MASTER

Scenario-based training in the energy conversion sector
application in Nuon Power buggenum IGCC power plant

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Scenario-Based Training in the energy conversion sector: Application in Nuon Power Buggenum IGCC power plant

by
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Errata

In page V, at the last line in stead of may be not read may not be.
In page 7, in the first sentence in stead of In gasification read For gasification.
In page 12, in the legenda of table 1, in stead of van der Chaaf read van der Schaaf.
In page 16, in the first line of the last paragraph, in stead of learning system are going to be used read learning system are not going to be used.
In page 20, in the first paragraph in stead of ballistic Recovery Systems read Ballistic Recovery Systems.
In page 29, in subsection 5.3.3 in the second paragraph in stead of not to availability should be selected read not availability should be selected.
In pages 29 and 30, in all the sections in stead of rapture read rupture.
In pages 65 and 66 in the Appendix A, in table A2 in stead of rapture read rupture.

Abstract

This thesis aims at developing a framework for improving operator training by helping them develop a structured way of reacting on abnormal conditions. The main idea is the implementation of Scenario-Based Training (SBT) to mitigate consequences. Especially the focus will be on how scenarios can be developed and used. Furthermore, based upon the developed scenarios, a concrete training format is going to be constructed. The research will be based on a case study in Nuon Power Buggenum IGCC (Integrated coal Gasification Combined Cycle) plant at Buggenum in the Netherlands. The implemented SBT framework differs from the SBT which is presented in literature.

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This Master Thesis was the first project that I had to conduct in a business environment. I feel very proud of having studied at the TU/e and for having conducted research for such a corporation as Nuon.

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Vasileios Kotzampasis

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Management summary

The present Master Thesis Project is over the implementation of a training framework in order to support the operators of IGCC power plants to make decisions under abnormal conditions. Abnormal conditions are the conditions that happen when disturbances cause the plant to deviate from its normal state. The training of the operators is going to be based on accident scenarios that will be developed in the context of the IGCC plant units. The project is conducted at Nuon's Power Buggenum IGCC plant.

With the IGCC (Integrated Gasification Combined Cycle) technology, electricity is being produced after a number of steps. First, coal is getting gasified to produce syngas (a mixture of hydrogen and carbon monoxide). The syngas gets cleaned. After the clean-up, the syngas is burned in a gas turbine which drives the electricity generator. The exhaust of the turbine is directed to the heat recovery generator to raise steam which then drives a steam turbine generator.

A typical IGCC power plant consists of several units: feed storage and handling, gasification, syngas treatment, syngas conditioning, power generation, air separation, sulphur recovery and waste water treatment. However, in the aforementioned units there is a risk of having an accident. For example, in the feed storage unit there is a risk of dust explosion or the explosion of the air separation unit. Risk can be defined as the "combination of severity and probability of an event. Risk takes into consideration the likelihood or the possibility of harm. Risk can be reduced by multiple ways. Possible options could be installation of safety systems, improvement of automation, reliability testing and focusing on the human element. This Thesis will focus on the human element and especially on how to train the plant operators to make structured decisions under abnormal conditions.

IGCC plants are owned by electric production corporations. However, IGCC plants are in fact at least partially chemical plants, which means that something unexpected can happen. The operators of these power plants come from the conventional plants and therefore, are not used to make decisions in the context of a chemical plant. These operators are not regularly trained to make decisions in the context of the possible abnormal conditions of a chemical plant. If something abnormal occurs, it is possible that it will lead to a disaster.

Complex IGCC plants require operators with both chemical and mechanical engineering background. However, this is rather difficult since the amount of people that following the combination of chemical and mechanical engineering studies is small. So, training is an appropriate way to familiarize operators with the plant and its risks.

Furthermore, the focus should be on operator training, since the operator is the one who plays a major role in the safety of the plant. This happens because of two reasons. First, due to the fact that a substantial amount of accidents happen because of "impossible" or unforeseen circumstances, the flexible human operator will be present in order to cope with despite having the same difficulties. Secondly, the safe handling of problems by the software (which is a result of a complex human activity) is never guaranteed because of hidden errors. Therefore, the human operator must be able to control the system manually. A trained operator is likely to be able to solve these problems.

Moreover, modern automatic control systems have taken the load of the routine operations and left the infrequent difficult and abnormal conditions in the operators' hands. The problem

is that by taking away the easy parts of the task, the difficult part can become more difficult. When an alarm or something unexpected happens, no standard response is available which means that operator has to know a step-by-step process of decision making to act safely. This behavioral change is a major reason of fatal accidents.

Furthermore, the personnel are critical to proper emergency response. Training assures that the role of each employee is clearly understood and that accidents can be reacted upon safely and without delay. On the other hand, untrained operators are unable to understand the heavy volume of information, to interpret the data and diagnose the situation. Unfortunately, untrained operators will make the wrong decisions.

Training plays a significant role to safety performance. It ensures that an employee is able to do what it takes in order to achieve the desired level of safety. Finally, operator training is forced by governmental legislation all over the world.

However, it is not yet known how the operators can be trained to anticipate abnormal conditions. Therefore, the main research question of this Master Thesis Project is:

How can the operators of an IGCC power plant be trained in order to make structured decisions under abnormal conditions?

The main research question can be divided into the following three sub-questions.

1. *What training method could be suitable for training the operators to make decisions under abnormal conditions?*
2. *How can the selected method be adapted to the context of an IGCC plant?*
3. *How can the selected training method be implemented?*

There are possible training methods that could be considered for the specific problem. Examples are group dynamics, simulation, lectures etc. The training method to be selected should fulfill three requirements. First, it should be suitable for training a diversity of employees-operators. In an IGCC plant the age, the experience and the background of the operators can vary. Secondly, the training method to be used should enhance the decision-making process of the trainees-operators. Finally, the method to be selected should have a concrete approach. However, the aforementioned methods are not suitable since they do not fulfill all the requirements. Especially, they do not provide a concrete approach on how the operators can be trained. Some of them could be partially used but not as a complete framework. In addition, Scenario-Based Training (SBT) and Event-Based Approach to Training (EBAT) were considered. EBAT focuses on the SBT but in simulated design. However, within the context of the IGCC technology the concept of simulators has not matured yet. Thus, a technique with a use of simulation could not be feasible. Therefore, SBT is the selected method.
SBT has advantages that fit with an IGCC plant. First, the operators could be prepared to anticipate abnormal conditions and go through them decisively, intuitively and efficiently with SBT. Secondly, with the implementation of the SBT the decision-maker will focus on the key decisions in order to avoid high consequences (for example fatalities, leakage of hazardous chemical etc). Finally, SBT mitigates the consequences when an abnormal condition occurs since the trained operators can respond adequately.

The main objectives of the SBT in the context of an IGCC plant are three; decision-making under abnormal conditions, process insight and be close to reality.

1. Decision-making under abnormal conditions. It is the main goal of the SBT. The purpose is to help them develop a structured way of reasoning by analyzing a potential accident without the effect of time-pressure.
2. Process insight. An objective of the SBT is to improve the operators' insight of the process that he monitors.
3. Be close to reality. The third objective is to have the scenario appear to the operators as close to reality as possible and feasible. The means to do that is visualization of the actual components and for example the control system the same as they appear in the plant.

There are differences between the SBT which is stated in literature and the SBT that is going to be implemented in an IGCC plant. First, the objectives are different. Furthermore, no model exists for SBT in IGCC. Finally, the format of the SBT session does not exist as well. In literature SBT is conducted in three steps: pre-test, training and post-test. These differences imply that some modifications should be done in order for SBT to be adapted within the context of an IGCC plant. First, possible accident scenarios should be identified since scenarios that could be used in an IGCC plant are not available yet. Afterwards, the unit in which the SBT will be implemented and scenarios to be taught in the training session should be selected. The third step is to model the selected scenarios in order to become suitable for operator training. Finally, the format of the SBT will be defined in the context of the IGCC plant.

The first step of the SBT adaptation to the context of the IGCC plant is the unit and scenario selection. First, possible scenarios within the plant units are identified. The sources of scenarios are the ARIE and the HAZOP studies. HAZOP study is not available for all plant units and in some units is partially conducted. This implies that not all the possible scenarios within the plant are identified. Thus, scenarios that could be relevant for SBT may be missing. The scenario identification is followed by the selection of a unit where the SBT will be conducted. Syngas treatment is selected because it fulfils the criteria of availability of information concerning scenarios and availability of information concerning recorded accidents or plant shut downs. The next step is the selection of scenarios within the syngas treatment unit. Based on criteria three scenarios are selected as relevant for SBT. The criteria that are used are: low probability, high consequence scenarios, and scenarios credible to operators and relevance for Noun's management. However, the scenarios that have high consequences concerning only unavailability are not considered since the focus is the well-being of the plant employees. One scenario is selected to demonstrate the SBT technique.

The SBT adaptation will be continued by modeling the selected scenarios to become suitable for SBT. First, the selected scenarios are modeled in order to show the sequence and the timing of events and to include the role of human factor on the prevention of the accident sequence. The method that is used to model scenarios is the Event-Tree Analysis (ETA), a technique that models the time and the sequence of events and can include the role of human operator. The last step is the explanation of the phenomena that are associated with the outcomes and the estimation their consequences only for the demonstration scenario. The effects are briefly explained. The models that are used are suitable only for simple estimations and their results may be not very accurate. However, the explanation of events and the calculations of their consequences are done only to stress the importance for SBT and to make the scenarios credible to the operators.

The next step is the implementation of SBT. SBT will be implemented in three steps: introduction, training and evaluation. The first step is the introduction. In this step the operators will get on board with what is going to be taught. Training is the second step. This step will be conducted in terms of a problem-solving group discussion. The discussion will enhance the decision-making process. The last step is the training evaluation. The evaluation step is twofold. First, the operators-trainees will have to evaluate the SBT from their point of view. Secondly, the trainer has to take notes concerning the previous aspects of the training. The two different sides of the training part are going to be considered. Based on the findings, possibilities for improvement could be identified.

The defined framework of implementing the SBT has to be tested to identify possible deficiencies concerning the structure (introduction, training evaluation) and the content of the steps (e.g. is the way in which the training evaluation is valid?). The SBT is tested by training the trainer of Nuon Power Buggenum (trainer's SBT). Not only will possible deficiencies and possibilities for improvement be identified, but also it could be a good opportunity to train the trainer and have him train the operators. The results of this test are very positive. The results showed that the implementation framework is suitable and the selected scenario appropriate. Only some minor modifications in the selected scenario have to be made.

Conclusions

Based on what is discussed previously, it can be concluded that the objective of this Master Thesis Project is fully met. The first two research questions are fully answered. SBT is a suitable method for training the operators to make decisions under abnormal conditions. Due to the fact that there are differences between the IGCC plant and the situations that are described in literature, SBT should adapt to context of the IGCC plant. The adaptation will be achieved by identifying scenarios, selecting a unit in which the SBT will be conducted, selecting scenarios relative for SBT and model the selected scenarios with ETA with estimation of the consequences of the final outcomes. The third question is not fully answered. An implementation framework is defined. SBT is implemented only for training the trainer of the plant. This implementation is more to a test of the defined framework for possible deficiencies and improvement possibilities. The results of this test (trainer's SBT) show that the implementation framework and the adaptation of SBT are successful. However, the SBT is not yet implemented to train the operators. This implies that some changes and modifications are possible to be made.

Recommendations

The conclusions that were presented imply that there are some actions that have to be done. There are five actions that are recommended.

First, SBT could be implemented to the selected unit and the other units of the plant. This would give the opportunity to train the vast majority of the plant operators. In addition, it will serve as an actual means of testing the proposed training framework. In case that it is proved successful, it could be implemented to other IGCC plants (e.g. Magnum project).

Secondly, it would be beneficial to put effort on identifying all the possible accident scenarios. A possible way to achieve this goal is to extend the HAZOP study to the rest units of the plant. In this way more scenarios will be available to select and the possibility of not considering relevant scenarios will be smaller.

Furthermore, more criteria could be added to select a unit and scenarios relevant for SBT. A multi criteria decision analysis method (such as Analytic Hierarchy Process) could be used in order to select scenarios available for SBT based on the pre-defined criteria. Also, scenarios that have high severity regarding only plant availability could be selected for SBT.

Moreover, the use of models (e.g. numerical) for detailed estimation of the consequences of the final outcomes of the scenarios is highly recommended. Not only will the results be interesting for the SBT conduction, but also for the safety of the plant (since they will show in detail what the examined outcome can cause to the plant and the employees).

Finally, additional research could be conducted on the introduction of simulators. It could be useful to check if it is possible to use simulation for training. If it is possible, it should be examined how the simulation can be integrated with the SBT implementation framework and if there are some modifications that have to be done.

Abbreviations

ARIE	Additional Risk Inventory Evaluation
EBAT	Event-Base Approach to Training
ETA	Event-Tree Analysis
FTA	Fault-Tree Analysis
HAZOP	Hazard Operability study
P&ID	Piping and Instrumentation Diagram
SBT	Scenario-Based Training
VCE	Vapor Cloud Explosion

Table of contents

Chapter 1: Project definition

1.1. Research background

This thesis is conducted in the areas of the sub-departments Quality and Reliability Engineering (QRE but now Industrial Design/Business Process Design) and Operations Planning Accounting and Control (OPAC) of the Department of Technology Management at Eindhoven University of Technology.

"The activities of OPAC are in the area of research, education and knowledge transfer of Operations Management". It can be understood that Operations Management is a broad area of interest. Within this area, OPAC's scope is the design and structuring or re-structuring of production and logistics control structures (tue webpage, 2008). Examples are service supply logistics, logistics in capital goods industry, aggregate production planning etc.

The research cluster quality and reliability consists of two sub-programs (each concentrates on different combinations of products and business processes): product quality in strongly innovative/dynamic business processes and product reliability (QIP), availability, maintainability and safety in stable business processes (RAMS). The conducted project is in the context of RAMS. Thus, only the RAMS sub-program will be introduced.

With regard to RAMS, its main topic of research is: "Development of methods and tools to predict and optimize the product reliability during the early stages of product development". The RAMS program consists of four parts:

1. RAMS1: development of fast methods to predict the occurrence of class 1 and 2 failures early in the development process using information from tests.
2. RAMS2: development of fast methods for prediction and reduction of the occurrence of class 2 failures early in the development process based on the relation of designable parameters, degradation/usage, and reliability.
3. RAMS3: development of methods to perform a quantitative analysis concerning safety of safety systems that can to handle uncertain data.
4. RAMS4: analysis of product maintenance processes regarding product Reliability, Availability and Safety.

Concerning the RAMS4, a PhD project is being conducted that addresses unavailability management in the energy conversion sector. Specifically, this project stresses the unavailability issues in the IGCC power plants.

Integrated Gasification Combined Cycle (IGCC) produces electricity from a solid or a liquid fuel. The fuel is converted to syngas (a mixture of hydrogen and carbon monoxide). Afterwards, the syngas is converted to electricity in the combined cycle power block (it is a combination of a steam and a gas turbine including a heat recovery steam generation) (Maurstad, 2005).

A few IGCC power plants exist in the world. Typical examples are: Nuon Power Buggenum plant at Buggenum in the Netherlands, ELCOGAS plant at Puertollano in Spain, Wabash River plant and finally the Tampa Electric plant in the United States of America (Wolters, 2007).
The availability of the IGCC plants was very low at the first years of operation (around 30%). In the present years the availability of the IGCC plants increased to 70-80%. However,

operational performance did not exceed 80% availability (Ansolabehere et al, 2007). For example, over the 14 years of operation, the peak of availability of the Nuon Power Buggenum plant was approximately 75% (Wolters, 2007). The availability of Nuon Power Buggenum Plant can be seen in figure 1.1 whereas the availability of some IGCC plants can be seen in figure 1.2.

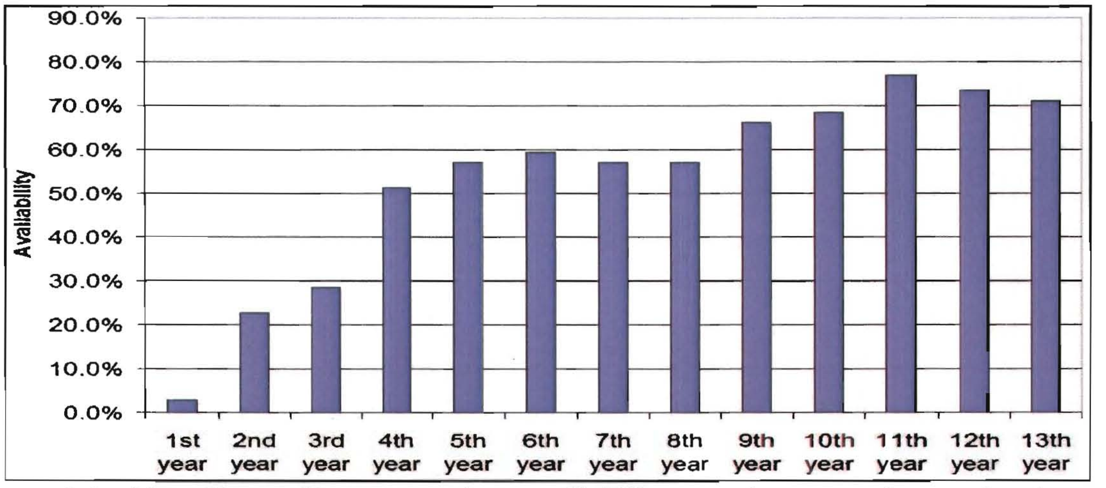

Figure 1.1.: *Nuon Power Buggenum plant availability over the years of operation (source: Wolters, 2007).*

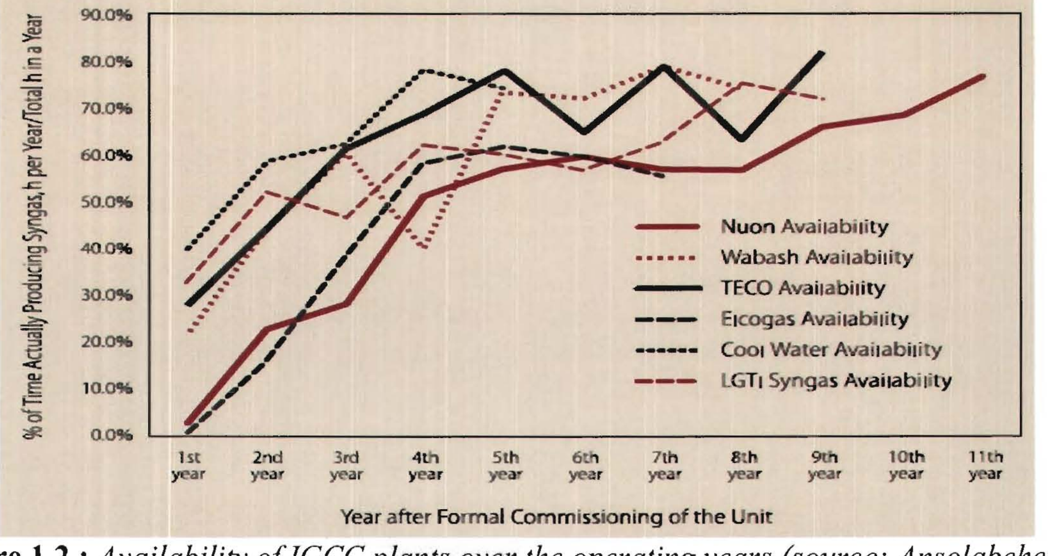

Figure 1.2.: *Availability of IGCC plants over the operating years (source: Ansolabehere et al, 2007)*

Taking these issues into consideration, it could be useful to conduct research on why unavailability issues occur and how the unavailability can be reduced. It could be considered that unavailability could be caused by problems in the supply of the raw material (logistics problem) or by an accident (safety issue).

1.2. Project description

Unavailability could be tackled by a number of methods. For example: technical improvement of the plant, personnel training, organizational restructure etc. However, the research focus is the training of the plant operators.

The present Master Thesis Project is over the implementation of a training framework in order to support the operators of IGCC power plants to make decisions under abnormal conditions. Abnormal conditions are the conditions that happen when disturbances cause the plant to deviate from its normal state. The training of the operators is going to be based on accident scenarios that will be developed in the context of the IGCC plant units. The project is conducted at Nuon Power Buggenum IGCC plant.

Well-trained operators will make structured decisions and therefore a possible accident could be prevented. In other words safety/availability is not going to be put in jeopardy. In this way the availability of the plant will not be reduced. Safety is closely related to availability since a safe plant implies that it can be available for use since the plant's function can work properly.

The developed accident scenarios can be useful for unavailability research. These scenarios show the potential route to a possible accident (state when a unit or the whole plant is not able to operate and then becomes unavailable). The risk scenarios are going to be further quantified in the context of the PhD project in order to assess the risk of possible plant unavailability. The quantification of the risk scenarios will not be part of the present thesis.

1.3 Company description

Nuon is active throughout the energy chain, operates in a global market and takes into consideration the worldwide environment problem. The number of employees at the end of 2007 was 9,980FTEs. Nuon is a leading energy company and it is located in the Netherlands, Belgium and Germany. The total revenue of Nuon is EUR 5.6 billion in 2007 (Nuon webpage, 2008). As explained earlier, this thesis is conducted in the Nuon Power Buggenum IGCC plant.

The Nuon Power Buggenum plant was decided to be built in 1989, as a demonstrational plant for coal gasification and started operating at 1994. The company that implemented the design of the plant was Demkolec (acronym for a demonstration of coal gasification with electricity generation and a subsidiary of the Sep, the collaborating electricity producer). In 1998, the plant started to operate commercially. At 2001 the plant was purchased by Nuon due to the context of the energy liberalization (nuonpower webpage, 2008).

Nowadays, Nuon is planning to implement a carbon dioxide sequestration technique. With the use of this technique the carbon dioxide is going to be captured before the combustion of the syngas and therefore the environmental emissions of carbon dioxide are going to be reduced. Furthermore, another IGCC plant of around 1200MW is going to be built in Eemshaven, in the north of the Netherlands. Finally, with regard to the corporate strategy, Nuon is evaluating possibilities of collaborating with other energy companies to become a key corporation in the energy market.

1.4. Structure of the report

The structure of the report is as follows. Chapter two is going to provide insight of the research. In other words, there is going to be a delineation of the research area and the research questions are going to be identified. Afterwards, the methodology will be presented and explained in chapter three. Chapter four focuses on selecting the SBT for the IGCC plants and will show the differences of the SBT to be implemented in the IGCC plant from the SBT which is presented in literature. Finally, the implications of the contextual differences will be presented. Chapter five will first focus on the selection of the appropriate unit in which the SBT will be conducted. The selection of scenarios suitable for operator training will follow. From the selected scenarios one scenario will be selected to demonstrate the SBT. Chapter six will then target on modeling the selected scenarios and therefore make them suitable for operator training. In addition, the outcomes of the scenarios will be described and their consequences will be estimated. Also the implications of this chapter are going to be stated. In chapter seven, a framework of how the SBT session should be implemented is given. Finally, chapter eight will round up the report by providing conclusions and recommendations for future research.

Chapter 2: Identification of research questions

Introduction to the chapter

The aim of this chapter is to define the problem that has to be solved by the present Master Thesis Project. The main research question is going to be addressed. Afterwards, the main research question is going to be divided into sub-questions.

2.1. Delineation of research area

In chapter one a generic description of the IGCC technology was provided. In the starting part of this section, the IGCC technology is going to be clarified further (e.g. more specific definition of IGCC, gasification and the process is going to be given).

In its broadest sense, gasification "covers the conversion of any carbonaceous fuel to a gaseous product with a usable heating value. This definition excludes combustion, because the product flue gas has no residual heating value" (Higman & van der Burgt, 2003).

With the IGCC (Integrated Gasification Combined Cycle) technology, electricity is being produced after a number of steps. First, coal is getting gasified to produce syngas (a mixture of hydrogen and carbon monoxide). The syngas gets cleaned. After the clean-up, the syngas is burned in a gas turbine which drives the electricity generator. The exhaust of the turbine is directed to the heat recovery generator to raise steam which then drives a steam turbine generator (Ansolabehere et al, 2007). Alternative fuels are coke, petroleum residues, biomass and natural gas. In some plants a mix of some of the above fuels is possible.

The incentive for the implementation of the IGCC technology is the prosperity of better environmental performance at low marginal cost (Maurstad, 2005). Especially, IGCC offers the possibility for decreased amount of carbon dioxide emissions compared to the traditional Pulverized-Coal power plants. In addition, it is observed extremely low NOx emissions (typically below 10 ppm) and sulphur removal efficiency above 99%. Furthermore, zero emission of fly ash (less solid waste generated) occurs, chlorides and volatile heavy metals and waste water reused in the plant (Ghhoa, 2005). Moreover, the control of mercury is possible at a lower cost that is possible with the conventional coal power plants (Pashos, 2005). A challenging issue is the reduction of the carbon dioxide emissions with the implementation of the CO_2 capture. With the use of this technique the CO_2 can be captured from the syngas prior to its combustion. The captured CO_2 can have numerous uses. For example, it can be injected to oil wells making oil exploration more efficient (Zwirn, 2006).

Coal-based IGCC plants are not yet fully commercial. A small number of demonstration plants with output of approximately 300MW have been built all over the world, with financial support from the local governments (Maurstad, 2005). The plants started operating as demonstrational plants of the IGCC technology and after some years of operation they began operating commercially. The IGCC is neither well established nor mature. It could be possible that it is going to undergo several changes when it matures. On the other hand, the IGCC is well-established commercially in the setting of refinery (built in refineries and use such feeds as coke or petroleum residues) and achieved better operating performance than coal-based IGCC (Ansolabehere et al, 2007).
The IGCC technology faces the competition with conventional Pulverized Coal plants. There are two main challenges in order to successfully compete the conventional PC plants; availability and capital cost (Maurstad, 2005).

As explained in chapter one, IGCC plants cannot reach a level of availability of 80%. The complexity of the process (which is going to be presented later in this section) implies that no single process unit or component in the total system is responsible for the vast majority of the unplanned shutdowns of the units, which resulted in the reduction of the unit availability. The gasification complex has been the largest factor for reducing IGCC availability. Running an IGCC plant is similar to running a refinery where mechanical, process and equipment problems should be continuously solved. In this sense, the operation of an IGCC unit is different from that of a PC unit and it requires a different operational strategy (Ansolabehere et al, 2007).

IGCC plant units are "integrated" in a sense that a possible unavailability of one unit can cause all the plant to become unavailable. The fluctuation of the operational performance due to this integration may cause a significant increase of both capital and variable cost (Ansolabehere et al, 2007). This issue could be a drawback and could be an explanation why the IGCC is not yet fully commercialized.

2.1.1. IGCC plant description

A typical coal-based IGCC power plant consists of several units: feed storage and handling, gasification, syngas treatment, syngas conditioning, power generation, air separation, sulphur recovery and waste water treatment. An overview the configuration of the IGCC technology can be seen in figure 2.1.

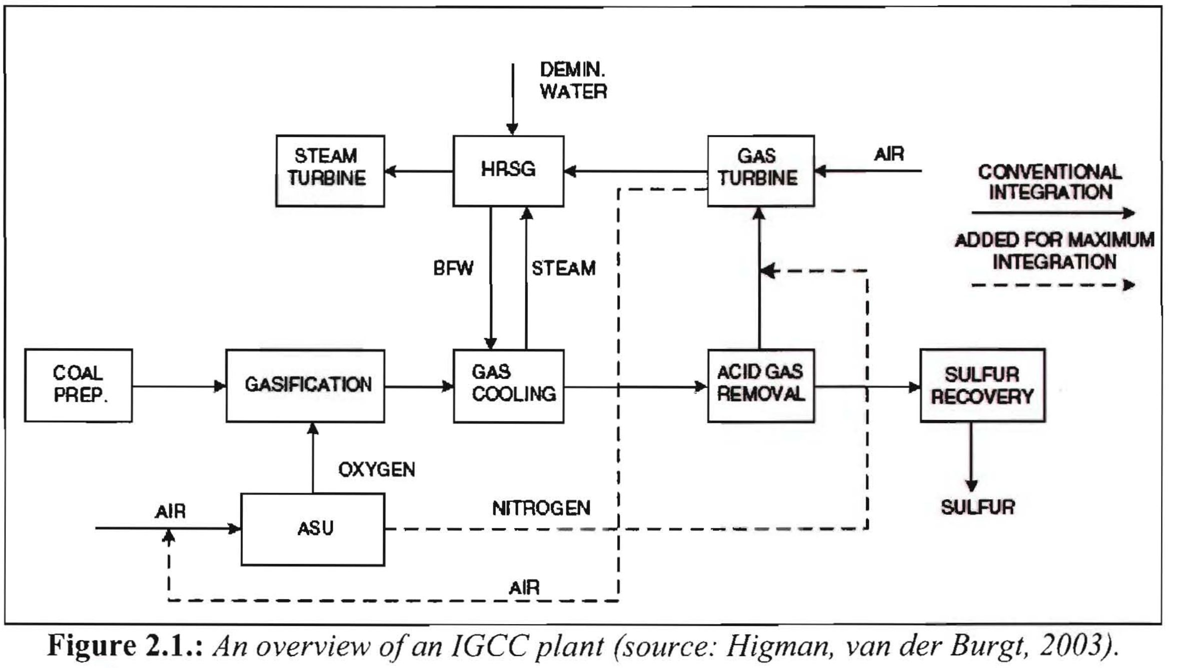

Figure 2.1.: *An overview of an IGCC plant (source: Higman, van der Burgt, 2003).*

The first step within an IGCC plant is the feed storage and handling (or coal preparation). This step consists of three processes; grinding, drying, and pressurization. Grinders reduce crushed feed to powder (McCabe, Smith, 1976). Drying is the next process. Coal drying is accomplished by the use of conventional drying processes that are thermally based and use natural gas as a fuel. Another possibility is to use a cleam gas to dry the coal. The final process is the pressurization of the feed in order to be able to be transported from the atmospheric conditions to the high pressure of the gasifier (Higman, van der Burgt, 2003).

Next is the coal gasification. In gasification three types of gasifiers can be used; the moving bed, the fluidized bed and the entrained-flow reactor. Many companies created several patents based on these three mentioned types of reactors. For example, Shell developed the Shell Gasification and Prenflo Process an entrained-flow gasifier, which is suitable for coal, oil and natural gas feeds (Higman, van der Burgt, 2003). The product of the gasification is the syngas, a mixture of hydrogen and carbon monoxide.

The next step is the syngas treatment. Syngas treatment consists of syngas cooling, particulate removal, chlorides removal and acid gases removal (Higman, van der Burgt, 2003). The produced syngas contains pollutant components (which vary from particulates to chloride compounds, tars or others); therefore it should undergo specific treatment to be appropriate for combustion. These components can be removed only in temperatures less than the operating temperature of the gasifier itself. Therefore cooling the syngas is a necessity (Higman, van der Burgt, 2003). The particles that are contained to the syngas will be deposited in the turbine and therefore problems will be created in the generation of power, thus particulate removal should be accomplished. The next step is the chlorides and fluorides removal, that it the removal of HF and HCl. However, particulates that remained in the syngas stream can also be removed. The final step of syngas treatment is the acid gas removal. "The term acid gas removal is a general term that is often used as a synonym for desulfurization, but strictly speaking in the synthesis gas environment it includes also CO_2 removal" (Higman, van der Burgt, 2003).

The clean syngas gets conditioned or saturated. The syngas stream gets saturated with water and then mixed with residual nitrogen. Saturation of the syngas ensures that NO_x formation during the combustion processes will be reduced.

The saturated syngas gets combusted in the power generation module; the heart of an IGCC plant. For this purpose the combined cycle is used. The combined cycle has two basic components. The first is a high efficiency gas turbine which is widely used in power generation today, burns the clean syngas to produce electricity. The second is the traditional high efficiency steam turbine in which exhaust heat from the gas turbine is recovered to produce steam to power (Higman, van der Burgt, 2003).

The air separation unit separates air into nitrogen and oxygen. This unit supplies the gasification plant with the necessary oxygen for the gasifier and the Claus unit (the unit where hydrogen sulfide is converted to elementary sulfur) and nitrogen that is used for the storage and transportation of the coal feedstock.

The "dirty" water that was used within the plant units is treated with a separate wastewater treatment unit. The technologies for treating industrial wastewater are divided in three categories; chemical, physical and biological methods (Woodard, 2001). Moreover, since water is re-circulated within the units a lot of companies demineralize it. The removal of minerals which are potential to cause corrosion enables the proper function of the unit in which the demineralized water is used.

Finally, in the sulfur recovery unit hydrogen sulfide is converted to non-toxic and useful elementary sulfur. It has to be stressed that H_2S is a highly toxic (some ppm are enough to kill a person), corrosive and smelly gas. It also deactivates industrial catalysts (Sulfotec Corporation webpage, 2007). Within an IGCC plant sulfur is recovered from the gas that exits the acid gas removal process.

2.1.2. IGCC plant risks

From the description of the aforementioned units, it could be inferred that there is a risk of having an accident. Risk can be defined as the "combination of severity and probability of an event" (McDonald, 2004). Risk takes into consideration the likelihood or the possibility of harm (Roland & Moriarty, 1983).

With respect to the feed storage and handling unit, a lot of accidents are possible to occur. For example, there is a possibility of a coal tank explosion and dust explosion. Dust explosions are a very difficult phenomenon to prevent. This happens because coal dust contains volatile combustible hydrocarbons. One of the possible ignition parameters is static electricity (Perrin et al, 2007). There were serious underground coal dust explosions in July 2000 in Utah (2 fatalities and 8 injuries), in September 2001 in Alabama (13 fatalities and 3 injuries), in January 2006 in West Virginia (12 fatalities and 1 injury), and in May 2006 in Kentucky (5 fatalities). Other mine explosions occurred in the USA in recent years but did not result in any injuries, but the mine recovery efforts took several months (Cashdollar et al, 2007).

The gasifier has four major potential hazards; toxic, fire, explosion and environmental. The produced gas of the gasifier (syngas) is a mixture of hydrogen and carbon monoxide. Carbon monoxide is toxic and dangerous due to the fact that it is prone to combine with the hemoglobin of the blood. This combination results in the prevention of oxygen absorption and distribution to the human body causing fatality (FAO webpage, 2007; FAO, 1986). Three are the main causes of fire: risks of sparks during refueling, high surface temperature of equipment and "flames through gasifier air inlet on refueling lid" (FAO webpage, 2007; FAO, 1986). Furthermore, an explosion can occur when sufficient amount of air is present. Air can be present in the gasifier due to four reasons. First is the leakage of the air into the gas system. Secondly, is the leakage of air in the gasifier contains gas which ignites. There is a possibility of backfiring from the fan of the exhaust burner in case the system is filled with a combustible mixture of air and gas in the start-up of the gasifier. Last but not least is the penetration of air in the system during the refueling of the gasifier. Environmental issues could occur when the feed contains amounts of wood and agricultural residues. Then, ashes and condensate are produced. Ashes can be removed and stored. However, the condensate can contain phenollic and tars which can be harmful to the environment (FAO webpage, 2007; FAO, 1986).

As far as the syngas treatment is concerned, there is a possibility of syngas leakage which means a leakage of hydrogen and carbon monoxide. Hydrogen is an explosive gas. Its release can result in major disasters. In addition, carbon monoxide is flammable. Mixtures of carbon monoxide and air in the flammable range will ignite if a flame or a spark is present (Industrial Accident Prevention Association, 2003). Also, as explained in the previous paragraph, carbon monoxide can be extremely toxic. For example, a concentration of about 2000 parts per million (ppm) in the air can cause unconsciousness and death (Industrial Accident Prevention Association, 2003).

Keeping in mind that the syngas treatment consists also of particle removal, the possibility of filter failure has to be considered. High temperature and pressure can cause the filters to brake. If this occurs, then the particles contained in the gas can go to the turbine causing a fraction and maybe an explosion. Therefore, several companies are putting a lot of effort in order to produce a safety filter element (Choi et al, 2002).

In addition, the sulphur recovery unit incorporates the hazard of hydrogen sulfide. In a occurrence of a hydrogen sulfide a disaster might occur since hydrogen sulfide is a colorless, extremely flammable and toxic gas. Despite the fact that it has a characteristic "rotten egg" smell when it is detected at concentrations as low as 0.5 part per billion (ppb), fatigue occurs rapidly and at low concentrations. In addition, when a person is exposed to concentrations of 500 parts per million (ppm) loss of consciousness is caused, and exposure to concentrations greater than or equal to 700 ppm can cause immediate death (U.S. Chemical and Hazard Investigation Board report, 2003).

Furthermore, as mentioned earlier the Combined Cycle consists of a steam and a gas turbine. Therefore, there is a probability that one of them or both will explode. If an explosion occurs, then the workers can be injured but also no electricity can be produced. For example, it has been observed that a sudden blade fraction of a stem turbine in an oil refinery caused its explosion and the injury of workers (APTECH webpage, 2007).

Finally, as far as the air separation unit (ASU) is concerned, there is a risk of explosion. Several explosions occurred, such as on in the ASU of the Bintulu plant in Malaysia in December 1997. This happened because combustible airborne particles had passed through the main purification section and accumulated on the aluminium main vaporizers of the distillation column. The combustion of hydrocarbons triggered the aluminium combustion, which in turn generated heat and vaporized cryogenic units which in turn led to high pressure and explosive rupture of the distillation column (van Hardeveld et al, 2001).

2.1.3. Safety management

The previous examples could be considered as evidence that the risk of having an accident (and therefore the plant becomes unsafe) is practical and not philosophical. Therefore the management of an IGCC plant should consider strategies to maintain plant safety. According to Roland and Moriarty (1983), safety is the "condition of being free from undergoing or causing hurt, injury or loss"; this means that safety is the freedom from potential harm (Roland, Moriarty, 1983).

"Safety management involves the provision of a safe working environment for all persons involved in the manufacturing process. It extends to cover the safety of the environment and the security of the business losses" (McDonald, 2004). "Risk management is the culture, process and structure, which come together to optimize the management of potential opportunities and adverse effects" (McDonald, 2004). Risk management has a lot of areas of implementation such as business and occupational health and safety. Reading the definitions of both safety management and risk management it can be concluded that safety management is the same with regard to effectiveness as the risk management (which is a more general term). However, safety management is applied specifically to risks that are associated with the harm to environment, property and persons (McDonald, 2004).

Safety management can be implemented in an IGCC plant by taking into consideration a number of strategies. Risk can be reduced by installing safety systems, improving automation, reliability testing and focusing on the human element.

Safety systems (such as alarms, pressure relief valves) have already been installed at the operating IGCC plants. The installed safety systems have already reduced the risk of having an accident to an acceptable limit regarding the safety regulations. Installation of any additional safety instruments could minimize the risk even more. On the other hand, this installation requires concrete studies concerning the type of safety systems to be installed and the exact location where the safety systems has to be located. In addition, this installation will imply dramatic cost increase. Installation of additional safety systems is not going to be considered in this thesis because it is not a part of present project.

IGCC plants posses complicated automation systems. Depending on the plant the automation could be state-of the art or relatively old. Regardless the state, the automation is very costly. In fact it is so costly that it is very unlikely to be changed. Some alteration could be possible but are beyond the scope of the present thesis.

Reliability testing is being conducted at several periods in the plant. It could be possible to organize more frequent testing. However, three issues have to be taken into consideration. The frequent testing could be extremely costly. Its cost could overcome the budget of the plant management. Secondly, it is possible that the frequent testing could degrade the equipment. Finally, there is a risk that the equipment could become unavailable during testing. Thus, reliability testing is not going to be considered further.

The focus should be on supporting the human operator to make proper decisions under abnormal conditions (e.g. a closed valve that should be normally open during the operation). Even at the best equipped plant (with the best maintenance, safety systems etc), operators are the ones who have to react immediately and prevent undesired outcomes. A possible improper decision could lead to catastrophic consequences (e.g. ruptures, explosions)

2.1.4. Focus on operator training

A possibility to help the operators to make proper decisions under abnormal conditions is the restructuring of the organization of the plant such as hiring specialized professionals that make decisions in case of abnormal conditions. This possibility could be unrealistic. In addition, it is costly to hire new people and restructure the organization of the IGCC plant. The idea is to utilize better the existing operators of the plant in order to make decisions under abnormal conditions. Therefore, in this thesis an appropriate training method is selected to support the operators make decisions under abnormal conditions.

The Department of Employment has defined training as "the systematic development of attitudes, knowledge and skill patterns required by the individual to perform adequately a given task or a job. It is often integrated with further education" (Stranks, 2007). Appropriate training is the planned training, which is the part of the training process which is done systematically by the organization "as opposed to the portions of the training process daily by supervisors with their people" (Heinrich et al, 1980). A systematic training implies "a defined training objective, the presence of trained instructor and suitable trainee, a content of skill analyzed into elements, a content of knowledge broken down into learnable units, a clear and orderly program, an appropriate place in which to learn, suitable equipment and visual aids and sufficient time to attain a desired standard of knowledge and competence" (Stranks, 2007). There are numerous reasons why appropriate training could be a suitable option for the present project.

First, IGCC plants are owned by electric production corporations. For example, it was mentioned that the IGCC plant at Buggenum in the Netherlands is owned by NUON. Theses corporations are very experienced in the traditional PC (pulverized coal) plant technology and not with the chemical technology. However, IGCC plants are in fact at least partially chemical plants (as described in the former section), which means that something unexpected can happen (which is true for every chemical plant). Also, the operators of these power plants come from the conventional plants and therefore, are not accustomed to making decisions in the context of a chemical plant and consequently in case of abnormal conditions. If something abnormal occurs, it is possible that it will lead to a disaster. Therefore, in order to enable the operators of these companies able to become familiar with possible problems, operator training is highly recommended. Complex IGCC plants require operators with both chemical and mechanical engineering background. However this is rather difficult since the amount of people that following the combination of chemical and mechanical engineering studies is small. So, training is an appropriate way to familiarize operators with the plant and its risks.

In addition, the technological progress made clear that the safety of man-machine systems (that is the process industry-IGCC power plant) depends on the quality of the human component (Moraal, 1992). At the early years of the safety management studies, errors of human behavior have been described as misbehaviors on the side of the operator who committed the wrong act. Therefore, he was to blame for it (Moraal, 1992). That was the so-called person approach. However, after the passing of the years the safety management experts came up with the system approach of human error. According to this approach, all humans are fallible and errors are to be expected in each organization, which means that the system approach concentrates on the conditions under which individuals work and tries to build defenses to avert errors or mitigate the consequences (van der Schaaf, Habraken, 2005; Reason 2000). Operator training can be a good solution of averting errors and mitigating consequences. Furthermore, the focus should be on operator training, since the operator is the one who plays a major role in the safety of the plant. This happens due to two reasons. First, due to the fact that a substantial amount of accidents happen because of "impossible" or unforeseen circumstances, the flexible human operator will be present in order to cope with despite having the same difficulties. Secondly, the safe handling of problems by the software (which is a result of a complex human activity) is never guaranteed because of hidden errors. Therefore, the human operator must be able to control the system manually (van der Schaaf, 1992). A trained operator is likely to be able to solve these problems.

Moreover, modern automation made the situation more difficult. Modern automatic control systems have taken the load of the routine operations and left the infrequent difficult and abnormal conditions in the operators' hands (Karydas, 2007). The problem is that by taking away the easy parts of the task, the difficult part can become more difficult (Bainbridge, 1987). To be more specific, in the process industries the operators due to the fact that they deal with routine information and standard procedures show more skill-based behavior. This type of behavior is about routine tasks that require little or no conscious attention during the task execution. An example of routine information is to see a temperature level in the control panel and decide if things are going well; if not the operator will contact the supervisor. On the other hand, when an alarm or something unexpected happens, there is no standard response which means that operator needs to show a knowledge-based behavior. This means that he will deal with a problem where no readily available solutions exist (Moraal, 1992; Rasmussen 1986). This behavioral change is a major reason of fatal accidents.

According to Rasmussen (1986), there is a transition from knowledge-based behavior to skill based behavior. A brief distinction of the types of behavior can be seen in Table 2.1. For example, when a student does his first driving lessons, the first thing that he is taught is how to change gears (at with speed he has to change from first to second etc.). At that lesson, all his focus is on how to change gears and he does not pay attention to the other vehicles in the road. In this sense he has a knowledge-based behavior. Gradually, knowing these rules he is enabled to determine when he has to change the gears by monitoring the speedometer. Thus, he switches to the so-called rule-based behavior. After a while the sounds of the engine will tell him "unconsciously" that it is time to change gears. This behavior is called skill-based behavior (van der Schaaf, 1992). The goal of training to enable the operators make decisions under abnormal is to make the transition from knowledge-based behavior to skill-based behavior. It is desired that the operators respond immediately to abnormal conditions without having to think about their decision for a long time because abnormal conditions could evolve to accidents ivery quickly

Table 2.1: *Distinction of the different types of behavior (source: van der chaaf, 1992; Rasmussen 1986).*

Behavior type	Explanation
Skill-based	Refers to "routine tasks that require little or no conscious attention during the task execution".
Rule-based	Refers to "familiar procedures that are applied to frequent decision-making procedures".
Knowledge-based	Refers to problem-solving activities when the decision-maker faces situations where no readily available solutions exist.

The personnel are critical to proper emergency response. Training assures that the role of each employee is clearly understood and that accidents can be reacted upon safely and without delay (Theodore et al, 1989). On the other hand, untrained operators are unable to understand the heavy volume of information, to interpret the data and diagnose the situation. When a very dangerous situation takes place, the operators should react within a couple of minutes or even in seconds and it is very difficult to identify and deploy the right strategy and to make hard decisions. Unfortunately, untrained operators will make the wrong decisions (Karydas, 2007).

According to the supervisory performance model (which is applicable to safety or any other performance), the fulfillment of supervisors' safety responsibilities depends on four issues. The first is the task definition. Secondly is the training (to know what to do). Another important issue is if they know that their boss checks whether they do it correctly or not. Finally, there is an issue if there will be a reward (Petersen, 1996). In figure 2.1 the influence on training according to the supervisory performance model can be seen. Looking at this figure, it can be clear that performance is driven by the supervisor's perception of what the boss wants to be done, their perception on how their boss will measure them and the perception on how they will be rewarded for that performance (Petersen, 1996). Training plays a significant role to safety performance. It ensures that an employee is able to do what it takes in order to achieve the desired level of safety.

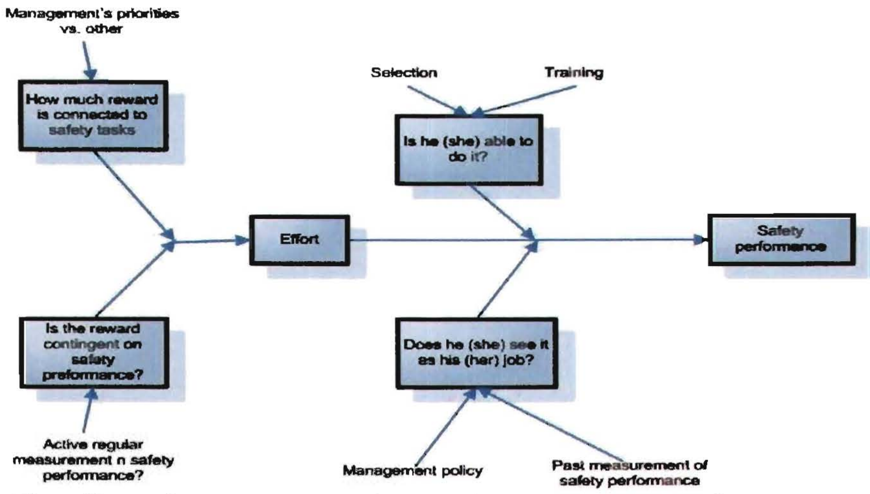

Figure 2.1: *The effect of training according to the supervisory performance model (Source: Petersen, 1996).*

Finally, operator training is forced by governmental legislation all over the world. According to Kjellen (2000), government regulations require employers to provide their employees with appropriate training (Kjellen, 2000). As explained earlier, appropriate training is planned training. It could be easily said that operators' training has become a must.

To sum up, as explained and justified before, operator training in decision making under abnormal conditions could mitigate the consequences of a possible abnormal condition and as a side effect could decrease the likelihood of occurrence. The next step is the decision on which training is appropriate for the specific project.

2.2. Upcoming research questions

In the previous section it was argued that in order to mitigate the consequences of a potential accident, training the operators to enable them make decisions under abnormal conditions could be a solution. However, it is not yet known how the operators can be trained to anticipate abnormal conditions. Therefore, the main research question of this Master Thesis Project is:

How can the operators of an IGCC power plant be trained in order to make structured decisions under abnormal conditions?

First, a method suitable for the present project should be selected. However, the method to be selected is implemented in a context which could be different from that of an IGCC plant. This means that the selected training method should be adapted in the context of an IGCC plant. Finally, it should be determined how the selected method could be implemented. Thus, the main research question can be divided into the following three sub-questions.

1. *What training method could be suitable for training the operators to make decisions under abnormal conditions?*
2. *How can the selected method be adapted to the context of an IGCC plant?*
3. *How can the selected training method be implemented?*

The next chapter will continue with the methodology for answering these research questions.

Chapter 3: Methodology

Introduction to the chapter

In chapter two, the research questions were identified. In this chapter the approach for answering the research questions will be explained. The overview of the methodology is presented in section 3.1.

3.1. Methodology overview

The approach starts with the IGCC plant experience and a literature review concerning the risk management techniques (e.g. HAZOP, ETA), the possible training methods, and the IGCC technology. Based on the literature regarding the available training methods, a suitable method will be selected. Based on the interviews with the plant operators, the unit handbooks, the P&ID's and the risk analysis studies that were conducted in the plant, the selected method will be adapted to fit to the context of the IGCC plant. Finally, the last step is the implementation of the selected method. That is the definition of an implementation framework and its testing to assess if it fits within the IGCC environment and if it has some weak points that have to be improved. An overview of the methodology can be seen in figure 3.1.

As it was explained, the sources based on which the selected method will be adapted to the content of the IGCC plant are: operator interviews, unit handbooks, Piping and Instrumentation Diagrams (P&ID's) and the risk analysis studies that have been conducted within the Nuon plant. Operator interviews will serve two purposes. First, the researcher will be guided in each unit and will see how things work in real life and what actually is happening to each unit. Secondly, the most challenging reason is that there will be the opportunity to see the possible problems that the operators faced and the way that they solved them. In addition, the purpose of unit handbooks is twofold. The first is to understand how the units are designed to work and the procedures that must be followed in order for the units to be safely operated. Secondly, reading the unit handbooks will help the researcher to identify any possible deficiencies and problems that the unit has. P&ID diagrams offer a detailed representation of the unit's functions. They provide the ability of the exact identification of the possible deficiencies of each unit. Based on the information contained in the P&ID's, the sequence of possible abnormal situations could be modeled. Finally, the risk analysis studies that were conducted in the plant serve as a means of identifying possible abnormal conditions and their consequences. Two risk analysis methods were conducted in the plant; HAZOP (Hazard and Operability Study) and ARIE (Additional Risk Inventory Evaluation). Detailed description of these studies will be given in the next chapters.

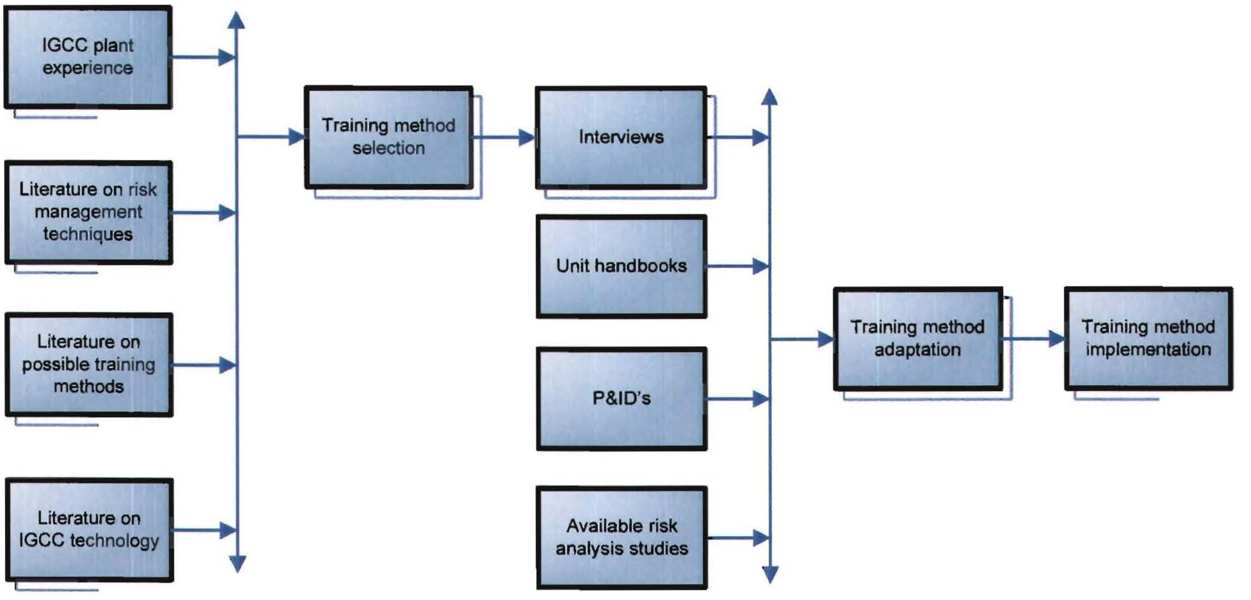

Figure 3.1: *An overview of the methodology.*

Chapter 4: Training selection and adaptation

Introduction to the chapter

The aim of this chapter is the selection of an appropriate training method to support plant operators to make decisions under abnormal conditions. It will be argued that an appropriate method is the Scenario-Based Training (SBT). Furthermore, the context differences between the SBT to be implemented in the IGCC and SBT mentioned in literature will be explained. Finally, the implications of the context difference will be presented.

4.1. Training method selection

In chapter two it was argued that in order for an operator to make structured decisions in case of an abnormal condition, training is a solution. It is suggested to tackle abnormal situation management with training (Bullemer& Nimmo, 1998), but no training method is proposed. Therefore, a selection of an appropriate training method for abnormal situation will be the focal point of this section.

According to Stranks (2007), training methods are dependent to the learning system that was adopted (passive or active). Active learning (e.g. group discussion) systems are suitable for a subject when there are no 100 percent correct answers. In addition, the interest and the level of arousal of the trainees are maintained and it is more likely to make a change in the attitude of the trainees. On the other hand, the objective of passive learning is the imparting of knowledge. Its advantage is that it provides a framework that can be used when a large numbers of trainees exist (Stranks, 2007). The available training methods will be categorized based on their underlying learning structure. In tables 4.1 and 4.2, an overview of available methods with an underlying active and passive learning system respectively can be seen.

The training method to be selected should fulfill three requirements. First, it should be suitable for training a diversity of employees-operators. In an IGCC plant the age and the background of the operators can vary. Secondly, the training method to be used should enhance the decision-making process of the trainees-operators. Finally, the method to be selected should have a concrete approach.

The training methods with a passive learning system are going to be used for this research. Training methods with a passive learning system do not fulfill the aforementioned requirements. In the present research the trainees (operators) vary from young to older. Passive methods work best with younger people but are less acceptable to older people. The issue with older people is that it is difficult to maintain their level of interest arousal (Stranks, 2007). Secondly, the methods that can be seen in table 4.1 could not support the operators to make decisions under abnormal conditions. These methods do not provide a concrete approach. Therefore, training methods with an active learning system will be considered. It has to be stipulated that a method with a passive learning system could be used partially for the purposes of this research. For example, a lecture could be used as a small introduction to the actual training.

Table 4.1: *Training methods with a passive learning system (source: Stranks, 2007).*

Training method	Brief Description
Guided reading	A trainee is given a standard company material to read and comment upon a decision.
Lectures	"A straight talk or exposition but without group participation other than through questions after the conclusion".
Demonstration	Indicates why, where and when something is done.
Individual coaching	It is designed to inspire and develop individual skills. It is based on the relationship between trainer and trainee.

Table 4.2: *Training methods with an active learning system (source: Stranks, 2007).*

Training Method	Brief Description
Guided practice	The trainee has to perform the operation or procedure being taught under controlled conditions.
Group discussion	In this method trainees have the opportunity to express their opinions and therefore the level of interest is remarkably high.
Syndicate exercises	It helps a large group be broken in small subgroups for discussion on problem-solving exercises.
Group dynamics	Situations are presented and trainees' behavior is examined by other trainees and group behavior is examined by trainees.
Programmed instruction/learning	It is clear what the trainee is expected to do, the material to be learned and of course the feedback of the trainee's actions.
Simulation	It increases trainee involvement in the learning process by introducing a realistic element into instruction.
Projects	A project enhances interest and decision-making, creativity and information on the trainee's knowledge
Assignments	The task is undertaken to close guidelines after a session of information absorption.
On the job training	It is carried out when the employee is at the workplace and during the working time.

Training methods with an active learning system provide an increase in the interest and arousal of the trainees. In that sense they fulfill the first requirement. Secondly, they could be a means of changing the trainees' attitude (Stranks, 2007). In that sense they fulfill the first requirement.

Looking at table 4.2, it could be inferred that only simulation and group discussion fulfill the second requirement (proper to enhance decision-making process). Group discussion offers the participants the opportunity to express their opinions and in that sense helps the process of making decisions with their ideas. It stimulates the decision-making (Stranks, 2007). Simulation could be interesting in the present situation because with the realistic events that are introduced enhance the trainees' involvement and consequently the decision-making process will be enhanced.

Simulators are now being designed in order to model the IGCC technology. However, these simulators are not yet finalized in order to focus on training the operators on how to react if an abnormal condition occurs. At this stage the simulator could only help them to familiarize with the IGCC process technology. For example, a proposed simulator has two main functions. The first is to train the operator how to make the start up and the shut down load shedding etc. The second is for engineering and system studies (for unit optimization etc.) (Zitney & Erbes, 2006; Stiegel, 2007; Electric Power research Institute, 2006). The simulation technology in the context of the IGCC technology is not mature yet. Therefore, simulation could not be implemented in the present project.

Group discussion does not fulfill the third requirement. It does not have a concrete approach to train the operators. The way in which the operators will be trained (e.g. material, steps of training) is unknown. This implies that it cannot be implemented explicitly. Notwithstanding, it is a useful method and can be incorporated in training the operators to support them make decisions under abnormal conditions.

Two methods that could fit within the context of an IGCC plant are Scenario-Based Training (SBT) and Event-Based Approach to Training (EBAT). Scenario-Based Training has been applied to the police, aviation etc. Several definitions of SBT were given and are dependent on the field of application. Scenario-Based Training is defined by the U.S Department of Public Safety Standards and Training as "a highly effective approach that allows students to learn, and then apply their knowledge as they participate in realistic scenarios. This method of instruction and learning allows students to move from theory to practical application of skills during their training. When officers learn to apply their learning in scenarios while they are students, they are better prepared to react appropriately in the situations they encounter in the workplace" (U.S Department of Public Safety Standards and Training, 2002). EBAT is a "framework based on a systematic structuring of learning opportunities using appropriate learning methods, strategies and tools" (Oser et al, 1998). Both methods meet the three requirements.

EBAT focuses on the SBT design but in simulated design (Oser et al, 1999a). Note that the EBAT is being implemented in areas where the simulation is mature (e.g. medical field) and not within an IGCC plant. It was explained that simulators in IGCC are not yet ready. This means that a method that is based on simulation could not be feasible in the present project. Therefore, the method which is going to be used for training the operators to make decisions under abnormal conditions is the Scenario-Based Training (SBT).

Scenario-Based Training has a lot of advantages. First of all, operators can be prepared to anticipate abnormal conditions and go through them decisively, intuitively and efficiently with SBT. Scenario-Based Training simulates real-life conditions through events that can occur at any time under the appropriate abnormal conditions (Karydas, 2007). As Debra Elkins stated: things can be applied off-line and do scenario envisioning rather than having to deal with the real event (Elkins, 2004).

Secondly, scenario development helps the organization to focus on the consequences and key decisions (Fred Cohen and Association webpage, 2007). Numerous disastrous situations could occur in an IGCC power plant (for example fatalities, leakage of hazardous chemical etc). With the implementation of the SBT the decision-maker will focus on the key decisions in order to avoid these consequences. For example, a possible decision could be to shut down the plant.

Moreover, "a wide range of operators can benefit, from novices without any specialized knowledge to expert users who wish to familiarize themselves with a new product" (Strally, 2005; Loftin, Wang&Baffes, 1989). In an IGCC plant young with little experience and older experienced people work. They can familiarize with making decisions under abnormal conditions.

Finally, last but not least SBT mitigates the consequences when an abnormal condition occurs since the trained operators can respond adequately. For example, when a valve from a gas transporting pipe closes suddenly, the operator could guide the gas stream to the flare and thus prevent a possible overpressure at the pipe.

4.2. SBT Contextual differences

According to Oser et al (1999b), the SBT approach consists of four important aspects: learning objectives, scenario events, performance measures and feedback (Oser et al, 1999b). The SBT approach can be seen in figure 4.1.

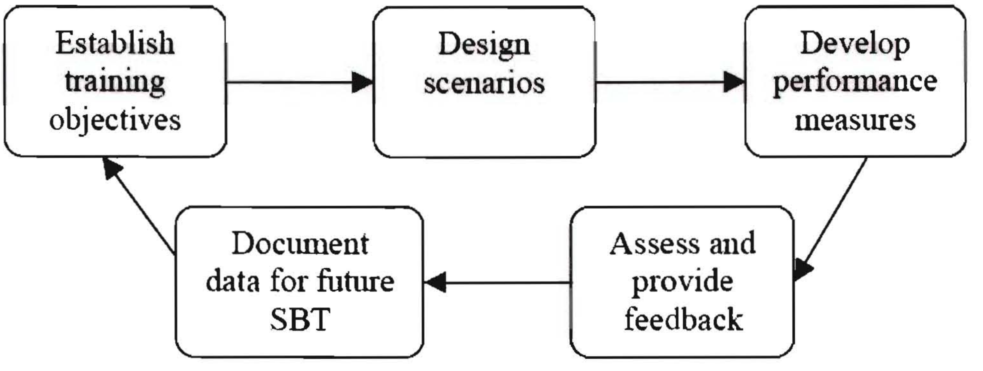

Figure 4.1: *Scenario-Based Training approach (sources: Strally, 2005; Oser et al, 1999b).*

The training objectives are based on a need of new skills development, a need for capabilities improvement and the introduction of unfamiliar equipment. The next step is to design scenarios based on the stated objectives. Based on the trainee's performance on the scenarios feedback is given by the trainer. The feedback will enable the trainee to what has to be corrected to improve his/her performance at the next scenario (Strally, 2005).

It could be inferred that the trainees' actions and performance are assessed. Basically, it is desired to examine the effectiveness of the method by measuring and assessing what the trainees learned by the used method. This is consistent with the objectives of the SBT that were stated above. In some conducted studies the participants should first complete a pre-test to assess their current level of knowledge. The participants receive training and then they have to take a post-test to assess what they have learned from the training.

For example, in the study of Owen et al (2006) the objective was the examination which simulation method could be used in order to treat medical emergencies occurring in a hospital setting. All the participants had an initial assessment (pre-training) by written tests. Then the simulations were conducted. After the conduction of the simulation the participants were tested again post-training using similar simulations to the initial scenario and a new scenario (Owen et al, 2006).

In addition, in a study which was conducted to examine the effects of Scenario-Based Training on pilot's use of a ballistic Recovery Systems, the objectives were the development of SBT and the addition of research base concerning the efficacy of SBT. The three above mentioned training stages were used. The participants did a pre-test scenario (assessment of their knowledge before training), then attended the SBT training and after that they did a post-test scenario (assessment of their knowledge after training) in order to the researchers to identify if the training method was successful (Strally, 2005; Strally & Blickensderfer, 2006). Both studies measured the effectiveness of the applied training method by examining the trainee's' knowledge and response before and after the training session.

As it was mentioned in the previous section in the context of the public safety, Scenario-Based Training is defined by the U.S Department of Public Safety Standards and Training as "a highly effective approach that allows students to learn, and then apply their knowledge as they participate in realistic scenarios. This method of instruction and learning allows students to move from theory to practical application of skills during their training. When officers learn to apply their learning in scenarios while they are students, they are better prepared to react appropriately in the situations they encounter in the workplace" (U.S Department of Public Safety Standards and Training, 2002).

This definition is in the context of the police forces operation. It does not fit within the context of an IGCC plant. Thus, Scenario-Based Training can be redefined as "A highly effective approach that shows the operators to both improve understanding and decision-making under abnormal conditions through training based on realistic scenarios".

In addition, the training objectives within an IGCC plant differ from the aforementioned ones. The objective is not to teach the operators how the plant works; they know already. Therefore, the main SBT objectives in the context of an IGCC plant are three; decision-making under abnormal conditions, process insight and be close to reality.

1. Decision-making under abnormal conditions. It is the main goal of the SBT. In case of an abnormal condition (e.g. a valve that should normally be open closes), the operators have to think fast which could stress them very much. This implies that the training should target the decision making process in conditions that are adverse to the operators, since in reality the conditions will be adverse. It has to be stipulated that the purpose of the training is not the evaluation of the response of the operators to the examined scenario. The purpose is to help them develop a structured way of reasoning by analyzing a potential accident without the effect of time-pressure.
2. Process insight. An objective of the SBT is to improve the operators' insight of of the process that he monitors. For example, in a unit in which lubrication oil is used, it could be useful to ask the operators if they have an oil level meter. In this sense the operators will deepen in the process. In case that the operator is not fully aware of the existence of the level indicator, he will go to the unit to see if a lubrication oil level indicator exists If a level indicator does not exist then the operator is likely to order one. In that sense, the operator, will increase his insight of the unit.
3. Be close to reality. The third objective is to have the scenario appear to the operators as close to reality as possible and feasible. The means to do that is visualization of the actual components and for example the control system the same as they appear in the plant. The visualization will make the accident sequence plausible to the operators and thus make them think about how they should act to prevent each step from evolving into an accident.

Looking at the objectives stated in literature (develop new skills and/or improve capabilities and/or introduce the trainee to unfamiliar equipment), it can be inferred that there are some similarities between the objectives. The first objective of the SBT to be conducted within an IGCC plant it the decision-making under abnormal conditions. In that sense the objective is to improve an existing skill and develop a new skill. The process insight is similar to the capabilities improvement. However, the third objective differs from the objective stated in literature (introduction to unfamiliar equipment).

Furthermore, an underlying model of SBT is discussed in literature. However, no model exists for an IGCC context. In figure 4.2, constructed model of SBT is presented and explained.

Finally, the format of the SBT session does not exist as well. It could be possible that some of the steps mentioned in literature could be used but with some alterations. The differences of SBT between the context discussed in literature and the context of the IGCC technology can be seen in table 4.3.

Table 4.3: *Summary of differences in SBT.*

	Literature	**IGCC plant**
Objectives	1. Development of new skills. 2. Capabilities improvement. 3. Introduction to unfamiliar equipment.	1. Decision-making under abnormal conditions. 2. Process insight. 3. Be close to reality
Underlying model	Introduced by Oser et al (1999b). Can be seen in figure 4.1.	To be adapted. Example can be seen in figure 4.2.
Format of session	Pre-test Training with scenarios Post-test	To be defined.

4.3. Implications for SBT adaptation

The results of the previous section imply that some modifications should be done in order for SBT to be adapted within the context of an IGCC plant. First, possible accident scenarios should be identified. Note that concerning the SBT that is mentioned in literature scenarios are available. However, this is not true for the IGCC plants. Afterwards, the unit in which the SBT will be implemented and scenarios to be taught in the training session should be selected. The third step is to model the selected scenarios in order to become suitable for operator training. Finally, the format of the SBT will be defined in the context of the IGCC plant. These steps could compose the underlying SBT model. This model can be seen in figure 4.2.

Before proceeding it may be useful to clarify what a scenario means. An accident scenario is being defined by to Kahn and Abbasi (1998) as "a combination of different likely events that may occur in an industry". "Accident scenario is described as a description of a situation and the expected frequency of occurrence". (Kim et al, 2003, Kahn &Abbasi, 1998). It is an event or series of actions and events (e.g. blow off valve does not work and the pressure relief valve does not work as well) that may lead to an accident.

As far as scenario identification (chapter five) is concerned (chapter 5), two scenario sources will be used; HAZOP (Hazard and Operability Study) and the ARIE study (Additional Risk Inventory Evaluation). No additional source will be used. Some scenarios were available in literature. However, in order to a scenario to be plausible to the operators, it should be from their own plant. Therefore, the scenarios for training should be from the examined IGCC plant. In the plant where the study was conducted available scenario sources were the HAZOP and the ARIE studies. Last but not least, the researcher could "invent" a scenarios based on the plant configuration. Notwithstanding, there would be a high risk that these scenarios will not be plausible to the operators or they will believe that it was an abstracted guess.

HAZOP analysis (Hazard and Operability Study) examines a well defined process or operation either planned or unplanned. HAZOP has three purposes: the identification and the evaluation of hazards within a planned process or operation, the identification of practical problems associated with the maintenance operations and the identification of significant operating or quality problems (McDonald, 2004).

ARIE study stands for Additional Risk Inventory Evaluation. In this study possible scenarios for each unit have been identified and counter measures were suggested. However, the possibility of operator training was not included in the proposed countermeasures.

After possible accident scenarios are identified, the next step is to select the unit where the SBT will be implemented because of the plant complexity and the fact that possibility of a detailed examination of specific process (e.g. gasification). The next step is the selection of the relevant scenarios for SBT training (chapter five). It is possible that not all the identified scenarios are useful for SBT training.

The selected scenarios will be modeled to become suitable for SBT (chapter six). Before modeling the selected scenarios, it will be checked if they contain sufficient detail for successful operator training. Detail concerns the sequence of events and the way the consequences are mitigated with respect to the human aspect (what is the human intervention). If the level of the detail is insufficient the scenarios will be modeled by the Event-Tree Analysis. The method will be explained in chapter six. In addition to the modeling of sequence of events, consequences of the scenarios (e.g. gas release, vapor cloud explosion) are going to be estimated. The estimation of the consequences will make the scenarios more plausible to the operators and it will serve as an argument to the plant management to implement SBT in order to avoid the estimated outcomes.

The last part is the definition of the format of SBT. This is about the implementation of the SBT in the context of an IGCC plant. This means that guidelines will be given on how the SBT should be conducted. It is argued that the training format should consist of three parts: introduction, training part and training evaluation. The functions and the purposes of these parts are going to be explained in chapter seven. Finally, the SBT will be tested to assess if it fits within the IGCC environment and if it has some weak points that have to be improved.

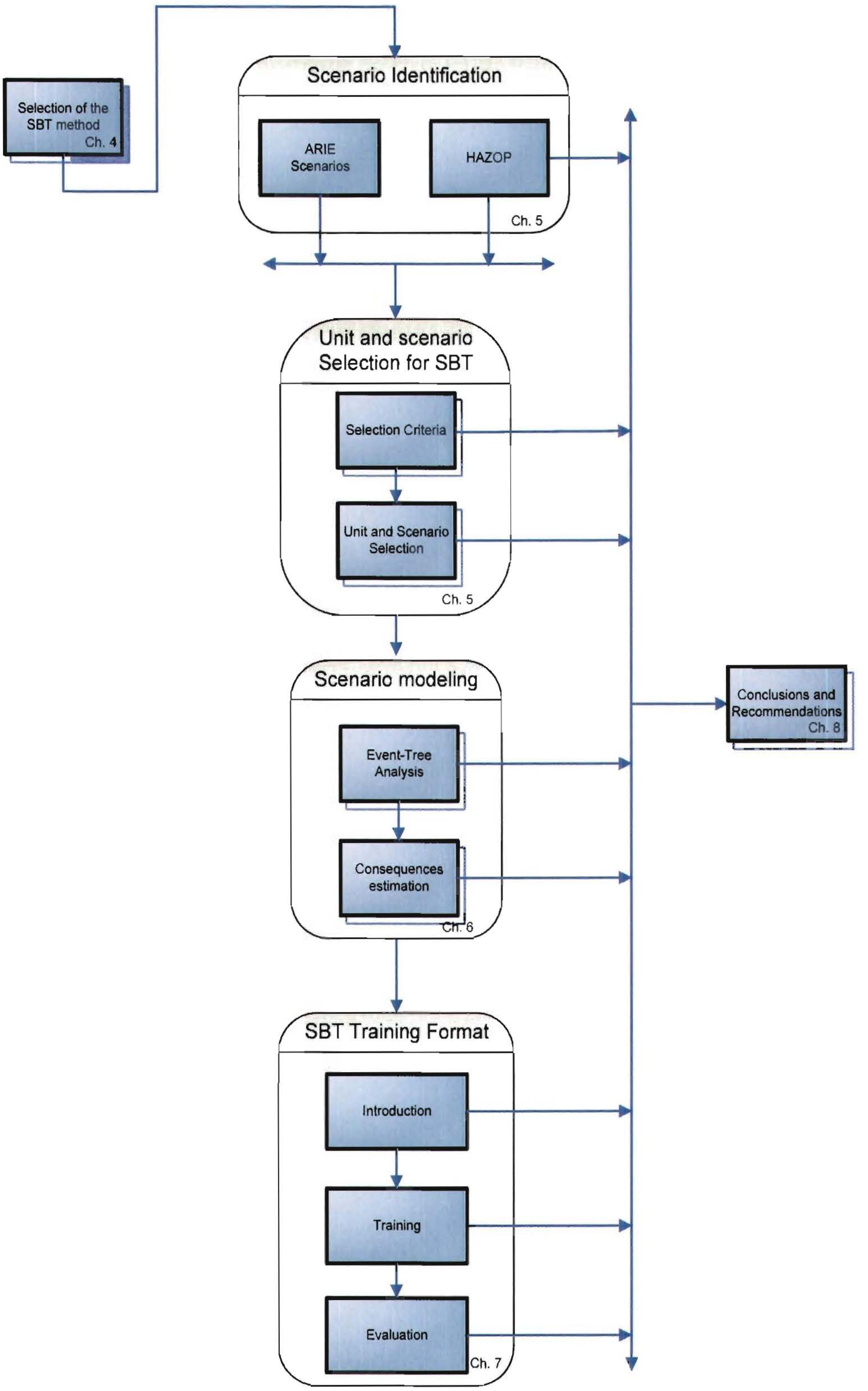

Figure 4.2: *SBT model.*

Chapter 5: Scenario identification and selection

Introduction to the chapter

This chapter sets the area where the SBT will be applied. It tackles the starting stages of the SBT adaptation to the context of an IGCC plant. First accident scenarios are going to be identified. Then, due to the high complexity of an IGCC plant, the unit where the SBT will be conducted will be selected. The next step is the selection of the relevant scenarios for operator SBT. The selection of both unit and scenario is going to be accomplished based on a list of criteria. Finally, a demonstration scenario will be selected to demonstrate the SBT implementation technique to Nuon.

5.1. Scenario identification

With regard to scenario identification, scenarios are identified based on two sources; HAZOP (Hazard and Operability Study) and the ARIE study (Additional Risk Inventory Evaluation). Additional source of accident scenario identification (e.g. literature) was not used. Also, the researcher did not construct scenarios.

The scenarios that will be used for training should be identified in the context of the examined IGCC plant. Scenarios related to functions of the IGCC plant could be found in literature. However, these scenarios would have been identified in other plants where the configuration of the components is different from the configuration of an IGCC plant. The scenario to be used for training should be identified in the plant in which the training will take place. In this way it will be plausible to the plant operators.

The identification of scenarios could be possible to be conducted by the researcher. However, there is a risk that the identified scenarios will not be correct since the researcher is not experienced. Even if the correct scenarios are identified, it is possible that the operators will not find them legitimate (that the are correct) since they will doubt that the researcher is so experienced in order to identify properly scenarios. The sources where scenarios were identified are the HAZOP and ARIE studies. General overview of these two methods was given in chapter three.

5.1.1. ARIE

ARIE is a risk analysis procedure that is conducted additionally to the risk analysis methods that are conducted in Nuon. It was conducted due to the laws concerning plant safety in the Netherlands.

ARIE study stands for Additional Risk Inventory Evaluation. In the context of ARIE the risk of having possible malfunctions in each unit of the plant is identified with the use of Failure Mode and Effects Analysis (FMEA). The final outcome of this study is a list of scenarios for each unit, the risk (including likelihood and severity) and some guidelines which explain very shortly what has to be done in order for these scenarios to be prevented. An example of an ARIE scenario can be seen in figure 5.1.

This figure is not shown in the public version of this report because of reasons of confidentiality.

Figure 5.1: *Example of an ARIE scenario (source: Nuon Power Buggenum).*

With regard to ARIE, the vast majority of the scenarios are caused by poor maintenance, corrosion and problems in the seals. However, there are numerous reasons that can cause an accident. For example, a malfunction of a control valve can result in extreme pressure which in turn can result in an accident. In addition, the sequences of events which will result to the accidents are not included. Finally, the human intervention is not included in the evolvement of the scenarios.

5.1.2. HAZOP

The goal of Hazop is the examination of the possible deficiencies of the plant with regard to reliability of equipment and safety. HAZOP aims at the improvement of the current safety situation.

HAZOP analysis (Hazard and Operability Study) examines a well defined process or operation either planned or unplanned. HAZOP has three purposes: the identification and the evaluation of hazards within a planned process or operation, the identification of practical problems associated with the maintenance operations and the identification of significant operating or quality problems. It takes small sections or modes of the plant and applies all deviations to design intent. It searches for both causes and effects. Furthermore, it can be used at any stage where P&ID diagrams are available. HAZOP has a lot of advantages. First of all, it is very systematic. Secondly, it is the most widely used methodology for hazard identification. Moreover, it improves the operability of the unit. Finally, it provides high level of confidence in detection of hazards (McDonald, 2004).

HAZOP comprises four sequential steps; definition phase, preparation phase, examination phase and reporting and follow-up phase. In the definition phase, the scope and the objectives of the study are set. In the preparation phase the study is planned, data is collected and the schedule is arranged. The examination phase proceeds with dividing the system into elements. Then the elements are examined for deviations from the design intent. All the possible deviations cause, consequences and protection needs are identified. Finally, in the reporting and follow-up phase the final report is issued (McDonald, 2004).

It is being conducted by Nuon for plant units. In each unit the most important vessels according to the management are examined. The examination format is a round table format where the safety manager, asset manager and the unit engineers ask questions with respect to the possible process deviations and the causes, the consequences and the associated risk. An example of a HAZOP can be seen in table A2 in the Appendix A.

HAZOP is a source of abnormal operating conditions. The identified by HAZOP cause of a process deviation can be an initiating event for the accident scenarios that can be used for operator training. Furthermore, a harmful situation identified by HAZOP can be explained in terms of an accident scenario. The scenario will then start with the process deviation (e.g. high pressure) and will end with the harmful consequence (e.g. explosion). As it will be explained in chapter six, the scenarios described by the HAZOP technique will be modeled with ETA (Event-Tree Analysis).

Looking at the HAZOP sheets it can be understood that accident scenarios start with an initiating event (the so called cause). Then, the process deviation will take place (e.g. too high pressure). Depending on the response of the installed safeguards, this deviation will lead to an accident (e.g. vessel rapture). However, like ARIE, the whole sequence of events and the human intervention in the evolvement of the scenarios are not shown.

5.2. Unit selection

After the possible scenarios within the plant units are identified, the next step is the selection of a unit where the SBT will be conducted. A unit will be selected for two reasons; IGCC plant complexity and the possibility to zoom in to the plant.

As mentioned in chapter two, an IGCC plant is very complex. It consists of a number of units which are "integrated". Also, each unit is very complex itself. It is very difficult to implement the SBT to all of the units simultaneously. Therefore, a unit in which the SBT will be implemented has to be selected. Besides, the risk analysis methods (HAZOP and ARIE) with which scenarios were identified were conducted in unit level and not in plant level. In addition, the selection of one unit can give the opportunity to zoom in on a part of the plant. A specific process (e.g. gasification) can be examined in detail.

5.2.1. Criteria

In order for a unit to be selected, it should score high in both of the following two criteria.

1. Availability of information concerning scenarios
2. Availability of information concerning recorded accidents or plant shut downs.

First, the unit to be selected should have available identified scenarios with both HAZOP and ARIE studies. In this way it will be possible to make a scenario selection from a relatively big list of scenarios. This criterion is weighted more because without scenarios, the training will be implemented without material.

Furthermore, the unit to be selected should have available accidents or near misses (incidents) recorded. Incidents are situations of unsafe behavior but without damage or injuries (Moraal, 1992). This criterion could provide an argument that accidents in that unit and/or sudden shutdowns can occur which could cause the plant to become unavailable. Therefore, SBT should be conducted to support the operators to make decisions under abnormal conditions and thus prevent the accident.

5.2.2. Method

The method that will be used to select a unit will be the Elimination By Aspects (EBA) decision-modeling method. The EBA heuristic supposes that the decision-maker follows a process of sequential choice and eliminates at each stage all the options not having an expected given attribute, until only one option remains (Laurent, 2006). The EBA fits in the context of the thesis since the unit to be selected meet both criteria.

5.2.3. Results

The units to be considered are: feed storage and handling, gasification, syngas treatment, syngas conditioning (saturator), steam and gas turbine (or combined cycle), air separation unit and wastewater treatment.

With regard to the first criterion (availability of information concerning scenarios) the units that were eliminated are: feed storage and handling, steam and gas turbine, air separation unit and wastewater treatment. The above mentioned units did not have the HAZOP scenarios unavailable.

The units that are considered for the second criterion (information concerning recording accidents and shut downs) are: gasification, syngas treatment and syngas conditioning. The "winner" was the syngas treatment. This units provides information concerning accidents (e.g. leakages).

For example, in 1999, the syngas scrubber inlet piping of the Tampa Electric Company IGCC plant had some deterioration problems due to simple erosion by the dry particulate lad syngas from the syngas coolers. This led to the lost of production for approximately 13 days (McDaniel& Snelnut, 1999). Moreover, in March 26, 2006 in the Shell Oil Products U.S Martinez Refinery sulphur dioxide was released form the SCOT reactor. This release resulted in the shutdown of the unit (cchealth webpage, 2008). An overview of the syngas treatment of Nuon Power Buggenum can be seen in figure 5.2.

Figure 5.2: *Overview of the Nuon Power Buggenum syngas treatment unit (source: Nuon Power Buggenum).*

5.3. Scenario selection

The syngas treatment was selected. Scenarios are available within the HAZOP and the ARIE studies. It is possible that not all the identified scenarios are relevant for SBT. Therefore, the next step is the selection of scenarios that are relevant to be used for operator training.

5.3.1. Criteria

The scenarios that are going to be selected should meet all of the following criteria.

1. Low probability, high consequence scenarios
2. Scenarios credible to operators
3. Relevance for Noun's management

First, the scenario to be selected should have outcomes with the combination of high consequence with regard to people or plant availability and low probability of occurrence. The focus of this research is the scenarios that will lead to disasters and accidents or plant unavailability which is going to cause monetary loss to the corporation, environmental pollution and fatalities. According to the safety regulations in Europe, the scenarios can have high consequence but not high likelihood. This combination implies that the plant is not safe and the regulations are not followed by the company. Therefore the operating license of the plant will be recalled by the government. Scenarios with combination of high probability and high consequence are not expected in the current IGCC plant. In table 5.1 the risk matrix and the examined area can be seen.

Table 5.1: *Risk matrix and area of interest.*

		Consequence	
		Low	High
Probability	High	Daily	Unacceptable
	Low	Negligible	Focal area

The scenario should also be credible (or reasonably believable) to the operators. It should be the worst credible scenario. Worst credible is the accident with high consequences but is also plausible or reasonably believable to the operators that can actually happen (Kim et al, 2003, Kahn &Abbasi, 1998). From the previous criterion it was stated that the scenario to be selected should have high consequences. The worst credible scenario has high consequences but it is also plausible to the operators. Otherwise the operators could not be interested in the scenario and the SBT could not meet the desired training objectives. A criterion that could be used is the worst possible accident. Worst possible is the accident which has high consequence and is physically possible regardless of likelihood (Kim et al, 2003, Kahn &Abbasi, 1998). However, this will not be used as a criterion because the scenario has to be plausible or reasonably believable to the operators. For example, it is possible that an airplane can crash into a unit. This scenario is worst possible; however, no operator is going to believe it, since they cannot imagine this event can happen.

Furthermore, the selected scenario should be relevant to Nuon. This research is about the implementation of the SBT method to Nuon. Thus, the selected scenarios should be of interest to the management of Nuon. It can be understood that the management could have different perception of a relevant scenario for training. It is possible that the management of Nuon will find that some of the pre-selected scenarios are not relevant for training. The interests and the objectives of the researcher should be at the same line with that of Nuon. Otherwise the scenarios are not going to be used for operator training.

5.3.2. Method

The method that will be used to select relevant scenarios will be the Elimination By Aspects (EBA) decision-modeling method. The EBA heuristic supposes that the decision-maker follows a process of sequential choice and eliminates at each stage all the options not having an expected given attribute, until only one option remains (Laurent, 2006). The EBA fits in the context of the thesis since the scenarios to be selected meet the three criteria.

5.3.3. Results

In total approximately 15 ARIE and 50 HAZOP scenarios were identified. With regard to the first criterion, 2 ARIE scenarios and approximately 25 HAZOP scenarios passed the first criterion. Also this number of scenarios is credible to the operators. Therefore they passed the second criterion.

It could be inferred that the list of scenarios is extensive. It could be wise to refine them. Two steps can be made. First, the scenarios with high consequence regarding only to people and not to availability should be selected. There are scenarios that have high consequences regarding plant availability but very low regarding people. However, the focus is on people. With this step the number of scenarios (regarding ARIE and HAZOP) reduced to 17.

The next step is to try to infer if in the new list there are some combine scenarios. Combined scenarios are the scenarios where multiple different components can fail due to common cause. After this step the number of accidents reduced to 7 (5 HAZOP and 2 ARIE). The list of these scenarios can be seen in table B.2 in the Appendix B.

According to the third criterion (relevance of Nuon management) four scenarios were eliminated. The three selected scenarios are:

1. The pipe that transports sour gas (mixture of hydrogen sulfide and carbon dioxide) between the sulfinol regenerator and the Claus unit will break due to corrosion during normal operation. The sour gas which is going to be released is prone to cause fatalities and plant destruction if it ignites. This scenario was identified from ARIE.
2. Too high pressure in the acid gas removal part of the unit. It is caused during shutdown or startup of the unit when the valve in the inlet pipe which transports syngas to the unit is closed, the valve of outlet pipe of the unit (inlet pipe of syngas saturation unit) is closed and high pressure nitrogen is transferred to the system. The continuous increasing high pressure will cause the rapture of eight vessels which are included in the system (e.g. heat exchangers, sulfinol absorber). Nitrogen will be released which could cause suffocation. This scenario was identified by HAZOP.
3. Too high pressure of the sour gas recirculation vessel which is cased by a closed valve. During normal operation, sour gas exits the sour gas recirculation vessel from its top and then goes to the Claus unit. However, one of two or both valves which are located in the recirculation vessel outlet pipe could close suddenly. The increase of the pressure will cause the recirculation vessel to rapture. Sour gas is going to be released, which is prone to cause fatalities and plant destruction if it ignites. This scenario was identified by HAZOP.

These three scenarios are relevant for SBT. However, they are not yet suitable for operator training since the event sequence and the human intervention to prevent the steps from evolving to the accident are not clear. In that sense the selected scenarios are going to be modelled further to become suitable for SBT.

5.4. Selecting the demonstration scenario

The SBT will be demonstrated by teaching the employees of Nuon one scenario. Consequently two of the selected scenarios should be excluded. The scenario that will be used for demonstrating the technique should: include the role of the human operator and lead to outcomes (e.g. rapture) which in turn can cause events (e.g. fire) with catastrophic consequences (e.g. plant destruction).

The ARIE scenario is not going to be the demonstration scenario because the role of the human operator in preventing the gas release is limited. He does not have many options (e.g. only to do some checks in the field). The second scenario is excluded since its outcomes will not cause other events. It is realized that nitrogen can cause suffocation but it will not lead to further plant destruction.

The third scenario is going to be used for demonstrating the SBT. The human operator has options in preventing the evolvement of the accident. Finally, the rupture of the vessel will lead to sour gas release, blasts and fragmentation effects. It is also possible to cause jet fire, flash fire and vapor cloud explosion.

5.5. Generalization of unit and scenario selection approach

In order for the SBT to be conducted to an IGCC plant, a selection of a unit in which the SBT will take place should be the first step. It has to be stipulated that the SBT should be conducted to all units of the plant because every unit is crucial to the plant operation. The unit selection will define the sequence with which the SBT will be conducted to all the plant. The selection of scenarios relevant for training will follow. Risk analysis studies could be conducted to all the parts of the plant. This will give the opportunity to have a variety of scenarios to select. Finally, scenarios with high consequences only in terms of availability could also be an option for operator training.

Chapter 6: Scenario modeling and phenomena explanation

Introduction to the chapter
The aim of this chapter is to model the selected scenarios in order to become suitable for operator training. The scenarios will be modeled with the Event-Tree Analysis method. In addition, the phenomena that are associated with the outcomes are going to be described. Afterwards, the consequences that are associated with the outcomes of the scenarios are going to be estimated. Only the consequences of the demonstration scenario are going to be estimated. Finally, the implications of these steps will be presented.

6.1. Scenario modeling

As explained earlier, the three selected scenarios are not yet suitable for operator training because of two reasons. First of all, the sequence of the events is not shown. Secondly, the human intervention possibility is not available in these accidents. Therefore, in order for the scenarios to be suitable for SBT they should be modeled in a way that they include these two characteristics.

In order for a scenario to be used for operator training, it must have a clear sequence of events. Looking at the definition of the accident scenario, it is an event or series of events that may lead to an accident. Thus, in a scenario the sequence of the events should be clear. A clear sequence implies an ability to focus on each step and therefore concentrate on training the operators to enable them to prevent each step from evolving to an accident.

In the SBT the human intervention is essential. In some steps of an accident scenario the operator has a critical function in order to prevent the continuation of the sequence. For example, when the pressure is too high an operator can open a valve to the flare and therefore depressurize the system to a safe mode. In every scenario that will be used for SBT, all the possible human interventions in all the possible steps of the scenario should be included and distinguished.

6.1.1. Selection of the modeling technique

Since the selected scenarios are not suitable for reasons that were explained before, they must be modeled with a legitimate method in order to become appropriate for SBT. The method to be selected should fulfill the following requirements.

1. Risk quantification.
2. Event sequences and timing clearly shown.
3. Ability to include a wide spectrum of events.

The method to be used should be a quantitative since the quantification of risk is of high interest. Note that the risk of the scenarios is not going to be estimated in this project. The results of the project will be an input to the TU/e research. The focus now is which quantitative method to select.

In addition, scenarios are about sequence of events and actions where timing plays significant role. The method to be selected should show clearly these features. Based on the sequence and the timing, the operators are going to be trained on how the scenario will evolve to an accident and how to make decisions in order to prevent each step from evolving to accident.

Before explaining the third requirement, a clarification about accident scenario will be given. Accident scenario was defined as a series of events that may cause an accident. The HAZOP and the ARIE studies provide scenarios at a very high astraction level. For example a blocked valve in a vessel when the pressure relief valve fails will lead to rupture of the vessel. However, it could be commented that the initiating event (blocked valve) can have a wide spectrum of outcomes. For example an outcome can be rupture but also routing the stream to the flare. It is possible that the same outcome can occur but with different sequence. A rupture could occur if the valve is blocked, the cascade system does not blow off the stream to the flare and the pressure relief valve does not open. Another possibility of vessel rupture is that the valve gets blocked, the cascade system does not blow off the stream to the flare, the operator cannot open the cascade valve manually and the pressure relief valve does not open. So within one scenario, there can be different sequences of events. A more detailed example can be seen later in this chapter.

It was explained that an initiating event can have a wide spectrum of outcomes ranging from catastrophic to minor. This wide spectrum is required to be shown by the selected method. In that sense it could be possible to explain the operators what action could be taken in order to prevent the catastrophic outcome.

Since risk quantification is required only four methods can be considered: Fault-Tree Analysis (FTA), Event-Tree Analysis (ETA), Markov processes and Monte Carlo simulation (TNO Red Book, 2005).

Fault trees are a valuable aid to risk assessment and the development of protection schemes. This technique is used after the HAZOP study has identified a potentially hazardous event and the team has requested some analysis of the likelihood and the consequences (McDonald, 2004; Lewis, 96). An example of a Fault-Tree can be seen in figure 6.1.

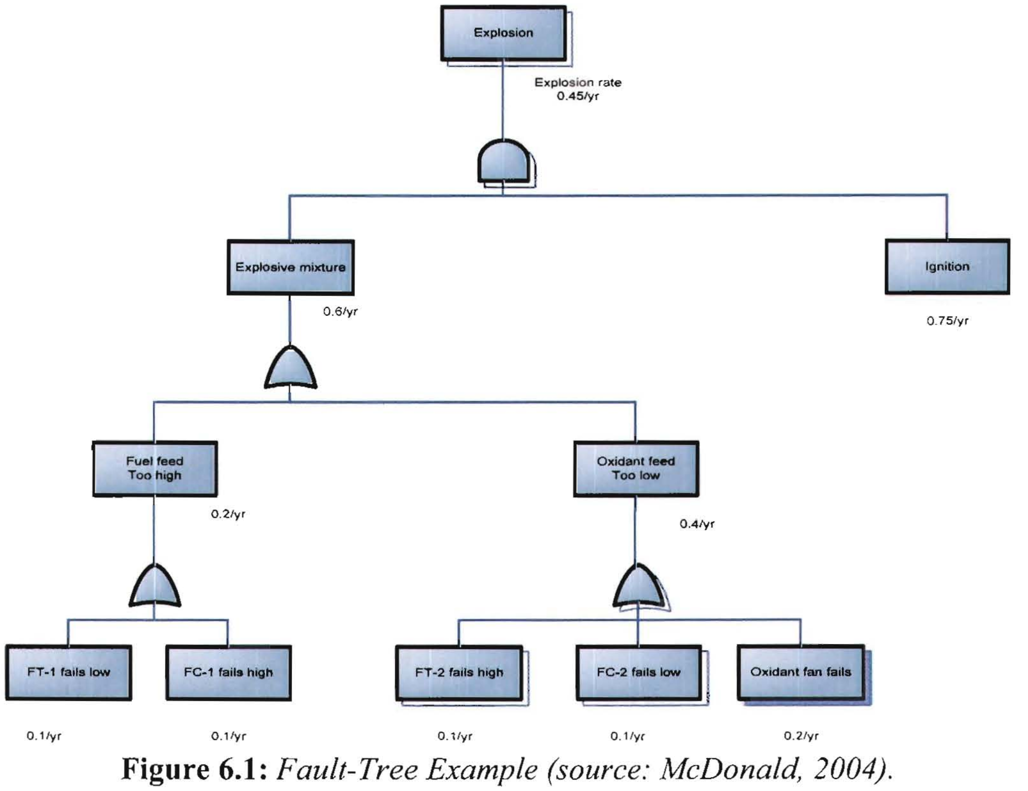

Figure 6.1: *Fault-Tree Example (source: McDonald, 2004).*

Event Tree Analysis is a widely used method which is related to FTA. It takes the initiating event and divides the possible consequences into as many options as may exists and defines the possible splits (McDonald, 2004). It could be easily said that an event tree is a visual representation of all the events which can occur in a system. As the number of events increases, the picture fans out like the branches of a tree (Relex Software webpage, 2007). An example of an Event-Tree can be seen in figure 6.2.

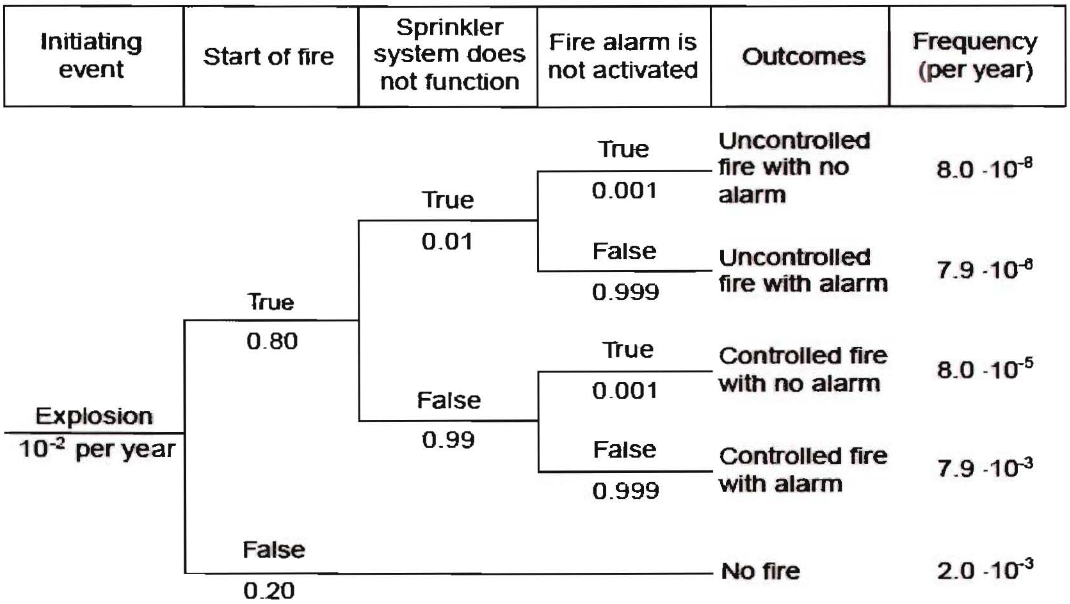

Figure 6.2: *Event-Tree Example (source: Rausand, 2005).*

In the Markov processes a state diagram is being constructed. This state diagram represents the status of the system with respect to failure states. Failure states are represented by one node of the state diagram. The arrows between the nodes represent the repair or failure events. These arrows are weighted with the corresponding failure or repair rates (TNO Red Book, 2005). An example of Markov process can be seen on figure 6.3.

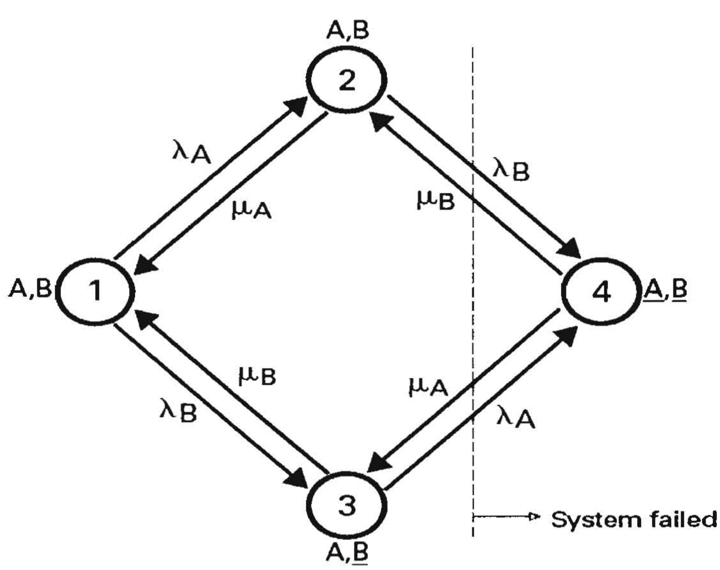

Figure 6.3: *Markov Model Example (source: TNO Red Book, 2005).*

Monte Carlo can be used in problems which cannot be solved by analytical methods and require simulation. Monte Carlo techniques represent the distributions as sequences of discrete random values. A probabilistic model of the system under investigation is built (TNO Red Book, 2005).

With regard to the sequences and timing of the events only ETA could be used. Markov modeling cannot be used because the focus of this research is not to identify the failure and repair states. The subject of this project is not the reliability of the equipment (which is the subject of the Markov modeling). Moreover, Monte Carlo is not going to be used in this project because simulation is not going to be conducted. Finally FTA does not show the sequence and the timing of the events. Event Trees are a suitable means to enhance scenarios. Based on the event sequence the operators can be trained in order to understand what each step means to the accident and also how to act in order to prevent the step from evolving into an accident.

ETA also models the wide spectrum of different outcomes. The consequences may be determined by how the accident progression is affected by subsequent failure or operation of other components (especially safety and protection devices) and by human errors made in response to the initiating event (Lewis, 1996). This fits perfectly with the present project. For example we can have an initiating event (e.g. blocked valve) and depending on the safety measures (e.g. pressure relief valve) and the responses of the human operators (e.g. try to open another valve in the field) a range from a small disturbance of production to a rupture or an explosion of a vessel can occur.

Finally, in an Event-Tree the chain of the events following an accidental event is visualized (Rausand, 2005; Rausand, Høyland, 2004). In that sense it is easier to train the operators to prevent every step of the accident scenarios. Key decisions can be made in order to prevent every step from evolving into accident.

Based on the arguments presented above, it is clear that only ETA fits with the overall requirements to conduct SBT. Therefore, ETA will be used to model the selected scenarios to become suitable for operator training.

In order to perform ETA, 7 steps must be followed (Rausand, 2005; Rausand, Høyland, 2004). These are:

1. Identification and definition of the initial event that may give rise to unwanted consequences. Initiating event can vary from a blocked valve that should normally be open to rupture.
2. Identification of the barriers that are designed to deal with the accidental (initiating) event. This simply means the identification of all the possible safety systems which are designed to prevent the accident from occurring. Possible barriers are blow off valves, pressure relief valves, alarms etc.
3. Construction of the event tree.
4. Description the potential resulting accident sequences. It is the description of the branches of the Event-Tree.
5. Determination of the frequency of the accidental event and the probabilities of the branches in the event tree. This step is useful for understanding "tendency" of the initiating event to occur and to evolve into a certain outcome.
6. Calculation of the probabilities/frequencies for the identified consequences. In that sense the frequency of every outcome could show which is prone to occur and if there is a need for improving the safety status of the plant.

7. Compilation and presentation of the results from the analysis.

These steps are going to be explained thoroughly in the next session by using an example.

6.1.2. Example of ETA modeling

The description of the steps to conduct an ETA was very brief. There is a possibility of confusing the reader. Therefore, a detailed example will be presented. The detailed example is the first scenario that was selected for operator training. It is about sour gas pipe break due to corrosion. The ETA modeling is the same for the syngas pipe break due to corrosion. The steps in detail are:

Step 1: Identification of the initial event

Before explaining the initiating event of this specific accident it has to be stipulated that in literature the initiating event concerns the outcome which was predicted by the risk analysis tool (e.g. HAZOP). Specifically, two types of initiating events exist; (1) leakages, pipe breaks or vessel rupture and (2) transient initiators which can create a need for shut down (e.g. instrumentation air which can cause total failure of the safety systems) (TNO Red Book, 2005).

This research focuses on enabling the operators to make decisions under abnormal conditions. The initiating event will then be the cause (corrosion) of the outcomes (syngas/sour gas leakage) of the selected scenario. All the sequence until the end consequences (e.g. fatalities) of the outcomes identified by the risks analysis tools (HAZOP, ARIE) will be modeled.

In addition, only one initiating event should be modeled with ETA at a time (Rausand, 2005; Rausand, Høyland, 2004). For example, in the Hazop, valve 1and/or valve 2 will fail. It could be said that these are two different ETA since there could be a different sequence. Notwithstanding, it is not possible train the operator basedon two different event trees since there is a high risk of confusing them. Also, it is desired to help the operators become aware of the different possible causes that will trigger the accidental event. Therefore, an initiating event can be: valve 1 and/or valve two are closed.

With regard to the first scenario (pipe break and sour gas/syngas leakage due to corrosion), the initiating event is the corrosion.

Step 2: Identification of the barriers that can deal with the accidental event

The barriers that can deal with the initiating event are divided in technical and human interventions. Technical barriers are: gas alarm system, process indicator alarm (e.g. when the pipe is leaking the operator can see that the system is depressurizing and thus can do corrective action), manual shutdown system (system which shutdowns the plant), fire alarm. The human interventions are: plant evacuation, manual fire fight.

Step 3: Construction of the Event-Tree

Due to the fact that this section is demonstrating the technique of ETA, the sequence will be presented until the gas leakage. The rest sequence of this scenario plus the other two selected scenarios can be seen in figures B7-B11 in Appendix B. The sample Event-Tree can be seen in figure 6.4.

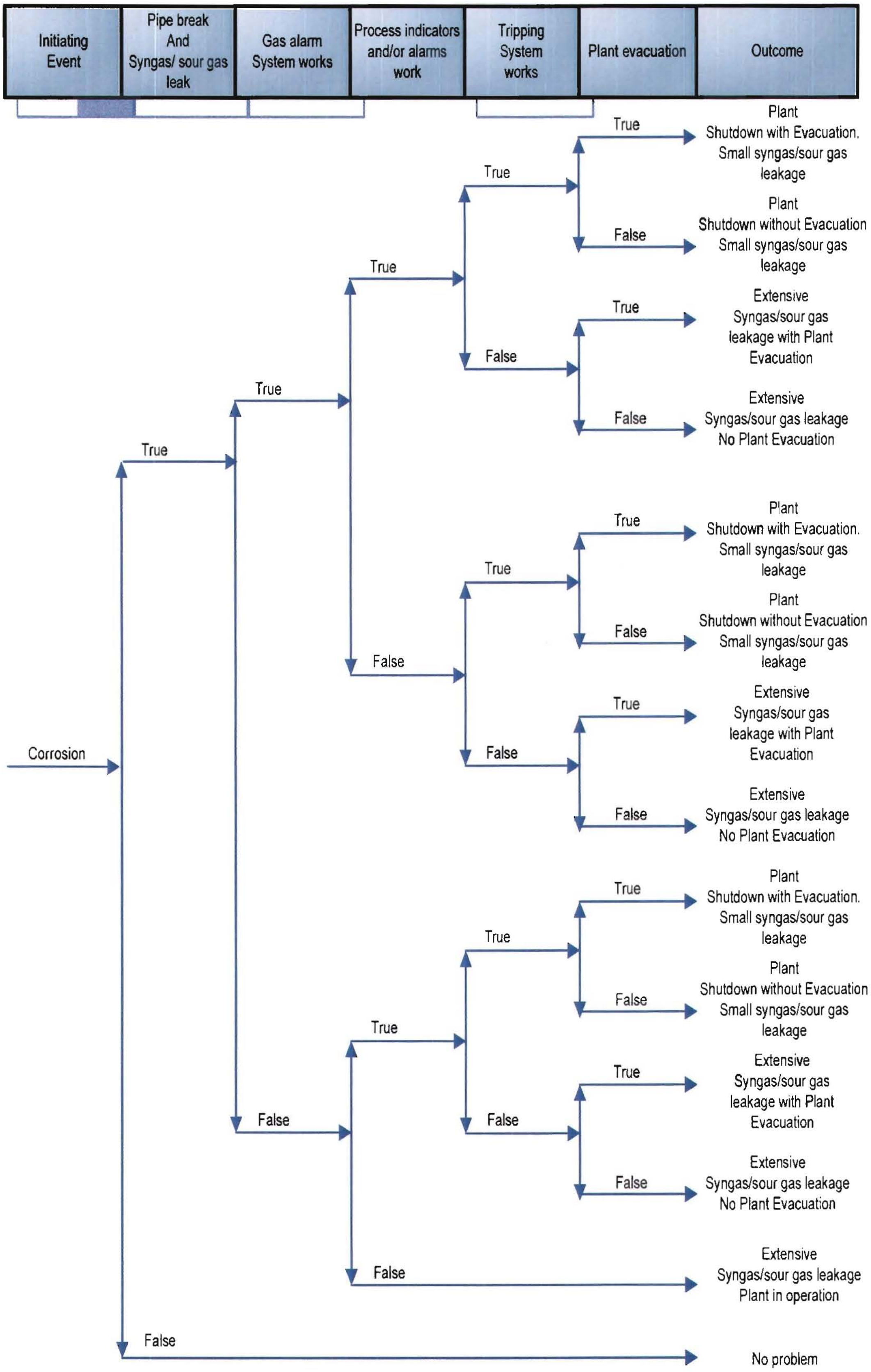

Figure 6.4: *Event-Tree example for the first scenario.*

Looking at the constructed Event-Tree, the clarification about scenario can be seen. In HAZOP or in ARIE the high level of a scenario is presented (e.g. corrosion will lead to gas leakage). In the Event-Tree possible scenarios within a high level scenario can be seen. The possible scenarios are the different paths of the Event-Tree.

Step 4: Description of the potential resulting accident sequences.

Looking at the event-tree, there are numerous of potential resulting accidents sequences. However, it will be too extensive to conduct this step. Besides, not the whole sequence is available in this example. An example of a description could be the following. Corrosion leads to pipe break and gas leakage. If the gas alarm system does not work and the process indicators/alarms do not work as well, an extensive gas leakage will occur with the plan being in operation.

It has to be stipulated that in the training session, the training should be conducted based on a selected scenario (one sequence in the Event-Tree). The trainer could select which potential sequence to select.

Step 5: Determination of the frequency of the accidental event and the probabilities of the branches in the event tree.

This step will explain how frequent is an initiating event and what are the probabilities to have certain paths in the Event-Tree. This step requires specific data (e.g. reliability sheets) and mathematical modeling. The quantification is not the main objective of this project. Therefore this step is not going to be conducted. However, it will be interesting to extend the scenarios in terms of quantification.

Step 6: Calculation of the probabilities/frequencies for the identified consequences.

This step will show how likely a consequence to occur is. It is known for reasons that were explained in chapter five about risk, the likelihood will be very low. It requires specific data (e.g. reliability sheets) and mathematical modeling as well. The quantification is not the main objective of this project. Therefore this step is not going to be conducted. However, it will be interesting to extend the scenarios in terms of quantification.

Step 7: Compilation and presentation of the results from the analysis.

This step is too extensive for the purpose of the SBT. Therefore, it will be omitted.

The event-trees of the three selected scenarios can be seen in the Appendix B.

6.2. Phenomena explanation and consequences estimation

As explained earlier, the scenarios are going to be modeled in two steps. The first step is to model the sequence of the events that will result in the accident and to include the human aspect in this sequence. Next goes the description of the phenomena that are associated with the outcomes of the ETA (e.g. description of the gas release mechanism when a vessel ruptures). In addition, the consequences of the described outcomes are going to be estimated with simplified models. The phenomena explanation and consequences evaluation are going to be conducted only for the demonstration scenario.

The purpose of explaining the phenomena and estimating the consequences is twofold. First, the credibility of the scenario to the operators will increase. As it will be seen in the next chapter, in the discussion session the scenario is going to be more plausible to the operators when the phenomena are going to be explained and some draft estimations are presented. It will also serve as an argument to the plant management to implement SBT in order to avoid the estimated outcomes and their consequences.

Looking at the Event-Trees of the demonstration scenario it can be seen that the most catastrophic event is the collapse of the sour gas recirculation vessel with an outbreak of sour gas. The gas that is going to be released is so-called sour gas. In the context of Nuon, sour gas is a mixture of hydrogen sulfide and carbon dioxide with a mixture ratio of 45%-55% approximately. The maximum theoretical percentage of hydrogen sulfide is 50%. This percentage is going to be used for the calculations since the target is to train the operators with regard to the worst credible scenario. Carbon dioxide is not flammable but it is a gas that causes the so-called greenhouse effect. The accident is assumed to occur at a temperature of 40^0C and a pressure of 8 bar.

This vessel rupture can trigger a number of effects which can be categorized as primary and secondary. The primary effects concern the release of the vessel contents, fragmentation of the vessel coupled with missile effects and finally a blast due to the expansion of the pressurized contents. The secondary effects are jet fire, toxic cloud dispersion, flash fire and vapor cloud explosions (TNO Yellow Book, 2005).

When an amount of sour gas is released to the open air, a jet fire will occur if an immediate ignition source is present. Otherwise, there is a possibility that the released gas will be ignited with delay. If this happens, then the accumulated gas cloud is going to explode in case of place confinement or turbulence. This is the so-called vapor cloud explosion (VCE). In case of neither confinement nor turbulence, a flash fire will occur.

The fragments of the vessel have the potential to become missiles with high velocities. These missiles will be propelled over a long distance and will heat everything they find on their way. The vessel's contents internal energy is going to be partly converted into the kinetic energy of the fragments (TNO Yellow Book, 2005).

A blast, that is the third primary effect, will occur when the other part of the internal energy will be converted into expansion of the contents of the vessel. This form of mechanical energy will be transmitted to the surrounding atmosphere (TNO Yellow Book, 2005).

All of the aforementioned phenomena (primary and secondary) are going to be discussed in the next sessions. The consequences are going to be estimated with the use of specific methods. This detail is going to be discussed further on.

6.2.1. Primary effects

The primary effects are the effects that originate from the source itself (TNO Yellow Book, 2005). These are: dense gas release, fragments of the vessel and blast wave. These phenomena are going to be discussed in the following paragraphs. Before explaining the phenomena and their consequences it should be made clear that for all models it is assumed that Rupture occurs at pressure of 8 bar and the temperature of 40°C.

Dense gas release

Brief explanation

The too high pressure of the vessel will lead to its rupture. The sour gas will flow out of the ruptured vessel. The outflow of the gas out of the vessel will cause the rapid depressurization and expansion of the remaining gas in the vessel (TNO Yellow Book, 2005; Haque et al, 1990).

Model

The model that will be used is a simplified model for gas outflow through holes in a vessel. With this model the gas outflow rate will be calculated (TNO Yellow Book, 2005). As it will be shown in next sections, the calculation rate will be the input for jet fire calculations. In addition, the time that all amount of gas will be discharged was calculated. The exact model can be seen in Appendix C2.

Assumptions

The calculations were conducted using the following assumptions:

1. Sour gas consists of 50% hydrogen sulphide and 50% carbon dioxide.
2. Two cases of rupture:
    a. Sour gas outbreaks from the inner diameter of the inlet pipe.
    b. Total vessel collapse. Sour gas outbreaks from the inner diameter of the vessel.

Results

With the use of the aforementioned model the calculations were conducted. The data and the results for both cases can be seen in table D1 in Appendix D. The results are not going to be presented because of reasons of confidentiality.

In both cases the gas will be released rapidly. This stresses the need to train the operators to make decisions under abnormal conditions to prevent this event. The used model was not fully suitable for the present case because gas outflows either from the inner pipe diameter or by the diameter of the vessel and not from a hole. The results of case one seem realistic. A better model that could be used is the outflow from pipelines of vessels which is described in the TNO Yellow Book. This model is based on the gas outflow model through holes but takes into account the pressure at the downstream of the pipe. The results of case two are unrealistic. This happens because the used model is not able to model a rupture of such magnitude. However, no model that estimates the outflow for a total rupture was found.

Blast

Brief explanation

As explained in an earlier section of this chapter, a blast will be a result of the transformation of a part of the internal energy of the vessel into kinetic. This kinetic energy will be transmitted to the atmosphere as a blast over a certain distance. This blast has a potential of causing further destruction (TNO Yellow Book, 2005). A blast is defined as "a rapidly propagating pressure or shock wave in atmosphere with high pressure, high density and high velocity" (TNO Yellow Book, 2005).

Model

For the present project the Baker's method is going to be used. This method is used for the calculation of the blast effects due to overpressure in a vessel. The main advantage of this method is that it distinguishes between close and far ranges from vessel bursts with ideal gas (TNO Yellow Book, 2005). The used model can be seen in Appendix C2.

Assumptions

The calculations were conducted using the following assumptions:

1. 60% of the vessel is filled with sour gas. The remaining 40% is dirty water.
2. The vessel ruptures totally and only due to the sour gas.
3. Sour gas is assumed as ideal gas.
4. The blast effects are calculated at a distance of 10m because at this distance a major component of the syngas treatment unit, the sulfinol regenerator, is located.

Results

With the use of the aforementioned model the calculations were conducted. The data and all the results of the model can be seen in table D2 in Appendix D. The results are not going to be presented because of reasons of confidentiality. A domino sequence is possible to follow with a potential to destroy a big part of the plant.

Fragmentation effects

Brief explanation

When a vessel ruptures, a part of its internal energy is converted into kinetic energy of the fragments. Due to the fact that the kinetic energy of the fragments is relatively high, the fragments can become missiles that can hit anything on their way (TNO Yellow Book, 2005).

Model

The model that will be used for the estimation of the fragmentation effects is a simplified algorithm which can be found on the TNO Yellow Book. This model is a combination of the so-called kinetic energy method and the algorithm of Moore (TNO Yellow Book, 2005). The model to be used can be seen in Appendix C3.

Assumptions

The calculations were conducted using the following assumptions:

1. 60% of the vessel is filled with sour gas. The remaining 40% is dirty water.
2. Half of the vessel will be propelled over the plant.
3. Fragmentation of the vessel is caused only by the sour gas.

Results

With the use of the aforementioned model the calculations were conducted. The data and all the results of the model can be seen in table D3 in Appendix D. The results are not going to be presented because of reasons of confidentiality. It has to be stipulated that the used model is a generic model suitable for very simple estimations and it does not have a high level of accuracy. Therefore, it is possible that the results are not fully realistic.

6.2.2. Secondary effects

The secondary effects are the effects that occur in the second instance and/or that originate from other sources. Examples are jet fire, toxic cloud dispersion, flash fire and vapor cloud explosion (TNO Yellow Book, 2005). These phenomena will be explained in the following subsections.

Jet fire

Brief explanation

Fire is "a process of combustion characterized by heat or smoke or flame or any combination of these" (TNO Yellow Book, 2005). Fire can cause fatalities in the extent of its flame. In addition, fire causes thermal radiation the magnitude of each can cause problems to the plant from small rise of temperature to equipment collapse. Jet fire (or jet flame) is defined as "the combustion of material emerging with significant momentum from an orifice (hole)" (TNO Yellow Book, 2005). Jet fire will occur if the released gas "finds" an immediate ignition source. Possible ignition sources are static electricity and sparks (Biennal Report on Hydrogen Safety, 2007). A jet fire can be seen in figure 6.5.

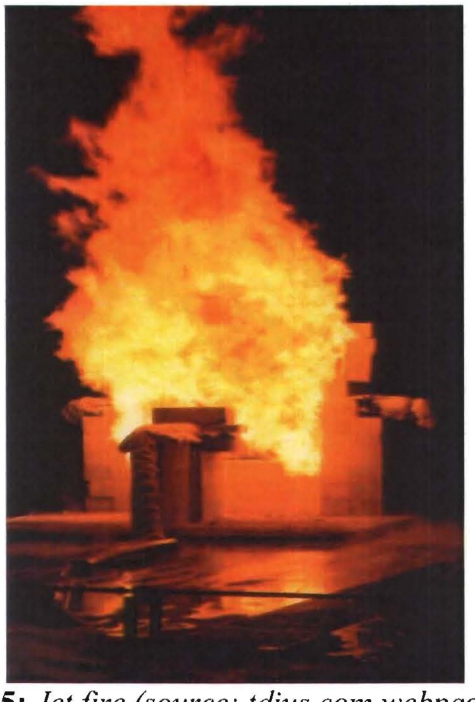

Figure 6.5: *Jet fire (source: tdius.com webpage, 2008).*

Model

The model that is going to be used to calculate the radiation of fire is the so-called Chamberlain model which has been used for the calculation of the flame speed and the radiation field of the flare stacks (TNO Yellow Book, 2005; Chamberlain, 1987). The used model can be seen in Appendix C5.

Assumptions

The calculations were conducted using the following assumptions:

1. Sour gas consists of 50% hydrogen sulphide and 50% carbon dioxide.
2. Two cases of rupture:
    a. Sour gas outbreaks from the inner diameter of the inlet pipe.
    b. Total vessel collapse. Sour gas outbreaks from the inner diameter of the vessel.
3. The wind will blow with velocity of 4.5m/s.
4. The angle between hole axis and the horizontal in the direction of the wind (Θ_{jv}) is 85^o with the assumption that the wind blows vertically to the pipe and the vessel.
5. View factor is equal to unity. This means that the receiver "sees" only the flame (Salader et al, 2002).

Results

With the use of the aforementioned model the calculations were conducted. The data and all the results of the model can be seen in table D5 in Appendix D. The results are not going to be presented because of reasons of confidentiality.

It could be concluded that the results (especially for the second case) are not the most accurate. This could be understandable since the implemented model is used for calculation of jet fire in flares. Other simplified models are not mentioned in literature. Note that this section is for draft estimation of consequences in order to make the scenario credible to the operators and to stress the need for SBT to prevent the abovementioned phenomena. It is possible that the jet fire that will occur will not have the calculated features but will be similar to the one that is shown on figure 6.5. In order to a more detailed and more accurate analysis to be conducted, a Computational Fluid Dynamics model could be applied.

Vapor cloud dispersion

Brief explanation

If the released sour gas immediately ignites after release, a jet fire will follow. If not, the sour gas will be dispersed in the form of a vapor cloud. Dispersion is defined as "mixing and spreading of gases in air, which causes clouds to grow" (TNO Yellow Book, 2005). The gas cloud is generated in the atmosphere due to forces resulting from the internal energy of the gas and/or the energy inside the system, from which the gas has escaped. When there is no early ignition, the vapor cloud shape will be further determined by the density differences, atmospheric conditions and topography. Especially the wind conditions influence the gas cloud by changing its height (Biennal Report on Hydrogen Safety, 2007).

Model

The model that will be used will calculate the distance that the gas will spread, the radii of the formed cloud and the time to form the cloud. The model to be used is the Britter and McQuaid model and it will be used for instantaneous release. This model is suitable for making indications (TNO Yellow Book, 2005). The model can be seen in Appendix C4.

Assumptions

The calculations were conducted using the following assumptions:

1. Sour gas consists of 50% hydrogen sulphide and 50% carbon dioxide.
2. Two cases of rupture:
   a. Sour gas outbreaks from the inner diameter of the inlet pipe.
   b. Total vessel collapse. Sour gas outbreaks from the inner diameter of the vessel.
3. The release of the sour gas is instantaneous.
4. The ratio of and maximum concentration of sour gas in the air to sour gas concentration at initial release is 0.001 (c_{max}/c_0=0.001). The calculated spread will be the maximum and thus the results will comply with the worst credible scenario examination.

Results

With the use of the aforementioned model the calculations were conducted. The data and all the results of the model can be seen in table D4 in Appendix D. The results are not going to be presented because of reasons of confidentiality.

It can be concluded that for both cases the results remain the same. A possible explanation is that the exit hole does not play sufficient role to the dispersion of the cloud. In literature it is stated that the cloud dispersion depends on the cloud density, topography and atmospheric conditions. In that sense, the calculations are in the same line with the literature. Note that the model is used only for indication. For detailed modeling, a Computational Fluid Dynamics (CFD) model could be used (e.g. SLAB) (TNO Yellow Book, 2005).

The model indicates that the toxic cloud can travel a relatively long distance in possible units of the plant. At this distance the cloud can have a radius of approximately 100m. People inside this radius will perish due to poisoning. It is possible that the cloud "travels" to the air separation unit (since it is relatively close to the syngas treatment unit. An ignition of that cloud can lead to flash fire or vapor cloud explosion; a rupture in a vessel in one unit could cause a destruction of another unit of the plant. Domino effect is also possible.

Flash fire

Brief description

Flash fire is defined as "the combustion of flammable vapor and air mixture in which flamme passes through that mixture at less than sonic velocity, such that negligible damaging overpressure is generated" (TNO Yellow Book, 2005). A flash fire is going to occur in the case of a delayed ignition only when there is not a space confinement (that is a very "crowded" space configuration). In case of space confinement, a vapor cloud explosion will occur. An example of a flash fire can be seen in figure 6.6.

Figure 6.6: Example of a flash fire (source: nanscoinc.com webpage, 2008).

Model

The model that is going to be used is that of Raj and Emmons (Lees, 1995). With this simplified model, the flame height and the width will be calculated. The model can be seen in Appendix C6.

Assumptions

The calculations were conducted using the following assumptions:

1. Sour gas consists of 50% hydrogen sulphide and 50% carbon dioxide.
2. Flame width is half the flame height.

Results

The flash fire height and width was calculated using the results of the toxic cloud dispersion model. Specifically speaking, the input from the toxic cloud dispersion model is the cloud depth. For both cases the data are the same. Therefore no differentiation is needed. With the use of the aforementioned model the calculations were conducted. The data and all the results of the model can be seen in table D6 in Appendix D. The results are not going to be presented because of reasons of confidentiality.

Note that these results are simplified and that the used model is based on pool fires. But pool fires are "the combustion of material evaporating from a layer of liquid at the base of the fire" (TNO Yellow Book, 2005). As explained in the jet fire, the purpose is not the full modeling of the consequences but only indications. No matter what exactly the height and the width of the flame will be, it will be similar to the one that is shown on figure 6.6.

Vapor cloud explosion

Brief explanation

A vapor cloud explosion (VCE) is defined as an explosion which occurs outdoors and produces overpressure. The initiation source is an unplanned release of a large quantity of high pressure gas or a flammable vaporizing liquid from a process vessel, storage tank, transportation vessel or pipeline (FM Global, 2005). In order for a VCE to occur several factors must be present. First of all, the released material should be flammable and held or processed on high temperature and/or pressure, conditions that are highly suitable to produce a VCE. Furthermore, prior to the ignition, a substantial amount of cloud. Moreover, in order to overpressure to be caused, a sufficient amount of the cloud must be within the flammable range of the material. The percent of the vapor cloud depends on factors like the amount and the type of the released material, the release pressure, the direction of release and the size of the release opening etc (FM Global, 2005). Finally, the gas to be released, or the liquid that will vaporize after its release must be heavier that the air in order to accumulate in the ground, otherwise it will be diluted to the open air (Wilcox, 2006; Baker et al 1983). An example of a VCE can be seen in figure 6.7.

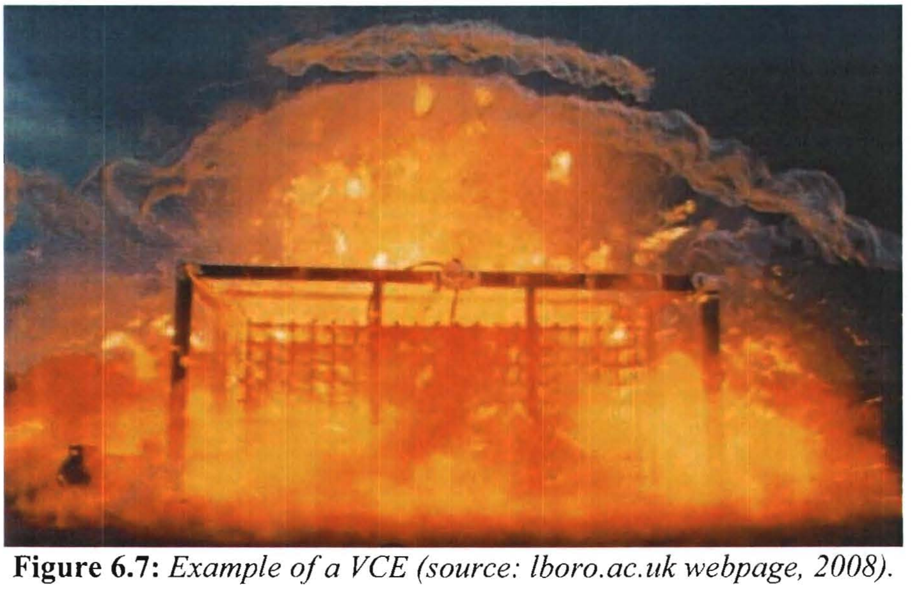

Figure 6.7: *Example of a VCE (source: lboro.ac.uk webpage, 2008).*

Model

The model that is going to be used is the ideal blast wave (TNT equivalency). It is suitable for approximate evaluation of property damage (FM Global, 2005). This fits with the purpose of the section. The model can be seen in Appendix C7.

Assumptions

The calculations were conducted using the following assumptions:

1. Sour gas consists of 50% hydrogen sulphide and 50% carbon dioxide.
2. Only hydrogen sulphide will be taken into consideration for the calculation of the effects of the VCE. Carbon dioxide is incombustible.
3. Hemispherical surface explosion at 1 bar.

Results

With the use of the aforementioned model the calculations were conducted. The data and all the results of the model can be seen in table D7 in Appendix D. The results are not going to be presented because of reasons of confidentiality. The explosion will destruct the surrounding units of the plant and it is potential to cause a domino sequence in the plant.

6.3. Implications

An identified scenario is not yet suitable for SBT because the time and the sequence of events is not show and the human intervention in the prevention of the accidents is not clear. Therefore, ETA has to be applied. The constructed Event-Tree has now multiple possible scenarios (different sequences in the tree). The trainer should select which has to be used for SBT. The ETA has to be followed by a draft estimation of the consequences of possible outcomes of the Event-Tree. In that sense, the scenario will become more credible to the operators and the plant management will realize that SBT could be implemented to enable the operators make decisions under abnormal conditions in order to avoid the estimated outcomes and their consequences. The calculations of the consequences of the demonstration scenario showed that the units of an IGCC plant are "integrated" in terms of accidental consequences. A vessel rupture is potential to cause a complete destruction of the IGCC power plant. The calculation of the consequences of the scenario outcomes is the last step of the adaptation of SBT to the context of an IGCC plant. Now the scenario has to be used to train the plant operators; implementation of the SBT.

Chapter 7: Scenario-Based Training implementation

Introduction to the chapter

In chapter six the selected scenario for SBT demonstartion was modeled in terms of event tree and its consequences were estimated. The present chapter focuses on the implementation of the SBT; what are the steps that have to be followed and how these steps will be followed. The implementation framework will be tested in order to assess possible deficiencies and possibilities for improvement. Based on the results of the testing, recommendations for systematic SBT conduction within the context of the IGCC plant will be made.

7.1. Implementation framework

Identification, selection and modeling of the scenarios that are appropriate for operator training were conducted. As it can be seen in chapter three (methodology), the focus will be on how the selected training method will be implemented in NUON Power Buggenum IGCC plant.

In chapter four it was explained that the objectives of SBT mentioned in literature are based on a need of new skills development, a need for capabilities improvement and the introduction of unfamiliar equipment (Strally, 2005). A training method is conducted. The effectiveness of this method is evaluated by measuring the performance of the trainee before and after the training session using pre-test and post-tests respectively.

However, the training objectives within an IGCC plant differ from the aforementioned ones. The objective is not to teach the operators how the plant works; they know already. As it was shown in chapter four, the main SBT objectives in the context of an IGCC plant are three; decision-making under abnormal conditions, process insight and to be close to reality. Taking these objectives into consideration, the pre-test will be replaced by introduction and the post-test by training evaluation.

The first step is the introduction. In literature, the effectiveness of SBT is measured by assessing the knowledge and the response of the trainees. The objective of the SBT is not to make the operators learn something new but to enable them to make decisions under abnormal conditions. Therefore, the assessment of their knowledge and response is not of interest. In addition, operators are very busy with monitoring the plant and they do not have much time to do tests. In this sense the situation in a plant deviates from literature. There is a possibility that they will feel stressed and they will think they are going to be assessed and the outcomes of this assessment will affect their careers. In that sense they could be very hesitant to participate in SBT. Taking these differences into consideration it could be inferred that pre-test evaluation is out of question. An appropriate solution is a small introduction to the get the trainees on board.

The training follows the introduction. The training part of SBT which is mentioned in literature is conducted with the use of simulation. However, in chapter four it was explained that the simulation technology concerning an IGCC plant is immature. The used training method should be group discussion. Specifically, a problem-solving discussion could be used. This form of group discussion attempts to answer a question or to solve a problem. The case is that there is no best answer and the trainer wants to find an acceptable solution. The trainer should define the problem and encourage free and open participation of all participants to the discussion (Stranks, 2007). A group discussion has major advantages. First of all, in a well-planned and skillfully directed discussion, interest level is very high. In addition, due to the fact that the trainees participate actively to the development of the instructions, it is more likely to accept the validity and the importance of the content and therefore become more deeply committed to decisions or solutions. Moreover, the trainer is able to use the trainee's experience, abilities and knowledge to the benefit of everyone in the group (Stranks, 2007). In that sense it fit perfectly with the main objective of the SBT (decision-making under abnormal conditions).

The last part will be the training evaluation. In literature, after the end of the training session, a post-test follows to assess the response and the gained knowledge of the trainees. In that sense the trainees have to fill-in a post-test questionnaire or to do an extra scenario where their response will be assessed. By evaluating the trainees, the effectiveness of the SBT will be measured. However, in the context of an IGCC plant, the level of knowledge that the operators gain will not be assessed. Moreover, the training method will not be evaluated by assessing the operators' response. SBT targets on the stimulation of decision-making under abnormal conditions. By assessing the responses and the decisions of the operators, the level of participation will decrease because it is possible that the operators will get stressed. This will conflict with the SBT target. Thus, a post-test evaluation is not realistic. Training evaluation could be suitable. The evaluation type is twofold. First, the operators-trainees will have to evaluate the SBT from their point of view. The opinion of the operators will be asked concerning the objectives, training implementation, selected scenario and relevance of the training and recommendations for improvements. Secondly, the trainer has to take notes concerning the previous aspects of the training. The two different sides of the training part are going to be considered. Based on the findings, possibilities for improvement could be identified.

The defined framework of implementing the SBT is not yet tested to identify possible deficiencies concerning the structure (introduction, training evaluation) and the content of the steps (e.g. is the way in which the training evaluation is valid?). The SBT can be tested by implementation to train the trainer of Nuon Power Buggenum (trainer's SBT). This could be a pilot test. Not only will possible deficiencies and possibilities for improvement be identified, but also the trainer will be clarified how SBT should be implemented (train the trainer and have him train the operators). The trainer will be exposed to the same implementation steps that will be used for the operators.

Depending on the results there are numerous possibilities of proceeding. If the results of the testing of the SBT concerning the structure and the content of the steps show that there is no problem or there are some minor details that should be fixed, then the SBT will be conducted to train the operators of the plant (operators' SBT). In case of major necessary changes (e.g. the introduction should be excluded or the group discussion is not successful), the trainer's training should be conducted again (having remedied the deficiencies before conduction). In this way the implementation method that will be used to train the operators could be ensured that it does not have severe deficiencies.

With regard to the operators' SBT, it is the actual implementation of the SBT. The implementation of the SBT to the plant ooperators will imply three possibilities. First, it is possible that after an operator SBT session, a deficiency of the trainer's SBT is going to be identified (for example it could be possible that the trainer misunderstood a part of the SBT). Then, actions have to be made in order to remedy the problem. These actions imply that the trainer's SBT should be conducted again. A second possibility is that SBT is implemented successfully. In this case, the operator SBT should be repeated with another scenario. The third option is that all of the selected scenarios are taught to the operators. Then the adaptation stage should start (unit selection and scenario selection, scenario modeling to be suitable for operator training). Since the implementation framework is being tested a number of times, the trainer's SBT can be skipped and the operator SBT can be conducted again. It has to be stipulated that SBT is not only once. The first test is the trainer's training. As it was shown previously it is tested upon conduction. The abovementioned possibilities can be seen in figure 7.1.

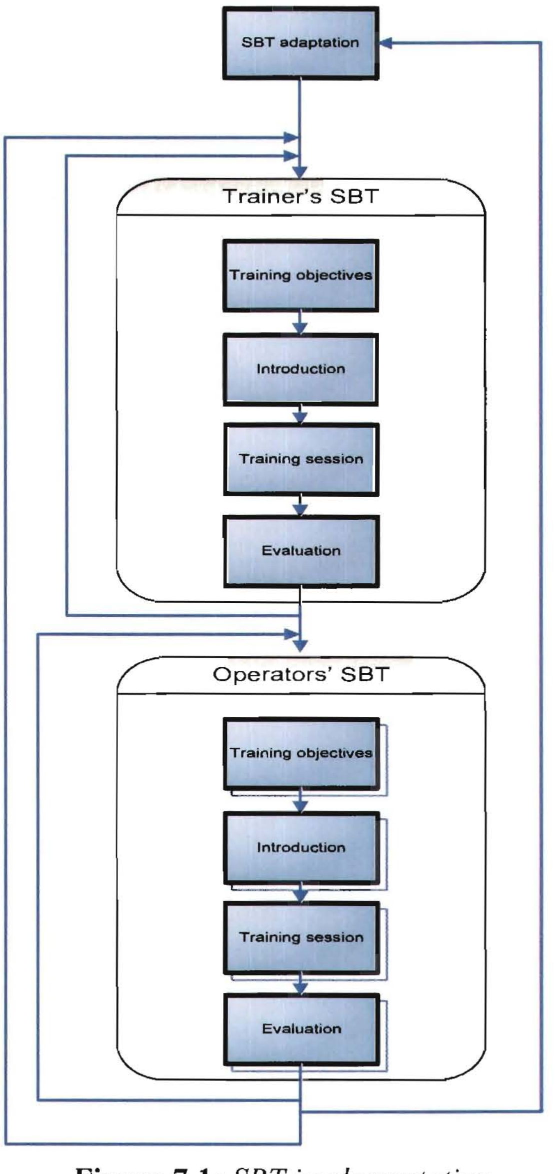

Figure 7.1: *SBT implementation.*

7.2. Trainer's SBT

In section 7.1 it was argued that the SBT should be implemented in three steps: introduction, training and evaluation. Due to the fact that it is not certain that this implementation framework is suitable, it should be tested. An option of testing is to conduct SBT to train the trainer of the plant.

Besides the fact that the framework will be tested, the training of the trainer will ensure that the responsible person for training will fully understand the SBT framework. In other words, train the trainer and have him train the operators. Otherwise the training to be conducted for the operators will be based on a wrong perception and thus it will not have the desired outcomes.

In this section, the exact content of the implementation steps will be proposed. Based on the conduction of the trainer's SBT, changes will or will not be made (figure 7.1). The objectives will remain the same.

7.2.1. Introduction

A brief introduction will be conducted at the start of the actual training session; in the group discussion. This means that in the part of the explanation of the normal operation mode the trainer should ask about how the parts of the examined process work. In that sense the level of understanding of the process will be realized without offending the operators. In addition, the operators are going to get on board and become familiar with what will follow next.

7.2.2. Training

There are three issues that have to be considered in order to the training session to be successfully conducted. First of all, the number of participants should be determined. Then the material that the "trainees" have to read should be prepared. Last but not least, the structure if the group discussion should be determined.

Participants

With regard to the trainer's SBT, the composition of the participants will be the following; the trainer and the engineers of the syngas treatment unit and the maintenance and a senior operator. The syngas treatment and maintenance engineers could help the validation of the selected scenario in terms of credibility. Also, they could help to examine how the components (e.g. valves) can fail. Finally, the chief operator will help the conversation evolve.

Reading material

According to literature before the training the trainees should read material in order to familiarize with the situation that they are going to be trained in. Because of the different objective of this project which is not about aquiring new knowledge but on different use of existing knowledge, litearture for familiarisation is not required. Thus it is not recommended to distribute reading material at any part of the training.

Group discussion

The group discussion is going to be accomplished by the combination of an audio/visual presentation and with interaction with the audience in a way that will be explained later in this section. A presentation is an effective and also a fast method of getting things done through or in conjunction with other people. A presentation can be successful only if there if it is properly planned with defined objectives and a structure (Stranks, 2007).

For the presentation, a stepwise approach is going to be used. First, a stepwise approach offers the opportunity to familiarize with the components of the selected scenario. Secondly, it enhances the examination of the components. In addition, we can observe the possible interactions of the examined components. Furthermore, the potential failure modes of the examined components are going to be identified. Next is the decision-making under abnormal conditions which is of course the ultimate goal of the training session. Last but not least is the consequence presentation which will give an extra incentive to the trainees that a shutdown is not the best action but will at least prevent the presented consequences.

Specifically speaking, the steps to be followed in order to have a presentation for SBT are the following:

Step 1: State the objectives of the training. In other words explain why the SBT session is being conducted.

Step 2: Present the normal operation mode. It is the background information. This step will enable the trainees to become familiarized with the examined part and also to trigger their thoughts of what is going to follow next. This step is going to be executed both verbally and visually. By saying verbally, it is meant that the presenter is asking questions in order to get consensus on how the unit works and simultaneously he will show the parts in the P&IDs that are going to be handed in the trainees. In addition, for the better understanding, the various components (such as valves, pipelines, vessels, controllers etc.) are going to be presented in terms of pictures. For example, live screens from the process control systems (figure 7.2) can be presented.

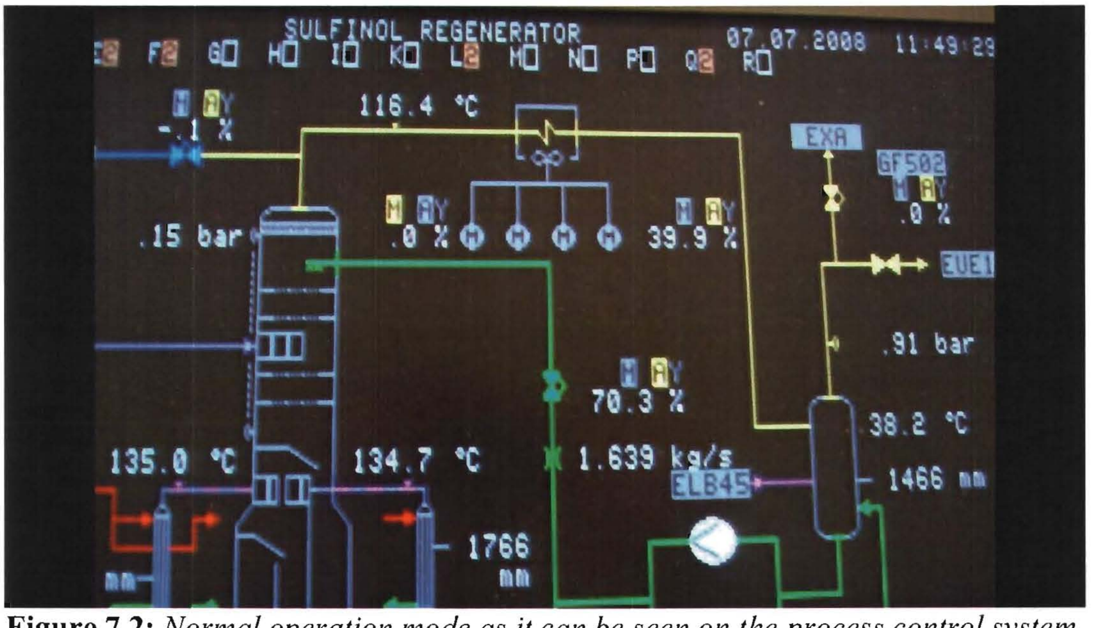

Figure 7.2: *Normal operation mode as it can be seen on the process control system.*

Step 3: Introduce event by event the selected scenario according to the event-tree. In that sense the audience will be get on board to the abnormal conditions and of course their possible outcomes.

Step 4: Present the initiating event (e.g. closed valve). The presentation has to be conducted both verbal and visual. This way of presentation will follow exactly the sequence of the event-tree of the scenario to be presented.

Step 5: The introduction of the initiating event will be followed by four questions with regard to prevention and mitigation of the consequences.

1. How this event can be prevented? Due to the fact that the objective of the SBT is the prevention of an accident, the first question's purpose is to make the operators think the accident from its root cause. This question will help the trainees get on board training. Besides, asking them why has a high likelihood that they will feel offended.
2. How do you detect this event? It is of major importance to detect a problematic situation. Otherwise it may evolve to an accident and no one understands it and of course prevents it. If the operators detect the problem it is likely that they will remedy it. In that sense the accident will be prevented, this is of course the target of the SBT.
3. What does it step mean? The detection of a problem (in this situation the initiating event) is crucial; however it should be followed with the correct interpretation. Otherwise, the detection will have no meaning. Correct interpretation means correct diagnosis, which is the understanding, of the situation. Correct diagnosis will lead to better understanding of the possible actions to be taken and therefore prevent the accident form occurring.
4. What are the actions that should be taken? This is simple the decision step. When an operator detects and understands the failure mode then the nest step is to decide and to act upon it. A good action will "save the day".

An example can be seen in figure 7.3.

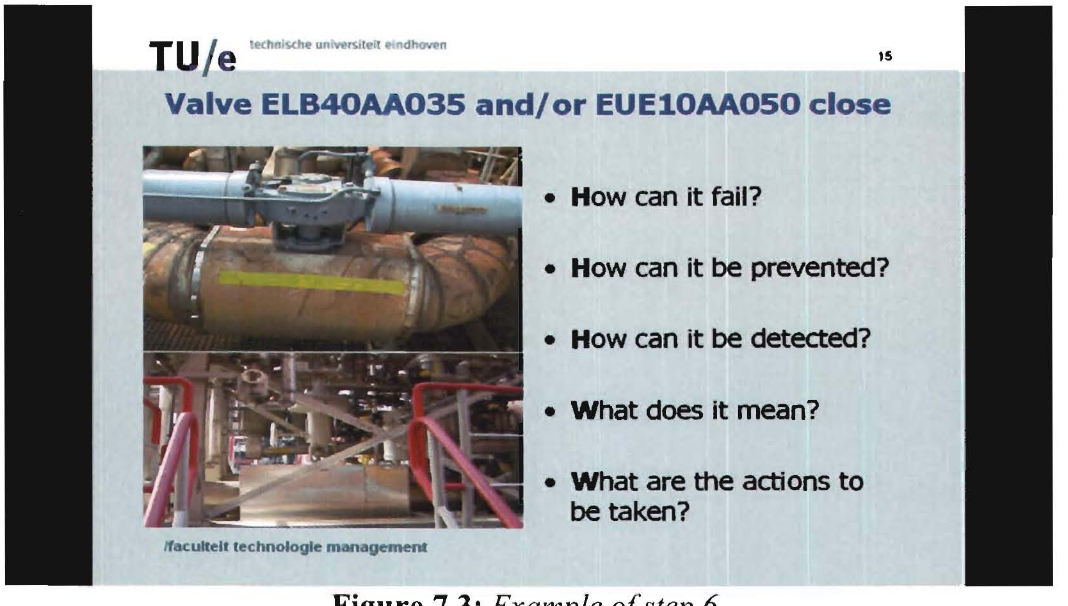

Figure 7.3: *Example of step 6.*

Step 6: Present next event (according of course to the constructed event tree), both verbally and graphically.

Step 7: Ask the same questions as step 4.

Step 8: Repeat steps 6 and 8 until all the events are presented.

Step 9: Present all the (intermediate and final) outcomes. Fro example, in case of a gas release, VCE and jet fire present the effects as estimated in chapter six. It will be wise to include pictures of the outcomes.

7.2.3. Evaluation

The lecture will be followed by evaluation of the training. It has to be clarified that the evaluation concerns only the session and not the trainees. However, in literature a post-test is being conducted after the training session and its purpose is to assess the level of trainees' level of understanding. Keep the discussed differences concerning the function of the participants and the training objectives which were discussed I previous paragraph in mind Therefore, a post-test as it is described in literature (evaluation how much was learned) is out of question. Evaluation will follow the training format.

This evaluation consists of two parts. The first part is going to be conducted by the researcher. The second part is about the evaluation with regard to the trainee's point of view.

As far as the first part is concerned, the evaluation should be conducted by a person who is not participating in the lecture. The person should be present in the lecture but he should not interact with the trainer and the trainees. This will enable him to be free from biases that are possible to be associated when he interacts in the session.

In order to have a structured evaluation not only for the scenario that is going to be presented in the pre-test session and also the training and post-test session should has criteria. A successful session should score high in the evaluation criteria. The evaluation criteria are the following:

1. Is the training objective clearly stated? Did the operators understand why they are in the session or they just think that they are there because they must?
2. Is the presentation as simple as possible? The key of the presentation is to be simple such that the audience can easily follow it. If this is not the case then the trainees may not be able to follow the sequence of the presentation and then the lecture and the whole training session will become a complete fiasco.
3. Is the presentation exciting? It is very important to have a simple presentation, but it should be taken into consideration that is should be exciting to the operators as well. Otherwise, the audience will get bored and pay no attention to the session. Pictures and visual effects can make a presentation exciting..
4. Is the scenario credible? In other words, is it correct? Are the presented steps and the countermeasures correct or they are totally unrealistic. If they are totally unrealistic then the operators will refuse to participate. If the observer identifies such a situation, he has to ultimately understand that there is a problem in the credibility of the selected scenario and research should be conducted on why it is not credible.
5. How deep do the operators go into the examined problem with respect to the simulation? In other words; will they realize that they are participating in an accident or they think that it is just a game?
6. Can the operators make decisions? If they can, to what extend, are these decisions realistic?

With regard to the second part, it is the evaluation from the trainee's point of view. This part is crucial since it will help the researcher to see if he has biased his evaluation and also what are the feelings of the "opposite part". After the training session the trainees should fill in an evaluation form. In this evaluation form questions can be categorized into five parts. The first part is about the training objectives. Second is the training format. The third area is the examination of the selected scenario. The fourth part is about the relevance of the training to the trainees/operators. The last but not least part concerns the recommendations for improvements with regard to SBT. The evaluation form can be seen in Appendix E.

7.3. Lessons learned form trainer's SBT testing

The trainer's SBT will be followed by the operators' SBT. However, before setting up the SBT for operator training it will be at almost beneficial to test the SBT concerning the trainers. This test simply means that the selected scenario is going to be taught to the trainers with the exact structure which was described in the trainers training part. This test and the lessons learned from it are going to be followed by the recommendations for operators' SBT. These recommendations will be based on the results of the testing session.

First of all, the observations of the researcher during the testing session will be stated. Then the findings based on the evaluation of training from the participants' point of view (that is the post-test questionnaire) will be presented. The recommendation for operator SBT will be made based on both findings.

7.3.1. Researcher observations concerning SBT

The findings with regard to the researcher's angle can be listed as:

1. The composition of the audience was ideal for testing. The audience consisted of the trainer, maintenance engineers and the chief of the operators. Therefore, every single detail of the training session can be analyzed critically with regard to different perspectives. For example a maintenance engineer can see if the technical information concerning the examined part is valid, the trainer can be critical on the methodology of the training format and the operator will be critical on the sequence of events.
2. At the start of the session, the willingness for participation was very low. This is logical since in the start the scene was set up and the participants tried to adapt to the requirements of the training session. However, when the discussion evolved and several issues were stressed (e.g. why a valve close) the participation rose dramatically.
3. A misunderstanding occurred when a participant was asked what decision he should make at an occurrence of a process deviation (pressure). After a conversation with the operator later on it was found out that he got stressed by the way that the question was posed. He did not know what to decide in that situation. This is a very important point. In fact it shows the ultimate goal of the scenario based training; decision making under abnormal situations (abnormal situations are on only the failure of some parts but also the mental condition of the decision maker-operator). In the session, the operator got stressed with the way in which the question was posed but despite that abnormal condition he was able to make a decision. It should be stipulated that in a real-life event the operator will be stressed and nevertheless he will have to make a decision as soon as possible.
4. It was commented that the P&ID's of the examined part and also the software diagrams concerning the operation of the valves and the controllers should be available to the participants. This will enhance the discussion since every single aspect can be inspected in detail by all the participants.
5. As far as the operation of control instruments are concerned, not all the input and output signals were known because in the P&ID's this information was not very clear. This was a reason why I was advised to study thoroughly the software diagrams of the controllers.

6. During the session, the likelihood of occurrence of the selected accident was stressed. It was commented that due to the fact that the scenario had many lines of defense (e.g. trip valve to flare, safety valves etc), the likelihood of occurrence should be very low and thus it is very difficult to occur. Therefore, it was not very clear if the particular scenario could be suitable for SBT. The answers to that comment were the following:
    a. It is definitely a low likelihood but also high consequence scenario. This complies with the laws which say that the risk of having an accident in a plant should be very low in terms of likelihood of occurrence and high in terms of severity of its outcomes. Otherwise, the operating license of the plant will be recalled.
    b. The target of the SBT is to train the operators in scenarios which have the combination of low likelihood and high consequence. The operators are trained with regard to normal operation of the plant. If something abnormal happens then the operator will be much stressed and may take the wrong decision.
    c. For a scenario to be suitable for SBT should include the human intervention steps. In other words we have to select a scenario in which the operator plays a significant role in the prevention of thje sequence of accident steps. Otherwise it will be impossible to train them with a scenario in which they cannot intervene.

    The answers made the audience understand that the scenario is appropriate for SBT.
7. At the end of the session the participants were delighted.

To sum up, the signs from the conductions of the trainer SBT can be commented as more than promising. The only doubt was the suitability of the selected scenario. However, this doubt was overcome.

7.3.2. Findings from the evaluation questionnaire

Before proceeding to the findings there are two things that should be stressed. The first is the fact that the findings are very important since they will show us what the participants really believe and not just what we think. Secondly, due to the fact that the training session lasted more than 2 hours, the participants were very tired and of course not willing to fill in the questionnaire. Distributing the questionnaires and wait a couple of days to fill them is not an option since the participants will forget the basic details and this will lead to biases and wrong feedback. Therefore, all of the questions were asked and the audience should answer. The results were reported in the evaluation form.

The findings for every module of the questionnaire are:

1. Concerning the training objectives, they are clearly stated.
2. Training format. The training reaches the objectives. In addition, the presentation and the discussion during the session were found very interesting. The training format will be improved if the software diagrams of the valves and the control instruments and the P&ID become available to each trainee in the session.
3. Selected scenario. The selected scenario was found both credible and suitable for training. Furthermore, the scenario is sufficiently detailed for the purpose of the training. Last but not least, more cases should be considered for SBT training. The selected ARIE scenario about corrosion and the high pressure build up the syngas treatment unit are more than suitable.

4. Relevance for trainees/operators. The trainees learned something useful and some parts of the scenario were experienced by the chief operator. Details with regard to what exactly happened and what actions were taken were not mentioned.
5. Suggestions for improvements. It was suggested that in the operator training session the audience should include some experienced operators because they will help the discussion to evolve.

To summarize, according to the remarks of the participants, the discussion was well conducted. Moreover, there was an agreement for the selected scenario. Software diagrams and P&ID's should be handed in to the participants during the discussion. In addition, in order to the scenario to be improved, the software diagrams should be read in deep. Finally, the operator training session must include some experienced operators to help the discussion.

7.4. Recommendations for operators' SBT

After observing the trainees training session and taking into consideration the crucial remarks of the participants, recommendations with regard to the operator SBT will be made. Overall, these recommendations are about the conduction or modification of the parts of the SBT framework; introduction, training session (reading material, participants, group discussion) and evaluation.

With regard to the introduction and the evaluation part, they will remain the same. Some alteration will be made on the training sessions. To be specific these alterations concern the participants and the group discussion.

As far as the participants are concerned, they will be the operators from the unit under study. Experienced operator should be included in the panel of the operators because with their experience and competences they will help the discussion evolve. The experienced operators have more insight of the plant since they are working in the plant for a lot of years. This implies that they possess all the relevant knowledge concerning the plant units. Furthermore, since they are the most experienced, they are the ones who are going to make the decisions in case of an emergency. The number of the operators-participants must be determined with regard to the operators that can join the session without causing problems to the monitoring of the unit; there will still be people who will monitor the unit when their colleagues are being trained.

In addition, there are some aspects in the demonstration scenario that could be improved. Thus, its credibility to the audience will be improved. The actions that have to be done to improve the existing scenario are:

1. Study the software diagrams of the valves and the controllers to see the input and the output signals of them. This will result in the precise understanding of how and the components operate and why they may fail. It was agreed that a document which will contain a summary of the input and output signals of the components as well as with why the components of the initiating event will fail will be written. If it is applicable, make alteration of the event-tree of the selected scenario.
2. Continuation of the estimation of the consequences of the selected scenario. This means verification of results concerning the vapor cloud explosion, toxic gas release and the flash fire. In addition the consequences of a toxic cloud dispersion and jet fire have to be modeled.

Finally, the structure of the group discussion will remain approximately the same. Only two things are going to change. The first is the incorporation of the introduction in step 2 as explained earlier. Finally, the software diagrams and the P&ID's of the examined part are going to be handed in to every participant of the discussion.

However, a very crucial difference between the participant mentalities must be taken into consideration. The participants of the trainer's SBT were all engineers and thus very motivated to learn more and to implement something new. However, it is possible that the operators could be hesitant since they might think that they will be assessed or that they are going to loose time from monitoring the unit or even find the training not very interesting because it is for situations that will not probably encounter in their career. A possible way of overcoming that obstacle is by explaining them that they could save the whole plant in a case of an abnormal condition. Another possibility is to describe similar accidents which occurred in another plant. In this way the operators could be convinced that the scenario with which they are going to be trained is really possible to happen and therefore, their participation will increase.

Chapter 8: Conclusions & Recommendations

8.1. Conclusions

In section 2.2 a research question was identified and in order for this question to be answered, it was analyzed into three sub-research questions. In the present chapter it will be discussed if these three research questions were answered from the findings of chapters four until seven.

The research questions are:

1. What training method could be appropriate for training the operators to make decisions under abnormal conditions?
2. How can the selected method be adapted to the context of an IGCC plant?
3. How can the selected training method be implemented?

In chapter four possible training methods are considered for application to the specific problem. Examples are simulation, group discussion, lectures etc. The training method to be selected should fulfill three requirements. First, it should be suitable for training a diversity of employees-operators. In an IGCC plant the age and the background of the operators can vary. Secondly, the training method to be used should enhance the decision-making process of the trainees-operators. Finally, the method to be selected should have a concrete approach. However, the aforementioned methods are not suitable since they do not fulfill all the requirements. Especially, they do not provide a concrete approach on how the operators can be trained. Partially, some of them could be used but not as a complete framework. For example a lecture could be used as an introduction to the actual training. In addition, Scenario-Based Training (SBT) and Event-Based Approach to Training (EBAT) are considered. EBAT focuses on the SBT but in simulated design. However, within the context of the IGCC technology the concept of simulators has not matured yet. Thus, a technique with a use of simulation could not be feasible. Therefore, SBT is the selected method. SBT has advantages that fit with an IGCC plant. First, the operators could be prepared to anticipate abnormal conditions and go through them decisively, intuitively and efficiently with SBT. Secondly, with the implementation of the SBT the decision-maker will focus on the key decisions in order to avoid high consequences (for example fatalities, leakage of hazardous chemical etc). Finally, SBT mitigates the consequences when an abnormal condition occurs since the trained operators can respond adequately. For example, when a valve from a gas transporting pipe closes suddenly, the operator could guide the gas stream to the flare and thus prevent a possible overpressure at the pipe. There are differences between the SBT which is stated in literature and the SBT that is going to be implemented in an IGCC plant. First, the objectives are different. Furthermore, no model exists for SBT in IGCC. Finally, the format of the SBT session has not been defined yet. In literature SBT is implemented in three steps: pre-test, training and post-test. These differences imply that some modifications should be done in order for SBT to be adapted within the context of an IGCC plant. First, possible accident scenarios should be identified since scenarios that could be used in an IGCC plant are not available yet. Afterwards, the unit in which the SBT will be implemented and scenarios to be taught in the training session should be selected. The third step is to model the selected scenarios in order to become suitable for operator training. Finally, the format of the SBT will be defined in the context of the IGCC plant.

In chapter five, the first step of the adaptation of SBT within the IGCC context is conducted; unit and scenario selection. First, possible scenarios within the plant units are identified. The sources of scenarios are the ARIE and the HAZOP studies. HAZOP study is not available for all plant units and in some units is partially conducted. This implies that not all the possible scenarios within the plant are identified. Thus scenarios that could be relevant for SBT may be missing. The scenario identification is followed by the selection of a unit where the SBT will be conducted. Syngas treatment is selected because it fulfills certain criteria. The next step is the selection of scenarios within the syngas treatment unit. Based on criteria three scenarios are selected as relevant for SBT. However, the scenarios that have high consequences concerning only unavailability are not considered since the focus is the well-being of the plant employees. One scenario is selected to demonstrate the SBT technique.

In chapter six the SBT adaptation is continued. First, the selected scenarios are modeled in order to show the sequence and the timing of events and to include the role of human factor on the prevention of the accident sequence. The method that is used to model scenarios is the Event-Tree Analysis (ETA), a technique that models the time and the sequence of events and can include the role of human operator. The last step is the explanation of the phenomena that are associated with the outcomes and the estimation their consequences only for the demonstration scenario. The effects are briefly explained. The models that are used are suitable only for draft estimations and their results may be not very accurate. However, the explanation of events and the calculations of their consequences are done only to stress the importance for SBT and to make the scenarios credible to the operators.

In chapter seven the implementation framework of the SBT is set. The first step is the introduction. In this step the operators will get on board with what is going to be taught. A pre-test evaluation could not be done since the knowledge and response of the operators are not assessed. The objective of SBT is not to help the gain new knowledge but to enable them to make decisions under abnormal conditions. Training is the second step. This step will be conducted in terms of a problem-solving group discussion. The discussion will enhance the decision-making process. The last step is the training evaluation. The evaluation step is twofold. First, the operators-trainees will have to evaluate the SBT from their point of view. Secondly, the trainer has to take notes concerning the previous aspects of the training. The two different sides of the training part are going to be considered. Based on the findings, possibilities for improvement could be identified. The defined framework of implementing the SBT has to be tested to identify possible deficiencies concerning the structure (introduction, training evaluation) and the content of the steps (e.g. is the way in which the training evaluation is valid?). The SBT is tested by training the trainer of Nuon Power Buggenum (trainer's SBT). Not only will possible deficiencies and possibilities for improvement be identified, but also it could be a good opportunity to train the trainer and have him train the operators. The results of this test are very positive. The results showed that the implementation framework is suitable and the selected scenario appropriate. Only some minor modifications in the selected scenario have to be made.

Based on what is discussed previously, it can be concluded that the objective of this Master Thesis Project is fully met. The first two research questions are fully answered. SBT is a suitable method for training the operators to make decisions under abnormal conditions. Due to the fact that there are differences between the IGCC plant and the situations that are described in literature, SBT should adapt to the context of the IGCC plant. The adaptation will be achieved by identifying scenarios, selecting a unit in which the SBT will be conducted, selecting scenarios relative for SBT and model the selected scenarios with ETA with estimation of the consequences of the final outcomes. The third question is not fully answered. An implementation framework is defined. SBT is implemented only for training the trainer of the plant. This implementation is more to a test of the defined framework for possible deficiencies and improvement possibilities. The results of the test (trainer's SBT) show that the implementation framework and the adaptation of SBT are successful. However, the SBT is not yet implemented to train the operators. This implies that some changes and modifications are possible to be made.

It has to be stipulated that the project had some limitations. First, not many training methods that could be applicable for training operators under abnormal conditions are mentioned in literature. It is suggested to tackle abnormal situation management with training, but no training method is suggested. Thus, not numerous options that can be selected for the present project exist. In addition, due to the fact that HAZOP was not conducted for all the units, not all the possible scenarios were identified. This means that there is a risk that relevant scenarios for SBT are not selected. Finally, the models that were used for calculation of the consequences of the phenomena that could result from abnormal conditions are simple. It is possible that some of the estimations could not be the most accurate but that does not mean that the described phenomena will not occur.

8.2. Recommendations

The conclusions that were presented in section 8.2 imply that there are some actions that have to be done. There are five actions that are recommended.

First, SBT could be implemented to the selected unit and to the other units of the plant. This would give the opportunity to train the vast majority of the plant operators. In addition, it will serve as an actual means of testing the proposed training framework. In case that it is proved successful, it could be implemented to other IGCC plants (e.g. Magnum project).

Secondly, it would be beneficial to put effort on identifying all the possible accident scenarios. A possible way to achieve this goal is to extend the HAZOP study to the rest units of the plant. In this way more scenarios will be available to select and the possibility of not considering relevant scenarios will be smaller.

Furthermore, more criteria could be added to select a unit and scenarios relevant for SBT. A multi criteria decision analysis method (such as Analytic Hierarchy Process) could be used in order to select scenarios available for SBT based on the pre-defined criteria. Also, scenarios that have high severity regarding only plant availability could be selected for SBT.

Moreover, the use of models (e.g. numerical) for detailed estimation of the consequences of the final outcomes of the scenarios is highly recommended. Not only will the results be interesting for the SBT conduction, but also for the safety of the plant (since they will show in detail what the examined outcome can cause to the plant and the employees).

Finally, additional research could be conducted on the introduction of simulators. It could be useful to check if it is possible to use simulation for training. If it is possible, it should be examined how the simulation can be integrated with the SBT implementation framework and if there are some modifications that have to be done.

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Appendix A: Selected scenarios

Table A1: *Selected ARIE scenarios.*

Unit	Scenario	Likelihood	Severity	Risk	Direct Cause
OZW	Pipe break in the transportation of syngas to get desulfurized, break in the H2S pipe	Very low	Catastrophic	High	Corrosion in OZW

Table A2: *Selected Hazop scenarios.*

Unit	Part	Device	Deviation	Cause	Consequences	Lik.	Conseuqences				Risk	Safeguard	Actions
							Peo.	Av.	En.	Rep.			
OZW Syngas treatment	ELA20BH010	ELA20BR010/30	Too high pressure	Problems with EVB60AA050 / ELB10AA007/050	Pressure rises and the vessel raptures open	1	5	5	2	2	0	Safety inst. ELA20AA090	Check reliability
	ELA10AC020	ELA30BR010			Syngas leakage to open air								
	ELA10AC010 ELA30BB010	ELA10BR020 ELA30BR060			Pressure rises and the vessel raptures open								
	ELB10BD010	ELA30BR070			Pressure rises and the vessel raptures open								
	ELA30AC010	ELA30BR030	Too high pressure	Block the system and bring N2 to EVB61AA350	Head rapture	1	5	4	2	5	0	See ELA20BR010	
	ELA30AC020	ELA30BR050			Pipes stop jacket rapture								

	ELA20BH010	ELA20BR010/30	Too high Temperature	A lot of incoming air during the bring of oxygen in the system and then burn it	Bed damage	1	1	4	1	1	-	Procedure Temperature met. ELA20CT003-4-5-6-8-9	Check procedure for afbranden SIS temp EVB60CT002 /007/008 check temo. Ind
	ELA10AC020	ELA10BR019			See ELA20BR010								
	ELA10AC010	ELA10BR020											
	ELA30AC010	ELA30BR030		see ELA10AC020	Head rapture	1	5	4	2	5	0	Alarm on syngas tem. ELA30CT002/003	
	ELA30AC020	PGM10BR020	As well as			3	1	4	1	1	X	Laboratory control	CEA
	ELB40BB010	ELB40BR020	Too high pressure	Closed ELB40AA035 and/or EUE10AA050	Tank collapses, Sour gas leak to open air	2	5	5	2	5	X	SIS ELB40AA090/091	Maintenance and checking

Appendix B: Event-Trees of the selected scenarios

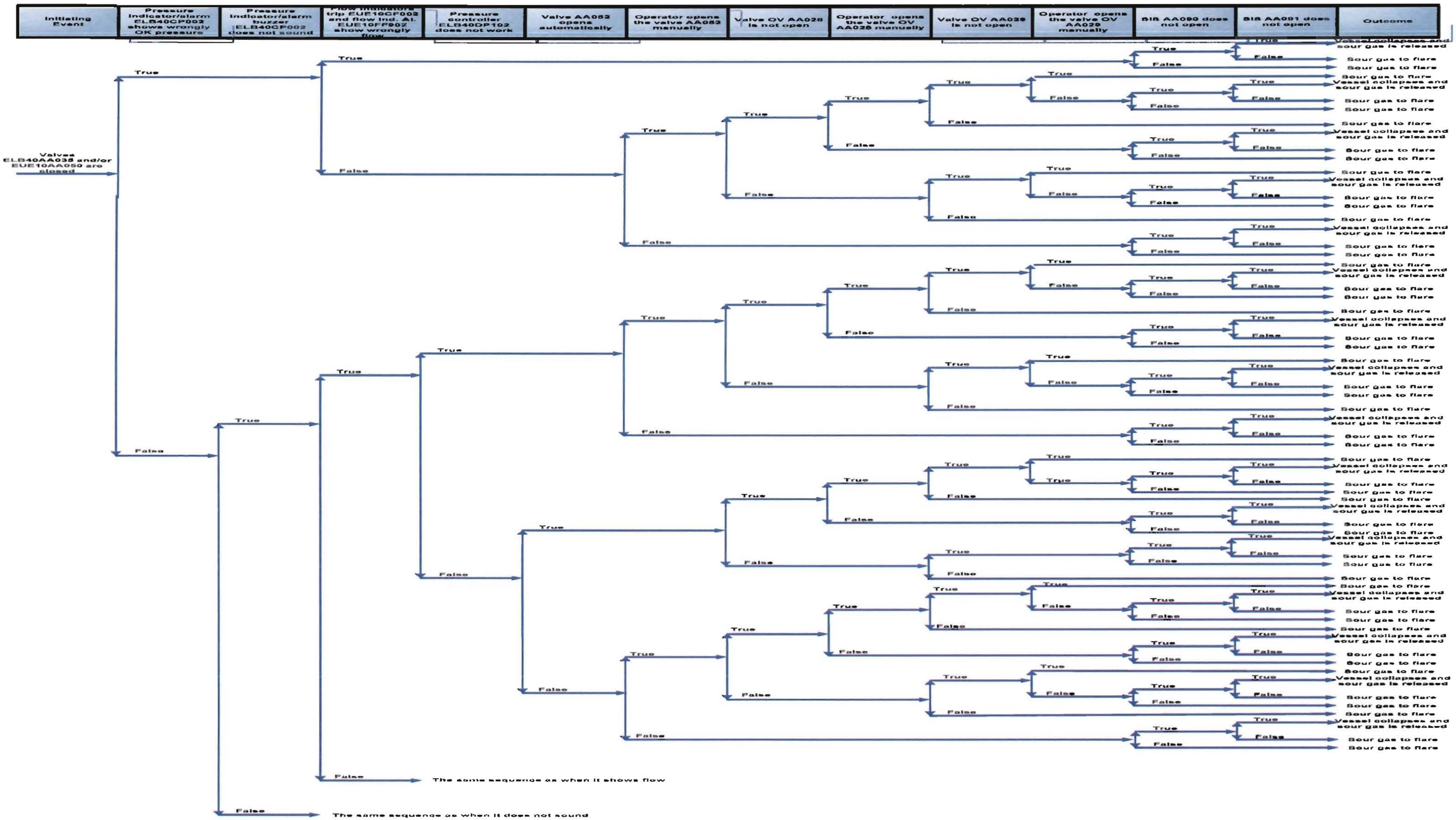

Figure B1: *ELB40 scenario-start.*

Assumptions: Worst case and operator is in front of his console.

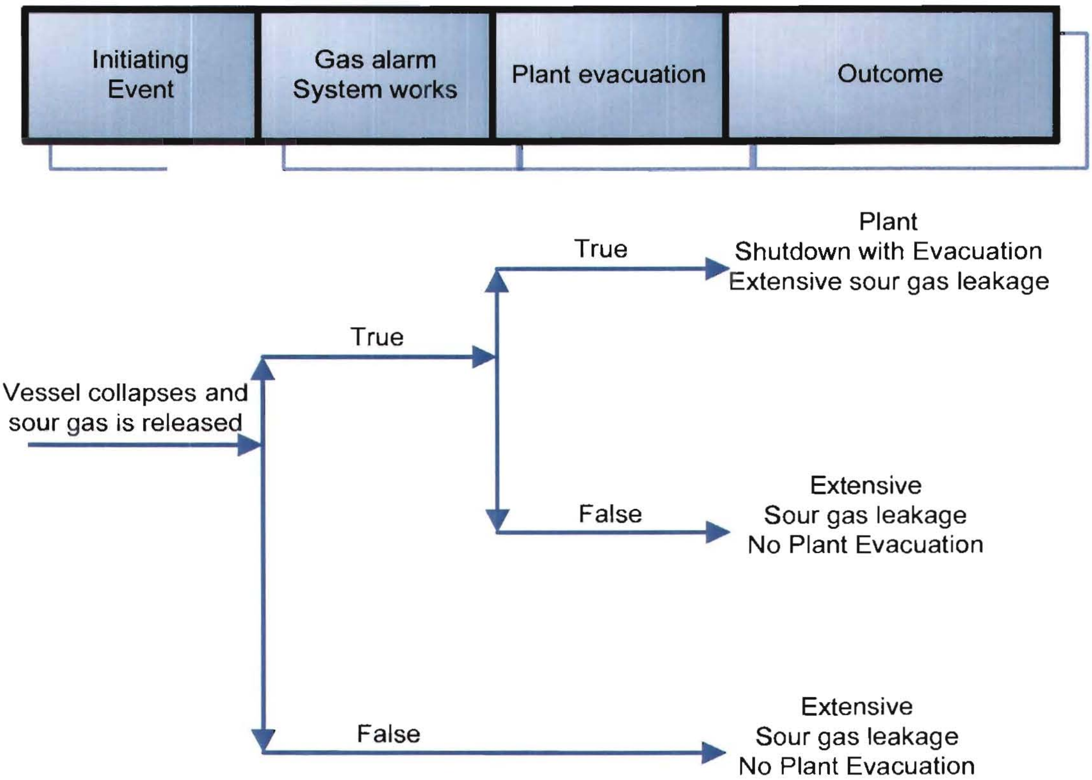

Figure B2: *ELB40 scenario-continuation of tank collapse.*

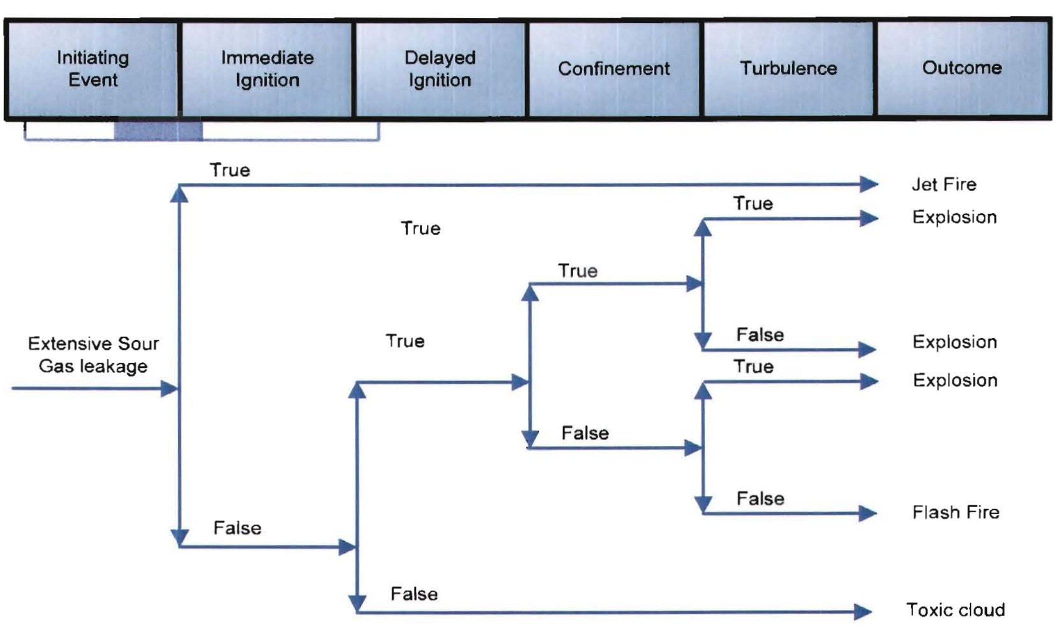

Figure B3: *ELB40 scenario-continuation of sour gas leakage.*

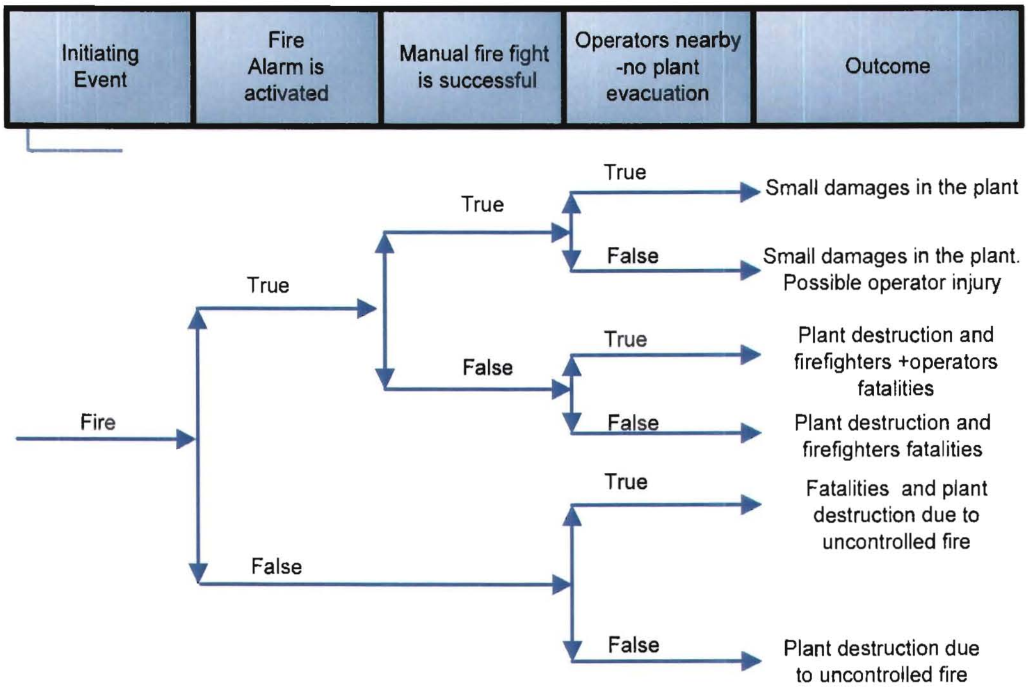

Figure B4: *ELB40 scenario-continuation of fire.*

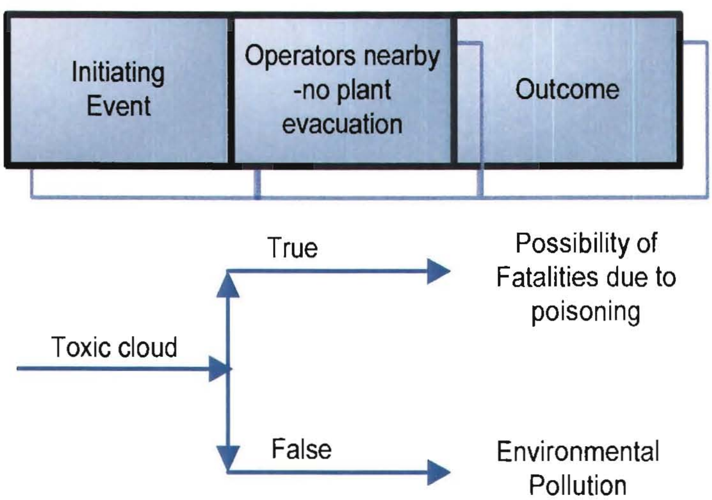

Figure B5: *ELB40 scenario-continuation of toxic cloud.*

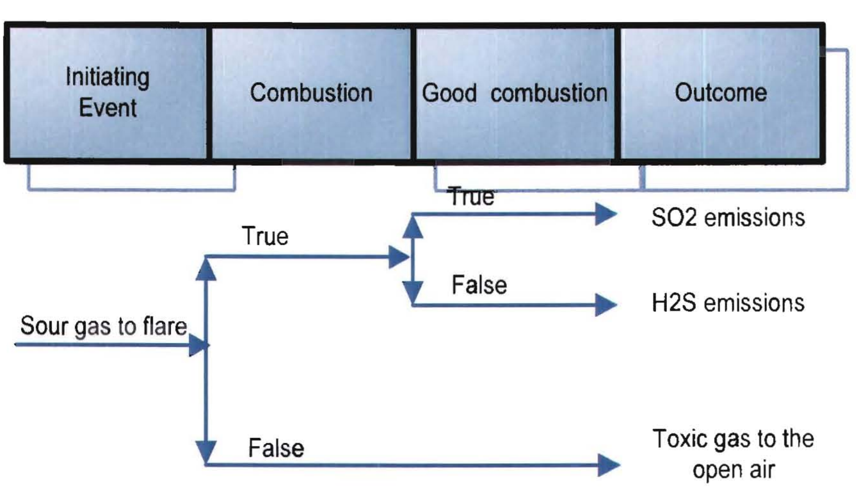

Figure B6: *ELB40 scenario-continuation of sour gas to flare.*

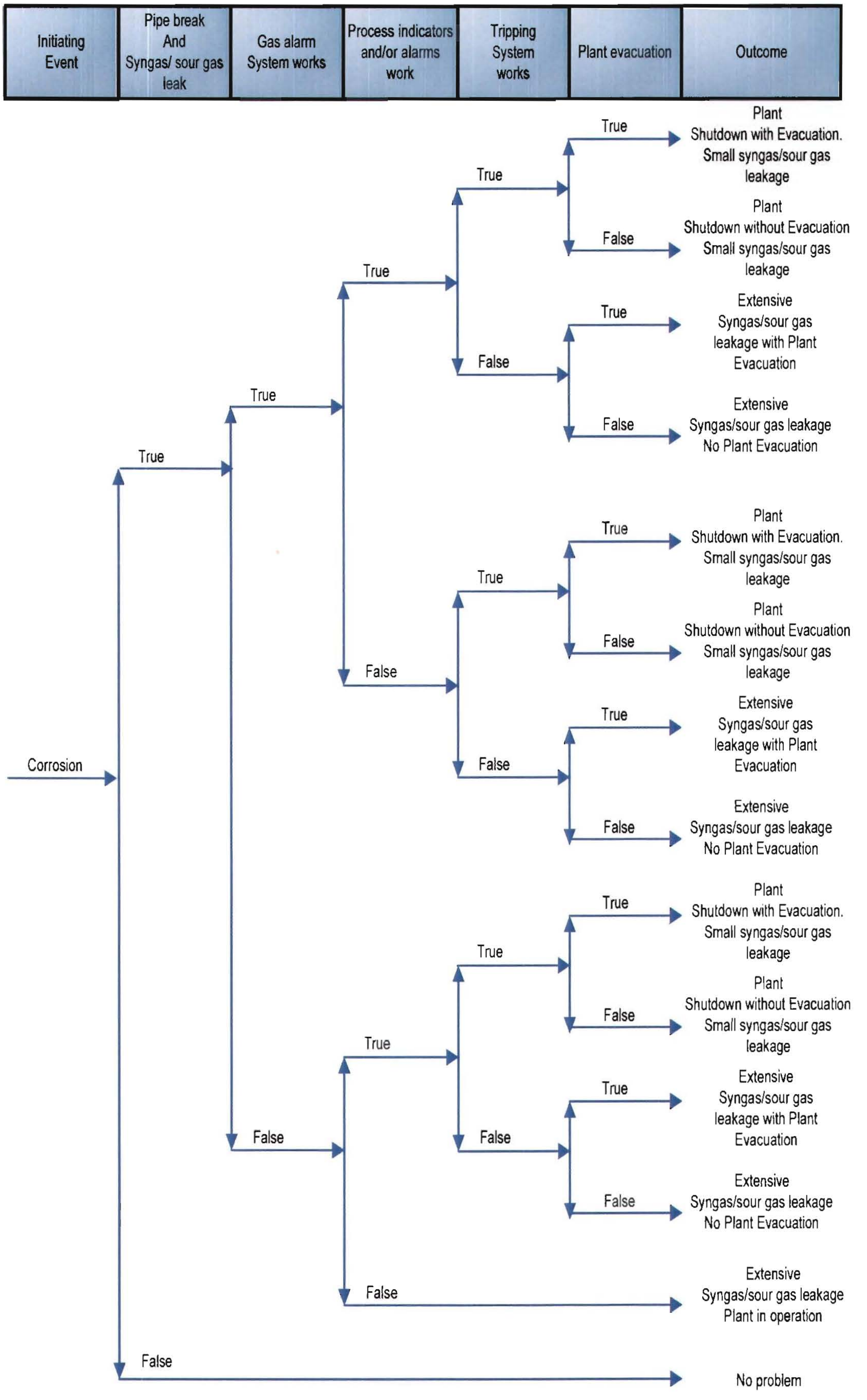

Figure B7: *ARIE scenario start.*

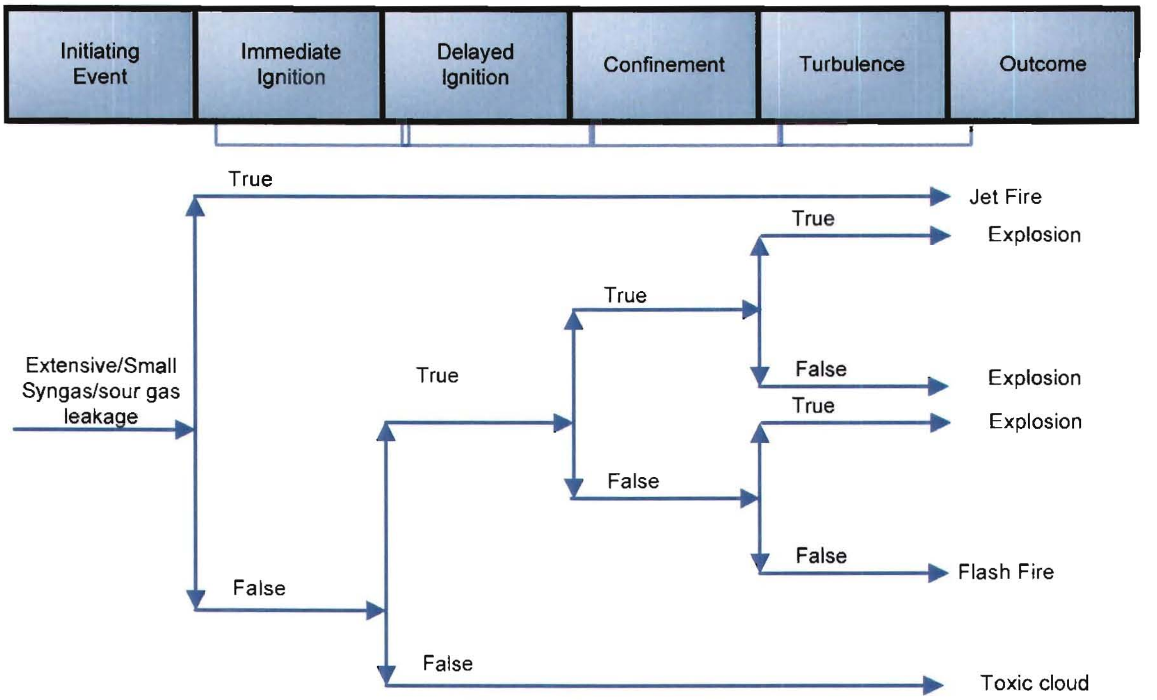

Figure B8: *ARIE scenario-continuation of syngas/sour gas leakage.*

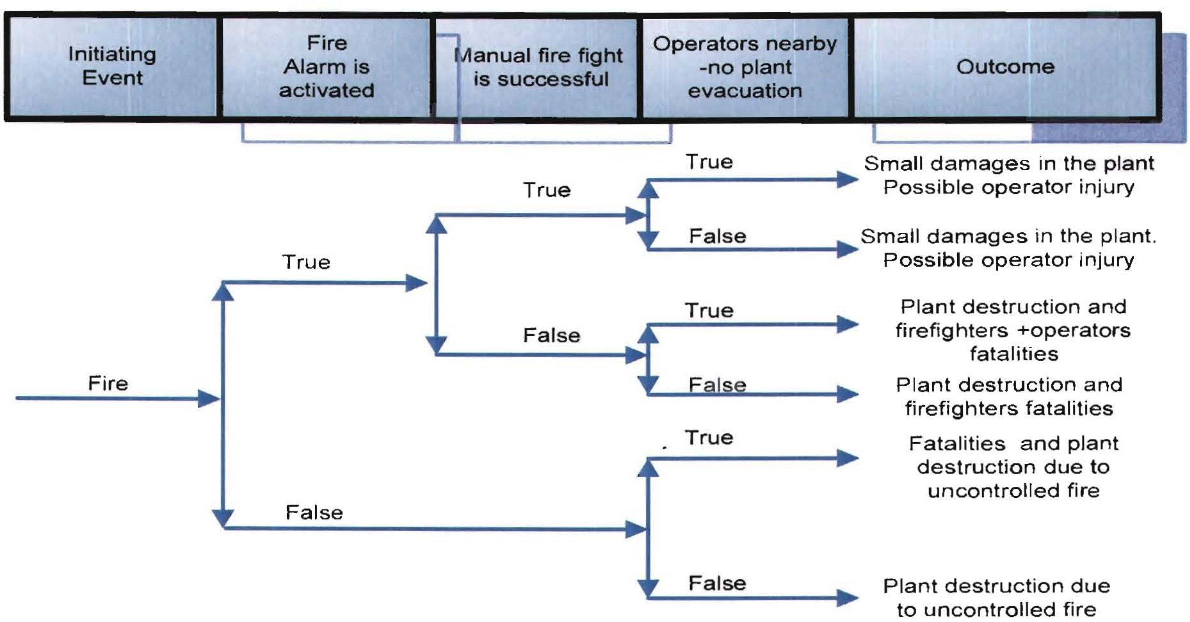

Figure B9: *ARIE scenario-continuation of fire.*

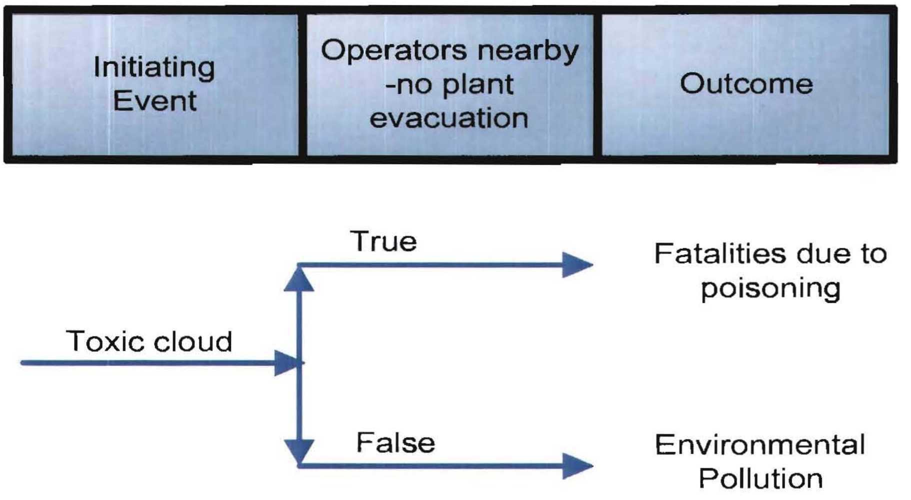

Figure B10: *ARIE scenario-continuation of toxic cloud.*

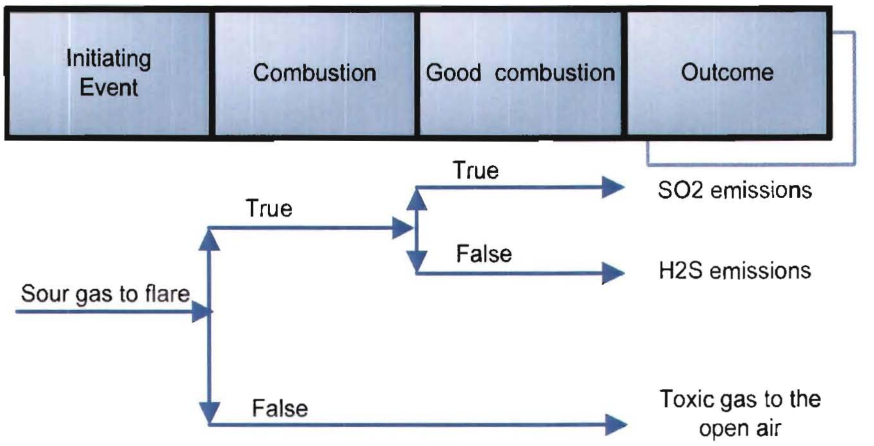

Figure B11: *ARIE scenario-continuation of syngas/sour gas to flare.*

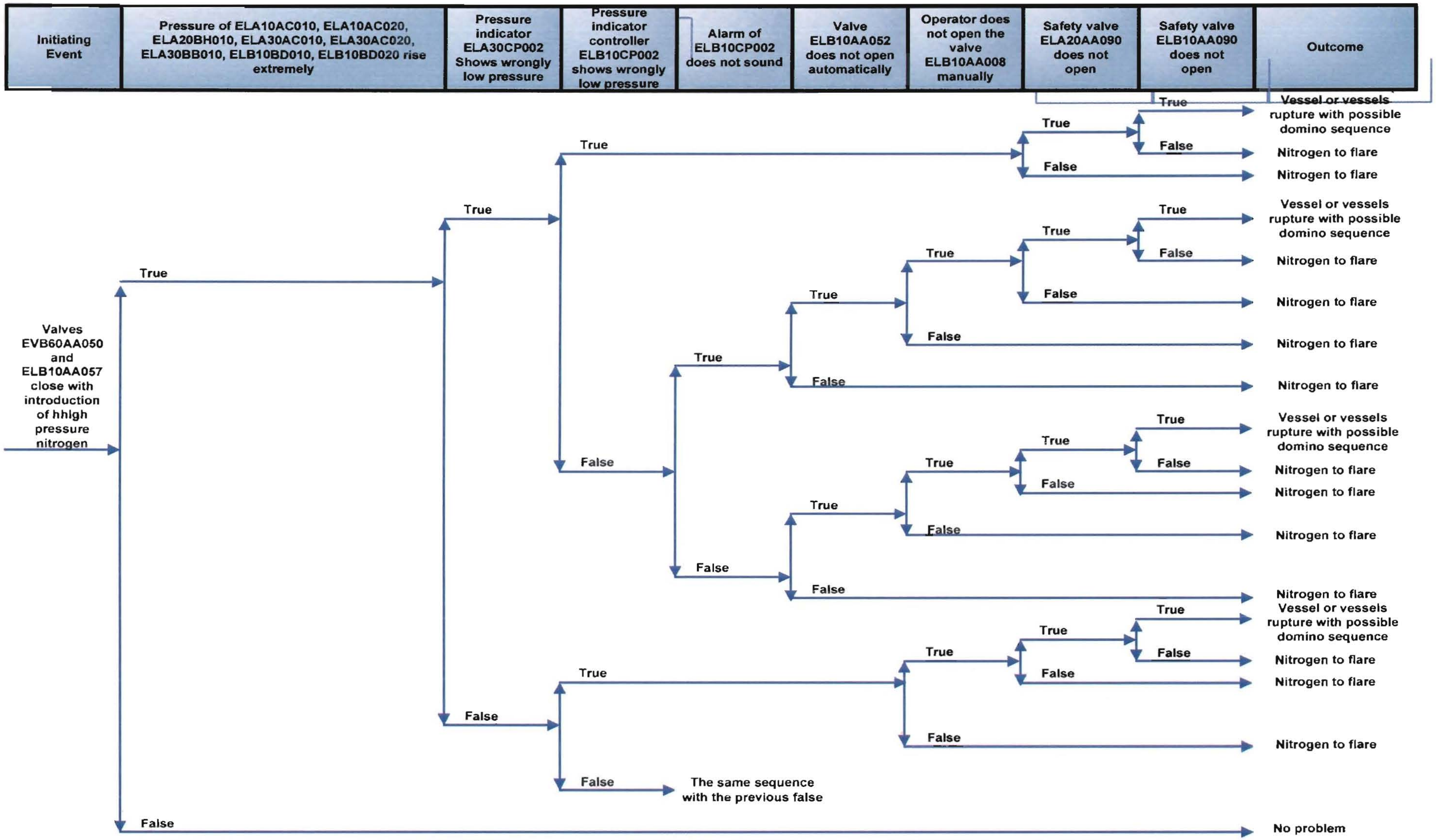

Figure B12: *Syngas treatment scenario-start.*

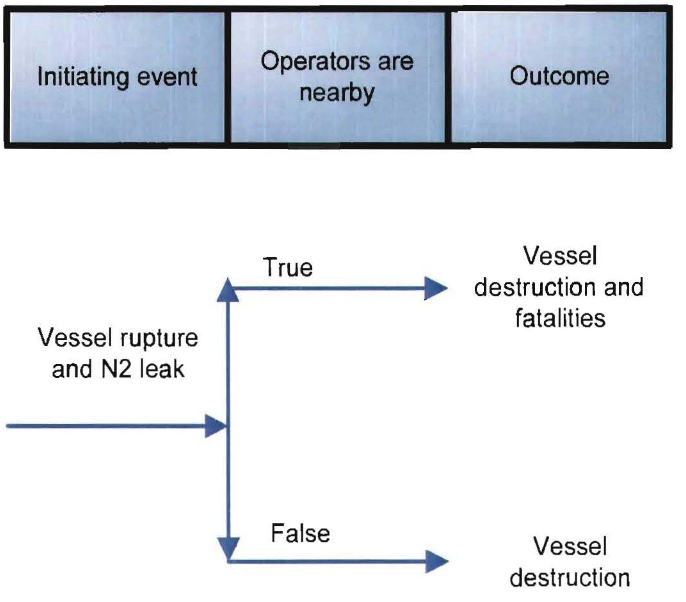

Figure B13: *Syngas treatment scenario-continuation of vessel rapture.*

Appendix C: Models used for the consequences estimation

C.1. Dense gas release

The equations to be used are (TNO Yellow book, 2005):

$$q_s = C_d A_h \Psi \sqrt{\left(\rho_0 P_0 \gamma (2/(\gamma+1))^{(\gamma+1)/(\gamma-1)}\right)} \text{ (kg/s)}$$

First we have to determine if we have chocked or no chocked flow. The flow is critical when:

$$\frac{P_0}{P_a} \geq ((\gamma+1)/2)^{(\gamma/(\gamma-1))}$$

For critical outflow $\Psi^2 = 1$

For sub-critical outflow

$$\Psi^2 = \frac{2}{(\gamma-1)\cdot((\gamma+1)/2)^{(\gamma+1)/(\gamma-1)}\cdot(P_a/P_0)^{2\gamma}\cdot(1-(P_a/P_0)^{((\gamma-1)/\gamma)}}$$

With

$$\gamma = C_p / C_v$$

Where
q_s mass flow rate (kg/s)
C_d discharge coefficient (-). For sharp orifices is 0.62 but for rounded orifices it is 0.95-0.99.
A_h cross-sectional area hole (m^2)
Ψ outflow coefficient (-)
ρ_0 initial gas density (kg/m^3)
P_0 initial gas pressure (N/m^2)
P_a ambient air pressure (N/m^2)
γ Poisson ratio (-)
C_p specific heat at constant pressure (J/kg*K) or (kJ/kmol*K)
C_v specific heat at constant volume (J/kg*K) or (kJ/kmol*K)

Note that the C_p and C_v are a function of temperature. According to Geersen (1988), the equations for the calculation of C_p are:

$C_p = A + B\cdot T + C\cdot T^2 + D\cdot T^3 + E\cdot T^4$ (kJ/kmol*K)
$C_v = C_p - R$

Where
T temperature (K), the temperature of the accident.
A, B, C, D, E constants that are dependant on the gas (Geersen, 1988).

C.2. Blast

This method consists of 14 steps (TNO Yellow book, 2005). As it will be explained later, some steps are going to be omitted due to the specific constraints of the situation.

Step 1: Collect the following data:

1. Vessel contents (e.g. ideal or non ideal gas)
2. Type of possible vessel burst (in this situation there is a pressure vessel burst).
3. Vessel's internal absolute pressure at failure p_1.
4. The ambient pressure p_a.
5. The ratio of the specific heats of the gas γ (here is a mixture of 50% hydrogen sulfide and 50% carbon dioxide).
6. The distance from the center of the vessel to the so-called target r_t.
7. The shape of the vessel (in the present situation cylindrical).
8. The volume of the gas-filled part of the vessel V_g.

Before explaining the next steps a critical remark should be mentioned. The volume of the gas-filled part of the vessel concerns only the part of the vessel and not al the piping. As it will be seen in the results in this part of the vessel not all of the sour gas which is potential to escape is considered. It is only a small percentage of it. In addition, the model assumes that the vessel raptures totally. Therefore there is no differentiation of cases as it was done with the dense gas release.

Step 2: Calculation of the liberated pressure of a pressure vessel burst with an ideal gas.

$$E_{av} = \frac{(p_1 - p_a) \cdot V_g}{\gamma_1 - 1} \quad \text{(J)}$$

Where
E_{av} liberated energy of the compressed gas (J)
p_1 absolute pressure of gas (Pa)
p_a absolute pressure of ambient air (Pa)
V_g volume of gas-filled space in vessel (m^3)
γ_1 ratio of specific heats of gas in system (-)

Next go to step 6.

Step 6: Determine the effective blast wave energy

This will be done with the use of the following equation:

$$E_{ex} = A_{sb} \cdot E_{av} \quad \text{(J)}$$

Where
E_{av} liberated energy of the compressed gas (J)
E_{ex} effective blast wave energy (J)
A_{sb} factor that takes the value of 1 if he vessel is high in the air and 2 if it is less that 15 degrees above the horizon from the target

Step 7: Calculate $\overline{R}$ of the target

$$\overline{R} = r_t \cdot \left[\frac{p_a}{E_{ex}}\right]^{1/3} \text{ (-)}$$

Where
p_a absolute pressure of ambient air (Pa)
E_{cx} effective blast wave energy (J)
r_t the distance from the center of the vessel to the so-called target
$\overline{R}$ the non-dimensional distance from the so-called target (-)

Step 8: Check the value of $\overline{R}$

Continue according to the following list:
$\overline{R} \geq 2$ then go to step 9
$\overline{R}$ <2, ideal gas then go to step 10
$\overline{R}$ <2, other pressure vessel bursts then go to step 9 but realize that the results will be conservative.
As it will be seen later, for our situation, $\overline{R}$ <2, which means that we have to go to step 10.

Step 10: Determine $\overline{P_s}$ for a pressure vessel burst with an ideal gas and $\overline{R}$ <2. This is a refined method.

Step 10a: Calculate the ratio of the speed of the sound in the compressed gas to its speed in the ambient air.

$$\left[\frac{a_1}{a_a}\right]^2 = \frac{\gamma_1 \cdot T_g \cdot \mu_a}{\gamma_a \cdot T_a \cdot \mu_1} \text{ (-)}$$

Where
T_a absolute temperature of ambient air (K)
T_g absolute temperature of compressed gas (K)
μ_1 molar mass of compressed gas (kg/kmol)
μ_a molar mass of ambient air (kg/kmol)
γ_a and γ_1 are specific heat ratios (-)
Then go to step 10b

Step 10b: Calculation of the initial distance

$$r_0 = \left[\frac{3V_g}{2\pi}\right]^{1/3} = 0.782 \cdot V_g^{1/3} \text{ (m)}$$

Where
r_0 the equivalent bursting radius (m)
V_g volume of gas-filled space in vessel (m^3)

$$\overline{R_0} = r_0 \cdot \left[\frac{p_a}{E_{ex}}\right]^{1/3} \quad (-)$$

Where
r_0 the equivalent bursting radius (m)
p_a absolute pressure of ambient air (Pa)
E_{cx} effective blast wave energy (J)
$\overline{R_0}$ non dimensional equivalent bursting radius (-)
Continue with step 10c.

Step 10c: Calculation of the initial peak overpressure $\overline{P_{so}}$.

The $\overline{P_{so}}$ will be found be solving by iteration the following equation:

$$\frac{p_1}{p_a} = \left(\overline{P_{so}} + 1\right) \cdot \left[1 - \frac{(\gamma_1 - 1)\cdot(a_a / a_1)\cdot \overline{P_{so}}}{\left[2\cdot\gamma_a\left(2\cdot\gamma_a + (\gamma_a + 1)\cdot\overline{P_{so}}\right)\right]^{1/2}}\right]^{\left(\frac{-2\cdot\gamma_1}{\gamma_1 - 1}\right)} \quad (-)$$

Where
p_1 absolute pressure of gas (Pa)
p_a absolute pressure of ambient air (Pa)
$\overline{P_{so}}$ non-dimensional peak shock overpressure directly after burst (-)
γ_a and γ_1 are specific heat ratios (-)
a_a speed of sound in ambient air (m/s)
a_1 speed of sound in compressed gas (m/s)

Step 10d: Locate the starting point at the diagram 7.5 of the TNO Yellow Book.

In the diagram 7.5 locate the correct curve by plotting ($\overline{R}$, $\overline{P_{so}}$).

Step 10e: Determine $\overline{P_s}$

The non-dimensional side-on overpressure $\overline{P_s}$ is going to be determine by reading the $\overline{P_s}$ from the diagram 7.5 of the TNO Yellow Book for the appropriate $\overline{P_s}$ (calculated in step 7).

Step 11: Determine the non-dimensional side-on impulse $\overline{I}$

The determination of the $\overline{I}$ can be done by reading it from figure 7.10 of the TNO Yellow Book.

Step 12: Adjust $\overline{P_s}$ and $\overline{I}$ for geometry effects.

The adjustment depends on the value of $\overline{R}$

Step 13: Calculate p_s and i_s

The side-on peak pressure p_s-p_a can be calculated from the equation:

$$p_s - p_a = \overline{P_s} \cdot p_a \quad \text{(Pa)}$$

The side-on impulse can be calculated from the equation:

$$i_s = \frac{\overline{I} \cdot p_a^{2/3} \cdot E_{ex}^{1/3}}{a_a} \quad \text{(Pa*s)}$$

Where
a_a speed of sound in ambient air (m/s), a value of 340m/s is assumed
p_a absolute pressure of ambient air (Pa)
E_{ex} effective blast wave energy (J)
$\overline{I}$ non dimensional side-on impulse (-)

Step 14: Check p_s

This step simply means to check is p_s is more than p_l. If this is the case then take p_l as the peak pressure. Else take p_s.

C.3. Fragmentation effects

The steps that have to be conducted in order to calculate the effects of the fragments are (TNO Yellow book, 2005):

Step 1: Estimation of the number of fragments.

Due to the fact that the examined vessel is cylindrical, for simplification of the calculations it is assumed that two will be the fragments. In other words, half the tank is going to be the fragment.

Step 2: Estimation of the fragment mass M_f

Due to step 1 the fragment mass can be calculated with the following equation:

$$M_f = M_v/2 \text{ (kg)}$$

Where
M_v mass of the empty vessel (kg)
M_f fragment mass

Step 3: Kinetic energy method to roughly predict the initial fragment velocity.

The initial fragment velocity can be calculated with the use of the following equation:

$$v_i = \sqrt{\frac{2 \cdot A_{ke} \cdot E_{av}}{M_v}} \quad \text{(m/s)}$$

Where
E_{av} liberated energy of the compressed gas (J) as it was calculated in the paragraph 1.1.2.
v_I initial fragment velocity (m/s)
M_v mass of the empty vessel (kg)
A_{kc} the fraction of the liberated energy that goes into kinetic energy of the fragments. For this model it has a value of 0.2.

This is a rough estimate and there is a risk that the initial velocity can be underestimated. Therefore, go to step 3c.

Step 3c: Moore's empirical method for the initial fragment velocity in case of a high scaled pressure $\overline{P_1}$, decomposition of energetic materials, or to check the calculated v_I.

Step 3c1: Calculate the initial fragment velocity v_I.

It will be done with the use of the following equation:

$$v_1 = 1.092 \cdot \left[\frac{E_{av} A_{AM}}{M_v} \right]^{0.5} \quad \text{(m/s)}$$

Where
E_{av} liberated energy of the compressed gas (J) as it was calculated in the paragraph 1.1.2.
M_v mass of the empty vessel (kg)
A_M for cylindrical vessel can be calculated as

$$A_{AM} = \frac{1}{1 + M_c / 2M_v} \quad (-)$$

Where
M_c is the total mass of the vessel contents (kg).

Step 3c2: Check v_i calculated to the other method.

If the initial velocity calculated before is higher than according to Moore's method, then the velocity is too high. If this is the case then use the value found with Moore's equation. Continue with step 4.

Step 4: Calculate the range of flying fragments

Step 4a: Calculate the scaled initial velocity.

It will be done with the use of the following equation:

$$\overline{v_1} = \frac{\rho_a C_D A_D v_i^2}{M_f g} \quad (\text{-})$$

Where
ρ_a ambient air density (kg/m^3)
g acceleration due to gravity (m/s^2)
$C_D A_D = 0.47 \cdot \frac{\pi}{4} \cdot d_v^2$
$C_L A_L / C_D A_D = 0$

Step 4b: Read the scaled maximal range $\overline{R_f}$ from the diagram 7.12 of the TNO Yellow Book.

Step 4c: Calculate the maximal range R_f.

This can be done with the use of the following equation:

$$R_f = \frac{\overline{R_f} M_f}{\rho_a C_D A_D} \quad (\text{m})$$

D.4. Vapor cloud dispersion

The model to be used is the so-called Britter and McQuaid model and it will be used for instantaneous release. The procedure consists of three steps (TNO Yellow book, 2005).

Step 1: Calculate the down-wind distance x. This will be done with the use of the nomograms of the methods. From a given c_{max}/c_0 and $\left(\frac{g_0 \cdot V_0^{1/3}}{u_a}\right)^{1/2}$ the $\frac{x}{V_0^{1/3}}$ will be calculated and therefore the x.

Where:

C_{max} the maximum concentration of dispersed gas in volumetric units (sour gas-hydrogen sulfide)
C_0 the initial concentration of dispersed gas in volumetric units (sour gas-hydrogen sulfide)
g_0 (m/s^2) effective gravity at source, $g(\rho_0-\rho_\alpha)/\rho_\alpha$ with ρ_0, ρ_α the densities of the gas at the source and the air respectively (kg/m^3).
V_0 the initial volume (m^3)
u_a the air velocity m/s

Step 2: Calculate the arrival time of at x from the equation

$x = 0.4u_a t + b(t)$

$0.4u_a$ is an empirical estimate of the advection velocity
Where b(t) is the cloud radius with $b(t) = \sqrt{b_0^2 + 1.2t\sqrt{(g_0 V_0)}}$ and b_0 the source radius (m).

The mean height of the cloud will be calculated with use of the following equation:

$b_z(t) = c_o \cdot V_o / (\pi \cdot b(t)^2 c_{\max}(t))$

Step 3: The radius b(t) is the is the half-width of the cloud at time t.The safe position is outside the range of the b(t). Then draw x, $b_{0,}$b.

C.5. Jet fire

The model is going to be used for both cases (pipe gets out from the vessel, vessel opens totally). This model consists of 30 steps (TNO Yellow book, 2005; Chamberlain, 1987). The steps of the used model are the following.

Step 1: Determination of the mass fraction of the flammable material

$$W = W_g / (15.816 W_g + 0.0395) \quad (-)$$

Where
W_g is the molecular weight of the released gas (kg/mol)

Step 2: Calculation of the Poisson constant γ with $\gamma = C_p / C_v$

Where
C_p specific heat capacity at constant pressure (J/kg*K)
C_v specific heat capacity at constant volume (J/kg*K)

Step 3: Determination of the temperature of the expanding jet.

$$T_j = T_s \cdot (P_{air} / P_{init})^{((\gamma-1)/\gamma)} \qquad \text{(K)}$$

Where
T_s the initial temperature of the gas (K)
P_{air} atmospheric pressure (N/m^2)
P_{init} initial pressure (N/m^2)

Step 4: Determination of the static pressure at the hole exit plane

$$P_c = P_{init} \cdot (2/(\gamma+1))^{(\gamma/(\gamma-1))} \quad (\text{N/m}^2)$$

Step 5: Determination of Mach number (depends on the fact if we have a chocked or unckocked flow see section of dense gas release).

For chocked flow

$$M_j = \sqrt{\frac{(\gamma+1)\left(\left(\frac{P_c}{P_{air}}\right)^{(\frac{\gamma-1}{\gamma})} - 2\right)}{\gamma - 1}}$$

Where

P_c the static pressure at the hole exit plane (N/m^2)

For unchocked flow

$$M_j = \sqrt{\frac{\sqrt{1+2(\gamma-1)F^2} - 1}{\gamma - 1}}$$

Where

$$F = 3.6233 \cdot 10^{-5} \cdot \frac{m}{d_0^2}\sqrt{\frac{T_j}{\gamma \cdot W_g}}$$

m the mass flow rate (kg/s)
d_0 diameter of hole (m)
T_j temperature of the gas in the jet (K)
W_g molecular weight of gas kg/mol

Step 6: Determination of the exit velocity of the expanding jet.

$$u_j = M_j \cdot \left(\gamma \cdot R_c \cdot T_f / W_g\right)^{1/2} \quad \text{(m/s)}$$

Where
R_c gas constant 8.314 j/mol*K
T_j temperature of the gas in the jet (K)
W_g is the molecular weight of the released gas (kg/mol)

Step 7: Determination of the ratio of the wind velocity

$$R_w = u_w / u_j \ (-)$$

Where
u_w the wind velocity (m/s)
u_j the jet velocity (m/s)

Step 8: Determination of the air density

$$\rho_{air} = P_{air} \cdot W_{air} / (R_c \cdot T_{air}) \quad \text{(kg/m}^3\text{)}$$

Where
P_{air} atmospheric pressure (N/m^2)
T_{air} air temperature (K)
W_{air} Molecular weight of air (kg/mol)
R_c gas constant 8.314 j/mol*K
ρ_{air} density of air (kg/m^3)

Step 9: Determine combustion effective source diameter

For unchecked flow

$$D_s = \left(4 \cdot m / \left(\pi \cdot \rho_{air} \cdot u_j\right)\right)^{1/2} \text{ (m)}$$

Where

D_s effective hole diameter (m)
m mass flow rate (kg/s)
ρ_{air} density of air (kg/m^3)
u_j velocity of the jet (m/s)

For chocked flow

$$\rho_j = P_c \cdot W_g / (R_c \cdot T_j) \text{ (kg/m}^3\text{)}$$

$$D_s = d_j \left(\frac{\rho_j}{\rho_{air}} \right)^{1/2}$$

Where
P_c the static pressure at the hole exit plane (N/m^2)
W_g is the molecular weight of the released gas (kg/mol)
R_c gas constant 8.314 j/mol*K
T_j temperature of the gas in the jet (K)
d_j diameter of the jet at the exit hole 9M0
ρ_{air} density of air (kg/m^3)
ρ_j density of gas in the jet (kg/m^3)

Step 10: Calculate the first auxiliary variable Y by iteration of the equation:

$$C_a \cdot Y^{5/3} + C_b \cdot Y^{2/3} - C_c = 0$$

Where:
Y is a dimensionless variable
$C_a = 0.024*(gD_s/u_j^2)^{1/3}$
$C_b = 0.2$
$C_c = (2.85/W)^{2/3}$

Step 11: Determination of the length of the jet flame in still air with the equation:

$$L_{b0} = YD_s$$

Where
L_{b0} flame length in still air

Step 12: Determination of the length of the jet flame measured from the tip of the flame to the centre of the exit plane.

$$L_b = L_{b0} \cdot ((0.51 \cdot e^{(-0.4u_w)} + 0.49)) \cdot (1.0 - 6.0710^{-3} \cdot (\Theta_{jv} - 90^0)) \text{ (m)}$$

Where
Θ_{jv} Angle between hole axis and the horizontal in the direction of the wind

Step 13: Determination of the Richardson number of the flame in still air

$$Ri(L_{b0}) = (g/(D_s^2 \cdot u_j^2))^{1/3} \cdot L_{b0} \text{ (-)}$$

If $R_w \leq 0.05$ then the flame is jet nominated. The tilt angle is given by

$$\alpha = \left(\Theta_{jv} - 90^0\right) \cdot \left(1 - e^{-25.6Rw)}\right) + \frac{(8000 \cdot R_w)}{Ri(L_{b0})} \text{ (°)}$$

Where
Θ_{jv} Angle between hole axis and the horizontal in the direction of the wind (°)
$Ri(L_{b0})$ Richardson number based on L_{b0}

If $R_w > 0.05$ then the flame tilt becomes increasingly dominated by wind forces.

$$\alpha = \left(\Theta_{jv} - 90^0\right) \cdot \left(1 - e^{-25.6Rw)}\right) + (134 + 1726 \cdot (R_w - 0.026)^{1/2}) / Ri(L_{b0})) \text{ (°)}$$

Step 14: Determination of the lift off of the flame by the following empirical equation:

$$b = L_b \cdot \frac{\sin K\alpha}{\sin \alpha} \text{ (m)}$$

Where
L_b flame length, flame trip of exit flame (m)

$$K = 0.185e^{-20Rw} + 0.015$$

In still air (α=0°), b equals to $0.2L_b$. For flames pointing directly into high winds (α=180°), $b=0.015L_b$.

Step 15: Determination of length of frustum (flame):

$$R_l = \left(L_b^2 - b^2 \cdot \sin^2(\alpha)\right)^{1/2} - b \cdot \cos(\alpha) \text{ (m)}$$

Where
R_l length of frustum (m)

Step 16: determination of the ratio between air and jet density.

$$\frac{\rho_{air}}{\rho_j} = \frac{T_j \cdot W_{air}}{T_{air} \cdot W_R} \text{ (-)}$$

Step 17: Determination of the Richardson number based on the combustion source diameter and factor C', used for the calculation of the frustum base width.

$$Ri(D_s) = \left(\frac{g}{D_s^2 \cdot u_j^2} \right)^{1/3} \cdot D_s \quad (-)$$

$$C' = 1000 \cdot e^{(-100 \cdot Rw)} + 0.8 \quad (-)$$

Step 18: Determination of the frustum base width.

$$W_1 = D_s \cdot \left(13.5 \cdot e^{-6Rw} + 1.5\right) \cdot 1 - \left(1 - \frac{1}{15} \cdot \sqrt{\frac{P_{air}}{P_j}} \right) \cdot e^{-70 Ri(Ds)^{C' Rw}} \quad (m)$$

Where
W_1 width of frustum base (m)

Step 19: Determination of the frustum tip width.

$$W_2 = L_b \cdot \left(0.18 \cdot e^{9-1.5Rw)} + 0.31\right) \cdot \left(1 - 0.47 \cdot e^{(-25Rw)}\right) \quad (m)$$

Where
W_2 width of frustum tip (m)

Step 20: Determine the surface area of frustum including end discs.

$$A = \frac{\pi}{4} \cdot \left(W_1^2 + W_2^2\right) + \frac{\pi}{2} \cdot \left(W_1 + W_2\right) \cdot \left(R_1^2 + \left(\frac{W_1 - W_2}{2}\right)^2 \right)^{1/2} \quad (m^2)$$

Where

A Surface area of frustum including end discs (m^2)

An alternative for calculation of the frustum space area, the surface area for a cylinder with an average width can be applied:

$$A = \frac{\pi}{2} \cdot \left(\frac{(W_1 - W_2)}{2} \right)^2 + \pi \cdot R_1 \cdot \frac{(W_1 - W_2)}{2}$$

Where

A Surface area of a cylinder including end discs (m^2)

Step 21: Determination of the near heat per unit time released.

$$Q' = m' \cdot \Delta H_c$$

Where

Q' combustion energy per second (J/s)
m' mass flow rate (kg/s)
ΔH_c Heat of combustion (J/kg).

Step 22: Determination of the fraction of heat radiated from the surface of the flame.

$$F_s = 0.21 \cdot e^{(-0.00323 \cdot uj)} + 0.11 \quad (\text{-})$$

Where
F_s fraction of the generated heat radiated from the flame surface

Step 23: Determine the surface emissive power.

$$SEP_{max} = F_s \cdot Q' / A \quad (\text{J/m}^2\text{s})$$

Where SEP_{max} maximum surface emissive power (J/m^{2}s)

Step 24 and 25: Calculation of the atmospheric transmissivity

At first, given a certain flame temperature T_f, the absorption factor of the water in the air is going to be estimated. The first is the calculation of the partial vapor pressure of the water at 15°C and relative humidity RH of 0.7.

$$p_w = RH \cdot p_w^o$$

Where
p_w^o Saturation pressure of the water (N/m^2)

Assuming distance x of the object from the flame we calculate the $P_w x$ and with data we go to the graphs (Figure 6.2 TNO yellow book) and we calculate the absorption coefficient of water a_w.

As far as the absorption coefficient a_c of the carbon dioxide is concerned, $p_c x$ and from figure 6.3 of the TNO Yellow Book the a_c will be estimated. The atmospheric transmissivity will be calculated as:

$$\tau_a = 1 - a_w - a_c$$

With regard to the view factor, several models exist which are beyond the scope of this project. The view factor F_{view} takes values from 0 to 1. In this research a value of 1 will be assumed. A value of 1 implies that the segments that absorb radiation "see" nothing but an optical thick flame. According to Salater et al (2002), a conservative assumption involves the use of a view factor of 1 since the calculation of view factors is very difficult (Salater et al, 2002).

Step 26: Calculation of the heat flux at a certain distance x (which was discussed in the previous step).

$$q''(x) = SEP_{act} \cdot F_{view} \cdot \tau_a$$

With the assumption of the sour gas flame has hardly any soot formation:

$$SEP_{act} = SEP_{max}$$

After the calculation of the heat flux the last step is to estimate damages to people and to equipment (steel). This will be done by comparison of the calculated values with the threshold values. The threshold values can be found from the TNO Green Book (TNO Green Book, 2003).

C.6. Flash fire

The model that is going to be used is that of Raj and Emmons (Lees, 1995). In this model the flame height and the width will be calculated. Please note that treatment of the flame height is based on pool fires. The calculation equations are the following:

$$H = 20D\left[\frac{S^2}{gD}\left(\frac{\rho_o}{\rho_a}\right)^2 \frac{wr^2}{(1-w)^3}\right]^{\frac{1}{3}} \text{ (m)}$$

With

$S=2.3U_w$

Where:
D cloud depth or cloud height (m)
g acceleration due to gravity (m/s^2)
r the stochiometric air-fuel mass ratio
S flame speed (m/s)
U_w wind speed (m/s)
H visible flame height (m)
ρ_o density of fuel-air mixture (kg/m^3)
ρ_a density of the air (kg/m^3)
w a parameter that takes the value of 0 if the cloud is lean or has a stoichiometric composition (which is the case with this project)
The air density can be simply be calculated as

$$\rho_a = P_a \cdot W_a /(R_c \cdot T_a) \text{ (kg/m}^3\text{)}$$

Where
P_a atmospheric pressure (N/m^2)
T_a air temperature (K)
W_a Molecular weight of air (kg/mol)
R_c gas constant 8.314 j/mol*K

For the calculation of the fuel-air density the following equations, which are based on the model of the jet fires of Chamberlain in the TNO yellow book, are going to be used (TNO Yellow Book, 2005, Chamberlain, 1987).

Step 1: Determination of the mass fraction of the flammable material

$$W = W_g / (15.816 W_g + 0.0395) \quad (-)$$

Where
W_g is the molecular weight of the released gas (kg/mol)

Step 2: Calculation of the Poisson constant γ with $\gamma = C_p/C_v$

Where
C_p specific heat capacity at constant pressure (J/kg*K)
C_v specific heat capacity at constant volume (J/kg*K)

Step 3: Determination of the temperature of the expanding jet.

$$T_j = T_s \cdot (P_{air} / P_{init})^{((\gamma-1)/\gamma)} \quad (K)$$

Where
T_s the initial temperature of the gas (K)
P_{air} atmospheric pressure (N/m^2)
P_{init} initial pressure (N/m^2)

Step 4: Determination of the static pressure at the hole exit plane

$$P_c = P_{init} \cdot (2/(\gamma+1))^{(\gamma/(\gamma-1))} \quad (N/m^2)$$

The density of fuel-air mixture is then

$$\rho_o = P_c \cdot W_g / (R_c \cdot T_j) \quad (kg/m^3)$$

Where
P_c the static pressure at the hole exit plane (N/m^2)
W_g is the molecular weight of the released gas (kg/mol)
R_c gas constant 8.314 j/mol*K
T_j temperature of the gas in the jet (K)
d_j diameter of the jet at the exit hole 9M0
ρ_{air} density of air (kg/m^3)
ρ_o density of gas in the jet (kg/m^3)

Last but not least, the flame width can be simply calculated with the use of the analogy of H/W=2

C.7. Vapor cloud explosion

The method is going to be used is the ideal blast wave (TNT equivalency) method. The TNT equivalency method consists of seven steps. These are (FM Global, 2005):

Step 1: Determine a need to conduct a vapor cloud explosion study. In this research a flammable gas (sour gas) is going to be released and can form a vapor cloud.

Step 2: Determination of material release scenario. This simply means that there is a process system that collapses due to high pressure and sour gas is released.

Step 3: Determination of the material release rate. It is calculated from the equation of the dense gas release calculation (see dense gas release section).

In this step the discharge time is also going to be calculated. The discharge time can be simply calculated by dividing the hold up (that is the maximum mount of gas that can escape from the rapture) with the release gas rate. The discharge time is very important since it the time that an operator can think and make a decision before there vapor cloud is formed and ignited.

Step 4: Determination of energy release.
This means that the energy released which is expressed in TNT equivalency is going to be calculated with the equation 2:

$$W_e = W_g \cdot \frac{\Delta H_C \cdot f}{1.111 \cdot 10^6}$$

Where:
W_e is the mass of the equivalent energy yield (tones)
W_g is the mass of gas released, in the situation of the vapor cloud explosion the hold up (kg)
ΔH_C is the heat of combustion of material (Kcal/kg)
f is the explosive yield efficiency factor (that is 0.05 because the sour gas is assumed to consist only of hydrogen sulfide which is a class I material, material with normal risk).
$1.111*10^6$ is based on the energy of decomposition for TNT of 111Kcal/kg

Step 5: Determination of overpressure radii
First the scaled ground distance factor is going to be obtained by the tables of hemispherical surface explosion. Then the radial distance from energy release is going to be calculated with the use of equation 3.

$$R_g = Z_g \cdot W_e^{1/3}$$

Where:
R_g is the radial distance from energy release epicenter at given overpressure (m or ft)
Z_g is the scaled ground distance ($m/kg^{1/3}$)
W_e is the TNT equivalent (kg)

Step 6: Determination of cloud drift and explosion epicenter
This means that the distance that the vapor cloud is going to drift. This evaluation is going to be done with the use of empirical charts based on the class of the released material and the weight of vapor which is released.

Step 7: Determination of damage
It is a qualitative assessment of damage. This step is not going to be conducted since it is not the intension of the research to estimate the damage to buildings etc.

Appendix D: Data and results for the selected models

Data and results are not shown in the public version of the report because of reasons of confidentiality.

Appendix E: Evaluation form-trainees/operators.

Evaluation form-trainees

Date:
Time:

Training objectives

1. Are the objectives clearly stated?

2. Do you agree with the stated objectives?

Training format

3. Does the training reach the objectives set in your opinion?

4. Did you find the session/presentation interesting?

5. Did you find the discussion during the session and afterwards interesting?

6. Is there any room for improvement in the training format? If yes, what & how?

Selected scenario

7. Is the scenario both credible and suitable fro training in your opinion?

8. Is the scenario detailed enough fro the purpose of this training?

9. What other scenarios do you think should be part of the scenario based training?

Relevance for operators

10. Did you learn something useful?

11. Have you experienced parts of the scenario? If yes, what did you do?

Suggestions for improvements

12. Do you have any other suggestions for improvements?