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The Role of Management Analysis in Identifying the Problems of Combustion Stoppage During the Production Process of Gas Lembam in the Inert Gas Generator

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Abstract

The reliability of the inert gas generator system plays an important role in maintaining operational safety and combustion stability in shipboard systems. However, operational disturbances often occur due to failures in the combustion detection process, particularly in the flame eye detector component that monitors flame intensity during ignition and operation. These disturbances can cause interruptions in the combustion process and reduce the performance of the inert gas generator system. Therefore, this study aims to analyze the utilization of management analysis in identifying and mapping problems occurring in the inert gas generator in order to determine the root causes and appropriate corrective actions.

This research employs a descriptive qualitative method to obtain comprehensive data related to the operational performance of the inert gas system. The research process begins with systematic problem mapping followed by field observations to collect real operational data from the inert gas generator system. Data collection is conducted continuously to identify the primary cause of the disturbance. The analysis focuses on several aspects, including the set-point regulation of light intensity readings detected by the flame eye detector, the timer set-point requirements during ignition, and the system's response to combustion light intensity. The results indicate that failures in the flame eye detector reading process and improper set-point timer configuration significantly influence the interruption of the combustion process in the inert gas generator. Predictive analysis assists in narrowing down the potential causes and identifying the most critical factors affecting system performance. These findings highlight the importance of systematic management analysis in diagnosing operational problems and improving the reliability of inert gas generator systems.

Keywords: Inert Gas System, Flame Eye Detector, Combustion Monitoring, Ship Safety System, Predictive Maintenance

1. INTRODUCTION

Operational safety on tanker vessels is a critical aspect that must be maintained during cargo loading and unloading activities. One of the major risks faced in tanker operations is the potential occurrence of fire or explosion caused by the presence of flammable cargo vapors. The possibility of fire or explosion generally arises from the interaction of three main elements that form the fire triangle: oxygen, flammable substances, and heat. When these three elements meet in sufficient proportions, a combustion process can occur and potentially lead to a large-scale fire or explosion. Therefore, preventive measures are necessary to eliminate or reduce at least one of these elements, particularly the oxygen content in the air within cargo tanks.

Introduction

In tanker operations, reducing the oxygen concentration in cargo tanks is commonly achieved with inert gas systems. Inert gas is a gas mixture with low oxygen content that functions to prevent the formation of a combustible atmosphere inside cargo tanks. The use of inert gas is recognized as one of the most effective safety mechanisms in tanker ships because it significantly reduces the risk of ignition during cargo handling operations. In general, inert gas on board can be produced through two main methods. The first method utilizes flue gas generated from boiler combustion processes, which is commonly referred to as inert gas. The second method involves the combustion of fuel within a dedicated equipment unit known as an inert gas generator.

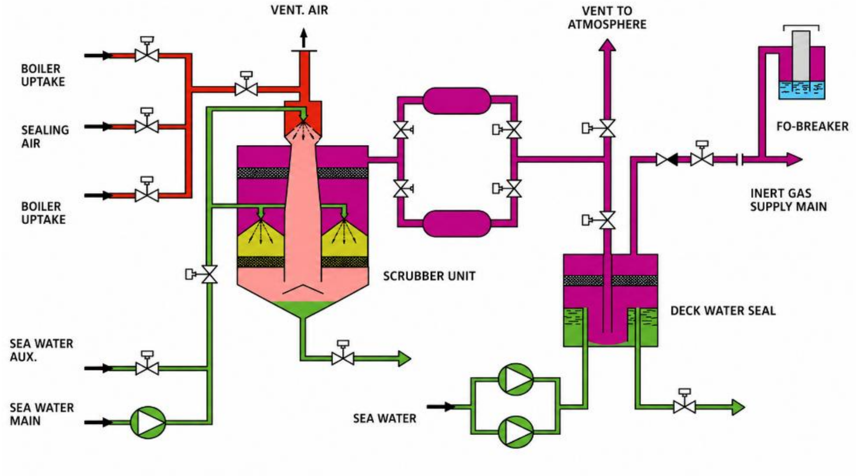


Figure 1. Inert Gas System on Tanker Vessel

Figure 2 illustrates the operational flow of the inert gas system, where combustion gases are processed through the scrubber unit to reduce temperature and remove impurities before being delivered to the cargo tanks. The system also includes safety components such as deck water seals and pressure-vacuum breakers to prevent backflow and maintain safe oxygen levels inside the cargo tanks.

The inert gas generator operates by burning fuel to produce combustion gases that are subsequently processed into inert gas. The produced gas is then directed into the cargo tanks to reduce the oxygen concentration below the allowable safety limits. In tanker safety standards, the oxygen concentration inside cargo tanks must be maintained below 8% as the primary safety threshold, while the secondary maximum allowable limit is 10%. Maintaining oxygen concentration below these thresholds is essential to ensure that the atmosphere within the cargo tanks remains outside the flammable range. Failure of the inert gas generator to produce inert gas properly may result in insufficient inert gas supply during cargo operations, which increases the risk of fire or explosion and threatens the safety of tanker operations.

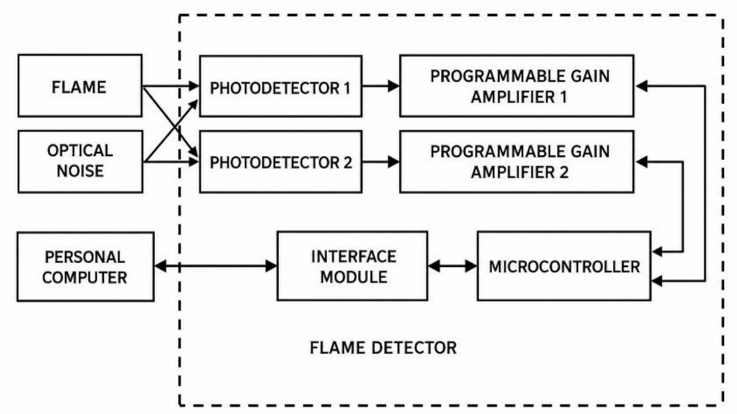


Figure 2. Block Diagram of Flame Detector System

Figure 7 illustrates the architecture of the flame detection system. The photo detectors capture optical signals emitted by the combustion flame, which are then amplified by programmable gain amplifiers. The processed signals are transmitted through an interface module to a microcontroller that analyzes the signal characteristics and determines whether a valid flame is present.

Previous studies on shipboard safety systems have emphasized the importance of combustion monitoring systems, gas detection technologies, and automated control systems in ensuring the reliability of inert gas production. Flame detection devices, combustion control mechanisms, and timing control systems are among the critical components that support the proper operation of inert gas generators. In particular, flame detection technology plays a vital role in monitoring the stability of the combustion process. Flame detectors operate by detecting light intensity emitted by combustion flames using several detection technologies such as ultraviolet (UV), infrared (IR), spectroscopy, and visual flame imaging.

Figure 3 illustrates the working principle of a flame monitoring system that detects the intensity of light produced during the combustion process. The flame eye detector captures the radiation emitted by the flame and converts it into electrical signals that are processed by the control module to determine whether combustion is occurring properly.

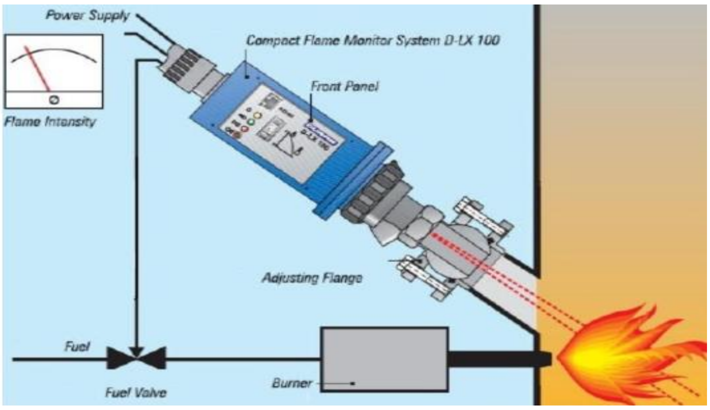
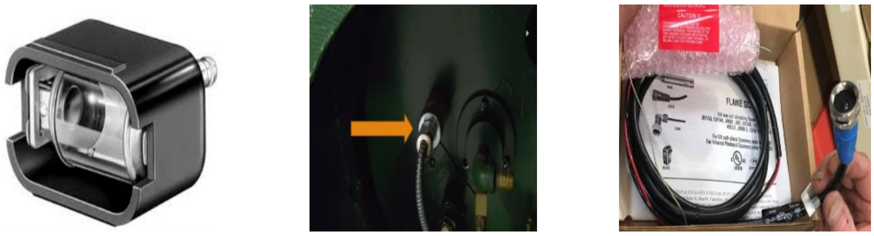


Figure 3. Flame Monitoring System (Flame Eye Detector)

These systems are designed to detect flame presence accurately while minimizing false alarms caused by other light sources. In addition to flame detection systems, timer relays are essential components in automated combustion control because they regulate the ignition monitoring sequence and determine the allowable time for flame confirmation. In the inert gas generator system, the timer relay ensures that the flame signal is detected and validated within a predetermined time interval. If the flame confirmation signal is not received within this interval, the safety interlock may stop the burner fuel supply to prevent unsafe operating conditions. Therefore, synchronization between the flame eye detector, controller module, and timer relay is critical for maintaining continuous combustion and reliable inert gas production.



Photocells Infrared Ultraviolet

Figure 4. Flame Eye Detector

In addition to flame detection systems, timing control mechanisms such as timer relays are also essential components in automated combustion systems. Timer relays regulate operational sequences in electrical control circuits and ensure that the ignition process, flame detection, and combustion monitoring occur in the correct sequence.


Figure 5. Timer Relay Used in Combustion Control Systems

Figure 6 illustrates a timer relay device used in automated control systems to regulate the timing sequence of electrical operations. In combustion systems, the timer relay ensures that ignition processes and flame monitoring occur according to predetermined time settings. Sequential control systems allow automated operations to proceed step by step based on predefined conditions, time schedules, or operational commands. Such automated control systems are widely used in industrial processes, including shipboard machinery systems, to maintain operational stability and safety.

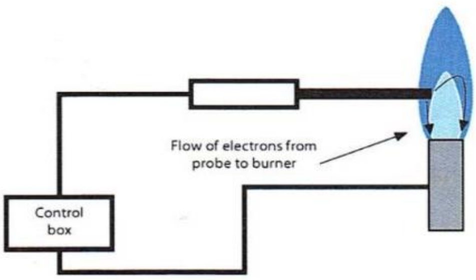


Figure 6. Flame Rods

Figure 5 illustrates the working principle of the flame rod sensor, where the presence of flame creates an ionization path that allows the flow of electrons from the probe to the burner. This electrical signal is detected by the control system and used to confirm the stability of the combustion process. Despite the existence of these monitoring and control technologies, operational failures in inert gas generator systems may still occur due to various technical factors. One of the common issues encountered in inert gas generator operations is the interruption of the combustion process caused by failures in flame detection systems. In particular, malfunction or inaccurate readings of the flame eye detector can result in combustion signals not being properly received or processed by the control module of the inert gas generator system. As a result, the system may interpret the absence of flame incorrectly and automatically stop the combustion process, leading to operational disturbances in inert gas production.

Although inert gas systems have been widely studied in maritime safety engineering, there remains a need for more detailed analysis regarding the operational disturbances related to combustion detection systems, particularly those associated with flame eye detector performance and timer set-point configurations. Previous research has largely focused on system design and safety standards, while limited attention has been given to the application of systematic management analysis approaches to identify and diagnose operational failures in inert gas generator systems.

Therefore, this study aims to analyze the root causes of operational disturbances in the inert gas generator by utilizing a management analysis approach. The study focuses on identifying and mapping problems related to combustion interruption influenced by the flame eye detector's ability to detect light intensity from the combustion process. Through systematic analysis involving detailing, mapping, narrowing down, and determining critical values from operational data, the research seeks to identify the primary factors contributing to the malfunction of the inert gas generator system and to propose appropriate corrective measures.

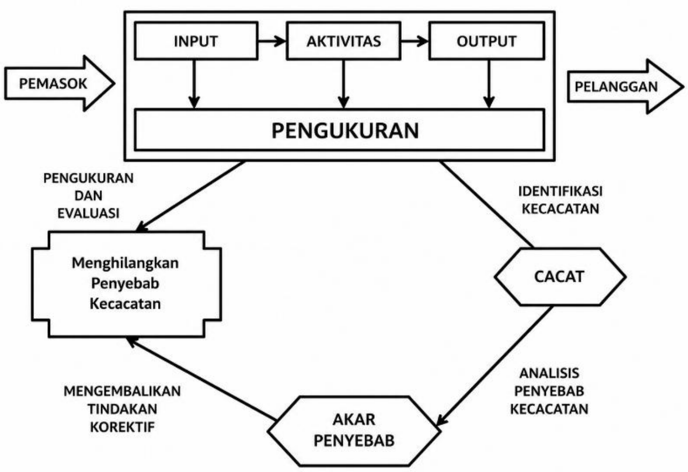


Figure 7. Business Proccess Quality Improvement (BPQI)

The BPQI model illustrates a systematic process that begins with input, activities, and outputs, followed by measurement, defect identification, root cause analysis, and the development of corrective actions to eliminate the causes of operational failures. The remainder of this article is organized as follows. The next section presents the research methodology used in this study, including data collection and analysis procedures. This is followed by the results and discussion section, which explains the findings obtained from field observations and system analysis. Finally, the conclusion summarizes the key findings and highlights the significance of the study in improving the reliability and operational safety of inert gas generator systems on tanker vessels.

Although previous studies have discussed inert gas systems, flame detection technologies, and burner management systems in relation to maritime safety and industrial combustion control, most of them have mainly focused on system design, general operational principles, and safety compliance. Limited attention has been given to the detailed analysis of combustion stoppage problems in inert gas generators, particularly failures caused by the mismatch between flame eye detector response time and timer relay set-point configuration. This indicates a research gap in understanding how sensor performance, signal detection delay, and control timing synchronization contribute to combustion interruption during inert gas production.

The issue of combustion stoppage in an inert gas generator is important to investigate because the continuity of combustion directly affects the availability of inert gas required to maintain a safe atmosphere inside tanker cargo tanks. When the inert gas generator fails to operate continuously, the supply of inert gas may be interrupted, potentially increasing oxygen concentration in the cargo tank and raising the risk of fire or explosion during cargo operations. Therefore, identifying the root causes of combustion interruption is not only relevant from a technical perspective but also essential for improving ship operational safety and supporting compliance with maritime safety requirements.

The novelty of this study lies in the integration of several management and risk analysis methods, namely Root Cause Analysis (RCA), Fault Tree Analysis (FTA), 5-Why Analysis, and Failure Mode and Effects Analysis (FMEA), to systematically identify, map, and prioritize the causes of combustion stoppage in the inert gas generator. Through this combined approach, the study does not merely describe the occurrence of system failure but also provides a structured framework for tracing the root cause, explaining the logical failure sequence, validating the critical timing mismatch, and determining priority corrective actions based on risk level. Therefore, this research contributes to a more comprehensive diagnostic approach for improving the reliability, maintainability, and safety performance of inert gas generator systems on tanker vessels.

2. METHODS

This study applies an integrated analytical framework by combining Root Cause Analysis (RCA), 5-Why Analysis, Fault Tree Analysis (FTA), and Failure Mode and Effects Analysis (FMEA) to identify, trace, and prioritize the causes of combustion stoppage in the inert gas generator system. The integration of these methods is intended to provide a systematic diagnostic process, starting from problem identification, root cause investigation, logical failure mapping, risk evaluation, and formulation of corrective actions.

The analytical process begins with field observation of the inert gas generator operation, particularly the combustion monitoring system involving the flame eye detector, timer relay, controller module, and burner fuel supply system. Operational data are collected to identify abnormal conditions, including the difference between the flame eye detector response time and the timer relay set-point duration. These findings are then used as the basis for applying Root Cause Analysis.

Root Cause Analysis is used as the main framework to determine the fundamental causes of combustion interruption. In this stage, the problem is first defined as the failure of the inert gas generator to maintain continuous combustion during inert gas production. The suspected causes are then classified based on technical components, control sequence, sensor response, and timing configuration. To deepen the RCA process, the 5-Why Analysis is applied to trace the causal chain of the failure step by step. This method helps explain why the combustion process stops, why the timer relay cuts off the fuel supply, why the controller relay fails to activate the bypass function in time, and why the flame confirmation signal is delayed.

After the root causes are identified through RCA and 5-Why Analysis, Fault Tree Analysis is used to map the logical relationship between the top event and its contributing factors. In this study, the top event is defined as the failure of the inert gas generator to sustain combustion. This event is then broken down into intermediate and basic events, such as flame eye detector response delay, timer relay cut-off before controller relay activation, reduced sensor sensitivity, delayed signal transmission, and mismatch between timer setting and flame validation time. FTA provides a structured visualization of how these factors interact and lead to combustion stoppage.

Finally, Failure Mode and Effects Analysis is applied to evaluate the risk level of each identified failure mode. Each failure mode is assessed using three parameters: Severity, Occurrence, and Detection. The Risk Priority Number is calculated using the formula RPN = S × O × D. The RPN value is then used to determine which failure mode requires the highest priority for corrective action. Through this stage, the study can recommend practical maintenance and troubleshooting strategies, such as flame eye detector replacement, timer relay adjustment, sensor recalibration, and synchronization between the timer and controller module.

Therefore, the integration of RCA, 5-Why, FTA, and FMEA provides a comprehensive analytical framework. RCA identifies the main problem and possible causes, 5-Why deepens the investigation of the causal chain, FTA maps the logical structure of failure, and FMEA prioritizes risks and corrective actions. This integrated approach allows the study to move beyond descriptive troubleshooting and provides a more systematic method for improving the reliability and safety performance of the inert gas generator system.

2.1. Research Object

The object of this research is the inert gas generator system installed on a tanker vessel, particularly the combustion monitoring subsystem that utilizes a flame eye detector to ensure stable combustion during inert gas production. The reliability of this system is essential for maintaining safe oxygen levels in cargo tanks and preventing the formation of flammable atmospheres during cargo loading and unloading operations.

The study focuses on identifying operational disturbances occurring in the combustion process that may cause interruptions in inert gas production. Special attention is given to the performance of the flame eye detector in detecting combustion flame intensity and transmitting signals to the control module of the inert gas generator system.

Research data were obtained through direct field observations and operational monitoring of the inert gas generator system. Data acquisition includes the recording of flame intensity signals, timer relay settings during ignition processes, and the system's response to combustion light intensity. These data were collected continuously to obtain comprehensive operational information and to identify patterns of disturbances that occur during system operation.

2.2. Treatment of Research Objects and Problem-Solving Method

This study analyzes the operational behavior of the inert gas generator system by focusing on the interaction between flame detection, timer relay configuration, and combustion stability. The research object is treated as an integrated combustion control system consisting of mechanical components, sensor elements, and control devices. The fixed variables in this study include the mechanical configuration of the inert gas generator unit, the combustion chamber structure, and the installed control module used for flame detection and combustion monitoring. These components are considered constant because they represent the existing system configuration during the observation period.

The variable parameters analyzed in this research include the set-point configuration of flame intensity detection measured by the flame eye detector, the timer relay set-point during the ignition and combustion process, and the response of the flame eye detector to variations in combustion light intensity produced by burning fuel. Variations in these parameters were observed to evaluate how changes in sensor sensitivity and timing control influence combustion stability and the operational continuity of the inert gas generator system. By examining these parameters, the study aims to identify whether combustion interruption is caused by mechanical failure, sensor response delay, improper set-point configuration, or a mismatch between the timer relay and controller module.

This research employs a descriptive qualitative approach supported by Root Cause Analysis (RCA), 5-Why Analysis, Fault Tree Analysis (FTA), and Failure Mode and Effects Analysis (FMEA). The descriptive qualitative method is used to analyze real operational conditions through field observation and system performance evaluation. This approach allows the researcher to interpret the operational behavior of the inert gas generator and identify anomalies in the combustion monitoring system, particularly those related to flame detection signals and timer relay operation.

Root Cause Analysis (RCA) is applied to systematically determine the fundamental causes of operational disturbances in the inert gas generator system. RCA is used not only to identify the visible symptoms of combustion interruption, but also to trace the underlying causes that contribute to system malfunction. Through RCA, the problem is detailed, potential contributing factors are mapped, possible causes are narrowed down, and the most significant root cause affecting system performance is identified. To strengthen the causal investigation, 5-Why Analysis is used to examine each suspected cause in greater depth until the basic cause of the failure can be determined.

Fault Tree Analysis (FTA) is used as a supporting analytical method to describe the logical relationship between system failure and its contributing factors. In this study, the failure of the inert gas generator to maintain combustion is defined as the top event. This top event is then broken down into intermediate events and basic events, such as flame eye detector delay, timer relay mismatch, incorrect set-point configuration, weak flame signal, and controller response failure. This structure helps explain how different components of the combustion monitoring system interact and contribute to premature burner shutdown.

In addition, Failure Mode and Effects Analysis (FMEA) is applied to prioritize the identified failure modes based on their severity, occurrence, and detectability. The Risk Priority Number (RPN) is calculated to determine which failure modes require the most urgent corrective action. Through FMEA, potential failures related to the flame eye detector, timer relay, controller module, and combustion monitoring system can be ranked systematically, allowing maintenance recommendations to be developed based on risk priority.

The research procedure consists of several stages. First, system mapping is conducted to identify the operational components of the inert gas generator and their interrelationships. Second, field observation is performed to collect operational data during the ignition and combustion processes. Third, data identification and classification are carried out to identify abnormal conditions related to flame detection signals, timer relay settings, and combustion interruption. Fourth, RCA and 5-Why Analysis are applied to determine the root causes of the operational disturbance. Fifth, FTA is used to model the logical failure structure of the inert gas generator system. Sixth, FMEA is conducted to prioritize the failure modes and determine corrective actions based on the RPN value. Finally, predictive analysis is performed to evaluate the collected data and determine the critical values affecting flame detection performance and combustion stability.

Through the integration of these analytical methods, the study is able to narrow down the possible causes of combustion interruption and identify the most significant factors affecting the reliability of the inert gas generator system. Field observation is used to identify the operational failure, RCA is applied to determine the root causes, 5-Why Analysis is used to deepen the causal investigation, FTA is employed to map the logical structure of the failure, and FMEA is used to prioritize risks and formulate corrective actions. This combined framework provides a systematic basis for evaluating the reliability of the inert gas generator and improving the performance of its combustion monitoring system.

2.3. Tools and Materials

The main tools used in this research include the inert gas generator unit, flame eye detector sensor, timer relay (time relay), and the control module of the inert gas generator system. Supporting equipment includes combustion monitoring instruments and interface modules used to observe signal responses generated by the flame detection system.

The primary material used in the research process is fuel utilized in the combustion chamber of the inert gas generator, which produces the flame detected by the flame monitoring system. The interaction between the combustion process, detection sensors, and control components forms the basis for evaluating the operational performance and reliability of the inert gas generator system.

3. RESULTS AND DISCUSSION

The field observation showed that the inert gas generator was able to initiate combustion at the early stage of operation. The fuel system, ignition electrode, furnace draft blower, and combustion chamber sight glass were found to be in good condition. However, the combustion process could not be sustained because the flame confirmation signal from the flame eye detector was not validated within the timer relay operating period. This indicates that the problem was not caused by the failure of initial flame formation, but by a mismatch between the flame detection response time and the timer relay set-point.

During the ignition monitoring sequence, the timer relay operated for 30 seconds, while the flame eye detector required approximately 35 seconds to reach the required signal value for relay activation. This 5-second difference prevented the controller relay from activating the bypass function before the timer relay disconnected the burner fuel supply. As a result, the control system interpreted the condition as a flame failure and automatically stopped the combustion process, interrupting inert gas production. The relay control mechanism activated by the flame eye detector sensor is illustrated in Figure 8.

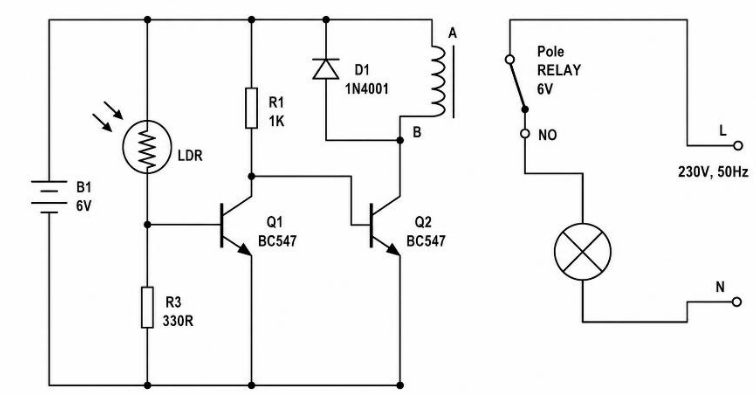


Figure 8. Relay Control Scheme Activated by the Flame Eye Detector Sensor

The timing mechanism used to regulate the ignition monitoring process can be represented by a simple time-delay circuit, as shown in Figure 9.

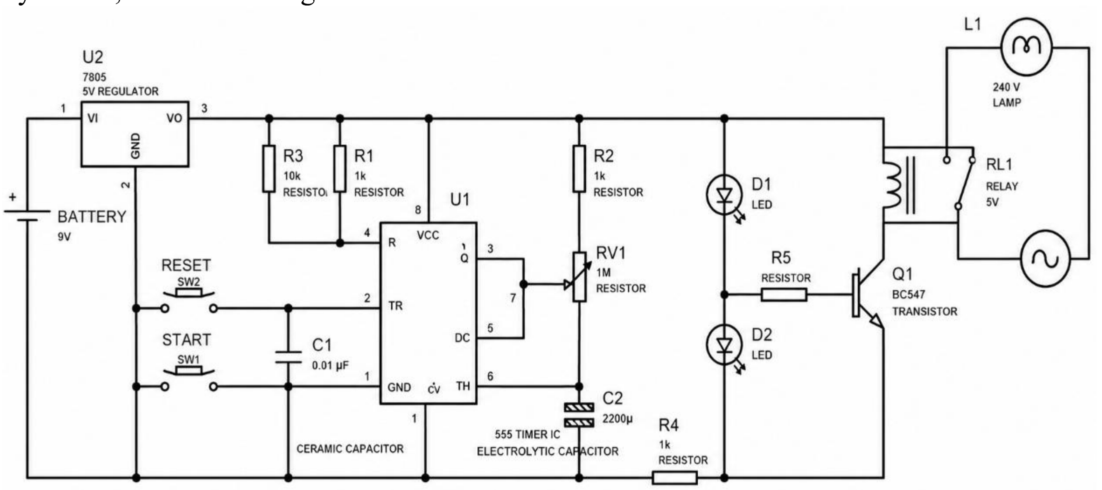


Figure 9. Simple Time Delay Circuit Diagram Using a 555 Timer IC

Table 1. Inspection Results of Inert Gas Generator Equipment

No	Activity	Result
1	Fuel system inspection	System condition is in good condition
2	Electrode system inspection	System condition is in good condition
3	Furnace draft blower operation inspection	System condition is in good condition
4	Testing the flame detector reading compared with the required response time	The obtained value meets the requirement; however, to reach the highest reading value it requires a longer time than specified. The monitoring result shows approximately 35 seconds
5	Timer inspection	The timer operates at 30 seconds
6	Inspection of the combustion chamber sight glass for flame illumination	System condition is in good condition

Table 2. Inspection Results of the Controller Module Panel

No	Activity	Result
1	Inspection of the controller module panel using a voltage potentiometer to manipulate the flame eye detector signal as an input to the controller module	The results indicate that the relay response of the controller module operates properly

Table 3. Comparison of Flame Detector Signal Response and Timer Control

No	Activity	Result
1	Comparing the relay response of the controller module based on flame intensity readings from	The results show a difference in timer response time. The control power timer relay changes its contact position from NO (Normally Open) to NC (Normally Closed) or from NC to NO

No	Activity	Result
	the flame eye detector with the control power timer	faster than the relay response of the controller module. This condition causes the control power timer to shut down the burner fuel system, resulting in the interruption of the combustion process and the stoppage of inert gas production.

Table 4. Timing Validation of Flame Eye Detector Response and Timer Relay Operation

Observation Aspect	Timing Evidence	Interpretation
Timer relay operation	30 seconds	Timer reaches cut-off point at 30 seconds
Flame eye detector response	Approximately 35 seconds	Flame signal reaches the required value after timer cut-off
Timing difference	5 seconds	Controller relay response is delayed
System consequence	Burner fuel system shutdown	Combustion stops before inert gas production continues

The empirical validation of the 5-second delay was obtained by comparing the response time of the flame eye detector with the operating duration of the timer relay during the ignition monitoring process. Based on the inspection results, the timer relay was confirmed to operate at 30 seconds, while the flame eye detector required approximately 35 seconds to reach the required flame signal value. This means that the flame confirmation signal from the detector was received by the controller module 5 seconds later than the timer cut-off point. As a result, the controller relay was unable to activate the bypass function before the timer relay disconnected the burner fuel system.

This timing difference provides clear evidence that the combustion stoppage was not caused by the absence of flame formation, because the initial combustion process had already occurred. Instead, the failure was caused by a delay in flame validation, where the flame eye detector response was slower than the timer relay setting. The 5-second delay is therefore technically significant because the control system depends on precise synchronization between flame detection, controller relay activation, and timer relay operation. When the flame signal is validated after the timer has reached its limit, the system interprets the condition as flame failure and automatically shuts down the burner fuel supply.

To strengthen the reliability of this finding, the timing comparison between the flame detector and the timer relay can be presented as repeated operational evidence. The consistent difference between the 30-second timer setting and the approximately 35-second flame detector response indicates that the combustion interruption was caused by a timing mismatch in the control sequence. This finding confirms that the main operational problem lies in the synchronization failure between the flame eye detector response time and the timer relay set-point configuration.

Based on the analysis of the three observational datasets, the ignition process in the inert gas generator was found to operate properly at the initial stage. Combustion was successfully initiated when the three essential elements, namely the required air composition, the ignition spark from the electrode, and the fuel spray from the burner, interacted under normal operating conditions. This indicates that the fuel system, ignition electrode, and draft blower were functioning properly during the initial combustion stage.

During operation, the combustion process was monitored simultaneously by two main control elements, namely the timer relay and the flame eye detector. The timer relay provided an ignition monitoring period of 30 seconds, while the flame eye detector continuously measured the light intensity produced by the combustion flame and transmitted the detected signal to the controller module. The controller module then processed this signal to activate the control relay, which functions as a bypass mechanism to maintain the continuity of the combustion process after the timer period has elapsed.

However, the analysis results show that the control relay in the controller module began to respond only at 35 seconds, whereas the timer relay had already reached its cut-off point at 30 seconds. This condition created a 5-second response delay between the flame detection system and the timer control system. As a consequence, the controller relay was unable to establish the required bypass function before the timer deactivated the burner fuel supply. This caused the combustion system to shut down even though flame generation had already occurred at the beginning of the process.

From an engineering perspective, this finding indicates that the problem does not originate from the initial combustion formation, but rather from the mismatch between flame signal detection time and timer set-point duration. In other words, combustion was successfully generated, but the flame confirmation signal required by the control system was received too late to sustain continued operation.

3.1. Root Cause and Failure Analysis

The root cause analysis shows that the main cause of the inert gas generator failure is the mismatch between the flame eye detector response time and the timer relay setting. The flame eye detector requires approximately 35 seconds to detect the combustion flame and transmit a signal that reaches the controller set-point. However, the timer relay is configured to allow only 30 seconds for flame validation. As a result, the timer relay cuts off the fuel supply before the controller receives the flame confirmation signal, even though combustion has already occurred.

This condition indicates that the failure is not caused by a total malfunction of the flame detector or controller module, but by delayed flame validation within the combustion monitoring sequence. The delay may be influenced by reduced flame eye detector sensitivity, signal processing delay, or sensor aging. Since the timer setting does not provide sufficient margin for the delayed sensor response, the system interprets the condition as flame failure and automatically shuts down the burner.

The 5-Why analysis further confirms this causal relationship. The combustion process stops because the timer relay cuts off the fuel supply. The timer relay cuts off the system because it completes its 30-second monitoring period before receiving the flame confirmation signal. The flame confirmation signal is delayed because the sensor reaches its required signal level at approximately 35 seconds. This delay may occur due to reduced sensor sensitivity, mismatched timer settings, or signal processing delay. The condition was not corrected earlier because the maintenance procedure did not fully consider sensor aging and changes in ignition dynamics.

Based on the Fault Tree Analysis, the top event is defined as the failure of the inert gas generator to sustain combustion and continue inert gas production. This failure is caused by several interrelated events, including flame eye detector response delay, timer relay cut-off before controller relay bypass activation, and interruption of the combustion process. These events are linked to basic causes such as reduced flame sensor sensitivity, delayed signal transmission, mismatch between flame detection time and timer setting, and the inability of the controller relay to replace the timer relay function before fuel shutdown occurs.

Overall, the analysis confirms that the operational disturbance results from a synchronization failure between sensor response and timer control. When the flame signal is not validated within the timer limit, the system interprets the condition as combustion failure and stops the fuel supply. Therefore, improving flame sensor sensitivity, recalibrating the detection set-point, and extending the timer relay duration are necessary corrective actions to prevent premature shutdown and maintain continuous inert gas production.

3.2. Technical Interpretation of the Delay

The observed 5-second delay is technically significant because the timer relay and the control relay operate in a sequential dependency. The timer relay serves as the initial combustion supervision mechanism, while the control relay is expected to take over the circuit once the flame signal is validated. If the flame validation process exceeds the timer duration, the sequence is broken and the fuel system is shut down. Therefore, even a relatively small-time difference can produce a major operational failure in the inert gas generator system.

This finding also shows that the reliability of the inert gas generator is highly dependent on the synchronization between sensor response, signal processing, and timer control logic. A delay in any one of these elements can compromise the entire combustion continuity process.

The analysis confirms that the combustion stoppage in the inert gas generator was caused by a delay in the flame validation sequence rather than by a failure of the initial combustion process. The timer relay reached its cut-off point at 30 seconds, while the flame eye detector required approximately 35 seconds to generate a signal that met the controller module set-point. This mismatch caused the burner fuel supply to be disconnected before the controller relay could activate the bypass function. Therefore, the main issue lies in the lack of synchronization between the sensor response, controller relay activation, and timer relay configuration.

This finding indicates that the reliability of the inert gas generator depends not only on the mechanical condition of the burner and fuel system, but also on the accuracy of the combustion monitoring and control sequence. Regular inspection, sensor calibration, timer verification, and post-maintenance testing are required to ensure that flame validation occurs within the permitted time window. Improving this synchronization will reduce nuisance trips, maintain combustion continuity, and support safer tanker operations.

3.3. Operation of the Inert Gas Generator in Producing Inert Gas

The Inert Gas Generator (IGG) is a critical safety system used on tanker vessels and in oil and gas facilities. Its main function is to produce inert gas with a low oxygen concentration in order to prevent the formation of explosive atmospheres inside cargo tanks. By maintaining the oxygen level below the flammable limit, the inert gas system plays an important role in supporting safe cargo loading, unloading, and tank preparation operations.

The operation of the inert gas generator begins with the combustion stage. In this stage, fuel, typically Marine Diesel Oil (MDO) or Intermediate Fuel Oil (IFO), is burned inside the combustion chamber. The combustion process is supported by air supplied by a blower to ensure that the burner can generate a stable flame. The stability of this flame is essential because continuous combustion determines the ability of the system to produce inert gas consistently.

During the combustion process, the inert gas is formed as a mixture of combustion products, mainly carbon dioxide (CO_2), nitrogen (N_2), and a small amount of oxygen (O_2). The oxygen concentration in the produced gas is typically maintained below 5%, making the gas suitable for inerting cargo tanks. This low-oxygen gas reduces the possibility of ignition by limiting the availability of oxygen required for combustion.

After the inert gas is produced, the hot gas passes through a cooling and scrubbing process. In this stage, seawater is used in the scrubber system to reduce the gas temperature and remove particulate matter, soot, and sulfur compounds. This process is important to ensure that the inert gas supplied to the cargo tanks is sufficiently cooled and cleaned before distribution. Proper scrubbing also helps protect downstream components and cargo tank structures from contamination and corrosion.

The treated inert gas is then distributed to the cargo tanks through the inert gas main line. Its function is to maintain the cargo tank atmosphere at a low oxygen concentration, thereby preventing the formation of a flammable or explosive atmosphere. The continuous supply of inert gas is particularly important during cargo loading, unloading, and tank cleaning operations, where vapor release and changes in tank pressure may occur.

The success of inert gas production depends heavily on the continuity and reliability of the combustion process. If the flame is extinguished or incorrectly detected by the monitoring system, the inert gas supply may stop. This condition can increase the oxygen concentration inside the cargo tanks, raise the risk of fire or explosion, and disrupt cargo loading or unloading operations. Therefore, reliable flame detection, stable burner operation, and proper control system performance are essential to ensure the safe and continuous operation of the inert gas generator.

3.4. Maintenance Management and Troubleshooting of the IGG

Maintenance management and troubleshooting of the Inert Gas Generator (IGG) require a systematic approach to prevent similar operational failures. Preventive maintenance should include regular calibration of the flame eye detector and related sensors, inspection and cleaning of burner nozzles, ignition electrodes, and combustion chamber sight glasses, as well as periodic testing of controller modules and timer relays to ensure proper synchronization. Predictive maintenance can be carried out by monitoring sensor signal trends to detect decreasing sensitivity and by establishing threshold limits to identify early signs of sensor degradation. In troubleshooting, if the flame signal fails to be detected, cross-testing should be performed using an external signal source such as a potentiometer. If a time delay occurs, for example around five seconds, the timer parameters or sensor set-point values should be adjusted. If the problem persists, the flame eye detector sensor should be replaced with a new unit. From the operational management perspective, a standard operating procedure for timer–controller synchronization should be established, a dedicated IGG logbook should be maintained to record flame failure events, and operators should be trained in basic troubleshooting procedures to enable rapid initial response before involving specialized technicians.

3.5. Practical Implementation and Maintenance Strategy

The practical implementation of the findings should be carried out through a structured maintenance strategy that combines corrective, preventive, and predictive maintenance approaches. Since the main problem identified in this study is related to the mismatch between flame eye detector response time and timer relay setting, the first implementation priority is to restore synchronization between the sensor, controller module, and timer relay. This can be achieved by replacing or recalibrating the flame eye detector, readjusting the timer relay duration, and verifying the response of the controller relay during cold-start and warm-start conditions.

Corrective maintenance should be performed immediately after the combustion stoppage problem is identified. The flame eye detector should be inspected to determine whether its sensitivity has decreased due to aging, contamination, or optical signal disturbance. If the sensor response remains slower than the required flame validation time, the sensor should be replaced with a new unit. At the same time, the timer relay setting should be adjusted to provide a sufficient safety margin for flame confirmation. In this study, extending the Trial-for-Ignition window from 30 seconds to 45 seconds is recommended to provide adequate time for flame validation before the fuel supply is cut off.

Preventive maintenance should be implemented through regular inspection and calibration of the combustion monitoring system. The inspection should include cleaning the flame eye detector lens or optical port, checking the combustion chamber sight glass, inspecting burner nozzles and ignition electrodes, and verifying the performance of the controller module and timer relay. Periodic testing of the timer–controller synchronization is necessary to ensure that the controller relay can activate the bypass function before the timer relay reaches its cut-off point. These actions can reduce the possibility of false flame failure signals and prevent unnecessary burner trips.

Predictive maintenance can be applied by recording and monitoring flame signal trends during each start-up sequence. The vessel operator should maintain an IGG operational logbook containing flame validation time, timer setting, flame signal level, alarm history, and corrective actions taken. If the flame validation time gradually increases over repeated operations, this condition can be used as an early warning indicator of sensor degradation or control system delay. Therefore, maintenance actions can be performed before the system experiences another combustion stoppage.

From an operational perspective, the implementation strategy should also include the development of a standard operating procedure for troubleshooting combustion stoppage in the inert gas generator. The SOP should guide operators to check the flame eye detector response, timer relay setting, controller module relay, fuel solenoid valve, burner condition, and signal input from the sensor. Operator training is also required so that ship engineers can identify early symptoms of sensor delay, conduct basic diagnostic checks, and respond quickly before the failure disrupts inert gas production.

To ensure the effectiveness of the maintenance strategy, post-repair verification testing must be carried out after corrective actions are completed. The system should be tested through several consecutive start–stop cycles to confirm that the flame validation signal is received before the timer cut-off point. The acceptance criteria may include flame validation time below the allowable limit, stable controller relay response, successful bypass activation, and continuous combustion without nuisance trips. Through this implementation strategy, the inert gas generator can operate more reliably, reduce the risk of combustion interruption, and support safer tanker cargo operations.

Table. 5 Practical Implementation and Maintenance Strategy for IGG Reliability Improvement

Maintenance Strategy	Implementation Action	Purpose	Responsible Personnel
Corrective maintenance	Replace or recalibrate the flame eye detector	Restore sensor sensitivity and reduce flame validation delay	Instrument technician
Corrective maintenance	Adjust timer relay setting from 30 seconds to 45 seconds	Provide sufficient time for flame confirmation	Electrical technician
Preventive maintenance	Clean flame detector lens, sight glass, burner nozzle, and ignition electrode	Prevent low flame signal caused by dirt or contamination	Engine crew
Preventive maintenance	Periodically test timer–controller synchronization	Ensure bypass relay activates before timer cut-off	Electrical/instrument team
Predictive maintenance	Record flame validation time and flame signal trend in IGG logbook	Detect early symptoms of sensor degradation	Watchkeeping engineer
Operational management	Develop SOP for IGG combustion stoppage troubleshooting	Standardize operator response during failure	Chief engineer
Verification testing	Conduct repeated start–stop tests after maintenance	Confirm stable combustion and prevent repeated burner trip	Engine and electrical team

3.6 Technical Solution Design

The technical solution design focuses on synchronizing the burner setpoint, timer setting, and controller response to prevent premature shutdown during the ignition process. The Trial-for-Ignition (TFI) time should be adjusted to 45 seconds, providing a safety margin of at least 10 seconds compared to the worst-case flame validation time of 35 seconds. In addition, a latching logic mechanism should be implemented so that once the flame has been validated, the timer circuit is bypassed and premature shutdown can be avoided. Signal persistence validation for 1–2 seconds should also be applied to prevent false flame detection caused by temporary signal spikes or electrical noise.

Sensor calibration and validation are also important to ensure reliable flame detection. The flame sensor signal curve should be recalibrated against actual flame intensity measurements to verify its accuracy and sensitivity. The sensor setpoint should be defined based on the baseline signal value with an additional safety margin of approximately 20–30%. Furthermore, cold-start and warm-start tests should be conducted to confirm that the flame validation time does not exceed 25 seconds under normal operating conditions. These tests are necessary to ensure that the flame sensor and controller module respond within the required ignition window.

Signal processing optimization should be carried out to improve the dynamic response of the flame detection system. The filtering time constant should be reduced so that the sensor can respond more quickly to flame presence without excessive signal delay. In addition, diagnostic alarms for slow flame validation should be implemented as an early warning indicator of potential sensor degradation, contamination, or aging. This approach allows maintenance personnel to detect abnormalities before they lead to system trips or burner shutdown.

A preventive maintenance and spare parts strategy should also be established to support system reliability. Flame sensors should be replaced according to the manufacturer's recommendations or when performance degradation is detected during calibration. Critical spare components should be maintained on board, including two flame sensors and one ready-to-install control module. Quarterly sensor calibration and periodic cleaning of optical ports should also be scheduled to prevent signal attenuation caused by dirt, soot, or contamination on the sensor lens.

Post-repair verification testing must be conducted to confirm that the corrective actions have effectively restored system performance. The acceptance criteria should include a flame validation time of not more than 25 seconds during cold start and not more than 15 seconds during warm start. The timer safety margin should be maintained at a minimum of 10 seconds. In addition, the system should successfully complete three consecutive start–stop tests without nuisance trips. Continuous monitoring of flame signal levels and interlock status should also be performed to verify stable operation after repair.

Based on the identified root causes, two main corrective actions are proposed. First, the flame eye detector should be inspected, recalibrated, or replaced if its sensitivity has decreased. Restoring the sensor sensitivity is expected to reduce the flame validation time and allow the controller module to receive the flame confirmation signal within the required period. Second, the timer relay setting should be adjusted to provide an adequate safety margin for flame validation. Extending the Trial-for-Ignition window from 30 seconds to 45 seconds is recommended to ensure that the controller relay can activate the bypass function before the timer reaches its cut-off point. These corrective actions are expected to maintain the burner fuel supply, prevent unnecessary combustion shutdown, and improve the continuity of inert gas production.

3.7. Setpoint Accuracy and Safety Significance of the Flame Eye Detector

The flame eye detector functions by measuring the light intensity emitted by the combustion flame and converting it into an electrical signal that is transmitted to the controller module. For the inert gas generator to operate reliably, the sensor signal must reach the predetermined set-point within the timer duration. In this case, the flame eye detector reaches the required signal level at approximately 35 seconds, while the timer relay only allows 30 seconds for flame validation. This mismatch causes the system to interpret the condition as flame failure and shut down the fuel supply, even though combustion is still present.

The operational principle of the system depends on the relationship between sensor signal and set-point value. If the sensor signal remains below the set-point during the timer duration, the system identifies the condition as flame failure and activates fuel shutdown. Conversely, if the sensor signal reaches or exceeds the set-point before the timer cutoff, the controller maintains the fuel supply and allows combustion to continue. Therefore, sensor accuracy and synchronization between the timer relay and controller module are critical factors in maintaining combustion stability.

The findings show that operational disturbances in the inert gas generator may occur not only due to mechanical failure, but also because of timing mismatch within the combustion control system. This condition highlights the importance of periodic inspection of the flame eye detector, timer relay, controller module, and burner interlock system. Proper synchronization between flame detection and timer control is essential to prevent premature burner shutdown and ensure continuous inert gas production.

From the perspective of SOLAS principles and maritime safety requirements, the reliability of the inert gas generator is closely related to tanker safety. The inert gas system must maintain cargo tanks in a non-flammable condition by controlling oxygen concentration. If combustion stops, the generator cannot continuously supply low-oxygen inert gas to the cargo tanks, increasing the risk of unsafe tank atmospheres during cargo loading, unloading, or tank preparation operations.

Therefore, the proposed corrective actions, including flame eye detector inspection, sensor recalibration, timer relay adjustment, and verification of timer–controller synchronization, are not only technical maintenance measures but also support compliance with tanker safety operations. Maintaining the reliability of the inert gas generator contributes to safer cargo operations, reduces fire and explosion risk, and supports the implementation of maritime safety regulations.

3.8. Failure Mode and Effects Analysis (FMEA) Parameters

Failure Mode and Effects Analysis (FMEA) was applied to evaluate and prioritize potential failure modes affecting the operation of the inert gas generator (IGG) system. In this study, each failure mode was assessed using three main parameters: Severity (S), Occurrence (O), and Detection (D). These parameters were used to quantify the risk level of each failure mode and to determine the priority of corrective actions.

Severity (S) represents the level of impact caused by a failure mode on system operation, safety, equipment reliability, and the surrounding environment. The severity scale ranges from 1 to 10, where a higher value indicates a more serious consequence. A score of 1–3 represents a minor impact with insignificant operational disturbance, 4–6 indicates a moderate impact that may disrupt operation but can still be managed, 7–8 represents a major impact that may cause operational shutdown or significant losses, and 9–10 indicates a critical impact that may directly affect safety and lead to fire, explosion, or severe system damage. In the IGG system, premature shutdown of the combustion process may stop inert gas production and increase the oxygen concentration inside cargo tanks. This condition can create a potential safety hazard during tanker operations. Therefore, the severity level of this failure mode is categorized as S = 9.

Occurrence (O) represents the probability or frequency of a failure mode occurring during system operation. The occurrence scale also ranges from 1 to 10, where a higher value indicates a higher likelihood of failure. A score of 1–2 indicates an extremely rare occurrence, 3–4 indicates a rare but possible occurrence, 5–6 represents occasional occurrence, 7–8 indicates frequent occurrence, and 9–10 represents an almost inevitable or regularly occurring failure. In this study, the delay in flame validation caused by sensor aging or reduced sensor sensitivity may occur occasionally under certain operating conditions. Therefore, the occurrence level is estimated as O = 6.

Detection (D) represents the ability of the existing control system, alarm system, or inspection procedure to detect a failure before it causes operational disruption. The detection scale ranges from 1 to 10, where a higher value indicates that the failure is more difficult to detect. A score of 1–2 indicates that the failure is very easy to detect through alarms or indicators, 3–4 indicates that the failure is relatively easy to detect, 5–6 indicates that the failure is moderately difficult to detect and may require manual inspection, 7–8 indicates that the failure is difficult to detect and is usually identified only after an operational disturbance occurs, and 9–10 indicates that the failure is almost impossible to detect before a critical event occurs. In the IGG case, the delay in flame validation is difficult for operators to detect in real time unless signal logging or detailed monitoring is available. The problem is usually identified only after the timer relay trips and shuts down the burner system. Therefore, the detection level is classified as D = 7.

The risk level of each failure mode was determined using the Risk Priority Number (RPN). The RPN value was calculated by multiplying the Severity, Occurrence, and Detection scores, as shown in the following equation: $RPN = S \times O \times D$. Where S represents Severity, O represents Occurrence, and D represents Detection. A higher RPN value indicates a higher level of risk and a higher priority for corrective action. Therefore, failure modes with the highest RPN values must be addressed first to reduce operational disruption and improve the reliability and safety of the inert gas generator system.

Based on the FMEA results, the highest RPN value was obtained for the failure mode related to the Trial-for-Ignition (TFI) window being too short. In this case, the timer relay was set to 30 seconds, while the flame eye detector required approximately 35 seconds to validate the combustion flame. This failure mode obtained an RPN value of 378, calculated from Severity = 9, Occurrence = 6, and Detection = 7. $RPN = 9 \times 6 \times 7 = 378$ This value indicates a very high-risk level and shows that the timing mismatch between the timer relay and the flame eye detector is the most critical failure mode in the IGG system. Therefore, immediate corrective action is required, including extending the TFI setting, improving flame signal validation, and synchronizing the timer relay with the controller module. Overall, the S/O/D parameters provide a systematic basis for evaluating potential system failures and prioritizing maintenance or corrective measures to improve the reliability and safety of the inert gas generator system.

Table 6. Failure Mode and Effects Analysis (FMEA) of the Inert Gas Generator System

No.	Function / Process	Failure Mode	Effect	S	Main Cause	O	Current Control	D	RPN	Recommended Action	PIC	Target
1	Flame proving during TFI window	TFI window too short, where 30 s is shorter than the flame validation time of approximately 35 s	Burner trip and IGG stops producing inert gas	9	Timer relay is set to 30 s, while sensor response requires approximately 35 s	6	Standard interlock system	7	378	Increase TFI to 45 s, add 1–2 s debounce on the flame-proven signal, and implement latch bypass for the timer after flame validation	Instrument	2 weeks
2	Accurate flame detection	Flame sensor sensitivity drift due to sensor aging	Delayed flame detection or false trip	8	Sensor aging or calibration drift	5	Periodic cleaning	6	240	Replace the flame sensor, recalibrate the set-point based on signal output versus flame intensity, establish a new baseline, and monitor MTBF trend	Instrument	1 week
3	Signal processing	Slow filtering or integration in the controller input	Slow flame validation	8	Filtering time constant is too large	4	Factory default parameters	6	192	Reduce the filter time constant and implement a moving window filter of 0.5–1 s	Control	2 weeks
4	Reliable timing control	Timer drift or incorrect setting	Premature burner trip	7	Timer tolerance deviation or setting changes	4	Functional testing	5	140	Recalibrate the timer relay and verify its operation through cold-start testing	Electrical / Mechanical	1 week
5	Optical signal path	Viewing port is dirty or fogged	Low flame intensity reading	6	Dirt, soot, or condensation on the optical port	3	Periodic inspection	5	90	Add optical port inspection and cleaning to the start-up checklist	Engine	1 week
6	Initial flame stability	Slow low-fire ramp due to air–fuel ratio imbalance	Slow increase in flame intensity	7	PID ramp setting is too conservative	2	Default control setting	6				

4. CONCLUSION

Management analysis plays a crucial role in guiding the actions taken to systematically map suspected problems to identify the root causes. Through a structured analytical approach, the work process can be carried out more effectively while minimizing the risk of errors that may occur during each stage of problem handling. The results obtained from the application of management analysis in addressing the inert gas generator problem indicate that the quality of the combustion process significantly influences the light intensity value detected by the flame eye detector. Therefore, continuous inspection and measurement of the combustion light intensity detected by the flame eye detector are necessary in order to identify early signs of performance degradation. Early detection allows corrective actions to be implemented promptly whenever a decrease in combustion quality is observed. Furthermore, the analysis shows that the time discrepancy between the controller module relay response and the timer set-point becomes the primary factor causing the interruption of the combustion process in the inert gas generator. This mismatch in response time prevents the controller relay from successfully replacing the timer relay operation, resulting in the automatic shutdown of the burner system before stable combustion can be maintained. Consequently, the inert gas generator fails to continue producing inert gas. These findings highlight the importance of maintaining proper synchronization between the flame detection system, controller module, and timer settings to ensure the continuous and reliable operation of the inert gas generator system.

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