

Process Safety Risk Analysis of a Secondary Reformer in an Ammonia Production Industry

Riny Yolanda Parapat ^{*1}, Sulistya Nurul Fitri ², Santi Puji Astuti ³

^{1,2,3} Chemical Engineering Departement, Faculty of Industrial Technology, Institut Teknologi Nasional Bandung, Indonesia

Email: ¹rinyyolandha@itenas.ac.id, ²sulistya.nurul@mhs.itenas.ac.id, ³santi.puji@mhs.itenas.ac.id

Abstract

Ammonia production is one of the most important processes in the chemical industry and involves several interconnected units operating under high-temperature and high-pressure conditions. Among these units, the secondary reformer plays a critical role in completing methane conversion and supplying nitrogen required for ammonia synthesis. Due to the presence of flammable gases, elevated operating temperatures exceeding 900°C, and highly exothermic reactions, the secondary reformer presents significant process safety challenges that require systematic hazard identification and risk assessment. This study aims to analyze process safety risks associated with the secondary reformer unit in an ammonia production plant using the Hazard and Operability Study (HAZOP) method. The analysis was conducted through field observations, interviews with operating personnel, and evaluation of Process Flow Diagrams (PFD) and Piping and Instrumentation Diagrams (P&ID). Key process parameters, including temperature, pressure, flow rate, and gas composition, were systematically assessed to identify potential deviations, determine their causes and consequences, evaluate existing safeguards, and propose risk mitigation measures. The results identified 17 potential process deviations with risk scores ranging from 2 to 10. The highest-risk deviations were associated with overheating and excessive combustion in the combustion zone, as well as gas leakage and overpressure in the reactor shell and pressure control system. These deviations may result in refractory damage, catalyst deterioration, thermal runaway, fire, explosion, and loss of containment. Existing safeguards, including temperature and pressure monitoring systems, gas detectors, alarms, pressure safety valves, and interlock systems, were found to significantly reduce risk levels. The findings demonstrate that HAZOP is an effective tool for identifying process hazards and prioritizing mitigation measures, thereby improving process safety and operational reliability in ammonia production facilities.

Keywords: Secondary Reformer; Hazard and Operability Study (HAZOP); Process Safety; Risk Assessment; Ammonia Production.

1. INTRODUCTION

Ammonia (NH₃) is one of the most important chemical products worldwide and serves as a fundamental raw material in fertilizer manufacturing, chemical production, refrigeration systems, and various industrial applications. The increasing global demand for food and industrial products has resulted in a continuous rise in ammonia consumption, making ammonia production a strategic component of the chemical industry. Industrial ammonia is primarily produced through the Haber–Bosch process, which synthesizes ammonia from hydrogen and nitrogen under elevated temperature and pressure conditions. To generate the hydrogen required for ammonia synthesis, natural gas undergoes several reforming and purification stages involving multiple interconnected process units. These units operate under severe process conditions, including high temperatures, elevated pressures, and the presence of flammable gases, making process safety a critical aspect of ammonia plant operation.

Among the process units involved in ammonia production, the secondary reformer plays a particularly important role. This unit functions to complete methane conversion from the primary reformer while simultaneously introducing nitrogen through process air injection to establish the appropriate hydrogen-to-nitrogen ratio required for ammonia synthesis. Inside the secondary reformer, partially reformed gas reacts with oxygen through highly exothermic partial oxidation reactions, generating temperatures that commonly exceed 900–1000°C. In addition, the unit operates under elevated pressure and handles combustible gases such as hydrogen, carbon monoxide, and methane.

These operating characteristics make the secondary reformer one of the most critical process units from both operational and safety perspectives. (Saputra, 2025)

The combination of high temperatures, high pressures, combustible materials, and exothermic reactions significantly increases the potential for hazardous events. Deviations in temperature, pressure, flow rate, or gas composition may result in overheating, refractory failure, catalyst degradation, unstable combustion, gas leakage, overpressure conditions, fire, and explosion hazards. (Huang et al., 2025.) Such incidents may not only interrupt production and reduce plant reliability but also pose serious threats to personnel safety and the surrounding environment. Therefore, systematic identification and evaluation of process hazards are essential to ensure safe and reliable operation of the secondary reformer unit.

Hazard identification and risk assessment are fundamental elements of process safety management in the chemical industry. One of the most widely accepted methods for identifying process hazards is the Hazard and Operability Study (HAZOP). HAZOP is a structured and systematic technique that examines potential deviations from intended operating conditions through the application of guide words to process parameters such as flow, temperature, pressure, and composition. By evaluating the causes, consequences, existing safeguards, and corrective actions associated with each deviation, HAZOP provides a comprehensive framework for improving process safety and operational reliability.

Several researchers have successfully applied HAZOP to evaluate process safety risks in chemical processing facilities. Previous studies have demonstrated that HAZOP is effective in identifying operational hazards, equipment failures, abnormal operating conditions, and potential accident scenarios within complex industrial systems. In ammonia production facilities, risk assessments have primarily focused on plant-wide safety evaluations, reforming systems, and primary reformer operations. For example, Parapat et al. (2025) reported that deviations in temperature, pressure, flow rate, and steam-to-carbon ratio in the primary reformer could lead to catalyst deterioration, coke formation, burner malfunction, and process shutdown. These findings highlight the importance of systematic hazard analysis in reforming units operating under severe process conditions. (Parapat et al., 2025.)

Although numerous studies have investigated process safety in ammonia plants, detailed analyses specifically addressing the secondary reformer remain relatively limited. Existing studies generally emphasize overall plant risk assessment or focus on upstream reforming units without comprehensively evaluating the relationship between process deviations, their causes, consequences, safeguard effectiveness, and risk prioritization within the secondary reformer itself. (Xu et al., 2025) Furthermore, the operating characteristics of the secondary reformer differ significantly from those of other reforming units because of the simultaneous occurrence of combustion and catalytic reforming reactions under extremely high thermal loads. Consequently, a more focused investigation is required to improve understanding of the dominant hazards associated with this critical process unit.

In addition to its critical operating conditions, the complexity of the secondary reformer system further justifies the need for detailed safety analysis. The unit consists of interconnected process equipment, piping systems, control loops, instrumentation devices, and safety systems that must operate reliably under demanding process conditions. Any malfunction of process equipment, control systems, or operating parameters may propagate throughout the system and increase the likelihood of hazardous events. Therefore, a systematic methodology is required to identify potential deviations, evaluate associated risks, and determine the adequacy of existing protection measures. (Parapat, Hannindyah, et al., 2025)

To address these challenges, this study employs the Hazard and Operability Study (HAZOP) methodology as the primary tool for process safety risk assessment. The overall workflow adopted in this study is presented in Figure 1. The methodology begins with process data collection and node selection based on process documentation, followed by deviation identification using HAZOP guide words. Potential causes, consequences, existing safeguards, and risk levels are subsequently evaluated before appropriate mitigation measures are proposed. This structured workflow enables a comprehensive assessment of process safety risks associated with the secondary reformer unit. (Li & Zhao, 2025)

Therefore, the objective of this study is to analyze process safety risks in the secondary reformer unit of an ammonia production plant using the HAZOP method. The analysis focuses on key operating

parameters, including temperature, pressure, flow rate, and gas composition, in order to identify potential deviations, evaluate their causes and consequences, assess the effectiveness of existing safeguards, and propose suitable risk mitigation measures. The results are expected to contribute to improved process safety performance, enhanced operational reliability, and more effective risk management practices in ammonia production facilities.

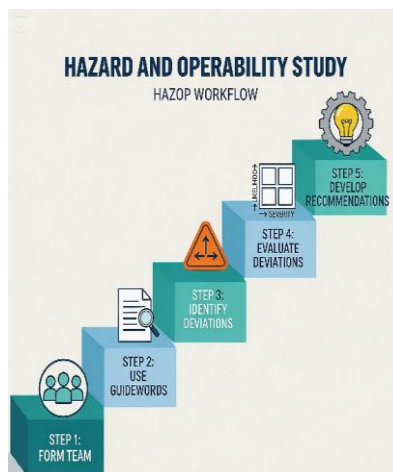


Figure 1. Workflow of the Hazard and Operability Study (HAZOP) methodology used for process safety risk assessment.

Several previous studies have investigated process risk assessment in ammonia production facilities using the Hazard and Operability Study (HAZOP) method as a systematic approach for identifying potential operational hazards. (Lestari et al., 2019; Noriyati et al., 2017; Tian et al., 2015) However, limited studies have specifically focused on risk assessment in the secondary reformer unit, which operates under extremely high temperatures and presents significant process safety challenges. Industrial processes operating under elevated temperature and pressure conditions pose substantial safety risks due to the increased likelihood of material degradation, equipment rupture, and uncontrolled process deviations. (Biswas et al., 2025; Ghaib et al., 2016; Ravi et al., 1989) This is particularly relevant in the secondary reformer unit, where reactions occur at temperatures exceeding 900 °C and involve flammable gases such as Hydrogen.

Ammonia Production Process

The industrial production of ammonia generally utilizes natural gas as the primary feedstock, which mainly consists of Methane. The process involves several sequential stages designed to convert methane into hydrogen and subsequently synthesize ammonia through the Haber–Bosch Process. (Nath Chakraborty, 2022)

1. Feed Gas Treatment

The first stage of ammonia production involves the purification of natural gas to remove sulfur-containing compounds that may poison the reforming catalyst. Sulfur compounds are initially converted into Hydrogen Sulfide through hydrodesulfurization. Subsequently, the hydrogen sulfide is removed via adsorption using zinc oxide (ZnO), producing a sulfur-free gas stream suitable for downstream reforming processes.

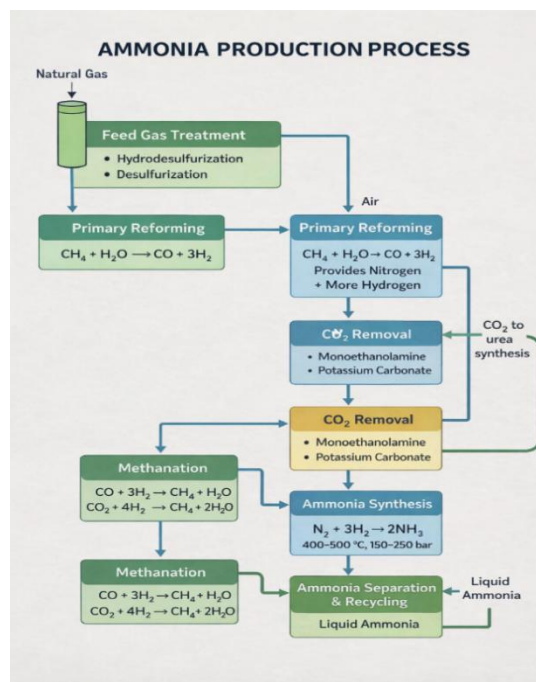
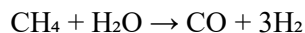


Figure 2. Simplified Block Flow Diagram of the Industrial Ammonia Production Process Based on the Haber–Bosch Process.

2. Primary Reforming

In the primary reforming stage, natural gas reacts with steam at high temperatures typically ranging from 800 to 900 °C within a reformer furnace. The main reaction occurring in this stage is the steam reforming of methane, which produces hydrogen and carbon monoxide according to the following reaction:



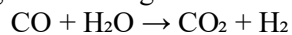
The resulting gas mixture mainly contains hydrogen, carbon monoxide, and residual methane. The primary objective of this stage is to generate a large quantity of hydrogen for subsequent ammonia synthesis.

3. Secondary Reforming

In the secondary reforming stage, air is introduced into the reactor to provide the nitrogen required for ammonia formation. This step also enhances methane conversion through partial oxidation reactions. Due to the exothermic nature of the oxidation reaction, the temperature may increase to approximately 1000 °C. (Ebrahimi et al., 2010) The resulting synthesis gas contains hydrogen, nitrogen, carbon monoxide, and carbon dioxide in proportions suitable for further processing.

4. Water Gas Shift Reaction

The reforming gas still contains a significant amount of carbon monoxide, which must be reduced because it can negatively affect downstream processes. In this stage, carbon monoxide reacts with steam to form carbon dioxide and additional hydrogen according to the following reaction:



This reaction is typically carried out in two stages: the high-temperature shift (HTS) reactor and the low-temperature shift (LTS) reactor. These sequential reactions maximize hydrogen production while reducing the carbon monoxide concentration in the gas stream. (Huang et al., 2025)

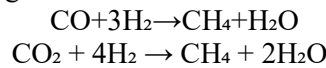
5. CO₂ Removal

The carbon dioxide formed during the shift reaction must be separated from the synthesis gas mixture. This separation is commonly achieved through chemical absorption processes using solvents

such as Monoethanolamine or potassium carbonate solutions. The captured carbon dioxide is often utilized as a feedstock in downstream processes, particularly for the production of urea fertilizer.

6. Methanation

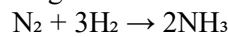
Residual carbon monoxide and carbon dioxide must be further removed because they can poison the catalyst used in ammonia synthesis. This purification step is achieved through methanation reactions in which these compounds react with hydrogen to form methane and water:



After this stage, the gas mixture consists primarily of hydrogen and nitrogen in proportions suitable for ammonia synthesis.

7. Ammonia Synthesis

The final stage of the process involves the synthesis of ammonia from hydrogen and nitrogen using an iron-based catalyst. The reaction takes place in the ammonia synthesis reactor under elevated temperature and pressure conditions according to the following reaction:



Typically, the reaction is carried out at temperatures between 400 and 500 °C and pressures ranging from 150 to 250 bar. The ammonia produced is subsequently cooled and condensed into liquid form for storage and further processing (Musa et al., 2025)

8. Ammonia Separation and Gas Recycling

Because the ammonia synthesis reaction does not achieve complete conversion in a single pass, unreacted hydrogen and nitrogen are separated from the produced ammonia and recycled back into the synthesis reactor. This recycling process significantly improves the overall efficiency of ammonia production.

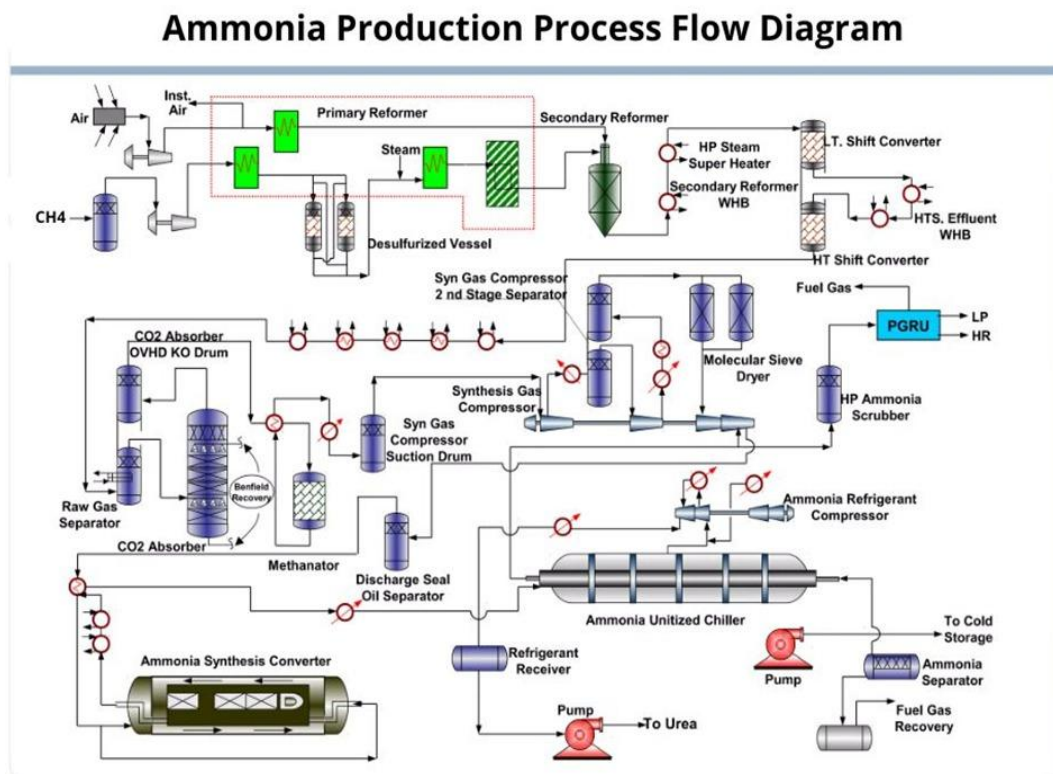


Figure 3. Ammonia Production Process Flow Diagram

2. METHODS

Research Approach

This study employs a qualitative–descriptive approach using the Hazard and Operability Study (HAZOP) method for hazard identification and operability analysis. This method is selected because it enables the systematic identification of potential process deviations based on operational parameters such as flow, pressure, temperature, and composition. The research is conducted through a field study at an ammonia production plant, particularly focusing on the secondary reformer unit. The field study aims to obtain direct operational information, identify potential process hazards, and understand the safety control systems implemented in the industry.

Research Location and Object

The study is conducted at an ammonia production facility in a fertilizer plant that operates a natural gas reforming unit as the initial stage of ammonia production. The research object focuses on the secondary reformer unit, which functions to continue the reforming process after the primary reforming stage and to provide nitrogen from air required for ammonia synthesis. The secondary reformer unit is selected as the research object because it operates at very high temperatures (approximately 900–1000°C) and involves partial oxidation reactions of process gases containing Hydrogen, which pose significant process safety risks.

Data Collection Techniques

Data collection in this study is conducted using several methods

1. Field Observation

Field observations are carried out by visiting the plant process area to directly observe the operational conditions of the secondary reformer unit. This observation aims to understand the equipment configuration, operating conditions, and safety control systems implemented in the plant.

2. Interviews with Safety Personnel and Operators

Interviews are conducted with personnel directly involved in operational and process safety management, including occupational health and safety (OHS) personnel, process engineers, and plant operators. These interviews aim to obtain information regarding potential process hazards, operational experiences, and existing risk control systems implemented in the secondary reformer unit.

3. Documentation Study

This study also utilizes technical documents available in the plant, such as Process Flow Diagrams (PFD), Piping and Instrumentation Diagrams (P&ID), operating condition data, and safety procedures related to the secondary reformer unit.

Risk Analysis Method

Risk analysis in this study is conducted using the Hazard and Operability Study (HAZOP) method. Data obtained from field observations, interviews, and document reviews are integrated into the HAZOP analysis process. Field observations are used to verify equipment configurations, operating conditions, and existing safety systems in the secondary reformer unit. Information obtained from interviews with operators and safety personnel is utilized to identify potential causes of process deviations and operational issues. Meanwhile, Process Flow Diagrams (PFDs), Piping and Instrumentation Diagrams (P&IDs), operating data, and safety documents are used to define analysis nodes, identify process parameters, and determine existing safeguards. The analysis identifies deviations from normal operating conditions based on key process parameters, including:

1. Flow
2. Temperature
3. Pressure
4. Composition

Each deviation is analyzed to determine:

1. Causes of the deviation
2. Possible consequences
3. Existing safety safeguards
4. Risk mitigation recommendations

The results of the analysis are then compiled in the form of a HAZOP table to facilitate hazard identification and the evaluation of system operability.

Node Selection

The HAZOP study was conducted by dividing the secondary reformer system into several nodes based on process functions and equipment boundaries. The selected nodes included the feed gas line (A-101-F), air injection and mixing zone (A-103-D), combustion zone (A-103-D), catalyst bed (A-103-D), reactor shell (A-103-D), waste heat boiler (A-101-C), and outlet line to the high-temperature shift converter (A-101-B). The node selection was based on significant variations in operating parameters and potential process safety hazards identified from the Process Flow Diagram (PFD) and Piping and Instrumentation Diagram (P&ID). Node boundaries were established considering changes in flow, temperature, pressure, and composition, as well as equipment functions and the severity of potential hazards.

HAZOP Team

The hazard identification process was carried out by a multidisciplinary HAZOP team consisting of a HAZOP team leader (Process Safety Engineer), a Process Engineer, and a field operator. The involvement of personnel from different technical backgrounds was intended to ensure a comprehensive evaluation of potential process hazards, operational deviations, equipment reliability issues, and the effectiveness of existing safety systems. Through collaborative discussions and systematic analysis, the team identified potential causes, consequences, existing safeguards, and recommendations for risk mitigation associated with the secondary reformer unit. To comply with the confidentiality agreement established between the company and the researchers, specific information regarding the company identity, operational data, and personnel involved in the HAZOP study is not disclosed in this publication.

Deviation Identification

Process deviations are identified using HAZOP guide words combined with process parameters. The guide words used include various standard HAZOP guide words, with their selection adjusted according to the characteristics of each parameter to ensure meaningful and relevant deviation identification. The guide words used include:

GUIDE WORD	MEANING	COMMENTS
NO (NOT, NONE)	Negation of design intent	No part of the intention is achieved but nothing else happens.
MORE (MORE OF)	Quantitative increase	The intention occurs in a way that is quantitatively greater. Usually applies to quantities, properties and activities.
LESS (LESS OF)	Quantitative decrease	The intention occurs in a way that is quantitatively lesser.
AS WELL AS (ALSO)	Qualitative increase	All of the intention is achieved together with something else.
PART OF	Qualitative decrease	Some of the intention is achieved but some is not.
REVERSE	Logical opposite	The opposite of the intention happens. Often applies to activities.
OTHER THAN	Complete substitution	No part of the intention is achieved and something quite different happens.

These guide words are applied to process parameters such as flow, temperature, pressure, and composition to identify possible deviations from normal operating conditions.

Risk Evaluation

Each identified deviation is evaluated based on its cause, consequences, and existing safeguards. Likelihood and severity ratings are determined based on field observations of actual operating conditions, structured interviews with experienced operators and process engineers, and direct verification of equipment conditions in the field. The risk level is determined using a risk matrix that considers both likelihood and severity. Severity is classified into five levels, ranging from insignificant impacts (Level 1) to catastrophic consequences involving major equipment damage, fire, explosion, or multiple injuries (Level 5). Similarly, likelihood is classified from very rare occurrences (Level 1) to highly probable occurrences (Level 5), based on historical operating experience and expert judgment.

		Probability				
		Very Unlikely (1)	Unlikely (2)	Possible (3)	Likely (4)	Very Likely (5)
Severity	Minor (1)	1	2	3	5	5
	Modera (2)	2	4	6	8	10
	Major (3)	3	6	9	12	15
	Serious (4)	4	8	12	16	20
		5	10	16	20	25
		Probability				

The risk score is calculated as:

$$\text{Risk} = \text{Likelihood} \times \text{Severity}$$

The resulting scores are categorized into Low, Medium, High, and Extreme risk levels.

Research Stages

The research stages in this study include:

1. Conducting a literature review on ammonia production processes and process risk analysis methods.
2. Identifying the process unit to be analyzed, namely the secondary reformer.
3. Collecting data through field observations and interviews with the plant's safety personnel.
4. Identifying process deviations using guide words.
5. Evaluating potential risks and possible consequences in the secondary reformer unit.
6. Developing recommendations to improve process safety in the unit.

3. RESULTS AND DISCUSSION

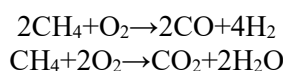
This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation as well as the experimental conclusions that can be drawn.

3.1. Result

The ammonia production process begins with the feed gas treatment stage, in which natural gas is purified to remove sulfur compounds prior to entering the reforming section (Anggi, 2022). After passing through the primary reformer, the partially reformed synthesis gas containing CH₄, H₂, CO, CO₂, and steam directed to the Secondary Reformer (A-103-D), a critical unit responsible for adjusting the synthesis gas composition to meet the requirements of ammonia synthesis.

In the presented P&ID, the process gas from the primary reformer enters the top section of the secondary reformer through a controlled inlet distribution system. At this point, air injection is introduced, serving two essential functions: supplying nitrogen (N₂) and providing oxygen for partial combustion. The air flowrate is precisely controlled to achieve the desired stoichiometric ratio of hydrogen to nitrogen (H₂ : N₂ = 3 : 1), which is crucial for the downstream ammonia synthesis reaction.

Within the combustion zone, highly exothermic reactions occur between oxygen and combustible species such as methane, hydrogen, and carbon monoxide. The principal reactions include:



Additionally, partial oxidation of hydrogen and carbon monoxide takes place. These reactions significantly increase the gas temperature, typically reaching 950–1000°C, thereby supplying the thermal energy required for subsequent reforming reactions under autothermal conditions. Following the combustion zone, the gas flows downward into the nickel-based catalyst bed, where further steam methane reforming and dry reforming reactions occur. In this section, residual methane is converted into hydrogen and carbon oxides, approaching thermodynamic equilibrium. The methane conversion efficiency in the secondary reformer is typically very high (>99%), resulting in a residual methane concentration below 0.5% at the outlet.

The P&ID also illustrates a pressure control system using a Pressure Indicator Controller (PIC) integrated with a split-range control strategy. This system maintains stable operating pressure by modulating flow distribution between downstream processing units or bypass lines. Pressure stability is essential for maintaining flame stability, ensuring proper flow distribution, and preventing catalyst damage due to localized overheating (hotspots). The high-temperature gas exiting the secondary reformer is then routed to a Waste Heat Boiler (WHB), indicated in the diagram as part of the Reformed Gas Waste Heat Boiler system (A-101-C). In this unit, sensible heat from the process gas is recovered to generate high-pressure steam, thereby improving the overall thermal efficiency of the ammonia plant and reducing external energy requirements. Subsequently, the partially cooled gas is sent to the High Temperature Shift Converter (HTS), where the water-gas shift reaction increases hydrogen production by converting carbon monoxide into carbon dioxide. The typical outlet composition of the secondary reformer consists of approximately H₂ (35%), H₂O (35%), N₂ (15%), CO (8%), and CO₂ (5%), which is further processed in downstream purification units before entering the ammonia synthesis loop.

Overall, the P&ID demonstrates that the secondary reformer operates as an autothermal reforming reactor integrating partial oxidation and catalytic reforming within a single unit. This unit performs a dual function: completing hydrocarbon conversion and introducing nitrogen into the synthesis gas. Consequently, several critical nodes identified from the PFD and P&ID were further evaluated using the HAZOP method to determine potential process deviations and associated risks.

The HAZOP results indicate that the Feed Gas Line (A-101-F) is susceptible to deviations such as no flow, low flow, and excess flow. As the primary pathway supplying process gas to the secondary reformer, disturbances in this line can reduce reforming efficiency and destabilize reactor operation. In particular, excess gas flow may increase the thermal load in the combustion zone, potentially contributing to catalyst degradation and process instability.

Another critical area identified from the P&ID is the Air Injection Line and Mixing Zone (A-103-D), where process air is introduced to supply both oxygen for partial oxidation and nitrogen for ammonia synthesis. The HAZOP analysis identified no air supply, excess air, and incorrect H₂:N₂ ratio as dominant deviations in this node. Among these, excess air obtained a risk score of 8 due to its potential to cause over-oxidation and excessive temperature increases within the reactor. These findings emphasize the importance of maintaining accurate air-to-gas ratio control to ensure safe and efficient operation.

The most critical hazards were identified within the Combustion Zone (A-103-D), where highly exothermic oxidation reactions occur. Based on the HAZOP analysis, overheating and excess combustion were assigned the highest risk score of 10, indicating a high-risk category. These deviations

may result from excessive oxygen supply, improper combustion control, or abnormal feed conditions. The consequences include hotspot formation, refractory damage, thermal runaway, catalyst deterioration, and, in severe cases, fire or explosion. Therefore, the combustion zone represents the most critical node within the secondary reformer system and requires continuous temperature monitoring and effective combustion control strategies.

The Reactor Shell (A-103-D) was also identified as a critical node due to the potential occurrence of gas leakage. Operating under high-temperature and high-pressure conditions, any loss of containment may release flammable process gases into the surrounding environment. The HAZOP analysis assigned this deviation a risk score of 10 because of its potential to initiate fire and explosion events if an ignition source is present. This finding highlights the importance of maintaining reactor integrity through periodic inspection, leak detection systems, and preventive maintenance programs.

Similarly, pressure-related hazards were identified within the reactor pressure control system. Although the likelihood of overpressure is relatively low due to the presence of pressure safety valves (PSVs) and automatic control systems, the potential consequences remain severe. The HAZOP analysis assigned overpressure a risk score of 10 because it may lead to vessel rupture, loss of containment, and major process safety incidents. Consequently, pressure monitoring systems, control loops, and relief devices represent essential safety barriers that must be continuously maintained and verified.

Overall, the integration of PFD, P&ID, and HAZOP results demonstrates that the combustion zone, reactor shell, and pressure control system constitute the most critical safety nodes within the secondary reformer. These areas exhibit the highest risk levels due to the combination of elevated temperatures, high operating pressures, and the presence of combustible gases. Therefore, risk mitigation efforts should prioritize combustion control, temperature monitoring, pressure protection systems, equipment integrity management, and preventive maintenance to ensure safe, stable, and reliable operation of the secondary reformer unit.

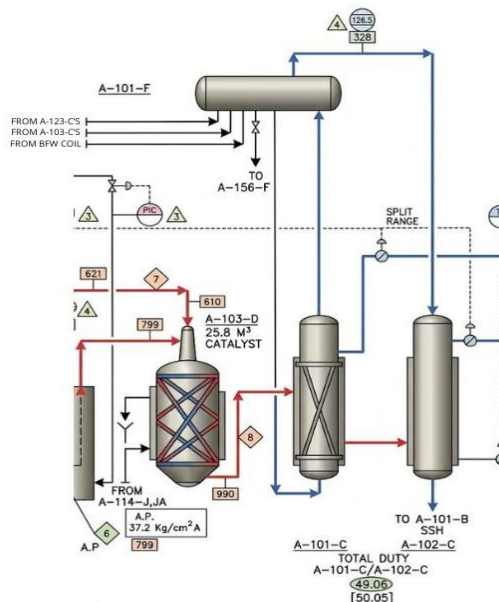


Figure 4. P&ID of Secondary Unit in Ammonia Production Process.

3.2. HAZOP Analyst

The Piping and Instrumentation Diagram (P&ID) illustrates the overall process flow of an ammonia production unit, starting from feed gas treatment, followed by the primary reformer where steam methane reforming produces synthesis gas. The gas then enters the secondary reformer (A-103-D), where air injection supplies nitrogen and initiates partial oxidation reactions, significantly increasing the temperature and enabling further conversion in the catalyst bed. The high-temperature gas is subsequently directed to a waste heat boiler (WHB) for heat recovery, enhancing energy efficiency, and

then flows through downstream units such as the shift converter and gas purification systems to adjust its composition before ammonia synthesis. The diagram also highlights the integration of control systems, including flow, temperature, and pressure control, along with safety systems such as alarms and interlocks to ensure stable and safe plant operation.

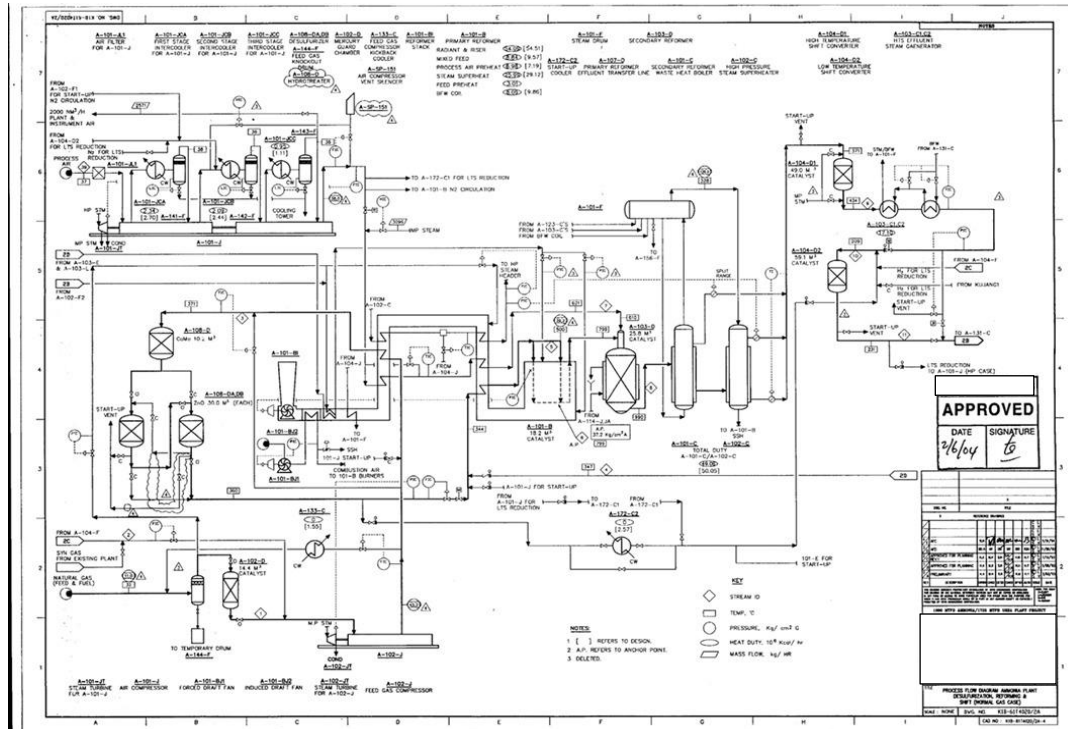


Figure 5. PFD of Unit in Ammonia Production Process.

3.3. Tables and Figure

This table presents a theoretical Hazard and Operability Study (HAZOP) for the Secondary Reformer unit in an ammonia production plant. It is prepared based on process safety theory and typical operating conditions in ammonia plants. The HAZOP table was developed using information obtained from process documentation, field observations, and interviews with plant personnel. The resulting analysis provides a structured evaluation of potential process deviations, their causes, consequences, existing safeguards, and recommended mitigation measures for the secondary reformer system.

The HAZOP analysis identified 17 process deviations across the secondary reformer system, with risk scores ranging from 2 to 10. Based on the risk matrix, the identified deviations were classified into low, medium, and high-risk categories. No deviation was categorized as extreme risk; however, several deviations were classified as high risk and therefore require priority attention.

The highest risk score (10) was identified in the combustion zone (A-103-D), particularly for the deviations of overheating and excess combustion, as well as in the reactor shell and reactor pressure nodes associated with gas leakage and overpressure conditions. These deviations are considered critical because they involve high operating temperatures and pressures that may lead to refractory damage, thermal runaway, fire, explosion, equipment rupture, and loss of containment. The presence of combustible process gas combined with elevated temperatures significantly increases the severity of potential consequences. Similar findings have been reported by Lestari et al. (2019), who identified the secondary reformer as one of the most critical units in ammonia production due to its high-temperature operation and potential for fire and explosion incidents.

Among the identified hazards, overheating in the combustion zone deserves particular attention. This deviation may occur due to excess oxygen supply or improper air-to-gas ratio control, resulting in localized hot spots and refractory deterioration. The consequences extend beyond equipment damage

because excessive temperature can accelerate catalyst degradation and increase the likelihood of process instability. The importance of temperature control in reforming units has also been highlighted in studies of ammonia reformer safety, where abnormal temperature excursions were identified as major contributors to reformer failures and shutdowns.

Gas leakage and overpressure in the reactor shell also represent significant hazards. Although their likelihood values are relatively low, the severity ratings are very high due to the possibility of fire, explosion, and major equipment damage. This finding indicates that maintaining the integrity of the reactor shell, pressure-containing components, and pressure relief systems is essential for safe operation. The existence of safeguards such as gas detectors and pressure safety valves (PSV) reduces the probability of catastrophic events but does not eliminate the consequences if failure occurs.

Most other deviations, including low gas flow, low air supply, catalyst deactivation, waste heat boiler overheating, and outlet flow interruption, were classified as medium risk with scores between 5 and 8. These deviations primarily affect process efficiency, hydrogen production, catalyst performance, and plant reliability rather than causing immediate catastrophic accidents. Nevertheless, if left uncontrolled, these deviations may develop into more severe operational problems and contribute indirectly to unsafe operating conditions.

The lowest risk scores (2–3) were observed for incorrect H₂:N₂ ratio, pressure drop, unstable pressure control, and low flow in the waste heat boiler. These deviations mainly influence process performance and ammonia synthesis efficiency rather than directly threatening process safety. However, continuous monitoring remains necessary because prolonged operation under these conditions may reduce plant productivity and increase operational costs.

Overall, the HAZOP results indicate that temperature-related deviations, pressure-related deviations, and loss-of-containment scenarios constitute the dominant safety concerns within the secondary reformer system. Therefore, risk mitigation efforts should prioritize combustion control, temperature monitoring, pressure protection systems, reactor integrity inspection, and preventive maintenance programs. The findings confirm that the secondary reformer is a critical process unit requiring rigorous operational monitoring due to its inherently hazardous combination of high temperature, high pressure, and flammable process gases.

The HAZOP analysis identified 17 process deviations across the secondary reformer system, with risk scores ranging from 2 to 10. Based on the risk matrix, the identified deviations were classified into low, medium, and high-risk categories. No deviation was categorized as extreme risk; however, several deviations were classified as high risk and therefore require priority attention.

The highest risk score (10) was identified in the combustion zone (A-103-D), particularly for the deviations of overheating and excess combustion, as well as in the reactor shell and reactor pressure nodes associated with gas leakage and overpressure conditions. These deviations are considered critical because they involve high operating temperatures and pressures that may lead to refractory damage, thermal runaway, fire, explosion, equipment rupture, and loss of containment. The presence of combustible process gas combined with elevated temperatures significantly increases the severity of potential consequences. Similar findings have been reported by Lestari et al. (2019), who identified the secondary reformer as one of the most critical units in ammonia production due to its high-temperature operation and potential for fire and explosion incidents.

Among the identified hazards, overheating in the combustion zone deserves particular attention. This deviation may occur due to excess oxygen supply or improper air-to-gas ratio control, resulting in localized hot spots and refractory deterioration. The consequences extend beyond equipment damage because excessive temperature can accelerate catalyst degradation and increase the likelihood of process instability. The importance of temperature control in reforming units has also been highlighted in studies of ammonia reformer safety, where abnormal temperature excursions were identified as major contributors to reformer failures and shutdowns.

Gas leakage and overpressure in the reactor shell also represent significant hazards. Although their likelihood values are relatively low, the severity ratings are very high due to the possibility of fire, explosion, and major equipment damage. This finding indicates that maintaining the integrity of the reactor shell, pressure-containing components, and pressure relief systems is essential for safe operation.

The existence of safeguards such as gas detectors and pressure safety valves (PSV) reduces the probability of catastrophic events but does not eliminate the consequences if failure occurs.

Most other deviations, including low gas flow, low air supply, catalyst deactivation, waste heat boiler overheating, and outlet flow interruption, were classified as medium risk with scores between 5 and 8. These deviations primarily affect process efficiency, hydrogen production, catalyst performance, and plant reliability rather than causing immediate catastrophic accidents. Nevertheless, if left uncontrolled, these deviations may develop into more severe operational problems and contribute indirectly to unsafe operating conditions.

The lowest risk scores (2–3) were observed for incorrect H₂:N₂ ratio, pressure drop, unstable pressure control, and low flow in the waste heat boiler. These deviations mainly influence process performance and ammonia synthesis efficiency rather than directly threatening process safety. However, continuous monitoring remains necessary because prolonged operation under these conditions may reduce plant productivity and increase operational costs.

Overall, the HAZOP results indicate that temperature-related deviations, pressure-related deviations, and loss-of-containment scenarios constitute the dominant safety concerns within the secondary reformer system. Therefore, risk mitigation efforts should prioritize combustion control, temperature monitoring, pressure protection systems, reactor integrity inspection, and preventive maintenance programs. The findings confirm that the secondary reformer is a critical process unit requiring rigorous operational monitoring due to its inherently hazardous combination of high temperature, high pressure, and flammable process gases.

Tabel 1. Hazard and Operability Study (HAZOP) Analysis of the Secondary Reformer Unit in an Ammonia Production Plant

Node	Para meter	Guide Word	Deviation	Possible Causes (Nath Chakraborty, 2022)	Possible Consequences	Typical Safeguards	Risk Matrixs			Recommended Actions
							Severity	Likelihood	Risk Score	
Feed Gas Line A-101-F	Flow	No	No process gas flow	Valve closed, compressor failure, blockage	Reaction stops, system shutdown	Flow Indicator (FI), alarm	2	3	6	Inspect valves & compressor + alarm system
Feed Gas Line A-101-F	Flow	Less	Low gas flow	Fouling, partially closed valve	Unstable reaction, incomplete reforming	Flow Control Valve (FCV)	2	3	6	Continuous monitoring + fouling detection
Feed Gas Line A-101-F	Flow	More	Excess gas flow	Control valve malfunction	Overheating, catalyst damage (A-103-D)	Flow Controller (FIC)	3	2	6	High-flow alarm + interlock cut-off
Air Injection Line Mixing Zone (A-103-D)	Flow	No	No air supply	Compressor failure, valve damage	No N ₂ formation, reaction failure	Alarm, backup compressor	2	2	4	Preventive maintenance + backup system
Air Injection Line	Flow	Less	Low air supply	Inefficient compressor	Insufficient N ₂ production	Flow meter (FI)	2	3	6	Monitor compressor performance

Node	Parameter	Guide Word	Deviation	Possible Causes (Nath Chakraborty, 2022)	Possible Consequences	Typical Safeguards	Risk Matrix			Recommended Actions	
							Severity	Likelihood	Risk Score		
Mixing Zone	Air Injection Line	Flow	More	Excess air	Valve malfunction	Over-oxidation, extreme temperature	Temperature monitoring	4	2	8	Closed-loop air-gas ratio control + interlock
Mixing Zone A-103-D inlet	Compensation	Other	Incorrect	H ₂ :N ₂ ratio	Feed imbalance	Disturbance in NH ₃ synthesis	Gas analyzer	1	2	2	Online analyzer + Advanced Process Control (APC)
Combustion Zone A-103-D inlet section	Temperature	High	Overheating	Excess O ₂ or feed	Hotspot, refractory damage, explosion risk	Temperature sensor, alarm	5	2	10	Multi-point monitoring + Emergency Shutdown (ESD)	
Combustion Zone A-103-D	Reaction	More	Excess combustion	Excess oxygen	Thermal runaway	Control system	5	2	10	O ₂ analyzer + burner control system	
Catalyst Bed A-103-D	Reaction	Less	Low activity	Catalyst poisoning, sintering	Reduced H ₂ production	Temperature monitoring	2	3	6	Performance monitoring + catalyst replacement plan	
Catalyst Bed A-103-D	Temperature	High	Hotspot	Maldistribution	Catalyst damage	Temperature sensor	3	2	6	Improve flow distribution	
Reactor Shell A-103-D	Integrity	Leakage	Gas leakage	Corrosion, gasket failure	Fire / explosion	Gas detector	5	2	10	RBI inspection + corrosion monitoring	
Reactor A-103-D	Pressure	High	Overpressure	Outlet blockage	Rupture, gas release	Pressure Safety Valve (PSV)	5	1	5	Pressure monitoring + blockage detection	
Reactor A-103-D	Pressure	Low	Pressure drop	Leakage, compressor issue	Reduced efficiency	Pressure Indicator (PI)	1	2	2	Leak detection system	
Pressure Control (PIC –	Pressure	Other	Unstable control	Poor tuning	Process fluctuation	PIC system	1	2	2	PID tuning + advanced control	

Node	Parameter	Guide Word	Deviation	Possible Causes (Nath Chakraborty, 2022)	Possible Consequences	Typical Safeguards	Risk Matrix			Recommended Actions
							Severity	Likelihood	Risk Score	
Split Range)										
Waste Heat Boiler A-101-C	Temperature	High	Overheating	Cooling failure	WHB damage	Temperature control (TIC)	3	2	6	Heat recovery monitoring + shutdown
WHB A-101-C	Flow	Less	Low flow	Fouling	Reduced efficiency	Flow meter (FI)	1	3	3	Fouling monitoring + cleaning schedule
Outlet Line A-101-B (to HTS)	Flow	No	No outlet flow	Blockage	Upstream overpressure	PSV	4	2	6	Pipeline cleaning + pressure monitoring

2. DISCUSSION

Based on the PFD and P&ID analysis, the Combustion Zone (A-103-D) represents the most critical node within the system. This section is the location where air is injected into the process gas stream and highly exothermic partial oxidation reactions occur. The HAZOP analysis identified overheating and excess combustion as the dominant hazards in this node, both obtaining a risk score of 10. These deviations may arise from excessive oxygen supply, improper air-to-gas ratio control, burner malfunction, or unstable process conditions. The resulting consequences include hotspot formation, refractory damage, catalyst deterioration, thermal runaway, and potential explosion incidents. Similar findings were reported by Lestari et al. (2019), who identified abnormal combustion conditions and elevated temperatures as major contributors to fire and explosion hazards in secondary reformer systems.

Gas leakage obtained a risk score of 10 because the release of flammable process gas may initiate fire or explosion events when exposed to ignition sources. Similarly, overpressure conditions also achieved a risk score of 10 due to the possibility of vessel rupture and major loss-of-containment incidents. These findings are consistent with the observations of Soloman and Sunilkumar (2023), who reported that loss-of-containment events and pressure excursions are among the most severe hazards in ammonia reforming units.

Within the Catalyst Bed (A-103-D), the identified hazards included low catalyst activity and hotspot formation. Both deviations were associated with moderate risk scores but remain operationally significant because they directly affect methane conversion efficiency and hydrogen production. Previous studies have shown that catalyst deactivation and uneven temperature distribution can reduce reforming efficiency and shorten catalyst lifetime (Mannan, 2012).

Overall, the HAZOP results demonstrate that the dominant hazards within the secondary reformer are concentrated in nodes associated with combustion reactions, pressure containment, and flammable gas handling. This observation is consistent with previous investigations on ammonia reforming units,

which identified combustion instability, overpressure, and loss-of-containment scenarios as the primary contributors to major process safety incidents (Lestari et al., 2019; Soloman & Sunilkumar, 2023).

3. CONCLUSION

This study applied the Hazard and Operability Study (HAZOP) method to identify potential process hazards and operational deviations in the secondary reformer unit of an ammonia production plant. The analysis identified a total of 17 process deviations distributed across several critical nodes, including the Feed Gas Line (A-101-F), Air Injection and Mixing Zone (A-103-D), Combustion Zone (A-103-D), Catalyst Bed (A-103-D), Reactor Shell (A-103-D), Waste Heat Boiler (A-101-C), and Outlet Line to the High Temperature Shift Converter (A-101-B).

The risk assessment results showed that the identified deviations were classified into low, medium, and high-risk categories, with risk scores ranging from 2 to 10. The highest risk scores were associated with overheating and excess combustion in the Combustion Zone, as well as gas leakage and overpressure in the Reactor Shell and Reactor Pressure System. These deviations represent the most critical hazards because they may lead to hotspot formation, refractory damage, thermal runaway, fire, explosion, equipment rupture, and loss-of-containment incidents.

The integration of PFD, P&ID, and HAZOP analysis demonstrated that the Combustion Zone, Air Injection System, Reactor Shell, and Reactor Pressure System constitute the most critical safety nodes within the secondary reformer. The findings indicate that temperature-related deviations, pressure excursions, and flammable gas releases are the dominant risk factors affecting the safe operation of the unit.

Based on the identified hazards, priority risk mitigation measures should focus on improving combustion control, maintaining accurate air-to-gas ratio regulation, enhancing temperature and pressure monitoring systems, strengthening equipment integrity programs, and implementing preventive maintenance strategies. Overall, the study confirms that HAZOP is an effective tool for systematically identifying hazards, evaluating process risks, and supporting the development of appropriate risk control measures to improve the safety and reliability of secondary reformer operations in ammonia production plants.

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