Error provides positive contribution to off-site risk at Site A. However for Site B the difference is insignificant indicating negligible impact of Human Error on the QRA results.

6.6.4.3 The impact of considering Human Error component in Fault Tree Analysis for QRA results

Analysis No.5 and No.6 show the impact of considering Human Error component in Fault Tree Analysis for QRA results. For site A, the inclusion of Human Error components beside the hardware components as base events in Fault Tree Modelling for QRA reduce the off-site risk by a factor of 0.8. One possible explanation is that the high level of manual operation for ammonia road tanker loading at Site A affords a higher level of recovery in the event of hardware failures.

As for Site B the QRA result is higher by a factor of about 1.2 when considering Human Error as base events beside the hardware failures in Fault Tree Modelling. Similarly one possible explanation is that the higher level of process automation for ammonia road tanker loading at Site B reduce the chances of manual recovery the event of hardware failures

6.7 Conclusions

Based on the experience in conducting the QRA as well as results of the analysis a number of significant conclusions could be made.

- The site specific weather data is one of the most dominant factors influencing the off-site risk level at the two sites. So more resources should be allocated in establishing such data if a fairly accurate and reliable QRA results need to be used to assist decision making, e.g. for land use planning. This finding seems to agree with finding by other researchers such as Kukkonen (Kukkonen et al, 1993) and Marshall (Marshall et al, 1995). This is especially true in developing countries where there is lack of reliable weather data for QRA. Developing countries which still without the necessary local weather data should make its development as one of the top priorities if they intend to use QRA as a tool to assist decision making, e.g. for land use planning.

- QRA runs using FTA which takes into consideration the hardware failures and HEPs showed a lower off-site risk values as compared those which only consider hardware failures for the two sites as shown in Table 6.13. The results suggested that human action reduces the off-site risk level. Analysing the Fault Tree components showed that human actions provide some form of recovery in the event of hardware failures. This finding shows the importance of human factors contribution to QRA, the outcomes shared by Purdy and Wasilewski (Purdy et al, 1994).

- Site specific PSMS performance do provide significant impact on off-site risk at the two sites. PRIMA Modification Factor is used as a means to explicitly consider the effect of site specific management influence. The effect could be positive or negative depending on the PSMS performance in the form of

Modification Factor of the site under consideration. In the study Site A has a poor than average PSMS performance so the off-site risk level is higher than the baseline QRA that uses generic failure rate. As for Site B, it has an average PSMS performance hence the off-site risk level using the generic failure rate would be representative. As Site A is a locally owned site while Site B is an ex-multinational site, the finding seem to suggest that the poor PSMS performance of Site A as rated using PRIMA contributed to the higher off-site risk as compared to Site B. This finding provides an indication on the influence of site specific PSMS on off-site risk from major hazard sites in Malaysia considering the fact the two sites might not be representative of the whole industry.

- THERP and HEART nominal data bases provide an equivalent of the generic human error rates or human error probability or HEPs, while SLIM generated HEPs is a means to explicitly considered the site specific management and organisational influences on HEPs. As shown in Table 6.13 results of off-site risk using these 'generic human error rates' for Site A is lower as compared to the one using SLIM generated human error rates. While results of QRA run using these 'generic human error rates' for Site B showed almost the same off-site risk values as compared to using SLIM generated human error rates. Even though far from conclusive the results could imply a neutral to negative effect (not a positive effect) of site specific management and organisational influence on the generic human error rates.

Chapter 7

Using PRIMA as an integrated audit for PSMS and HEA

7.1 Introduction

PSMS are made up of comprehensive set of policies, procedures, and practices designed to ensure that barrier to process incidents are in place, in use and effective (AIChE, 1993). This implied the requirement for an effective interaction between procedures, human and organisation. As such some form of site specific common factors will influence both the PSMS and human performance. The interplay between these factors is fairly complex as its involved the multiple interaction at many levels (Moieni, 1993) in a format known as 'many to many mappings' (Embrey, 1992). For example ineffective feedback from operational experience could not only affect the quality of training programme but it also could make the existing operating procedures obsolete as it should be reviewed and updated regularly from lesson learnt from operational experience. A number of approaches have been put forward by various researcher such Embrey (1992), Aspotolaskis (1994), and Pete'-Cornell (1996) in attempting to capture human influences to system safety.

Development of new approach either in the form technique or framework is beyond the scope of this research. What is apparent while conducting the current research is that there are some common attributes of PSMS and Human Error that could be derived through PRIMA audit results. If these attributes could be assess using PRIMA audit then an opportunity to link part of HEA with PSMS assessment be realised. This will enhance the effectiveness of PRIMA audit by providing an additional feature to assess certain attributes that essential for HEA.

7.2 Common attributes that essential for both PSMS Audit and HEA

The common attributes that are essential for both PSMS Audit and HEA are mainly in the form of some organisational factors such as procedures, training, stress, communication and feedback, and hardware factors such as operator/equipment interfaces, process safety system, as well as operating environment such heat, humidity and lighting. For PSMS audit these factors are important aspect to be considered in assessing its performance for a particular site. As for the HEA these factors are called Performance Influencing Factors that influence the human/operators for successful execution of a particular task. Assessing both attributes using a common field auditing technique such as PRIMA would enable the efficient use of resources, which is critical in developing countries.

7.3 How PRIMA Audit assessed the attributes

PRIMA audit assesses such attributes in order to evaluate the key components of PSMS. It's audit questions extract the information at four levels of the socio-technical pyramid i.e. Level 2 - operator reliability, Level 3 - communication, control and feedback, Level 4 - organisational process and structure, and, Level 5 - system climate under four different themes (i.e. Theme A- procedures and process to do the job, Theme B - standards for the jobs, Theme C - other pressures that interfere with the job, and Theme D-resources for the job). Such an approach was found could yield valuable information on the common attributes that influence both the site specific PSMS and the PIFs in HEA. This could lead to the possible integration of PSMS and HEA site audit through a proven audit technique like PRIMA.

7.4 Examining the possibility of assessing PIFs for HEA using PRIMA Audit

To examine the possibility of such approach a detailed analysis of PRIMA audit results of the two sites was carried out. Information obtained through the audit questionnaires was analysed in trying to extract the relevant information that could be used to assess the PIFs. The assessment is made based only on response made by the interviewees without involving auditors judgement as it may involved information gathered through other means such as site inspection and document reviews. This enabled the comprehensiveness of the PRIMA audit questionnaires to be examined independently, minus the expert judgement input that needed to form the PSMS control loops. To find out the feasibility of such approach PIFs that have been selected for the quantification of Human Error of the two sites namely Experience, Procedures, Stress and Feedback study were analysed. Results of the analysis using information gathered through PRIMA questionnaires for Site A and for Site B is shown in Appendix 18.

As can be seen from Appendix 18 there are useful information that could be extracted from PRIMA Audit Questionnaires which could be use to assess the PIFs situation at each site. As an example for Site A the information for PIF of Experience in Theme A is available from Level 5 to Level 3 even though is not adequate. However information on Level 2 i.e. operator reliability is not available at all. For Theme B information on Experience is available to certain extent in Level 5 and Level 4 but none is available in Level 3 and Level 2. Summary of the PIFs evaluation using PRIMA audit results for Site A is shown in Table 7.1 and for Site B is shown in Table 7.2. The two tables showed that PIFs information is not available from all theme that made the PRIMA audit questionnaires. However by combining the PIFs information made available from the questionnaires for all the 8 key audit areas (each made up of 4 Levels and under 4 different Themes) a reasonable judgement could be made for their qualitative ratings as shown in Table 7.3. These qualitative ratings represent the overall situation of the site PIFs or at 'global' level. For example the PIF of Experience for Site A is judged to be of Average, Procedure is of Poor, Stress is of Average and Feedback is Poor. For Site B the PIF of Experience is judged to be of Average, Procedure is of Average, Stress is of Average and feedback is Good.

Table 7.1. Results of PIFs assessment using PRIMA Audit findings at Site A

PIF	THEME A		THEME B		THEME C		THEME D			
(Performance Influencing Factors)	(Procedures and Process to do the Job)	PIF info. from PRIMA audit	Standards to do the Job	PIF info. from PRIMA audit	Other Pressures Interfere with the Job	PIF info. from PRIMA audit	Are there adequate resource to do the job	PIF info. from PRIMA audit	RATING	OVERALL RATING
EXPERIENCE	Level 5 - Climate	Yes(NA)	Level 5-	Yes(NA)	Level 5-	Yes(NA)	Level 5	Yes(NA)	Average	Average
	Level 4 - Org.Process	Yes(NA)	Level 4 -	Yes(NA)	Level 4 -	None	Level 4 -	Yes(NA)	Poor	
	Level 3 - Communication	Yes(NA)	Level 3 -	None	Level 3 -	None	Level 3 -	Yes(NA)	Average	
	Level 2 - Op.Reliability	None	Level 2-	None	Level 2-	Yes(NA)	Level 2	Yes(A)	Average	
PROCEDURE	Level 5 - Climate	Yes(NA)	Level 5-	Yes(NA)	Level 5-	Yes(NA)	Level 5-	None	Poor	Poor
	Level 4 - Org.Process	Yes(A)	Level 4 -	Yes(NA)	Level 4 -	None	Level 4 -	Yes(NA)	Poor	
	Level 3 - Communication	Yes(A)	Level 3 -	Yes(A)	Level 3 -	None	Level 3 -	Yes(NA)	Poor	
	Level 2 - Op.Reliability	Yes(A)	Level 2-	Yes(A)	Level 2-	Yes(NA)	Level 2	Yes(A)	Average	
FEEDBACK	Level 5 - Climate	Yes(NA)	Level 5-	Yes(NA)	Level 5-	None	Level 5 -	None	Poor	Poor
	Level 4 - Org.Process	Yes(A)	Level 4 -	None	Level 4 -	Yes(NA)	Level 4 -	Yes(NA)	Poor	
	Level 3 - Communication	Yes(A)	Level 3 -	Yes(NA)	Level 3 -	Yes(NA)	Level 3 -	Yes(NA)	Average	
	Level 2 - Op.Reliability	Yes(A)	Level 2-	None	Level 2-	None	Level 2-	Yes(NA)	Poor	
STRESS	Level 5 - Climate	Yes(NA)	Level 5-	Yes(NA)	Level 5-	Yes(NA)	Level 5-	Yes(A)	Average	Average
	Level 4 - Org.Process	None	Level 4 -	None	Level 4 -	Yes(NA)	Level 4 -	Yes(NA)	Average	
	Level 3 - Communication	Yes(NA)	Level 3 -	None	Level 3 -	None	Level 3 -	Yes(A)	Average	
	Level 2 - Op.Reliability	Yes(NA)	Level 2-	None	Level 2-	Yes(NA)	Level 2-	Yes(NA)	Average	

Keys : NA - Not Adequate Org. - Organisation
A - Adequate Op. - Operator

Table 7.2 Results of PIFs assessment using PRIMA Audit findings at Site B

PIF	THEME A		THEME B		THEME C		THEME D			
(Performance Influencing Factors)	(Procedures and Process to do the Job)	PIF info. from PRIMA audit	(Standards to do the Job)	PIF info. from PRIMA audit	(Other Pressures Interfere with the Job)	PIF info. from PRIMA audit	(Are there adequate resource to do the job)	PIF info. from PRIMA audit	RATING	OVERALL RATING
EXPERIENCE	Level 5 - Climate	Yes(NA)	Level 5-	Yes(NA)	Level 5-	Yes(NA)	Level 5	Yes(NA)	Average	Average
	Level 4 - Org.Process	Yes(NA)	Level 4 -	Yes(NA)	Level 4 -	None	Level 4 -	Yes(NA)	Average	
	Level 3 - Communication	Yes(NA)	Level 3 -	None	Level 3 -	None	Level 3 -	Yes(NA)	Average	
	Level 2 - Op.Reliability	None	Level 2-	None	Level 2-	Yes(NA)	Level 2	Yes(A)	Good	
PROCEDURE	Level 5 - Climate	Yes(NA)	Level 5-	Yes(NA)	Level 5-	Yes(NA)	Level 5-	None	Average	Average
	Level 4 - Org.Process	Yes(A)	Level 4 -	Yes(NA)	Level 4 -	None	Level 4 -	Yes(NA)	Average	
	Level 3 - Communication	Yes(A)	Level 3 -	Yes(A)	Level 3 -	None	Level 3 -	Yes(NA)	Average	
	Level 2 - Op.Reliability	Yes(A)	Level 2-	Yes(A)	Level 2-	Yes(NA)	Level 2	Yes(A)	Good	
FEEDBACK	Level 5 - Climate	Yes(NA)	Level 5-	Yes(NA)	Level 5-	None	Level 5 -	None	Good	Good
	Level 4 - Org.Process	Yes(A)	Level 4 -	None	Level 4 -	Yes(NA)	Level 4 -	Yes(NA)	Average	
	Level 3 - Communication	Yes(A)	Level 3 -	Yes(NA)	Level 3 -	Yes(NA)	Level 3 -	Yes(NA)	Good	
	Level 2 - Op.Reliability	Yes(A)	Level 2-	None	Level 2-	None	Level 2-	Yes(NA)	Good	
STRESS	Level 5 - Climate	Yes(NA)	Level 5	Yes(NA)	Level 5	Yes(NA)	Level 5	Yes(A)	Average	Average
	Level 4 - Org.Process	None	Level 4 -	None	Level 4 -	Yes(NA)	Level 4 -	Yes(NA)	Average	
	Level 3 - Communication	Yes(NA)	Level 3 -	None	Level 3 -	None	Level 3 -	Yes(A)	Average	
	Level 2 - Op.Reliability	Yes(NA)	Level 2-	None	Level 2-	Yes(NA)	Level 2-	Yes(NA)	Average	

Keys : NA - Not Adequate Org. - Organisation
A - Adequate Op. - Operator

PIFs rating obtained using this approach is then compared with PIFs assessed solely using auditor judgement as obtained from Table 5.15 Section 5.4.4 in Chapter 5 and shown in Table 7.3. As can be seen from the table PIFs rating as assessed using PRIMA Audit results differs on Stress for Site A and on Experience for Site B. Even that the difference is small i.e. from Average to Poor for Stress (Site A) and Good to Average for Experience (Site B). This indicates that based on the four PIFs under consideration i.e. Experience, Procedures, Feedback and Stress, the information made available in PRIMA Audit results is quite adequate to rate the site specific PIF. However the four PIFs under consideration i.e. Experience, Procedures, Feedback and Stress are common factors that influence human error on majority of tasks in chemical process engineering environment. It remains to be seen whether PRIMA audit results could also provide similar information for other PIFs such Distraction and Task Complexity.

Table 7.3. Comparing PIFs assessed using PRIMA Audit results with PIF assessed using auditor's judgement

PIFs	**Site A**		**Site B**	
	PIFs Rating from PRIMA Audit	PIFs Rating using auditor judgement	PIFs Rating from PRIMA Audit	PIFs Rating using auditor judgement
Experience	Average	Average	Average	Good
Procedures	Poor	Poor	Good	Good
Feedback	Poor	Poor	Good	Good
Stress	Average	Poor	Average	Average

7.5 A simple method to quantify PIFs rating

A simple method to quantify PIFs rating which converts the qualitative rating of PIF into a quantitative form is presented here. Using some form of quantitative scale, these qualitative rating could be converted to a quantitative rating. The SLIM technique used a nine scale rating for expressing a particular PIF situation that influenced the likelihood of success in executing a particular task. The ideal value (that most favourable) could be at any point of the scale. For example the ideal value for training would be 9 (the most comprehensive and effective) while the lowest would be on the scale of 1 (grossly inadequate training done in ad-hoc manner). While for Stress the ideal value could be 6 (the right amount of stress that keep an operator alert but not created undue stress) and the lowest would be 1 (too little stress that to keep the operator alert). The ideal values for SLIM used by Gertman (1994) and Chien (1992) is shown in Figure 7.1.

By using the ideal value as the maximum value for 'good' and the associate lowest range of scale as maximum value for 'poor', a quantitative scale could be made from the qualitative input as shown in the Figure 7.1. This quantitative scale then could be used for example for apportioning weighting of PIFs contribution in SLIM technique. However difficulty arised when deciding the scale for stress as it has a different ideal value i.e. 6 instead of 9. This difficulty could be overcome by re-assigning its ideal value to 9 and making appropriate judgement based on this ideal value.

Results of apportioning PIFs weighting to calculate HEPs in SLIM using such method for Site A is shown in Table 7.4. For example the qualitative rating of Procedures for Site A is judged to be Poor indicating that it will have small contribution in the successful execution of a particular task. As SLIM technique calculates the probability of success in executing a particular task in the form of Success Likelihood Index (SLI), Procedures contribution to SLI will be small which is reflected by its weight of 0.14. On the other hand the Experience contribution to SLI is Good, meaning that they will have large contribution to the probability of success in executing a particular task. In this case the weighting for Experience on SLI is higher as reflected by a value of 0.36.

Figure 7.1 - Proposed quantification scheme for PIFs derived from PRIMA Audit

	Poor							Good		Ideal
1. Plant Interface and Indications of Conditions	1	2	3	4	5	6	7	8	9	9
2. Significant Preceding and Concurrent Actions	1	2	3	4	5	6	7	8	9	9
3. Task complexity	1	2	3	4	5	6	7	8	9	1
4. Procedural Guidance	1	2	3	4	5	6	7	8	9	9
5. Training and Experience	1	2	3	4	5	6	7	8	9	9
6. Adequacy of Time to Accomplish Action	1	2	3	4	5	6	7	8	9	9
7. Stress	1	2	3	4	5	6	7	8	9	6

PSF RATING	PRIMA RATING
1	
2	Poor
3	
4	
5	Average
6	
7	
8	Good
9	

For comparison purposes the weighting obtained using the quantification of PIFs rating from PRIMA Audit results is compared with the weighted assigned for these PIFs using expert judgement as describe in Section 5.5.4 of Chapter 5 (Table 5.19) as given in the last column of Table 7.4. The difference for PIFs weighting is quite small for all the PIFs indicating some form of agreement between the two approaches.

Table 7.4. Comparing PIFs weighting for Site A

PIFs Rating from PRIMA Audit	Quantitative Rating using conversion method in Figure 7.1	Weighting assigned for SLIM using conversion method in Figure 7.1	Weighting assigned for SLIM using Expert Judgement
Experience - Average	5	5/9 x 9/14 = 0.36	0.4
Procedures - Poor	2	2/9 x 9/14 = 0.14	0.2
Feedback - Poor	2	2/9 x 9/14 = 0.14	0.2
Stress - Average	5	5/9 x 9/14 = 0.36	0.2

Results of apportioning PIFs weighting to calculate HEPs in SLIM using such method for Site B is shown in Table 7.5. For comparison the weighting assigned for these PIFs using expert judgement as describe in Section 5.5.4 of Chapter 5 (Table 5.19) Chapter 5 is given in the last column of Table 7.5. Similarly the difference for PIFs weighting is also quite small. However between the two approaches, at for least for the four PIFs under consideration, the conversion method using PRIMA Audit results provide better transparency as it is based on all the information gathered through the audit questionnaires.

Table 7.5 - Comparing PIFs Weighting for Site B

PIFs Rating from PRIMA Audit	Quantitative Rating using conversion method in Table 7.1	Weighting assigned for SLIM using conversion method in Figure 7.1	Weighting assigned for SLIM using Expert Judgement
Experience - Average	5	5/9 x 9/24 = 0.2	0.4
Procedures - Good	7	7/9 x 9/24 = 0.3	0.2
Feedback - Good	7	7/9 x 9/24 = 0.3	0.2
Stress - Average	5	5/9 x 9/24 = 0.2	0.2

However the influence of each PIF on specific task varies requires separate assessment. This is due to the fact that each task comes under a different degree of influences from each PIFs as being discuss in detail under the topic of PIF analysis in Chapter 5. Thus the usefulness of PIF analysis using PRIMA Audit questionnaires seem unable to go beyond determining the overall or global weighted of PIF at a particular site. The quantification of HEP of a specific task requires a more rigorous assessment to reflect the varying degree of PIFs influences on that particular task.

7.6 Conclusions

In conclusion the PRIMA audit questionnaire was found able to address a number of areas that could provide basic information to determine the overall or 'global' PIFs influence, at least for the four PIFs under consideration. However it is less rigorous as compared to the dedicated PIF analysis such that has been carried out in Section 5.4.4 of Chapter 5. Nevertheless for the purpose of quantification using SLIM, such information is adequate to assist in assigning appropriate weighting of the overall PIFs on each site. Such weighting could be used to reflect the overall influences of a particular PIF on all tasks under consideration for quantification purposes at each site. Further investigation is needed to look at the existing PRIMA Audit structure to find out whether it is capable to accommodate other components of HEA.

Findings, Conclusions and Suggestions for Further Work

8.1 Introduction

This chapter presents the outcome of the overall research. The outcome is presented under three different headings namely finding, suggestions for further work and finally the conclusions.

8.2 Findings

A discussion of the salient points from findings of the overall research is given below. The discussion is made under each major heading of the research component for ease of explanation. The aim of this discussion is to highlight key research findings based on findings from the three different research areas namely PSMS, HEA and QRA.

8.2.1 PSMS performance differs between the 3 sites

Results from the analysis of PSMS for the 3 sites using the PRIMA technique show significant differences in performance. As shown in Table 4.5 in Section 4.6 Chapter 4, Site A, which is the locally owned and managed fared the worst. The overall PSMS fall under Poor category with a Modification Factor of about 4 based pipework loss of containment data base.

Site B was assessed to have a Modification Factor of 0.9. This indicated that Site PSMS performance is slightly less than the average plant as defined under PRIMA. Even though this site benefit from a good PSMS laid down by the previous multinational owner, recent management structure change has deprived the site with the resources needed to maintain an above average PSMS. This is especially true in term of the absence of dedicated Safety Department specialists such as the instrumentation and electrical technicians.

The best PSMS performance among the 3 sites is Site A. This site was assessed to have a Management Factor of 0.4 using the PRIMA assessment. This site was able to retain most of the Safety Management structure and human resources laid down by the previous multinational owner. The key contribution to the site's good PSMS performance was a dedicated safety department answerable straight to the Managing Director and the ability to retain most of the skill and experienced operators and supporting technicians.

The PRIMA audit results showed a Modification Factor difference of about a factor of 10 between the Site A and Site C. This significant difference showed the need to consider the site specific PSMS performance influence when conducting QRA using generic failure rate.

8.2.2 Strengths and weaknesses of PSMS of locally owned Site

The main strengths and weaknesses of the locally owned plant, i.e. Site A as assessed using PRIMA technique are given below. Evidence of these findings is given in Section 4.5.2(i) in Chapter 4 and in Table 5.15 Section 5.4.4 Chapter 5.

Strength

- Less rigid work division, i.e. operator and maintenance allow multi-skilling for rotation of job. Such arrangement allowed operator to switch role e.g. from maintenance to operation when the needs arise. It also avoids boredom and creates equal opportunity for promotion that normally favour the operators as compared to other supporting staff such as the maintenance crew.

Weaknesses

- lack of good working procedures

- lack of qualified and experienced personnel to conduct safety assessment such as HAZOP for design and modifications
- lack of structured training for new personnel and lack of specialist/continuous training for existing workers
- lack of clear safety policy - only to meet minimum regulatory requirements.
- fairly high turnover of operator and supporting staff due tight labour market, experienced workers move to new sites which offer better wages and less hazardous working conditions, e.g. at electronic components assembly.

8.2.3 Strengths and weaknesses of PSMS Sites owned by multinational

The main strengths and weaknesses of PSMS Sites owned by multinational are given below. Evidence of these finding could be found in Section 4.5.2(ii) and 4.5.2(iii) in Chapter 4 and in Table 5.15 Section 5.4.4 in Chapter 5.

Strengths

- Good written safety policy which is fairly comprehensive and practical.
- Well laid organisational structure for safe operations of plant including a dedicated safety department
- Possesses well trained personnel which have stayed with the company since its inception
- Good training programme for operators and supporting staff. Apprenticeship style training creates steady stream of qualified personnel
- The availability of comprehensive written work standards and procedures based on worldwide experience of the former multinational owner

Weaknesses

- Rigid division of work into operations and supporting services (i.e. maintenance) has hindered job rotation or multi-skilling. The situation creates dissatisfaction among the supporting personnel due to lack of promotion chances as compared to their counterparts in the operations.

- Current downsizing exercise will reduce the overall number of experienced personnel including safety in the near future. The policy of not replacing retired personnel means there will be fewer people to do the same amount of job that could create stress and low morale among workers.
- Early signs of deterioration in PSMS e.g. falling behind the schedule to review the current work procedures which are supposed to be conducted yearly as specify in the written work standards

8.2.4 Multinational influences on site specific PSMS

PRIMA Audit results showed that the previous multinational owner did impart their experience and implement a safety system which benefited the current local owner who took over the site. Such evidences can be found in PSMS results discussion in Table 4.2 Section 4.5.2 in Chapter 4 as well in PIFs discussion in Table 5.15 Section 5.4.4 Chapter 5. Strong safety organisation, comprehensive training and adequate written work standards and work procedures are the critical features. Furthermore being the first large scale chemical plant in Malaysia the company more or less set the work standard and became training ground of many technical personnel who work for a number of chemical plants build later in Malaysia.

At the same time the company also introduced a fixed division of work into departments like operation and technical support which includes project, maintenance, electrical and instrumentation and safety. Technical personnel who joined the company are put under apprenticeship style of training under the specific department for a lifetime long career. This type of training produces workers with good specialist knowledge and worked well in large scale organisation with non-competitive business environment. However under current highly competitive business environment such rigid division of work hinders the flexibility of the company to compete, e.g. through multi-skilling. It also creates discontent among the technical support personnel who over the years get less promotional chances as compared to their counterpart in the operations.

8.2.5 The different effectiveness of ammonia road tanker loading task on the two sites

Despite carrying out a similar task, i.e. ammonia road tanker loading operation the effectiveness of the plan and procedures used to execute the task is different between the two sites. Evidence to support the findings can be seen from the summary of PIF analysis in Table 5.15 and the detailed PIF analysis in Appendix 6.

The Hierarchical Task Analysis (HTA) has revealed that Site B has a better work plan and procedures to successfully undertake the task of ammonia road tanker loading operation as compared to Site A. The work plan and procedures in place is appropriate and comprehensive which would be able to reduce the chances of the operator making planning errors. The usage of specialist (i.e. maintenance crew) to carry out the connection and disconnection of filling hoses also reduces the chances of operational errors. Error recovery is enhanced by better process safety hardware, e.g. the use of weight trip system to prevent overfilling of road tanker and the presence of independent checks by the maintenance crew of certain critical tasks such as the venting-off filling line prior to disconnection. However the use of maintenance crew at Site B to carry out the filling hose connection and disconnection increase the duration of filling as compared to Site A due to the waiting period for their availability.

8.2.6 PIFs situation at Site A is better than Site B

The research showed that PIFs situations differ on the two sites. Evidence to support the findings can be seen from the summary of PIF analysis in Table 5.15, the detailed PIF analysis in Appendix 6 and PSMS audit results in Section 4.5.2 of Chapter 4. The difference for each of PIF under consideration is given as follows;

- Experience

  Site B operator has better experience than Site A. Good training programme, low turnover from job security and job specialisation of operator at Site B contributed to this factor. However the multi-skilling approach being implemented on Site A has indicated a positive impact on the operator performance as compared to Site B.

- Procedure

  Site A has inadequate procedures as compared to Site B. The procedures are poorly written, lack depth and are mostly not compatible with the actual tasks that need to be executed on-site. Unlike Site B, this site did not have the benefit of the experience and resources of a multinational organisation in preparing and implementing effective working procedures. Lack of resources also minimised the effort to up date the resources regularly. It was also noted that this trend beginning to take place at Sight B.

- Stress

  Time stress for ammonia tanker loading operations is higher on at Site A as compared to Site B. Site A carry loads not only road tankers but also lorry mounted skid tanks. As the major movement of ammonia is using rail tanker to its sister company Site Bs do very few of road tanker loading. Work stress that arises from the need to perform fairly demanding physical activities under hot and humid environment involving hazardous substances is higher at Site A as the loading bay is not provided with solar canopy as being provided at Site B.

- Feedback

  Lack of process control automation prevented operators at Site A from getting the necessary information that could tell that they are in error mode. It also reduced the ability to recover error or to minimise its consequences through remote operations. Critical information on plant status has to be gathered manually some of which requires looking at small dial gauges at height under hot tropical sun. The main control room provided most of the critical information at Site B. It also allowed certain recoveries to be made in the event of failures of manual operations.

8.2.7 Critical task predicted by PHEA is similar for the two sites

Results from the PHEA conducted showed that use of consequences (i.e. severity and frequency) provides a simple and effective means to predict tasks that under strong influence of human error. However lack of site specific information on the two attributes, e.g. from accidents or near miss records forced the use of expert judgement which at best lacks transparency. For both sites tasks associated with the connection and disconnection of filling hoses, the establishment of correct filling weight to prevent overfilling and the movement of road tanker that could result in collisions and hose pull away has been identified as those most likely to fail due to human errors. Evidence to support the findings can be seen in Table 5.12 and in Appendix 5. The analysis also allowed appropriate recommendations to be made to reduce the impact of human error through the appropriate error reduction strategies. The recommendations made vary for the two sites depending on PSMS available on each site as shown in Table 5.13 and Table 5.14. Using PRIMA technique the relevant key audit areas and the control loop levels within the PSMS for each site could be determined. This approach also indicated one possible means to integrate human error with PSMS.

8.2.8 HEPs value strongly influenced by PIFs.

Proper selection of PIFs is important as they provided the basis for determining the HEPs values. Assigning appropriate rating of these PIFs for each tasks also needs careful judgement as shown in Table 5.17 and Table 5.18. This could only make possible by a thorough qualitative analysis prior to human error quantification exercises. Evidence to support the findings can be seen in Table 5.22 and Table 5.23.

8.2.9 Calibration points influenced the HEPs calculated using SLIM

Selecting appropriate calibration points for HEPs calculation using SLIM was found to be one of the main difficulty of the quantification exercises. They strongly influenced the outcome of HEPs values for all tasks under consideration. Sensitivity runs using calibration points obtained from various sources showed a maximum difference is about a factor of 30 for the values of HEPs calculated as shown in Table

5.22 and Table 5.23. However taking into consideration the large differences normally associated with human error data base such difference is acceptable.

8.2.10 Site A has higher HEPs as compared to Site B

Results of HEPs calculated using SLIM techniques in Table 5.22 and Table 5.23 showed that Site A has higher value of HEPs as compared to Site B for identical tasks. This finding suggested that the ammonia road tanker loading operation Site A is subject to a higher influence of human error as compared to Site B.

8.2.11 Site specific PSMS performance increases off-site risk for Site A

Results of QRA run using RISKAT software are shown in Table 6.16 for Site A and Table 6.18 for Site B. Analysis of the results yield the following findings:

Off-site risk calculated by RISKAT using generic failure rate for Site A was less when site specific PSMS performance is not taken into consideration. This evidence is shown in Table 6.16. The difference of risk results between baseline QRA using generic failure rate, i.e. without Modification Factor (Run No. A1) and the one using Poor Modification (Run No. A2) is about a factor of 2 or 200% based on individual risk distance of 10E-06. As Site A is judged to have poor PSMS performance, the use of generic failure rate for QRA underestimated the actual risk posed by ammonia road tanker loading operation.

8.2.12 Site specific PSMS performance does not affect off-site risk for Site B

As Site B is judged to have an Average PSMS performance, the use of generic failure rate for QRA is appropriate. These mean that site specific PSMS performance does not affect off-site risk for Site B. This evidence is shown in Table 6.16. However any attempt to equate its PSMS performance with Site C which belongs to same owner will have resulted in underestimating the actual risk posed by ammonia road tanker loading operation by about a factor of almost 4. This can be seen when comparing the difference of risk results between baseline QRA using generic failure rate, i.e. without Modification Factor (Run No. B1) and the one using Good Modification (Run No. B3) which is about a factor of 4 based on individual risk distance of 10E-06. This showed that even though the two sites belong to the same owner they not necessarily posses similar PSMS performance. So there is a need to conduct a separate PSMS audit for each site to avoid making a wrong assumption.

8.2.13 Site specific weather data is a dominant factor in QRA

The site specific weather data is one the most dominant factor influencing the off-site risk level at the two sites. The evidence can be seen at individual risk distance of 10E-06 from in Table 6.16 for Site A and from in Table 6.19 for Site B. For Site A the use of U.K weather data (Run No.A10) resulted an overprediction by a factor of 3 when compared to baseline QRA using FTA approach in Run No.A4. Meanwhile for Site B the use of U.K weather data (Run No.B10) resulted an overprediction by a factor of about 2 when compared to baseline QRA using FTA approach in Run No.B4. So more resources should be allocated in establishing such data if fairly accurate and reliable QRA results need to be used to assist decision making, e.g. for land use planning. This finding seems to agree with findings by other researcher such as Kukkonen (Kukkonen et al, 1993) and Marshall (Marshall et al, 1995). This is especially true in developing countries with a lack of reliable weather data for QRA in place. Any developing country still without the necessary local weather data should make its development of top priority when QRA is used as a tool to assist decision making for land use planning.

8.2.14 Site specific organisational factors influence QRA results

THERP and HEART nominal data base provides an equivalent of the generic human error rates or human error probability or HEPS. SLIM generated HEPs is a mean to explicitly considered the site specific organisational influences (in the form of PIFs) such as work stress, training and experience of personnel and availability of good operating procedures on HEPs. Result of QRA runs using these 'generic human error rates' for Site A showed a higher off-site risk values by a factor of about 1.2 as compared to using SLIM generated human error rates. However result of QRA runs using these 'generic human error rates' for Site B showed almost the same off-site risk values as compared to using SLIM generated human error rates. Such evidences can be seen in Table 6.7 (Runs No.A5 and A6) for Site A and Table 6.10 (Runs No. B5 and B6) for Site B and their summary in Table 6.13. Eventhough the difference is quite small the results indicated that site specific organisational (in the form of PIFs) influences the generic human error rates which in turn affect the QRA results.

8.2.14 PRIMA Audit provides a viable alternative to assessed site specific organisational impact on QRA

The PRIMA Audit produces Modification Factors (MF) which were used to obtained site specific generic failure rate which takes into account the site specific PSMS performance. Results of QRA using these factors showed a significant difference of off-site risk for Site A which was assessed to have a Poor PSMS performance in term of individual risk, increased by a about a factor of 2. Site B which was assessed to have an Average PSMS performance in term of individual risk showed only a small difference of about a factor of 1.2.

Similarly the SLIM calculated HEPs that takes into consideration the site specific factors that influenced human error rates. While THERP and HEART databases provided the generic human error rates. Comparing the off-site risk results for site A using the generic and site specific HEPs showed a difference of about a factor of 1.2 while Site B showed insignificant differences. The results showed that similar to site specific PSMS performance, the site specific human error rates also affect the QRA results (increase the risk) eventhough less pronounces than the former.

As such the results appear to suggest that despite its simplistic approach, the PRIMA Audit technique seem capable of predicting the direction of effect of site specific organisational characteristics (which include human error) on QRA results, comparable to the more rigorous approach of using fault tree modeling which requires the decomposition of hardware and human failure rates and establishing their respective values.

8. 3 Conclusions

The research has met its main objectives as set in the research methodology:

- to study the impact of PSMS performance on off-site risk
- to investigate the contribution of Human Error to off-site risk
- to look into the possibility of linking PSMS and Human Error analysis through PRIMA Audit

Several other conclusions could be made from results and findings of the research. However it should be stressed here that they are only based on the MHI sites under investigation. Further study would need to be carried out to verify whether they represent nationwide situation of MHI in Malaysia .

- *PRIMA audit, SLIM and RISKAT were found suitable to be used for developing countries with minor modifications*
- *There is a need to take into consideration site specific PSMS performance in QRA as they exert significant influence on QRA results*
- *Multinational company provided positive contribution in PSMS performance at least for the sites under study. It also provided positive contribution in managing human error through better training, able to keep experience personnel and preparing good operating procedures.*
- *The influence of human error on QRA is complex, while human actions increases system failure rate, they also provide recovery in the event of hardware failures*
- *QRA requires reasonably good site specific weather data as it is strongly influenced the outcome of the risk results especially for toxic materials. There is a need to develop good weather data which is quite scarce in developing countries.*

- *The attempt to integrate PSMS and HEA audit through PIF from PRIMA audit is partly successful at least at the organisational (global) level, which could be used to provide 'weighting' (as in SLIM) for an overall PIF influence. However the present PRIMA audit questionnaires structure is not able to facilitate a comprehensive PIF analysis which is needed to assess task specific HEP.*

8.4 Suggestions for Further Work

A number of limitations have been encountered that prevent more definite conclusion being made. These limitations were noticed through the actual practical experience in carrying out the field work, the use of qualitative and quantitative technique to analyse data collected from field study which included the use of relevant computer code and finally through attempts made to link the complex relationship between PSMS, Human Error and QRA. These limitations in the author's opinion could be reduced by conducting further analysis on a number of areas that could further strengthen the research's findings.

As the research involved three distinct areas, the suggestions for further work will be given for each area. These suggestions could be carried out by a separate exercise or by combining a few together. The suggestions given are looking purely from research point of view without considering the resources requirement, i.e. manpower, time, and cost. Obviously some suggestion could be implemented with minimum resources while others require much more.

8.4.1 PSMS Auditing

The following further works are suggested for PSMS audit using PRIMA;

a) Conducting similar PSMS audits on other MHI

Three MHI were audited during the research exercises. While the three sites roughly represent the cross section of MHI in Malaysia, more similar audits on other MHI are needed in order to answer several questions arising from the current research. First is whether other MHI which is more automated (i.e. less manual operation with more complex process system) than ammonia loading operations will provide similar results. Secondly whether MHI owned by big Malaysian national corporation PSMS performance is similar to those owned by the multinational. Thirdly by what margin is the risk from MHI that handles flammable and explosive hazards (such as gas processing plant) would be affected by PSMS performance. So by conducting more audits on a cross section of other MHI installations some of the above mentioned questions could be answered.

b) Conduct PRIMA Audit using different set of auditors

As the audit relies heavily on human judgement by the team members, a separate audit conducted by different audit teams on a same site will provided some indication on the reliability of PRIMA technique.

c) The use of loss containment data base that reflect the scenarios in developing countries for PRIMA Modification Factor

Modification factors used in PRIMA to modify generic failure rate currently is based on weighting provided by data bases on the loss of containment of pressure vessels and piping mainly obtained from developed country. In developing countries like Malaysia the percentage of contribution of each key audit area may differ significantly as suggested the current data base. This could be due to different quality of design, operation and maintenance in developing countries that would result in different percentage of contribution to the loss containment data base. So the use of a suitable data base that reflect the country specific situation would yield more accurate modification factor in PRIMA Audit.

8.4.2 Human Error Analysis

The following further works are suggested for Human Error Analysis;

a) Use of other quantification techniques to calculate HEPs

The contribution of human error on off-site risk in the study was obtained using the SLIM technique. The use of other technique such as HEART or THERP will provide different set of HEPs values on human activity associated with ammonia road tanker loading operations. These HEPs values then could be compared with the ones obtained using SLIM technique and checking the differences of off-site risk results when using these values as input for QRA.

b) To include Psychological Error Mode (PEM) in Human Error Analysis

The Human Error analysis conducted for the research only considered the operator error in the form of External Error Mode (EEM). It is concerned with predicting failure of planning, actions, checking, selection and communications. However it did not consider the other error mode, i.e. the Psychological Error Mode (PEM). This type of error deal with higher level of error, mostly in the cognitive domain such as lapse of attention, stereotype fixation and stimulus overload (Kirwan, 1994). The inclusion of PEM in HEA will provide better insight of underlying causes that influence the operator in committing an error. This in turn could allow more effective error reduction strategies be recommended.

8.4.3 Quantitative Risk Assessment (QRA)

The following further works are suggested for QRA

a) Conduct QRA on MHI with different process

The ammonia road tanker loading operations on which the QRA were conducted is fairly simple process that involved quite a lot of human operation. It would be useful to find out the differences when QRA is conducted on more complex process with high degree of process automation, where human operations are mainly in supervisory roles. The type of human error associated with such process will be different and their influences of human error on off-site risk would be different. Such a study would allow the influence of process automation over manual operation in reducing human error to be fully explored.

b) Investigating the influence of PSMS performance and Human Error for on-site risk

The research that has been conducted specifically looked at the PSMS performance and Human Error influence on off-site risk. As such only human errors that could result in large consequences were taken into account. However the HEA analysis indicated that the effects of human error are mainly towards low and medium consequences events that would not lead to off-site risk. As such events could pose risk to workers on-site, it would be useful to investigate their influence of human error on on-site risk.

c. Compare QRA results using PSMS Management Factor and QRA using with site specific failure rate using process safety hardware approach

HSE has carried out an initial study where the site specific failure rate is modified using process safety hardware approach (Gould et al, 1997). The rational of this approach is that process safety hardware is more permanent on a specific site as compared to PSMS. This is due to much easier changing of personnel and procedures that made up the site specific PSMS. Comparison of results from the two approaches would highlight the differences in QRA results for the a particular site. It could then be used to assist decision making whether to invest in process hardware or the improvement of site PSMS (for example through better procedures and training) in order to reduce risk from the site.

8.4.4. Integrating PSMS and Human Error Analysis

The current research look at the possibility of linking the PSMS assessment with Human Errror assessment through Performance Influencing Factor (PIFs). Site specific PIFs are shaped by the characteristics of people, tasks and organisation that influence human performance. As PRIMA audit also looks for similar factors to assess site specific PSMS performance this information could be used to evaluate the overall PIF situation. However result of the analysis that has been carried out showed that information made available from PRIMA Audit results is not sufficient to make critical analysis of the site PIFs. So a more rigorous approach is needed. The Influence Diagram approach (Phillips et al 1985, and Embrey, 1992) could be capable of providing the interelationship between management influences, immediate causes and operational errors. The approach is also claimed to be able to quantify the effect of organisational influences on risk arising from human error. However the need to collect data from each site to develop site specific form of generic model requires large resources which is beyond the scope of the present study. Where resource is not a constraint this approach is worth pursuing.

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