HAZOP analysis of Ship Inert Gas System: A Case Study

Ozcan Durukan[1,2*]
[1] Maritime Faculty, Istanbul Technical University, Tuzla 34940, Istanbul, Türkiye
[2] Maritime Vocational School, Galatasaray University, Besiktas 34349, Istanbul, Türkiye

Yasin Arslanoglu
Maritime Faculty, Istanbul Technical University, Tuzla 34940, Istanbul, Türkiye

Bugra Arda Zincir[1,2]
[1] Maritime Faculty, Istanbul Technical University, Tuzla 34940, Istanbul, Türkiye
[2] Maritime Vocational School, Galatasaray University, Besiktas 34349, Istanbul, Türkiye
[*] Corresponding author. E-mail: odurukan@gsu.edu.tr (O. Durukan)

Abstract

HAZOP (Hazard and Operability Analysis) is a method first used in the chemical industry to understand operational problems and potential hazards. In the process, hazard identification skills were developed, and the method was started to be used for system evaluation and development in different fields. In this study, an inert gas system, mostly used in crude oil tankers, where the gas is obtained from the boiler or stack, is analysed using the HAZOP method. Operational problems and potential hazards that the system may have in normal operation are identified. As a result of the examination carried out by the HAZOP team, 27 deviations are found, and root cause analyses are performed for them and preventive actions are determined. It is considered that the findings obtained as a result of the analysis can be an important data for the sector. It is thought that analysing the data obtained from HAZOP method with different risk assessment methods (FTA, LOPA, etc.) can give more ideas about the probability of existing risks.

Keywords: *HAZOP, inert gas system, hazard, operability, safety*

1. Introduction

A systematic design analysis, HAZOP, has been developed to understand the system's operational problems and potential hazards [1], [2]. It is a highly scientific process to monitor process equipment exposed to hazards. The system is designed to identify malfunctions and deviations which may lead to obvious events like explosion, fire and release of toxic materials [3].

HAZOP is the process by which a multidisciplinary team 'brainstorms' the design of the installation during the installation review meetings, according to the experience of the team leaders and the outline of the guide [4]. Stimulating creativity and generating ideas is the main benefit of these brainstorms. This happens as the team interacts with one another and draws on their different past experiences. That is why the process requires everyone to be involved. Team members should try not to criticise each other for making suggestions for reflection. In this case, the design team's task is to identify the nodes in the design. At each node the team uses guidelines to analyse deviations in process parameters in detail. The purpose of the guidelines is to ensure that the design is under control in every possible way, and that the design is under control in every possible way. Once the design is fairly well established, it is best to carry out a HAZOP analysis [5].

There are many factors that can influence whether a HAZOP succeeds or fails. It has been tried to generalise these factors in the form of [6]:

- Correctness and consistency of the data (drawings, etc.) used to support the work carried out.
- Team's intuition and technical ability
- Team capacity to focus on most critical risks

  This is a systematic process, and it is helpful to define the terms used [7].
- Process nodes: Points on the pipework, on the equipment drawings and on the procedures where the process parameters are searched for variations.
- Target: Definition of how the plant should operate without deviations at the nodes.
- Deviations: Deviations from the target which have been identified through systematic cueing.
- Reasons: There are several reasons why deviations may occur. When a reliable reason for a deviation is given, it is called a significant deviation. These reasons can be hardware failures, human errors, unexpected process situations (change of composition, etc.), external failures (power failure, etc.).
- Results: Consequences of the deviations that should have occurred are included. Results that are not considered to be significant for the purpose of the study will not be included.
- Guiding Words: Simple words used to describe objectives, identify deviations and stimulate brainstorming. The most common words used in HAZOP are listed in table 1 [8]. At the point of inspection in the plant, each guide word is used for process variables.

Table 1. Guide words, deviations, and explanations

Guide word	Typical deviation	Explanation
No, None	No flow	Line blockage, valve system failure or malfunction
More	Flow, pressure, temperature	Excessive pump activity, extra liquid entering the line, blockage in the line, valve is closed, abnormal high pressure, failed cooling
Less	Flow, pressure	Line blockage, pump or/and fan failure
As well as	Soiled product	Carry over, inward leaks from valves
Part of	Composition	Incorrect composition of the materials used
Reverse	Pressure, flow	Backpressure, backflow
Other than	Unusual conditions, Maintenance, Abnormal operations	Loss of services/supplies, fire, flood, insulation, venting, flushing, emptying, starting, partial loading, etc.

2. Literature Review

HAZOPs were developed by Imperial Chemical Industries (ICI, London) in 1960's when they were reviewing their phenol factory plans. This is a development from using critical inspection studies to identify design defects and deviations. The critical review method is an accepted way of examining activities and generating alternatives by asking questions such as "Has it been achieved?", "What else could be achieved?", "What should be achieved?", "How is it being achieved?" and so on [9]. A guide to hazard and operability studies was published by the Chemical Industries Association in 1977 [6]. This method, which is used for the operational evaluation of the system, has been used in different fields in the literature.

Penelas and Pires made an application of the HAZOP methodology to process and safety operations in the oil production industry. A unit used to produce crude oil was divided into smaller sections which were analysed. Seventy-one relevant risk probabilities were identified by applying HAZOP methodology. The assessment of environmental, health and economic impacts was the basis for establishing safety priorities for these risks. Forty-seven recommendations to mitigate the identified problems were derived from the application of this methodology and the identified safety measures. The contributions of the study are to demonstrate the effectiveness of the HAZOP methodology in identifying potential hazards for new or existing process plants and in assessing the resulting potential for equipment and asset failure, and to be a useful tool to provide company executives, decision makers and plant managers with the necessary information [10].

A Tier 1 PSA of TRR-1/M1 (Thailand Research Reactor-1/ Modification 1) for internal events and human error was the objective of the study by Vechgama et al. In view of the tiered approach, the Hazard and Operability Analysis (HAZOP) and the Human Hazard and Operability Analysis (Human HAZOP), which require a moderate level of detail, were selected to assess the hazardous events and ultimately to identify the initiating events (IEs). Fault Tree Analysis (FTA), Event Tree Analysis (ETA) and Bayesian updating were used to calculate the consequence frequencies (CDFs). The evaluation showed that the HAZOP analysis, which does not require long computation times and detailed failure data, is suitable for a simple research reactor such as TRR-1/M1. Natural operational failures, which had been overlooked in TRR-1/M1, were identified by the human HAZOP analysis. Specifically, the case where valves V-3 and V-4 were kept open to speed up reactor startup. IE1: Loss of Cooling Water Accident (LOCA), IE2: Excess Reactive Additive and IE3: Failure of Fuel Handling Equipment have been identified as the most important IEs. The highest CDF of IE3 (4.36E-02 1/yr) indicates that this is the main risk issue requiring more attention by operators during TRR-1/M1 operation [11].

Lim et al. discuss a recent concept of applying the industrial assessment practice of Hazard and Operability Analysis (HAZOP) to literature review. To guide the literature review process, the traditional HAZOP methodology is modified. As a case study, an overview of a model for the optimisation of the biomass supply chain is presented. To enable a detailed evaluation, the system is broken down for independent analysis. Differences considered are quantity, quality, logistics and market cost/value in the study. The keywords more/higher, less/no and less/low were used to identify potential process hazards. Each hazard identified has been cross-checked against the literature to identify any possible corrective actions. Suggestions are made where protection against the identified hazards is insufficient and potential research gaps are highlighted. HAZOPs provide a systematic platform for detailed evaluation of a complex investigation through guided procedures [12].

Lim et al. aimed to conduct a detailed review of the current status of the palm oil industry's development towards Industry 4.0 by applying the HAZOP concept to investigate the possible adaptation of Industry 4.0 technologies to improve the palm oil industry. In order to determine the feasible adaptation in the industry, existing Industry 4.0 technologies and their characteristics were assessed. This Hazard Analysis resulted in 23 recommendations for palm oil industry improvement using Industry 4.0 technologies for higher level of sustainable manufacturing. Thirteen specific Industry 4.0 characteristics were identified as potential development gaps for palm oil industry stakeholders, including adoption of IoT sensors, cloud computing, blockchains and smart imaging technologies [13].

The primary objectives of this study are a risk analysis of a current inertisation system schematic and the determination of the accident potential of system errors during inertisation. The analysis will be carried out on a shielding gas system diagram where the shielding gas is taken from the boilers. This was followed by descriptive and cross-cutting research to identify the possible risks that could lead to failure of a ship's inert gas system and to assess the risks on a ship. HAZOP provides qualitative and quantitative results to identify, analyse and correct potential faults in protective gas systems and related equipment.

3. Case Study

The inert gas system will be the subject of this study.

3.1. Inert Gas System

The purpose of an IG system is the prevention of tank fires or explosions. They are not permanent firefighting equipment. It can, however, be used to assist in the control of fires and the prevention of explosions [14]. Controlling the atmosphere in a cargo tank to prevent the formation of flammable mixtures is the main use of inert gas. A low oxygen content is the main requirement for inert gas. Otherwise, the composition of the inert gas may differ [14]. O2 contents depend on the nature of the cargo and the presence of volatile and flammable gases. The maximum oxygen content of a hydrocarbon-emitting cargo is 11%. By contrast, the highest oxygen level for a hydrogen gas

releasing cargo is 5%, in accordance with the International Convention for the Safety of Life at Sea (SOLAS 1974) [15].

In the flue gas inertisation system, the high temperature contaminated gas passes from the boiler to the scrubber and demister via a shut-off valve in the boiler outlet line. Here the gas is cleaned of its contaminants and cooled. Immediately afterwards, the gas is drawn into the cargo tanks by means of fans, passing through the deck water seal, non-return valve and deck isolation valve respectively. A gas pressure control valve installed after the fans regulates the flow to the cargo tank. To prevent damage to the cargo tank from overpressure or vacuum, a liquid-filled pressure/vacuum switch is also installed in the circuit. A vent is fitted between the pressure/vacuum relief valve and the gas pressure regulating valve to vent any leaks when the system is not in use [16]. Inert gas piping is routed from the deck isolating valve to the front across the entire cargo deck. It is used to supply gas to cargo tanks during cargo unloading, de-ballasting, tank cleaning and to increase tank gas pressure for other voyaging phases. Side pipes exit from the main blanketing pipe at the top of each cargo tank [16]. A standard inert gas system generally consists of the following components:

- Flue gas source: As it contains flue gases, the boiler or main engine exhaust ports are used to extract the inert gas.
- Boiler uptake valve: Serves as a feed valve between the inlet and the rest of the plant, separating the two systems when not in operation.
- Scrubber: The fumes enter the scrubber tower from below and pass through a number of water spray and deflector plates to cool, clean and humidify the gases. The result is a reduction in the SO2 content of the gas to 90% and no soot in the gas.
- Demister: It is usually polypropylene and is used for the extraction of moisture and water from the cleaned flue gas.
- Gas Blower: Typically, there are two different types of blower, a turbine blower for IG and an electric blower for filling.
- I.G pressure regulating valve: Depending on the oil and atmospheric conditions, the pressure in the tanks will vary. To control this variation, a pressure relief vent has been fitted after the fan outlet to return surplus gas is returned to the scrubbing tower.
- Deck seal: It is designed to prevent gases from the bellows returning to the cargo tanks. A wet deck seal is normally used for this. A demister is in place to remove moisture from the gases.
- Mechanical non-return valve: A mechanical non-return valve compatible to deck seal.
- Deck isolating valve: With this valve, the system in the engine room can be completely isolated from the system on deck.
- Pressure Vacuum (PV) breaker: Over- and under-pressure in cargo tanks can be controlled using the PV breaker. To ensure there is no fire in the harbour during loading or unloading operations, the PV breaker vent is fitted with a flame trap.
- Cargo tank isolating valves: A ship has several cargoes holds, each equipped with an isolation valve. The valve controls the flow of inert gas into the hold and can only be operated by a responsible officer on board.
- Mast riser: During loading, the valve remains open to avoid over pressurisation of the cargo tanks.

3.2. Findings

HAZOP provided systematic analysis of the operation of the ship's protective gas system. The analysis begins with the formation of a HAZOP team of ten maritime experts responsible for the use and control of the relevant protective gas systems on crude carriers. A diagram of the system is then drawn up on the basis of a sketch of the crude oil tanker. As shown in figure 1, the HAZOP team divides the system diagram into five separate nodes.

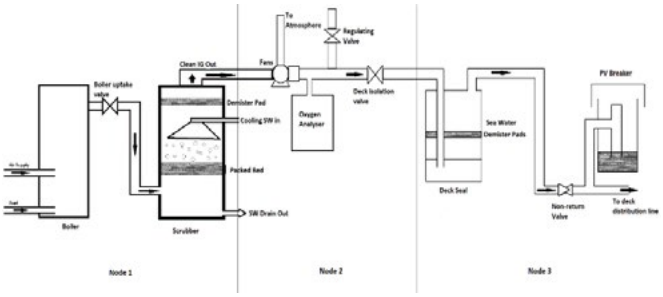


Figure 1. Inert gas system diagram with operating points.

The operational nodes divided by the HAZOP team and analysed with guide words are shown in tables 2, 3 and 4:

Table 2. HAZOP worksheet for node 1 (Boiler to scrubber)

No	Guide Words	Deviation	Possible Cause	Consequence	Action Required
1	None	No flow	(1) Line blockage	Loss of time, high soot concentration in inert gas lines.	(1.1.1) Establish regular patrols & inspections of the boiler receiving line. (1.1.2) Mount the on/off display onto the valve. (1.1.3) Prior to the boiler inlet valve, install a pressure gauge on the line.
2	More of	More heat	(2) Boiler over fuelled (3) Malfunction of the automatic fuel regulator	Physical deterioration of the scrubber and inert line.	(1.2.1) Fit a thermal probe and thermometer to the scrubber assembly and set up periodic control heat. (1.2.2.) Fit the boiler's fuel line with a fuel pressure gauge. (1.2.3) Arrange for the fuel automatic regulator to be inspected and serviced on a regular basis.
3	Part of	High O_2 concentration in IG	(4) Excessive supply of air to the boiler Like in (3)	Loss of time due to unsuitable inert gas.	(1.3.1) Fit a manometer to the boiler air inlet pipe. (1.3.2) Periodically monitor the boiler's O2 level. Encompassed by (1.2.3)
		High SO_2 concentration in IG	(5) Low quality of the fuel Like in (2) Like in (3)	Accelerated corrosion on ship's structure.	(1.3.3) Fuel analysis to be performed regularly. Encompassed by (1.2.2) Encompassed by (1.2.3)
4	Reverse	Seawater coming from the scrubber into the boiler	(6) High level of water in the scrubber unit	Boiler malfunction.	(1.4.1) Scrubber unit should be fitted with high level alarm. (1.4.2) Check the water level in the scrubbing unit on a regular basis.
5	Other	Maintenance	(7) Leakage of gas from the boiler, the IG line and/or the scrubber tower.	Injury to personnel Release of toxic gas into the public environment.	(1.5.1) Regularly carry out a pressure test on the IG line. (1.5.2) Continue to check pressure while running. (1.5.3) Installation of engine room atmosphere monitoring system.

Table 3. HAZOP worksheet for node 2 (Scrubber to deck seal unit)

No	Guide Words	Deviation	Possible Cause	Consequence	Action Required
6	None	No flow	(8) Blockage of the line (9) Faulty inert gas blower (10) Excessively high-water level in scrubber unit (11) Clogging of scrubber tower deflectors	Time wasted, physical destruction of scrubbing unit and inert gas pipework	(2.6.1) On the scrubber outlet line, mount a manometer. (2.6.2) Regular inspection and/or testing of the conditions of the inert gas blowers. (2.6.3) On the scrubber plant, install a high-level alarm. (2.6.4) Periodic inspection and cleaning of the scrubber tower interior.
7	Less of	Less flow	Like in (8) Like in (9) Like in (10)	Loss of time, structural damage to the scrubber tower and inert gas line.	Encompassed by (2.6.2) Encompassed by (2.6.3) Encompassed by (2.6.4)
8	More of	More heat	(12) Inadequate coolant flow in the scrubber plant	Structural damage to gauges and sensors on IG pipework.	(2.8.1) Regular check scrubber seawater line of scrubber. (2.8.2) Place manometer and flow meter on the sea water line of the scrubber.
9	Part of	High SO_2 concentration in IG	(13) Scrubbing deflectors in bad condition. (14) Fuel quality is low	Air pollution.	(2.9.1) Fuel analysis to be performed regularly. (2.9.2) Check the deflector plate condition periodically. (2.9.3) Install a fixed gas detector on the outlet pipe of the scrubber.
10	More than	Soot	Like in (13) Like in (14)	Soot build-up in IG system pipework, air pollution.	Encompassed by (2.9.1) Encompassed by (2.9.2) Encompassed by (2.9.3)
11	Other	Maintenance	(15) Inert gas pipework, connection points and fans in poor condition	Personnel injury. Toxic gas release to public space.	(2.11.1) Carry out regular pressure tests on the IG line. (2.11.2) Continuous pressure monitoring during operation. (2.11.3) In the engine room, fit an atmospheric monitoring system.

Table 4. HAZOP worksheet for node 3 (Deck seal to tanks)

No	Guide Words	Deviation	Possible Cause	Consequence	Action Required
12	None	No flow	(16) O2 content in IG above 5% (17) Automatic diverter valves and/ or Oxygen analyser failure (18) Deck seal with higher water level	Waste of time	Encompassed by (1.2.3), (1.3.1), (1.3.2) (3.12.1) Periodically inspect and test automatic diverter valves. (3.12.2) Fit a high-level alarm on the deck sealing.
13	More of	More pressure	(19) IG blowers in overdrive. (20) Inside the PV breaker the oil level is too high.	Deterioration on IG pipework, oil pollution	(3.13.1) Provide IG fans with get started and usage guides. (3.13.2) Check the PV breaker oil level regularly. (3.13.3) Set up the patrol on the deck with the IG system turned on. (3.13.4) Have an oil spill kit ready to hand in the vicinity of the PV breaker.
14	Less of	Less flow	(21) Blocked deck isolating valve (22) The supply valve to the cargo tank is open more than the system can handle. Like in (18)	Waste of time	Encompassed by (3.12.2) (3.14.2) Arrange for the deck isolating valve to be checked and tested at regular intervals. (3.14.3) Check the supply valve of all tanks. Provide a tank inerting procedure.
15	As well as	Water	(23) Deck sealing demister pads in bad condition	Cargo damage	(3.15.1) Periodically inspect, clean and replace the demister pad. (3.15.2) Fit the deck seal water outlet filter.
10	More than	Soot	(24) Deck seal with low water level (25) Deck seal unit is dirty	Cargo damage	(3.15.3) On the deck seal, mount a low-level alarm. (3.15.4) Inspect and keep deck seals clean at regular intervals.
16	Part of	High O_2 concentration in IG	(26) Oxygen analyser fails to operate	Fire, explosion, cargo damage	(3.16.1) Periodically check the O2 analyser with reference gas detector. (3.16.2) The Oxygen analyser must be calibrated with a test gas prior to each inerting operation.

4. Conclusion

The result of this work was the identification of dangerous deviations in the safe inert gas system on tankers by a team of experts. The consequences of the identified dangerous deviations should be carefully considered. At this point, the consequences of the deviation may affect not only the node concerned, but also other nodes or other processes within the system and may lead to serious incidents. Other nodes that contain the findings of the outcome investigation should also be reviewed at this stage. A bias in one node may cause an unforeseen bias in another node.

The results of the HAZOP study should be evaluated in order of importance. The results can be grouped into the following categories.

i. Hazardous (causing accidents or fatalities)
ii. Critical (causing significant loss of production or damage to the facility)
iii. Significant (situations causing delays or failures)
iv. Low (does not cause significant damage to the system or production, but may require planned maintenance)

The HAZOP method is a method for the identification of hazards and does not provide any quantitative results. However, the results of the HAZOP study can be converted into numerical data by various methods such as LOPA or FTA.

Nomenclature

CDF	Core Damage Frequencies
ETA	Event tree analysis
FTA	Fault Tree Analysis
HAZOP	Hazard and Operability Analysis
ICI	Imperial Chemical Industries
IE	Initiating event
IG	Inert gas
LOCA	Loss of coolant accident
LOPA	Layers of Protection Analysis
PSA	Probabilistic Safety Assessment
PV	Pressure vacuum
SOLAS	International Convention for the Safety of Life at Sea
SW	Sea water
TRR-1/M1	Thailand Research Reactor-1/Modification 1

References

[1] C. Ay, T. Güler, and E. Bal Beşikçi, "Implementation of ARAMIS methodology in the risk assessment of chemical tankers: The case of loading operation," *Ocean Engineering*, vol. 261, Oct. 2022, doi: 10.1016/j.oceaneng.2022.112211.

[2] R. Mokhtarname, A. A. Safavi, L. Urbas, F. Salimi, M. M. Zerafat, and N. Harasi, "Application of multivariable process monitoring techniques to HAZOP studies of complex processes," *J Loss Prev Process Ind*, vol. 74, Jan. 2022, doi: 10.1016/j.jlp.2021.104674.

[3] H. R. J. Solukloei, S. Nematifard, A. Hesami, H. Mohammadi, and M. Kamalinia, "A fuzzy-HAZOP/ant colony system methodology to identify combined fire, explosion, and toxic release risk in the process industries," *Expert Syst Appl*, vol. 192, Apr. 2022, doi: 10.1016/j.eswa.2021.116418.

[4] J. Dunjó, V. Fthenakis, J. A. Vílchez, and J. Arnaldos, "Hazard and operability (HAZOP) analysis. A literature review," *Journal of Hazardous Materials*, vol. 173, no. 1–3. pp. 19–32, Jan. 15, 2010. doi: 10.1016/j.jhazmat.2009.08.076.

[5] L. Kotek and M. Tabas, "HAZOP study with qualitative risk analysis for prioritization of corrective and preventive actions," in *Procedia Engineering*, Elsevier Ltd, 2012, pp. 808–815. doi: 10.1016/j.proeng.2012.07.473.

[6] F. Crawley and B. Tyler, "Factors for a Successful HAZOP Study," in *HAZOP: Guide to Best Practice*, Elsevier, 2015, pp. 92–94. doi: 10.1016/b978-0-323-39460-4.00012-8.

[7] N. L. Rossing, M. Lind, N. Jensen, and S. B. Jørgensen, "A functional HAZOP methodology," *Comput Chem Eng*, vol. 34, no. 2, pp. 244–253, Feb. 2010, doi: 10.1016/J.COMPCHEMENG.2009.06.028.

[8] F. Crawley and B. Tyler, "The Detailed HAZOP Study Procedure," in *HAZOP: Guide to Best Practice*, 2015. doi: 10.1016/b978-0-323-39460-4.00004-9.

[9] T. A. Kletz, "HAZOP - Past and future," *Reliab Eng Syst Saf*, 1997, doi: 10.1016/S0951-8320(96)00100-7.

[10] A. de J. Penelas and J. C. M. Pires, "Hazop analysis in terms of safety operations processes for oil production units: A case study," *Applied Sciences (Switzerland)*, vol. 11, no. 21, Nov. 2021, doi: 10.3390/app112110210.

[11] W. Vechgama, K. Silva, A. Pechrak, and S. Wetchagarun, "Application of Hazard and Operability Technique to Level 1 Probabilistic Safety Assessment of Thai Research Reactor-1/Modification 1: Internal Events and Human Errors," *Progress in Nuclear Energy*, vol. 138, Aug. 2021, doi: 10.1016/j.pnucene.2021.103838.

[12] C. H. Lim, H. L. Lam, and W. P. Q. Ng, "A novel HAZOP approach for literature review on biomass supply chain optimisation model," *Energy*, vol. 146, pp. 13–25, Mar. 2018, doi: 10.1016/j.energy.2017.11.033.

[13] C. H. Lim *et al.*, "A review of industry 4.0 revolution potential in a sustainable and renewable palm oil industry: HAZOP approach," *Renewable and Sustainable Energy Reviews*, vol. 135, Jan. 2021, doi: 10.1016/j.rser.2020.110223.

[14] ICS OCIMF, "International Safety Guide for Oil Tankers and Terminals (ISGOTT) 6th Edition," London, 2020.

[15] D. Yazir, B. Sahin, and M. Alkac, "Selection of an Inert Gas System for the Transportation of Direct Reduced Iron," *Math Probl Eng*, vol. 2021, 2021, doi: 10.1155/2021/8529724.

[16] IMO, *Inert gas systems*, Third. London, United Kingdom: International Maritime Organization, 1990.