الجمهورية الجزائرية الديمقراطية الشعبية

PEOPLE'S DEMOCRATIC REPUBLIC OF ALGERIA

وزارة التعليم العالي والبحث العلمي

Ministry of Higher Education and Scientific Research

جامعة أمحمد بوقرة ببومرداس

M'Hamed Bougara University, Boumerdes

كليـــة المـحـروقـات والـكيمـيـاء

Faculty of Hydrocarbons and Chemistry

Department of Chemical and Pharmaceutical Process Engineering

MASTER'S THESIS

In partial fulfillment of the requirements for the degree of

RESEARCH MASTER IN ENGINEERING

Specialty: Process Engineering

Option: Health, Safety and Environment (HSE)

Theme

Risk assessment using Bow-Tie analysis method: Boiler case at the GL2Z complex in Bethioua, Oran

Presented by:

- **BENASLA Abdelkader**
- **BOUZARA Badre-eddine**

Supervised by:

Mme YOUNSI

Before the jury composed of:

Ms. BENRAHOU.F	**MCB**	**UMBB**	**President**
Ms. BRIKI.M	**MCB**	**UMBB**	**Examiner**
Ms. YOUNSI.F	**MCB**	**UMBB**	**Supervisor**

Academic year: 2023/2024

Acknowledgement

First and foremost, I would like to praise Allah, the Most Gracious and the Most Merciful, the protector and constant companion in our lives. His infinite mercy has been the key to the success of this work.

Mm. YOUNSI, we would like to express our deep gratitude to you for your essential role as the supervisor of our thesis. and believed in us and adapted our ideas, Your commitment, expertise, and unwavering support have been crucial elements of our academic success, and we warmly thank you for your invaluable contribution.

Your passion for research and dedication to your role as a supervisor have been a constant source of inspiration for us. Your insightful advice, availability, and ability to guide us throughout this process have been invaluable. Thanks to your support.

Dedication

BENASLA Abdelkader : I would like to express my heartfelt gratitude to a number of people whose support and encouragement have been instrumental in my journey.

First and foremost, I want to thank my **mother**, whose unwavering support and endless sacrifices have been a cornerstone in my life. Her guidance, love, and encouragement have helped shape the person I am today. Her nurturing spirit and dedication to our family have always been a source of inspiration.

I also extend my deepest gratitude to my **father RABI YARAHMOU**, His love, guidance, and support continue to inspire me every day. Though he is no longer with us, his belief in me remains my greatest motivation, I hope this work honors his memory.

To my sisters, **Khaira, Khaoula and Khadidja**, and my brother, **Abdessamed**, your companionship and love have made my life richer and more meaningful. Thank you for always being there for me, through thick and thin.

I am incredibly grateful to **my grandmother**, whose love and prayers have always been a protective shield around me. To **my grandfather** and all **my aunts** and **uncles** and **cousins**, thank you for your unwavering support and love.

To my friends, **Jalil** and **Oussama Rahmani**, and all the friends I have met throughout my life, your companionship and support have been invaluable. Each one of you has contributed to my journey in a unique and meaningful way.

I also extend my thanks to my friends from **MAHSE19**. A special thanks to **Mm. YOUNSI** and **Mm. BENRAHOU** for their unwavering support and guidance.

BOUZARA Badre-eddine : Praise to allah , thanks to my parents , friends , teachers and my classmates.

List of content

List of Figures

List of Tables

Acronym

Acronym	Definition
SIL	Safety Integrity Level - Evaluates the reliability of safety instrumented systems (SIS).
HAZID	Hazard Identification - High-level screening to identify early-stage hazards.
LOPA	Layer of Protection Analysis - Evaluates the effectiveness of protection layers.
QRA	Quantitative Risk Assessment - Uses mathematical modeling to estimate risk levels.
HAZOP	Hazard and Operability Study - Identifies hazards and operability issues.
PRA	Preliminary Risk Analysis - Early-stage assessment to identify significant risks.
FTA	Fault Tree Analysis - Analyzes causes of system failures using a tree structure.
ETA	Event Tree Analysis - Explores outcomes of an initial event.
FMECA	Failure Mode, Effects, and Criticality Analysis - Identifies and prioritizes potential failure modes.
PPE	Personal Protective Equipment - Minimizes exposure to workplace hazards.
EF	Escalation Factor - Factors that can worsen hazard consequences.
OAP	Upper Air Port - Reduces NOx levels in the combustion system.
IR	Infrared - Used in gas detectors to monitor gas leaks.
NOx	Nitrogen Oxides - Pollutant gases from high-temperature combustion.
SIS	Safety Instrumented Systems - Automated systems to ensure safe operation.

Introduction

Introduction

In the complex and high-risk environment of industrial operations, ensuring safety and mitigating hazards are paramount. The focus is on the application of the Bow Tie method for risk assessment, a comprehensive approach that identifies potential threats, their causes, and consequences, and implements barriers to prevent and mitigate risks. The Bow Tie method is particularly effective in visualizing the pathways from potential hazards to their consequences, allowing for a structured and systematic analysis of risks and the implementation of effective control measures.

Industrial boilers play a crucial role in numerous industrial processes, providing the necessary heat and energy for various operations. Despite their importance, boilers pose significant risks if not properly managed, including the potential for catastrophic failures. This necessitates a thorough risk assessment to identify and address potential hazards.

In this context, various scenarios involving industrial boilers are explored. Boilers, while essential for operations, pose significant risks if not properly managed. The scenarios examined include defective gas detectors, leaky fuel gas line valves, bypassed purging operations, faulty ignition systems, and corroded fuel lines. Each scenario is analyzed to identify threats and propose barriers to prevent and mitigate potential incidents. These threats can lead to severe consequences, such as explosions, fires, environmental releases, structural damage, and toxic exposures, which can have devastating impacts on human life, property, and the environment.

The proposed barriers range from advanced detection technologies and automated control systems to enhanced training programs and robust structural assessments. By implementing these measures, the likelihood of hazardous incidents is reduced, and the overall safety and resilience of operations are improved. Advanced gas detection technology, automated system checks, installation of redundant valves, and use of high-quality ignition components are just a few examples of how technological advancements can significantly enhance safety. Similarly, training and supervision of personnel, regular maintenance and inspections, and adherence to stringent operational procedures are critical in minimizing human error and ensuring safe operations.

Furthermore, the consequences of potential incidents, such as explosion damage, fire injuries, environmental releases, structural damage, and toxic exposure, are addressed. For each consequence, specific recovery barriers are proposed to minimize impact and ensure rapid and effective response. Implementation of automated emergency shutdown systems, use of blast-resistant building materials, provision of advanced fire suppression technologies, and continuous environmental and air quality monitoring are some of the measures that can effectively mitigate the aftermath of an incident.

This content serves as a comprehensive guide for risk assessment and management in industrial settings, providing detailed analyses and practical solutions to enhance safety and operational efficiency. Through the meticulous application of the Bow Tie method, it aims to contribute to the prevention of accidents and the protection of personnel, infrastructure, and the environment. The ultimate goal is to create a safer industrial environment where risks are proactively managed and the potential for accidents is significantly reduced.

By adopting these advanced risk assessment techniques and implementing robust preventive and mitigative measures, industries can achieve higher levels of safety and operational excellence. This proactive approach not only protects lives and assets but also enhances regulatory compliance and fosters a culture of safety and continuous improvement. The insights and methodologies presented here are valuable tools for engineers, safety professionals, and decision-makers in industrial settings, helping them to better understand and manage the complex risks associated with industrial operations.

Chapter I
Risk Analysis Methods

1. General Risk Analysis Methods [1]

Risk analysis is a fundamental process used by organizations to identify, assess, and manage risks that could potentially impact their operations, assets, or stakeholders. Effective risk analysis helps in making informed decisions by understanding potential threats and uncertainties, thus enabling better preparedness and response strategies. Several methodologies are utilized for risk analysis, each with its own strengths and applications. Common risk analysis methods include:

1.1. Qualitative Risk Analysis:

This approach involves identifying risks and assessing their impact and likelihood without using numerical estimates. It often employs techniques like brainstorming, the Delphi method, and risk matrices. This method is particularly useful for initial risk screening and for situations where precise data is unavailable.

1.2. Quantitative Risk Analysis:

This method involves numerical analysis to determine the probability and impact of risks. Techniques include Monte Carlo simulations, decision tree analysis, and fault tree analysis. Quantitative risk analysis is essential for providing detailed risk assessments and for making decisions based on statistical data.

1.3. Failure Mode, Effects, and Criticality Analysis (FMECA):

Failure Mode, Effects, and Criticality Analysis (FMECA) is a systematic method for evaluating processes to identify where and how they might fail and assessing the relative impact of different failures. This analysis aims to prioritize the failure modes according to their potential impact on system operations and helps in implementing corrective actions to mitigate those failures. FMECA is extensively used in industries such as aerospace, automotive, manufacturing, and particularly in the oil and gas sector, where safety and reliability are paramount.(see figure I-1)

Process Step	Potential Failure Mode	Potential Failure Effect	SEV[1]	Potential Causes	OCC[2]	Current Process Controls	DET[3]	RPN[4]	Action Recommended
What is the step?	In what ways can the step go wrong?	What is the impact on the customer if the failure mode is not prevented or corrected?	How severe is the effect on the customer?	What causes the step to go wrong (i.e., how could the failure mode occur)?	How frequently is the cause likely to occur?	What are the existing controls that either prevent the failure mode from occurring or detect it should it occur?	How probable is detection of the failure mode or its cause?	Risk priority number calculated as SEV x OCC x DET	What are the actions for reducing the occurrence of the cause or for improving its detection? Provide actions on all high RPNs and on severity ratings of 9 or 10.
ATM Pin Authentication	Unauthorized access	• Unauthorized cash withdrawal • Very dissatisfied customer	8	Lost or stolen ATM card	3	Block ATM card after three failed authentication attempts	3	72	
	Authentication failure	Annoyed customer	3	Network failure	5	Install load balancer to distribute workload across network links	5	75	
Dispense Cash	Cash not disbursed	Dissatisfied customer	7	ATM out of cash	7	Internal alert of low cash in ATM	4	196	Increase minimum cash threshold limit of heavily used ATMs to prevent out-of-cash instances
	Account debited but no cash disbursed	Very dissatisfied customer	8	• Transaction failure • Network issue	3	Install load balancer to distribute workload across network links	4	96	
	Extra cash dispensed	Bank loses money	8	• Bills stuck to each other • Bills stacked incorrectly	2	Verification while loading cash in ATM	3	48	

1. **Severity**: Severity of impact of failure event. It is scored on a scale of 1 to 10. A high score is assigned to high-impact events while a low score is assigned to low-impact events.
2. **Occurrence**: Frequency of occurrence of failure event. It is scored on a scale of 1 to 10. A high score is assigned to frequently occurring events while events with low occurrence are assigned a low score.
3. **Detection**: Ability of process control to detect the occurrence of failure events. It is scored on a scale of 1 to 10. A failure event that can be easily detected by the process control is assigned a low score while a high score is assigned to an inconspicuous event.
4. **Risk priority number**: The overall risk score of an event. It is calculated by multiplying the scores for severity, occurrence and detection. An event with a high RPN demands immediate attention while events with lower RPNs are less risky.

Figure I- 1: FMECA Example

1.4. Hazard and Operability Study (HAZOP)

A Hazard and Operability Study (HAZOP) is a structured and systematic examination of a complex planned or existing process or operation to identify and evaluate problems that may represent risks to personnel or equipment, or prevent efficient operation. The primary goal of HAZOP is to identify potential hazards and operability issues to ensure safe and reliable operation. (see figure I-2)

Node: 1. *Tank T-001 and nitrogen purge*

Deviation	Session	Causes	Consequences	CAT	Risk rating before safeguarding: Original risk S	Original risk F	Original risk RR	Enablers/Modifiers/Design	Corrected risk S	Corrected risk F	Corrected risk RR	Safeguards: Instrumental: Sensor TAG-nr	Final element: TAG-nr	Final element: Action	Effective Action	Other safeguards (e.g. Alarm + operator action/Mechanical/Mitigation)	Critical safeguards: Description	Type	RRF	Risk rating after safeguarding: S	F	RR	HAZOP Recommendations	Responsibility for recommendation	Risk rating after completion of recommendations: S	F	RR
1. Flow High	1. 9-11-2018	1. V-003 is open during solvent filtration. Human error.	Continuous evaporation of solvent in T-001 (towards Vapor Return). T-001 level decreases; P-001 / P-002 runs dry. Potential pump damage.	A	S1	F5	Low Alarp					2. LS-002	1. P-001 2. P-002 3. P-100 4. P-200	Stop pump Stop pump Stop pump Stop pump	1. Yes		7. LS-002 stops pump P-001 & P-002 (and P-100 & P-200)	Instrumental	10x	S1	F4	Low					
2. Flow Low	1. 9-11-2018	1. No credible causes/consequences identified.																									
3. Flow No	1. 9-11-2018	1. No credible causes/consequences identified.																									
4. Flow Reverse	1. 9-11-2018	1. No credible causes/consequences identified.																									
5. Pressure High	1. 9-11-2018	1. PC-001 fails open or wrong setpoint. Nitrogen purge is only used during solvent operation.	Pressure in system rises to max 16 barg. P operation is >> P design T-001, T-001 will fail mechanically. Assumption: T-001 fails at its top lid. Lid will lift; People may come into contact with harmful (corrosive) vapor/liquid (spray). Expected to be severity S3 (medical treatment).	P	S3	F5	Very High	1. People present: 100% during nitrogen purging. 2. Probability of being hit by liquids and obtain S3 severity: 10%	S3	F4	High Alarp						1. V-xxx pressure control valve can relief max 25 m3/h.	Mechanical	10x	S3	F3	Low Alarp	1. Install pressure relief valve on vessel (outlet to safe location) to protect against -overfilling scenario (sizing according to max feed flow). -Nitrogen supply failure (fail open)		S3	F1	Low

Figure I- 2: HAZOP Example

1.5. Preliminary Risk Analysis (PRA)

Preliminary Risk Analysis (PRA) is an early-stage risk assessment tool used to identify and evaluate potential risks in a project, process, or system. The primary goal of PRA is to provide an initial assessment of risks to inform decision-making and prioritize further detailed analysis and risk management efforts. (see figure I-3)

Preliminary Risk Analysis Worksheet
Item analyzed: e-PCCMOW Course (Feb 18 version)
Risk analysis project: Formative evaluation
Risk Question: What are the risks of a TECHNOLOGY RELATED issue with the e-PCCMOW course?

	Step #1	*Step #2*	*Step #3*	*Step #4a*	*Step #4b*	*Step #4c*	*Step #5*
Risk ID #	**Unwanted Event/ Hazard**	**Consequences / Harm**	**Contributing Causes**	**Likelihood of Occurrence**	**Severity of Consequence**	**Risk Score**	**Possible Additional Controls/Actions**
	What could happen?	*What is the potential negative impacts to patient, product, regulatory status, other things of value?*	*What could cause this unwanted event to happen?*	*What is the likelihood that the event & the harm will occur? (rating scale)*	*What is the impact of this consequence? (rating scale)*	*(calculated)*	*What might be done to reduce the likelihood and/or severity?*
1	Incompatibility of browser with website	> Limited access to sections of course > No access to parts of pages	> Set-up of browser > Internal browser thing > Coding issue	1	3	**3**	1) Recommendations of browsers NOT to use 2) Determine cause of problem if possible 3) Tell what browers are supported
2	Bandwidth issue (user side)	> User can't get timely access to videos, docs	> Local provider bandwidth issue	2	3	**6**	1) Send out DVD of videos and docs
3	Government (of participant) blocks server sites (e.g., VIMEO)	> User can't get any access to videos, documents, or course	> Local political issues	2	3	**6**	1) Send out DVD (via express shipment e.g., DHL) 2) Have mirrored alternative sites for videos, etc 3) Make videos available as downloads (e.g. DROPBOX or Yousendit) 4) Inform participants of the possibilty; have them communicate to mentors if there is a problem
4	DVDs/downloads get distributed to others	> Information (e.g., imbedded poor practices) gets distributed and used out-of-correct-context	> Information not controlled (e.g., via streaming)	1	3	**3**	1) Have mirrrored sites available for videos whenever possible 2) Put notice on DVD 3) Have participant agree not to transfer to others
5	Server problems or outages – at host sites (host server, VIMEO	> Non-availability of site and resources when needed by participant	> Crashes – unplanned outages > Planned outages (e.g., for	1	2	**2**	1) Find out about site's contingency plans 2) Communicate planned outages with participants in advance

Figure I- 3: APR Example

1.6. Bow-Tie Method

The Bow-Tie Method is a powerful and versatile risk assessment tool that bridges the gap between qualitative and quantitative approaches. It provides a comprehensive visualization of risk scenarios by combining the concepts of Fault Tree Analysis (FTA) and Event Tree Analysis (ETA). This method is especially valued for its ability to clearly illustrate the pathways from potential hazards to their possible consequences, along with the preventive and mitigative controls in place. In this detailed analysis, we will delve into the origins, methodology, benefits, and challenges of the Bow-Tie Method, with a specific focus on its application in the oil and gas industry.

The Bow-Tie Method is designed to provide a holistic view of risk management by visually representing the relationships between hazards, their causes, and consequences, as well as the controls in place to manage these risks. The method's name derives from its distinctive diagrammatic shape, which resembles a bow-tie. The central "knot" represents the hazard, the left "wing" represents the threats (causes), and the right "wing" represents the consequences, with preventive controls on the left side and mitigative controls on the right.

- **History**

The Bow-Tie Method originated in the oil and gas industry in the 1970s and 1980s, during a period when the industry was seeking more effective ways to manage complex risks. It gained prominence following the Piper Alpha disaster in 1988, which highlighted the need for better risk management practices. The method was further refined and formalized in the 1990s and has since been adopted across various high-risk industries, including aviation, chemical processing, and healthcare.

- **Methodology and Procedure**

The Bow-Tie Method involves a systematic process that integrates elements of both Fault Tree Analysis and Event Tree Analysis. This comprehensive approach ensures that both the preventive measures (to stop threats from causing a hazard) and the mitigative measures (to reduce the impact of the hazard if it occurs) are thoroughly examined.

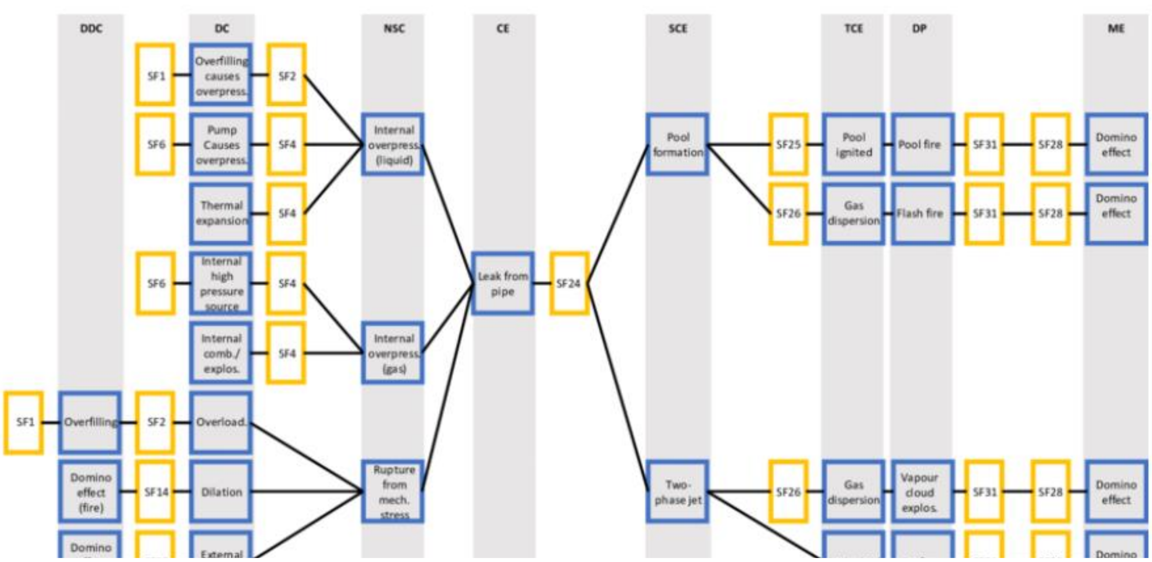

Figure I- 4: Bow-Tie Example

1) Hazard Identification

The first step in the Bow-Tie Method is to identify the hazard. A hazard is any potential source of harm or adverse effect. In the context of the oil and gas industry, hazards can range from equipment failures and operational errors to natural events and human factors.

2) Identify Threats

Once the hazard is identified, the next step is to identify the threats or causes that could lead to the occurrence of the hazard. These threats are potential events or conditions that can initiate the hazard scenario.

3) Identify Consequences

The next step is to determine the potential consequences if the hazard materializes. Consequences are the adverse outcomes that result from the hazard, affecting people, the environment, assets, and reputation.

4) Identify Preventive Controls

Preventive controls are measures implemented to prevent the occurrence of the hazard by managing the threats. These controls act as barriers to stop the threats from leading to the hazard.

5) Create the Bow-Tie Diagram

The final step is to construct the bow-tie diagram to visually represent the hazard, threats, preventive controls, consequences, and mitigative controls. The diagram has the hazard in the center, threats on the left side leading to the hazard, and consequences on the right side resulting from the hazard. Preventive controls are placed between the threats and the hazard, while mitigative controls are placed between the hazard and the consequences.

Figure I- 5: Bow-Tie Example

- **Benefits of the Bow-Tie Method**

The Bow-Tie Method offers numerous benefits, making it a preferred risk management tool in various industries, particularly in high-risk sectors like oil and gas.

- ✓ **Visual Clarity**

One of the most significant advantages of the Bow-Tie Method is its ability to provide a clear and intuitive visual representation of risk scenarios. This visual clarity helps stakeholders at all levels of the organization to understand the risk pathways and the controls in place, enhancing communication and understanding.

- ✓ **Integration of Controls**

The Bow-Tie Method effectively integrates both preventive and mitigative controls, offering a comprehensive view of risk management. By clearly delineating the controls that prevent the occurrence of a hazard and those that mitigate its consequences, the method ensures that all aspects of risk management are considered.

- ✓ **Enhanced Communication**

The visual nature of the bow-tie diagram facilitates communication of risks and controls across different levels of the organization. This enhanced communication is crucial for ensuring that all stakeholders are aware of the risks and the measures in place to manage them.

- ✓ **Structured Approach**

The Bow-Tie Method provides a structured approach to identifying, assessing, and managing risks. This structured methodology helps ensure that all relevant threats, consequences, and controls are systematically considered, reducing the likelihood of overlooking critical elements.

- ✓ **Regulatory Compliance**

Many regulatory frameworks require companies to demonstrate effective risk management practices. The Bow-Tie Method supports compliance with these regulatory requirements by providing a clear and documented approach to risk management. This documentation can be used to demonstrate to regulators that risks are being managed appropriately.

- ➢ **Challenges of the Bow-Tie Method**

Despite its many benefits, the Bow-Tie Method also has some challenges and limitations that need to be addressed.

- ✓ **Complexity**

For large systems with numerous hazards and controls, the Bow-Tie Method can become complex and unwieldy. Managing this complexity requires careful planning and the use of software tools to create and maintain the bow-tie diagrams.

- ✓ **Data Requirement**

Effective use of the Bow-Tie Method requires accurate and comprehensive data to identify and assess risks. This data can be difficult to obtain, particularly in cases where historical data is lacking or where the data quality is poor.

- ✓ **Subjectivity**

The Bow-Tie Method involves subjective judgment in identifying and assessing controls. This subjectivity can lead to variability in the quality and consistency of the risk assessments, depending on the experience and expertise of the individuals involved.

- ✓ **Maintenance**

The bow-tie diagrams need to be regularly updated to reflect changes in the operational environment, new threats, and the effectiveness of controls. This ongoing maintenance can be resource-intensive and requires a commitment to continuous improvement.

2. Risk Analysis in the Oil and Gas Industry [2]

The oil and gas industry is characterized by high-risk operations due to the involvement of hazardous materials, complex processes, and significant environmental and safety impacts. Effective risk analysis is crucial in this sector to prevent incidents, ensure safety, and maintain regulatory compliance. The industry employs various specialized risk analysis methods to manage these risks:

➢ **Layer of Protection Analysis (LOPA)**

A semi-quantitative method used to evaluate the effectiveness of different layers of protection in preventing accidents. LOPA helps in determining the adequacy of existing safety measures and identifying areas where additional protections are needed.[3]

➢ **Quantitative Risk Assessment (QRA)**

This method involves detailed mathematical modeling of potential accidents to estimate risk levels. QRA is used to assess the likelihood and impact of major accident scenarios, guiding the implementation of safety measures.[4]

➢ **Safety Integrity Level (SIL) Assessment**

Part of functional safety management, SIL assessment evaluates the required reliability of safety instrumented systems (SIS) to ensure they perform correctly in response to specific hazard scenarios.[5]

➢ **Hazard Identification (HAZID)**

A high-level screening process used to identify hazards in the early stages of design or planning. HAZID helps in recognizing potential safety issues and developing strategies to address them before they escalate.[6]

3. Importance of Risk Analysis in the Oil and Gas Industry

1) Safety

The primary concern in the oil and gas industry is safety. The extraction, transportation, and processing of hydrocarbons are fraught with potential hazards. These hazards can lead to catastrophic consequences, including loss of life, significant environmental damage, and substantial financial losses. Safety risks include explosions, fires, equipment failures, and worker accidents. By systematically analyzing risks, companies can identify potential hazards and implement measures to mitigate them, thus enhancing safety for workers, the public, and the environment.[7]

2) Types of Risks[8]

✓ **Explosions and Fires:**

The presence of flammable materials and high-pressure systems creates a constant risk of explosions and fires. These incidents can be triggered by equipment failure, human error, or natural events.

✓ **Equipment Failures:**

Machinery and equipment used in oil and gas operations are subject to wear and tear, which can lead to mechanical failures. Regular maintenance and monitoring are essential to prevent such failures.

- ✓ **Human Error:**

Mistakes made by personnel, whether due to inadequate training, fatigue, or miscommunication, can lead to accidents and unsafe conditions.

- ✓ **Natural Disasters:**

Earthquakes, hurricanes, and other natural disasters can severely impact oil and gas facilities, leading to accidents and operational disruptions.

3) Regulatory Compliance

The oil and gas industry is heavily regulated. Governments and international bodies impose stringent regulations to ensure that companies operate safely and responsibly. Non-compliance can result in severe penalties, including fines, shutdowns, and reputational damage. Risk analysis helps companies to understand and comply with regulatory requirements by identifying potential compliance issues and implementing necessary controls.[9]

4) Key Regulatory Requirements

- ✓ **Environmental Regulations:**

These regulations mandate measures to protect the environment from pollution and degradation. Companies must adhere to standards for emissions, waste disposal, and spill prevention.

- ✓ **Safety Regulations:**

These regulations ensure the safety of workers and the public. They include requirements for equipment safety, emergency response plans, and worker training.

- ✓ **Operational Standards:**

These standards govern the technical and operational aspects of oil and gas activities, including drilling, production, and transportation.

- ✓ **Reporting and Documentation:**

Companies are required to maintain detailed records of their operations and report any incidents or violations to regulatory bodies.

5) Environmental Protection

Oil and gas operations have the potential to cause significant environmental harm. Spills, leaks, and emissions can devastate ecosystems and affect local communities. Risk analysis is essential for identifying environmental risks and developing strategies to prevent and respond to environmental incidents.[10]

6) Environmental Risks[10]

- ✓ **Oil Spills:**

Oil spills can occur during drilling, transportation, or storage, leading to severe contamination of water and land. The impacts can be long-lasting, affecting wildlife, marine life, and local communities.

- ✓ **Air Emissions:**

The burning of hydrocarbons and operation of equipment produce air pollutants, including greenhouse gases, which contribute to climate change and air quality issues.

- ✓ **Water Pollution:**

Discharges of hazardous substances and wastewater from oil and gas operations can contaminate water sources, affecting both ecosystems and human health.

- ✓ **Habitat Destruction**

Exploration and drilling activities can lead to the destruction of natural habitats, affecting biodiversity and ecological balance.

The Bow-Tie Method is an invaluable tool for risk management in the oil and gas industry. Its ability to provide a clear and structured visualization of risk scenarios, integrating both preventive and mitigative controls, makes it particularly effective for managing complex and high-risk operations. By systematically identifying hazards, threats, consequences, and controls, the Bow-Tie Method helps organizations enhance safety, ensure regulatory compliance, protect the environment, and maintain financial stability.

Despite the challenges associated with its implementation, such as complexity, data requirements, and the need for ongoing maintenance, the benefits of the Bow-Tie Method far outweigh these drawbacks. With proper training, a robust risk management framework, and a commitment to continuous improvement, oil and gas companies can effectively use the Bow-Tie Method to navigate the complexities of their operations and ensure a safer and more sustainable future.

the Bow-Tie Method is not just a tool but a comprehensive approach to risk management that empowers organizations to proactively identify, assess, and mitigate risks, ultimately fostering a culture of safety and resilience in the oil and gas industry.

Chapter II

IHI Boiler Specification and Operation

In industrial settings, boilers play a vital role in steam production essential for various processes. This steam is generated by heating water using a heat source, which can be derived from fuels such as gas, oil, or coal, or through electric resistance.

1. Characteristics of IHI Boiler [15]

1.1. Design Criteria

The design criteria for boilers operating at nominal load, with maximum effective service time, include:

- ✓ Natural circulation system to reduce maintenance and energy requirements.
- ✓ Heating surface designed to allow complete drainage of water.
- ✓ Boiler constructed entirely gas-tight (welded finned tube construction).
- ✓ Forced draft fan with inlet damper to reduce operating costs.
- ✓ High reliability of internal components of the steam drum.

1.2. Equipment Description:

The main auxiliary equipment includes three (3) boiler feedwater pumps, one (1) degasser with storage tank, two (2) forced draft fans, and a fuel gas system for each unit (see Figure II-1).

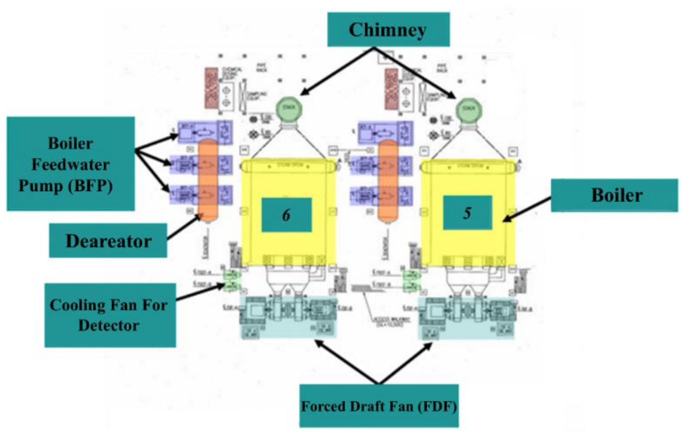

Figure II- 1: Boiler Layout Plan

Process gas is used as the primary fuel for steam generation facilities, while natural gas is used for ignition and startup.

Auxiliary steam is supplied to required equipment to ensure cost-effective operation. For example, the boiler feedwater pump and forced draft fan are powered by auxiliary steam, reducing auxiliary energy demand.

To monitor and maintain steam and water quality at acceptable levels, steam and water sampling systems, as well as a chemical dosing system, are provided.

Design considerations for variable load operation (25%L-110%L), with maximum effective service time, include:

- ✓ The boiler feedwater pump capacity is suitable for 75% boiler load.
- ✓ The heating surface is designed to allow complete drainage of water.

- ✓ Sufficient flexibility of tube connections reduces thermal stress fatigue.
- ✓ Burners are automatic and remotely controlled.
- ✓ Purge valves are remotely controlled.
- ✓ Air control dampers are remotely controlled

.

Each boiler is outfitted with a degasser, a forced draft fan (FDF), a chimney, a combustion chamber housing nine burners, two distinct primary and secondary superheaters separated by an evaporator. Additionally, it features an upper air port and an economizer.

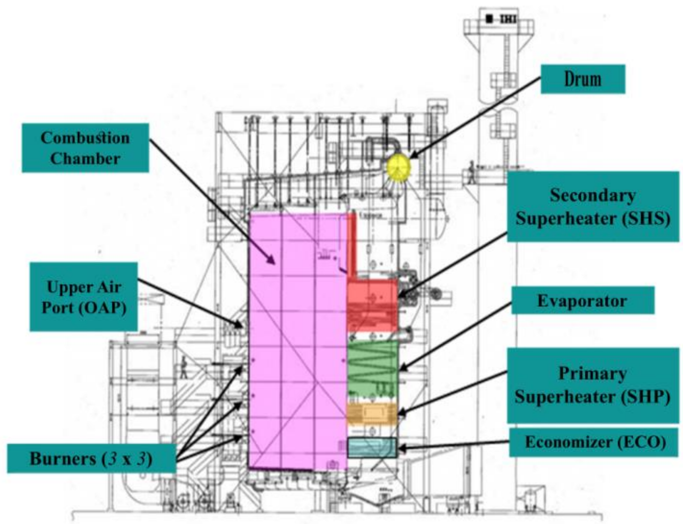

Figure II- 2: Boiler Layout

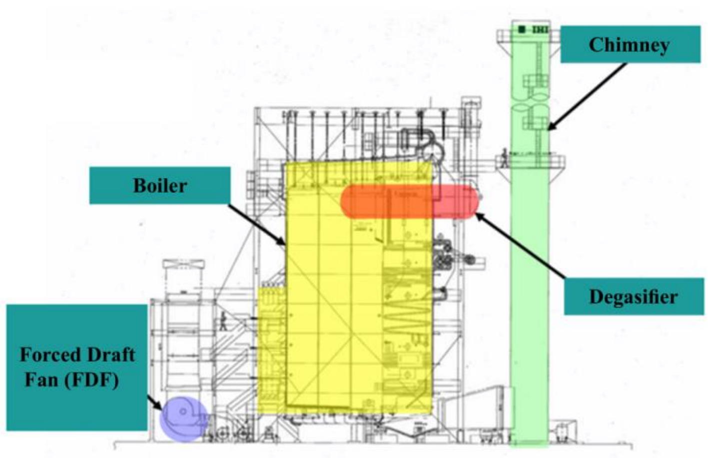

Figure II- 3: Boiler Layout 02

1.2.1. Economizer:

The economizer serves the following functions

- ✓ Preheating the feed water before entering the steam drum
- ✓ Recovering energy from the flue gas

1.2.2. Evaporator

Function of the evaporator

- ✓ Heating the water inside the steam drum
- ✓ Recovering energy from the flue gas

1.2.3. Steam Drum

Function of the steam drum

- ✓ Separating saturated steam from the steam-water mixture
- ✓ Mixing feedwater and saturated steam after separation
- ✓ Holding water to accommodate changes in service conditions, steam demand, steam pressure, and other variations in the mixture between water and steam
- ✓ Chemicals for water treatment are injected into the steam drum.

1.2.4. Combustion Chamber and Heat Recovery Zone

Function of the combustion chamber

- ✓ The combustion chamber is a large-volume container with water-cooled walls where combustion occurs to direct flue gases to the convection zone.
- ✓ The tubular wall of the combustion chamber boils water from the rear wall of the heat recovery zone.
- ✓ Combustion products are cooled by the tubular wall of the combustion chamber to the appropriate gas temperature.

1.2.5. Superheater

Function of the superheater

- ✓ The superheater overheats the steam and raises the steam temperature to the required level.
- ✓ The superheater recovers energy from the flue gas.

2. Boiler Operation [15]

2.1. Control Parameters

The operation of the boiler is schematically represented by the figures below, which indicate the evolution of the steam and feedwater flow rate (t/h) as a function of the reduced maximum continuous rating (MCR), and the evolution of temperature and pressure at different boiler levels as a function of MCR, respectively.

2.1.1. Flow Rate Evolution

The boiler operates with a steam and feedwater flow rate that varies proportionally with the reduced maximum continuous rating. According to the design, the boiler starts at 25% of the required maximum load with a flow rate of 100 t/h, and the steam flow rate reaches 400 t/h at 100% of MCR. On the graph, it is noted that the steam production capacity can exceed 440 t/h.

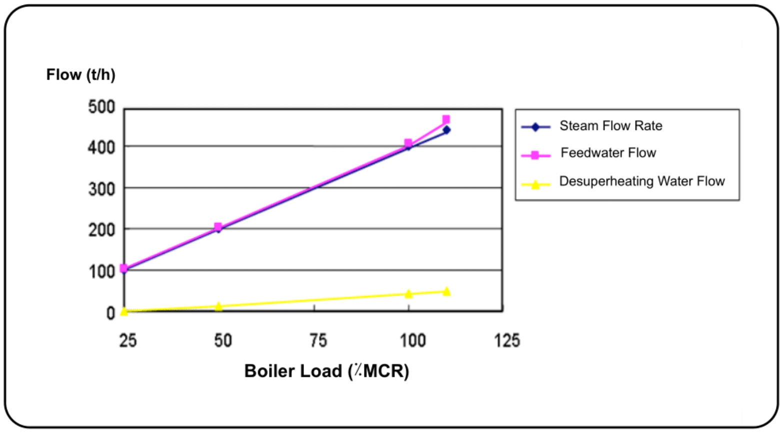

Figure II- 4: Steam and Feed water Flow

This figure illustrates the flow rates of steam and feedwater within the system. It provides a visual representation of the quantities of steam generated and the amount of feedwater supplied to the boiler.

2.1.2. Temperature Evolution

The temperatures remain nearly constant, with the temperature at the outlet of the secondary superheater reaching 450°C, and the temperature of the saturated steam in the steam drum remaining around 300°C.

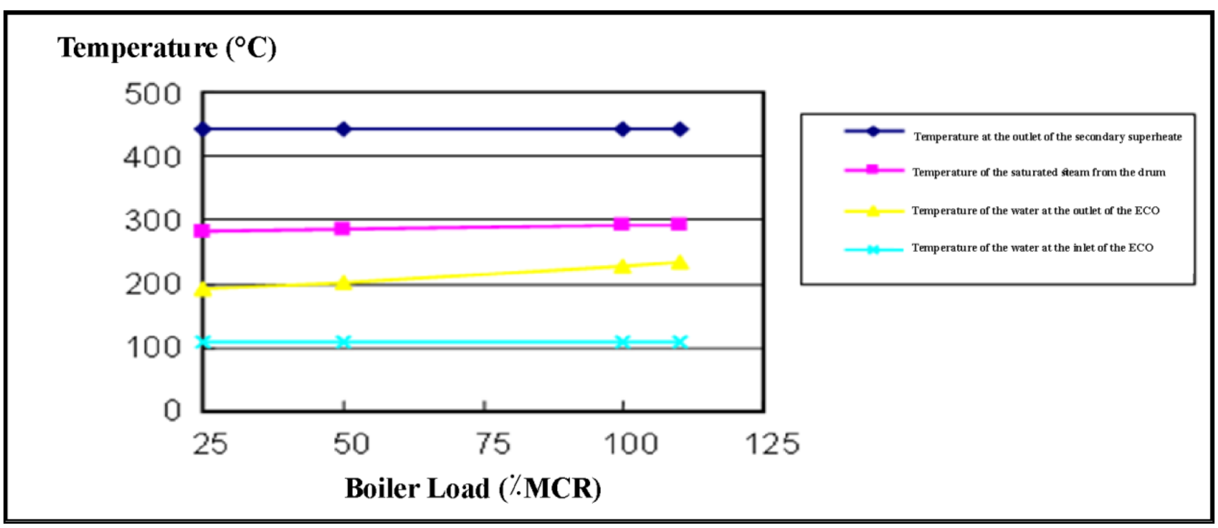

Figure II- 5: Variation de la température en fonction de la MCR

This figure demonstrates the relationship between temperature variations and the Maximum Continuous Rating (MCR) of the boiler. It visually depicts how temperature changes correspond to different operating conditions, particularly at varying levels of steam production.

2.1.3. Pressure Evolution

The pressure evolution inside the boiler follows a defined pattern corresponding to changes in steam demand and operating conditions. Typically, as steam demand increases, the pressure within the boiler rises to maintain adequate steam supply. Conversely, when steam demand decreases, the pressure decreases accordingly.

The boiler's pressure evolution is closely monitored and controlled to ensure stable operation within safe operating limits. Pressure fluctuations may occur due to changes in load, fuel quality, or external factors such as ambient temperature.

Pressure sensors located at various points within the boiler continuously monitor pressure levels, providing real-time data to the control system. The control system adjusts fuel and airflow rates, as well as other operating parameters, to maintain optimal pressure conditions and ensure efficient and safe boiler operation.

Overall, the pressure evolution within the boiler is carefully managed to meet steam demand while ensuring safe and reliable operation.

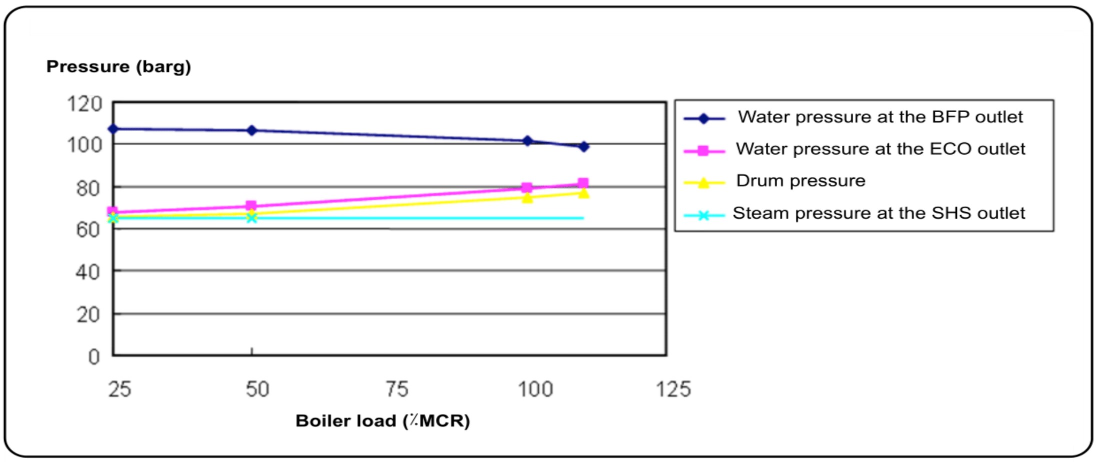

Figure II- 6: Pressure Variation Inside the Boiler

This figure illustrates the changes in pressure within the boiler. It provides a visual representation of how pressure fluctuates under different operating conditions, offering insights into the boiler's internal dynamics.

2.2.Function of Boiler Components:

2.2.1. Steam and Water System

The boiler's steam and water system is characterized by a water-steam cycle. In the diagram above, the cycle begins at the degasser (DEA). Condensate water feeds into the degasser, where dissolved oxygen is removed. The treated water is then pumped to the boiler by the boiler feedwater pumps (BFP).

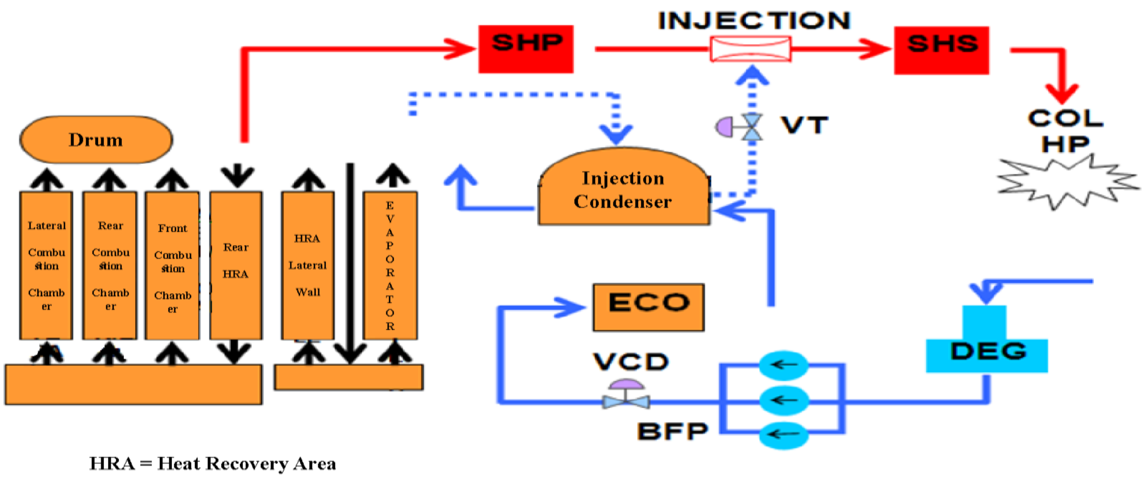

Figure II- 7: Steam and water system

The feedwater pumped passes through the feedwater control valve (FCV), the economizer (ECO), and the condenser by injection before entering the steam drum.

This figure illustrates the steam system within the boiler, depicting the various components and their interconnectedness. It provides a visual representation of how steam is generated, circulated, and utilized within the boiler system.

2.2.2. Steam Drum Level

Maintaining an adequate water level in the steam drum is crucial for the boiler's operation to:

- ✓ Protect the boiler against damage caused by overheating and carryover.
- ✓ Maintain a stable steam flow rate. In the steam drum, feedwater is mixed with water circulating from the furnace wall, the primary and secondary superheaters, and the evaporator. The steam produced in these components is discharged into the steam drum in the form of a steam-water emulsion. Steam is separated in the steam drum into dry saturated steam and superheated steam by the superheater.

2.2.3. Combustion System

The combustible gas is supplied by the fuel gas collector. This fuel gas for the main burner passes through the flow control valve and the isolation valve. The gas flow rate is regulated according to the boiler load by the flow control valves. The isolation valve can shut off the fuel supply in case of boiler trip. Nitrogen lines are provided for nitrogen purging of each gas line.

The draft system is of the forced draft type. Air from two forced draft fans (FDF) enters either through the separate air vent box or through the upper air port (OAP). The OAP system is a device designed to reduce NOx levels.

The air from the separate air vent box not only rotates but is also regulated by air regulators and is mixed with the combustible gas before entering the combustion chamber.

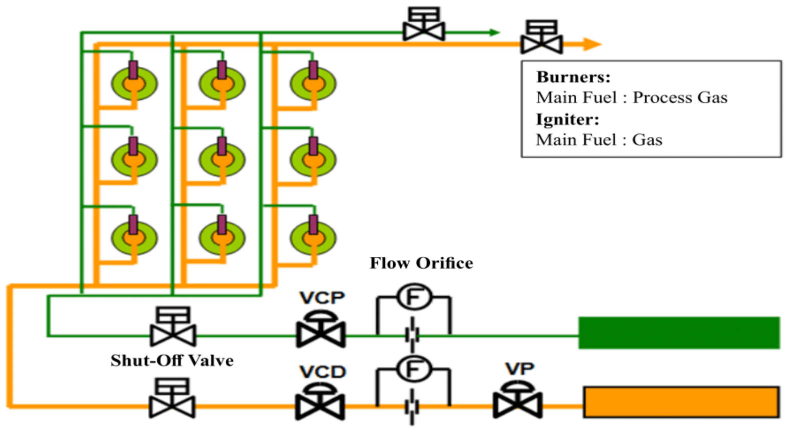

Figure II- 8: Schematic of the Combustion System

3. Boiler Startup Procedure [15]

The boiler startup procedure involves several steps to ensure safe and efficient operation. These steps may include:

1) Pre-Startup Checks

Conduct a thorough inspection of the boiler and its auxiliary equipment to ensure everything is in working order. Check for leaks, proper ventilation, and adequate water levels.

2) Purge the Boiler

Before ignition, purge the boiler and combustion chamber of any remaining gases to ensure a clean start. This is typically done by introducing an inert gas such as nitrogen or steam.

3) Ignition

Initiate the ignition sequence according to the manufacturer's instructions. This may involve lighting the pilot burner or igniting the main burners using a spark or flame.

4) Monitor Parameters

Once ignition is successful, monitor key parameters such as fuel and air flow rates, steam pressure, and temperature to ensure they are within safe operating limits.

5) **Ramp-Up**

Gradually increase fuel and air flow rates to bring the boiler up to its desired operating pressure and temperature. Monitor parameters closely during this phase to prevent any sudden fluctuations.

6) **Stability Checks**

Once the boiler reaches its operating conditions, perform stability checks to ensure all systems are functioning correctly. Monitor for any abnormal vibrations, noises, or fluctuations in pressure or temperature.

7) **Handover**

Once the boiler is stable and operating within specifications, hand over control to the regular operating team. Provide them with relevant operating instructions and safety protocols.

8) **Continuous Monitoring:**

Throughout the boiler operation, continuously monitor key parameters and respond promptly to any deviations or alarms. Regularly inspect equipment and perform routine maintenance as needed to ensure continued safe and efficient operation.

By following these steps, the boiler startup procedure can be conducted safely and effectively, ensuring reliable operation and minimizing the risk of accidents or downtime.

3.1.Preliminary Checks for Boiler Startup

Before initiating the boiler startup process, it is essential to perform preliminary checks to ensure that all systems are properly connected and operational. These checks include:

- **Piping and Pipe Supports**
  Verify that all piping and pipe supports are correctly installed and secured to prevent leaks or structural issues during operation.

- **Pipelines**
  Check the integrity of all pipelines to ensure they are free from blockages, leaks, or other damage that could impede the flow of fluids.

- **Boiler Casings**
  Inspect the boiler casings to ensure they are intact and provide adequate protection for internal components.

- **Expansion Joints**
  Check the condition of expansion joints to ensure they can accommodate thermal expansion and contraction without leaking or failing.

- **Instrumentation**
  Verify the functionality of all instrumentation devices such as local gauges, transmitters, and sensors to accurately monitor process parameters.

- **Access Doors and Personnel Passages**

  Ensure that all access doors and personnel passages are securely closed to prevent unauthorized access and maintain safety.

- **Removal of Locking Pins**

  Remove any locking pins from pipe hangers or supports to allow for free movement and flexibility of piping systems.

- **Auxiliary Machinery (Fans, Pumps)**

  Verify that all auxiliary machinery such as fans and pumps are operational and ready for use during the startup process.

By performing these preliminary checks, potential issues or hazards can be identified and addressed before initiating the boiler startup procedure, ensuring a safe and smooth startup process.

3.2.Water Filling

3.2.1. Preliminary Checks

Before each water filling operation, it is important to perform several checks:

a) Normal Chemical Injection System

- Pump Function: Ensure that the chemical injection pump is operational and able to deliver chemicals to the boiler water.
- Tank Level: Verify that the chemical storage tank has an adequate level of chemicals to meet the boiler water treatment requirements.
- Analyzer: Check the functionality of any water quality analyzers to monitor the chemical composition of the boiler water.

b) Required Boiler Water Quality

- Acid Conductivity [25°C]: Preferably less than 0.05 mS/cm.
- Ph [25°C]: Ideally between 8.5 and 9.5.

If the boiler has been stored in a humid state, check the chemical properties of the water in the steam drum. Purge and refill if necessary to ensure that the water meets the required chemical composition.

3.2.2. Boiler Water Filling Sequence

1. Start the Boiler Feed Pump
2. Open the Feedwater Control Valve (FCV) a) Starting the Boiler Feed Pump:

Before starting the boiler feed pump, ensure the following conditions are met:

- ✓ Lubricating oil pump is running.
- ✓ Lubricating oil pressure is sufficiently high.

Conditions for triggering the boiler feed pump shutdown:

- ✓ Low-low lubricating oil pressure.

- ✓ Low-low degasser level.

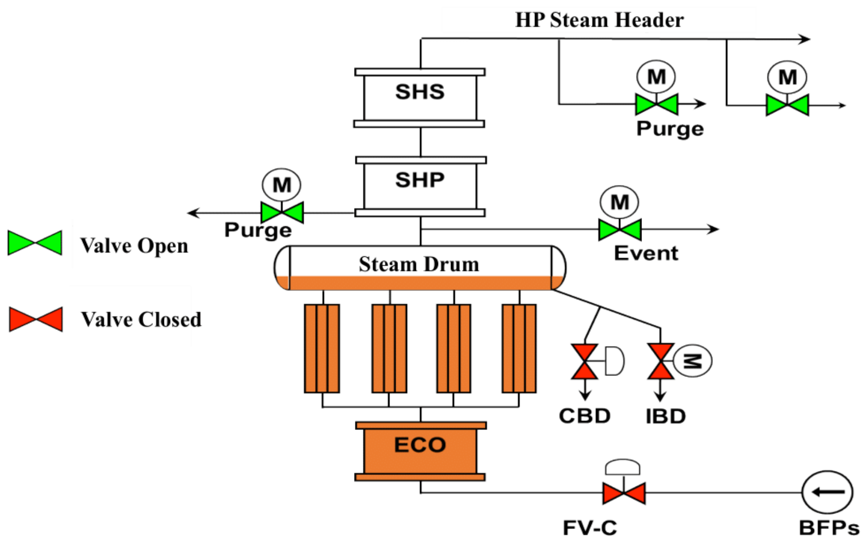

Figure II- 9: System Diagram

3.2.3. Initial Ignition Preparation

a. Start of Draft System:

- ✓ Forced Draft Fans (Motor-Driven and Steam-Driven)
- ✓ Cooling Fans for Flame Detector (two motor-driven fans)

b. Conditions for Motor-Driven Forced Draft Fan (FDF) Startup

- ✓ Lubricating oil pump is running.
- ✓ Lubricating oil pressure is sufficiently high.
- ✓ Fan inlet vane is closed.

c. Conditions for Steam-Driven Forced Draft Fan (FDF) Startup

- ✓ Lubricating oil pump is running.
- ✓ Lubricating oil pressure is sufficiently high.

d. Motor-Driven FDF Startup Sequence

- ✓ Confirmation of all air inlet vanes being open.
- ✓ Start the lubricating oil pump.
- ✓ Check lubricating oil pressure, ensuring it is sufficient.
- ✓ Close the inlet vanes.
- ✓ Start the FDF:

- ✓ Start the air cooling FDF (*1).
- ✓ Three minutes later, if lubricating oil pressure is sufficient, stop the lubricating oil pump.
- ✓ Confirm operation of other blowers and opening of all air registers.

e. Combustion Chamber Purge & Fuel Leak Check

- ✓ 5-minute purge of the combustion chamber (NFPA guidelines).
- ✓ 1-minute fuel leak checks.
- ✓ Main burner gas system.
- ✓ Ignition gas system.

f. Conditions to Fulfill Before Combustion Chamber Purge

- ✓ No main fuel trip.
- ✓ Main gas shut-off valve closed.
- ✓ Fuel leak test valve closed.
- ✓ Ignition gas shut-off valve closed.
- ✓ All burner shut-off valves closed.
- ✓ All ignition shut-off valves closed.
- ✓ One FDF running.
- ✓ Combustion air flow > 25% MCR.
- ✓ All burner vent valves open.
- ✓ Normal burner and ignition gas supply pressure.

g. After Combustion Chamber Purge & Fuel Leak Check

- ✓ Reset main fuel trip (MFT).
- ✓ Ignition gas shut-off valve open.
- ✓ Main gas shut-off valve open.

h. Readiness for Ignition of Igniter

- ✓ Reset MFT.
- ✓ Ignition gas shut-off valve open.
- ✓ One FDF running.
- ✓ Combustion air flow > 25% MCR.
- ✓ Normal instrument air pressure.
- ✓ Normal flame detector cooling air pressure.
- ✓ Normal ignition gas pressure.
- ✓ Successful ignition of the first igniter.
- ✓ Both A & B combustible gases of the combustion chamber normal.

i. Ignition of Gas Burner

- ✓ One burner ignited.
- ✓ Recommended temperature rise rate:
- ✓ Up to 100°C: 28 °C/hr.
- ✓ Above 100°C: 55 °C/hr.
- ✓ Planned number of gas burners in operation:

- ✓ Up to 100°C: One (1) burner.
- ✓ Above 100°C: Two (2) to three (3) burners.

3.3.Preheating and Pressurization of the System

3.3.1. Steam Drum Level Control

- **Swelling of Steam Drum Level**

The level in the steam drum rises abruptly due to swelling as the boiler water temperature approaches 100°C. It is recommended to maintain the steam drum level at -100 to -150 mm when the boiler water temperature reaches 100°C.

- **Intermittent Blow down Valve**

In case of swelling of the steam drum level, open the intermittent blowdown valve to maintain the desired level.

- **Up to 30% Boiler Load**
  - Feed water Control Valve
  - Single-element control (Steam drum level)

- **Above 30% Boiler Load**
  - Feed water Control Valve
  - Three-element control (Steam flow + Feed water flow + Steam drum level)

These control measures ensure that the steam drum level is effectively managed during the preheating and pressurization process, maintaining safe operating conditions for the boiler system.

3.3.2. Fuel Flow & Combustion Air Flow Control

- **Fuel Flow Control Valve**
  - ✓ One (1) main burner in operation:
    - Gas pressure control
  - ✓ At least two (2) main burners in operation:
    - Gas flow control
  - ✓ Boiler pressure control: Typically manual control until the boiler reaches its nominal pressure and sufficient steam flow.

- **Combustion Air Flow Control**
  - ✓ Automatic mode (Minimum flow control)

3.3.3. Main Steam Temperature Control

It is not recommended to use the superheater spray during startup until reaching 20% boiler load, as the steam flow is insufficient, except in emergencies.

- ✓ Open the motorized valve at the inlet of the desuperheating valve (Spray Control Valve) when the boiler load is at 20%.
- ✓ Set the desuperheating valve to AUTO mode when the boiler load is at 20%.

These measures ensure that the main steam temperature is controlled effectively during the preheating and pressurization phase, maintaining safe operating conditions for the boiler system.

3.4. Operating Set points

3.4.1. Main Fuel Trip (MFT)

- ➢ **Shutdown of both FDF**
- ✓ Very low steam drum level
- ✓ Very high steam temperature
- ✓ Very high furnace pressure
- ✓ Loss of all fuels (all burner valves closed or GFT)
- ✓ Partial loss of flame
- ✓ Very low combustion air flow
- ✓ Manual emergency stop button
- ✓ BCS system failure
- ✓ Loss of all flames
- ✓ Firefighting system MFT signal

3.4.2. Gas Fuel Trip (GFT)

- ✓ Very low main gas pressure
- ✓ Very high main gas pressure
- ✓ All main burner shut-off valves closed
- ✓ Manual GFT push-button ON
- ✓ Main gas shut-off valve closed

3.4.3. Igniter Fuel Trip (IFT)

- ✓ Very low ignition gas pressure
- ✓ Very high ignition gas pressure
- ✓ Manual IFT push-button ON
- ✓ Main ignition gas shut-off valve closed

3.4.4. Safety Valve Set point

The set points for safety valve tripping are illustrated in Table II-1 below.

Table II- 1: Steam Drum and Super heater Outlet Safety Valve Set points

Valve	Set point [bars]
Steam Drum A	82.3 bar
Steam Drum B	85.0 bar
Superheater Outlet	70.0 bar

This table presents the triggering points of the safety valves installed in steam drums A and B, as well as at the superheater outlet. These valves are designed to open automatically when the pressure in the steam drums or at the superheater outlet reaches the specified thresholds.

For steam drum A, the valve will trigger when the pressure reaches 82.3 bars, while for steam drum B, the threshold is 85.0 bars. At the superheater outlet, the valve will trigger when the pressure reaches 70.0 bars.

These thresholds are important because they represent the pressure limits beyond which it is necessary to release steam to prevent an excessive pressure increase that could jeopardize the equipment's integrity.

3.4.5. Cooling Air Fans for Flame Detector

- ✓ Automatic startup in case of :
  - ➢ Fan in service stops
  - ➢ Low outlet fan pressure in service
- ✓ Manual shutdown when both blowing fans are stopped, and the boiler water temperature is <70 °C (To prevent flame detector overheating).

3.4.6. Main Steam Temperature Control Set point

- ✓ 441 °C.

3.5.Operation Inspection

3.5.1. Preliminary Parameter Verification

- ✓ Maintain boiler cleanliness and ensure instruments are operational for quick response in emergencies.
- ✓ Note any unstable operation during service.
- ✓ Check combustion stability in the combustion chamber.
- ✓ Identify abnormal sounds.
- ✓ Detect vibrations.
- ✓ Observe any discoloration.
- ✓ Confirm water quality within required limits.
- ✓ Address minor defects immediately; plan shutdown for major repairs if necessary.

3.5.2. Boiler Inspection Procedure

1) Combustion Chamber, ZRC, and Duct Interior Check

- ✓ Complete air purging and open all manholes for ventilation before entry.
- ✓ Ensure temperature is sufficiently low to prevent injury.

2) Pressure Parts Inspection

a. Isolation

- ✓ Close valves on pipes connected to other boilers or systems, securing valve handles to prevent accidental operation.
- ✓ Use full flanges to isolate pressure parts if valves cannot be fully closed.

b. Draining

- ✓ When boiler pressure drops to 1 – 1.5 bars post-shutdown, ensure all vents and bottom drain valves are open, completely draining boiler water.

c. Pressure Part Opening

- ✓ Exercise caution for oxygen deficiency when entering steam drums.
- ✓ Ensure temperature is low enough to prevent injury.

d. Inspection and Cleaning

- ✓ Before internal cleaning of steam drums, manifolds, and other pressure parts, inspect internal condition for scale and corrosion.
- ✓ Maintenance teams advised to document inspection findings for future reference.

3.5.3. Restoration Procedure

Restore boiler condition once normalcy is ensured.

a. Ensure absence of foreign objects in steam drum; reassemble internal drum components.
b. Remove temporary full flanges.
c. Keep all valves closed.
d. Replace insulation.
e. Close manholes and inspection ports.
f. Remove temporary full flanges if used for flue gas ducts.

4. The Risks associated with Boiler Operation

The main risks associated with boiler operation are:

4.1.Fire and Explosion [16]

Risk Explosions pose one of the most serious dangers to personnel during boiler operation. Among the causes are:

- Accumulation of unburned fuel in the furnace due to incomplete combustion

- Flame extinguishment or leakage from gas valves
- Mixing of this unburned fuel with air in explosive proportions
- Application of sufficient heat to raise the temperature of part of this mixture to the ignition point

4.2.Pressure Risk [16]

This is essentially a danger of bursting characterized by the release of energy when pressure vessels or equipment are subjected to internal pressures exceeding a few bars, which can lead to cracking problems.

The damage is characterized by the amount of energy released as pressure is relieved from its initial value to atmospheric pressure. For this, materials must have mechanical properties that can be classified as follows:

- Elasticity or ability to undergo temporary deformation
- Surface hardness or resistance to penetration by other bodies.
- Certain special qualities, such as thermal conductivity, resistance to attack by a particular fluid, corrosion resistance.
- Toughness or resistance to slow and repeated stress.

Probable causes of these cracking phenomena are simultaneously:

- Metal fatigue
- Long-term repair operations (retubing)
- Presence of vibrations (which accentuate material fatigue) due to starts and stops and startups.
- Aging of supports that have degraded over time.

4.3.Chemical Risk [16]

In a boiler, the products used that are likely to cause harmful effects for the operator are phosphates and Eliminox. Their roles are respectively as follows:

➢ **Phosphate**

- Precipitate incrusting salts as sludge with the boiler water pH ($9.7<pH<10.1$)
- Maintain and protect steels by forming a protective film.

See figure table II-2

Table II- 2: risks associated with phosphate

Category	Risk Description	Potential Consequences
Environmental	**Water Pollution**: Runoff causes eutrophication in water bodies.	Algal blooms, death of aquatic life.
	Soil Degradation: Imbalance from excessive fertilizer use.	Reduced soil fertility.
Health & Safety	**Occupational Hazards**: Exposure to dust and chemicals.	Respiratory issues, skin irritation.
	Food Contaminants: Fertilizers may contain heavy metals.	Health risks to consumers.
Chemical Risks	**Reactivity and Storage**: Improper storage of compounds.	Spills, explosions, contamination.

- **Eliminox**

- Oxygen-reducing agent.

4.4.Electrical Risk [16]

Due to the absence of sensory organs to detect electric current, electrical hazards are particularly dangerous. Mitigation measures include insulation protection of personnel from floors and boiler walls, inaccessibility of metal masses, use of very low voltage (≤ 48V), grounding, and equipotential bonding.

4.5.Corrosion Risk [17]

Corrosion is the most common degradation phenomenon in process units, with boilers being a major concern due to tube perforations. Factors contributing to corrosion include:

- Poor boiler water treatment
- Insufficient chemical cleaning
- Absence of boiler preservation

4.6.Noise Pollution Risk

Daily exposure to high noise levels is a concern for personnel. Measures to assess noise levels and ensure compliance with standards are essential. The example table below illustrates noise measurements at the GL2/Z site.(see table II-3)

Table II- 3: Example of Noise Measurement Report for GL2/Z Site

Equipment	Noise [db]
Boiler 770 UE	100-104 db
Boiler 770 UF	105 db
Turbo-fan 770 UE	100 db
Turbo-fan 770 UF	102 db
Boiler 370 UA Turbo-fan	100 db
Boiler 370 UB	95 db
Boiler 370 UC	92 db
Turbo-fan 470UB	105 db
Turbo-fan Boiler 570UB	105 db
Turbo-fan Boiler 770UB	100 db
Boiler 770UC	110-113 db
Turbo-fan Boiler 770UD	104 db

4.7.Pollution Risk

4.7.1. The Boiler Emissions

See figure II-11

a) **Gaseous Emissions :** Mainly illustrated by

- The formation of CO_2, CO, and flue gases from combustion gas.
- A leak of superheated H_2O (steam) at valves, fittings, etc…

b) **Liquid Emissions :** Generally resulting from

- Discharge of chemicals into sewers: (Phosphates, Eliminox).
- Use of chemicals for boiler water treatment after precipitating the salts contained in the water, which are discharged into the sea and contribute to marine pollution."

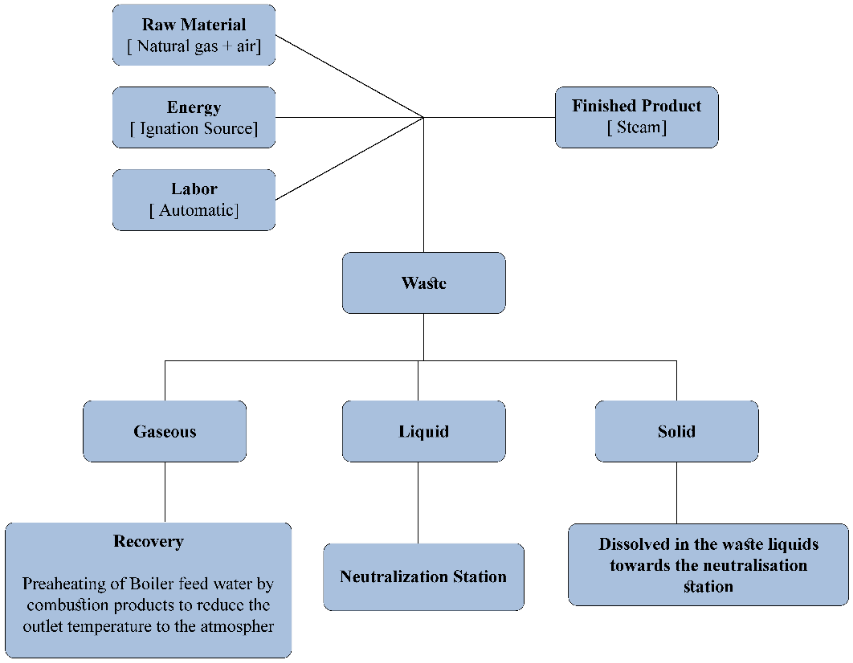

Figure II- 10: Chart summarizing the boiler effluent rejections and their sources

4.7.2. Impact on the Environment and Human Health

a) Greenhouse Effect [CO2 and Superheated H2O]

- Increase in temperature
- Migration of populations
- Rising sea levels
- Climate change
- Desertification of wildlife

b) Acid Pollution [CO.OH] [HC] Formation of oxidants that promote

- Forest decline
- Decrease in agricultural yields due to O3 effect
- Reduction in plant growth
- Disruption of photosynthesis
- Acidification of soils and lakes
- Forest decline

Chapter III

Risk Assessment Using Bow-Tie Method

1. Risk Indicators [18]

The goal of this risk assessment is to evaluate the risk levels posed by the IHI boiler at the GL2Z complex. The assessment process quantifies risks according to two indicators:

a. Individual Risk

The identification of individual risk assesses the probability of death for an individual who is permanently located at a specific site. Individual risk is calculated and expressed by risk ISO-contours drawn on a map. For example, a person permanently located on the individual risk contour of 10^-4 would, on average, be exposed to a fatal accident once every ten thousand years.

b. Collective Risk

Collective risk is calculated and expressed by F/N curves (Frequency of accidents/number of deaths). These curves can be interpreted as exceedance curves of the number of deaths in accidents. In other words, a point on the curve represents an accident frequency F, as a function of the number N of deaths.

2. Risk Assessment Process

The risk assessment process is illustrated in Figure III-1. The risk assessment is carried out in four work modules. Hazard identification constitutes the first module. Accident scenarios that may affect the public are determined in the hazard identification. These scenarios are then subjected to frequency and consequence evaluations, carried out in modules 2 and 3, respectively.

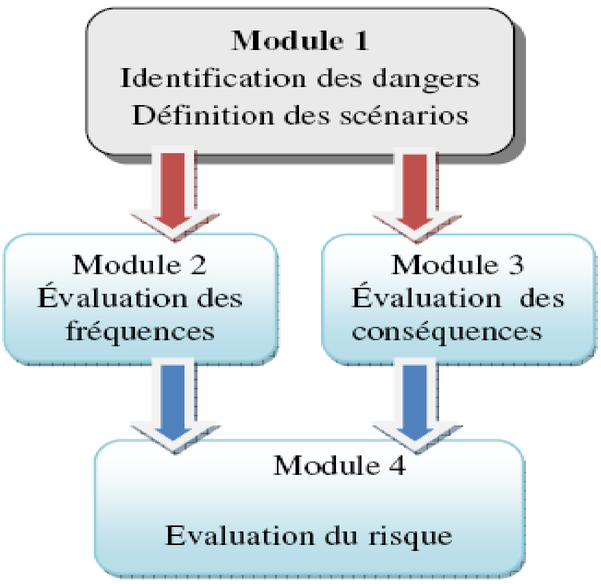

Figure III- 1: Risk Assessment Process

The hazards that could result from the operation of the boiler were identified during interviews with operation, maintenance, and safety teams. These teams consisted of members familiar with all aspects of the boiler. The goal of these interviews was to identify and evaluate potential hazards corresponding to the IHI boiler. The assessment involve the following six steps:

1) Choose a part of the process, represented in this study by the IHI boiler.
2) Define the function, location, and normal operating conditions of the boiler.
3) Select a hazard source or scenario for the chosen boiler.
4) Identify and comment on the probability factors for the scenario. Identify deviations from normal operating conditions that could impact the probability of the scenario.
5) Identify and comment on the consequence factors for the scenario. Identify deviations from normal operating conditions that could impact the event's consequences.
6) For the scenario, identify the safety measures taken during design or operation to control or mitigate the event's consequences.

3. Bases of Risk Assessment

➢ Study Scope

The basic data for the risk assessment at the IHI boilers of GL2/Z are presented in the following sections in terms of installation description, meteorological conditions, and other important factors.(see figure III-3)

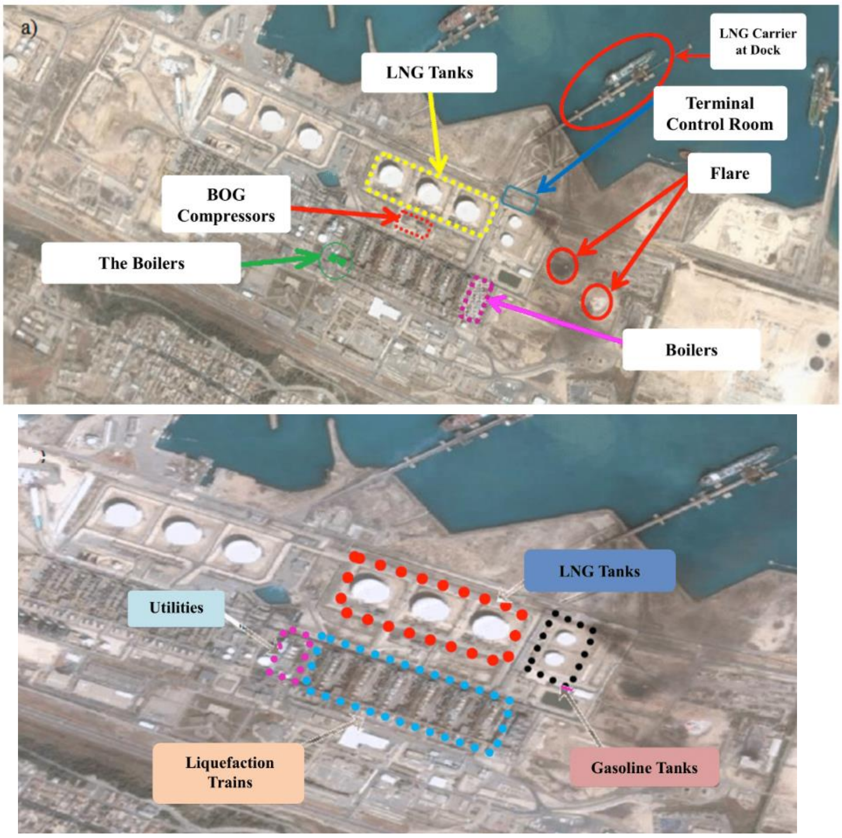

Figure III- 2: Layout of IHI Boilers at the GL2Z Complex

- **Geographical Data [19]**

The IHI boilers are located on the Arzew Bay with geographical coordinates: Latitude 35°48' North and 0°15' West. The boilers are situated north of the liquefaction trains and south of the Arzew Bay.

- **Domino Effects**

Accidents at the IHI boilers could propagate to other equipment or industrial facilities. The following potential domino effects have been evaluated arbitrarily:

- **Domino Effect to Another Industrial Facility**

The possibility of propagation to other industrial facilities is very probable since there are other complexes (GL1Z and HELIOS) near the boiler. Propagation to the loading dock gas pipeline is also probable since it is above ground and not protected from thermal radiation fluxes.

- **Internal Domino Effect of an Accident**

Accidents with internal propagation affecting personnel are varied and cannot be fully addressed in this report. No internal accident scenario has been evaluated for potential consequences.

4. Scenario Definition

- **Accident Hypotheses**

The boiler is assumed to be shut down, and the gas detectors are defective. It is also assumed that the fuel gas line valve feeding a burner fails to close or is defective (leaky valve). The accident occurs during the restart of the IHI boiler due to the accumulation of fuel gas in the boiler's furnace. This could have been avoided by purging the boiler, but this operation was bypassed (this type of scenario has occurred before).

5. Application of the bow tie method

Hazard

- ✓ Accumulation of fuel gas in the boiler's furnace

Top Event

- ✓ Explosion due to ignition of accumulated fuel gas

Threats and Preventive Barriers

Table III- 1: Threats and Preventive Barriers

Threats	Preventive Barriers	Proposed Barriers
Defective Gas Detectors	✓ Regular maintenance and calibration of gas detectors ✓ Installation of gas 16 IR detectors in the fuel gas duct to detect leaks	✓ Use of advanced gas detection technology with higher sensitivity and reliability ✓ Automated system checks and alarms
Leaky Fuel Gas Line Valve	✓ Regular inspection and testing of fuel gas valves ✓ IR open-path gas detectors used around the gas supply line	✓ Installation of redundant valves ✓ Automated valve control systems that can detect and respond to leaks immediately
Bypassed Boiler Purging Operation	✓ Training and supervision of personnel ✓ Strict adherence to startup procedures	✓ Automation of purging operations to eliminate human error
Faulty Ignition System	✓ Regular ignition system checks ✓ Automated ignition failure alarms	✓ Use of high-quality ignition components
Corroded Fuel Lines	✓ Regular inspection and replacement of fuel lines ✓ Monitoring for signs of corrosion	✓ Use of corrosion-resistant materials

Threats and preventive barriers

- ✓ Reliable gas detection is crucial to identifying and mitigating gas leaks promptly, preventing potential explosions or fires.
- ✓ Preventing leaks from fuel gas line valves reduces the risk of gas accumulation, which could lead to dangerous explosions or fires.
- ✓ Proper purging removes residual gases, preventing dangerous accumulations that could ignite and cause explosions during startup.
- ✓ A reliable ignition system ensures safe ignition of fuel, reducing the risk of delayed ignitions that could cause explosions.
- ✓ Maintaining the integrity of fuel lines prevents leaks and potential hazards associated with fuel escaping into the environment, which could lead to fires or explosions.

These barriers are crucial for maintaining the safety and integrity of the boiler operation. By implementing regular maintenance, inspections, and monitoring systems, as well as ensuring proper training and adherence to procedures, the risks associated with defective components and human error can be significantly reduced. This proactive approach helps in preventing accidents, protecting lives, and ensuring safe and efficient boiler operations.

Consequences and Recovery Barriers

Table III- 2: Consequences and Recovery Barriers

Consequences	Recovery Barriers	Proposed Barriers
Explosion Damage	✓ Emergency shutdown systems ✓ Immediate emergency response protocols	✓ Implementation of automated emergency shutdown systems that activate upon detection of hazardous conditions ✓ Use of blast-resistant building materials and structures to contain explosions
Fire Injuries	✓ Personal protective equipment (PPE) for workers ✓ Fire suppression systems ✓ Emergency evacuation plans ✓ Deployment of fire hydrants, hoses, and portable extinguishers in boiler areas	✓ Provision of advanced fire suppression technologies such as foam or gas-based systems
Environmental Release	✓ Gas containment systems ✓ Environmental monitoring and control systems	✓ Deployment of rapid response environmental containment units to manage gas leaks ✓ Continuous environmental monitoring for early detection of hazardous releases
Structural Damage	✓ Reinforced construction ✓ Structural health monitoring systems	✓ Regular structural integrity assessments to ensure long-term resilience
Toxic Exposure	✓ Air quality monitoring systems ✓ Provision of respiratory protective equipment ✓ Emergency medical response protocols	✓ Continuous air quality monitoring ✓ Advanced respiratory protection equipment

Consequences and recovery barriers

- ✓ Explosion damage barriers recovery reduces damage by halting operations, containing the explosion, and minimizing the risk of further damage.
- ✓ Fire injuries recovery barriers protect workers, provide tools for fire control and evacuation, ensuring safety, and reducing injuries.
- ✓ Environmental Release recovery barriers limit the spread of hazardous substances, monitor environmental impact, and protect public health.
- ✓ Structural damage recovery barriers enhance structure durability, provide real-time data for integrity management, and prevent collapses.

- ✓ Toxic exposure recovery barriers ensure early detection, provide medical intervention, and protect health and safety.

These recovery barriers are designed to mitigate the impact of consequences, ensuring the safety of personnel, the integrity of structures, and the protection of the environment. By implementing these barriers, organizations can enhance their resilience to accidents and emergencies, improving their ability to recover swiftly and effectively.

Escalation Factors and EF Barriers

Table III- 3: Escalation Factors and EF Barriers:

Escalation Factors	EF Barriers	
Poor Maintenance	✓ Scheduled audits and inspections ✓ Continuous training programs for maintenance staff	✓ Development of a comprehensive maintenance management system to track and schedule maintenance activities ✓ Continuous improvement programs to address recurring maintenance issues
Inadequate Training	✓ Comprehensive training programs ✓ Development of detailed training modules and certification programs for operators	✓ Use of simulation-based training to provide hands-on experience in handling emergency situations
Delayed Response	✓ Automated response systems ✓ Real-time monitoring and alert systems	✓ Establishment of clear communication protocols and rapid response teams to handle emergencies efficiently

Escalation factors and barriers

- ✓ Poor Maintenance EF barriers improve equipment reliability, prevent issues from becoming major problems, and ensure safe and efficient operation, reducing failures and accidents.
- ✓ Inadequate training EF barriers enhance personnel skill levels and knowledge, ensure operators are trained and certified for equipment and emergencies, reducing human error, and enhancing safety and efficiency.
- ✓ Delayed response EF barriers minimize incident response times, reduce impact, and ensure prompt mitigation. Rapid response is critical in preventing minor incidents from escalating. Automated systems detect and respond to problems without delay.

Addressing these escalation factors with the appropriate barriers is essential for maintaining a safe and efficient operational environment. Regular maintenance ensures the reliability of equipment, comprehensive training prepares personnel to handle situations effectively, and automated and real-time monitoring systems ensure prompt responses to any issues. These measures collectively enhance the overall safety and resilience of the operations.

- **Probability**

Probability of Threats

See figure III-4

Table III-4:Probability of Threats

Threats	Probability	Interpritation
Defective gas detectors	Medium (5-10% per year)	✓ This estimate is based on historical failure rates of gas detectors in industrial settings, maintenance records, and data from similar facilities. Studies have shown that gas detector reliability can vary, with failure rates typically ranging from 5% to 10% per year due to sensor degradation, calibration drift, and environmental factors.
Leaky fuel gas Line valve	Low to Medium (3-8% per year)	✓ Data from maintenance logs and incident reports in the oil and gas industry indicate that valve leaks occur less frequently but still present a significant risk. Regular inspections and maintenance reduce the probability, but occasional failures are observed in the range of 3% to 8% per year.
Bypassed boiler purging operation	Low (2-5% per year)	✓ The probability is derived from human error rates in operational procedures. Studies on procedural compliance indicate that bypassing critical operations like purging can happen due to oversight or intentional shortcuts, leading to an estimated occurrence rate of 2% to 5% per year.
Faulty ignition system	Medium (5-10% per year)	✓ Ignition system failures are common enough in industrial settings to be a notable risk. Historical data and reliability analyses show that ignition systems can fail at rates between 5% and 10% annually, often due to component wear, improper maintenance, or environmental factors.
Corroded fuel lines	Medium to high (10-15% per year)	✓ Corrosion is a prevalent issue in industrial piping systems. Studies on corrosion rates, particularly in harsh environments, suggest that without adequate corrosion protection and regular maintenance, the probability of significant corrosion-related failures can be as high as 10% to 15% per year.

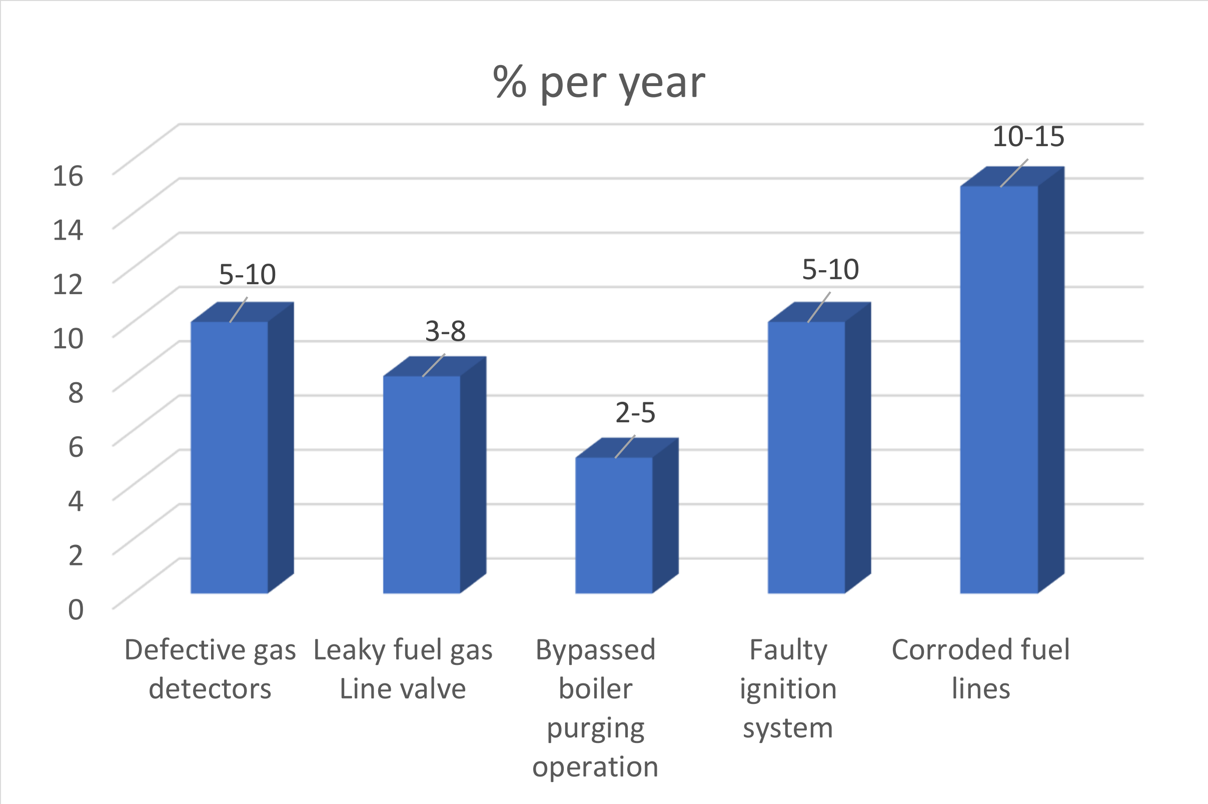

Figure III-4: Probability of Threats

Probability of Escalation Factors
See figure III-5

Table III-3: Probability of Escalation Factors

Escalation factors	Probability	Iterpritaion
Poor maintenance	High (15-20% per year)	✓ This estimate is based on industry surveys and maintenance record analysis, indicating that poor maintenance practices are a common factor in equipment failures and incidents, with occurrence rates ranging from 15% to 20% per year.
Inadequate training	Medium to high (10-15% per year)	✓ Data from industry training assessments and incident investigations suggest that inadequate training is a significant contributing factor to operational errors and accidents, with probabilities estimated between 10% and 15% annually.
Delayed response	Medium (5-10% per incident)	✓ The probability of delayed response is based on historical data from emergency response performance evaluations. Real-time monitoring and response system effectiveness vary, leading to an estimated occurrence rate of 5% to 10% per incident.

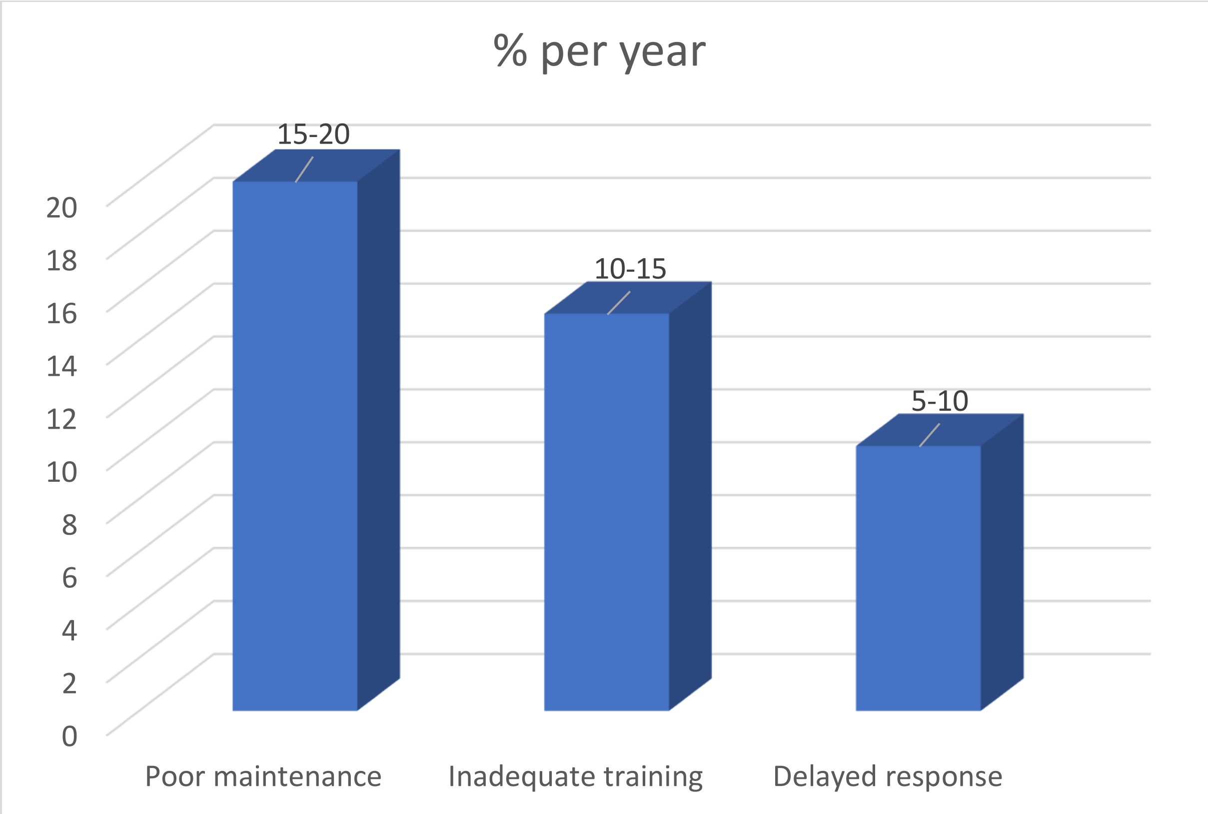

Figure III-5: Probability of Escalation Factors

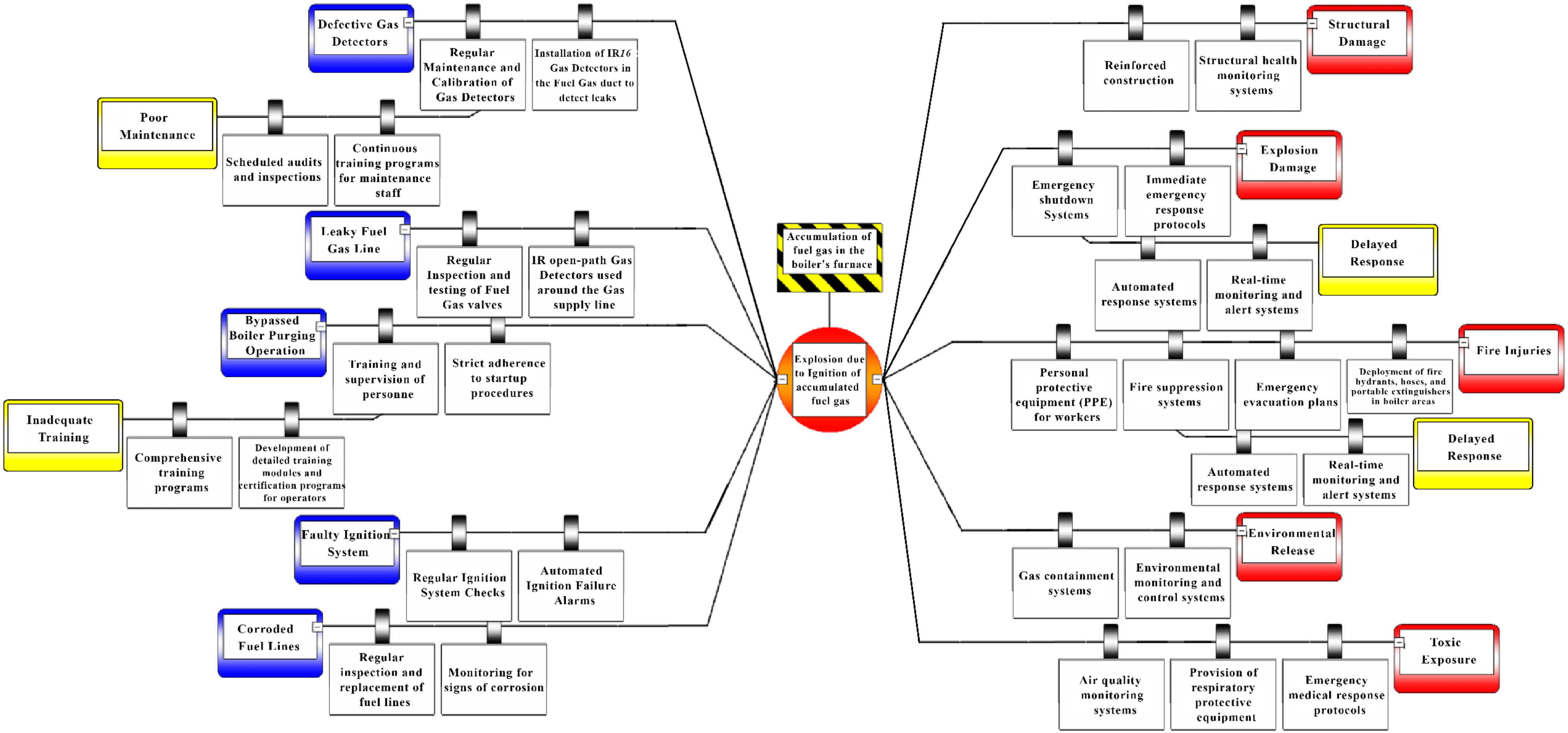

Figure III- 6: Bow-Tie Diagram before the suggestions

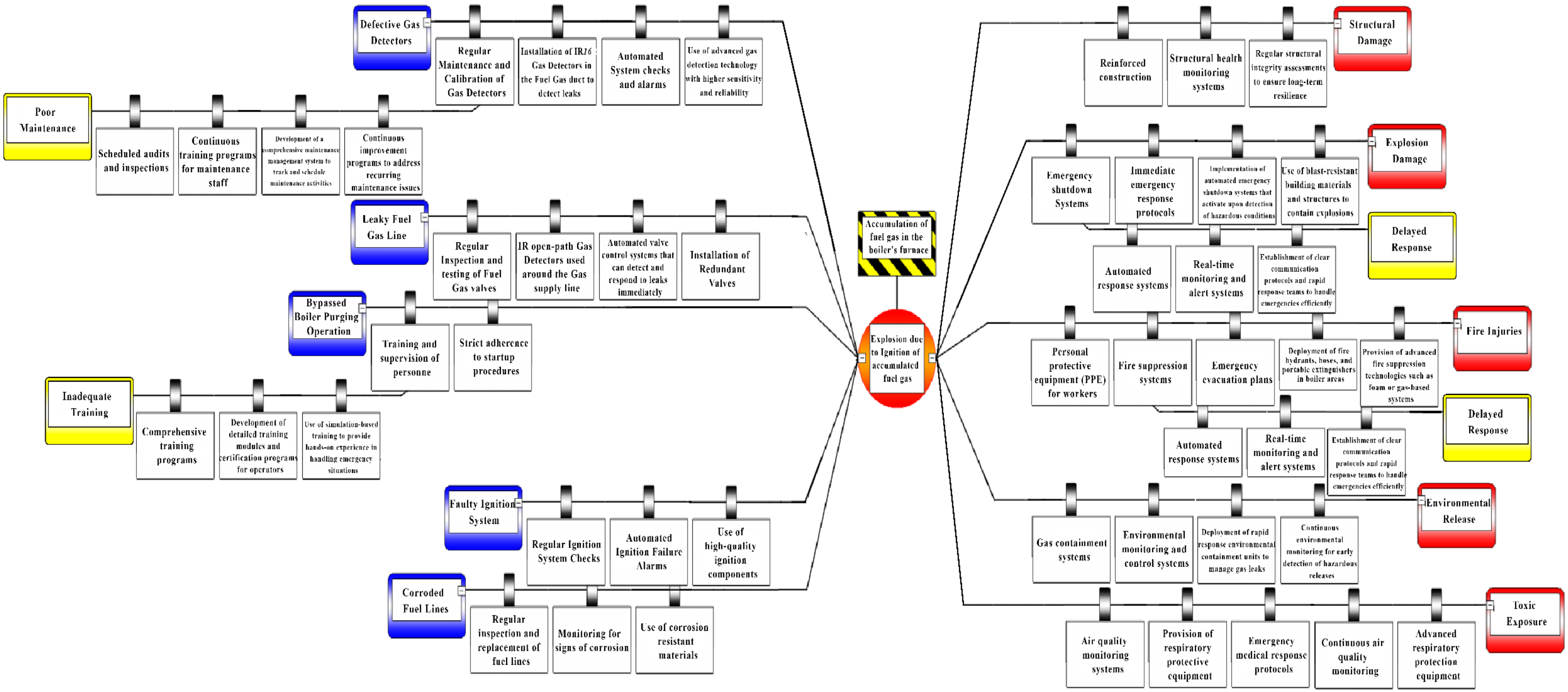

Figure III- 7: Bow-Tie Diagram after the suggestions

Interpretation of figure III- 7:

1) Defective gas detectors and proposed barriers:

Use of advanced gas detection technology with higher sensitivity and reliability:

- ✓ Upgrades the detection system to more advanced and sensitive technology.
- ✓ Ensures more accurate and reliable detection of gas leaks.

In the context of an IHI boiler, advanced gas detection technologies with higher sensitivity and reliability would be crucial for ensuring operational safety and environmental protection. Here are some specific examples tailored to the needs of monitoring and managing gases around an IHI boiler:

1. **Infrared (IR) Gas Detectors:**
   - **Application:** IR detectors can be used to monitor combustible gases such as methane (CH_4), hydrogen (H_2), and carbon monoxide (CO) emitted during boiler operation.
   - **Advantages:** They offer high sensitivity and specificity, capable of detecting gases at low concentrations even in the presence of steam or other contaminants.
2. **Electrochemical Sensors:**
   - **Application:** These sensors are ideal for detecting toxic gases like carbon monoxide (CO) and hydrogen sulfide (H_2S), which can be byproducts of incomplete combustion in boilers.
   - **Advantages:** They provide continuous monitoring and are well-suited for harsh environments, offering reliable performance over long periods.
3. **Wireless Gas Detection Systems:**
   - **Application:** Deployed throughout the boiler facility, these systems can monitor gas levels in real-time and transmit data wirelessly to a central control room.
   - **Advantages:** Enhances situational awareness, facilitates rapid response to gas leaks, and improves overall safety by monitoring critical areas continuously.
4. **Fiber Optic Sensing Technology:**
   - **Application:** Fiber optic sensors can be used for distributed sensing along pipelines or in confined spaces within the boiler to detect leaks or gas accumulation.
   - **Advantages:** They are highly sensitive, immune to electromagnetic interference, and can operate in high-temperature environments typical of boiler settings.
5. **Advanced Data Analytics and Integration:**
   - **Application:** Utilizing advanced data analytics, such as machine learning algorithms, to analyze sensor data and predict potential gas leak scenarios before they occur.
   - **Advantages:** Provides proactive maintenance strategies, improves operational efficiency, and enhances safety by identifying trends or anomalies in gas detection data.

These technologies combined provide a comprehensive approach to gas detection and monitoring around an IHI boiler, ensuring early detection of leaks, prompt response to emergencies, and overall safer operations in industrial settings.

Automated system checks and alarms:

- ✓ Integrates automated checks and alarms into the gas detection system.
- ✓ Provides continuous monitoring and immediate alerts for any malfunctions.

Implementing automated system checks and alarms for an IHI boiler is crucial for maintaining operational safety, efficiency, and reliability. Here are key components and features that can be integrated into such a system:

1. **Automated Monitoring Sensors:**
   - **Temperature Sensors:** Monitor temperatures at critical points (e.g., combustion chamber, superheater tubes) to detect overheating or abnormal fluctuations.
   - **Pressure Sensors:** Measure steam pressure levels to ensure they remain within safe operating limits.
   - **Flow Sensors:** Monitor water flow rates and fuel flow rates to ensure proper boiler operation.
   - **Level Sensors:** Detect water level in the boiler drum to prevent dry firing or flooding.
2. **Continuous Data Acquisition Systems:**
   - **Data Logging:** Collect real-time data from sensors and instrumentation systems.
   - **Historical Data Analysis:** Store and analyze historical data to identify trends and deviations from normal operating conditions.
   - **Remote Monitoring:** Enable remote access to monitoring data for operators and maintenance personnel.
3. **Automated Alarms and Alerts:**
   - **Threshold Alarms:** Set predefined thresholds for temperature, pressure, flow, and level parameters. Trigger alarms when these thresholds are exceeded.
   - **Emergency Shutdown Systems:** Integrate with control systems to automatically shut down the boiler in case of critical failures or safety breaches.
   - **Visual and Audible Alarms:** Provide visual indicators (e.g., flashing lights, on-screen alerts) and audible alarms (e.g., sirens, alarms) for immediate notification of abnormal conditions.
4. **Fault Diagnosis and Predictive Maintenance:**
   - **Fault Detection Algorithms:** Use algorithms to detect potential faults or anomalies based on sensor data patterns.
   - **Predictive Maintenance:** Predict equipment failures or degradation based on performance data to schedule proactive maintenance.
5. **Integration with Control Systems:**
   - **PLC (Programmable Logic Controller) Integration:** Use PLCs for logic control, sequencing of operations, and alarm management.
   - **SCADA (Supervisory Control and Data Acquisition) Systems:** Integrate with SCADA for centralized monitoring, control, and data visualization.
6. **Operator Interface and HMI (Human-Machine Interface):**
   - **User-Friendly Interface:** Provide operators with intuitive displays showing boiler status, alarms, and operational parameters.
   - **Alarm Acknowledgment and Response:** Enable operators to acknowledge alarms, view alarm details, and take appropriate actions.
7. **Testing and Validation:**
   - **Simulation and Testing:** Conduct simulation tests to validate alarm settings and response procedures.

- **Training:** Provide training for operators on using the automated system checks and responding to alarms effectively.

Implementing automated system checks and alarms enhances operational safety, reduces the risk of equipment damage, and ensures efficient boiler performance by enabling prompt response to abnormal conditions. It is essential to design the system according to specific operational requirements and continuously update it based on feedback and performance data.

These barriers enhance the accuracy and reliability of gas detection, ensuring timely identification and response to gas leaks or detector malfunctions, critical for early detection and prevention of gas leaks. This reduces the risk of explosions or fires.

2) Leaky fuel gas line valve and proposed barriers:

Installation of redundant valves:

- ✓ Adds backup valves to the fuel gas line system.
- ✓ Provides an additional layer of protection against valve failure.

Automated valve control systems that can detect and respond to leaks immediately:

- ✓ Implements automated systems to monitor and control valve operations.
- ✓ Ensures immediate detection and response to any leaks.

These barriers increases the reliability of valve operations, provides immediate containment and mitigation of leaks, preventing gas accumulation to prevents leaks that could lead to hazardous conditions, ensuring safer operations.

3) Bypassed boiler purging operation and proposed barriers:

Automation of purging operations to eliminate human error:

- ✓ Automates the purging process, removing the possibility of human error.
- ✓ Ensures purging is performed consistently and correctly every time.

These barriers ensure the purging process is always conducted, reducing the risk of gas accumulation, removing dependence on manual intervention, increasing reliability, to preventing dangerous gas accumulations that could lead to explosions during boiler startup.

4) Faulty ignition system and proposed barriers:

Use of high-quality ignition components:

- ✓ Employs more reliable and durable ignition components.
- ✓ Reduces the likelihood of ignition system failures.

The use of high-quality ignition components is critical for ensuring reliable and efficient operation of an IHI boiler. Here are key considerations and components typically used:

1. **Ignition Transformers:**

- **Purpose:** Convert electrical power to high voltage needed to create an electric arc or spark for ignition.
- **Quality Requirements:** High insulation resistance, robust construction to withstand environmental conditions (e.g., temperature variations, humidity).

2. **Ignition Electrodes:**
    - **Types:** Include spark electrodes and flame rods.
    - **Function:** Spark electrodes create an electric spark to ignite fuel-air mixtures, while flame rods detect the presence of a flame for monitoring and safety shutdown.
    - **Material:** Typically made from high-quality ceramics or metals resistant to corrosion and thermal stress.
3. **Ignition Cables and Wiring:**
    - **Material:** Use high-temperature resistant materials such as silicone rubber or fiberglass insulation to withstand heat from the combustion process.
    - **Design:** Ensure proper shielding and grounding to prevent interference and ensure reliable ignition signal transmission.
4. **Control Systems and Ignition Controllers:**
    - **Features:** Include programmable logic controllers (PLCs) or microprocessor-based controllers for precise timing and sequencing of ignition events.
    - **Safety Features:** Incorporate flame detection sensors and interlocks to ensure safe operation and prevent ignition in unsafe conditions.
5. **Spark Plugs (for some boiler types):**
    - **Function:** Similar to those used in internal combustion engines, spark plugs may be used in specific boiler designs for ignition of fuel-air mixtures.
    - **Quality:** High-quality materials and construction to withstand thermal cycling and combustion environment conditions.
6. **Maintenance and Replacement Practices:**
    - **Schedule:** Implement regular inspection and maintenance of ignition components as per manufacturer recommendations or operational experience.
    - **Testing:** Conduct performance tests (e.g., spark intensity, flame detection) periodically to ensure components are functioning correctly.
    - **Replacement:** Replace components proactively before they fail to prevent downtime and ensure continuous operation.

High-quality ignition components not only enhance the reliability and efficiency of an IHI boiler but also contribute to overall safety by ensuring proper ignition and combustion processes. Investing in reliable components and implementing rigorous maintenance practices is essential for maximizing the lifespan and performance of boiler ignition systems.

These barriers enhance the reliability and longevity of the ignition system, reduce the risk of ignition failures that could lead to dangerous delays in igniting the fuel, to ensure safe and reliable ignition of fuel, preventing potential explosions due to delayed ignitions.

5) Corroded fuel lines and proposed Barriers:

Use of corrosion-resistant materials:

- ✓ Uses materials that are resistant to corrosion for fuel lines.

Corrosion-resistant materials include:

- Stainless steel: Renowned for its corrosion resistance, ductility, and high strength.
- Aluminum: Non-toxic, recyclable, with high strength-to-weight ratio.
- Copper alloys: Offer good corrosion resistance.
- Titanium: Provides excellent mechanical and corrosion resistance properties at high temperatures.
- Superalloys: Specifically formulated for high-performance corrosion resistance

✓ Extends the lifespan of the fuel lines and reduces maintenance requirements.

These barriers reduce the risk of fuel line failures due to corrosion, enhance the durability and reliability of the fuel supply system, and prevent leaks and failures caused by corrosion, ensuring the integrity of the fuel supply system.

These proposed barriers aim to address the root causes of each threat by leveraging advanced technology and automation to enhance reliability and reduce the potential for human error. By upgrading detection systems, automating critical processes, and using high-quality materials, the overall safety and efficiency of operations are significantly improved. Implementing these barriers is crucial for preventing accidents and ensuring a safe working environment.

Consequences and Proposed Barriers

1) Explosion Damage

Implementation of automated emergency shutdown systems that activate upon detection of hazardous conditions:

✓ Automatically shuts down operations when hazardous conditions are detected.
✓ Isolates the affected area to prevent further damage.

Use of blast-resistant building materials and structures to contain explosions:

✓ Constructs buildings with materials that can withstand explosions.
✓ Minimizes the spread of damage and protects personnel and equipment.

These barriers reduce the extent of damage by quickly halting operations and containing explosions, protect critical infrastructure and personnel, and ensure a rapid response to hazardous conditions, preventing catastrophic damage and loss of life.

2) Fire Injuries

Provision of advanced fire suppression technologies such as foam or gas-based systems:

✓ Utilizes advanced fire suppression methods to quickly extinguish fires.
✓ More effective in different scenarios compared to traditional water-based systems.

Provisioning advanced fire suppression technologies for an IHI boiler involves deploying systems that can quickly and effectively suppress fires in high-temperature and high-pressure environments. Here are key technologies and considerations for implementing fire suppression systems:

1. **Foam Fire Suppression Systems:**

- **Application:** Foam systems are effective for Class B fires (involving flammable liquids) and can be adapted for use in boiler areas where fuel leaks or oil fires may occur.
- **Mechanism:** Foam blankets the fuel surface, preventing the release of flammable vapors and extinguishing the fire.
- **Types:** Aqueous film-forming foam (AFFF) and alcohol-resistant aqueous film-forming foam (AR-AFFF) are common types used in industrial settings.
- **Advantages:** Effective for suppressing fires involving hydrocarbons and can be used in open and semi-enclosed spaces.

2. **Gas-Based Fire Suppression Systems:**
    - **Types:** Includes clean agent systems such as FM-200 (HFC-227ea), CO2 (carbon dioxide), and inert gases like nitrogen or argon.
    - **Application:** Suitable for enclosed spaces or where water-based systems are impractical due to potential damage to sensitive equipment or electrical components.
    - **Mechanism:** Gas systems work by displacing oxygen to extinguish the fire or reduce oxygen levels below the combustion threshold.
    - **Advantages:** Fast-acting, leaves no residue, and minimizes potential damage to equipment.
3. **Water Mist Systems:**
    - **Application:** Water mist systems are suitable for suppressing fires in enclosed or semi-enclosed spaces where conventional water-based systems may not be effective.
    - **Mechanism:** Water mist systems atomize water into fine droplets, creating a mist that cools the fire and reduces oxygen availability.
    - **Advantages:** Effective for Class A (solid combustibles) and Class C (electrical) fires, reduces heat and smoke, and minimizes water damage.
4. **Integrated Detection and Suppression Systems:**
    - **Detection:** Use fire and heat detectors to activate suppression systems automatically when a fire is detected.
    - **Control Panels:** Centralized control panels manage system operation, monitor sensor inputs, and activate alarms and suppression mechanisms.
    - **Interlocks:** Integrate with boiler control systems for coordinated shutdowns and safety protocols in case of fire events.
5. **Maintenance and Testing:**
    - **Regular Inspections:** Conduct routine inspections and maintenance of fire suppression systems as per manufacturer guidelines and regulatory requirements.
    - **Testing:** Perform functional tests and simulations to ensure system readiness and effectiveness in emergency situations.
6. **Compliance and Standards:**
    - **Regulatory Compliance:** Ensure fire suppression systems comply with local regulations, codes, and standards (e.g., NFPA, FM Global) applicable to industrial boiler operations.
    - **Installation and Certification:** Install systems according to manufacturer specifications and obtain certification from relevant authorities.

Implementing advanced fire suppression technologies tailored to the specific risks and operational environment of an IHI boiler enhances safety, protects personnel and equipment, and minimizes downtime due to fire incidents. Regular training of personnel in fire response procedures and system operation is also essential for effective emergency preparedness.

These barriers enhance the ability to control and extinguish fires quickly, reduce the risk of fire-related injuries and damage, and protect personnel and assets by effectively controlling and extinguishing fires, reducing the risk of injuries and fatalities.

3) Environmental Release

Deployment of rapid response environmental containment units to manage gas leaks:

- ✓ Quickly deploys units to contain and manage gas leaks.
- ✓ Prevents the spread of hazardous substances into the environment.

The deployment of rapid response environmental containment units is crucial for effectively managing gas leaks to minimize environmental impact and protect public health. Here are examples of such units:

1. **Mobile Containment Units:**
    - **Mobile Skid Units:** These are portable containment systems mounted on skids or trailers, equipped with:
        - **Containment Booms:** Floating barriers used to contain and absorb spilled liquids.
        - **Absorbent Pads:** Used to soak up leaked gases or liquids.
        - **Pumps and Vacuum Systems:** To recover spilled materials and contaminated liquids.
2. **Environmental Response Vehicles:**
    - **Response Trucks:** Equipped with:
        - **Deployable Booms:** Long, floating barriers that can be quickly deployed on water to contain oil or gas spills.
        - **Sorbent Materials:** Absorbents such as pads, pillows, or socks used to clean up spilled substances.
        - **Portable Air Monitoring Equipment:** Instruments to detect and monitor gas concentrations in the air.
3. **Emergency Response Teams:**
    - **Trained Personnel:** Equipped with:
        - **Personal Protective Equipment (PPE):** Including respiratory protection, protective clothing, and gloves.
        - **Gas Detectors:** Portable devices for immediate detection of hazardous gas concentrations.
        - **Containment and Cleanup Tools:** Such as shovels, buckets, and sealants for temporary containment and cleanup.
4. **Remote Monitoring Systems:**
    - **Automated Sensors:** Deployed in sensitive areas or near pipelines to provide real-time data on gas leaks.
    - **Communication Networks:** Enable remote monitoring and rapid response coordination between control centers and response teams.

These units and systems are designed to swiftly respond to gas leaks, contain the spread of hazardous substances, and mitigate environmental damage. Their deployment ensures a rapid and effective response to protect ecosystems, communities, and infrastructure from the consequences of gas leaks.

Continuous environmental monitoring for early detection of hazardous releases:

- ✓ Monitors the environment in real-time for hazardous releases.
- ✓ Ensures early detection and prompt response to prevent environmental contamination.

These barriers limit the environmental impact by containing and managing leaks quickly, provide real-time data for early detection and response to hazardous releases, and protect the environment and public health by preventing the spread of hazardous substances.

4) Structural Damage

Regular structural integrity assessments to ensure long-term resilience:

- ✓ Conducts regular assessments of the structural integrity of buildings.
- ✓ Identifies and addresses any potential weaknesses before they lead to failures.

Regular structural integrity assessments are essential for ensuring the long-term resilience and safety of an IHI boiler. Here's how these assessments can be conducted:

1. **Visual Inspections:**
    - **Frequency:** Conducted regularly (e.g., monthly, quarterly) by trained inspectors.
    - **Purpose:** Identify visible signs of corrosion, leaks, deformation, or wear on boiler components such as tubes, headers, and casings.
2. **Non-Destructive Testing (NDT):**
    - **Methods:** Include ultrasonic testing (UT), radiographic testing (RT), magnetic particle testing (MPT), and dye penetrant testing (DPT).
    - **Purpose:** Detect internal flaws, cracks, or material degradation without damaging the boiler structure.
3. **Pressure Testing:**
    - **Procedure:** Test boiler components under pressure to ensure they can withstand operational loads and pressures safely.
    - **Purpose:** Confirm the structural integrity and leak-tightness of welds, joints, and pressure-bearing parts.
4. **Material Testing and Analysis:**
    - **Sampling:** Periodically take samples of boiler materials for laboratory analysis to assess material properties and degradation over time.
    - **Purpose:** Identify potential weaknesses, material fatigue, or susceptibility to corrosion.
5. **Thermal Stress Analysis:**
    - **Simulation:** Use computational models to simulate thermal cycles and stresses experienced by boiler components during operation.
    - **Purpose:** Predict potential areas of stress concentration, fatigue, or deformation under varying operational conditions.
6. **Corrosion Monitoring and Control:**
    - **Monitoring:** Implement corrosion monitoring techniques such as corrosion coupons or online corrosion probes.
    - **Purpose:** Track corrosion rates and conditions to apply appropriate corrosion control measures (e.g., coatings, inhibitors).
7. **Documentation and Reporting:**

- **Records:** Maintain comprehensive records of inspection findings, test results, and maintenance activities.
- **Purpose:** Track the boiler's condition over time, identify trends, and make informed decisions for maintenance and repair.

By conducting regular structural integrity assessments using these methods, operators can ensure that the IHI boiler remains in optimal condition, compliant with safety standards, and capable of operating reliably over its intended lifespan. These assessments contribute significantly to maintaining operational efficiency, minimizing downtime, and preventing costly repairs or accidents.

These barriers ensure that structures remain resilient and capable of withstanding damage over time, prevent sudden structural failures by addressing issues proactively, and maintain the safety and usability of buildings and infrastructure, preventing collapses and extensive damage.

5) Toxic Exposure

Continuous air quality monitoring:

- ✓ Monitors air quality in real-time for toxic substances.
- ✓ Ensures early detection of any harmful releases.

Advanced respiratory protection equipment:

- ✓ Provides personnel with advanced respiratory protection.
- ✓ Reduces the risk of inhaling toxic substances.

Respiratory protection is provided by two families of devices:

- **Filtering devices:** These purify surrounding air through filtration. They must never be used in oxygen-deficient atmospheres.

Filtering Device Example:

- **Respirator Mask with Particulate Filters:** This type of device filters out particulates such as dust, ash, or other solid particles that may be present during boiler maintenance or operation. It ensures that the user breathes clean air by removing airborne contaminants.

- **Isolating devices:** These supply breathable air from an uncontaminated source. The user is independent of the ambient atmosphere.

Isolating Device Example:

- **Self-Contained Breathing Apparatus (SCBA):** In situations where the atmosphere around the IHI boiler may contain hazardous gases or low oxygen levels, an SCBA would be used. It supplies a continuous flow of clean, breathable air from a separate, uncontaminated source (such as a compressed air cylinder), allowing the user to work safely regardless of the ambient conditions.

These barriers enhance the ability to detect and respond to toxic exposures quickly, protect personnel from the health risks associated with inhaling toxic substances, and ensure the safety and health of personnel by providing early detection and protection against toxic exposures.

These proposed barriers aim to mitigate the impact of various consequences by leveraging advanced technologies, materials, and monitoring systems. By implementing automated shutdown systems, blast-resistant materials, advanced fire suppression technologies, rapid response units, continuous monitoring, and regular assessments, the overall safety and resilience of operations are significantly enhanced. These measures are crucial for protecting personnel, infrastructure, and the environment from the severe impacts of explosions, fires, environmental releases, structural damage, and toxic exposures.

Escalation Factors and Proposed Barriers

1) Poor Maintenance

- ✓ Development of a comprehensive maintenance management system to track and schedule maintenance activities.

Developing a comprehensive maintenance management system for tracking and scheduling maintenance activities is crucial for ensuring the reliability, safety, and longevity of an IHI boiler. Here’s how such a system can be structured and implemented:

1. **Asset Register:**
    - **Purpose:** Create a detailed inventory of all boiler components and subsystems.
    - **Information:** Include specifications, installation dates, service history, and criticality ratings.
2. **Maintenance Planning and Scheduling:**
    - **Routine Maintenance:** Schedule regular inspections, lubrication, cleaning, and minor adjustments based on manufacturer recommendations and operational experience.
    - **Periodic Inspections:** Plan for non-destructive testing (NDT), visual inspections, and pressure tests at specified intervals.
    - **Predictive Maintenance:** Implement condition monitoring techniques (e.g., vibration analysis, thermography) to predict equipment failures and schedule proactive maintenance.
3. **Work Order Management:**
    - **Initiation:** Create work orders for planned maintenance tasks, including detailed instructions, safety precautions, and required materials.
    - **Assignment:** Assign tasks to maintenance personnel based on skills, availability, and priority.
    - **Tracking:** Monitor progress, resource utilization, and completion status of work orders in real-time.
4. **Inventory and Spare Parts Management:**
    - **Stock Control:** Maintain an inventory of critical spare parts and consumables required for boiler maintenance and repair.

- **Replenishment:** Implement reorder triggers based on usage rates, lead times, and criticality to ensure availability.

5. **Documentation and Reporting:**
   - **Recording:** Document maintenance activities, inspections, test results, and repairs in a centralized database or electronic system.
   - **Analysis:** Analyze historical data to identify trends, recurring issues, and opportunities for improvement.
   - **Reporting:** Generate reports on maintenance performance metrics, compliance with regulatory requirements, and equipment reliability.
6. **Training and Competency Management:**
   - **Skills Development:** Provide training and certification programs for maintenance personnel to enhance skills and knowledge.
   - **Competency Assessment:** Ensure personnel are competent to perform assigned tasks safely and effectively.
7. **Continuous Improvement:**
   - **Feedback Loop:** Solicit feedback from maintenance teams and stakeholders to identify areas for process improvement and efficiency gains.
   - **Benchmarking:** Compare performance metrics against industry standards and best practices to drive continuous improvement initiatives.

Implementing a robust maintenance management system for an IHI boiler involves integrating these components into a cohesive framework that promotes proactive maintenance, minimizes downtime, and enhances operational safety. Regular reviews and updates to the system ensure it remains aligned with organizational goals and evolving maintenance requirements.

- ✓ Continuous improvement programs to address recurring maintenance issues.

These barriers ensure equipment is properly maintained, reducing the risk of failures, improving reliability and safety by addressing root causes of problems, and reducing the likelihood of equipment failures and associated risks.

2) Inadequate Training

- ✓ Use of simulation-based training to provide hands-on experience in handling emergency situations.
- ✓ Establishment of clear communication protocols and rapid response teams to handle emergencies efficiently.

Utilizing simulation-based training is a highly effective method for providing hands-on experience in handling emergency situations related to an IHI boiler. Here's how simulation-based training can be structured and its benefits:

Structure of Simulation-Based Training:

1. **Scenario Development:**
   - **Identify Scenarios:** Develop realistic scenarios based on potential emergency situations specific to boiler operations (e.g., fuel leaks, overheating, pressure surges).
   - **Include Variability:** Introduce variability in scenarios to simulate different levels of severity and complexity.
2. **Simulation Platforms:**
   - **Virtual Simulations:** Utilize computer-based simulations that replicate the boiler environment, control systems, and emergency procedures.

    - **Physical Simulators:** Construct physical models or simulators that mimic boiler components and operations.
3. **Participant Roles:**
    - **Assign Roles:** Designate roles for participants (e.g., operators, maintenance personnel, emergency responders) based on their responsibilities during emergencies.
    - **Team Coordination:** Emphasize teamwork and coordination among participants to simulate real-time decision-making and communication.
4. **Training Modules:**
    - **Introduction and Orientation:** Provide an overview of the simulation objectives, scenario details, and safety protocols.
    - **Simulation Execution:** Conduct simulations where participants respond to evolving scenarios, applying emergency procedures and troubleshooting techniques.
    - **Debriefing Sessions:** Facilitate debriefing sessions to review performance, discuss challenges encountered, and identify opportunities for improvement.

Benefits of Simulation-Based Training:

- **Realistic Environment:** Simulations replicate real-world conditions, allowing participants to experience and respond to emergencies in a controlled setting.
- **Risk-Free Learning:** Provides a safe environment to practice without the risk of damage to equipment or personnel.
- **Skill Development:** Enhances decision-making, problem-solving, and critical thinking skills under pressure.
- **Team Building:** Promotes collaboration, communication, and coordination among team members during emergency responses.
- **Continuous Improvement:** Identifies gaps in procedures, equipment familiarity, and training needs that can be addressed to enhance emergency preparedness.

Implementation Considerations:

- **Customization:** Tailor simulations to reflect specific operational challenges and emergency scenarios relevant to IHI boiler operations.
- **Feedback Mechanisms:** Incorporate feedback mechanisms to gather input from participants and trainers for continuous improvement of simulation exercises.
- **Regular Updates:** Review and update simulation scenarios and training content based on evolving safety protocols, regulatory requirements, and operational changes.

By integrating simulation-based training into the training curriculum for IHI boiler operations, organizations can enhance readiness, improve safety outcomes, and foster a culture of proactive emergency preparedness among personnel.

These barriers improve readiness and effectiveness during real emergencies, reduce response times, and minimize the impact of emergencies, ensuring employees are adequately prepared to handle responsibilities and respond to unexpected situations.

3) Delayed Response

- ✓ Development of a comprehensive maintenance management system to track and schedule maintenance activities.

- ✓ Establishment of clear communication protocols and rapid response teams to handle emergencies efficiently.

Developing a comprehensive maintenance management system (MMS) for tracking and scheduling maintenance activities for an IHI boiler is essential for ensuring its reliability, safety, and longevity. Here's a structured approach to developing such a system:

Components of a Comprehensive Maintenance Management System:

1. **Asset Register and Inventory Management:**
   - **Asset Identification:** Create a detailed inventory of all boiler components, including critical systems, subsystems, and spare parts.
   - **Asset Classification:** Classify assets based on criticality and prioritize maintenance activities accordingly.
   - **Inventory Control:** Implement inventory management practices to ensure availability of spare parts and consumables.
2. **Preventive Maintenance Planning:**
   - **Routine Inspections:** Schedule regular inspections, lubrication, cleaning, and minor adjustments according to manufacturer recommendations and operational requirements.
   - **Condition-Based Maintenance:** Use sensor data (e.g., temperature, pressure) to schedule maintenance tasks based on actual equipment condition rather than fixed intervals.
   - **Predictive Maintenance:** Utilize predictive analytics and sensor technologies to forecast equipment failures and plan maintenance proactively.
3. **Work Order Management:**
   - **Work Order Generation:** Generate work orders for planned maintenance tasks, including detailed instructions, safety precautions, and required materials.
   - **Assign and Prioritize:** Assign work orders to maintenance personnel based on skill levels, availability, and task priority.
   - **Tracking and Completion:** Monitor work order progress, resource utilization, and completion status in real-time.
4. **Document Management and Compliance:**
   - **Documentation:** Maintain comprehensive records of maintenance activities, including inspection reports, test results, and maintenance logs.
   - **Regulatory Compliance:** Ensure adherence to regulatory standards and safety requirements in all maintenance procedures and documentation.
5. **Integration with Maintenance Technologies:**
   - **CMMS (Computerized Maintenance Management System):** Implement a CMMS software to centralize maintenance data, automate workflows, and facilitate reporting.
   - **IoT and Sensors:** Integrate IoT devices and sensors to monitor equipment health, collect real-time data, and enable condition-based maintenance strategies.
   - **Mobile Access:** Provide mobile access to maintenance personnel for real-time updates, work order management, and remote troubleshooting.
6. **Performance Analysis and Continuous Improvement:**
   - **Key Performance Indicators (KPIs):** Define and track KPIs such as mean time between failures (MTBF), mean time to repair (MTTR), and equipment uptime to measure maintenance effectiveness.

- **Root Cause Analysis:** Conduct root cause analysis for equipment failures to identify underlying issues and implement corrective actions.
- **Feedback Loop:** Solicit feedback from maintenance teams to identify process improvements, training needs, and optimization opportunities.

Implementation Steps:

- **Assessment:** Conduct an initial assessment of current maintenance practices, equipment condition, and organizational needs.
- **System Design:** Design a tailored maintenance management system that aligns with operational requirements and safety standards.
- **Training and Adoption:** Provide training to maintenance personnel on system usage, procedures, and safety protocols.
- **Pilot Phase:** Implement the system in a pilot phase to identify and address any operational challenges or refinements.
- **Full Deployment:** Roll out the system across the organization, ensuring user adoption and ongoing support.

By developing and implementing a comprehensive maintenance management system, organizations can optimize maintenance workflows, extend equipment lifespan, minimize downtime, and enhance overall operational efficiency for their IHI boiler systems.

These barriers improve response times and effectiveness during emergencies, ensure emergencies are managed efficiently and effectively, to minimize the impact of emergencies and prevent the escalation of risks.

Overall, these proposed barriers aim to mitigate the identified escalation factors and enhance safety in industrial settings by promoting proactive measures that reduce the likelihood of incidents and improve the organization's ability to respond effectively to emergencie

Conclusion

Conclusion

In conclusion, the application of the Bow-Tie method in the analysis of industrial boiler operations, particularly IHI boilers, demonstrates its effectiveness in identifying and managing risks. By providing a comprehensive visualization of potential hazards, threats, consequences, and control measures, the Bow-Tie method enhances the safety and reliability of boiler operations. This risk management approach is crucial in the oil and gas industry, where the consequences of accidents can be severe, including loss of life, environmental damage, and financial losses.

Implementing the Bow-Tie method ensures that all possible risks are identified and mitigated through preventive and protective measures, thereby reducing the likelihood of accidents and their potential impact. This proactive approach to risk management not only improves operational safety but also helps in maintaining regulatory compliance and protecting the environment. As industries continue to seek efficient and reliable risk management tools, the Bow-Tie method stands out as a valuable methodology for ensuring safer industrial operations.

Bibliography

[1] Center for Chemical Process Safety AIChE. Guidelines for Technical Management of Chemical Process Safety. New York, 1989.

[2] OSHA Washington DC. 29 CFR 1910.119 Process Safety Management of Highly Hazardous Chemicals; 1992.

[3] Dowell Iii AM. Layer of protection analysis for determining safety integrity level. ISA Trans. 1998;37(3):155-65.

[4] Berg AR. Applicability of layer of protection analysis to determine safety integrity levels in the process industry. Norwegian University of Science and Technology; 2007.

[5] Atkins China Ltd (1998). “Quantitative Risk Analysis to Assess Residual Landslip Risk to Squatters at LeiYue Mun”. Report prepared for the Geotechnical Engineering Office, Hong Kong

[6] Domínguez, Claudia Rivera, Jovana Ivette Pozos Mares, and Rosario Glendenit Zambrano Hernández. "Hazard identification and analysis in work areas within the Manufacturing Sector through the HAZID methodology." Process Safety and Environmental Protection 145 (2021): 23-38.

[7] Mearns, Kathryn, and Rhona Flin. "Risk perception and attitudes to safety by personnel in the offshore oil and gas industry: a review." Journal of loss prevention in the process industries 8.5 (1995): 299-305.

[8] Haridoss, S. (2017). Health and safety hazards management in oil and gas industry. Int. J. Eng. Res, 6, 1058-1061.

[9] ollnagel, E., Woods, D.D., Epilogue: Resilience engineering precepts. Resilience engineering: Concepts and precepts, 347–358 (2006)

[10] Gao, Zhiguo. "Environmental regulation of oil and gas." (1998): 1-652.

[11] Borgovini, Robert, Stephen Pemberton, and Michael Rossi. "Failure Mode, Effects and Criticality Analysis (FMECA)." Reliability Analysis Center (1993).

[12] Srinivasan R, Venkatasubramanian V. Automating HAZOP analysis of batch chemical plants. Comput Chem Eng. 1998;22(9):1345-55.

[13] Guenab, Fateh, Jean-Louis Boulanger, and W. Schon. "Safety of railway control systems: A new Preliminary Risk Analysis approach." 2008 IEEE International Conference on Industrial Engineering and Engineering Management. IEEE, 2008.

[14] Alizadeh, S. S., & Moshashaei, P. (2015). The Bowtie method in safety management system: A literature review. Scientific Journal of Review, 4(9), 133-138.

[15] Specification and Description of IHI Boilers, Ishikawajima-Harima Heavy Industries Co., Ltd.

[16] L. Brazier bureau VERITAS. Etude de danger du complexe GL2/Z. p 177-178; 2010.

[17] Understanding and Mastery of Physical and Chemical Phenomena, Metallic Materials – Industrial Corrosion: Metal Corrosion; April 2005.

[18] National Research Council, et al. "Risk assessment in the federal government: managing the process." (1983).

[19] *Incident Probabilities on Liquid Gas Ships*. UK Health and Safety Executive, AEA/CS/HSE R1014, 1994.