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Theme:

Application of Quantitative Risk Analysis (QRA) on an Industrial Installation: A Case Study of the Gas Treatment Unit at Guellala

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Abderrahmane...

DEDICATION

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Abderrahmane …

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List of Abbreviations

Abbreviation	Definition
ATEX model	Atmospheric Expansion model
BKH	Benkahla
BLEVE	Boiling Liquid Expanding Vapor Explosion
CCPS	Center for Chemical Process Safety
C1	Methane
C2	Ethane
DNV	Det Norske Veritas
EMA	Error Mode Analysis
ETA	Event Tree Analysis
FMEA	Failure Mode and Effect Analysis
FMECA	Failure Mode, Effect and Criticality Analysis
FTA	Fault Tree Analysis
GDP	Gross Domestic Product
GLA	Guellala
GTU	Gas Treatment Unit
HAZID	Hazard Identification
HAZOP	Hazard and Operability Analysis
HBK	Haoud Berkaoui
HP	High Pressure
IEC	International Electrotechnical Commission
IPL	Independent Protection Layers
LPG	Liquefied Petroleum Gas
LOPA	Layer Of Protection Analysis
LP	Low Pressure
MCS	Minimal Cut Sets
MP	Medium Pressure
N.A	Not Available
PD	Production Division
PHA	Preliminary Hazard Analysis
PHAST	Process Hazard Analysis Software Tool
P&ID	Piping and Instrumentation Diagram
QRA	Quantitative Risk Assessment
RAMIS	Reliability, Availability, Maintainability, Inspectability, and Safety
RN	Route Nationale
SAFETI	Safety Analysis for Engineering, Technology, and Innovation
SIF	Safety Instrumented Function
SIL	Safety Integrity Level

SONATRACH	Société Nationale pour la Recherche, la Production, le Transport, la Transformation, et la Commercialisation des Hydrocarbures
UIC	Union des Industries Chimiques
VCE	Vapor Cloud Explosion

General Introduction

Quantitative Risk Analysis (QRA) is a powerful methodology used to assess and quantify risks associated with potential hazards in various industries, including the gas treatment sector. It provides a systematic approach to identify, analyze, and evaluate risks, enabling informed decision-making and effective risk management strategies. The primary objective of QRA is to quantify the likelihood and consequences of hazardous events, such as fires, explosions, and toxic releases, in order to assess their impact on people, the environment, and assets. By considering factors such as failure frequencies, event probabilities, and potential consequences, QRA helps stakeholders gain a comprehensive understanding of the risks involved. In conjunction with QRA, supplementary risk analysis techniques are often employed to enhance the overall risk assessment process. Techniques such as Process Hazard Analysis (PHA), Hazard and Operability Study (HAZOP), Layers of Protection Analysis (LOPA), Fault Tree Analysis (FTA), and Event Tree Analysis (ETA) provide valuable insights into hazard identification, consequence analysis, and risk mitigation measures. The gas treatment unit of Guellala serves as a relevant context to apply QRA and explore the associated risk analysis techniques. This unit involves complex processes and operational activities that warrant a thorough assessment of potential risks. By focusing on specific components, such as the spheres within the unit, a detailed analysis can be conducted to identify failure frequencies and assess the impact of potential scenarios. Furthermore, the application of advanced software tools, such as SAFETI, developed by DNV, facilitates the quantitative assessment of risks in the gas treatment industry. These software solutions provide comprehensive risk modeling and analysis capabilities, enabling the calculation of individual and societal risk levels and aiding in decision-making processes. Overall, the application of QRA, in conjunction with supplementary risk analysis techniques, provides a systematic and quantitative approach to assess and manage risks in industrial installations. By applying these methodologies to the gas treatment unit of Guellala and utilizing software tools like SAFETI, the aim is to gain valuable insights into risk levels, identify critical scenarios, and develop effective risk mitigation strategies for ensuring the safety and operational integrity of the facility.

The primary focus of our study is to determine the risk frequency in Guellala, specifically whether it is characterized by a high or low level of risk. This investigation addresses a critical concern as it directly impacts the safety and well-being of the community and the surrounding environment. By conducting a thorough analysis, we aim to gain a comprehensive understanding of the potential hazards, their likelihood of occurrence, and the associated consequences. Through rigorous data collection, assessment, and analysis, we can quantify and evaluate the frequency of risk events in Guellala. The findings will shed light on the prevailing risk landscape and enable us to make informed decisions regarding risk management strategies. Whether the risk frequency is identified as high or low, the results will serve as a vital foundation for developing effective risk mitigation measures, enhancing safety protocols, and promoting a culture of proactive risk awareness. Ultimately, our study seeks to contribute to the overall safety and resilience of Guellala by providing valuable insights into the risk frequency and enabling stakeholders to make well-informed decisions to protect the community and mitigate potential hazards.

CHAPTER I: GENERALITIES ON QUANTITATIVE RISK ASSESSMENT (QRA)

Risk assessment is a crucial aspect of safety management in various industries. It involves identifying and evaluating potential hazards, and determining the measures needed to mitigate those risks. There are several methods of risk assessment, including qualitative and quantitative approaches. While qualitative risk assessment provides a general idea of the level of risk, Quantitative Risk Assessment (QRA) goes a step further by providing a numerical representation of the risk. QRA is a highly valuable tool in risk management, as it provides a more precise and objective evaluation of risk. It involves the use of mathematical models to estimate the likelihood and consequences of potential hazards, and to determine the level of risk associated with those hazards. This information can then be used to prioritize risk mitigation measures and allocate resources effectively.

Furthermore, QRA allows for the comparison of different scenarios and the impact of different mitigation measures on the overall risk level. This enables organizations to make informed decisions regarding safety and risk management, and to continually improve their safety practices. While qualitative risk assessment provides a general understanding of risk, QRA offers a more accurate and precise evaluation of risk. Its ability to provide numerical representations of risk and to compare different scenarios makes it a valuable tool in risk management and a key component of effective safety management.

In general, Quantitative risk analysis (QRA) is an effective technique for managing risk and enhancing safety in various industries. When executed correctly and with consideration for its theoretical and practical limitations, QRA offers a logical method for assessing process safety and evaluating alternative improvement options. However, it is not a solution to all issues, cannot make decisions for managers, or replace current safety assurance and loss prevention practices. In the case where QRA is preferred, qualitative results, which form the basis for QRA, should be utilized to validate and bolster any conclusions made from the analysis.[1]

1. *Objectives of QRA*

The goals of a quantitative risk assessment (QRA) can encompass:

• Evaluating the magnitude of risk and determining its significance, in order to determine the need for risk reduction.

• Determining the primary sources of risk, in order to gain a deeper understanding of the hazard and identify potential risk reduction strategies.

• Establishing design accident scenarios, which can be used as a foundation for emergency planning and training, or for fire protection and evacuation equipment design.

• Comparing design alternatives, which provides insight into risk factors in the selection of a concept design.

• Evaluating risk reduction strategies, which can be linked to cost-benefit analysis to determine the most cost-effective way of reducing risk.

• Demonstrating compliance to regulators and the workforce, showing that the risks have been minimized to the greatest extent possible.

• Identifying crucial safety procedures and equipment, which are essential for minimizing risk and need close monitoring during operations.

• Recognizing potential accident triggers, which may be monitored during operations to provide early warning of negative trends in incidents.[2]

These objectives of a QRA offer a systematic method for monitoring risk and providing guidance for safety-related decision-making.

2. *Steps of QRA*

The process of Quantitative Risk Assessment (QRA) involves a structured method for evaluating the potential dangers associated with a specific activity or system. This method typically involves a series of steps, including:

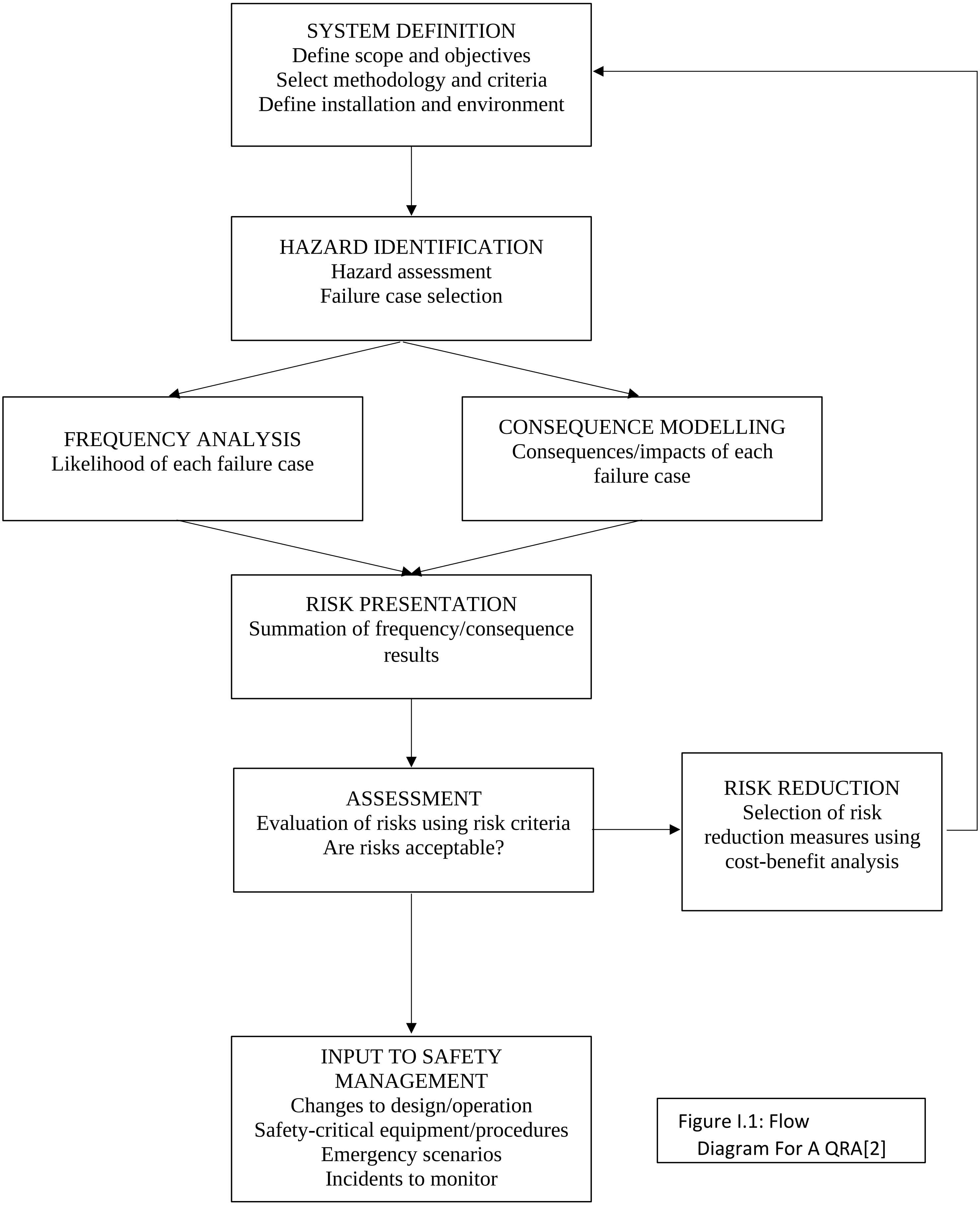

Figure I.1: Flow Diagram For A QRA[2]

2.1 System definition

A comprehensive description of the technical system must be provided, including an overview of the relevant operations and phases. The time frame of the analysis should be specified, along with the specific personnel groups, external environment, and assets being considered in the risk assessment. Additionally, the system's ability to withstand failures and its susceptibility to accidental consequences should be evaluated.[3]

2.2 dentification of Hazard

The identification of hazards is an important step in the risk assessment process and includes a comprehensive review of potential hazards and sources of accidents. This review should emphasize the need to not overlook any relevant hazards. A rough classification of hazards into critical and non-critical categories is performed to aid in subsequent analysis. Clear criteria for the screening of hazards should be established and the evaluations made for the classification of non-critical hazards should be thoroughly documented.[3]

The hazard identification process may be assisted by utilizing checklists, reviewing accident statistics, conducting HAZOP studies or HAZID, or drawing upon prior experience.

2.3 Cause analysis

The objective of hazard cause analysis is to identify the root causes of potential incidents and assess their likelihood of occurrence. This includes understanding the factors and conditions that could lead to an initiating event and the combinations that may result in such an event. Additionally, the analysis aims to determine the feasibility of implementing risk-reducing measures to mitigate the identified hazards. The first objective, identifying the combination of causes, is mainly qualitative while the latter, assessing the probability, is quantitative in nature.[3]

2.4 Qualitative Cause Analysis Techniques

The process of evaluating the causes of initiating events in a risk assessment is often a combination of qualitative and quantitative methods. When data is limited or not required for quantification, a qualitative analysis may be the sole step taken. The objective of a qualitative analysis is to identify the causes and conditions that may lead to the occurrence of initiating events, recognize combinations that result in such an event, and lay the foundation for further quantification if necessary. Techniques commonly used in cause analysis include Hazard and Operability Analysis (HAZOP), Fault Tree Analysis (FTA), Preliminary Hazard Analysis (PHA), Failure Mode and Effect Analysis (FMEA), and human error analysis techniques like Task analysis and Error Mode Analysis (EMA). These techniques are borrowed from the field of reliability analysis and aim to identify and analyze the root causes of initiating events.[3], [4]

1.1.1 Quantitative Cause Analysis Techniques

Quantitative risk analysis aims to determine the likelihood of hazards or initiating events happening by analyzing their possible causes. Common techniques used in this type of analysis include:

- Event tree analysis ETA
- Fault tree analysis FTA
- Layer of protection analysis LOPA

1.1.2 Consequence and Escalation Analysis

The term "consequence analysis" encompasses a range of activities, including estimating accidental loads, modeling escalation, and estimating responses to accidental loads. The distinction between cause analysis and consequence analysis may vary depending on the purpose and nature of the analysis.

A comprehensive consequence analysis typically involves the following sub-studies:

❖ **Leakage of inflammable substances**
- calculation of release (amounts, rates, duration, etc.)
- calculation of spreading of leakages
- calculation of ignition potential
- fire load calculation
- explosion load calculation
- response calculation (sometimes this may be separate studies)

❖ **Well blowouts (with respect to environmental loads)**
- calculation of releases
- calculation of release duration
- spill drifting calculation
- calculation of environmental effects

❖ **Well blowouts (non-environmental effects)**
- consequences related to ignition and subsequent effects are calculated as for leakages of
- inflammable substances

❖ **External impact (collision, falling load, helicopter crash on installation)**
- calculation of energy distribution
- calculation of load distribution
- calculation of impulse distribution

- response calculation (may also be separate studies)

❖ **Falling loads on subsea installations and pipelines**

- consequence calculations as for external impacts in general

❖ **Extreme environmental loads**

- calculations are usually carried out by the relevant discipline as part of the analyses of structural design, and the results from these studies may be integrated into the risk analysis

❖ **Loss of stability and buoyancy, catastrophic loss of anchor lines**

- calculations are usually carried out by the relevant discipline as part of the marine studies, and the results from these studies may be integrated into the risk analysis.[5]

3. Risk reduction

The outcome of a Quantitative Risk Assessment (QRA) is used to identify risk reducing measures, with the aim of reducing the risk level to an acceptable level. The results of the QRA process provide a basis for making decisions on risk reduction measures and prioritizing the measures to be implemented. The risk reduction measures may include modifications to the system, procedures or working practices, improvements in training, or changes to the physical design of the system.

The implementation of risk reducing measures should be monitored and reviewed to ensure that the desired effect is achieved and that the risk remains at an acceptable level. This can be done through regular re-assessments, performance monitoring, and updating of the risk assessment as new information becomes available or as the system evolves.

Quantitative Risk Analysis (QRA) is a valuable approach for assessing and quantifying risks associated with hazards. It finds applications in various industries, aiding in decision-making and risk management. The key steps of QRA include hazard identification, consequence analysis, frequency estimation, risk assessment, and risk management. By utilizing QRA, organizations gain insights into risks, prioritize measures, and enhance safety performance. Overall, QRA promotes informed decision-making and effective risk mitigation.

CHAPTER II: SUPPLEMENTARY RISK ANALYSIS TECHNIQUES IN CONJUNCTION WITH QRA

There are several other methods that can be used in conjunction with Quantitative Risk Assessment (QRA) to reduce risks and ensure safety.

These complementary methods can provide a more comprehensive view of risks, including both the likelihood of events and the consequences of events. By using a combination of these methods, organizations can more effectively identify risk reduction measures and prioritize them based on the level of risk they pose.

1. Preliminary Hazard Analysis (PHA)

Preliminary Hazard Analysis (PHA) method was developed in the early 1960s in the aeronautical and military fields. It has been used in many other industries since then, and the French Chemical Industries Union (CIU) has recommended its use in France since the 1980s. PHA is a widely used general purpose method for identifying risks at the preliminary stage of a facility or project design. As a result, this method generally does not require a detailed and in-depth knowledge of the studied facility.[6]

In this sense, it is particularly useful in the following situations:

- During the design phase of an installation, when the precise process definition has not yet been made. It provides a first safety analysis resulting in elements that form a draft of future operating and safety instructions. It also allows for the selection of the best-suited equipment.
- In the case of a complex existing installation, at the level of a risk analysis approach. As its name suggests, the PHA constitutes a preliminary step, highlighting elements or situations requiring more specific attention and therefore the use of more detailed risk analysis methods. It can then be supplemented by a method such as FMECA (Failure Modes, Effects and Criticality Analysis) or failure tree analysis.
- In the case of an installation whose level of complexity does not require more in-depth analysis in light of the objectives set at the start of the risk analysis.
- The PHA is a straightforward approach that is widely used to spot potential dangers during the design stage of a subject under study. The term "preliminary" is used because the findings may be revised as more in-depth risk assessments are performed. PHA can also be used in later stages of the system's lifecycle, and in the case of relatively uncomplicated systems, it may provide a full and adequate risk analysis. In some cases, a simplified version of PHA is referred to as Hazard Identification (HAZID).[7]

1.1 PHA Procedure

The three stages of a PHA study include:

Phase 1: preparation of the study

The first phase of a PHA study involves the collection of information on the system, including its mission and phases, as well as any relevant drawings. The process also involves the collection of hazard information from previous and similar systems, utilizing existing checklists where applicable. To facilitate the analysis, the system is broken down into manageable sections. Finally, the team leader and members are selected to conduct the study.[8]

Phase 2: implementation of the method

On each working section, the process of identifying hazardous elements begins by identifying elements of the system that are inherently dangerous. This can include sources of energy, system phases (such as takeoff in an airplane), and others. These elements can be hazardous by themselves or in combination with other elements. The identification process uses checklists, expertise, engineering judgment, and intuition. Next, for each identified hazardous element, the team must determine what events or circumstances could trigger the element to become a dangerous situation, such as unwanted events, failures, or mistakes.[8]

Table II.2: Typical PHA worksheet[8]

<table>
<tr><th colspan="9">PHA WORKSHEET</th></tr>
<tr><td colspan="5">Sub-system / Function:</td><td colspan="4">Phase:</td></tr>
<tr><td>Hazardous element</td><td>Event causing hazardous situation</td><td>Hazardous situation</td><td>Event causing potential accident</td><td>Potential accident</td><td>Effect</td><td>Severity class</td><td>Accident prevention measures</td><td>validation</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

The process of identifying potential hazardous situations that could result from the interaction between the system and each hazardous element within the system is described. A hazardous situation is defined as any item or function state that constitutes a threat or poses a risk to something of value within or related to the system. The identification of hazardous situations is done through the use of checklists, experience, engineering judgment, and intuition. Then, for each hazardous situation, the triggering events that could cause it to become a potential accident are identified. These triggering events are typically unwanted events or failures.[8]

The description of the consequences that may result from potential accidents is included. The accidents are ranked based on a pre-determined level of severity. Preventative measures to control or eliminate identified hazardous situations and potential accidents are determined. This involves ensuring that detection systems (such as sensors) are in place, and if not, identifying new systems that need to be installed. The validated preventive measures are documented and the status of any remaining recommended measures is recorded[8].

Phase 3: results of the study

The outcome of a PHA study includes a documented list of identified hazardous elements and potential accidents, along with validated preventive measures and areas that require further examination.[8]

2. Hazard and Operability Analysis (HAZOP)

The HAZOP (Hazard and Operability) study is a method used to systematically identify potential hazard scenarios that could affect various receptors such as people, the environment, and property. It also investigates operability scenarios, focusing on the process's ability to function correctly. The HAZOP study originated from Work Study and Critical Examination techniques. During a HAZOP study, deviations from the intended design are examined as they represent potential problems. These deviations are generated by applying guide words to process parameters at different nodes throughout the process. For example, guide words such as "No," "More," "Less," "As Well As," "Part Of," "Reverse," and "Other Than" are used to explore deviations in parameters like flow, pressure, temperature, composition, level, addition, cooling, and others. The goal of the HAZOP study is to identify all aspects of design intent where deviations may lead to scenarios within the study's scope and objectives. The study team brainstorms the causes of each deviation at each node and identifies the sequence of events that would result from each cause, including the potential failure of safeguards and the consequences of the scenario. By analyzing these scenarios, the HAZOP study helps in assessing the severity and likelihood of each consequence qualitatively, allowing for a risk estimate to be generated. This risk estimate aids in determining the need for risk reduction measures. The HAZOP study is a comprehensive and systematic approach that ensures the thorough exploration of deviations from design intent, contributing to the identification of potential hazards and operability issues in a process.[9]

2.1 HAZOP Procedure:

A HAZOP study is performed in three phases:

Phase 1: preparation of the study

the first step is to select a team leader and form a multidisciplinary study team. Then, the team collects information on the plant including updated Piping and Instrumentation Diagrams (P&IDs), piping schedule, safety valve rating, and other relevant details. The plant is then divided into homogeneous sections known as parts or nodes, where the design intention can be clearly defined based on factors such as pressure and temperature.[8], [10]

Phase 2: implementation of the method

The HAZOP method is applied to each node in several steps by the study team, which is led by the team leader.

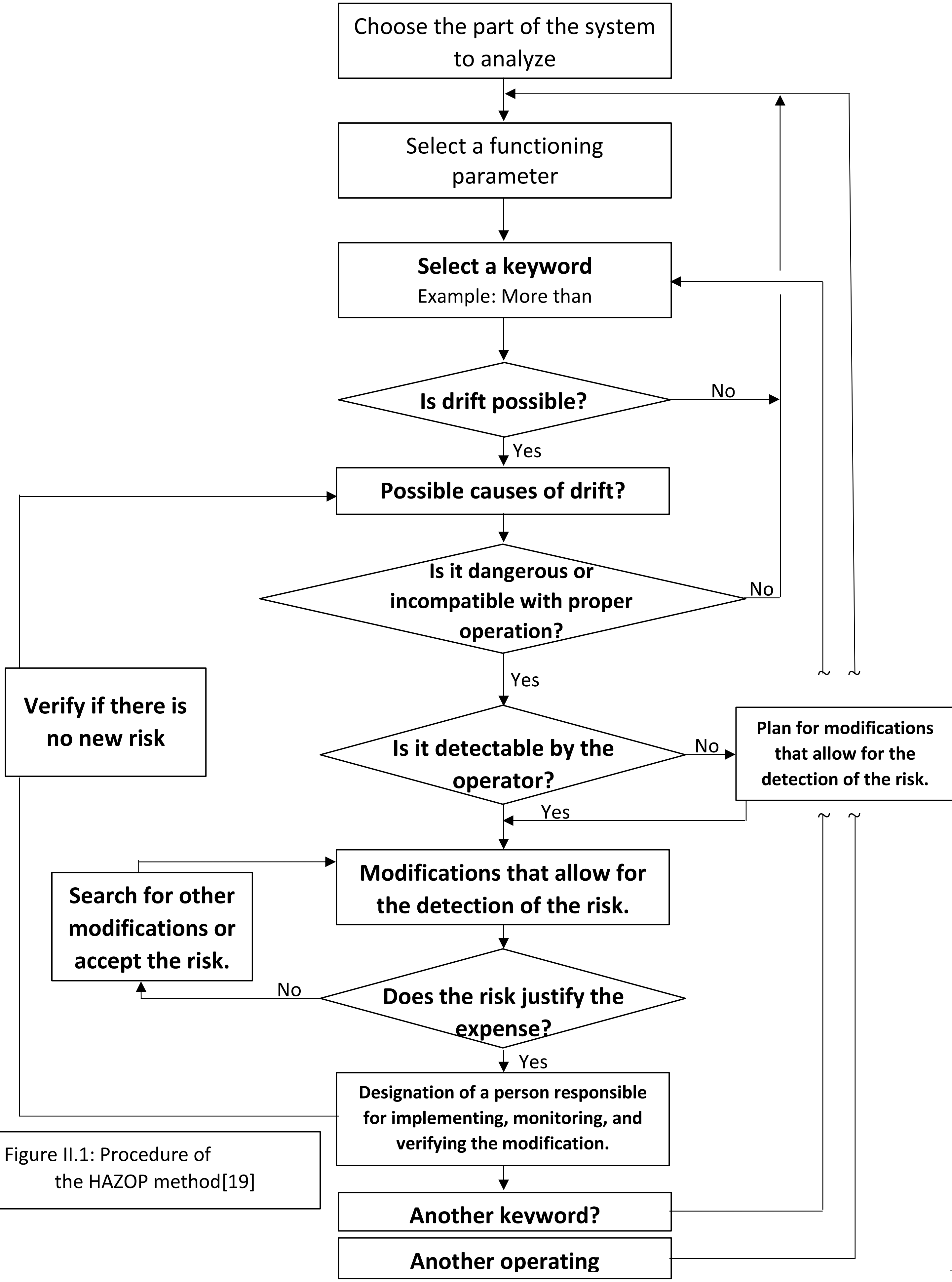

Figure II.1: Procedure of the HAZOP method[19]

- **Step 1.1:** Explain the design intention.
- **Step 1.2:** Select the first physical operating parameter (e.g., pressure):
- **Step 1.2.1:** Apply the first guide word (such as "More" on Table 1) to the parameter (which gives "more pressure than expected"):
  - Identify the possible causes of the deviation.
  - Assess the severity of the consequences of the deviation.
  - Define the existing safeguards.

Table II.2: Typical HAZOP worksheet[8]

HAZOP WORKSHEET				
Part:				
DEVIATION	POSSIBLE CAUSES	CONSEQUENCES	SAFEGUARDS	ACTION REQUIRED

Table II.3: HAZOP Main guide words and physical parameters considered[8]

Parameter	**Guide word**
Pressure	More
	Less
Flow	More
	Less (none)
	Reverse
Temperature	More
	Less
Level	More
	Less
Concentration	More
	Less
	Part of
Contamination	N. A.
Other	Start-up
	Maintenance
	Static electricity
	Utility failure
	Other than

The safeguards are the actions against the consequences of the deviation (as such they include the detection of the deviation).

- Determine whether an action (for improvement or investigation) is required.
- Define the required action if this one is obvious otherwise recommend a study to be made.

- **Step 1.2.2:** Apply the second guide word (e.g., “Less”) to the parameter (Which gives “less pressure than expected”) and rerun the above step.

- Apply all other guide words and rerun Step1.2.

- **Step 1.3:** Select the second physical parameter (e.g., flow) and rerun Step 1.2.

- Select all other parameters and rerun Step 1.1 in sequence.
- Step 2 to Step 3. Select all other nodes and rerun Step 1 in sequence.[8], [10]

Phase 3: results of the study.

The team leader reviews the proposed actions and builds an action plan.

3. Layer Of Protection Analysis LOPA

The LOPA method [CCPS 2001] was developed in the late 1990s by the CCPS (Center for Chemical Process Safety). LOPA stands for Layer of Protection Analysis. It is a barrier-oriented method just like RAMIS. The first steps are quite comparable to those of the ARAMIS method, in terms of general principles, although many differences remain in the details of the two methods. On the other hand, LOPA does not provide for a cartographic representation of severity and vulnerability.[11]

3.1 Procedure of LOPA

The LOPA method is typically divided into six main steps, each of which is designed to progressively refine the risk assessment process. These steps include:

3.1.1 Establishment of the criteria for selecting the scenarios to be evaluated

This step is a prerequisite for risk analysis. It provides a means of limiting the duration of the study by considering only the scenarios that are significant in terms of consequences. The criterion can be an intensity criterion (quantity of product released, flow measured at the source) or a consequence criterion that implicitly incorporates the existence of stakes in the surrounding areas.[11], [12]

3.1.2 *Development of accident scenarios*

The accident scenarios are developed based on a risk analysis using traditional tools such as FMEA or HAZOP. The scenarios are represented in the form of a Bow-Tie Diagram.[11]

3.1.3 *Identification of frequencies*

A detailed analysis of the scenarios is undertaken by considering each combination of initiating events associated with a consequence. The frequency of occurrence of each initiating event is estimated based on data from feedback or from the literature.[12]

3.1.4 *Identification of safety devices and their demand failure probabilities*

For each scenario, safety devices are identified, considering the qualification criteria for these devices, such as their independence from the phenomenon or event to which they apply, the ability to implement the device, and the possibility of inspecting the device. The devices that meet these criteria are called Independent Protection Layers (IPL); a concept similar to that of Safety Instrumented Functions (SIF).[11], [12]

Each safety device is associated with a probability of failure upon demand, which corresponds to a risk reduction factor. LOPA explicitly refers to the Safety Integrity Level (SIL) inspired by the IEC 61508 standard. The considered safety systems are essentially technical, but in theory, it is also possible to take into account human or organizational barriers .[11], [12]

3.1.5 *Risk estimation*

The probability of the accident scenario is then estimated by reducing the probability of the initiating event by several orders of magnitude corresponding to the SIL levels of the selected safety devices. As in the ARAMIS method, decision matrices are used to define the minimum risk reduction level that systems must present based on the possible consequence level of the scenario and the frequency of the initiating event. However, the LOPA method does not require the use of these matrices, and the user is free to implement more traditional safety function calculations if desired and has the possibility to do so.[11], [12]

3.1.6 *Risk evaluation against acceptability criteria*

The final step of the method is to ensure that the risk is controlled, i.e., that it is well below the acceptability criteria that were previously established. LOPA does not require a specific type of predefined criterion and thus proposes four categories of criteria:

- a criticality grid containing an acceptability limit in terms of severity and frequency;
- a purely quantitative criterion relating to the level of consequence of the scenario;

- a criterion specifying the number of independent safety devices required to consider a scenario to be sufficiently controlled;
- a maximum cumulative risk criterion for a site or a process.

LOPA does not provide useful information for urban planning. Thus, vulnerability assessment and severity mapping are not addressed in the method. [11], [12]

4. Fault Tree Analysis FTA

In 1962, the fault tree technique was introduced at Bell Telephone Laboratories to evaluate the safety of the intercontinental Minuteman missile launching system. The technique was later enhanced by The Boeing Company, which introduced computer programs for both qualitative and quantitative fault tree analysis. Today, fault tree analysis is widely used for risk and reliability studies, and has successfully been used to analyze safety systems in nuclear power stations like the Reactor Safety Study.[13]

A fault tree is a logic diagram that illustrates the relationships between a potential critical event, such as an accident, in a system and the factors that may lead to it. These factors may include environmental conditions, human errors, normal events that are expected to occur during the system's life span, and specific component failures. Depending on the analysis objectives, fault tree analysis can be qualitative, quantitative, or both. The analysis can result in a list of possible combinations of factors that could lead to a critical event in the system, or the probability that the critical event will occur within a specific time frame. [13]

4.1 FTA procedure

There are four steps an analyst must take to perform a Fault Tree Analysis: 1st defining the problem, 2nd constructing the fault tree, 3rd analyzing the fault tree model qualitatively, and 4th documenting the results.

Step 1: Defining the problem

Selecting both a Top event and boundary conditions for analysis is crucial in defining the problem. The boundary conditions encompass:

- System physical bounds;
- Not allowed events;
- Level of resolution;
- Existing conditions;
- Initial conditions;
- Other assumptions.

One of the crucial steps in the beginning is defining the Top Event. This event, which is typically identified through previous hazard evaluations, is the consequence or undesired event that serves as the focus of the Fault Tree Analysis. In order to conduct an effective analysis, it is essential to precisely define the Top event for the particular system or plant being evaluated, since analyzing broadly scoped or vaguely defined Top events can often result in an inefficient analysis. For instance, a Top event of "fire at the plant" is too general for Fault Tree Analysis. Instead, a suitable Top event should be precisely defined, such as "runaway reaction in process oxidation reactor during normal operation." This event description is properly scoped and well-defined because it identifies "what," "where," and "when." The "what" (runaway reaction) specifies the type of incident, the "where" (process oxidation reactor) identifies the system or process equipment involved in the incident, and the "when" (during normal operation) describes the overall system configuration. Even better is to define the Top event as a specific loss event (an irreversible, physical event), like a vessel rupture caused by an unrelieved runaway reaction. [14]

The equipment, its interfaces with other processes, and the utility/support systems that will be incorporated in the Fault Tree Analysis are part of the Physical System Boundaries. In addition to these boundaries, the analyst should indicate the level of detail for the fault tree events (which specifies the amount of detail to be included in the fault tree). For example, a motor-operated valve could be treated as a single piece of equipment or broken down into various hardware components (such as the valve body, valve internals, and motor operator), along with the necessary switchgear, power supply, and human operator required for the valve to function. The level of detail to be included in the breakdown should take into account the quantity of detailed failure information that is available to the analyst, possibly from a previous safety study or FMEA. The level of detail in the fault tree should be limited to the extent necessary to fulfill the analysis objective and should match the level of detail of the available information. [14]

An additional boundary condition is the equipment's initial configuration or operating conditions, which outlines the system and equipment configuration that is incorporated in the Fault Tree Analysis. For all equipment within the physical system boundaries, the analyst identifies which valves are open or closed, which pumps are on or off, and so on. These boundary conditions specify the system's normal, non-failed state. [14]

In the context of Fault Tree Analysis, events that are deemed implausible or are otherwise deemed inappropriate for consideration in the analysis are referred to as "not allowed" events. For instance, wiring faults may be excluded from the assessment of an instrument system. Meanwhile, "existing conditions" are events or conditions that are expected to occur as part of the analysis. While the effects of unallowed and existing events may not be depicted in the final fault tree, they must be factored into the development of other fault events during the construction of the fault tree. [14]

As required to establish the system for the Fault Tree Analysis, the analyst may establish other assumptions. For example, the analysis may assume that the system is operating at 50% of its usual capacity. Once the problem has been fully defined and all boundary conditions have been set, these additional assumptions can help to resolve any remaining uncertainties regarding the system's condition.[14]

Step 2: Constructing Fault Tree

To start constructing a fault tree, the analyst begins with the Top event and proceeds through each level until all fault events have been traced back to their basic contributing causes (basic events). Using deductive cause-and-effect reasoning, the analyst determines the immediate, necessary, and sufficient causes that result in the Top event at the next level. Typically, these are intermediate faults that require further development rather than basic causes. If the basic causes of the Top event can be identified immediately, the problem may be too straightforward for Fault Tree Analysis and could be evaluated by other methods, such as FMEA.[14]

The fault tree shown in Figure 5 serves as an example of the process of fault tree construction using the symbols previously defined. The fault tree starts with the immediate causes of the Top event, which are represented in relation to the Top event. An OR logic gate is used to connect any immediate cause that can directly result in the Top event. Conversely, an AND logic gate is used to connect all immediate causes if they are all necessary for the Top event to occur, as is the case in Figure 5. The same method is used for each intermediate event, where the causes are determined and displayed on the fault tree with the appropriate logic gate. This process is repeated by the analyst until all intermediate basic events have been developed to their fault causes.[14]

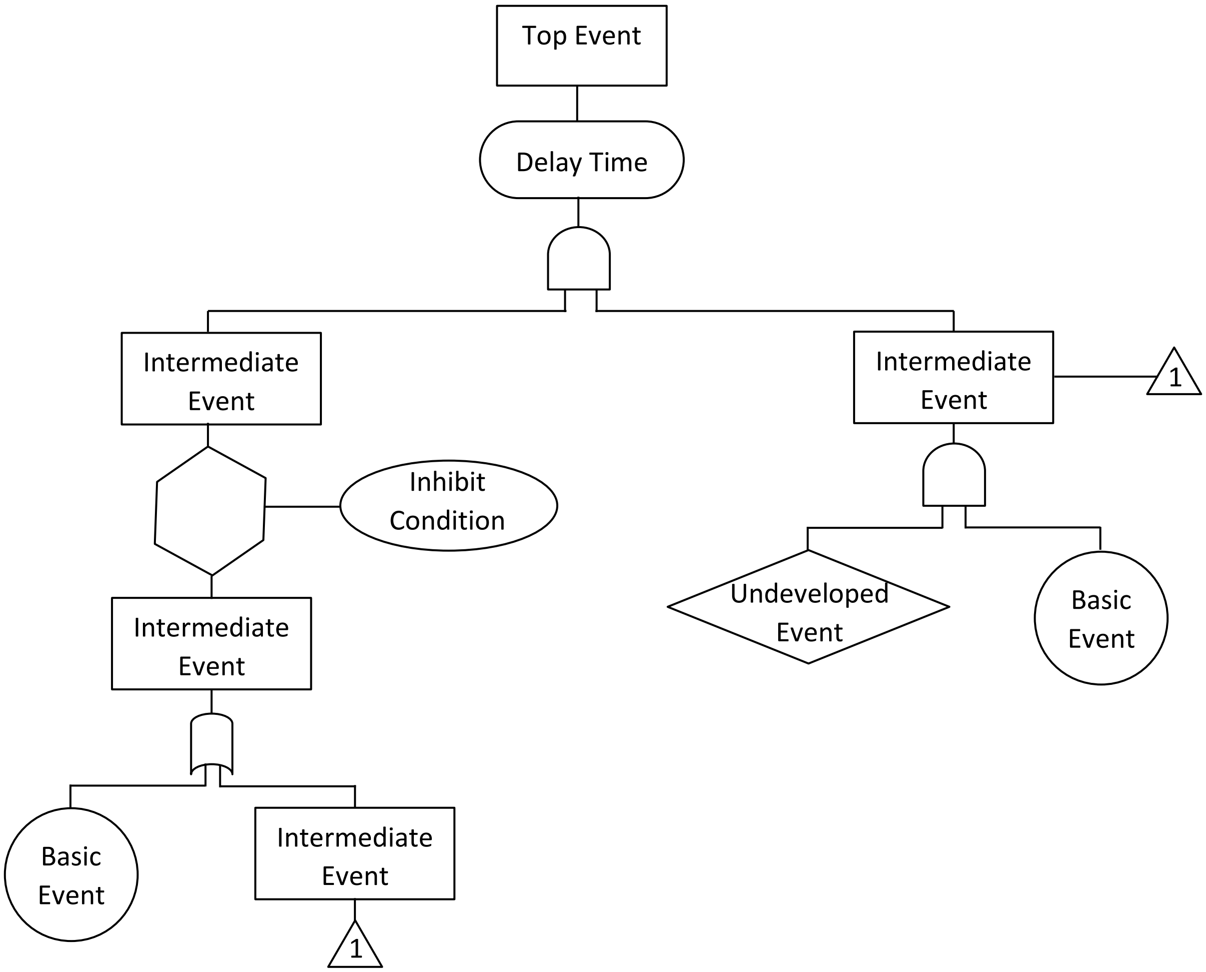

Figure II.2: Example of Fault Tree structure[14]

Table 4 provides a list of fundamental principles that have emerged to ensure uniformity and comprehensiveness in the process of constructing a fault tree. These principles are intended to stress the significance of a systematic and well-ordered approach to fault tree construction. Taking shortcuts that violate these rules may lead to an unfinished fault tree that disregards critical failure combinations. Moreover, such shortcuts restrict the fault tree's usefulness as a communication tool because only the analyst who created the fault tree will be able to comprehend the logic model.[14]

Table II.4: Rules for constructing fault trees[14]

Fault Event Statements	Write the statements that are entered in the event boxes and circles as malfunctions. State precisely a description of the component and the failure mode of the component. Making these statements as precise as possible is necessary for complete description of the fault event. The “where” and “what” portions specify the equipment and its relevant failed state. The “why” condition describes the state of the system with respect to the equipment, thus telling why the equipment state is considered a fault. These statements must be as complete as possible: the analyst should resist the temptation to abbreviate them during the fault tree construction process
Fault Event Evaluation	When evaluating a fault event, ask the question “Can this fault consist of an equipment failure?’’ If the answer is “yes,” classify the fault event as a “state-of-equipment fault.” If the answer is “no,” classify the fault event as a ‘state-of-system fault.” This classification aids in the continued development of the fault event. If the event is a state-of-equipment fault, add an OR gate to the fault event and look for primary, secondary, and command failures that can result in the event. If the fault event is a state-of-system fault. look for the causes of the fault event
No Miracles	If the normal functioning of equipment propagates a fault sequence, assume that the equipment functions normally. Never assume that the miraculous and totally unexpected failure of some equipment interrupts or prevents an incident from occurring
Complete Each Gate	All inputs to a particular gate should be completely defined before further analysis of any other gate. For simple models, the fault tree should be completed in levels, and each level should be completed before beginning the next level. However, experienced analysts may find this rule to be unwieldy when developing large fault trees
No Gate-to-Gate	Gate inputs should be properly defined fault events: that is, gates should not be directly connected to other gates. Short-cutting the fault tree development leads to confusion because the outputs of the gates are not specified

Step 3: Analyzing: The Fault Tree model

Once the fault tree is complete, it provides valuable information on how failures contribute to an incident. However, even an experienced analyst cannot determine all the possible combinations of failures that can lead to the incident of interest by solely examining the fault tree (unless it is very simple). This section describes a method to obtain these combinations (called minimal cut sets) for the fault tree, which is also known as "solving" the fault tree. The minimal cut sets represent all the possible combinations of failures that can lead to the fault tree's Top event and are logically equivalent to the information shown in the fault tree. These minimal cut sets aid in ranking the ways in which the incident can occur and, if appropriate data are available, enable the quantification of the fault tree. There are various methods, both manual and computerized, for obtaining the minimal cut sets of a fault tree. For complex fault trees, computer programs are required, but the approach described here enables the analyst to solve many simple fault trees encountered in practice.[14]

The fault tree solution method has four steps: 1st uniquely identify all gates and basic events, 2nd resolve all gates into sets of basic events, 3rd remove duplicate events within sets, and 4th delete all supersets (sets that contain other sets). The result of the procedure is a list of minimal cut sets for the fault tree. This procedure is demonstrated with an example using the fault tree shown in Figure 4.[14]

Step 3.1: To begin, it is necessary to assign unique identifiers to all gates and basic events in the fault tree. In Figure 4, the gates are labeled with letters and the basic events are numbered. Each identifier must be unique, and in cases where a basic event appears more than once in the fault tree, it must have the same identifier each time. For instance, in Figure 4, basic event 2 appears twice, but it has the same identifier both times.[14]

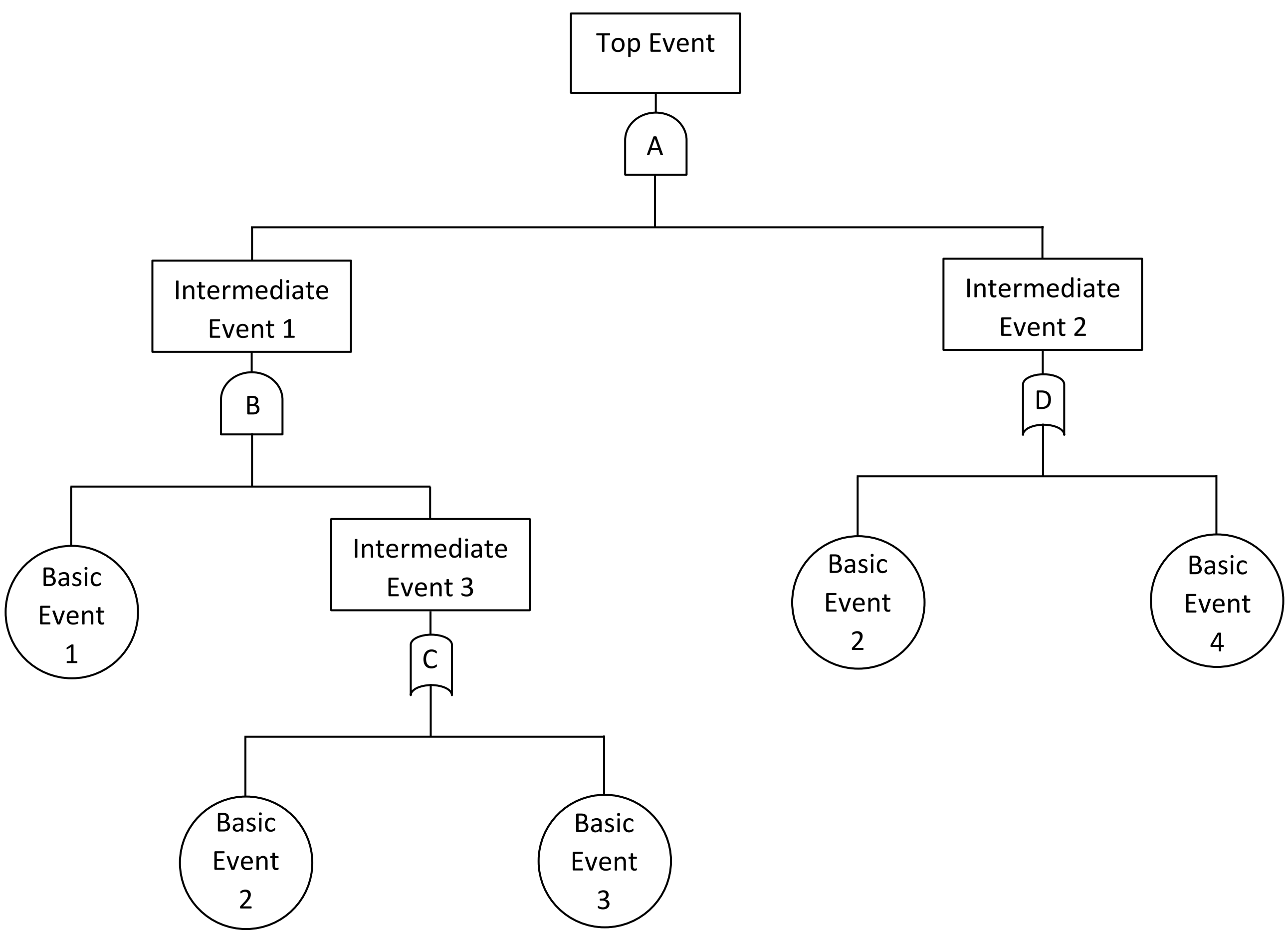

Figure II.3: Sample fault tree with gates and basic events identified[14]

Step 3.2: this step involves resolving all the gates into basic events in a matrix format. This process begins with the Top event and continues through the matrix until all gates have been resolved. Gates are resolved by replacing them in the matrix with their inputs. The Top event is always the first entry in the matrix and is entered in the first column of the first row. The remaining information is entered in the matrix according to two rules: the OR-gate rule and the AND-gate rule.[14]

The first input to an OR gate replaces the gate identifier in the matrix, while the other inputs are placed in the following empty rows, with each input in a separate row. Moreover, if there were previous entries in the same row as the OR gate, these entries should be repeated in all the rows that contain the other gate inputs[14].

To resolve an AND gate in the matrix, the first input replaces the gate identifier, and the other inputs are inserted in the next available column, on the same row as the AND gate. Any subsequent gates are resolved and their entries are included in the same row as the AND gate, and new rows are created as necessary. The rules for resolving INHIBIT and DELAY gates are the same as those for AND gates.[14]

Step 3.3: In the fault tree solution procedure, the third step involves eliminating redundant events that may exist within each set of basic events.[14]

Step 3.4: In the fault tree solution procedure, the fourth step involves eliminating all supersets present in the sets of basic events.[14]

Step 4: Documenting the results

The last step in conducting a Fault Tree Analysis is to record the findings of the study. The hazard analyst is responsible for explaining the system examined, discussing the problem definition, listing assumptions made, presenting the fault tree model(s) developed, documenting minimal cut sets, evaluating the importance of the MCSs, and providing any recommendations resulting from the FTA.[14]

5. Event Tree Analysis ETA

The ETA method is a probabilistic and graphical approach used for analyzing and modeling accident scenarios. This technique is based on forward logic and is inductive. The resulting diagram displays possible sequences of events or accident scenarios that may occur following a specified hazardous event. The event tree shows the responses of the system or plant to the hazardous event. The ETA method can start from any event in the accident scenario and can include external events that affect the scenario. Although the origins of the ETA method are not clear, it was first used in the Reactor Safety Study.[7]

The primary goals of an ETA include identifying potential accident scenarios that could arise from a hazardous event, as well as the barriers that are in place or planned to prevent or mitigate the harmful effects of such scenarios. The method also aims to evaluate the reliability and relevance of these barriers in the context of various accident scenarios, and to identify both internal and external events that could impact the event sequences and consequences of the scenario. ETA can be used to determine the frequency or probability of each accident scenario and to assess the spectrum of consequences for each scenario. It is a versatile tool that can be applied to all types of technical systems, with or without human operators. Event trees can be developed independently or in conjunction with fault tree analysis (FTA), which is focused on identifying the causes of hazardous events. ETA can be qualitative, quantitative, or both, depending on the analysis objectives and data availability. It has been widely used in the nuclear industry, chemical process industry, and other domains, as well as for human reliability assessment. Overall, ETA and FTA can be integrated within the bow-tie structure to provide a comprehensive and effective approach to risk analysis.[7]

5.1 ETA steps

The general procedure for Event Tree Analysis contains six steps: 1st identifying the initiating causes or loss events of interest that can result in the type of incident or impact of concern, 2nd identifying the safeguards designed to respond to the initiating cause or loss event, 3rd constructing the event tree, 4th describing the resulting event sequence outcomes, 5th determining the event sequence minimal cut sets, and 6th documenting the results. Each of these steps is discussed below.[14]

Step 1: Identifying a starting event of interest

Selecting an appropriate initiating cause (generally termed the initiating event when performing Event Tree Analyses) or loss event (if studying mitigation safeguards) is an important part of Event Tree Analysis. The event of interest, an initiating cause (initiating event) if a traditional event tree or a loss event if a mitigation event tree, will be referred to as the starting event. The starting event could also be an intermediate event, such as a process upset condition. If the starting event is an initiating cause, it should be a system or equipment failure or human error that could result in the effects of interest, depending on how well the system or operators respond to the event. If the selected event results directly in a specific incident, a Fault Tree Analysis is better suited to determine its causes. In most applications of Event Tree Analysis, the initiating cause is “anticipated”; that is, the plant design includes systems, barriers, or procedures that are intended to respond to and mitigate the effects of the initiating cause.[14]

Step 2: Identifying the safeguards designed to respond to the starting event

The measures that are in place to counteract the effects of the initiating cause or loss event are commonly referred to as the plant's defenses. These defenses may consist of various measures, including but not limited to:

- Alarm systems that alert the operator when the initiating cause is detected
- Required operator actions that should be taken in response to the alarms or as per the procedures
- Protective systems that automatically respond to the initiating cause
- Emergency safety systems such as pressure relief systems, quench systems, and scrubber systems
- Automatic isolation or other mitigation measures intended to restrict the impact of the loss event.

The safeguards that are designed to respond to the starting event have a significant impact on the potential consequences of any resulting incident. Therefore, it's crucial for the analyst to identify all the relevant safeguards that can prevent or reduce the effect of the starting event, in the order in which they are expected to act. The safeguards should be described with their intended purpose, and their effectiveness should be accounted for in the event tree, including both successful and unsuccessful responses.[14]

Step 3: Constructing the Event Tree

An important element of Event Tree Analysis is the construction of the event tree, which outlines the sequence of events from the starting event to the system's response. The event tree illustrates potential incidents that can arise from the starting event and identifies the safeguards that are in place to prevent or mitigate the adverse effects. The analyst aims to present the safeguards chronologically, even if some events happen almost simultaneously. The analyst should also account for the normal process control response when evaluating the safety system response to upsets. To construct the event tree, the starting event and relevant safeguards are listed on the left and top of the page, respectively.[14]

The next step in constructing the event tree is to assess the effectiveness of each safeguard, which is usually categorized into two options: success or failure. The analyst should assume that the initiating cause has occurred and determine the criteria for success or failure of the safeguard. Then, the analyst should determine if the success or failure of the safeguard would affect the course of the incident. If it does, the event tree divides into two paths at a branch point to distinguish between the success and failure of the safeguard. Typically, an upward path represents a successful safeguard while a downward path indicates a failed safeguard. On the other hand, if the safeguard does not have an impact on the incident, the incident path continues to the next safeguard with no branching point. To represent the success or failure of each safeguard, letters such as A, B, C, or D, are used for success, and a bar over the letter denotes a failure, such as A, B, C, or D.[14]

Each branching point in the event tree generates more incident paths that need to be assessed for each successive safety system. When assessing a safeguard along an incident path, the analyst must presume that previous successes and failures have occurred as directed by the path. This is illustrated in the example, where the second safeguard is evaluated. The upper path divides into two because the first safeguard was effective, but the second safeguard still has the potential to influence the course of the incident. If the first safeguard fails, the lower path does not provide the second safeguard with a chance to influence the course of the incident. The lower incident path proceeds straight to the third safeguard.[14]

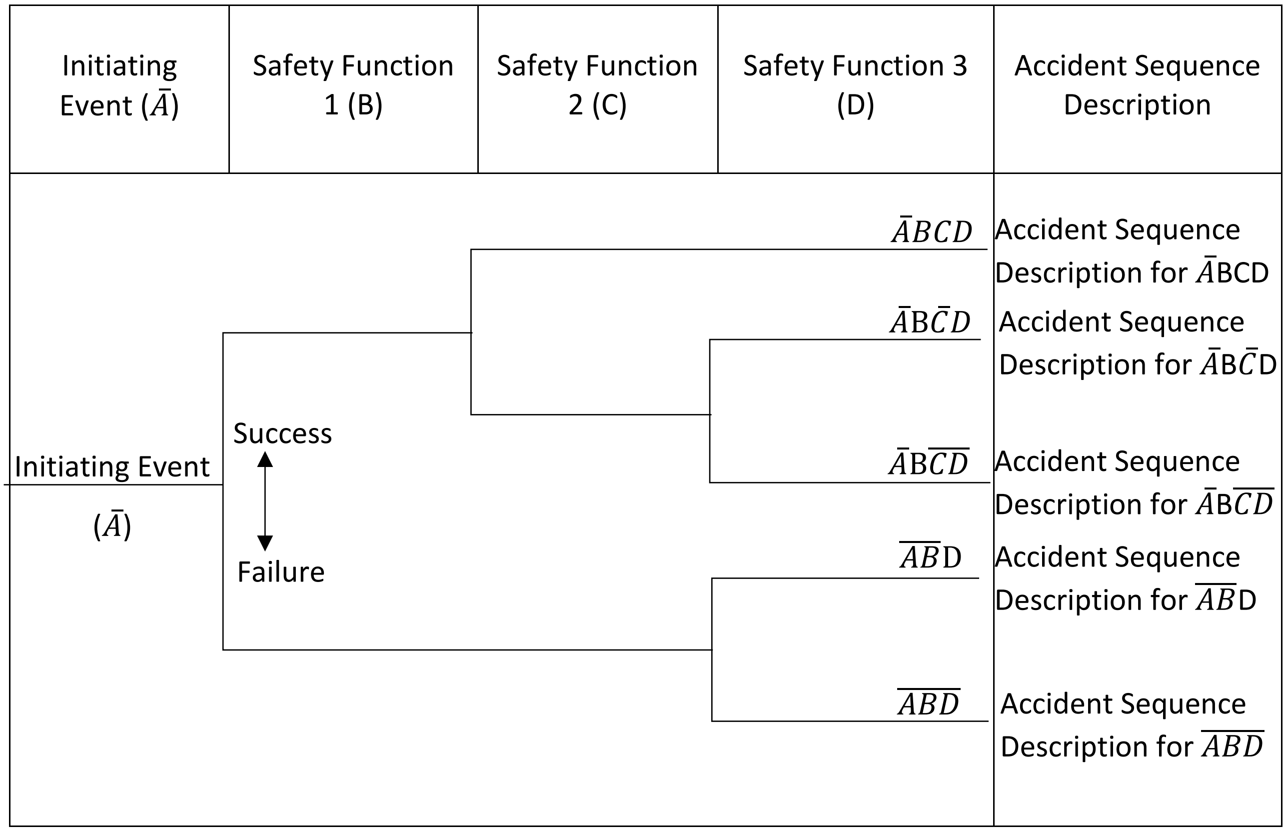

Figure II.4: Example of an Event Tree [14]

The finalized example Event Tree is depicted in Figure 5, which demonstrates that the uppermost incident path lacks a branch point for the third safeguard. This is because the system's design ensures that if the first two safeguards are successful, the third function is not at risk from an upset. On the other hand, the remaining incident paths include branch points for the third safeguard because it can still have an impact on the outcome of these paths.[14]

Step 4: Describing the resulting incident sequence outcomes

The subsequent stage of the Event Tree Analysis process involves outlining the different consequences resulting from the incident sequences. These sequences depict the potential outcomes following the starting event. Some of these sequences may signify a safe recovery and a return to regular operations, or an organized shutdown. The critical sequences, in terms of safety, are those that give rise to undesirable consequences.[14]

Step 5: Determining incident sequence minimal cut sets

The same approach used in analyzing fault trees can be applied to analyzing incident sequences in an event tree. This involves identifying the minimal cut sets for each incident sequence, which is essentially a logical "ANDing" of the initiating cause and the failures of subsequent safety systems. In this way, each incident sequence can be viewed as a distinct fault tree, with the incident sequence description serving as the Top event and an AND gate containing the initiating cause and all relevant safety system failures. It's important to note that the logic models for the safety system failures must assume that the defined successes of subsequent safeguards have already occurred.[14]

Step 6: Documenting the results

To complete an Event Tree Analysis, the hazard analyst should document the study's results. The documentation should include a system description, an explanation of the problem definition, including the initiating causes that were analyzed, a list of assumptions, the event tree models that were developed, a list of minimal cut sets for incident sequences, a discussion of the consequences of the various incident sequences, and an assessment of the significance of the incident sequence MCS. Additionally, any recommendations that emerge from the Event Tree Analysis should be presented.[14]

In conclusion, this chapter discussed key risk assessment methods that can be utilized alongside Quantitative Risk Analysis (QRA) in industrial installations. These methods include PHA, HAZOP, FTA, ETA, and LOPA. Each method offers a systematic approach to identifying hazards, analyzing consequences, assessing risks, and implementing appropriate risk reduction measures. Integrating these methods with QRA enhances the overall risk analysis process, enabling informed decision-making and effective risk management in industrial settings.

CHAPTER III: GAS PROCESSING AND FRACTIONATION OPERATIONS AT THE GUELLALA GAS TREATMENT UNIT (GTU)

SONATRACH is the Algerian national company specializing in hydrocarbon research, production, pipeline transportation, processing, and marketing. With a strong presence both in Algeria and globally, it holds a prominent position in Africa and contributes significantly to Algeria's GDP. Operating through four divisions, including the Production Division, SONATRACH employs 120,000 people and plays a crucial role in shaping the country's energy sector. [15]

In this chapter, we delve into the intricacies of the Guellala Field's gas treatment unit (GLA GTU) in the Haoud Berkaoui (HBK) region. The gas treatment process undergoes various phases to attain the desired end product, which is Liquified Petroleum Gas (LPG). We also focus on the storage aspect, specifically the spheres where LPG is stored. This study places particular emphasis on conducting a Quantitative Risk Assessment (QRA) to analyze the hazards associated with the storage spheres. By comprehensively exploring the gas treatment and LPG storage processes, we aim to provide valuable insights for improving safety measures and mitigating risks in the HBK region.[15]

1. Presentation of the Haoud Berkaoui (HBK) Region

The Haoud Berkaoui Regional Directorate is part of the Upstream Production Division of SONATRACH. The first oil processing center was commissioned in 1967. There is a total of 95 producing wells, including 49 gas lift wells for secondary recovery. To enhance recovery capacity, there are 28 water injection wells.[15]

Each production center receives crude oil from various wells, stabilizes it, stores it in tanks, and then ships it out. Along the RN49 road, known as the "oil road," which connects Ghardaïa to Hassi Messaoud, 35 km from Ouargla, a junction indicates the presence of an oil field. This is the Haoud Berkaoui region, located 772 km south of Algiers, 35 km northwest of Ouargla, and 100 km west of Hassi Messaoud. This region includes the Berkaoui (HBK), Benkahla (BKH), and Guellala (GLA) sites, as well as several small peripheral fields (S'Ahane-Boukhzane Oulouga, Haniet El Baida, N'Goussa, Drâa Tamra, Mokh El Kebch, Bab ElHattabat), covering an area of 6300 km².[15]

Today, the region has an oil processing capacity of 26,100 m³/day (5800T/day), a gas processing capacity of 1,236,000 Sm³/day, 500T/day for LPG, and 90T/day for condensate. The oil storage capacity is 28,300 m³, and the gas storage capacity is 3,400 m³. It includes the following industrial sites or units: Haoud Berkaoui, Benkhala, Guellala, Guellala Northeast, and DRT (Draa Tamra). The three main production centers are located in Haoud Berkaoui, Benkahla, and Guellala. All oil production is shipped to the Arzew terminal, and the recovered gas is sent to the Guellala Gas Treatment Unit (GTU) for processing.[15]

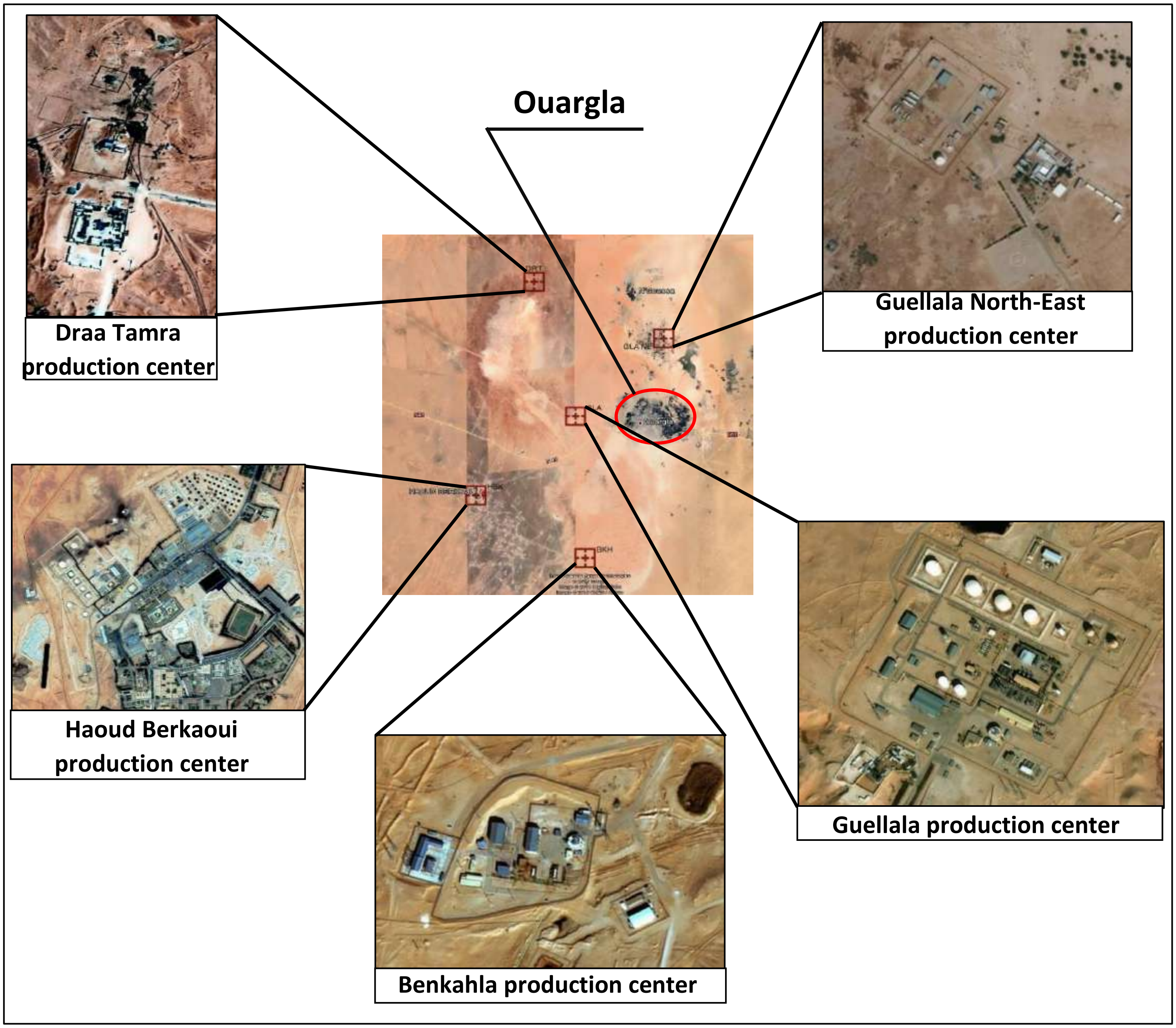

Figure III.1: Locations of production centers of Haoud Berkaoui

2. The Guellala Field

2.1 Description of the "GLA GTU" Process

Currently, the gas treatment unit consists of several sections, each performing operations with equipment selected based on process operating conditions.

2.1.1 Objectives of the process

- Recovery of associated gases from the separation of HP (High Pressure), MP (Medium Pressure), and LP (Low Pressure) crude oil.
- Production of lift gas as the main product.
- Production of LPG, commercial gas, and condensates as secondary products in accordance with specifications.

2.1.2 Operating Process

- Oil section.
- Boosting section ("section 300").
- Stabilization and dehydration section ("section 400").
- Propane refrigeration section ("section 500").
- Compression section ("section 600").
- Fractionation section ("section 700").

2.2 Oil Section

2.2.1 Activities of oil section

- Oil treatment: use of chemical demulsifiers and anti-paraffin agents.
- Three-phase separation of gas/water/oil.
- Atmospheric storage.
- Shipment.

2.2.2 Description of oil section

This unit was installed to perform the initial oil treatment operation for oil produced from different wells. It consists of two battery sets, one of which is designed for well testing. Each battery set consists of three separators:

1. High-pressure (HP) separator.

2. Medium-pressure (MP) separator.

3. Low-pressure (LP) separator.

After separation, the crude oil is stored in storage tanks, and the gas is sent to the Boosting section.

2.2.3 Crude oil storage

- The obtained oil is stored in four storage tanks with a capacity of 5000 m³.
- Two identical tanks are in service.
- Two identical tanks have been out of service since 2011.

2.2.4 Crude oil shipment

Two electric pumps, BJ1 and BJ2, are responsible for pumping the oil from the storage tank for shipment to northern plants such as Arzew.

2.3 Boosting Section

2.3.1 Activities of boosting section

- Recovery of associated gases from the separation of crude oil (LP, MP, and HP).
- Compression of LP gas and mixing it with MP gas.
- Compression of MP+HP gases to a pressure of 24 bars.

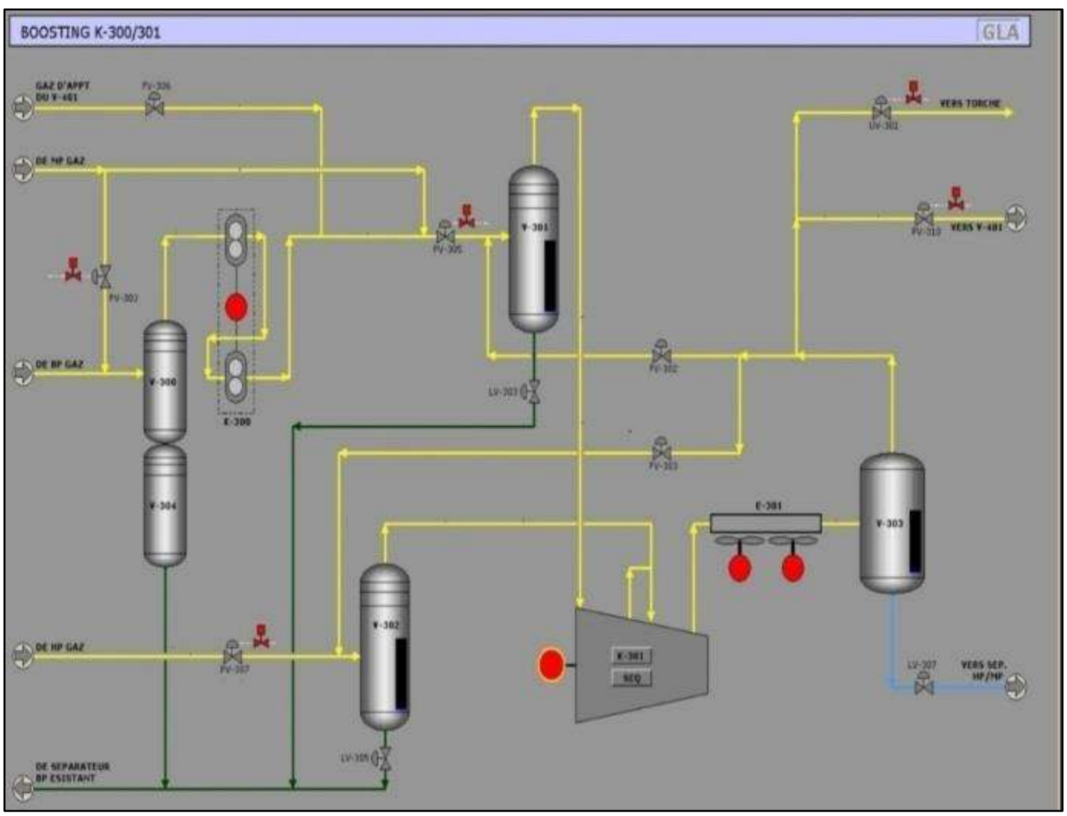

Figure III.2: Schema of boosting section GLA[15]

2.3.2 Description of boosting section

The LP, MP, and HP feed gases are available from the separation unit. The LP gas passes through the suction drum V-300, where remaining oil is removed and collected in the drum V-304, which is then sent back to the LP separators. The gas is then compressed to the MP gas pressure (2-2.5 bars) by the blower K-300. The compressed LP gas is mixed with the gases from the MP separators. An additional line through the valve FV-306 is connected from V-401 to compensate for gas shortage in the section and enters the suction drum V-301, the first stage of compressor K-301, where any entrained oil is removed and sent back to the LP separator. [15]

An MP gas line is collected with the LP gas input through the pressure control valve PV-303 before the drum V-300 to ensure a gas pressure at the suction of the blower K-300. The HP gas coming from the HP separators passes through the suction drum V-302, where crude oil entrainments are removed and sent back to the LP separator. Then, the gas enters the second stage of compressor K-301 and is mixed with the HP gas from the first stage. It is compressed up to 24 bars. At the compressor's outlet, the gas is cooled using the air cooler E-301. The cooled gas is then sent to the Gas Treatment Unit (GTU) passing through the water retention drum V-303, where water is drained off to the sump. [15]

A portion of the gas exiting V-303 is returned to V-301 via the pressure control valve FV-302 (recycle valve for the first stage of K-301) and to V-302 via FV-303 (recycle valve for the second stage of K-301) to protect the compressor from backflow. [15]

2.4 Stabilization and Dehydration Section "Section 400"

2.4.1 Activities of Section 400

- Recovery and stabilization of condensates.
- Removal of free water.
- Gas dehydration.

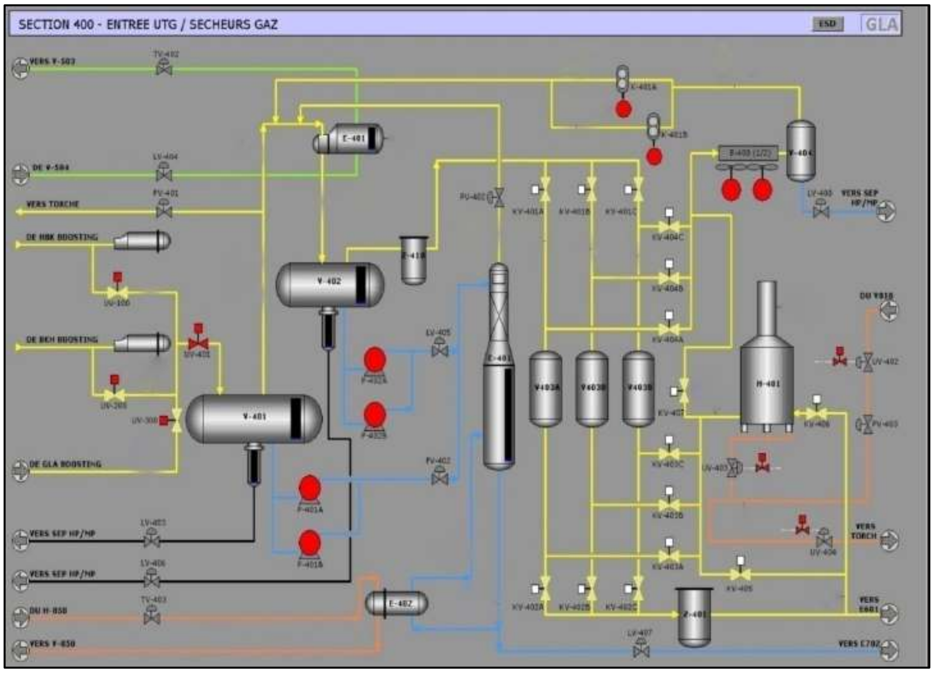

Figure III.3: Schema of Stabilization and Dehydration Section

2.4.2 Description of section 400

3.1.1.1 STABILIZATION

All gases transported from the Boosting stations of HBK and BKH, through the gathering networks, and also from the GLA Boosting station, are mixed at the inlet manifold and then introduced into the liquid trap V-401 to remove water and recover the maximum amount of condensate located at the bottom of the vessel through pumps P-401A/B. [15]

The gas exiting V-401 is cooled to 25°C in the propane cooler E-401 and then sent to the separator vessel V-402, which is located upstream of the dryers. [15]

In this case, water is discharged to the slop tank, and condensate is recovered from the bottom of the vessel by pumps P-402A/B. The condensate pumps' discharge supplies the stabilization column C-401, where the bottom is heated up to 138°C by a reboiler E-402 circulating gas oil, and the overhead vapors are vented upstream of the propane cooler E-401. The stabilized condensates are then sent to the Debutanizer C-702. [15]

Non-Stabilized condensates are returned to the existing MP separator without stabilization when the production rate of hydrocarbon condensates to be stabilized falls below the minimum operating load to maintain the stabilizer's performance. [15]

3.1.1.2 DEHYDRATION

Vapors from the separator vessel V-402 are sent to the gas dryers V-403-A/B/C and then pass through the low-temperature separation section. The drying system consists of three beds, with two beds operating in adsorption mode and one bed in regeneration mode. The dried gas is filtered using a dust filter Z-401 to remove dehydrant particles and other substances. [15]

3.1.1.3 DRYER REGENERATION

The regeneration gas is first heated in the regeneration gas heater H-401, bringing its temperature to 280°C. [15]

Then it serves as the regenerator for the dryer. After exiting the regenerator, the regeneration gas is cooled in the cooler E-403 and sent to the separator vessel V-404 to remove water.

The vapors exiting the regeneration gas separator vessel are recycled back to the feed gas cooler E-401 by the regeneration gas compressors K-401-A/B. The on/off control of the regeneration gas heater is automatically performed using the dryer regeneration sequence controller. [15]

2.5 Compression Section "Section 600"

2.5.1 Activities of section 600

- Separation of components in the dry gas through cooling.
- Primary compression of dry gas up to 72 barg and production of commercial gas.
- Secondary compression up to 140 barg and production of lift gas.

2.5.2 Description section 600

The dried gas from Section 400 is cooled in a plate heat exchanger E-601 to -22°C using the propane loop and then sent to the cold separator V-600. The gas exiting the top of separator V-600 can be sent to the existing compression and shipping system or to the new compression and shipping line. [15]

3.1.1.4 EXISTING COMPRESSION SYSTEM

The existing first stage of compression consists of two gas turbo compressors K-603A/B. These compressors provide the first pressure increase (from 20 barg to 75 barg) at the outlet of compressor K-603A/B. The gas is then cooled by air cooler E-605. [15]

The existing second stage of compression consists of two parallel reciprocating compressors K-604A/B, driven by two electric motors, one serving as a backup. These reciprocating compressors provide the second pressure increase (from 75 barg to 140 barg), and then the gas is cooled by air cooler E-606 from 120°C to 60°C. Afterward, it is sent to the existing lift gas manifold for the three fields, HBK, BKA, and GLA. [15]

3.1.1.5 NEW COMPRESSION LINE

The new gas compression and shipping installation consist of a single compression line that replaces the existing line. The existing line will remain available and ready to start in case of malfunctions or unavailability of the new line. [15]

The new installation receives the gas downstream of the existing air cooler E-601 and compresses it (from 20 barg to 75 barg) through a centrifugal compressor K-605 driven by an electric motor. The compressed gas is then cooled by air coolers E-608 before being sent to the second stage of compression in the new installation. [15]

The second stage performs the second pressure increase (75 barg to 145 barg) using a second centrifugal compressor K-606 driven by a second electric motor. The compressed gas is sent to the existing manifold (145 barg) for lift gas. If the existing manifold (145 barg) is unable to handle the entire flow generated by the compression line, the excess flow is throttled downstream of the second stage discharge. [15]

If the existing gas cooling system (propane loop) is operational, the excess flow can be sent either to the manifold (GR1/GR2) or to the flare. On the other hand, if the propane loop is shut down, the excess gas must be exclusively sent to the flare since its molecular weight exceeds the maximum allowable value (24 g/mol). [15]

The new compression line is equipped with a separator V-609 at the inlet for separating any liquid carryover in the supplied gas, an inter-stage separator V-610, and two final separators. The first separator V-611 receives any condensate from the discharge of the second stage of compression, and the second separator V-612 separates the condensate present in the excess gas sent to the flare or the GR1/GR2 manifold. [15]

These condensates may form due to the presence of light compounds (propane and butane) that cool during the throttling from 140 barg to 74 barg, and they can be present if the cooling system (propane loop) is not operational.[15]

The new compression line is equipped with two inter-stage heat exchangers E-608 and E-609, one for each centrifugal compressor stage.[15]

The new line is connected to the existing line via Tie-in 001 (suction downstream of E-601), Tie-in.[15]

2.6 Fractionation Section "Section 700"

2.6.1 Activities of section 700

- Removal of C1 and C2 light components at C-701.
- Production of LPG and condensates at C-702.
- Pressure storage of LPG at T-701 A/B.

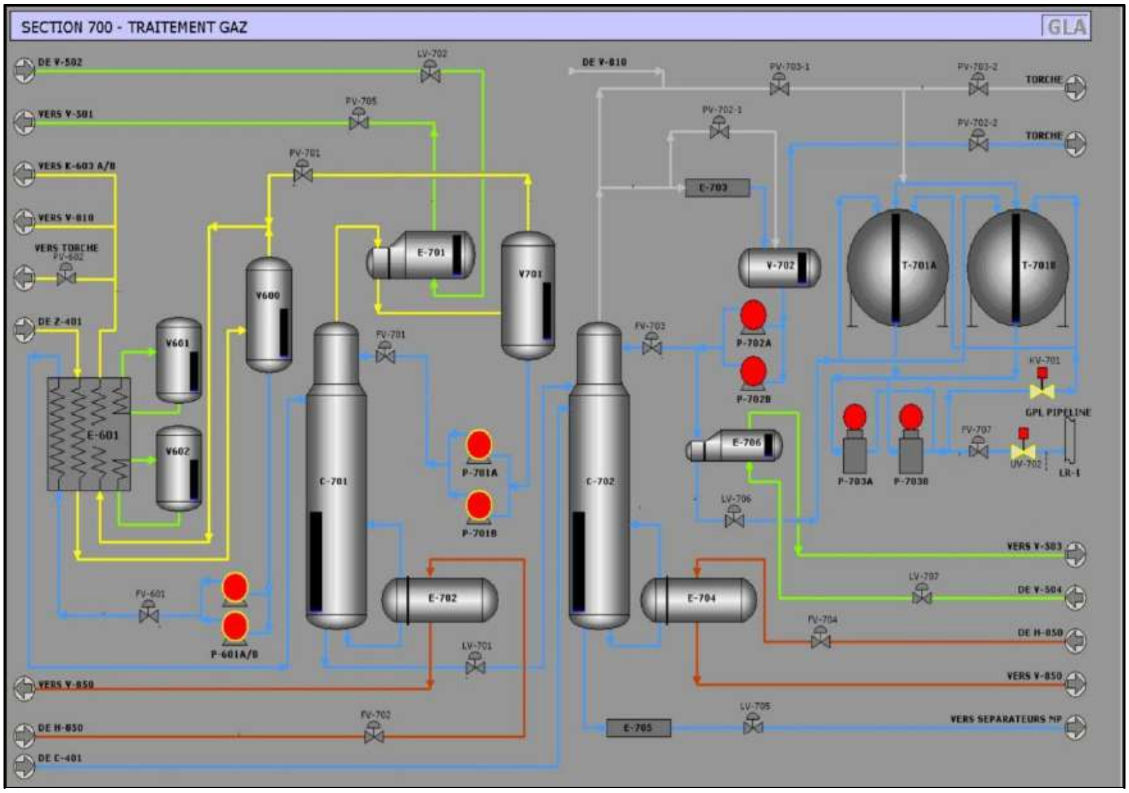

Figure III.4: Fractionation Section "Section 700"[15]

2.6.2 Description of section 700

3.1.1.6 DE-ETHANIZER

In the De-ethanizer process, the liquid from the refrigeration section “sec-600” is introduced into the de-ethanizer column C-701 at the 14th tray. This is accomplished by utilizing pumps P-601 A/B. At the top of the column, the gas is partially condensed through the use of the condenser E-701, which utilizes refrigerant propane. The condensed gas is then separated in the reflux drum V-701. The liquid obtained from the reflux drum is fully pumped back to the top of the column as cold reflux, with the aid of pumps P-701 A/B. The gas obtained from V-701 is preheated in the heat exchanger E-601 and subsequently directed to the compression section “sec-600”. The condensates obtained from the bottom of C-701 undergo stabilization through the condensate/hot oil reboiler E-702. Following stabilization, they are sent as feed to the de-butanizer C-702, with level control in place.[15]

3.1.1.7 OPERATING CONDITIONS

- Head pressure: 23 bars
- Head temperature: -5.7°C
- Bottom temperature: 89°C
- Number of trays: 38

3.1.1.8 DEBUTANIZER

The feed to the debutanizer column C-702 originates from two sources, namely:

- De-ethanizer column C-701
- Stabilization column C-401

The overhead gas obtained is completely condensed within the air condenser E-703 A/B and subsequently separated in the reflux drum V-702. Pumps P-702 A/B are used to pump the liquid from the reflux drum, with a portion of it utilized as reflux while the remainder is sent as LPG for storage in the spheres T-701A/B. Prior to storage, the LPG is cooled to 45°C in the propane exchanger E-706. The condensates obtained from the bottom of C-702 undergo stabilization through the reboiler E-704 and are then directed to the existing MP separator at the Guellala production center after cooling in the air cooler E-705.[15]

3.1.1.9 OPERATING CONDITIONS

- Head pressure: 14 bars
- Head temperature: 65.7°C
- Bottom pressure: 15.4 bars
- Bottom temperature: 152°C
- Number of trays: 38

2.7 LPG Storage

The site is equipped with two storage spheres, namely T-701A and T-701B, each having a capacity of 1697.4 m3. These spheres are utilized for storing LPG.

Figure III.5: LPG Storage Spheres

Table III.1: Characteristics of LPG storage spheres[15]

Characteristics	Values	Unit
Installation type	Storage sphere	/
Substance	LPG	/
Operating temperature	35	°C
Operating pressure	11	barg
Test pressure	15.4	barg
Volume	1697.4	m^3
Density	540	kg/m^3

3. LIQUEFIED PETROLEUM GAS (LPG)

LPG stands for "Liquefied Petroleum Gas." It is a flammable hydrocarbon gas mixture that is commonly used as fuel in various applications. LPG is composed primarily of propane and butane, with other hydrocarbons present in smaller amounts. It is produced through the refining of crude oil or natural gas processing.

LPG is stored and transported in a liquefied state under moderate pressure or refrigeration, which allows for easier handling and increased energy density. When LPG is released from its container and exposed to normal atmospheric conditions, it vaporizes back into a gaseous state and can be used as a fuel for heating, cooking, and powering various appliances, vehicles, and industrial processes.

Due to its high energy content, portability, and relatively clean combustion properties, LPG is widely used in residential, commercial, and industrial settings as an alternative to natural gas or other fossil fuels. It is considered a versatile and convenient source of energy with applications ranging from household cooking and heating to powering vehicles, forklifts, and even large-scale industrial operations.

3.1 Chemical and physical characteristics of LPG

LPG (Liquefied Petroleum Gas) has certain chemical and physical characteristics that define its properties. Here are some of the key characteristics of LPG:

3.1.1 Chemical Characteristics

COMPOSITION: LPG is primarily composed of propane (C_3H_8) and butane (C_4H_{10}), with other hydrocarbons present in smaller amounts. The specific composition can vary depending on the source and production methods.

3.1.2 Physical Characteristics

DENSITY: LPG is denser than air, with a density ranging from approximately 1.5 to 2.0 times that of air. This characteristic causes LPG to settle at ground level or low-lying areas when released.

VAPOR PRESSURE: LPG has a vapor pressure that is dependent on temperature and the specific mixture of hydrocarbons. The pressure inside an LPG storage vessel or cylinder is equal to the vapor pressure corresponding to the LPG's temperature.

FLAMMABILITY: LPG is highly flammable, with an explosive range of 1.8% to 9.5% volume of gas in air. It requires an ignition source to ignite and can burn in the presence of air or oxygen.

COMBUSTION: When LPG undergoes combustion, it generates heat and increases the volume of products. Adequate ventilation is necessary when burning LPG in enclosed spaces to prevent asphyxiation due to oxygen depletion.

ODOR: LPG itself has a very faint smell, so an odorant, such as ethyl mercaptan, is added to facilitate the detection of any gas leaks.

COLOR: LPG is colorless in both its liquid and vapor phases. However, during a leakage, the rapid vaporization of the liquid can cool the atmosphere and condense water vapor, creating a whitish fog that may help visualize the gas escape.

TOXICITY: LPG is slightly toxic but not poisonous in its vapor phase. However, in high concentrations, it can displace oxygen and lead to suffocation. LPG vapor possesses mild anesthetic properties.

Table III.2: Properties of gases present in LPG

Gas Properties	Isobutane	Butane	Propane
Chemical Formula	C_4H_{10}	C_4H_{10}	C_3H_8
Energy Content: MJ/m^3	110.4	111.4	95.8
Energy Content: MJ/kg	45.59	47.39	49.58
Energy Content: MJ/L	25.0	27.5	25.3
Boiling Temp: C^o	-11.75	-0.4	-42
Pressure @ 21^{o}C: kPa	310.9	215.1	858.7
Flame Temp: C^o	1975	1970	1967
Expansion: m^3/L	0.234	0.235	0.270
Gas Volume: m^3/kg	0.402	0.405	0.540
Relative Density: H_2O	0.60	0.58	0.51
Relative Density: air	2.07	2.00	1.53
specific volume: L/kg	1.669	1.724	1.96
density: kg/L	0.60	0.58	0.51
Specific Gravity @ 25^{o}C	2.06	2.07	1.55

CHAPTER IV: RISK ASSESSMENT WITH HAZOP & ETA ON THE SPHERES OF GTU GLA

The GLA GTU, involved in LPG production and processing, faces risks such as BLEVE and UVCE due to safety system failures. These failures can lead to catastrophic events, causing infrastructure damage, fires, toxic gas releases, and potential harm to personnel. Conducting a Quantitative Risk Assessment (QRA) is crucial to calculate individual risk and inform decision-making. By identifying vulnerabilities and implementing risk reduction strategies, the study enhances safety, protects personnel and the environment, and ensures smooth operations of the GLA GTU.

1. The process of storing LPG

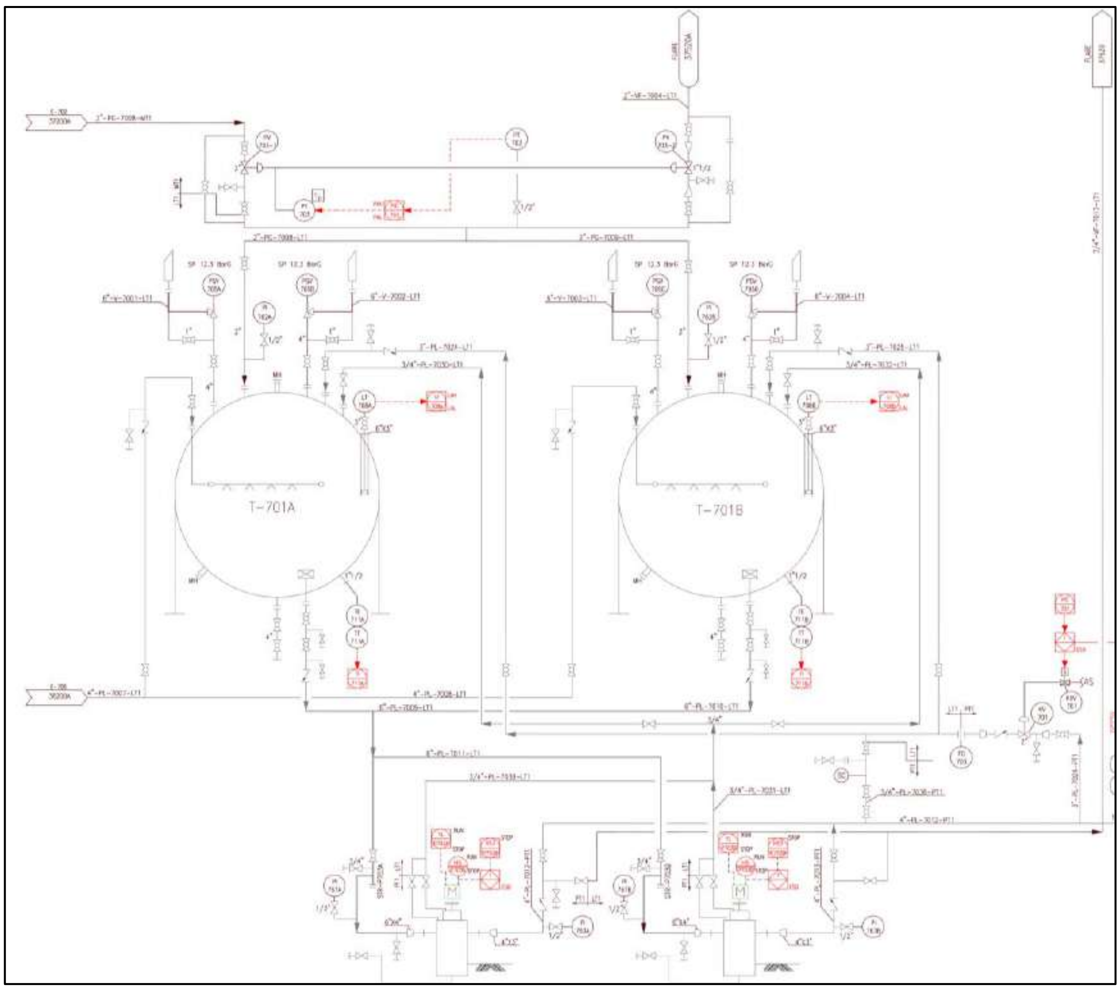

Figure IV.1: P&ID of GLA's LPG storage system[15]

The P&ID (Piping and Instrumentation Diagram) for the LPG storage system in UTG GLA provides a comprehensive overview of the process flow and instrumentation details related to the LPG storage system. The LPG, originating from the de-butanizer unit, is routed to the two spheres, namely T-701A and T-701B. This transfer is facilitated through a dedicated pipeline. To maintain a stable pressure of 11 barg, there is a specific line dedicated to the control of components C1 and C2. This line is regulated by valve PV 703-1, which helps ensure precise pressure management. In addition to the pressure control line, there is a separate line connected to the flare system. This line incorporates valve 703-2, which allows for controlled release of excess pressure to the flare. Importantly, this valve also has a bypass option, enabling alternative routing when necessary. To ensure the safety and integrity of the LPG spheres, each sphere is equipped with two pressure safety valves (PSVs). These PSVs act as fail-safe devices, preventing the occurrence of over-pressurization in the spheres. In the event of excessive pressure, the PSVs automatically open, releasing the excess pressure and maintaining the integrity of the storage system.

The P&ID also includes various instrumentation indicators to monitor key parameters of the LPG. The level indicators (LI) identified as LI 708A and LI 708B provide real-time information about the LPG level within each sphere. This data aids in managing the storage capacity and prevents overfilling or underutilization. Additionally, pressure indicators (PI) denoted as PI 762A and PI 762B continuously monitor the pressure inside the spheres. These indicators offer crucial insights into the pressure conditions and allow for prompt corrective actions if deviations occur.

Furthermore, temperature indicators (TI) identified as TI 711A and TI 711B provide continuous temperature monitoring of the LPG. This information is vital for maintaining optimal operating conditions and preventing any potential hazards associated with extreme temperatures. By incorporating these instrumentation elements into the P&ID, the LPG storage system can be effectively monitored and controlled. The detailed visualization of the system's components and their interconnections helps ensure safe and efficient operation, minimizing risks and maintaining the integrity of the UTG GLA LPG spheres.

2. HAZOP study for LPG spheres

HAZOP (Hazard and Operability Study) is an integral part of the Quantitative Risk Assessment (QRA) study due to its effectiveness in identifying and analyzing potential hazards and operability issues. HAZOP provides a systematic and structured approach to systematically examine the design and operational aspects of a system or process, identifying deviations from intended conditions that could lead to hazardous situations. By thoroughly analyzing process variables, equipment interactions, and potential deviations, HAZOP helps uncover potential scenarios that can contribute to accidents or failures. The insights gained from the HAZOP process contribute to a comprehensive understanding of risks, enabling the QRA study to accurately quantify the likelihood and consequences of potential incidents. Incorporating HAZOP into the QRA study enhances the accuracy and reliability of the risk assessment, leading to informed decision-making, targeted risk mitigation measures, and improved safety performance.

3.2 Construction of HAZOP table:

Table IV.1: HAZOP study table of Guellala's spheres

Parameter	Guide Word	Deviation	Causes	Consequences	Safeguards
Pressure	More	Higher pressure	-PV 703-1 failure open, PV 703-2 failure close & Manual valve bypass PV 703-2 failure close.	-Excessive overpressure in T701A. -Possible damage of equipment. -Possible rupture of T701A (possible BLEVE explosion).	-Alarm PAH-703 & Operators. -PI-762A. -PSV-705A/B.
			- External fire around T701A.		-PIC-703A loop & Operators. -Alarm PAH-703. -Fireproofing. -Water deluge system. -PSV-705A/B.
			- Manual valve of T-701A flare line maloperation close during the filling operation.		-PSV-705A/B.
	Less	Lower pressure	-PV-703-1 failure close & PV-703-2 failure open.	-Excessive evaporation of LPG. -Possible P-703A/B cavitation and damage (during shipment). -Possible off-spec product.	-Alarm PAL-703 & Operators. -PI-762A.
			-PSV 705 A/B failure open.		- PIC-703A & Operators. -PI-762A.
			- Manual valve of T-701A flare line maloperation close during shipment operation (Human error).		-PI-762A.
Level	More	Higher Level	- Manual valve of T-701A filling line failure open.	-LPG overfilling in T-701A. - Possible flare damage.	-Alarm LAH-708A & Operators. -LT-708A. - PSV-705A/B.

			- Level transmitter LT-708A failure.	- Possible rupture & BLEVE.	-Operators. - PSV-705A/B.
	Less	Lower Level	- Manual valve of T-701A shipment line maloperation open.	- Lower level of LPG in T-701A. - Possible P-703A/B cavitation & damage.	-Alarm LAL-708A & Operators. -LT-708A.
			- Level transmitter LT-708A failure.		-Operators.
Temperature	More	Higher Temperature	-External fire around T-701A.	-Excessive evaporation of LPG. -Excessive overpressure in T-701A. -Possible equipment damage. - Possible rupture (possible BLEVE explosion).	-TI-711A. -PIC-703A. -Alarm PAH-703. -Operators. -PI-762A -Fireproofing. -Water deluge system. -PSV-705A/B.
			-LPG cooler E-706 stop.		-TI-711A. -PIC-703A & Operators. -PI-762A. -Water deluge system. -PSV-705A/B.
	Less	Lower Temperature	No significant cause identified.		

3. Event Tree Analysis

The application of Event Tree Analysis (ETA) in a Quantitative Risk Assessment (QRA) study involves constructing an event tree to assess the potential consequences of a Loss of Confinement, which serves as the initiating event. Loss of Confinement refers to the failure or breach of containment systems that can lead to the release of hazardous materials or energy. By utilizing ETA, the event tree branches out to consider various possible outcomes and subsequent events that may follow the Loss of Confinement. The goal of this analysis is to quantitatively evaluate the likelihood and severity of each branch in the event tree, providing valuable insights into the potential scenarios and their associated risks. This information is essential for decision-making, risk management, and developing effective strategies to prevent or mitigate the consequences of a Loss of Confinement event.

3.1 Event Tree construction

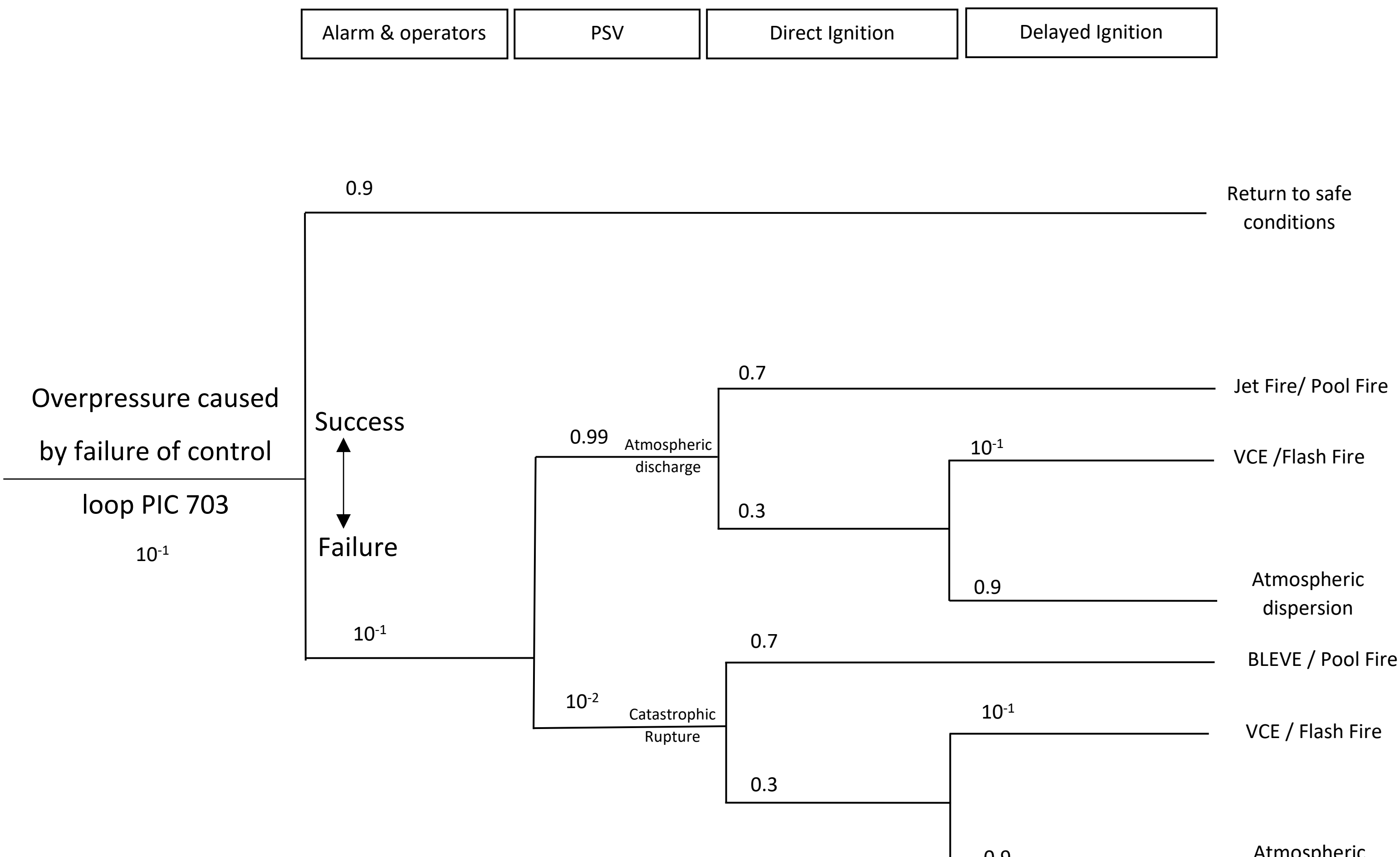

Figure IV.2: The application of ETA

3.2 ETA frequencies

3.2.1 Control system failure frequency

Table IV.2: Control system failure frequency[16]

Event	Failure of a control system
Values	Typical value is 10^{-1}/year
Observations	It is generally considered that failures in control systems are caused by logic in 15% of cases, by actuators in 50% of cases, and by sensors in 35% of cases

3.2.2 Alarm & operations frequency

3.2.2.1 ALARM:

Table IV.3: Alarm failure frequency[16]

Barrier	Activation of an alarm
Availability	Typical value of PFD (Probability of Failure on Demand) of 10^{-3} (probability of the siren not functioning when activated)
Effectiveness	Attention should be given to the human factor (reflex to evacuate in a disciplined manner)

3.2.2.2 OPERATION:

Table IV.4: Operator failure frequency[16]

Event	Inappropriate reaction to an unusual and non-procedural situation (thoughtful action)
Values	According to [Villemeur 1997], the range is between 1 (in emergency situations) and 10^{-1} per operation, to be multiplied by the number of operations per year to obtain a frequency.
Barrier	Operator's action in a control room in response to a solicitation (e.g., an alarm)
Observations	Sometimes, collective human action (involving all individuals present in the control room) is considered instead of the action of an individual operator. Points that can improve the effectiveness of human action: • Implementation of a double-check procedure: Two individuals performing a test using different procedures, with each person signing off (concept of defense in depth). However, the degree of frequency reduction from the same family of protection mechanisms should be limited. For example, it is not possible to use three presumed independent "human barriers" to achieve a risk reduction factor of 10^{-4}. • Existence of a detailed checklist. • Valuing the operator's actions: Tasks should have meaning for the operator.

3.2.3 Pressure Safety Valve failure frequency

Table IV.5:Pressure safety valve failure frequency[16]

Barrier	Pressure Relief Valve (PRV) for overpressure/ under-pressure protection
Values	Basic PFD of 10^{-2}, ranging from 10^{-1} to 10^{-3}. Remark: It is not reasonable to consider a value lower than 10^{-3}.
Observations	The given value pertains to the safe operation of the valve (non-opening upon solicitation). Factors reducing the probability of failure: - Observation/inspection procedures - Quality of the installation procedure - Cleanliness of the product - Combination with a rupture disk and intermediate monitoring - ... Factors increasing the probability of failure: - Fouling or corrosive product - Product temperature - Use with steam

3.2.4 Direct Ignition frequency

Table IV.6: Direct ignition frequencies[17]

Source		**Substance**	
Continuous	**Instantaneous**	**Gas, low reactive**	**Gas, average/ high reactive**
< 10 kg/s	< 1000 kg	0.2	0.2
10 - 100 kg/s	1000 - 10,000 kg	0.4	0.5
> 100 kg/s	> 10,000 kg	0.09	0.7

Table IV.7: Reactivity of a number of substances [CPR14][17]

Low reactivity	Average reactivity	High reactivity
1-chloro-2,3-epoxypropane 1,3-dichloropropene 3-chloro-1-propene ammonia bromomethane carbon monoxide chloroethane chloromethane methane tetraethyl lead	1-butene 1,2-diaminoethane 1,3-butadiene acetaldehyde acetonitrile acrylonitril butane chloroethene dimethylamine ethane ethene ethylethanamine formic acid propane propene	1-butanethiol acetylene benzene carbon disulfide ethanethiol ethylene oxide ethylformate formaldehyde hydrogen sulfide methylacrylate methylformate methyloxirane naphtha, solvent tetrahydrothiophene vinyl acetate

3.2.5 Delayed Ignition frequencies

To obtain the frequencies of delayed ignition, it’s possible to refer to the document from INERIS called "DRA 71 - Opération B," which proposes a semi-quantitative method for evaluating the probabilities of ignition or inflammation.

3.2.5.1 CONTINUOUS RELEASE

The probability values of delayed ignition for a long-duration continuous release of flammable gas presented in this report are summarized in the following table:

Table IV.8: Delayed Ignition frequencies on continuous release for long-duration[18]

Cloud contained within the area.	Highly reactive special gases (hydrogen, acetylene, ethylene oxide, etc.).	Moderately and highly reactive gases (excluding those identified in the first column).	Low-reactivity gases (excluding ammonia).
Absence of ignition sources (including absence of personnel and traffic routes, for example, the area between two production units, vertical venting of valves in open air...).	10^{-1}	10^{-3}	10^{-3}
Classified ATEX with occasional presence of personnel (e.g., during retention).	10^{-1}	10^{-2}	10^{-3}
Classified ATEX with high presence of personnel (e.g., during unloading operations).	1	10^{-1}	10^{-2}
Cloud contained in a non-ATEX classified area containing possible sources of ignition (e.g., outside the site).	1	1	10^{-1}

The probability values for delayed ignition of a short-duration continuous release of flammable gas, as presented in this report, are summarized in the following table:

Table IV.9: Delayed Ignition frequencies on continuous release for short-duration[18]

Cloud contained within the area.	**Highly reactive special gases (hydrogen, acetylene, ethylene oxide, etc.).**	**Moderately and highly reactive gases (excluding those identified in the first column).**	**Low-reactivity gases (excluding ammonia).**
Absence of ignition sources (including absence of personnel and traffic routes, for example, the area between two production units, vertical venting of valves in open air...).	10^{-1}	10^{-3}	10^{-3}
Classified ATEX with occasional presence of personnel (e.g., during retention).	10^{-1}	10^{-3}	10^{-3}
Classified ATEX with high presence of personnel (e.g., during unloading operations).	1	10^{-1}	10^{-2}
Cloud contained in a non-ATEX classified area containing possible sources of ignition (e.g., outside the site).	1	1	10^{-1}

3.2.5.2 INSTANTANEOUS RELEASE

The probability values for delayed ignition of an instantaneous release of flammable gas, as presented in this report, are equal to those of the long-duration continuous release, summarized in the following table:

Table IV.10: Delayed Ignition frequencies on instantaneous release for long-duration[18]

Cloud contained within the area.	**Highly reactive special gases (hydrogen, acetylene, ethylene oxide, etc.).**	**Moderately and highly reactive gases (excluding those identified in the first column).**	**Low-reactivity gases (excluding ammonia).**
Absence of ignition sources (including absence of personnel and traffic routes, for example, the area between two production units, vertical venting of valves in open air...).	10^{-1}	10^{-3}	10^{-3}
Classified ATEX with occasional presence of personnel (e.g., during retention).	10^{-1}	10^{-2}	10^{-3}
Classified ATEX with high presence of personnel (e.g., during unloading operations).	1	10^{-1}	10^{-2}
Cloud contained in a non-ATEX classified area containing possible sources of ignition (e.g., outside the site).	1	1	10^{-1}

3.3 The frequencies of hazardous phenomena

After constructing the event tree and calculating the frequencies of hazardous phenomena, the following results were obtained:

Table IV.11: Hazardous phenomena frequencies from ETA

Hazardous Phenomena	**Frequency**
VCE	$3x10^{-4}$
Flash Fire	$3x10^{-4}$
Pool Fire	$7x10^{-3}$
BLEVE	$7x10^{-5}$
Jet Fire	$6.93x10^{-3}$

In conclusion, this chapter applied HAZOP and ETA approaches to Guellala's spheres, identifying failure frequencies for the chosen scenario. These results contribute to the application of Quantitative Risk Analysis (QRA), supporting informed decision-making and effective risk management. By integrating HAZOP and ETA, a comprehensive understanding of failure frequencies and their consequences is achieved, enhancing safety measures for Guellala's spheres.

CHAPTER V: APPLICATION OF QRA WITH SAFETI SOFTWARE: RESULTS AND ANALYSIS

This chapter focuses on the presentation of two powerful software tools, PHAST and SAFETI, utilized in the field of quantitative risk analysis (QRA) for assessing explosion effects and individual risk. PHAST and SAFETI have emerged as invaluable resources in the domain of process safety management, providing robust methodologies and computational capabilities to evaluate potential hazards and their consequences. The chapter begins by introducing PHAST, an acronym for Process Hazard Analysis Software Tool, which offers a comprehensive platform for analyzing and visualizing potential hazardous scenarios. It enables users to identify and assess potential sources of accidents, estimate the associated risks, and evaluate the impact of these hazards on the surrounding environment. Next, the focus shifts to SAFETI, an acronym for Safety and Environmental Tools for Industrial Applications. SAFETI specializes in conducting QRA and assessing the consequences of hazardous events, such as explosions, on both individual and societal levels. It incorporates advanced modeling techniques to quantify risks, predict explosion effects, and evaluate individual risk levels. Furthermore, this chapter highlights the inputs utilized in SAFETI software to reach the desired results. These inputs encompass various factors, including hazard data, material properties, weather conditions, and scenario-specific parameters. Each input plays a critical role in accurately assessing the QRA, explosion effects, and individual risk levels.

1. Presentation of the simulation software (PHAST)

1.1 Introducing PHAST

PHAST is a software developed and updated by DNV to assess the consequences of gas leaks, fires, explosions, toxicity, and other technological hazards related to various industries.

The PHAST software (Process Hazard Analysis Software Tool) is a comprehensive tool for analyzing the risks of an industrial installation. It simulates the progression of an accidental release of a toxic and/or flammable substance from the initial leak to atmospheric dispersion in the far field. It includes the modeling of spreading and evaporation of pools. PHAST is capable of modeling release scenarios from various source terms such as tank wall leaks, pipeline ruptures, etc. These scenarios are then combined with PHAST's integral-type dispersion model, called Unified Dispersion Model (UDM), to obtain, for example, safety distances corresponding to toxic thresholds and the footprint of the cloud on the ground at a given moment.

1.2 SOURCE TERMS IN PHAST

The software, marketed by DNV Software, is widely used in the industry for estimating accident consequences. It allows for the modeling of different types of source terms and cloud dispersion

PHAST includes several models to calculate various source terms. The calculation of the source term consists of two parts: the first part is specific to each source term and defines the release conditions up to the orifice (for "Leak") or up to the breach in the pipeline (for "Short pipe" and "Long pipeline"). The second part of the calculation is performed using the ATEX model (Atmospheric Expansion model), which determines the final release conditions after expansion to atmospheric pressure. We present the main source term models in PHAST for continuous emission modes such as "Leak", "Line rupture" and "Disc rupture".

1.3 PHAST Unified Dispersion Model (UDM)

1.3.1 UDM (Unified Dispersion Model)

The original version of UDM was developed by Cook and Woodward in the early 1990s. In this version, different dispersion phases are simulated using sub-models that need to be cleverly assembled to model a given scenario. To eliminate discontinuities between the results of the sub-models, a new version of UDM was developed, which allows for the calculation of a uniform concentration profile integrating the different dispersion phases.

Furthermore, this new model takes into account phenomena such as evaporation, pool formation, cloud rise, and variable dispersion over time. UDM is capable of handling a large number of products, whether toxic and/or flammable, light, heavy, or neutral. It can handle liquid, gas, or two-phase releases. For two-phase releases, it models the formation and evaporation of pools.

PHAST can model the following phenomena:

- Jet fire
- Pool fire
- Flash fire
- BLEVE (Boiling Liquid Expanding Vapor Explosion)
- Explosion modeling

Three models to predict the effects of Vapor Cloud Explosions (VCE):

- TNT equivalent
- Multi-Energy
- Baker-Strehlow

1.3.2 PHAST Modeling Results

Typically, the results are presented in graphical and numerical form (reports). Some results can be presented on a map background (effect zones).

1.3.3 Definition of Scenarios and Simulation

To introduce a model, the following steps need to be followed:

- Introduce a general model
- Different types of scenarios (catastrophic rupture, leak, line rupture, etc.)
- Characteristics of the general models
- Important data (tabs)
- Influence of data - process parameters
- Introduce a general model in the "Model" tab
- Different types of scenarios (catastrophic rupture, leak, line rupture, etc.)
- Characteristics of the general models

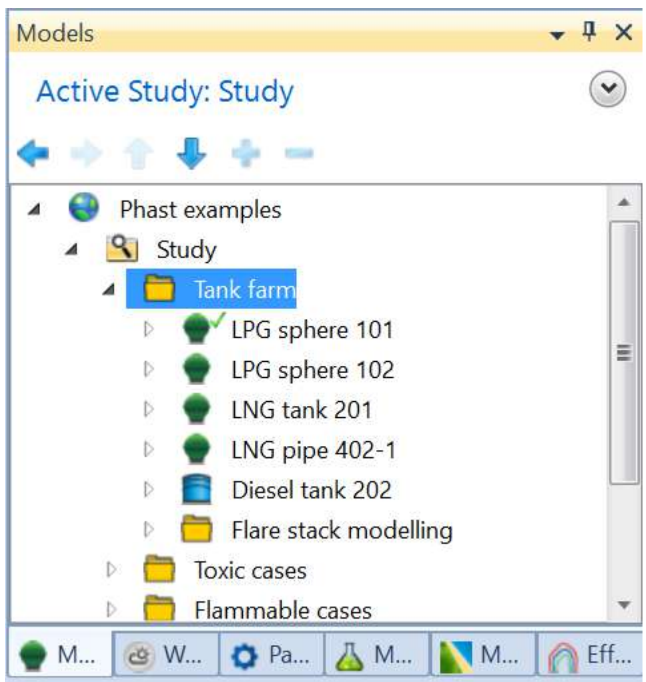

Figure V.1: Definition of scenarios

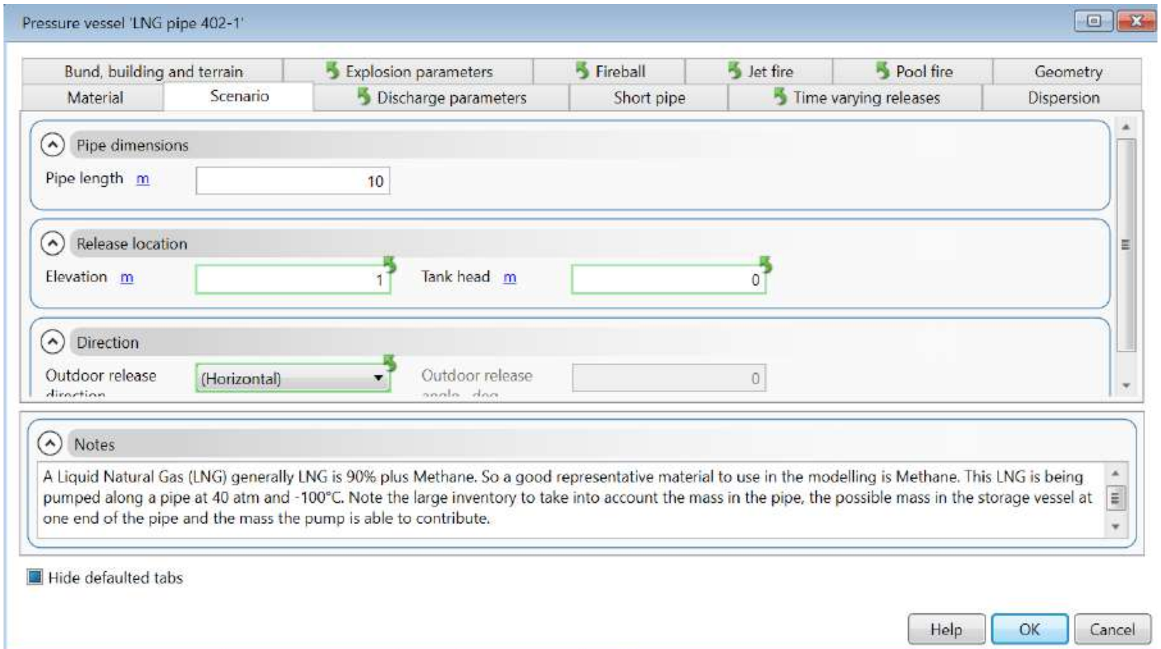

Figure V.2: Definition of sources

1.3.4 Important Data (Tabs)

In this step, it is essential to input the following data:

- Product: The specific substance involved in the scenario.
- Quantity: The amount or quantity of the product.
- Process Parameters: Parameters related to the process, such as temperature and pressure.
- Position: The location or position of the release or event.
- Height: The height at which the release or event occurs.
- Geometry: The geometrical characteristics relevant to the scenario.
- Release Direction: The direction in which the release or event is projected or occurs.

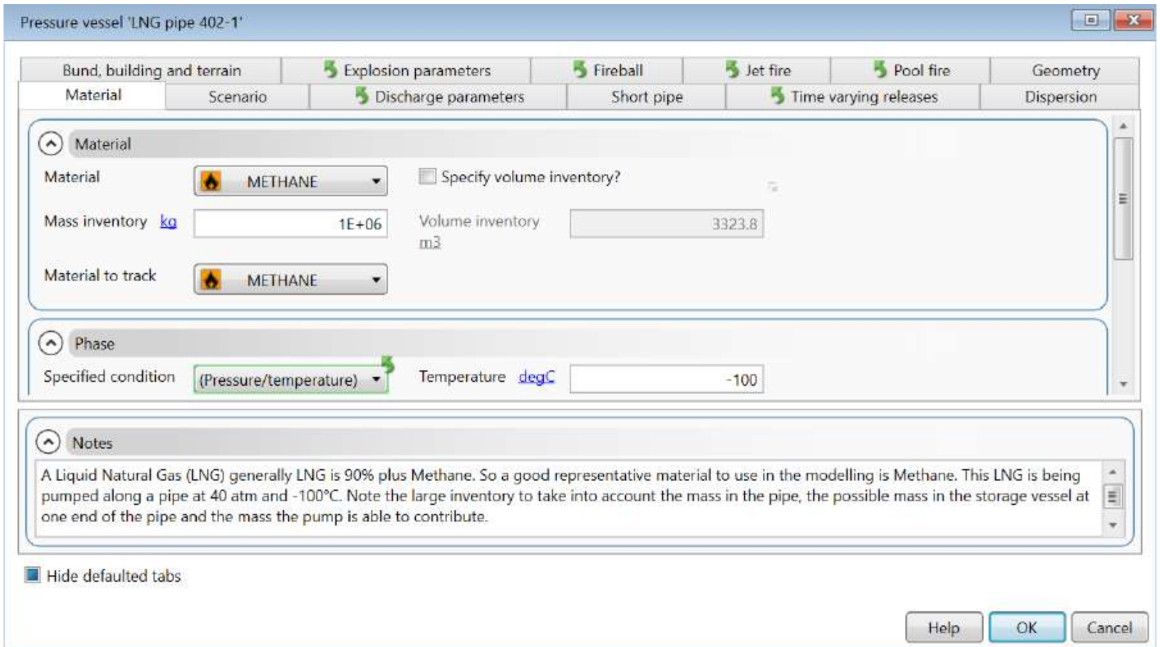

Figure V.3: Definition of products

1.3.5 Results and Effects of Radiation/ Overpressure/ Toxicity

The results are presented in two formats:

1.3.6 Reports

These reports include the following data:

- Summary: A brief overview of the scenario and its key details.
- Release: Information about the release event, such as the type and characteristics of the release.
- Dispersion: Details about the dispersion of the released substance in the environment.
- Radiation Effects: Information regarding the radiation effects, if applicable.
- Overpressure Effects: Information about the effects of overpressure resulting from the scenario.
- Toxic Effects: Details about the toxic effects caused by the release.

1.3.7 Graphs

These graphs represent the following information:

- Concentrations: Graphical representation of the concentration levels of the released substance over time.
- Radiation Effects: Graphs illustrating the radiation effects, if relevant.
- Overpressure Effects: Graphical representation of the overpressure effects resulting from the scenario.

- Toxic Effects: Graphs depicting the toxic effects caused by the release.
- Effects on Map: Graphical representation of the effects overlaid on a map.

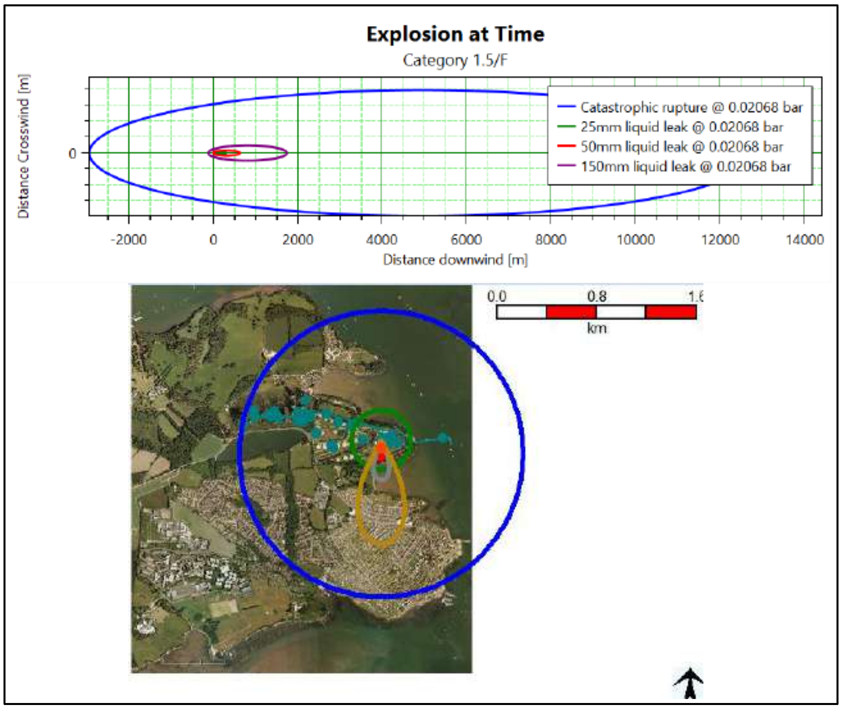

Figure V.4: Presentation of results

1.3.8 Custom Model and Scenario List

- Introducing a custom model
- Characteristics of custom models
- Introducing a scenario list
- Introducing a custom model (User Defined Source) in the 'Model' tab
- Characteristics of custom models

The following data must be entered: flow rate, duration, velocity, temperature.

2. Risk analysis using SAFETI

SAFETI is a software developed by DNV (Det Norske Veritas), a leading provider of risk management services. SAFETI is designed to assess and manage the consequences of potential hazardous events, including fires, explosions, and toxic releases. One of its key capabilities is calculating both individual and social risk. The software incorporates advanced modeling and analysis techniques to evaluate the impacts of these hazardous events on human safety and the surrounding environment. It takes into account factors such as the characteristics of the event, the proximity of affected individuals or populations, and the vulnerability of structures and systems. By utilizing SAFETI, users can quantify the risks associated with specific scenarios, enabling them to make informed decisions regarding risk mitigation and emergency response measures. The software provides valuable insights into the potential consequences of hazardous events, assisting in the development of robust safety strategies and the optimization of risk management efforts.

2.1 Input Requirements for SAFETI in GLA GTU

2.1.1 Specs of the pressure vessels (LPG spheres)

The specifications of pressure vessels are extracted from the hazard study conducted by GLA, and the obtained results are shown in table 5.

2.1.2 Composition of Guellala's LPG

The composition of LPG components is derived from the laboratory results of GLA, and these findings are utilized in SEFATI study by incorporating LPG as a mixture for material analysis.

Table V.1: Guellala's LPG composition[15]

Component	**Percentage (%)**
Ethane	0.9 – 1.5
Propane	54 - 59
I-Butane	8 - 12
N-Butane	30 - 34
I-Pentane	0.01 – 0.06
N-Pentane	0.01 – 0.06

2.1.3 Scenarios and frequencies

The selected scenarios for analysis in this study encompass the catastrophic rupture of a pressure vessel and a 10 mm leak. The frequencies associated with these events have been derived from the book

'PSG 3: Quantitative Risk Assessment,' which serves as a reference for quantitative risk assessment methodologies.

Table V.2: Frequencies of scenarios

Scenario	Frequency
Catastrophic rupture of a pressure vessel	10^{-6}/year
10mm Leak	10^{-4}/year

2.1.4 Weather condtions

In the hazard study, weather conditions have been classified into two categories: summer and winter, as well as day and night, to account for variations in environmental factors and their potential impact on the assessed hazards.

Table V.3: Atmospheric conditions for simulation

Conditions	Wind speed (m/s)	Air stability	Humidity (%)	Air temperature (°C)	Ground temperature (°C)	Solar radiation (kW/m2)
Summer Day	6	C	20	40	40	1.2
Winter Day	4	B	30	20	20	0.7
Summer Night	6	D	20	30	30	0
Winter Night	2	F	60	5	5	0

And the result of wind rose are typicaly the same in Hazards Study of GLA GTU and SAFETI:

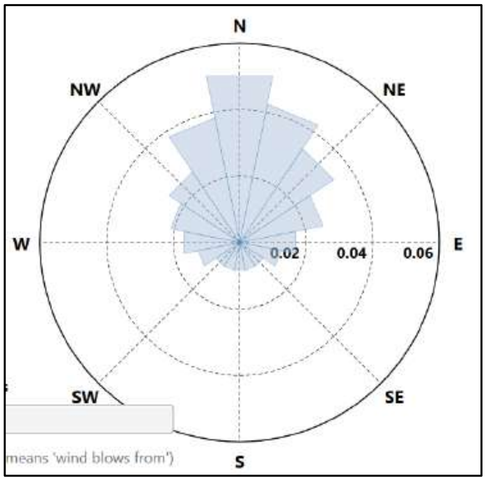

Figure V.5: Wind rose from SEFATI

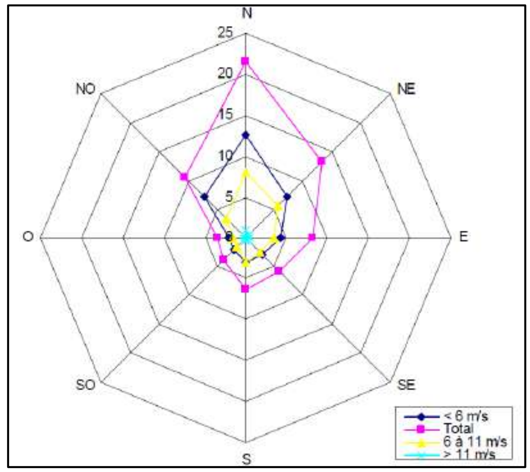

Figure V.6: Wind rose from Hazard Study[15]

2. Analysis and Findings of SAFETI Results: Assessing Hazardous Event Consequences

2.1 Catastrophic rupture explosion worst case results

In this particular scenario, the pressure vessel is assumed to be filled at maximum capacity, and the identified scenario is a catastrophic rupture. The ensuing worst-case explosion distances under different weather conditions are visually presented in the following figure. These results provide valuable insights into the potential extent of the explosion's impact, considering variations in weather conditions.

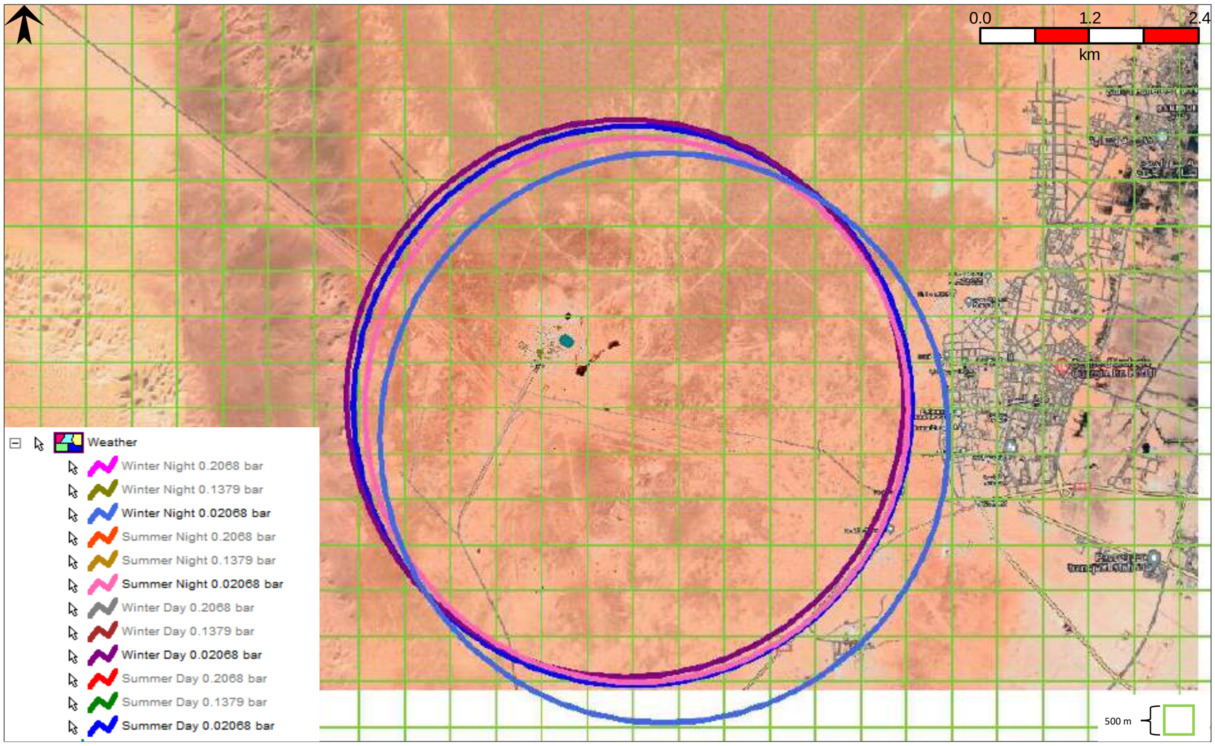

Figure V.7: Catastrophic rupture explosion worst case from SAFETI

In this scenario of a catastrophic rupture, the resulting explosion has a significant potential to reach a diameter of nearly 3 km. Moreover, the movement and dispersion of the explosion may vary based on the prevailing wind direction. Considering the influence of wind, the explosion can be expected to propagate in specific directions, impacting areas along its path. These findings highlight the substantial scale and potential directional impact of the explosion.

2.2 *Results of BLEVE Induced by Catastrophic Rupture*

The results obtained from the analysis of the fireball resulting from the catastrophic rupture of the sphere reveal that the intensity of the fireball extends approximately 2 kilometers. This indicates the significant scale and potential impact of the fireball in the event of a BLEVE. Understanding the size and intensity of the fireball is crucial for assessing the potential hazards, determining evacuation zones, and implementing appropriate safety measures in the surrounding areas. The findings provide valuable insights into the potential consequences of a catastrophic sphere rupture and aid in developing effective emergency response plans to mitigate the risks associated with such events.

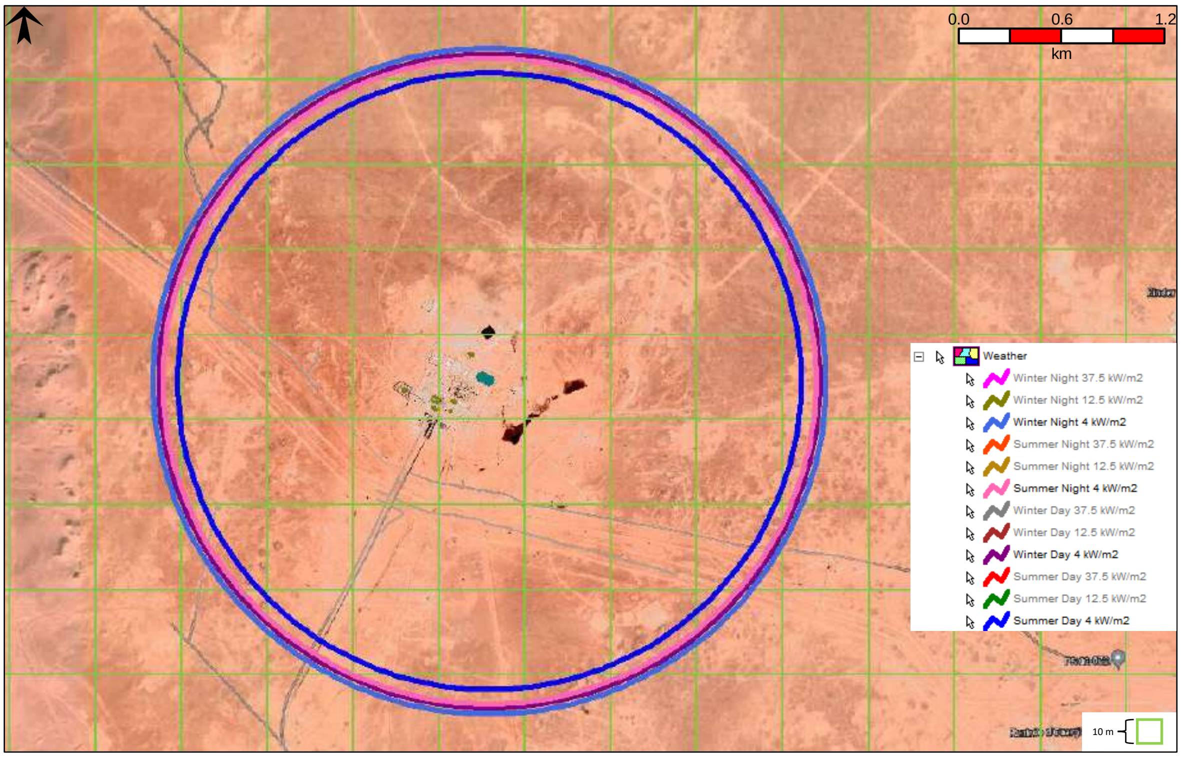

Figure V.8: Affected Zones by Fireball Resulting from BLEVE Caused by Catastrophic Rupture

The analysis of the fireball intensity-distance relationship reveals a gradual decrease in intensity as distance increases. Starting with an initial value of 400 kW/m2, the fireball's intensity steadily diminishes until reaching zero at an approximate distance of 2000 meters. This decline in intensity signifies the dissipation of heat and flames as the fireball expands and disperses. Understanding the intensity-distance characteristics of the fireball is vital for assessing the potential hazards and determining safe distances for personnel and nearby infrastructure. By incorporating this information into safety planning and risk mitigation strategies, the risks associated with fireball exposure can be effectively managed.

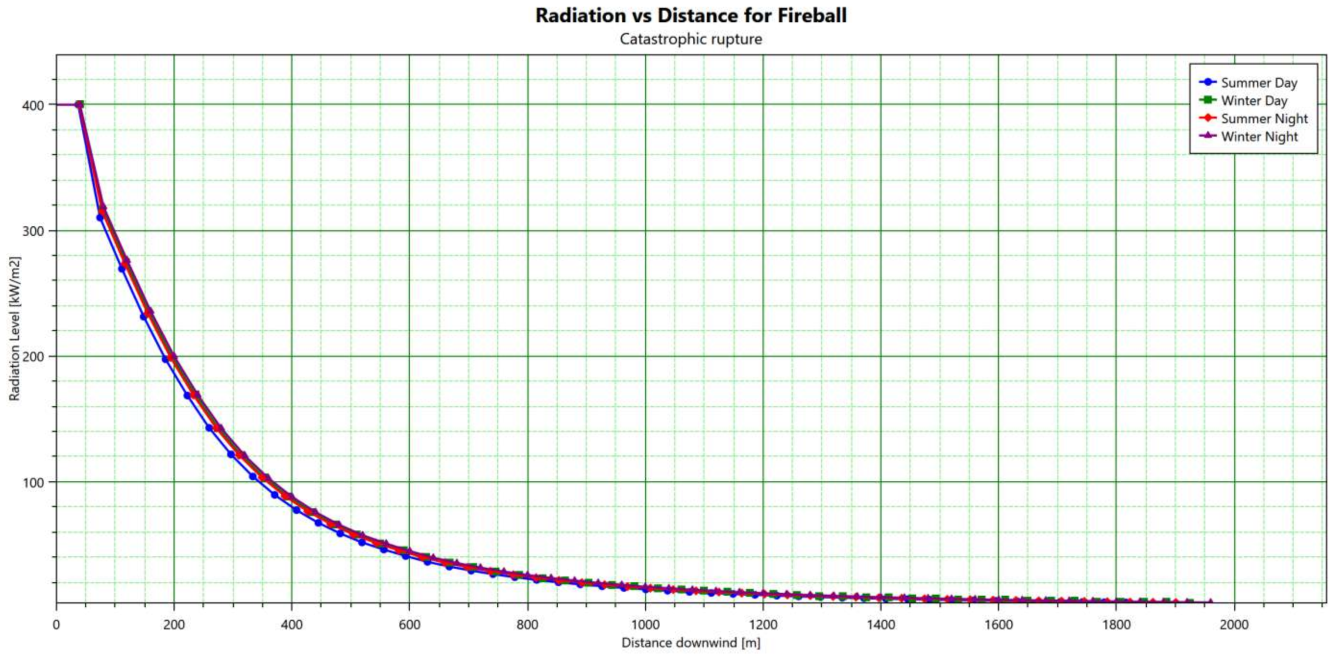

Figure V.9: Radiation vs Distance for Fireball

2.3 Jet fire from a 10mm leak results

The SAFETI software was utilized to assess the jet fire intensity zones resulting from a 10mm leak in the spheres under various weather conditions. The analysis revealed that the jet fire zones formed an oval shape with an approximate coverage of 30 meters. These intensity zones represent areas where the fire would exhibit the highest levels of heat and flames. By understanding the extent and shape of these zones, effective measures can be implemented to ensure the safety of personnel and surrounding infrastructure. The SAFETI results provide valuable insights into the potential impact and spread of the jet fire, aiding in the development of risk mitigation strategies and emergency response plans.

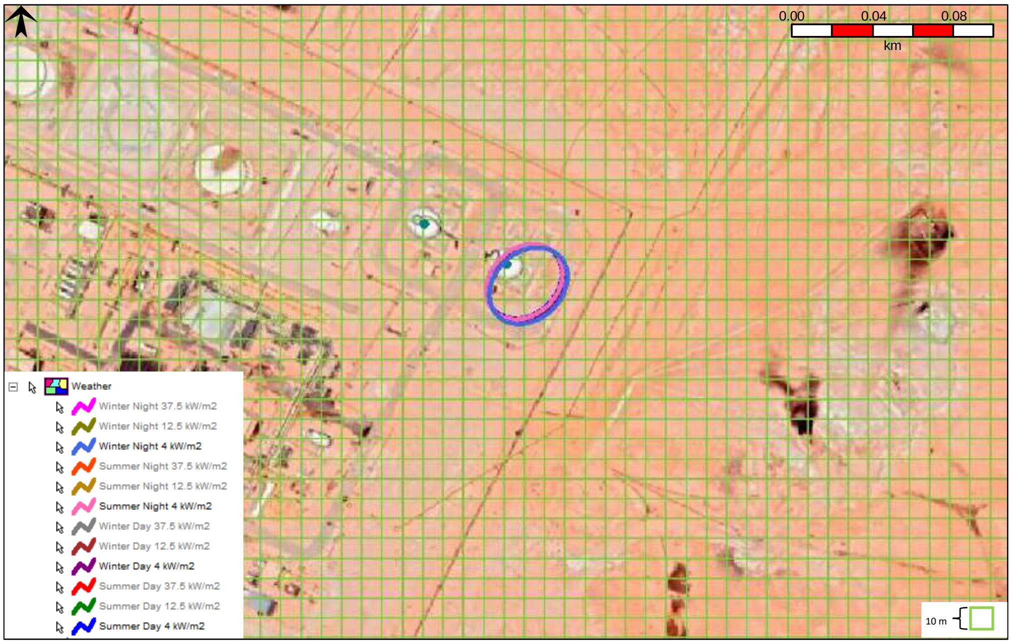

Figure V.10: Jet Fire Affected Zones by Intensity Resulting from a 10mm Leak

The radiation graph of the jet fire illustrates that the distance of radiation can reach up to 34 meters. Additionally, the intensity of radiation reaches its maximum value within a range of 12 to 16 meters, depending on the prevailing weather conditions. These findings highlight the potential hazards and extent of thermal radiation exposure associated with the jet fire scenario. Understanding these parameters is crucial for implementing appropriate safety measures and protecting personnel and nearby structures from the harmful effects of radiation. The radiation graph serves as a valuable tool in assessing the risks and developing effective risk mitigation strategies.

Figure V.11: Jet Fire Intensity-Distance Graph for a 10mm Leak

2.4 Leak explsion worst case results

In the given scenario, the pressure vessel is assumed to be operating at maximum capacity, with the identified event being a 10 mm leak. The resulting worst-case explosion distances, considering different weather conditions, are depicted in the accompanying figure. These findings offer valuable insights into the potential range of the explosion's impact, taking into account the influence of varying weather conditions.

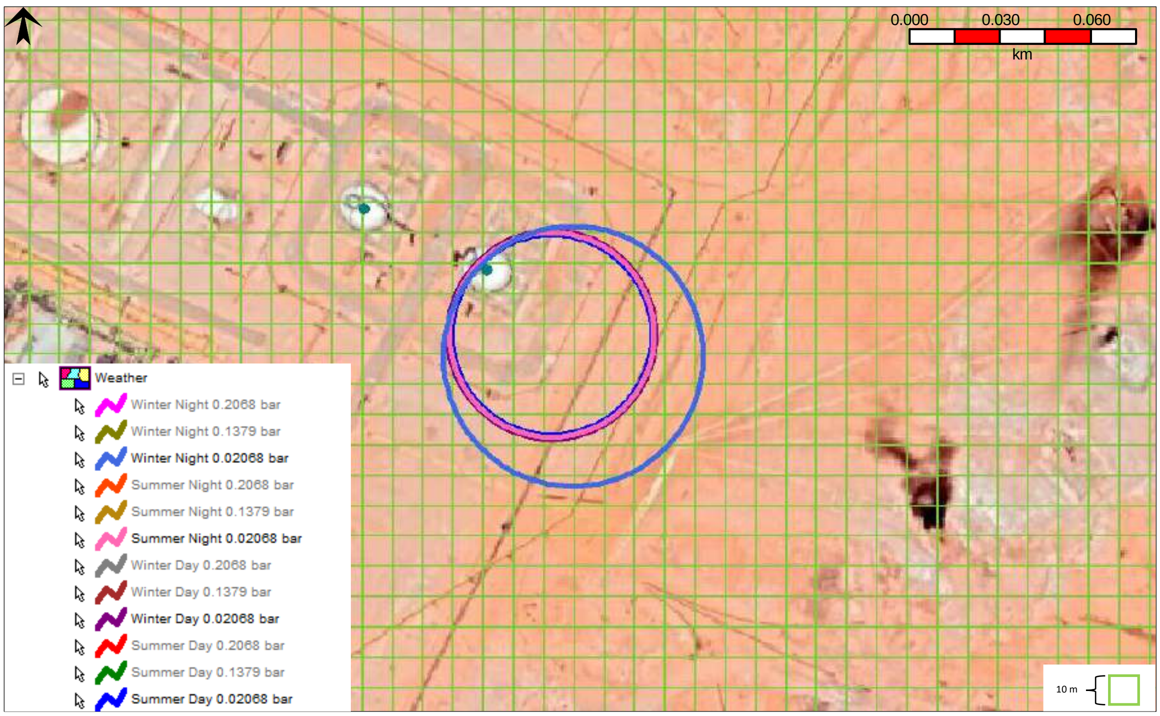

Figure V.12: Leak worst case explosion from SAFETI

In the event of a leak, this scenario presents a notable potential for the resulting explosion to reach a diameter ranging from 60 to 80 meters, depending on the wind speed. Furthermore, the explosion's movement and dispersion are subject to variations based on the prevailing wind direction. Taking into account the influence of wind, the explosion is expected to propagate in specific directions, impacting areas along its path. These findings underscore the significant scale and potential directional impact of the explosion.

2.5 Individual risk calculations

The figure presented below illustrates the results of the individual risk analysis, specifically focusing on the frequencies of death per year. The depicted data showcases the calculated risk levels corresponding to three different scenarios: death frequencies of 10-5, 10-6, and 10-8 per year. These values provide a quantitative understanding of the potential risks associated with the assessed hazards and their impact on individual safety. By visualizing the risk levels at varying magnitudes, this information offers valuable insights for decision-making processes and risk management strategies.

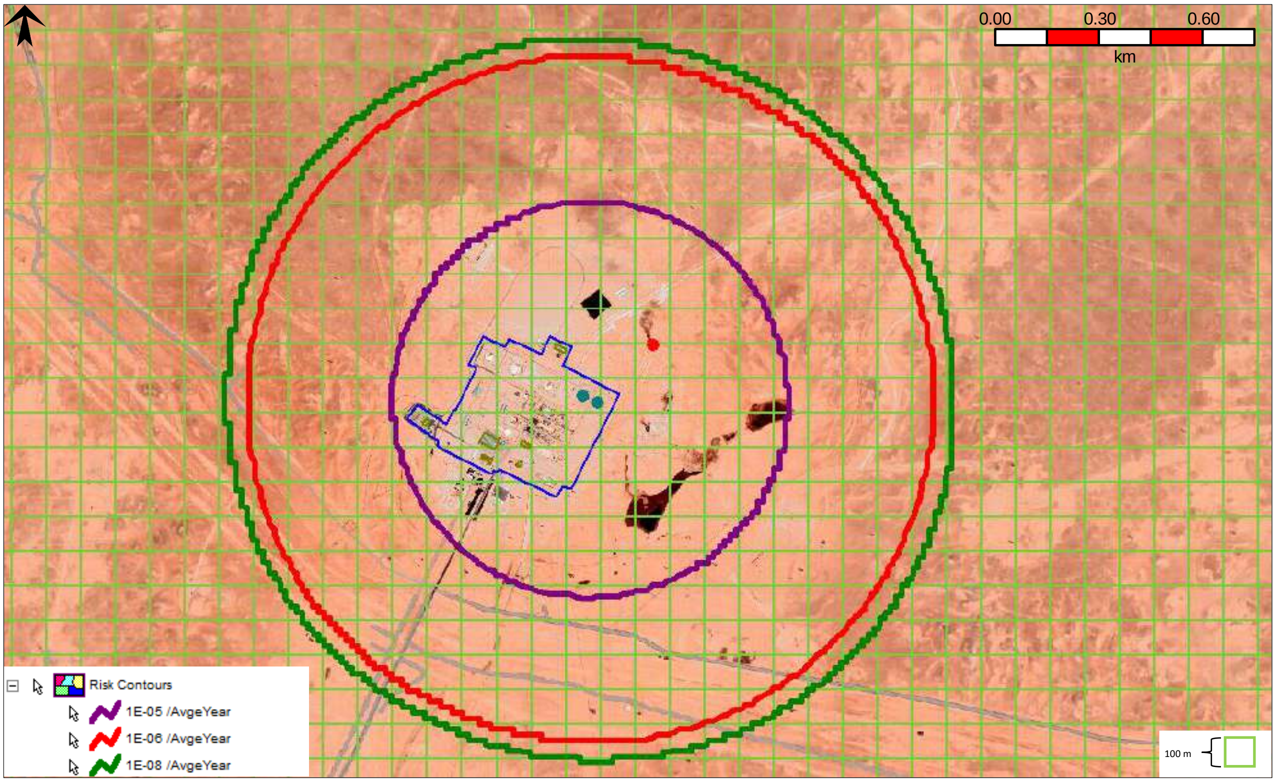

Figure V.13: Individual risk zones from SAFETI

In conclusion, this chapter has presented the PHAST and SAFETI software tools along with the inputs utilized to achieve results in quantitative risk analysis (QRA), explosion effects, and individual risk assessment. The application of these software tools and inputs has yielded valuable insights into the potential hazards and their consequences, aiding in effective decision-making and risk management strategies. SAFETI has proven to be a vital tool in conducting QRA and evaluating the consequences of hazardous events, particularly explosions. By incorporating advanced modeling techniques, SAFETI has quantified the risks involved, predicted the effects of explosions, and assessed individual risk levels. These results have served as crucial inputs for making informed decisions regarding safety measures and optimizing risk mitigation efforts. The results obtained through the application SAFETI, combined with the inputs used, have contributed to a comprehensive understanding of the potential risks posed by hazardous events. The assessment of explosion effects and individual risk levels has provided valuable data for prioritizing safety measures, allocating resources effectively, and implementing appropriate risk control measures.

NOTE: For more comprehensive and detailed results, please refer to Annex 1. This annex provides additional information and data that support the findings and analysis presented in this chapter.

GENERAL CONCLUSION

In conclusion, this thesis has successfully applied Quantitative Risk Analysis (QRA) in the gas treatment unit of Guellala, focusing on the spheres as the main subject of the study. Through the application of supplementary risk analysis techniques, including PHA, HAZOP, LOPA, FTA, and ETA, comprehensive insights into the operational risks and potential hazards have been obtained. The presentation of the gas treatment unit of Guellala, specifically the spheres, has shed light on the critical role they play in the processing and storage of gases. By conducting HAZOP and ETA analyses, the associated failure frequencies for different scenarios have been identified, providing crucial information for risk assessment. Moreover, the application of QRA using the SAFETI software by DNV has further enhanced the risk analysis process. The software's capabilities in assessing and managing the consequences of hazardous events have been effectively utilized, leading to valuable results and insights. The obtained results highlight the importance of robust risk assessment and management in industrial installations. The identified failure frequencies, along with the comprehensive understanding of potential hazards and their consequences, enable informed decision-making and the implementation of appropriate risk mitigation measures.

Overall, this thesis contributes to the field of risk assessment by showcasing the practical application of QRA in a real-world setting. The results obtained through the combination of various risk analysis techniques, the focus on the gas treatment unit of Guellala, and the utilization of the SAFETI software provide a comprehensive framework for managing and reducing risks effectively. These findings serve as a valuable resource for ensuring the safety and operational excellence of the gas treatment unit and can be extended to similar industrial installations.

After conducting an in-depth study, our findings have revealed that the risk frequency in Guellala is alarmingly high. The analysis encompassed various factors such as the specific hazards present, the characteristics of the industrial processes, and the surrounding population density. The calculated risk frequency serves as a quantitative measure of the likelihood of hazardous events occurring within the region. The results emphasize the urgent need for effective risk mitigation strategies and proactive safety measures to address the identified risks. The high-risk frequency underscores the potential consequences and impacts on both human lives and the environment. It also highlights the necessity for continuous monitoring, periodic reassessment, and the implementation of robust safety protocols to minimize the occurrence and severity of hazardous events. The identification of such a high-risk frequency in Guellala serves as a call to action for stakeholders to collaborate and prioritize the implementation of comprehensive risk management practices to safeguard the well-being and security of the community.

Our perspective is focused on calculating and assessing the social risk within the industrial sector. We recognize the importance of not only evaluating the individual risks associated with hazardous events but also understanding their broader societal impact. By considering factors such as population density, critical infrastructure, and the potential consequences on the surrounding community, we aim to provide a comprehensive analysis of the social risks involved. Our approach takes into account both the immediate and long-term effects of these risks, including economic, environmental, and social implications. By quantifying and evaluating the social risk, we can support decision-making processes, enhance safety measures, and promote sustainable practices within the industry to ensure the well-being and resilience of the surrounding communities.

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Abstract

This thesis applies Quantitative Risk Analysis (QRA) to assess and quantify risks in the gas treatment unit of Guellala. Supplementary risk analysis techniques, including HAZOP and ETA, are utilized to identify hazards, analyze consequences, and determine failure frequencies for different scenarios. The SAFETI software by DNV is employed for comprehensive risk assessment. The results obtained provide valuable insights into risk levels and guide effective risk mitigation strategies. This research contributes to the field of risk assessment by showcasing the practical application of QRA in the gas treatment industry.

Key Words: Risk Assessment, Quantitative Risk Analysis, Hazardous Events, Industrial Installation, PHAST and SAFETI.

Résumé

Cette thèse applique l'Analyse Quantitative des Risques (AQR) pour évaluer et quantifier les risques dans l'unité de traitement du gaz de Guellala. Des techniques supplémentaires d'analyse des risques, telles que HAZOP et ETA, sont utilisées pour identifier les dangers, analyser les conséquences et déterminer les fréquences de défaillance pour différents scénarios. Le logiciel SAFETI de DNV est utilisé pour une évaluation complète des risques. Les résultats obtenus fournissent des informations précieuses sur les niveaux de risque et guident des stratégies efficaces de réduction des risques. Cette recherche contribue au domaine de l'évaluation des risques en présentant l'application pratique de l'AQR dans l'industrie du traitement du gaz.

Mots-clés : Évaluation des risques, Analyse quantitative des risques, Événements dangereux, Installation industrielle, PHAST et SAFETI.

ملخص:

تهدف هذه الرسالة إلى تطبيق تحليل المخاطر الكمي (QRA) لتقييم وقياس المخاطر في وحدة معالجة الغاز في قولة. يتم استخدام تقنيات تحليل المخاطر الإضافية، بما في ذلك HAZOP وETA، لتحديد المخاطر، وتحليل النتائج، وتحديد تكرارات الفشل لسيناريوهات مختلفة. يتم استخدام برنامج SAFETI المطور من قبل DNV لتقييم الأخطار بشكل شامل. النتائج المحصل عليها توفر رؤى قيمة حول مستويات المخاطر وتوجه استراتيجيات فعالة للحد من المخاطر. تسهم هذه البحث في مجال تقييم المخاطر من خلال عرض تطبيق عملي لتحليل المخاطر الكمي في صناعة معالجة الغاز.

الكلمات الرئيسية: تقييم المخاطر، تحليل كمي للمخاطر، أحداث خطرة، تركيبات صناعية، PHASTوSAFETI

ANNEX 1

Consequence Summary Report

Workspace: GLA finale

Study: Study

Summary Basis

These tables will only report global values set in the parameters. Values that are modified in the study tree will not be reported.

The report is context sensitive, and filters up to the study level. You will need to generate multiple summary reports if you have multiple studies in your workspace.

Discharge Results (after atmospheric expansion)

Path	Scenario	Weather	Peak Flowrate [kg/s]	Temperature [degC]	Liquid mass fraction in material [fraction]	Droplet diameter [um]	Expanded diameter [m]	Velocity [m/s]	End time of release [s]
Study\T 710-B	Catastrophic rupture	Summer Day		-35.2778	0.632502	119.365		37.6886	
		Winter Day		-35.2778	0.632502	119.365		37.6886	
		Summer Night		-35.2778	0.632502	119.365		37.6886	
		Winter Night		-35.2778	0.632502	119.365		37.6886	
	10mm Leak	Summer Day	1.6292	-35.2778	0.632502	130.391	0.0393289	188.443	3600
		Winter Day	1.6292	-35.2778	0.632502	130.391	0.0393289	188.443	3600
		Summer Night	1.6292	-35.2778	0.632502	130.391	0.0393289	188.443	3600
		Winter Night	1.6292	-35.2778	0.632502	130.391	0.0393289	188.443	3600
Study\T 710-A	Catastrophic rupture	Summer Day		-35.2778	0.632502	119.365		37.6886	
		Winter Day		-35.2778	0.632502	119.365		37.6886	
		Summer Night		-35.2778	0.632502	119.365		37.6886	
		Winter Night		-35.2778	0.632502	119.365		37.6886	
	10mm Leak	Summer Day	0.407299	-35.2778	0.632502	130.391	0.0196644	188.443	3600
		Winter Day	0.407299	-35.2778	0.632502	130.391	0.0196644	188.443	3600
		Summer Night	0.407299	-35.2778	0.632502	130.391	0.0196644	188.443	3600
		Winter Night	0.407299	-35.2778	0.632502	130.391	0.0196644	188.443	3600

Dispersion Results

Input dispersion parameters

Core averaging time	18.75	s
Flammable averaging time	18.75	s
Toxic averaging time	600	s
Height of interest	0	m

Distance downwind to defined concentrations

The reported concentration of interest is defined at the scenario

Path	Scenario	Weather	Distance to UFL [m]	Distance to LFL [m]	Distance to LFL fraction [m]
Study\T 710-B	Catastrophic rupture	Summer Day	442.314	1068.58	1405.36
		Winter Day	369.743	989.402	1304.99
		Summer Night	432.371	1065.76	1416.48
		Winter Night	329.311	1260.9	1603.33
	10mm Leak	Summer Day	n/a	n/a	21.4976
		Winter Day	n/a	n/a	24.1026
		Summer Night	n/a	n/a	23.5052
		Winter Night	n/a	n/a	40.8898
Study\T 710-A	Catastrophic rupture	Summer Day	442.314	1068.58	1405.36
		Winter Day	369.743	989.402	1304.99
		Summer Night	432.371	1065.76	1416.48
		Winter Night	329.311	1260.9	1603.33
	10mm Leak	Summer Day	n/a	n/a	n/a
		Winter Day	n/a	n/a	n/a
		Summer Night	n/a	n/a	n/a
		Winter Night	n/a	n/a	n/a

Jet Fire Results

Distance downwind to defined radiation levels

The reported radiations are defined in the parameters

Path	Scenario	Weather	Flame length [m]	Distance downwind to intensity level 1 (4 kW/m2) [m]	Distance downwind to intensity level 2 (12.5 kW/m2) [m]	Distance downwind to intensity level 3 (37.5 kW/m2) [m]
Study\T 710-B	10mm Leak	Summer Day	12.471	28.3615	20.9866	16.4017
		Winter Day	13.7896	29.5019	22.146	17.5406
		Summer Night	12.471	28.6074	21.1134	16.4747
		Winter Night	16.7242	31.7226	24.5243	19.8876
Study\T 710-A		Summer Day	6.80417	15.0067	11.1712	8.73782
		Winter Day	7.52359	15.5958	11.7813	9.34292
		Summer Night	6.80417	15.1124	11.2276	8.77008
		Winter Night	9.1247	16.8046	13.0651	10.5907

Late Pool Fire Results

Distance downwind to defined radiation levels

The reported radiations are defined in the parameters

Path	Scenario	Weather	Pool diameter [m]	Distance downwind to intensity level 1 (4 kW/m2) [m]	Distance downwind to intensity level 2 (12.5 kW/m2) [m]	Distance downwind to intensity level 3 (37.5 kW/m2) [m]
Study\T 710-B	Catastrophic rupture	Summer Day	260.1	792.555	513.46	319.794
		Winter Day	286.728	860.323	546.019	327.01
		Summer Night	275.988	847.212	546.344	344.761
		Winter Night	313.243	904.418	554.314	311.835
Study\T 710-A		Summer Day	260.1	792.555	513.46	319.794
		Winter Day	286.728	860.323	546.019	327.01
		Summer Night	275.988	847.212	546.344	344.761
		Winter Night	313.243	904.418	554.314	311.835

Fireball Results

Distance downwind to defined radiation levels

The reported radiations are defined in the parameters

Path	Scenario	Weather	Fireball diameter [m]	Distance downwind to intensity level 1 (4 kW/m2) [m]	Distance downwind to intensity level 2 (12.5 kW/m2) [m]	Distance downwind to intensity level 3 (37.5 kW/m2) [m]
Study\T 710-B	Catastrophic rupture	Summer Day	551.05	1816.27	1071.9	619.458
		Winter Day	551.05	1924.61	1127.68	649.258
		Summer Night	551.05	1900.79	1115.43	642.729
		Winter Night	551.05	1959.92	1145.83	658.933
Study\T 710-A		Summer Day	551.05	1816.27	1071.9	619.458
		Winter Day	551.05	1924.61	1127.68	649.258
		Summer Night	551.05	1900.79	1115.43	642.729
		Winter Night	551.05	1959.92	1145.83	658.933

Flash Fire Results

Distance downwind to defined concentrations

The reported LFL and LFL fraction are defined in the respective material property

Path	Scenario	Weather	Distance downwind to LFL [m]	Distance downwind to LFL Fraction [m]
Study\T 710-B	Catastrophic rupture	Summer Day	1068.58	1405.36
		Winter Day	989.402	1304.99
		Summer Night	1065.76	1416.48
		Winter Night	1260.9	1603.33
	10mm Leak	Summer Day		21.4976
		Winter Day		24.1026
		Summer Night		23.5052
		Winter Night		40.8898
Study\T 710-A	Catastrophic rupture	Summer Day	1068.58	1405.36
		Winter Day	989.402	1304.99
		Summer Night	1065.76	1416.48
		Winter Night	1260.9	1603.33
	10mm Leak	Summer Day		
		Winter Day		
		Summer Night		
		Winter Night		

Maximum distance to LFL fraction at any height

Path	Scenario	Weather	Max flash fire distance [m]	Height of the max flash fire distance [m]	Time [s]
Study\T 710-B	Catastrophic rupture	Summer Day	1380.12	0	165.284
		Winter Day	1290.44	0	238.701
		Summer Night	1402.97	0	201.755
		Winter Night	1594.85	0	520.329
	10mm Leak	Summer Day	30.6759	0.691882	7.51572
		Winter Day	31.3994	0.568176	7.516
		Summer Night	31.5643	0.628788	7.51588
		Winter Night	40.8831	0.0635739	210.681
Study\T 710-A	Catastrophic rupture	Summer Day	1380.12	0	165.284
		Winter Day	1290.44	0	238.701
		Summer Night	1402.97	0	201.755
		Winter Night	1594.85	0	520.329
	10mm Leak	Summer Day	8.56837	0.946926	1.91797
		Winter Day	9.18255	0.92924	1.91798
		Summer Night	8.84469	0.938171	1.91797
		Winter Night	13.5369	0.652084	23.8464

Explosion Results

Explosion scenarios for worst-case maximum downwind distance to defined overpressures.

These results are produced during the consequence run and depend on the precise setting of the scenario. These results may be quite different to the explosion results calculated during the risk or effects modelling as these will depend on the obstructed regions defined on the map.

The reported overpressures are defined in the explosion parameters

Path	Scenario	Weather	Overpressure level [bar]	Maximum distance [m]	Diameter [m]
Study\T 710-B	Catastrophic rupture	Summer Day	0.02068 0.1379 0.2068	4053.4 1737.21 1642.58	6126.8 814.418 525.154
		Winter Day	0.02068 0.1379 0.2068	3924.44 1635.71 1549.2	6108.88 691.422 518.402
		Summer Night	0.02068 0.1379 0.2068	4031.64 1732.8 1649.52	5963.28 665.598 499.04
		Winter Night	0.02068 0.1379 0.2068	4600.06 2086.45 1946.12	6240.13 1192.9 772.233
	10mm Leak	Summer Day	0.02068 0.1379 0.2068	62.9852 36.4109 34.8067	65.9705 12.8218 9.6133
		Winter Day	0.02068 0.1379 0.2068	64.3576 36.6776 35.0066	68.7152 13.3553 10.0133
		Summer Night	0.02068 0.1379 0.2068	63.7164 36.553 34.9132	67.4328 13.106 9.82639
		Winter Night	0.02068 0.1379 0.2068	82.8951 48.337 46.2507	85.7902 16.6739 12.5015
Study\T 710-A	Catastrophic rupture	Summer Day	0.02068 0.1379 0.2068	4053.4 1737.21 1642.58	6126.8 814.418 525.154
		Winter Day	0.02068 0.1379 0.2068	3924.44 1635.71 1549.2	6108.88 691.422 518.402
		Summer Night	0.02068 0.1379 0.2068	4031.64 1732.8 1649.52	5963.28 665.598 499.04
		Winter Night	0.02068 0.1379 0.2068	4600.06 2086.45 1946.12	6240.13 1192.9 772.233
	10mm Leak		0.02068 0.1379 0.2068	29.9752 13.8823 12.9108	39.9505 7.76465 5.82163

Supplementary data for worst-case explosion scenarios

Path	Scenario	Weather	Overpressure level [bar]	Explosion flammable mass [kg]	Ignition time [s]	Ignition source [m]	Cloud center [m]	Explosion center [m]
Study\T 710-B	Catastrophic rupture	Summer Day	0.02068 0.1379 0.2068	326094 104324 66364	73.997 148.52 165.244	990 1330 1380	373.672 300.733 157.646	990 1330 1380
		Winter Day	0.02068 0.1379 0.2068	323242 63837.1 63837.1	75.0214 237.976 237.976	870 1290 1290	255.606 140.684 140.684	870 1290 1290
		Summer Night	0.02068 0.1379 0.2068	300676 56948 56948	85.8464 199.601 199.601	1050 1400 1400	412.56 163.886 163.886	1050 1400 1400
		Winter Night	0.02068 0.1379 0.2068	344527 327838 211018	352.297 366.928 469.342	1480 1490 1560	303.601 315.744 400.743	1480 1490 1560
	10mm Leak	Summer Day	0.02068 0.1379 0.2068	0.407091 0.407091 0.407091	7.15943 7.15943 7.15943	30 30 30	6.41344 6.41344 6.41344	30 30 30
		Winter Day	0.02068 0.1379 0.2068	0.460045 0.460045 0.460045	6.90036 6.90036 6.90036	30 30 30	6.58353 6.58353 6.58353	30 30 30
		Summer Night	0.02068 0.1379 0.2068	0.434766 0.434766 0.434766	6.79295 6.79295 6.79295	30 30 30	6.49664 6.49664 6.49664	30 30 30
		Winter Night	0.02068 0.1379 0.2068	0.895272 0.895272 0.895272	68.2629 68.2629 68.2629	40 40 40	8.90326 8.90326 8.90326	40 40 40
Study\T 710-A	Catastrophic rupture	Summer Day	0.02068 0.1379 0.2068	326094 104324 66364	73.997 148.52 165.244	990 1330 1380	373.672 300.733 157.646	990 1330 1380
		Winter Day	0.02068 0.1379 0.2068	323242 63837.1 63837.1	75.0214 237.976 237.976	870 1290 1290	255.606 140.684 140.684	870 1290 1290
		Summer Night	0.02068 0.1379 0.2068	300676 56948 56948	85.8464 199.601 199.601	1050 1400 1400	412.56 163.886 163.886	1050 1400 1400
		Winter Night	0.02068 0.1379 0.2068	344527 327838 211018	352.297 366.928 469.342	1480 1490 1560	303.601 315.744 400.743	1480 1490 1560
	10mm Leak		0.02068 0.1379 0.2068	0.0904083 0.0904083 0.0904083	2.35449 2.35449 2.35449	10 10 10	3.91123 3.91123 3.91123	10 10 10