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Use of Operational Data for SIS Follow-up Activities

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Reliability, Availability, Maintainability and Safety (RAMS)
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Preface

This master thesis is carried out at Department of Production and Quality Engineering, NTNU and it is in collaboration with Equinor. The master thesis is a part of education program TPK 4950 in the Master Program RAMS (Reliability, Availability, Maintainability and Safety Engineering.

The report is written for readers with some background of reliability analysis especially in Safety Instrumented System. Operation personnel may also be benefited from the analysis. Readers unfamiliar with the subject may refer to the literature study provided and the reference given in each section.

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Raden Mailisa Fitria

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Abstract

The integrity of SIS shall be maintained during its lifetime including operational and maintenance phase. Guidelines for follow-up SIF in the operating phase by SINTEF is one of the guidelines widely used, but it has not been updated for more than ten years. It is desirable to evaluate the applicability of this guideline for the existing maintenance data. The main objective of this master thesis is to use the failure notification data to analyze SIS performance during SIS follow-up activity. The starting point is classifying the failure notification data into DU failures. The simplified FMEDA is found as a feasible method. The OREDA Multi-Sample is used to calculate the aggregated failure rate for detector type and the detector model. The Bayesian method is used to calculate the failure rate for each model in a facility. The Bayesian method is required a priory failure rate as prior knowledge. It is investigated that the aggregated failure rate by OREDA Multi-Sample can be used as a priory failure rate. The master thesis concludes that the guideline is found practical and useful to be used in the existing facility. However, a few modifications can be valuable. The proposed modifications are defining a method to classify DU failure, updating the formula to calculate Bayesian failure rate, and updating the method of doubling or halving the test interval.

keywords: failure rate, test interval, SIS follow-up, failure classification, Bayesian, OREDA Multi-Sample

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Chapter 1

Introduction

1.1 Objectives

The Safety Integrated System (SIS) shall be maintained regularly to ensure its performance is in accordance with Safety Requirement Specification (SRS) throughout the SIS lifetime. The SIS performance shall not be below the specified Safety Integrity Level (SIL). During the operational phase, a proof test is performed to reveal a failure within a component of SIS which can be undetected otherwise. The proof test interval is determined at the early stage of the design and it should be updated during the operational time when the equipment performance is changed from the performance stated in the design. Guidelines for follow-up SIF in the operating phase by SINTEF is one of the guidelines widely used in Norwegian Continental Shelf to update the proof test interval during the operational time. There is a need for evaluating the existing method for updating the proof test interval due to the existing method has not been updated for ten years. The operator input during these ten years of operation will be valuable for updating the method. The updating proof test interval method is evaluated in this master thesis.

The use of maintenance data effectively to analyze SIS performance during SIS follow-up activity is the primary objective of the master thesis. The objective is achieved by performing several simple tasks as detailed below.

1. Provide a systematic method on the classification of IEC 61508 failure method
   In the current practice, most of the oil and gas operators record the failure during the operation and maintenance phase based on ISO 14224 requirement. The functional safety engineer as the assessor uses the written information in failure notification data for classifying the failure into IEC 61508 failure class. This process can be time-consuming. Besides, the information in failure notification data is sometimes not adequate for the assessor to perform classification, and it is prone to human error and subjectivity. A method for systematically classifying the failure will help for standardization of the process.

2. Analyze different calculation approach for calculating the operational failure rate
   The task is to perform failure rate calculation based on the operational DU failure num-

bers and the data collection period. Guideline for SIS Follow-up activities by SINTEF suggests a combination of using operational experience and a priory knowledge of the failure rate by a Bayesian method. The focus on the task is to analyze the value to be used as a priory failure rate. The value of the failure rate from PDS handbook and aggregated failure rate by OREDA multi-sample approach will be used as a priory failure rate. The impact in the calculated failure rate is discussed.

3. Evaluate the algorithm for selecting new functional test intervals
   The final task is for evaluating the existing algorithm proposed by the guideline for SIS follow-up activities to update the test interval of the SIS Component (Hauge and Lundteigen, 2008). The test interval is optimized from the calculated operational failure rate. If the operational failure rate proves that the equipment is more reliable than the assumptions in the design and hence, the test interval can be increased. A method for doubling or halving test interval based on the operational data will be explored during the master thesis.

1.2 Background

Oil and gas platforms are handling highly flammable and toxic materials. The flammable and toxic materials are a source of the threat that may cause a hazardous event such as toxic gas dispersion, fire, and explosion. In order to prevent such as accident, safety barriers are installed at the oil and gas platforms. Rausand and Høyland (2004) classified a safety barrier as a proactive barrier and a reactive barrier. A proactive barrier function is to prevent or reduce the probability of a hazardous event. A reactive barrier function is to avoid or reduce the consequences of a hazardous event. One example of a proactive barrier is Safety Instrumented System (SIS).

SIS is a system designed to ensure safe operation in the facility by using electrical, electronic or programmable electronic (E/E/PE) technologies. The SIS is designed around individual functions, called Safety Instrumented Functions (SIF). A SIF typically contains a sensor, a logic solver and a final element. The performance required from a SIF to achieve a safe state is measured by Safety Integrity Level (SIL). SIL can be defined as the target level protection of a SIF. The IEC 61508 classifies SIL into four levels, where SIL 4 is the highest reliability requirement level and SIL 1 is the lowest level. The SIL of a SIF shall be determined through a risk analysis as a Risk Reduction Factor (RRF) (Smith and Simpson, 2016). For each SIL, a certain range of reliability level requirement is specified. The reliability level is measured as the probability of failure on demand (PFD) for low demand function and as the probability of dangerous failure per hour (PFH) for high demand function. When a SIL requirement is classified for a SIF, it is necessary for the offshore installation operator to ensure SIL is maintained throughout the life-cycle of a SIF including the operational phase. The SIS shall be followed-up during the operational phase to ensure its reliability are complying with the SIL requirement throughout the operational phase.

SINTEF establishes a guideline for SIS follow-up action during operational time based on IEC 61508 and IEC 61511 (Hauge and Lundteigen, 2008). The guideline covers main aspect of follow-up activities from planning, managing until the method to update the failure rate and the test interval. The guideline is focusing on low demand SIL function.

For a safety function operating in a low demand mode, the reliability of the component is measured by the average probability of a dangerous failure on demand (PFD). DU failure is the primary source of a PFD (Hauge et al., 2010). DU failure is a hidden failure which can only be revealed during a proof test or a demand scenario. From the number of classified DU failure throughout the platform operation time, the updated failure rate can be calculated. The quantification of random failure rates is uncertain but this method is general basis for monitoring the reliability of SIS during operational phase (Kallambettu and Viswanathan, 2018). The newly updated failure rate based on operational data will be used for updating the length of the test intervals.

Vatn (2006) proposes a Bayesian approach for calculating the operational failure rate during operation and then updating the test interval. The Bayesian approach is recommended for the 1oo1 system since the failure rates are lower for a higher voting system. The approach is the basis of guideline for follow-up SIS component by SINTEF(Hauge and Lundteigen, 2008). The Bayesian approach has been widely used to estimate the reliability of equipment by using prior information and hence saving the testing time for production acceptance (Ye and Qin, 2018).

Norwegian oil and gas have established a guideline for the application of IEC 61508 and IEC 61511. The guideline specifies several safety functions, one of them being fire or gas detection (NOGA-070, 2018). This function shall comply with SIL 2 requirements, which means the detector shall have high reliability. This requirement includes alarm signal generation, processing, and action signal transmission. A fire detection or gas detection function comprises of sensor and logic solver. The type of fire detection equipment is a flame detector, heat detector, or smoke detector. The type of gas detection equipment is an ultrasonic detector, an infrared gas detector or catalytic detector. Reliability of gas detector or fire detector shall be maintained during the operational time of platform through SIS follow-up activities. The number of installed detectors are high. It might be relevant to apply site-specific data only for updating the test interval (Hauge et al., 2010).

The master thesis is a collaboration between NTNU and Equinor to evaluate the practices of SIS-follow-up activities. The main focus is to analyze the existing method of updating the failure rate and test interval. The fire and gas detector failure notification data will be used as raw data for this master thesis.

1.3 Scope & Limitations

The scope of SIS follow-up during the operation phase is including operation, maintenance, monitoring and management of changes (Hauge and Lundteigen, 2008). The activities are also including management of bypasses, inhibit and overrides. The scope of this master thesis is limited to monitoring SIS integrity during maintenance and normal operation. The impact of monitoring and management of changes is excluded from the scope of work.

The master thesis is a continuation from specialization project perform in 2018 with the title

"Safety Instrumented System Follow-Up Activities in the Operational Phase by using Fire and Gas Equipment as a Case Study" by Raden Mailisa Fitria in Autumn 2018. During the specialization project, the systematic failure effect to failure rate is investigated. The conclusion is the existing data is not adequate for further classification to random and systematic failure. Hence further DU classification into random and systematic is not performed during the master thesis.

The scope of the master thesis is limited to perform reliability assessment from operational data by using fire and gas equipment as the case study. Equinor will perform the classification of maintenance data into DU failure and the thesis will suggest the effective method based on the classified data.

1.4 Approach

The research is semi-quantitative research by using the failure notification data from Equinor. At the beginning of the research, the development of a theoretical framework will perform through a literature study. In the literature study, the writer will learn about SIS follow-up method during operational from the international standard e.g. IEC 61511 and IEC 61508, Norwegian standard e.g. OLF 070, engineering guideline e.g. guideline from SINTEF (Hauge and Lundteigen, 2008).

For enhancing the theoretical framework, the Scopus database is used for searching SIS follow-up related journal. The main topic related to research is failure rate calculation, failure classification, systematic failure on SIS, future research in SIS, data collection, common cause failure during the operational phase and Bayesian approach.

The master thesis will focus on fire and gas detector as a case study. The Norwegian petroleum standard Norsok S-001 and NFPA 72 National Fire Alarm and Signaling Code will be used as the primary theory sources for fire and gas detectors. Besides, the literature from the supplier such as datasheet, general arrangement drawing, installation and operation manual are also used.

There are two main activities for this research. The first one is data quality checking and the failure and test interval calculation. Data quality checking was performed from the start of the research until 8 April 2019. The purpose of data quality checking is to categorize each of functional location or equipment tag number into the correct detector type, detector measurement principle, manufacturer and model type. The activity was performed with the help of Equinor, including Maintenance Engineer. Clarification meeting was held every week to discuss the findings with Functional Safety Engineer. A final clarification meeting was held with the responsible maintenance personnel in the facilities.

1.5 Structure of The Report

A proposed structure of the master thesis has been made according to the objective, as mentioned in Section 1.1 of this report.

Chapter one provides an introduction of SIS follow-up practices in the oil and gas industry. The task to achieve objective was described, including the approach for the master thesis. This chapter also includes the limitation of the master thesis.

Chapter two is a literature study on the detector and SIS follow-up activity. This chapter will describe the essential background knowledge and relevant aspects related to the master thesis. It will include details of how the detector work and how detector failure diagnostic.

Chapter three is a detail of data collection and analysis approach. It is presenting the approach of the research and describing all methods used for calculating the result.

Chapter four is presenting the result of the research and analysis of the result.

Finally, conclusions and recommendations for further work from this master thesis are presented in chapter five.

Chapter 2

Literature Study: SIL Follow-Up

The master thesis is a continuation from the previous specialization project titled Safety Instrumented System Follow-Up Activities in the Operational Phase by using Fire and Gas Equipment as a Case Study (Fitria, 2018). This master thesis is focused on the SIS follow-up maintenance activities by evaluating the required test interval for SIS component. The basic theory and literature study will follow the previous report. Some part is re-written for the clarity of the report.

The literature study starts with a short introduction of the Safety Instrumented System in chapter 2.1 and then it will continue to how to manage and maintain the SIS requirement during the operational phase. Chapter 2.2 will describe general practice of SIS follow-up activities. The master thesis will focus only on evaluating SIS follow-up activities based on failure notification lifeline as illustrated in Figure 2.1 below.

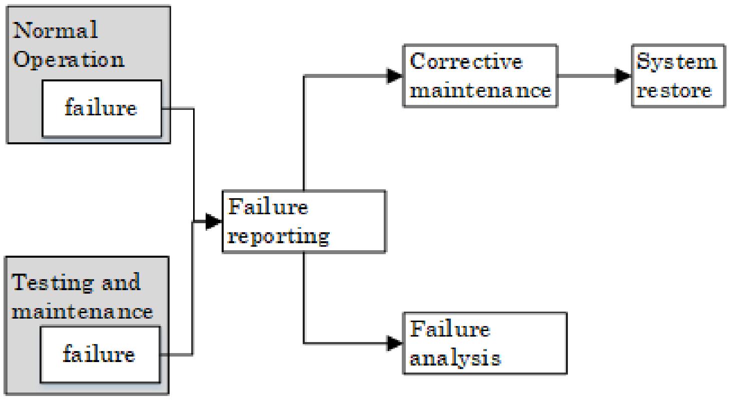


Figure 2.1: Failure notification lifetime

The starting point of the failure analysis is the aggregation of failure notification data during a certain time period. In this master thesis, the failure notifications data from 2012 until 2016 at 12 Equinor facilities are used. The failure analysis will be started with failure classification into IEC 61508 failure class as described in chapter 2.3. The quantitative analysis data will be performed by calculating the failure rate as one of the follow-up parameter of the SIS requirement and updating the functional test interval. They are described in chapter 2.4 and chapter 2.5. Fire and gas detectors are used for the case study in this master thesis and the description is detailed in Chapter 2.6.

2.1 SIS Introduction

The petroleum authority in Norway regulates that safety function shall be installed in the facilities to detect and prevent abnormal conditions and when the accident occurs due to the abnormal conditions, the damage shall be limited. One of the safety functions is the Safety Instrumented System (SIS). SIS is an instrumented system designed to ensure safe operation. SIS consists of three main components which are a sensor, a logic solver and a final element or an actuator. As SIS is one of a critical system for oil and gas, there are guidelines that regulate the design SIS. The guidelines used in oil and gas industry to design Safety Instrumented Function are IEC 61508 and IEC 61511. In the Norwegian Continental Shelf, the guideline is interpreted into Norsk Olje Gas (NOG) 070 standard.

IEC 61508 regulates SIS throughout its safety lifecycle to ensure that the SIS has high safety integrity during its lifetime. Figure 2.2 presents management of SIS lifecycle according to IEC 61508. The purposes of safety lifecycle management to ensure all important information related to the SIS are documented from the design phase until decommissioning phase, including SIS modification as illustrated in the overall safety lifecycle flowchart.

In accordance to IEC 61508, overall safety lifecycle includes the following phases as a minimum:

- Design phase, the stage where the system is engineered and the type of risk reduction measures is decided. The activities related to SIS design include concept determination to establish understanding of Equipment Under Control (EUC), scope definition to determine the boundary of EUC, hazard and risk analysis of EUC, overall safety requirements of EUC and overall safety requirement allocation to determine the required safety integrity level of the SIS.

- Installation and commissioning phase, the stage where the design is completed and the SIS ready to be installed and start the operation. In this phase the main purpose is to ensure that all the requirements and assumptions during the design phase are full-filled. The activities include planning SIS activities for commissioning and ensuring the requirements in SRS are implemented in the commissioning phase.

- Operation and maintenance phase, the activities include planning all operation and maintenance SIS related, document failure report for SIS component and functional testing the SIS component according to SRS.

- Decommissioning phase, the activity includes creates procedure to ensure the SIS is uninstalled and assessing the impact of SIS removal in the system.

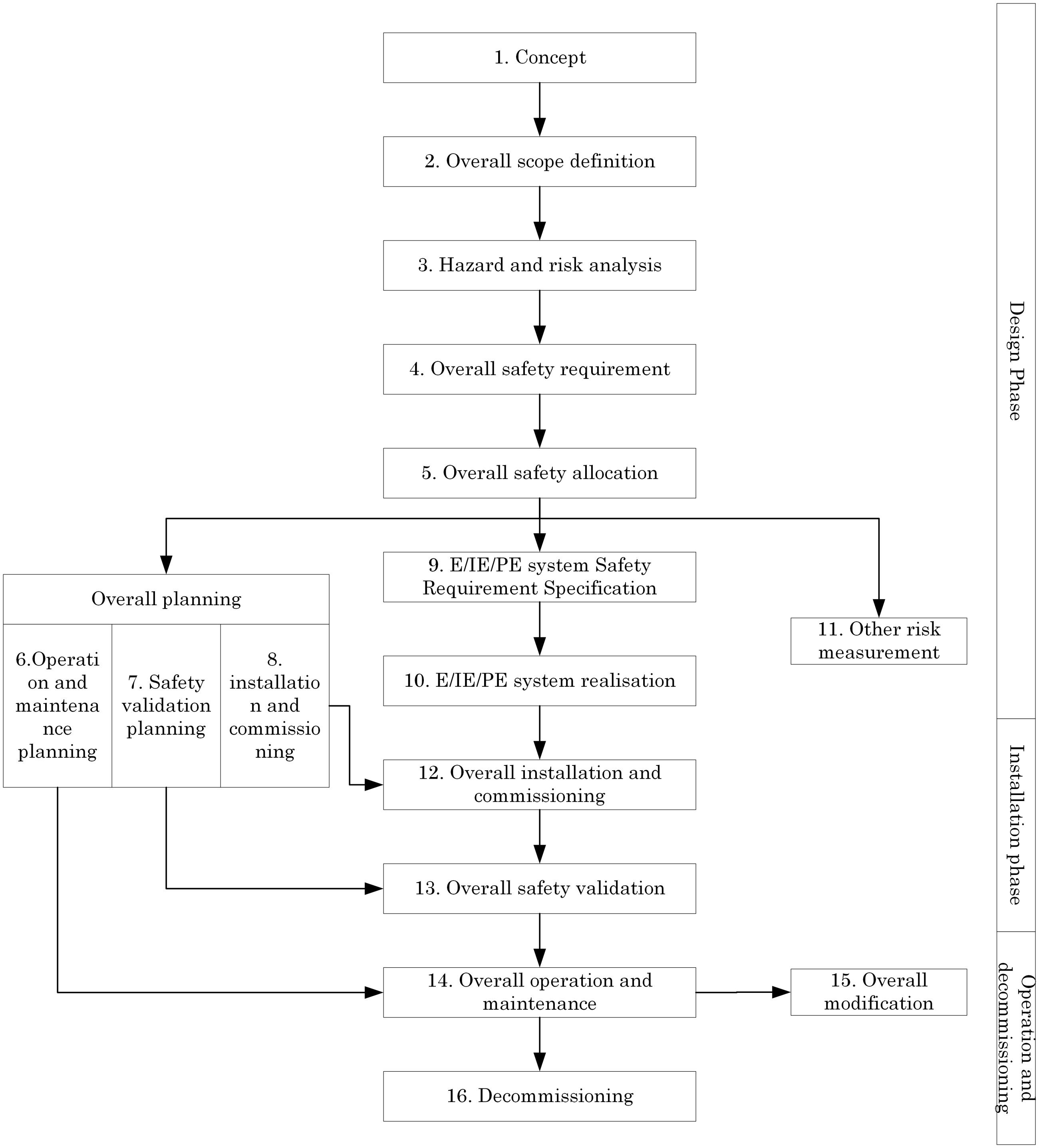


Figure 2.2: Overall safety lifecycle

The master thesis focuses into safety lifecycle phase overall operation, maintenance and repair(box number 14 in figure 2.2). During the operation and maintenance phases, it is required to ensure that the functional safety of SIS is maintained to the specified SIL as defined in Safety Requirement Specification (SRS). The objective shall be to ensure that the SIS is not degraded or disabled in such a manner that the SIF and allocated SIL are no longer retained. The activities associated to SIS component during operational phase is commonly labelled as SIS follow-up Activities. Research relates to SIS follow-up activities has been highlighted by Lundteigen and Rausand (2010), the journal states that the strategy of improving failure rates calculation during operational phase one of the future research related to the SIS subject.

2.2 SIS Follow-up Activities

Norwegian Petroleum Safety Authority (PSA) regulates that the oil and gas facility owner shall perform SIS follow-up activities in accordance to chapter 10 and chapter 11 of NOG guideline 070 (PSA, 2019). Chapter 10.3 NOGA 070 guideline illustrates SIS follow as Figure 2.3.

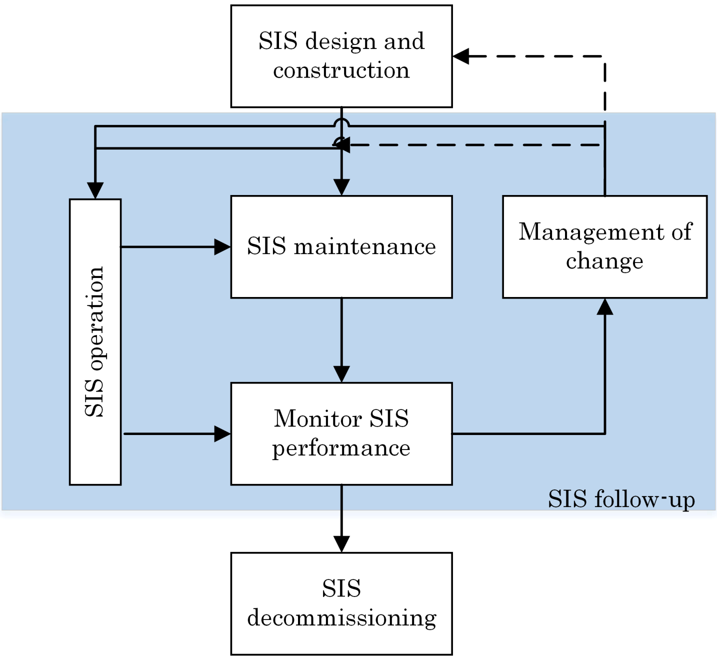


Figure 2.3: Illustration SIS Follow-up Activity (Hauge and Lundteigen, 2008)

Detailed description for each phase are described in the subsection below

2.2.1 Normal Operation

During normal operation, the facilities operate in a controlled manner. The operator shall perform day to day activities, including visual inspection of the SIS component. If there is a failure on an SIS component, the operator shall report and document the failure into the computerized maintenance management system (CCMS), such as SAP. During normal operation, failures can be observed during the regular visual inspection, alarm, or notification from equipment with diagnostic coverage and condition monitoring.

Hauge and Lundteigen (2008) states that maintenance preparation such as handling of a bypass, inhibit and overrides is also included as part of SIS follow-up activities during normal operation. When these activities are not handled with properly controlled manner, the possibility of human error causing a systematic failure will increase. Rahimi and Rausand (2013) also indicates that changing of an operational condition may cause the likelihood of Common Cause Failure. The journal states that to mitigate the CCF during normal operation, the inhibit and bypass shall be monitored.

2.2.2 Maintenance

There are four different types of maintenance for SIS, as listed below:

- functional testing of the function
- regular preventive maintenance to extend the useful lifetime of the equipment
- corrective maintenance to repair the failure or to change the equipment
- inspection to monitor the SIS regularly

The functional test is required for SIS, due to the SIS component, in oil and gas facility, normally not operating during normal operation. Functional testing is then the only way to reveal a failure. The functional test shall be performed based on predefined test interval in SRS and according to Macdonald (2003), the test interval can be decided based on the manufacturer recommendation, general practice and the required test interval to meet SIL requirement. The predefined test interval shall be included in the maintenance procedure.

The failures which reveal during the maintenance phase shall be documented in a traceable manner into the maintenance system. The activities include documenting the required action for repairing the defective component or changing the component. Failure reporting in Figure 2.1 is part of maintenance activities.

SIS is also subjected to a systematic failure during the maintenance period. The source of failures such as improper testing, poor maintenance procedure, or human error. The systematic failures can be addressed with a reliable management system.

2.2.3 Monitoring SIS Integrity

Failure analysis in Figure 2.1 indicates the activities to monitor SIS integrity. In this phase, qualitative and quantitative analysis are performed. The qualitative checking of failure notification shall be performed before failure classification. This activity was performed during the specialization project. One of the finding during the specialization project is indicating that the failure data notification report quality is very critical for good quality data classification (Fitria, 2018). A method to systematically classify the failure will be valuable. The method shall be easily understood by the operator who has limited reliability background. The quantitative analysis is performed by calculating the failure rate. The operational failure rates will be compared with the assumption failure rate, as stated in SRS. This step was also performed during the specialization project. Most of the facility or operation failure rate is lower than the assumption failure rate in the PDS handbook, but it is higher than the failure rate stated in vendor certification. The ratio of the operational failure rate and the assumption failure rate can be used for updating test interval (Hauge and Lundteigen, 2008).

2.2.4 Management of Change

Management of changes is critical to ensure that the safety barrier is in place during modification. A new risk analysis shall be performed during any modification of SIS, and hence the required safety integrity of the system is maintained. The modification shall not be performed before the risk analysis. Macdonald (2003) highlights that the Flixborough accident which killed 28 people in a major chemical plant was a result of poor management of changes.

The SIS modification may include software, hardware, procedure, assumptions or perquisite in SRS. The SIS owner shall identify the availability of competence and the required training when a modification is implemented. The management of changes is not included in the analysis.

2.2.5 SIS Management

Management of SIS follow-up activities is critical to ensure the transfer of all requirements and prerequisites in SRS to operation and maintenance activities in a systematic manner. A good SIS management system can prevent systematic failure of SIS according to Gentile and Summers (2006). SIS management is used as a method to prevent human error and improve the organizational factor to prevent failure. Schönbeck et al. (2010) suggests that human and organizational factors are most in need of improvement during operational and maintenance phase. A good management system can minimize failure caused by the human and organizational factor. The management of SIS follow up activities shall consist of a plan on how to prepare and execute the activities during the operational phase. The planning for the SIS follow-up activities is established during the engineering phase and the required initial procedures and instructions are available prior to plant start-up. Hauge and Lundteigen (2008) wrote in SINTEF SIS follow-up guideline that SIS follow-up may start at phase 6 of the IEC 61508 safety lifecycle. The preparation may include but not limited to, the following:

- establish personnel and organizational responsibilities as part of the maintenance management system,
- develop means for collecting all the SIS data, and
- information correction during operation and maintenance execution e.g., by using management tools such as Computerized Maintenance Management System (CMMS) and develop a method to incorporate management of changes.

2.3 Failure Classification Based on Failure Reporting

Failure is a condition when an equipment is not able to perform its function. A failure can be defined based on the root cause, failure mechanism and failure mode. The root cause is the basic cause of failure. The Failure mechanism is the process of failure occurring. Failure mode is failure definition based on how the fault is observed. All the failure observed during normal operation and maintenance are recorded in the failure notification data in CMMS. The failure reporting is executed by the maintenance personnel. It is recorded as long text and it is occasionally classified into failure cause, failure effects and detection method (Lundteigen and Rausand, 2007). The journal also suggested that the failure cause generate root cause which can be used to identify common cause failure (CCF).

Equinor records the failure notification data based on ISO 14224 requirement. The maintenance personnel performs a pre-defined classification of the notification data. Failure mode, failure impact on the function, failure mechanism and detection method are recorded besides the failure date and the follow-up actions. ISO 14224 recommends to include IEC 61508 failure classification in the failure notification data.

In the industrial practice, the failure mode, failure impact and failure mechanism are recorded by operational or maintenance personnel. While IEC 61508 failure classification is decided by the reliability engineer when the reliability data is evaluated. The classification is not performed at the same time as failure date notification created. This procedure is performed due to the operator or maintenance personnel has a lack of knowledge on the failure analysis.

As an assisting aid for the reliability engineer classifying the failure in accordance with IEC 61508; a long text is created about the failure description, failure cause and the corrective measure. Based on the detailed description of the failure, the engineer can review the data before further data analysis, such as failure rate calculation. Håbrekke and M.A. (2017) also stated that the reported failure in the notification should be reviewed before using it in reliability analysis.

There are two different IEC 61508 failure classifications. The failure classification based on the effect and the cause. Based on the cause of failure, failure is classified into random failure and systematic failure. The random failure is related to the physical of the equipment such as aging and systematic failure related to the non-physical failure. Hokstad and Corneliussen (2004) declares the systematic failure and random failure due to stress as the cause of the CCF. However, the calculation of the failure rate is based on random failure only.

The classification failure based on the cause is not common to perform. It is understandable as the systematic failure is supposed to be prevented by following the systematic avoidance method in IEC 61508 part 1. The supplier shall ensure systematic capability and the designer shall also avoid the systematic failure. The systematic failure of equipment is not considered to repeat itself.

Arguably, the classification of the failure notification data into systematic failure has no significant value in the reliability calculation. Goble and Bukowski (2016) suggests counting all failures for operational failure analysis, including systematic failure to avoid overoptimistic failure rates. Other studies that support the opinion is from Hauge et al. (2016) that states the identification of CCF is not essential to define if the failure is systematic or not. It is added the reasoning not to classify the failure based on the cause of failure.

2.3.1 Failure Classification Based on Effect

The existing practice is only to classify failure based on the effect only. An effort was performed during the specialization project to classify failure based on the cause of the failure, but the existing notification data does not have adequate information to perform the action(Fitria, 2018). The main limitation of failure classification into random and systematic failure is the different interpretation of defining that the failure is a systematic failure (Goble and Bukowski, 2016). Several studies also have a different interpretation of systematic failure. Further work is required to establish a more applicable practice to define the systematic failure and the advantages of the practice. Based on the effect failure is classified into dangerous and safe as indicated in Figure 2.4 below.

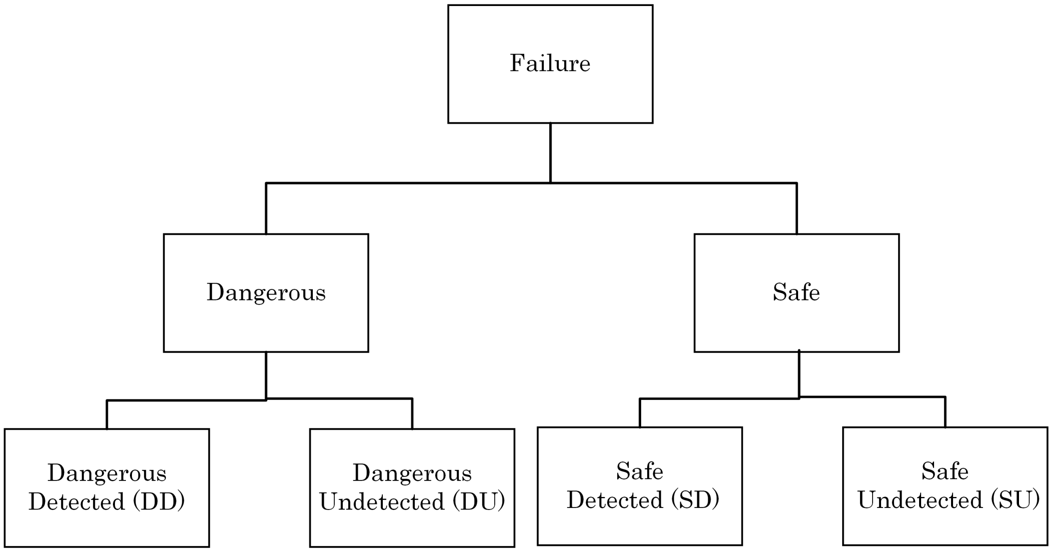


Figure 2.4: Failure classification by Effect

Dangerous failure is a failure of a component that prevents a safety function from operating when required or causes a safety function to fail such that the Equipment Under Control (EUC) is put into a hazardous state. Dangerous detected (DD) failure is a dangerous failure that can be detected by automatic diagnostic testing or personnel self-test. Dangerous undetected (DU) failure is a dangerous failure that can not be detected by the diagnostic test, operator intervention or through normal operation.

Safe failure is a failure that affects the safety function but does not have the potential to put the EUC in a hazardous or fail-to-function state. Such failures may result in a transition to a safe state of the component, which again may lead to a production shutdown. Safe detected (SD) failure is a spurious failure that can be detected by automatic diagnostic testing or personnel self-test. Safe undetected (SU) failures is a safe failure that cannot be detected by the diagnostic test, operator intervention or through normal operation.

Besides the above failures, PDS Handbook also includes non-critical (NONC) failures. NONC failure is defined as a failure that is not affected by the main equipment ability to perform the intended function, but it may gradually develop into a critical failure.

2.3.2 Failure Mode and Effect Diagnostic Analysis (FMEDA)

FMEDA is developed by EXIDA as extensions of the classic FMEA in the late 1980s(Grebe and Goble, 2007).The FMEDA approach was created to classify and calculate the various failure rate category at the product level. The method has been widely used by the product manufacturer such as conventional PLC, but this method has a limitation when the circuit is complex. Catelani et al. (2010) states the purposes of FMEDA for the SIS lifecycle, as mentioned below:

- As a method to identify the failure of the SIS component to perform its function and the consequences of the failure
- As a systematic way for defining the measures that can be implemented to detect or prevent failure.
- As a method for calculating the safe failure fraction (SFF)

The FMEDA method was created to allow practical prediction of an SIS component failure based on the failure rate and failure mode distributions from a database and diagnostic methods Bukowski. The identification of diagnostic method helps to decide the detected and undetected failure. Beside the FMEDA method is pertinent to measure the diagnostic coverage when component failure mode is known (Goble and Brombacher, 1999). Each failure mode is classified to determine if the failure is either safe or dangerous (Grebe and Goble, 2007).

In this master thesis, a simplified FMEDA is proposed to be used for IEC 61508 failure classification of a failure notification data. The method was proposed to improve the semi-automatic method proposed by Østebø and Dammen (2006) for converting ISO 14224 maintenance data to a format relevant to reliability calculation based on IEC 61508. The approach implies to be consistent with other research that suggested the FMEDA can be used for the other risk assessment. Catelani et al. (2010) uses FMEDA to perform complex safety analysis and the result that the FMEDA allow accurate SIL assessment. Messnarz and Sporer (2018) uses FMEDA for functional safety case of the brake system to calculate the failure in time. van Beurden and Goble (2015) uses FMEDA to calculate the failure rate for SIS verification by combining the failure rate from operational data and Exida database.

The simplified FMEDA method uses ISO 14224 failure data such as failure mode, failure mechanism, and detection method as the basis for failure classification. The classification on each failure notification is in line with a report by Selvik and Abrahamsen (2017). Failure mode and failure mechanism is used to define the critically of the failure. The failure mode shows how the failure is manifesting into the system, and the process of the failure induced into the component is labelled as failure mechanism(Traore et al., 2015). By defining the failure mode and failure mechanism, the effect of failure into system and equipment can be investigated. Catelani et al. (2018) performs failure effect analysis on temperature redundant sensor stage by defining failure mode and failure mechanism through Failure Mode, Mechanism and Effect Analysis (FMMEA). The method is found effective to identify incipient failure and to increase the number of Safe Failure Fraction (SFF).

A systematic SIS failure mode classification is required to ensure the quality of the result and as a method to allow the personnel to backtrack the classified failure, e.g., the new personnel is easily understand why the failure is classified as DU / DD / S. This may also improve the data quality and reduce the subjective interpretation of the assessor. The requirement to improve reliability data collection includes failure classification is also highlighted by Håbrekke et al. (2018).

2.4 Updating Operational Failure Rate

The integrity level of SIS component for a low demand function is measured by the probability of failure on demand (PFDavg). The PFDavg is a function of a dangerous failure rate during a defined test interval. The DD failures are arguably can be neglected for the PFDavg calculation as during the DD failure, the equipment is restored in condition as good as new during a short time period (Hauge et al., 2009). Hence the PFDavg is calculated based on the DU failures solely. The DU failures obtained from operational experience are used to calculate the failure rate. The operational failure rate is a preferable value for use in SIF calculation (van Beurden and Goble, 2015). The existing PDS forums use failure data from OREDA to create reliability data dossier.

There is a various method to calculate the failure rate from the operational data. In general, it is assumed that the equipment is in constants failure rate and maximum likelihood estimator for the exponential equation is used to estimate the failure rate. Maximum likelihood method is only applicable when the samples are homogeneous and several failures are observed in a certain period of time. Nevertheless, the samples in industrial practice sometimes are not homogeneous and failures may not occur in a component during the observed period. Vatn (2006) proposes a Bayesian procedure to estimate a component operational failure rate based on theoretical failure rate data. Bayesian statistic treats uncertainty in a stochastic process by updating the parameter distribution (Bernardo and Smith, 2009). Hryniewicz et al. (2015) claims Bayesian method is widely used by reliability engineer for combining the existing data and prior data from different data sets despite its controversy. The main controversy of Bayesian approach is the usage of prior information, which tends to subjective.

The Bayesian approach is not competent to predict operational failure rate from a non-homogeneous sample. This was investigated during the specialization project. During the project, two methods are used to calculate the failure rate. They are the Bayesian method and OREDA Multi-Sample. The conclusion is that the OREDA Multi-Sample is a better calculation method to represent the aggregate failure rate form the different facilities as representative of non-homogenous samples. While the Bayesian method is suitable for calculating the failure rate for a facility when the data does not have enough number of failure Fitria (2018), the Bayesian approach obtains the facility-specific statistical parameter that would be expected from the facility observed data based on the observation from other facilities in the same data pool (Hofer, 1999).

The equation was represented during the specialization project but it is rewritten for clarity.

2.4.1 Operational Failure Rate Only

The operational failure rate can be calculated by using maximum likelihood estimator as below.

$$\hat{\lambda_{DU}} = \frac{x}{t_n} \tag{2.1}$$

where:

x = the number of components in the population of comparable components

t_n = total aggregated time in operation (hour)

A 90% confident interval can represent the uncertainty of the estimated failure rate. The 90% confident interval of $\hat{\lambda_{DU}}$ can be calculated by using equation C.10 below.

$$\left(\frac{1}{2\tau} z_{0.95,2\,n}, \frac{1}{2\tau} z_{0.05,2(n+1)}\right) \tag{2.2}$$

where:

$Z_{0.95}$ = 5% lower limit confident interval

$Z_{0.05}$ = 95 % upper limit confident interval

τ = time observation period

n = number of DU failures

Hauge and Lundteigen (2008) states the operational data can be used for estimating failure rate solely when the confidence interval in $\hat{\lambda_{DU}}$ is comparable to the confidence interval of design λ_{DU}. Typically when the upper 95% percentile of $\hat{\lambda_{DU}}$ is approximately three times the mean value or lower. The guidelines also state that this requirement is usually fulfilled when the product of accumulated operational hours times the number of failures exceed 3×10^6 hours.

If during operation zero number of DU failure is observed, it is necessary to use the original failure rate for updating the failure rate of the equipment. One of the methods commonly uses is the Bayesian method.

2.4.2 Updating Operational Failure Rate by Bayesian Method

When the operational data is not statically adequate for updating the failure rate, the Bayesian method can be used. The method is combining the operational data and the conservative estimate of the failure rate from the existing database or data pool e.g. PDS Handbook data. The conservative failure rate shall be the maximum value between operational failure rate, database failure rate or deterministic value of 5×10^{-7} as equation 2.3.

$$\lambda_{DU-CE} = max\left(2\hat{\lambda_{DU}}, 2\lambda_{DU}, 5 \times 10^{-7}\right) \tag{2.3}$$

where:
λ_{DU-CE} = the conservative failure rate (per hour)
$\hat{\lambda_{DU}}$ = the calculated failure rate from operational data (per hour)
λ_{DU} = failure rate from database such as PDS (per hour)

? states that there is no operational failure better than the value of 5×10^{-7}. Hence this number is used for avoiding underestimated data. The next step is calculating the uncertainty of failure rate. Vatn (2006) defines the uncertainty parameter as equation C.11 and equation C.12.

$$\alpha = \frac{\hat{\lambda_{DU}}}{[\lambda_{DU-CE} - \hat{\lambda_{DU}}]^2} \tag{2.4}$$

$$\gamma = \alpha.\hat{\lambda_{DU}} \tag{2.5}$$

Hauge and Lundteigen (2008) recommends equation 2.6 below to update the failure rate.

$$\ddot{\lambda_{DU}} = \frac{\gamma + x}{\alpha + t_n} \tag{2.6}$$

The bayesian failure rate, $\ddot{\lambda_{D_U}}$, is normally in region of 90% confident interval of $\hat{\lambda_{D_U}}$.

The confident interval of Bayesian approached is called as a credibility interval, by using chi-square distribution the formula is depicted as below (Rausand and Høyland, 2004).

$$\left(\frac{1}{2(\alpha + t)} z_{0.95,2(\gamma+n)}, \frac{1}{2(\alpha + t)} z_{0.05,22(\gamma+n)}\right) \tag{2.7}$$

where:
$Z_{0.95}$ = 5% lower limit confident interval
$Z_{0.05}$ = 95 % upper limit confident interval
τ = time observation period
n = number of DU failures

2.4.3 OREDA Multi-Sample

OREDA handbook develops failure calculation for non-homogeneous data. In the industry practice, it is challenging to collect data with the same operational condition, environmental condition, or the same interaction between the equipment and human. It is expected a different value of the operational failure rate, $\hat{\lambda_{DU}}$ for a different facility or system. The method to calculate a non-homogeneous sample is called a Multi-Sample. This method will provide more realistic data and confident interval.

To calculate Multi-Sample OREDA estimator, the following procedure is used:

- define the number of the facilities, it is denoted as k
- calculate an initial estimate of the mean failure rate by pooling the data

$$\hat{\theta}_1 = \frac{\sum_{i=1}^{k} n_i}{\sum_{i=1}^{k} \tau_i} \tag{2.8}$$

where:
n_i= the number of DU failures
τ_i = total aggregated time in operation (hours)

- calculate the statistical coefficient

$$S_1 = \sum_{i=1}^{k} \tau_i \tag{2.9}$$

$$S_2 = \sum_{i=1}^{k} \tau_i^2 \tag{2.10}$$

$$V = \sum_{i=1}^{k} \frac{\left(n_i - \hat{\theta}_1\right)^2}{\tau_i} = \sum_{i=1}^{k} \frac{n_i^2}{\tau_i} - \hat{\theta}_1^{\,2}\, S_1 \tag{2.11}$$

- calculate an estimate for variance between sample

$$\hat{\sigma}^2 = \frac{V - (k-1)\hat{\theta}_1}{S_1^2 - S_2} \times S_1 \tag{2.12}$$

when the result is greater than 0, otherwise

$$\hat{\sigma}^2 = \sum_{i=1}^{k} \frac{\left[\frac{n_i}{\tau_i} - \hat{\theta}_1\right]^2}{k-1} \tag{2.13}$$

- calculate the mean failure rate

$$\theta^* = \frac{1}{\sum_{i=1}^{k} \frac{1}{\frac{\hat{\theta}_1}{\tau_i} + \hat{\sigma}^2}} \sum_{i=1}^{k} \left[\frac{1}{\frac{\hat{\theta}_1}{\tau_i} + \hat{\sigma}^2} \times \frac{n_i}{\tau_i} \right] \tag{2.14}$$

- calculate the gamma distribution parameter $\hat{\alpha}$ and $\hat{\beta}$

$$\hat{\alpha} = \hat{\beta} \times \theta^* \tag{2.15}$$

$$\hat{\beta} = \frac{\theta^*}{\hat{\sigma}^2} \tag{2.16}$$

- calculate the confident interval

$$\left(\frac{1}{2\hat{\beta}} z_{0.95,2\hat{\alpha}}, \frac{1}{2\hat{\beta}} z_{0.05,2\hat{\alpha}}\right) \tag{2.17}$$

The confident interval is following chi-distribution with $2\hat{\alpha}$ degree of freedom. The failure rate estimator cannot be used when the facility is only one and the number of DU failures are zero.

2.5 Updating Test Interval Method

IEC61511 (2003) part 1, 2015, states that "Periodic proof tests shall be conducted using a written procedure to reveal undetected faults that prevent the SIS (Safety Instrumented System) from operating in accordance with the SRS (Safety Requirement Specification). The entire SIS shall be tested, including the sensor(s), the logic solver and the final element(s).". The SIS owner is typically performing functional tests to individual SIS components based on the SRS requirement at the design phase.

During operational phase, the failure notification data for each individual SIS component is collected during certain time interval. Based on the data, the operational failure rate is calculated. From the operational data, the reliability of SIS component can be revealed. The equipment can be more reliable or less reliable than the assumptions in SRS. If the equipment is less reliable, a test interval maybe required to be decreased and hence the safety integrity is maintained. Hauge and Lundteigen (2008) proposed method for update test interval in SINTEF guideline and it is detailed below:

1. Calculate the failure rate based using Bayesian method as shown in Equation 2.6
2. Estimate the tolerable test interval changes by calculating the ratio of $\lambda_{DU}/\ddot{\lambda}_{DU}$
3. The first estimated test interval can be estimated by the following equation

$$\ddot{\tau} = \frac{\lambda_{DU}}{\ddot{\lambda}_{DU}} \times \tau \tag{2.18}$$

4. If the calculated $\ddot{\tau}$ is larger than τ:
    (a) The new test interval $\ddot{\tau}$ shall be rounded down to the first allowed test interval on a discrete scale in 1 month, 3 months, 6 months, 9 months, 12 months, 18 months, 24 months, 36 months.
    (b) If $\ddot{\tau}$ is doubled of the original test interval (τ) than the test interval can only be considered doubled if $\hat{\lambda}_{DU}$ is less than half the priory λ_{DU} and the entire estimated 90% interval for the $\hat{\lambda}_{DU}$ is below the priory λ_{DU}.If not fulfilled, then the new test interval shall again be rounded down to the next allowed test interval as in point (a) above.

5. If the calculated $\ddot{\tau}$ is smaller than τ:
    (a) The new test interval $\ddot{\tau}$ shall be rounded up to the first allowed test interval on a discrete scale in 1 month, 3 months, 6 months, 9 months, 12 months, 18 months, 24 months, 36 months.
    (b) If $\ddot{\tau}$ is half of the original test interval (τ) than the test interval can only be considered halved if $\lambda\hat{_{DU}}$ is more than twice the priory λ_{DU} and the entire estimated 90% interval for the $\lambda\hat{_{DU}}$ is above the priory λ_{DU}.If not fulfilled, then the new test interval shall again be rounded up to the next allowed test interval.

The above procedure has the following rules to be compiled:

1. The new test interval cannot be more than doubled or halved than the original test interval.
2. The maximum allowable test interval shall be 36 months
3. The original test interval τ is based on the original assumed λ_{DU} and it is selected to comply SIL requirement.

Zhu and Liyanage (2018b) proposes a modification from the SINTEF guideline. The modification is by increasing the test interval based on overall safety integrity level. The test interval can be increased if the PFDavg below the requirement. It will potentially increase test interval without compromises safety. In the writer opinion, this method is optimistic. It can double the test interval without adequate statistical data. Other suggestion for updating the test interval is by implementing Prognostic and Health Management (PHM). This method has been investigated effectively for the final element, such as valve (Zhu and Liyanage, 2018a).

2.6 SIS Component: Fire and Gas Detectors

Gas release or fire is one of typical Major Accident Event (MAE) at oil and gas installation. One of control measure for fire accident or gas release is by installing Fire and Gas Detection System (FGS) in the facilities. The purpose of fire and gas detection system is to perform continuous monitor of the presence of hazardous fire or gas conditions and to initiate control actions manually or automatically in order to minimize the likelihood of MAE escalation.

Fire and gas detection system is consisting of detectors and fire and gas logic solver. The system processes input signals from the field mounted detectors, manual call point and push buttons related to firefighting. It is designed to initiate shutdown actions, release fixed firefighting systems, alert personnel and isolate ignition sources. Several types of detector use a dedicated fire central interface between the detector to fire and gas logic solver. Generally, addressable fire central is used to enable identification of the detector's location when it is triggered.

Ensuring the functionality of fire and gas detection system is critical. Failure of the system may impact the safety of personnel in the facilities. Norwegian oil and gas association in guideline 070 is stated that fire detection or gas detection is a Safety Instrumented Function (SIF) with minimum Safety Instrumented Level (SIL) requirements of SIL 2. The requirement is applied to the sub-function for detection, given exposure to one detector. The SIF shall generate an alarm signal, processed and transmitting action signal to the final element. The fire detection or gas detection function Reliability Block Diagram (RBD) is indicated in Figure 2.5 below.

Figure 2.5: Reliability Block Diagram of fire detection or gas detection

The safe state of SIF is achieved when the logic solver sends a signal to activate final elements. The system is de-energized to safe state according to GL 070 (NOGA-070, 2018).

The detection coverage is an additional requirement to ensure the detector functionality. The detector shall be located in such a way it can detect gas release or flame. The general requirement is 90% of gas release should be detected (Basu, 2016).

Subsection below is detailed the detectors. The section is restated the specialization project section on the detector.

2.6.1 Flame Detector

The flame detector detects fire occurs and sending the detection signal to fire and gas system. There are several types of flame detection available in the market. However, the principle of detection is the same. The sensor detects the absorption of light at a specific wavelength. In the latest version of the flame detector, more than one sensor is installed inside the detector to differentiate the flame and false alarm such as welding arc, sunlight, etc.

The flame detector typically has the diagnostic capability. The condition of the flame detector is monitored through 0 to 20 mA and visually through the LED lamp. During normal condition where the flame is not present, the detector transmits 4 mA signal. It transmits 20 mA signal during the presence of fire. The 0 to 3 mA DC is indicating a fault condition. LED lights are typically installed at the flame detector to indicate fault condition(Emerson, 2018). The continuous test monitoring is applied to the voltage status of the sensor, relays, software, memory, oscillator frequency, 0-20 mA output, lens cleanness, sensors, electronic circuitry. The typical wiring schematic of the flame detector is indicated in Figure 2.6 below.

The flame detector should be functionally tested regularly as part of a site fire alarm test. The test is performed using a test lamp or a magnetic test. Prior to functional testing, the detector

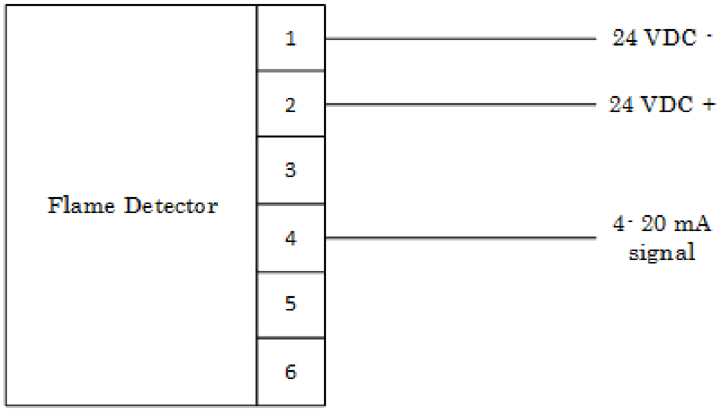


Figure 2.6: Typical termination wiring diagram of flame detector

lens shall be checked and cleaned. If the detector is not indicating alarm during testing, the detector fault is considered a dangerous fault. A low response is also may occur during functional testing. The other DU failure that may occur is when the detector fails to function on demand.

The other typical DU failure for the flame detector is a blockage on the flame detector cone vision as the flame detector cannot monitor object at shadow area. The flame detector is working as a camera. The detector shall see the fire and hence, the reduce viewing of the detector shall be avoided. This failure has typically occurred during the modification project. The new equipment or even new piping in the area can reduce the view of the flame detector. The failure is typically considered as systematic failure. When the failure is found only during the functional test, even it debatable, the failure can be categorized as DU failure. Figure 2.7 shows the principle of the area that can not be detected by the flame detector.

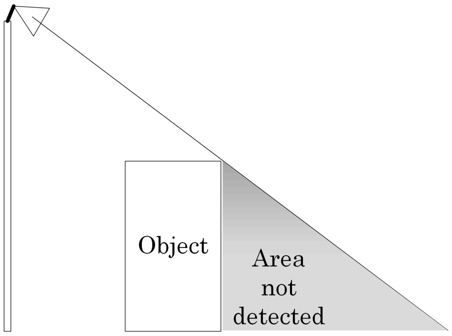


Figure 2.7: Flame detector cone vision obstruction- typical

2.6.2 Heat Detector

The heat detector is installed for detecting fire in an enclosed area where high-temperature fires may be expected in combination with a humid environment, such as turbine enclosures, workshop and galley (S-001, 2008). The heat detector principle is sensing the temperature rise as the by-product of a combustion reaction. There are two main types of heat detectors, a rate of rise and fixed temperature.

A fixed temperature heat detector consists of a fixed temperature sensor, the detector housing, 0-20 mA output, and sometimes an LED indicator. During heat detection, the LED turn on continuously. While its turn off at normal operation. The self-test function is normally embedded into the newer generation of heat detectors to ensure the highest grade of reliability. The fixed temperature heat detector is normally connected to fire central as an addressable unit. A rate of rise heat detector consists of detector housing, sensor, 0-20 mA output, and resistors for alarm.

Functional test of the detector shall be performed by using a test kit according to manufacturer recommendation. The standard test kit is a heat gun, hair dryer, industrial soldering iron, aluminum test block, magnetic equipment or heat lamp. The typical DU failure of heat detector is no signal during a functional test.

2.6.3 Smoke Detector

A smoke detector is a device for sensing the presence of smoke(Chen et al., 2007). The smoke detector is used in an indoor area where a flaming fire and a smoldering fire may occur. There are three types of smoke detectors which mainly used, the photoelectric aka optical detector, ionization detector and aspiration smoke detector.

The ability of a smoke detector to detect is depending on its location. The smoke shall enter the chamber for detection is occurred. The maximum distance between smoke detectors is 11 m, maximum distance from the smoke detector to bulkhead is 5.5 m and a minimum 0.5 m away from an outside wall or dividing partition(S-001, 2008).

The latest generation of smoke detectors is embedded with self-diagnostic function. This function reduces testing maintenance and increases reliability. It is usually connected to a fire panel and an addressable unit. The unit is self-checking its healthiness every second.

A functional check of the smoke detectors must be performed periodically by utilizing a suitable testing device. Detectors that do not respond or which are mechanically damaged must be replaced. The typical DU failure of heat detector is no signal during a functional test.

One of the latest inventions is combining smoke detection and heat detection technology. The detector is called as multi-sensor heat/smoke detector. This type of detector is usually located in high voltage electrical room for increasing sensitivity of detecting smoke. The multi-sensor smoke and heat detector are merging optical smoke detector with a temperature monitoring device. This detector is typically connected to fire central.

Self-verify Smoke Detector

The detector is designed to detect visible smoke and it is equipped with a built-in thermistor for reading the temperature. One of the remarkable features of the detector is self-verify. The self-verify feature ensures the detect to check its condition every second and this feature is automatically tested with automatic calibration test daily. It reduces the maintenance requirement of the detector and increasing reliability. The supplier also claims the detector has high detection coverage up to 94%.

The alarm turns on when the smoke is detected. An additional feature of the detector is the detector immune to electromagnetic disturbance, and hence, it can be located at the high voltage electrical room. The detector can be installed inside an explosion atmosphere because it is Zone 2 rated. Figure 2.8 shows the schematic drawing of the Self-verify smoke detector.

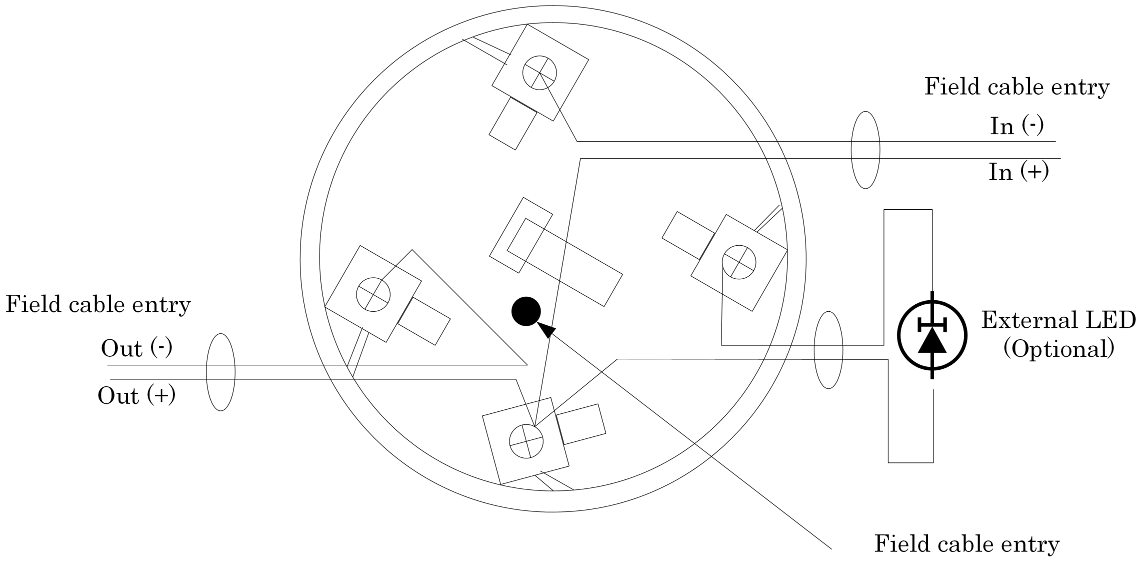


Figure 2.8: Schematic drawing of smoke detector Self-verify smoke detector

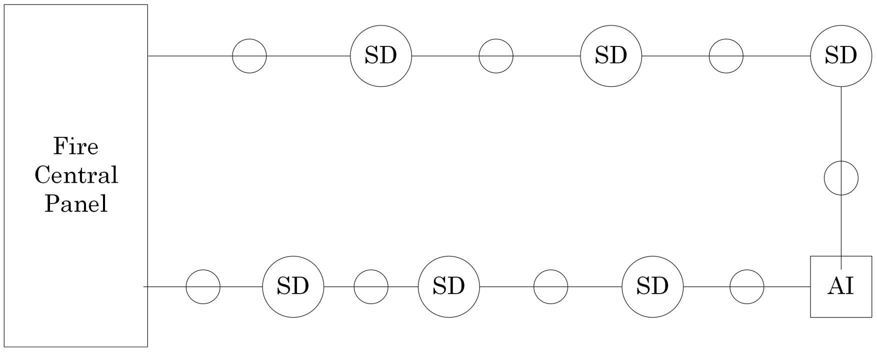


Figure 2.9: Loop diagram of self-verify smoke detector

The Self-verify smoke detector smoke detector is normally installed inside the fire alarm system loop, as illustrated in Figure 2.9. The fire alarm system with addressable unit enables the operator to know the location of the detector that is triggering during smoke detection. A fire alarm loop is a loop with wires carry power and signals inside the circuit boards. Addressable Input (AI) is normally installed at the loop to detect if there is a fault in the looping.

Safety requirement of self-verify smoke detector

The detection function requirement for a smoke detector according to NOG GL 070, in the given of a smoke exposure of one detector shall generate an alarm and the signal shall be processed by Fire and Gas (FG) logic solver to transmit actions signals. Figure 2.10 provides clear representative RBD of smoke detection function. It can be concluded that the smoke detector shall detect the smoke and ends with sending the signal to the FG system. The Fire central panel shall be included as the panel is the equipment that sends the signal to FG logic solver.

Figure 2.10: Reliability diagram of smoke detection function

The smoke detection function is normally energized; in the case of loss of power supply, the system is in the safe state. The safe state is achieved when a signal is transmitted and processed in the FG node. Hence it can be concluded that one of the failure mechanism is no / fault signal and the failure mode is no output or low output from the detector or fire central panel fails to perform its safety function. Typically initial test interval for this detector is 12 months with SIL 2 requirement.

2.6.4 Point Type-Infrared(IR) Gas Detector

The infrared gas detector is working based on measuring principle of hydrocarbon gas absorbs a certain band of infrared wavelength. The sensor inside the detector detects a volume of gas release when the infrared signal is absorbed by the gas.

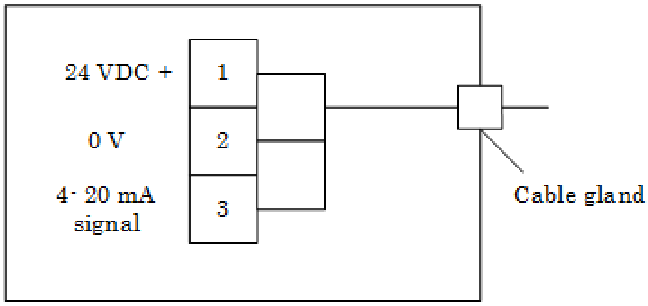


Figure 2.11: Point type gas detector termination wiring diagram

When the gas detected or the gas detector is in fault condition an output signal is sent to the controller. The typical output signal of point type - infrared detector is ranged from 4 to

20 mA, the current is corresponding to the gas concentration. 20 mA is indicating that the gas concentration is 100% Low Flammable Limit (LFL) or higher. Figure 2.11 shows an example of termination drawing of a point type gas detector.

The point type-IR gas detector is equipped with an alarm on dirty optics and detector failure. Typically, it is indicated with a 0-3 mA signal. An internal microprocessor performs continuous self-testing of optical and electronic functions. If a fatal error should occur in the electronics or optics, the processor generates a no output signal, indicating detector failure.

The point type infra-red gas detector is categorized as a fail-safe design. The IR lamp continuously sends an infrared signal to the IR sensors. Typically this radiation is monitored by the detector and self-maintained function is installed in the detector. However, most of the suppliers suggest that the gas detector should be tested regularly. The test is performed by using a test gas directly to the detector if it is reachable or through a test nozzle with a testing kit. The typical of DU failures for the gas detector is no output during a functional test, low output during a functional test, and the detector fails to function on demand.

The gas detector shall be located based on an assessment of gas leakage scenarios within each area considering potential leakage sources and rate, dispersion, density, equipment arrangement and environmental conditions such as ventilation, and the probability of detection of small leakages within the area (S-001, 2008). The distance between the gas detector shall ensure that the gas reaches the chamber in the detector. Necessary protection arranged when detectors are located. The weather protection is installed if the detector is located in the area with harsh environment e.g., the infra-red gas detector located at the perimeter of the deck.

Point type IR gas detector at an air intake ducting in a combustion engine is normally equipped with an aspirator apparatus. The aspirator apparatus is installed when impractical to install a point type IR gas detector inside the air intake ducting. The aspirator gas detector consists of point type IR gas detector, tubing, flow sensor with low low alarm and an aspirator panel. The gas inside a ducting enters small tubing of aspirator detector then it is detected by the point type gas detector. The flow sensor function is to ensure the air is flowing inside the tubing.

2.6.5 Open Path - Infrared (IR) Gas Detector

The open path-IR gas detector is an extended version of point type-IR gas detector. In the point type detector, the IR lamp as an infrared signal transmitter and a sensor is located inside one detector. In the open-path detector, the transmitter and receiver are located in a separate device to increase detection coverage. When a clear path is available, the preference is to install this type of detector. The same with point type detector, open path detector is also sending 0 - 20mA signal to the logic solver as the result of the detection. The receiver detector is producing 4 to 20 mA. The current is corresponding to the Low Explosion Limit meter (LELm). LELm is a special measurement of gas concentration that is adopted by an open path gas detector. The detector is equipped with an alarm on dirty optics and detector failure. This detector has a diagnostic function to measure its healthiness. However, all the suppliers suggest that the gas detector should be functionally tested regularly. The test is performed by using a test filter or a mirror to interrupt the path of the signal. Typical DU failure during a functional test is the same with point type infrared gas detector.

The receiver and transmitter shall be aligned during installing open path detector, fails to perform these activities lead to systematic failure. The detector shall not be installed in the structure that introduces vibration due to it leads to miss reading. During installation modification, the facilities shall ensure that the open path detector is not blocked. This may lead to systematic failure. However, unlike the flame detector, this failure typically can be diagnosed by the detector.

2.6.6 Catalytic Gas Detector

The catalytic detector is one of the oldest detection methods. The main principle of this detector is by oxidation reaction between catalytic pellistor and the hydrocarbon gas. The catalytic detector should only be used if another type of detector cannot be used e.g., inside the room with high temperature and inside the dusty room.

A catalytic gas detector senses the presence of gas inside its chamber. It consists of a catalytic pellistor and electronic circuit. A catalytic pellistor is a platinum wire coil embedded in a ceramic pellet. The wire is continuously heated by electrical current throughout the platinum wire to the required oxidation temperature. When a combustible gas is present inside the detector chamber, the gas oxidizes and the reaction releases heat and increases the temperature. Further, this rise in temperature results in a change in the electrical resistance and Wheatstone Bridge circuits converts the resulting change in resistance into a corresponding sensor signal. In addition, there is also reference pellistor that is passivized with a glass coating. The reference pellistor contains no catalyst, and it is called as a compensator. The compensator is used to remove the effects of temperature, pressure, and humidity.

The typical output signal of a catalytic gas detector is 0 to 20 mA. The current is corresponding to the gas concentration. 20 mA is indicating that the gas concentration is 100% LFL or higher. When the output loop is less than 3mA, it is indicating that the detector in a fault condition. The presence of volatile organic gases can cause false readings. The detector has lower life expectancy than another type of gas detector as the catalytic bead is consumed during the time. The gas detector should be functionally tested regularly. The test is performed by using a test gas through a test nozzle with a testing kit. In general catalytic detector is having a higher failure rate compares to another detection method. General test interval for the catalytic detector is 6 months (NOGA-070, 2018).

Chapter 3

Approach for Data Collection and Analysis

The research uses steps as indicated in the Figure 3.1 to evaluate the fire and gas detectors performance during operational phase. The approach is decided based on the Equinor practice on SIS follow-up activities.

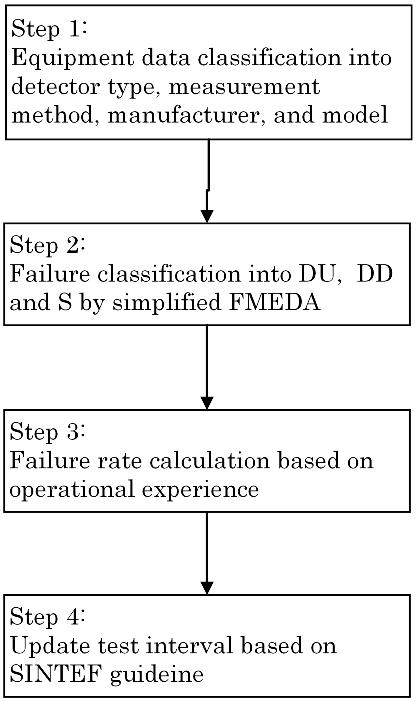


Figure 3.1: Data collection and analysis approach

It should be noted that each step mentioned above is going to be treated individually. The detailed procedure is introduced in the following:

3.1 Step 1: Equipment Data Classification

This step groups the equipment based on the functionality, measurement principle, manufacturer, and model. Each equipment group can be handled effectively and be analyzed individually.

In data classification, preparing equipment taxonomy is one critical step. According to ISO 14224, the taxonomy is a systematic classification of items into generic groups based on factors possibly common to several items. Many companies are following ISO 14224 for equipment taxonomy, including Equinor. Fire and gas detectors are under equipment sub-unit level in ISO 14224. The equipment unit is further divided into maintainable items.

One of the advantages of developing equipment taxonomy is to group the equipment based on the maintainable items and deciding its maintenance concept. In Equinor the same detector type is categorized in the same maintenance concept. If the failure rate calculation is only performed for each maintainable item level, the result is a generic failure rate only. The generic failure rate is mainly used during the design phase to give an early indication if the SIL requirement is fulfilled. In the operational stage, the equipment should be grouped into more specific relevant parameters that can explain variations in the reliability of different equipment inside the group. Håbrekke et al. (2018) suggests inventory attributes for failure rate calculation of fire and gas detector that are the manufacturer, measuring principle, and model type. In the project, Functional Safety expert from Equinor suggests inventory attributes for fire and gas detectors, as shown in Figure 3.2. The classification is adopting ISO 14224 taxonomy pyramid.

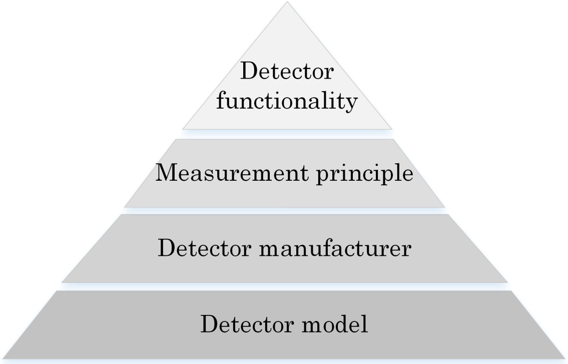


Figure 3.2: Detector classification

Detector type is a grouping of detector that relates to the function of the detector, for example, gas detector, catalytic detector, flame detector, etc. The measurement method is a grouping of the detector based on how the detector work. The purpose is to see which technology is more reliable. The manufacturer is a grouping of the detector based on the producer which manufactures the detector. The purpose is to investigate if a producer has a reliable detector in the later stages. Detector model is a grouping based on the model produced by the manufacturer. Håbrekke et al. (2018) indicates that the inventory attributes of the equipment can impact the reliability performance, e.g., the size, process fluid, environment. One of the attributes may have more influence than the others. The method is not suitable to evaluate fire and gas detector attributes as the detector does not have different attributes other than the model. The classification of the model level is to investigate the model which has better performance when the operational time is adequate.

3.2 Step 2: Failure Classification

For each detector in the facilities, all the maintenance notifications are collected during the operational period. The maintenance notification is recorded based ISO 14224 requirement. The maintenance notification consists of a failure impact, a failure mode, a failure detection, a failure mechanism and a detailed description of the failure. The purpose of the written detailed notification is to provide additional information when required. A simplified Failure Mode and Effect Diagnostic Analysis(FMEDA) is proposed to use for classifying each failure notification into the IEC 61508 failure class. A proposed FMEDA worksheet, as shown in Table 3.1 below, assists in documenting and sorting information.

Table 3.1: IEC failure classification worksheet

Unit identification		**Description of Unit**		**Description of Failure**			**Effect of Failure**		**Failure analysis**			**Remarks**
Noti ication num ber	Tag num ber	Part	Function	Fail Mode	Fail mechanism	Detection meth	on subsystem	on system	Cons	Diag.	Fail class	

The proposed step for failure classification is as follow.

1. Identify the unit and failure
   The failed unit shall have a unique tag number and the failure related to the unit shall also have a unique notification number. The information will be normally available in CMMS, e.g., SAP. The purpose of identification is to identify the equipment data in the failed unit. The equipment data includes manufacturer, model and data on the equipment started in operation. The notification number can be used to re-evaluate the failure and also for further follow-up action.

2. Describe the unit in a failure
   One component of a SIF can contain several parts. For example, a gas detector consists of the detector sensor, power cable, weather protection, and output card. In this column, the failed part and its function will be recorded. Some of the part functions are not related

to the main function and their failure are not impacting the main function. According to Hauge et al. (2010) in PDS method handbook, the failure which does not affect the main function of the component can be categorized as Non-Critical (NONC) failure.

3. Describe the failure
   The failure will be described into the failure mode, failure mechanism and detection method of failure. The typical failure mode for fire and gas detector according to ISO 14224 are as follows:

   - erratic output
   - failure to open on demand
   - no output
   - low output
   - high output
   - others
   - minor in service problem
   - spurious high alarm level
   - spurious low alarm level
   - spurious operation
   - unknown

   The common failure mechanism for fire and gas detectors are faulty signal/indication/ alarm, no signal, instrument failure and others. The detection method is a method used to identify the failure. There are 10 detection methods specified by ISO 14224 in Appendix B of the standard.

4. Determine the effect of the failure on the sub-system and overall system
   The effect of failure to the equipment and overall system are recorded in this column. Failure impacts will be decided if it is a local impact only or if it may cause a global impact. The column is also helping to decide whether the failure is dangerous or safe. The effect of the failure is analyzed based on failure mode and failure mechanism.

5. Analyse the failure to decide failure class,
   This column is recorded the failure consequences, the availability of diagnostic function to detect the failure and decision of the failure class. The consequences of failure are decided based on the effect of failure. The input will be dangerous or safe. The availability of the diagnostic system is decided based on the detection method. The input will be detected and undetected. From the consequences and diagnostic column, failure class will be decided.

6. Recording of the detailed failure description for further evaluation.
   The details of the failure description will be valuable data for auditing the worksheet.

Appendix A of this report shows an example of using the simplified FMEDA worksheet for failure classification based failure mode and failure mechanism in OREDA.

3.3 Step 3: Failure Rate Calculation

The main intention of this step is to calculate the operational failure rate for each detector model based on the number of DU failures collected in step 2 during the selected operational duration. The SINTEF guideline proposes a process for updating the failure rate based on operational experience, as shown in Figure 3.3 below.

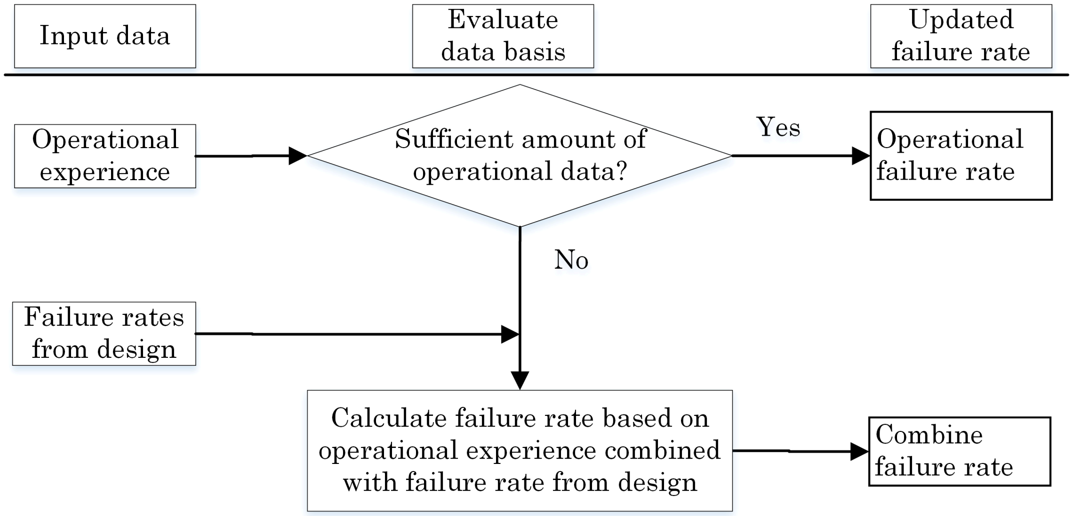


Figure 3.3: Process for updating failure rate based on operational experience

When the operational data is considered adequate, the failure rate can be directly calculated from the number of DU failure and the operational period. However, if the operational data is not considered adequate such as the data amount is not enough or there is no DU failure occurring during the observation period, the Bayesian method will be used to estimate the failure rate. The Bayesian method is calculating the failure rate by combining the operational data and a priory failure, as explained in chapter 2.3.2 of this report. In this master thesis, a priory failure rates will be using the PDS method handbook. In addition, the priory failure rate will also be calculated by using the OREDA Multi-sample method for all the reviewed facilities to investigate the possibility of aggregated operational data directly.

As the summary, in step 3 failure rates will be calculated with 3 different approaches as listed below and depicted in Figure 3.4:

- Calculate failure rate by operational experience only

- Calculate failure rate by combining with the failure estimate by PDS handbook
- Calculate failure rate in a facility by combining with the failure rate from aggregate operational failure which is calculated from OREDA Multi-Sample

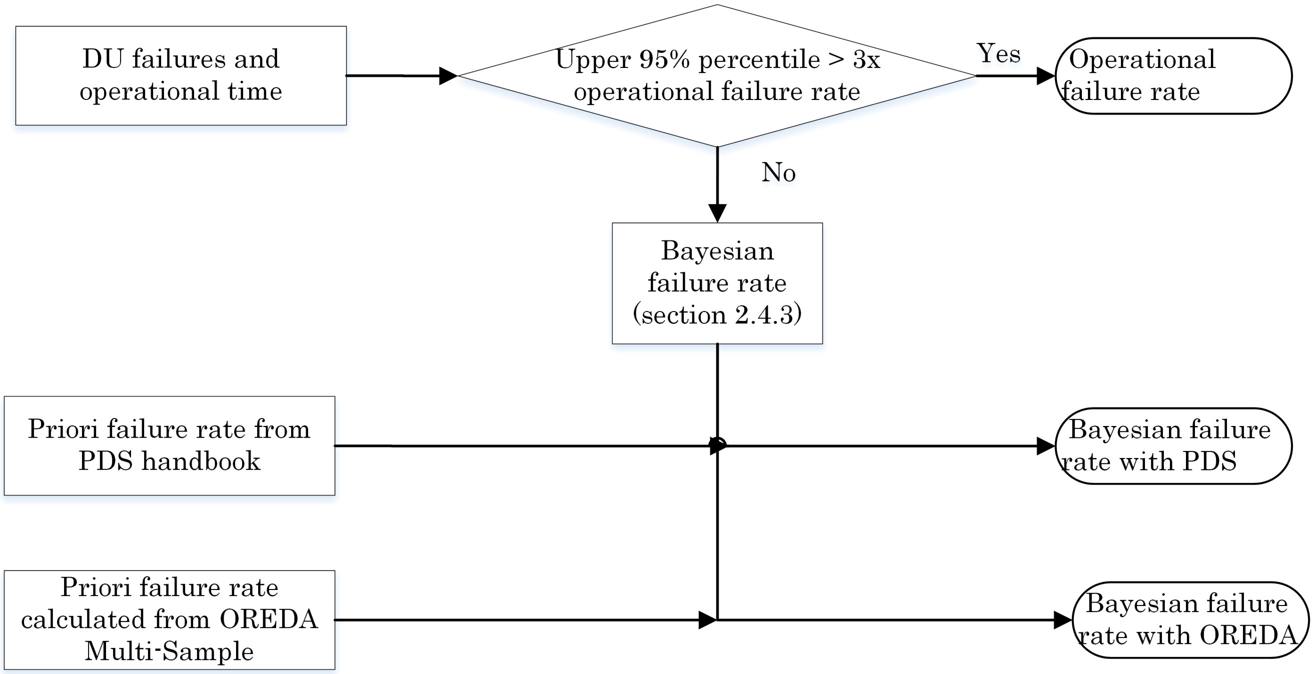


Figure 3.4: Failure rate result

3.4 Step 4: Test interval Update

The next step is calculating the test interval based on the operational failure rate. When the operational failure rate is significantly lower than the estimated failure rate, there is a possibility to increase the test interval. When the observed failure rate is higher than the original estimate, it may require to decrease the estimate test interval. SINTEF has proposed a method, as explained in chapter 2.4 of this report.

The basic approach of SINTEF method is by calculating the ratio of $\lambda_{DU}/\ddot{\lambda}_{DU}$ and estimate the new test interval based on the ratio. If the ratio is more than 1 then the test interval can be increased. If the ratio is less than 1, the test interval shall be decreased. In the guideline, it does not specify the required value of λ_{DU}. The value of λ_{DU} can be interpreted as the original failure estimate (priory failure rate such as PDS method data), or it also can be interpreted as the maximum failure rate and hence the SIL requirement can be achieved. Hence in this master thesis, the impact of different failure rates is investigated.

In addition there is also additional challenges of the method on calculating the failure rate ratio $\lambda_{DU}/\ddot{\lambda}_{DU}$. When the operational data is adequate, it may be more fair to calculate the ratio

$\lambda_{DU}/\hat{\lambda}_{DU}$. The impact of this is investigated in this master thesis.

The new estimate test interval is be calculated based on the different cases as mentioned below:

- calculating test interval where the ratio $\lambda_{DU}/\ddot{\lambda}_{DU}$, when λ_{DU} is based on a priory failure rate (PDS handbook failure rate)

- calculating test interval where the ratio $\lambda_{DU}/\ddot{\lambda}_{DU}$, when λ_{DU} is based on the maximum failure rate and hence the SIL requirement is fulfilled.

$$\lambda_{DU} = \frac{2PDF}{\tau} \tag{3.1}$$

- calculating test interval where the ratio $\lambda_{DU}/\hat{\lambda}_{DU}$, when λ_{DU} is based on a priory failure rate (PDS handbook failure rate). If the operational data is adequate, the operational failure rate is used and not the Bayesian failure rate as denominator.

In order to estimate fair assessment, the guideline is limiting the test interval changes into doubling and halving the test interval. The guideline stated that as below.

1. if the $\hat{\lambda}_{DU}$ is less than half of the priory failure rate and the entire estimate 90% confident interval is also lower than λ_{DU}, the test interval can be doubled

2. if the $\hat{\lambda}_{DU}$ is more than twice of the priory failure rate and the entire estimate 90% confident interval is higher than λ_{DU}, the test interval can be halved

In the calculation of the lower limit 90% confident interval and the upper limit of 90% confident interval, the fair distribution is used. The confident interval is calculated by the following equation.

$$\left[\frac{1}{2t_n} z_{0.9,2n}, \frac{1}{2t_n} z_{0.1,2n+1}\right] \tag{3.2}$$

It is interesting to investigate the impact when the confident interval is shifted to 97.5 % upper limit confident interval for doubled requirement and 70 % lower limit confident interval for halved requirement. The main reason is to get higher data for doubling the test interval and lower requirement for halving test interval. This impact is investigated in this master thesis.

Chapter 4

Result and Discussion

The master thesis adopts the method in SINTEF guideline for follow-up SIS in the operating phase to calculate the failure rate and to update the test interval. A qualitative assessment, such as failure classification is performed on the observed data prior to quantitative analysis. The failure notification data that are used in the master thesis is drawn from 12 facilities, owned by Equinor. Table 4.1 provides an overview of the facilities used for the project.

Table 4.1: Facility overview

Platform Name	Type of Facility	Start-up Year	Function
Facility A	Platform with condeep 4 shafts	1986	Drilling, oil producer, processing, quarter, and storage
Facility B	Platform with condeep 4 shafts	1988	Drilling, oil producer, processing, quarter, and storage
Facility C	Tension Leg Platform steel	1992	Drilling, processing, quarter
Facility D	Jacket 8 legs	2003	Drilling, oil producer, processing, quarter, and storage
Facility E	Jacket 4 legs	2014	Gas producer, oil producer, quarter, separation, and wellhead
Facility F	FPSO	1999	Offloading, processing, quarter, and storage
Facility G	Semisub steel	2000	Gas export, processing, and quarter
Facility H	Platform with condeep 4 shafts	1990	Drilling, oil producer, processing, quarter, and storage
Facility I	Jacket 4 legs	2004	Drilling, processing, quarter
Facility J	Semisub steel	1999	Drilling, processing, quarter
Facility K	Jacket 8 legs	1985	Drilling, oil producer, wellhead, processing, quarter
Facility L	Riser platform	2004	Distribution

*source: Norewegian Petroleum Directorate http://factpages.npd.no/factpages/

The summary overview of the number of fire detectors and gas detectors and the number of the DU failure at each facility is presented in Table 4.2.

Table 4.2: Detector summary for each facility

Facility Name	Number of fire and gas detectors	Data Collection	Number of DU failure
Facility A	3562	January 2012 to November 2016	34
Facility B	1892	January 2012 to November 2016	21
Facility C	2873	January 2013 to March 2016	13
Facility D	1143	January 2012 to October 2016	18
Facility E	783	Juni 2014 to May 2016	0
Facility F	2187	August 2013 to November 2016	51
Facility G	2356	January 2013 to December 2015	13
Facility H	3936	January 2012 to November 2016	41
Facility I	1407	October 2012 to October 2016	4
Facility J	1065	November 2012 to November 2016	23
Facility K	1526	January 2013 to January 2017	258
Facility L	139	January 2013 to January 2017	2

The discussion of this report is starting by failure classification using simplified FMEDA and continues with failure rate and test interval calculation. The failure rate of each detector is presented in a graphical diagram and the test interval result in tabulation form. The calculation result is presented in the Appendix and the summary of the calculation is presented in this section.

4.1 Failure Classification

Failure classification is the first gate of the failure analysis from the operational failure data. In this step, the DU failure is identified from failure notification data. Håbrekke and M.A. (2017) is pointing out some aspects that should be considered prior to use the field data for reliability calculation. One of them is the data that should be detailed enough and the failure reported shall be reviewed. At the beginning of the master thesis, data quality audit is executed for the failure notification data from the 12 facilities. The primary purpose of the audit is to classify the equipment into the correct group and to revisit the failure classification randomly and ensure the correct failure classification.

Guideline for follow-up SIS in the operating phase by SINTEF does not specify the method to classify the IEC failure class. In existing practice, the failure is classified based on failure description and the detail information of the failure notification data and this activity in general time-consuming. A simplified FMEDA approach is proposed to be used for the IEC failure classification from the failure notification data.

The FMEDA method has been widely used in the industry to predict the failure rate for a component and this method is allowing to define the availability of diagnostic coverage of the equipment (Goble and Bukowski, 2016). In contemplation of verifying the use of the simplified FMEDA approach, the author reclassified some of the failure notification data by using a structured FMEDA worksheet. The FMEDA worksheet uses for this study is presented in Appendix B of this report. As a note, the FMEDA presented in Appendix B is a representative of the overall failure notification data use for the study only.

Table 4.4 in Appendix B demonstrates the FMEDA approach is a feasible method to decide the IEC failure classification given that failure mode, failure mechanism, and detection method are classified correctly. During the observation, when the failure mode is recorded correctly, the need for "long text" information to decide the critically of failure can be minimized. Håbrekke and M.A. (2017) supports this view by stating that the data quality could be trusted if it has been classified correctly. As a summary from Appendix B, the common DU failures investigated during this observation period is listed in Table 4.3 below.

Table 4.3: Typical DU failure for a typical detector

Failure description	**Failure Mode**	**Failure Mechanism**	**Detection method**
The detector is not working during testing	No output	Instrument failure	Functional Test or Preventive Maintenance
The detector is broken	No output	not identified	Functional Test or Preventive Maintenance
The detector is not indicating alarm	No output	Instrument failure	Functional Test or Preventive Maintenance
The detector is indicating fault alarm in the field but there is no information in control room	Low output	not identified	Casual observation
The detector's sensitivity is reduced during testing, it is taking several tries during testing before the detector reach alarm	Low output	Instrument failure	Functional Test or Preventive Maintenance
Wrong type of detector is installed	Other	not identified	Inspection or casual observation
The failure in the I/O card and hence the detector is not indicating alarm. The failure is occurring for several detectors	No output	Instrument failure	Functional Test or Preventive Maintenance
The detector has reduced function and must be calibrated	Low output	Instrument failure	Functional Test or Preventive Maintenance

A general description of failure notification data arguably is not help failure classification into IEC 61508 failure class. The failure description, such as the detector is a defect or the detector is not working, does not give a clear indication of the detector failure. This type of description is quite often written in the failure notification data. It is preferable to use more detailed description e.g., the detector is not indicating alarm during testing; the lens of the detector is defect, the lamp indicator is defect.

The failure of the input/output (I/O) card is can arguably be excluded from the detector failure. Because, according to OREDA handbook, the I/O card is outside the boundary of the fire and gas detector(SINTEF, 2015). However, in practice, I/O card failure is often associated with detector failure. The main reason is that the I/O card does not have a specific identification or tag number. In this project, the failure of I/O card is included in the DU failure of the detector. The failure is associated with one detector even though it impacts several detectors. The main reason is that the result can be too conservative if the failure counted for each detector, and it is not a fair assessment of the detector.

There also DU failures that is linked to the detector type as there is a wide range of technology for fire and gas detectors. The specific failure for different detectors are presented in the Table 4.4 below.

Table 4.4: Typical DU failure for specific detector type

Detector	Failure description	Failure Mode	Failure Mechanism	Detection method
Flame detector	The detector lens is dirty but there is no fault alarm indicating the condition	Low output	Instrument failure	Functional Test or Preventive Maintenance
Flame detector	The detector view is blocked or the lens direction is changing	Other	Not identified	Casual observation or inspection
Heat / smoke detector	The detector is not working, but it might be due to the wrong loop location	Low output	Instrument failure	Functional Test or Preventive Maintenance
Heat / smoke detector	The detector is covered by painting but there is no diagnostic fault alarm	Other	Not identified	Casual observation or inspection
Catalytic / hydrocarbon point type detector	The detector does not reach high alarm during testing	Low output	Instrument failure	Functional Test or Preventive Maintenance
Open path gas detector	The detector does not reach high alarm during testing or the detector indicates 0 LELm	Low output	Instrument failure	Functional Test or Preventive Maintenance
Open path gas detector	The detector lens must be cleaned and no diagnostics to control room	Low output	Instrument failure	Functional Test or Preventive Maintenance
Aspirated gas detector	There is no air coming into the flow switch	No output	Not identified	Functional Test or Preventive Maintenance
Aspirated gas detector	The aspirator tube is blocked but there is no indication from the flow switch	No output	Not identified	Functional Test or Preventive Maintenance
Aspirated gas detector	There is a leakage in the aspirator tubing but there is no indication from the flow switch	No output	Not identified	Functional Test or Preventive Maintenance

The latest technology of flame detectors is equipped with self-diagnostic and gives an alarm when the lens is dirty and cleaning is required. The technology is also available in an open path gas detector, but when this function is not working, this fault is only detected during a functional test or preventive maintenance. Hence, it shall be considered as a DU failure. When a flame detector view is blocked, the failure can be considered as a DU failure even though this failure is not expected to be reoccurred after the flame detector position is corrected. The failure can be specified as a systematic DU failure. Goble and Bukowski (2016) agrees that systematic failure should be included in the failure rate calculation.

One of the observations during the master thesis, the failure alarm limit for a gas detector should be defined clearly. One of the facilities was having 227 DU failures of a particular model of the catalytic gas detector during the beginning of the classification. The classification was over conservative DU failure classification. It was defined that the detector was in DU failure when the gas detection reading was less than the test gas concentration. However, it is not required to classify the detector into DU with the strict rules. Because of the fact that the gas detector initiates alarm function during high alarm limit, e.g., 30% before it is even reading the same concentration of the test gas. After redoing the failure classification and classify DU failures by when the reading during the testing is less than the high alarm limit, the number of DU failures of the facility is reduced to 35 failures and that impacts the failure rate calculation.

4.1.1 Failure Classification Findings

The simplified FMEDA for failure classification disadvantages is the failure mode shall be defined correctly prior to IEC 61508 failure class. Equinor uses different definitions of failure mode compares with ISO 14224 or OREDA handbook. The failure mode in Equinor maintenance data is defined as the condition of the equipment after the failure. In the OREDA handbook, the failure mode is defined as the observed manner of a failure.

The failure mode of fire and gas detectors based on Equinor maintenance data consist of breakdown, contact danger, EX defective, and other. The failure mode for fire and gas detectors based on OREDA and ISO 14224 is including fail to function on demand; operates without demand, abnormal output low, abnormal output high, erratic output, spurious high level alarm, spurious low level alarm, high output, low output, no output, minor in service, and other. The ISO 14224s failure mode is defined as a failure mechanism in Equinor failure notification data. The issue is that the failure mechanisms is not always recorded for the failure notification data in Equinor's system. When the failure mechanism is classified in failure notification data, it is easier to define the critically of the failure, whether the failure is a dangerous failure or a safe failure. Hence one of the recommendations for Equinor is to follow ISO 14224 failure mode definition. The ISO 14224's failure mode should be specified in the failure notification data. The OREDA failure mode defines the failure condition more clear compared to the failure mode definition that is currently being used by Equinor.

Another concern is related to the failure mode classified as "other." There are substantially findings that identified as the failure mode class "other" . However, after further investigation on the "long text" that described the notification data, it can be concluded that the detector is a broken down and proving no output during testing. The operator may use the failure mode class "other" as a way of simplifying the job because arguably, when the failure cause is not clear, it can be defined as "other". A strict procedure and definition shall be available before a failure mode can be classified as "other". ISO 14224 defines "other" as a failure that is specified based on a comment in the field and this definition is not clear and may cause ambiguous interpretation.

There are also findings related to inconsistency between the detection method and the "long text" on the failure notification data. The observed finding is that the failure was classified as DU failure, even when the detection method is a condition monitoring. However, the classification as DU is correct because the "long text" failure notification data has indicated that the failure was observed during an inspection, not a condition monitoring. A detailed procedure for classification of detection method should be established with a clear description. It would be beneficial if the maintenance and operation personnel familiarized themselves with ISO 14224. Course on ISO 14224 for operation and maintenance personnel is valuable to improve data quality and it reduces the time consumed by the reliability engineer to analyze the failure notification data.

4.2 Failure Rate Calculation Result

The failure rate for each model is calculated with two different approaches. The first approach is to calculate the aggregated failure rate for each model by using the OREDA Multi-Sample method, as explained in Section 2.4.3. The second approach is calculating the failure rate for a model at a facility. When the operating data is considered sufficient by the requirement as defined in the guideline for SIS follow-up during the operational phase by SINTEF, the operational failure rate ($\hat{\lambda}_{DU}$) as indicates in Equation 2.1 is used. But when the operational data is not sufficient, the Bayesian failure rate ($\ddot{\lambda}_{DU}$) as indicates in Equation 2.6 is used. The Bayesian failure rate is calculated by using the failure rate from PDS data handbook as a priory failure rate (λ_{DU}). The example of the calculation is presented in Appendix C of this report.

The failure rate of each detector is described in detailed at subsection below. The detector model failure rate is presented in a graphical form. The result is maybe valuable for Equinor for future detector inquiry. In addition, different proposals to revamp the existing Bayesian approach is also discussed in the last subsection.

4.2.1 Failure Rate for Flame Detector

There are many flame sensing technologies for flame detectors. The flame sensing categories are labeled as measurement principle in this master thesis. Details of the flame detector quantity and DU failure in each facility are presented in Table 4.5.

Table 4.5: Flame detectors quantity

Facilitiy	**Measurement**	**Manufacturer**	**Model**	**Quantity**	**Operation Time (hour)**	**DU**
Facility A	Multi-spectrum -IR	Manufacturer 1	FD-IR3-M1-model A	498	20963808	0
Facility B	Multi-spectrum -IR	Manufacturer 1	FD-IR3-M1-model A	226	9513696	2
Facility B	Single frequency UV	Manufacturer 1	FD-UV-M1-model D	19	799824	3

Table 4.5: Flame detectors quantity

Facilitiy	**Measurement**	**Manufacturer**	**Model**	**Quantity**	**Operation Time (hour)**	**DU**
Facility C	Multi-spectrum -IR	Manufacturer 1	FD-IR3-M1-model A	12	312840	0
Facility C	Multi-spectrum -IR	Manufacturer 2	FD-IR3-M2-model B	65	1680000	0
Facility C	Multi-spectrum -IR	Manufacturer 2	FD-IR3-M2-model C	224	4864416	0
Facility D	Multi-spectrum -IR	Manufacturer 1	FD-IR3-M1-model A	14	483840	2
Facility D	Multi-spectrum -IR	Manufacturer 3	FD-IR3-M3-model G	160	5529600	6
Facility E	Multi-spectrum -IR	Manufacturer 2	FD-IR3-M2-model C	110	1921920	0
Facility F	Multi-spectrum -IR	Manufacturer 1	FD-IR3-M1-model A	99	2848824	4
Facility F	Multi-spectrum -IR	Manufacturer 2	FD-IR3-M2-model B	7	201432	1
Facility F	Multi-spectrum -IR	Manufacturer 2	FD-IR3-M2-model C	236	6791136	9
Facility G	Multi-spectrum -IR	Manufacturer 1	FD-IR3-M1-model A	282	7302672	3
Facility G	Multi-spectrum -IR	Manufacturer 2	FD-IR3-M2-model B	83	2149368	1
Facility H	Multi-spectrum -IR	Manufacturer 1	FD-IR3-M1-model A	58	2422080	0
Facility H	Single frequency IR	Manufacturer 1	FD-IR-M1-model E	75	3132000	1
Facility I	Multi-spectrum -IR	Manufacturer 1	FD-IR3-M1-model A	235	8121600	1
Facility J	Multi-spectrum -IR	Manufacturer 1	FD-IR3-M1-model A	7	241920	0
Facility J	Multi-spectrum -IR	Manufacturer 3	FD-IR3-M3-model G	98	3386880	0
Facility K	Multi-spectrum -IR	Manufacturer 1	FD-IR3-M1-model A	119	4112640	2
Facility K	Multi-spectrum -IR	Manufacturer 4	FD-IR3-M4-model H	1	34560	0
Facility K	UV/IR	Manufacturer 1	FD-UI-M1-model F	13	230832	0
Facility L	Multi-spectrum -IR	Manufacturer 1	FD-IR3-M1-model A	32	1105920	2

Figure 4.1 show the overview of the operational data and the number of DU failures for each model.

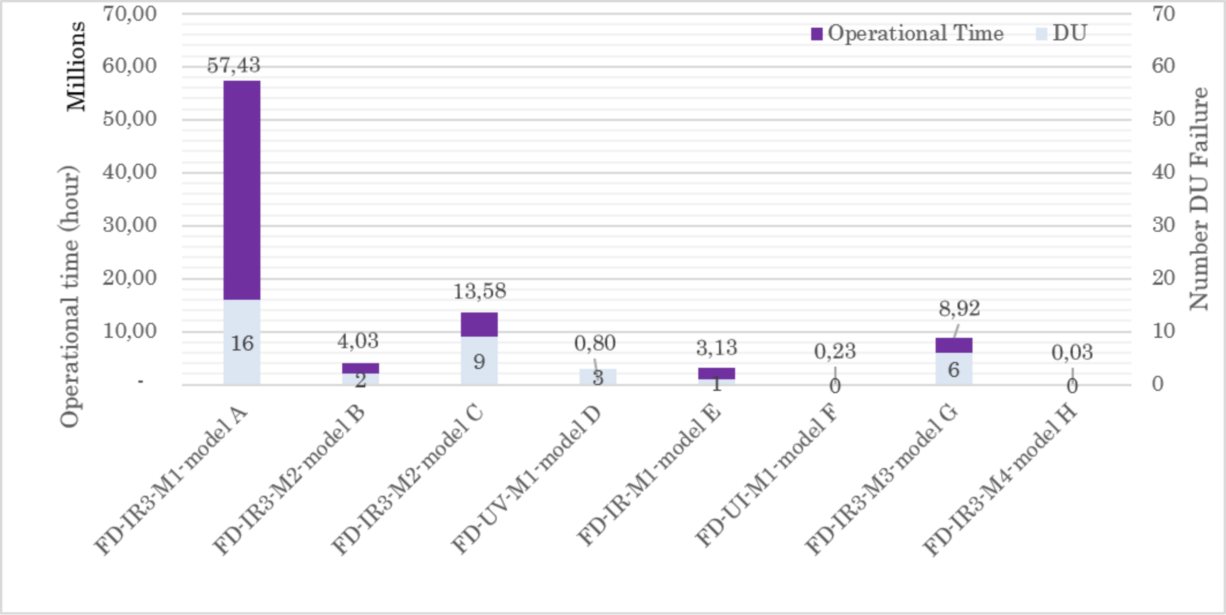
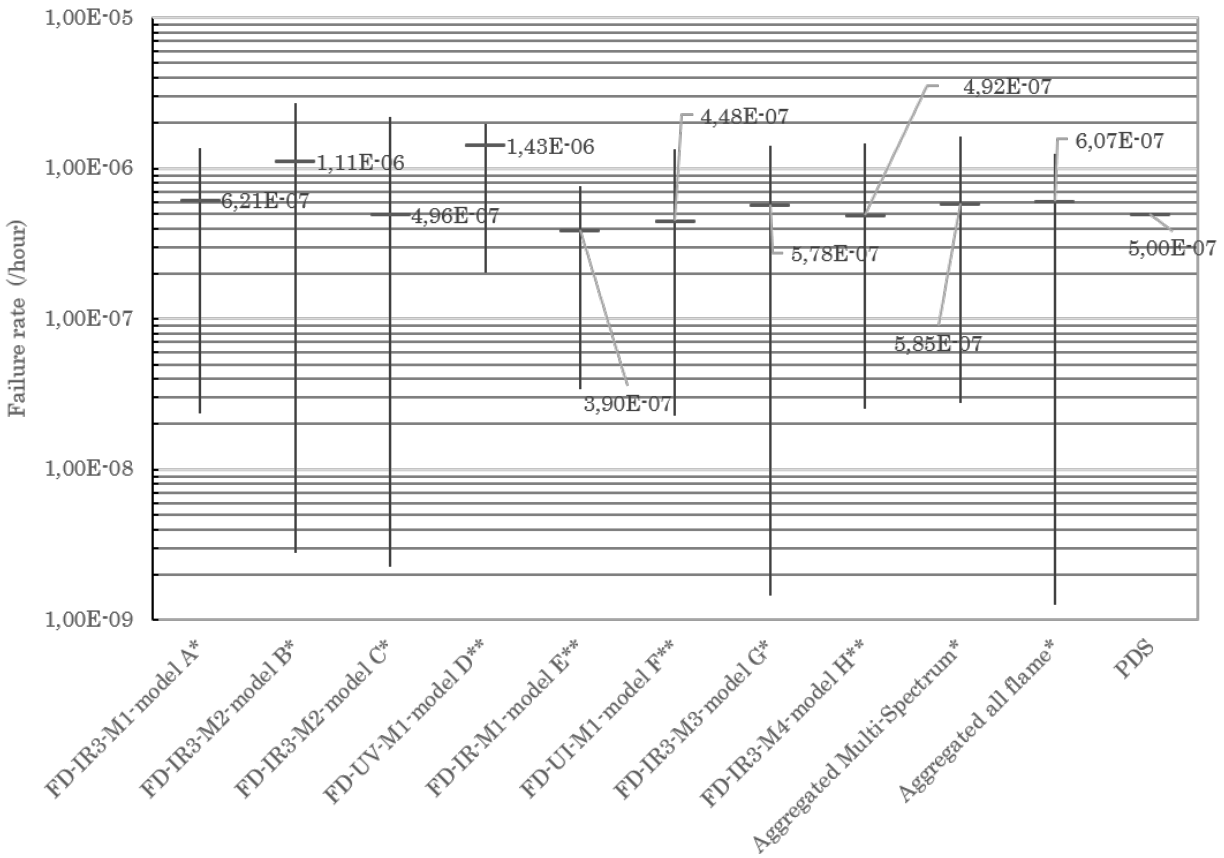


Figure 4.1: Flame detector model: operational time and DU failures

In general, Equinor uses a flame detector with Multi-Spectrum IR as the measurement principle. The Multi-Spectrum detector has a low possibility of false alarm because there is more than one sensor that can verify the IR spectrum of the flame. That is the reason for this detector widely used. The single frequency IR, UV, and UV/IR is only used in one facility. 8 models of flame detectors from 4 different manufacturers are installed.

FD-M1-model A is the one with the highest operational time of all the flame detectors used by Equinor. The number of DU failure and operational time is two parameters for calculating the failure rate. The aggregated failure rate of each model during the operational phase is calculated using the OREDA Multi-Sample method. The OREDA Multi-Sample is not suitable when the model is used only in one facility and when there is no failure observed during the operational time. In that case, the Bayesian approach is used to calculate the failure rate. A priory failure rate, λ_{DU}, is taken from PDS data handbook 5 $\times 10^{-7}$ per hour. The calculated failure rate for each model is shown in Figure 4.2.



*failure rate is calculated using OREDA Multi-Sample (θ^*)

**failure rate is calculated using Bayesian approach ($\ddot{\lambda}_{DU}$)

Figure 4.2: Flame detector failure rate for each model

Most of the models of flame detectors have failure rates approximately near to 5 $\times 10^{-7}$ per hour, the PDS data handbook failure rate for flame detector. The model C has the lowest aggregated failure rate. The UV detector has the highest failure rate, but the data quantity is small, and hence, additional data is required for further conclusion. The UV/IR detector and the single frequency IR has low operational data and no failure. The flame detector failure rates are also investigated for each facility. For each detector model in a facility, the failure rate is calculated based on operational data only when the operational data is adequate or Bayesian approach when the data is not adequate. The failure rate of each model in every facility is shown in Table 4.6 below. The FD-IR3-M2-model C in facility F has the highest failure rate for all the data.

Table 4.6: The failure rate of the flame detectors in all facilities

Facility	**Model**	**Method**	$\hat{\lambda_{DU}}(h^{-1})$	$\ddot{\lambda_{DU}}(h^{-1})$	**90% CI low** (h^{-1})	**90% CI up** (h^{-1})
Facility A	FD-IR3-M1-model A	Bayesian	-	4.35E-08	2.23E-09	1.30E-07
Facility B	FD-IR3-M1-model A	Bayesian	-	2.61E-07	7.10E-08	5.47E-07
Facility B	FD-UV-M1-model D	Operational	3.75E-06	-	1.02E-06	9.69E-06
Facility C	FD-IR3-M1-model A	Bayesian	-	4.32E-07	2.22E-08	1.30E-06
Facility C	FD-IR3-M2-model B	Bayesian	-	2,72E-07	1.39E-08	8.14E-07
Facility C	FD-IR3-M2-model C	Bayesian	-	1.46E-07	7.47E-09	4.36E-07
Facility D	FD-IR3-M1-model A	Bayesian	-	1.21E-06	3.29E-07	2.53E-06
Facility D	FD-IR3-M3-model G	Operational	1.09E-06	-	4.73E-07	2.14E-06
Facility E	FD-IR3-M2-model C	Bayesian	-	2.55E-07	1.31E-08	7.64E-07
Facility F	FD-IR3-M1-model A	Operational	1.40E-06	-	4.80E-07	3.21E-06
Facility F	FD-IR3-M2-model B	Bayesian	-	9.08E-07	1.61E-07	2.15E-06
Facility F	FD-IR3-M2-model C	Operational	1.33E-06	-	6.91E-07	2.31E-06
Facility G	FD-IR3-M1-model A	Operational	4.11E-07	-	1.12E-07	1.06E-06
Facility G	FD-IR3-M2-model B	Bayesian	-	4.82E-07	8.56E-08	1.14E-06
Facility H	FD-IR3-M1-model A	Bayesian	-	2.26E-07	1.16E-08	6.77E-07
Facility H	FD-IR-M1-model E	Bayesian	-	3.90E-07	6.92E-08	9.24E-07
Facility I	FD-IR3-M1-model A	Bayesian	-	1.98E-07	3.51E-08	4.69E-07
Facility J	FD-IR3-M1-model A	Bayesian	-	4.46E-07	2.29E-08	1.34E-06
Facility J	FD-IR3-M3-model G	Bayesian	-	1.86E-07	9.52E-09	5.56E-07
Facility K	FD-IR3-M1-model A	Bayesian	-	4.91E-07	1.34E-07	1.03E-06
Facility K	FD-IR3-M4-model H	Bayesian	-	4.92E-07	2.52E-08	1.47E-06
Facility K	FD-UI-M1-model F	Bayesian	-	4.48E-07	2.30E-08	1.34E-06
Facility L	FD-IR3-M1-model A	Bayesian	-	9.66E-07	2.63E-07	2.03E-06

4.2.2 Failure Rate for Heat Detector

Three different measurement principles of heat detectors are installed in 12 different facilities. The quantity of heat detector and DU failures in each facility are presented in Table 4.7.

Table 4.7: Heat detectors quantity

Facilitiy	**Measurement**	**Manufacturer**	**Model**	**Quantity**	**Operation Time (hour)**	**DU**
Facility A	Rate of Rise	Manufacturer 5	HD-ROR-M5-model A	26	1094496	0
Facility A	Fixed temperature	Manufacturer 6	HD-FT-M6-model G	25	1052400	0
Facility B	Rate of Rise	Manufacturer 5	HD-ROR-M5-model A	8	336768	0
Facility B	Fixed temperature	Manufacturer 6	HD-FT-M6-model G	14	589344	1

Table 4.7: Heat detectors quantity

Facilitiy	**Measurement**	**Manufacturer**	**Model**	**Quantity**	**Operation Time (hour)**	**DU**
Facility C	Rate of Rise	Manufacturer 5	HD-ROR-M5-model A	3	77568	0
Facility C	Fixed temperature	Manufacturer 6	HD-FT-M6-model E	12	193056	0
Facility C	Fixed temperature	Manufacturer 6	HD-FT-M6-model F	11	251568	0
Facility D	Rate of Rise	Manufacturer 5	HD-ROR-M5-model A	15	518400	2
Facility D	Fixed temperature	Manufacturer 6	HD-FT-M6-model F	34	1175040	1
Facility E	Fixed temperature	Manufacturer 6	HD-FT-M6-model F	12	205920	0
Facility F	Rate of Rise	Manufacturer 5	HD-ROR-M5-model A	12	345312	0
Facility F	Fixed temperature	Manufacturer 6	HD-FT-M6-model G	28	797232	0
Facility G	Rate of Rise	Manufacturer 5	HD-ROR-M5-model A	15	388440	0
Facility G	Fixed temperature	Manufacturer 6	HD-FT-M6-model G	44	1139424	0
Facility G	Linear heat	Manufacturer 7	HD-LN-M7-model I	10	258960	0
Facility H	Rate of Rise	Manufacturer 8	HD-ROR-M8-model B	672	28062720	7
Facility I	Fixed temperature	Manufacturer 6	HD-FT-M6-model F	29	1002240	0
Facility I	Rate of Rise	Manufacturer 8	HD-ROR-M8-model B	8	276480	0
Facility J	Fixed temperature	Manufacturer 6	HD-FT-M6-model D	1	32952	0
Facility J	Rate of Rise	Manufacturer 5	HD-ROR-M5-model A	12	381768	0
Facility J	Fixed temperature	Manufacturer 6	HD-FT-M6-model G	7	241920	0
Facility J	Rate of Rise	Manufacturer 3	HD-ROR-M3-model C	4	138240	0
Facility K	Rate of Rise	Manufacturer 8	HD-ROR-M8-model B	179	6186240	1
Facility K	Fixed temperature	Manufacturer 9	HD-FT-M9-model H	5	172800	0
Facility L	Fixed temperature	Manufacturer 6	HD-FT-M6-model F	3	103680	0

9 heat detector models from various manufacturers are installed across 12 facilities. Figure 4.3 shows the overview of the operational data and number of DU failures for each model.

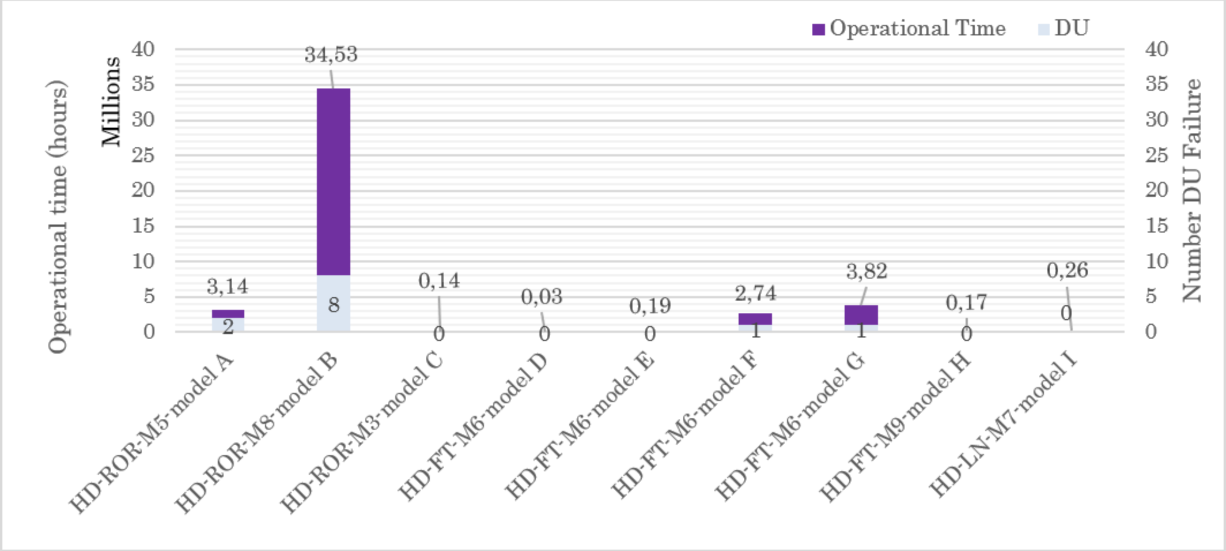
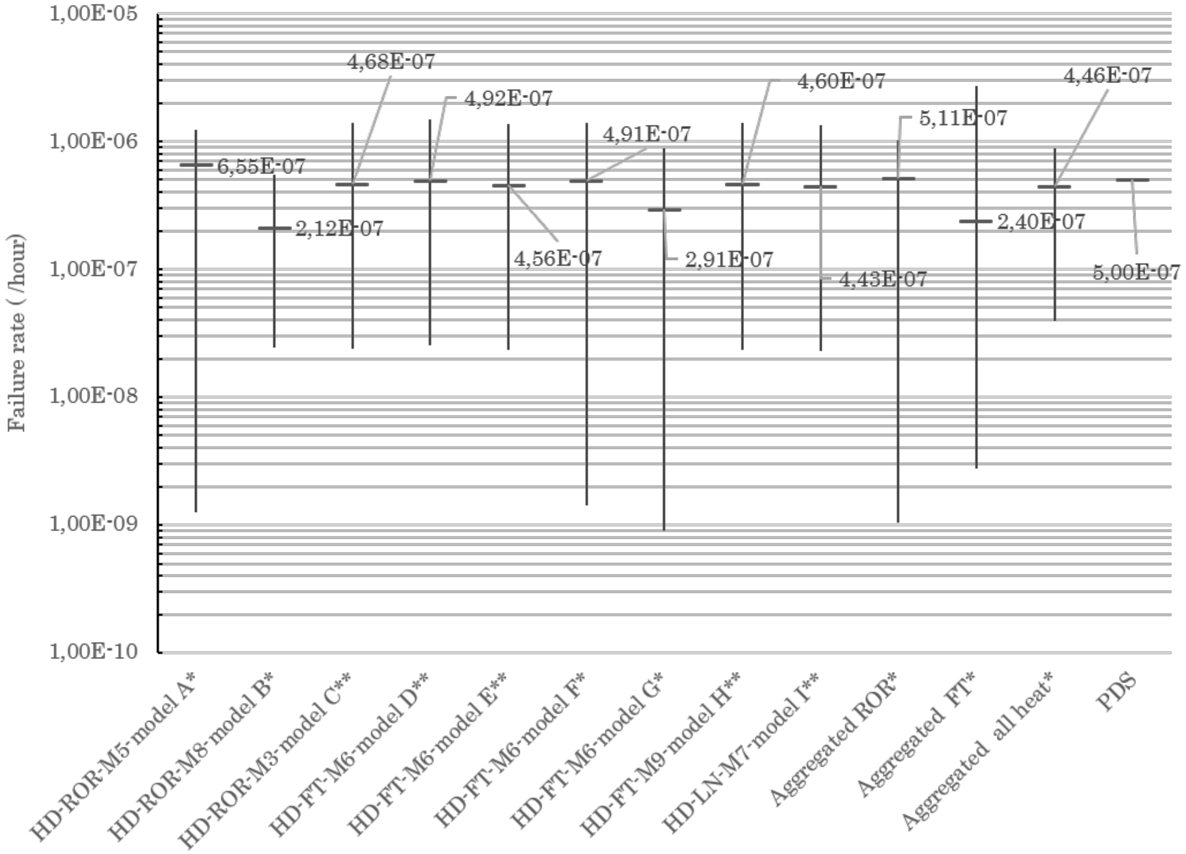


Figure 4.3: Heat detector model: operational time and DU failures

The HD-ROR-M8-model B is mainly used at all of the facilities, and the aggregated operating hour is 10× higher than the other detector models. Most of the models aggregated operating hours are less than the 3 million hours. The HD-ROR-M3-model C, HD-FT-M6-model D, HD-FT-M6-model F, and HD-FT-M9-model H aggregated operating hours are limited, and hence no failure is observed yet. The calculated failure rate for each model is shown in Figure 4.4.



*failure rate is calculated using OREDA Multi-Sample (θ^*)
**failure rate is calculated using Bayesian approach ($\ddot{\lambda}_{DU}$)

**ROR = Rate of Rise, FT = Fixed Temperature

Figure 4.4: Heat detector failure rate for each model

The aggregated failure rate of all heat detector models is almost similar to the PDS handbook heat detector failure. The fixed temperature heat detector aggregated failure rate is lower than the rate of rise heat detector type. It may be because the rate of rise detector is mostly located inside the turbine enclosure where it has a high-temperature environment and a dirty atmosphere. The fixed temperature heat detector mainly is installed inside the workshop room. It is suggested for PDS data handbook to separate this type of heat detector due to the fact that it has different design and it is used in a different working environment. The failure rate of each model in every facility is shown in Table 4.8. The highest failure rate is HD-FT-M6-Model G in facility B.

Table 4.8: The failure rate of the heat detectors in all facilities

Facility	**Model**	**Method**	$\hat{\lambda}_{DU}(h^{-1})$	$\ddot{\lambda}_{DU}(h^{-1})$	**90% CI low** (h^{-1})	**90% CI up** (h^{-1})
Facility A	HD-ROR-M5-model A	Bayesian	-	3.23E-07	1.66E-08	9.68E-07
Facility A	HD-FT-M6-model G	Bayesian	-	3.28E-07	1.68E-08	9.81E-07
Facility B	HD-ROR-M5-model A	Bayesian	-	4.28E-07	2.20E-08	1.28E-06
Facility B	HD-FT-M6-model G	Bayesian	-	7.72E-07	6.79E-08	1.51E-06
Facility C	HD-ROR-M5-model A	Bayesian	-	4.81E-07	2.47E-08	1.44E-06
Facility C	HD-FT-M6-model E	Bayesian	-	4.56E-07	2.34E-08	1.37E-06
Facility C	HD-FT-M6-model F	Bayesian	-	4.44E-07	2.28E-08	1.33E-06
Facility D	HD-ROR-M5-model A	Bayesian	-	1.19E-06	1.41E-07	1.88E-06
Facility D	HD-FT-M6-model F	Bayesian	-	6.30E-07	5.54E-08	1.23E-06
Facility E	HD-FT-M6-model F	Bayesian	-	4.53E-07	2.33E-08	1.36E-06
Facility F	HD-ROR-M5-model A	Bayesian	-	4.26E-07	2.19E-08	1.28E-06
Facility F	HD-FT-M6-model G	Bayesian	-	3.57E-07	1.83E-08	1.07E-06
Facility G	HD-ROR-M5-model A	Bayesian	-	4.19E-07	2.15E-08	1.25E-06
Facility G	HD-FT-M6-model G	Bayesian	-	3.19E-07	1.63E-08	9.54E-07
Facility G	HD-LN-M7-model I	Bayesian	-	4.43E-07	2.27E-08	1.33E-06
Facility H	HD-ROR-M8-model B	Operational only	2.49E-07	-	1.17E-07	4.69E-07
Facility I	HD-FT-M6-model F	Bayesian	-	3.33E-07	1.71E-08	9.98E-07
Facility I	HD-ROR-M8-model B	Bayesian	-	4.39E-07	2.25E-08	1.32E-06
Facility J	HD-FT-M6-model D	Bayesian	-	4.92E-07	2.52E-08	1.47E-06
Facility J	HD-ROR-M5-model A	Bayesian	-	4.20E-07	2.15E-08	1.26E-06
Facility J	HD-FT-M6-model G	Bayesian	-	4.46E-07	2.29E-08	1.34E-06
Facility J	HD-ROR-M3-model C	Bayesian	-	4.68E-07	2.40E-08	1.40E-06
Facility K	HD-ROR-M8-model B	Bayesian	-	2.44E-07	2.15E-08	4.77E-07
Facility K	HD-FT-M9-model H	Bayesian	-	4.60E-07	2.36E-08	1.38E-06
Facility L	HD-FT-M6-model F	Bayesian	-	4.75E-07	2.44E-08	1.42E-06

4.2.3 Failure Rate for Smoke Detector

There are two main measurement principles of smoke detectors; ionization and optical smoke detector. For differentiating the new self-checking technology with high diagnostic coverage, the optical detector is divided into the conventional and self-verify smoke detector. The number of smoke detectors and DU failure in each facility are presented in Table 4.9.

Table 4.9: Smoke detectors quantity

Facilitiy	**Measurement**	**Manufacturer**	**Model**	**Quantity**	**Operation Time (hour)**	**DU**
Facility A	Conventional Optical	Manufacturer 6	SD-OP-M6-model A	1015	42626592	1
Facility A	Conventional Optical	Manufacturer 3	SD-OP-M3-model B	360	15154560	7
Facility A	Self-verify optical	Manufacturer 6	SD-SOP-M6-model D	33	1389168	0
Facility A	Conventional Optical	Manufacturer 4	SD-OP-M4-model C	82	3451872	0
Facility A	Ionisation	Manufacturer 4	SD-ION-M4-model E	1	42096	0
Facility B	Conventional Optical	Manufacturer 6	SD-OP-M6-model A	635	26730960	0
Facility B	Ionisation	Manufacturer 4	SD-ION-M4-model E	269	11323824	0

Table 4.9: Smoke detectors quantity

Facilitiy	**Measurement**	**Manufacturer**	**Model**	**Quantity**	**Operation Time (hour)**	**DU**
Facility B	Ionisation	Manufacturer 6	SD-ION-M6-model G	20	841920	0
Facility C	Self-verify optical	Manufacturer 6	SD-SOP-M6-model D	1208	26666184	0
Facility C	Conventional Optical	Manufacturer 4	SD-OP-M4-model C	2	45432	0
Facility C	Ionisation	Manufacturer 4	SD-ION-M4-model F	5	116328	0
Facility D	Self-verify optical	Manufacturer 6	SD-SOP-M6-model D	510	17625600	5
Facility D	optical/thermal	Manufacturer 11	SD-OT-M11-model I	4	138240	0
Facility E	Self-verify optical	Manufacturer 6	SD-SOP-M6-model D	301	5366112	0
Facility F	Conventional Optical	Manufacturer 6	SD-OP-M6-model A	833	23935944	10
Facility F	Self-verify optical	Manufacturer 6	SD-SOP-M6-model D	66	1899216	0
Facility F	Infra-red	Manufacturer 10	SD-IR-M10-model H	4	115104	0
Facility F	Ionisation	Manufacturer 6	SD-ION-M6-model G	2	57552	0
Facility G	Conventional Optical	Manufacturer 6	SD-OP-M6-model A	998	25844208	5
Facility H	Conventional Optical	Manufacturer 6	SD-OP-M6-model A	1187	49541616	1
Facility H	Conventional Optical	Manufacturer 3	SD-OP-M3-model B	404	16871040	10
Facility H	Conventional Optical	Manufacturer 4	SD-OP-M4-model C	3	125280	0
Facility I	Self-verify optical	Manufacturer 6	SD-SOP-M6-model D	478	16519680	0
Facility J	Conventional Optical	Manufacturer 6	SD-OP-M6-model A	266	9192960	0
Facility J	Conventional Optical	Manufacturer 3	SD-OP-M3-model B	298	10298880	2
Facility K	Conventional Optical	Manufacturer 6	SD-OP-M6-model A	99	3421440	1
Facility K	Self-verify optical	Manufacturer 6	SD-SOP-M6-model D	449	15517440	1
Facility K	Conventional Optical	Manufacturer 4	SD-OP-M4-model C	173	5978880	7
Facility L	Self-verify optical	Manufacturer 6	SD-SOP-M6-model D	10	345600	0

Figure 4.5 show the overview of the operational data and number of DU failures for each model.

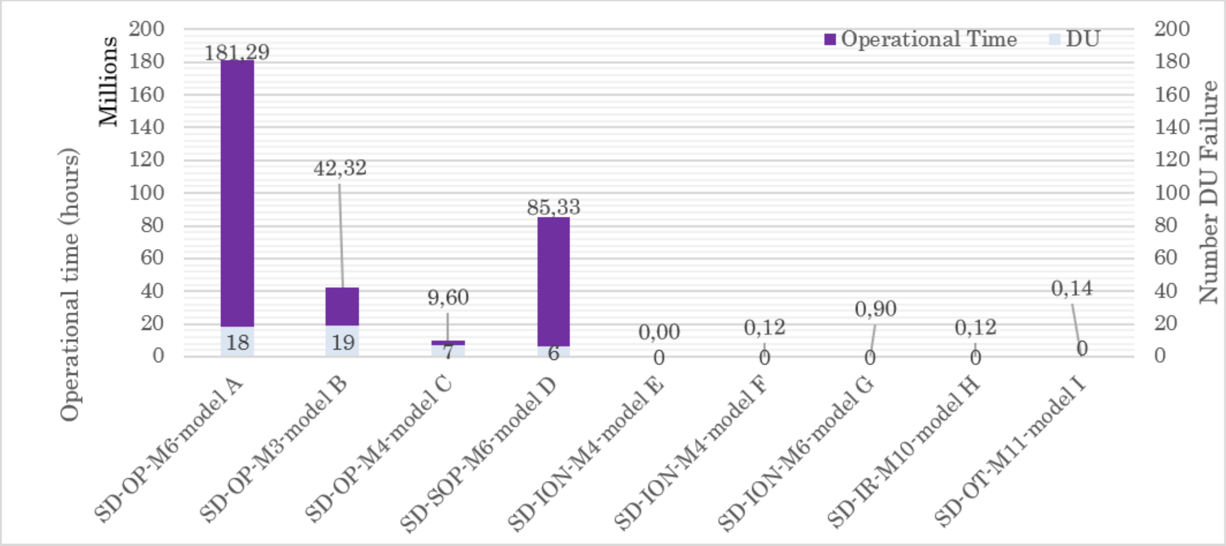
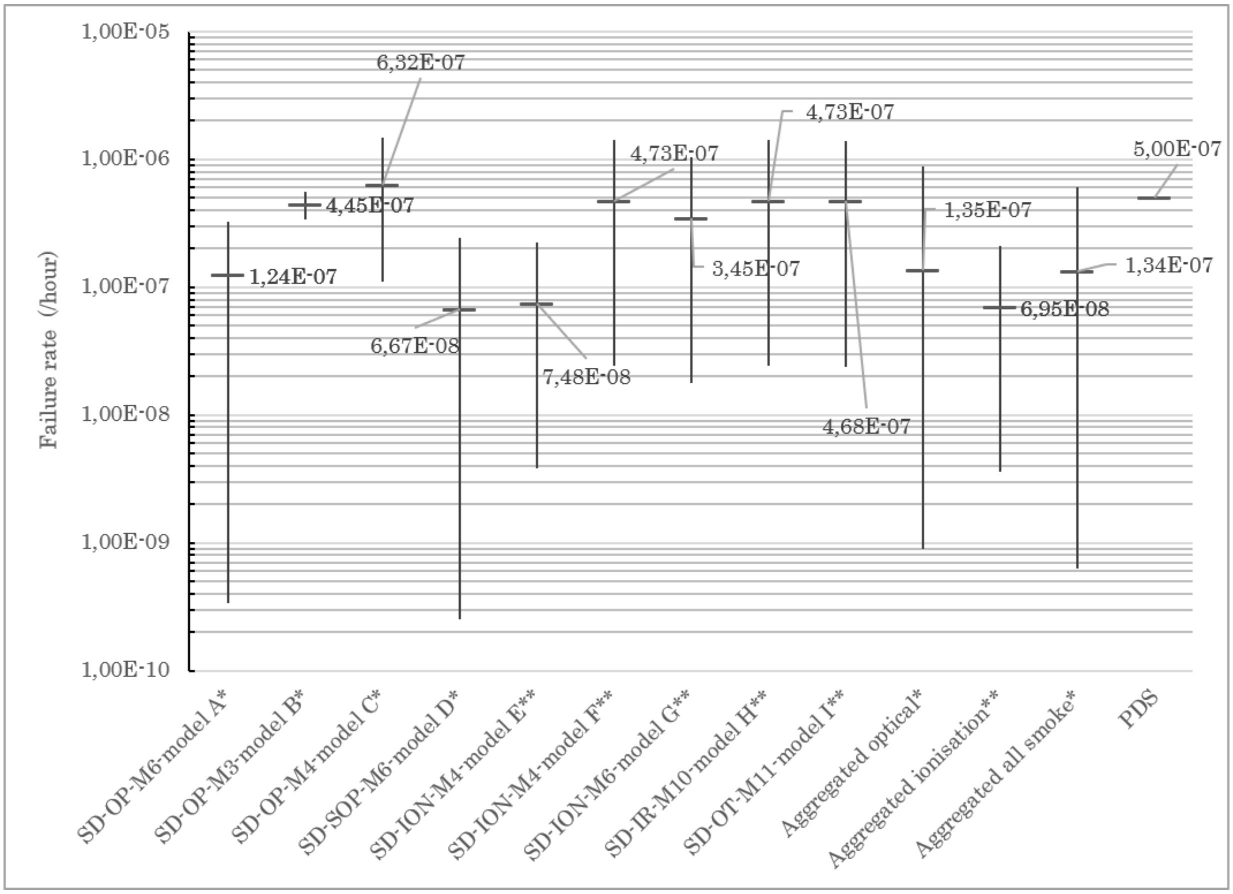


Figure 4.5: Smoke detector model: operational time and DU failures

The smoke detector SD-OP-M6- model A is the model that is mainly used by the facilities. The SD-SOP-M6- model D is the modification of the SD-OP-M6- model A, where it has better diagnostic coverage than the previous model. The SD-OP-M6- model A is having the highest number of DU failures, but it also has the highest operational time. The total operating hour of the detector is approximately 180 million hours. Figure 4.5 shows the failure rate for each model.



*failure rate is calculated using OREDA Multi-Sample (θ^*)

**failure rate is calculated using Bayesian approach ($\ddot{\lambda}_{DU}$)

Figure 4.6: Smoke detector failure rate for each model

All aggregated operational failure rates of the smoke detectors from operational data are lower than the failure rate stated by PDS data handbook, except SD-OP-M4-model C. This due to contribution of low failure rate from ionization smoke detectors and self-verify smoke detectors. The ionization smoke detector does not have a DU failure from approximately 12 million hour operation. The failure rate of self-verify smoke detector, SD-SOP-M6-model D, is half of the conventional smoke detector. It is indicated that the diagnostic coverage of the new detector is improving the reliability of the detector. It can be seen from the aggregated operational failure rate, that there is a noticeable difference in failure rate between each measuring principles in line with the failure rate for each measuring principles heat detector. This finding further support suggestion of PDS data handbook for providing more specific failure rate based on the measurement principle of the detector. The failure rate of each model in each facility is shown in Table 4.10. The highest failure rate is SD-OP-M4-Model C in facility K.

Table 4.10: The failure rate of the smoke detectors in all facilities

Facility	**Model**	**Method**	$\hat{\lambda}_{DU}$	$\ddot{\lambda}_{DU}$	**90% CI low** (h^{-1})	**90% CI up** (h^{-1})
Facility A	SD-OP-M6-model A	Bayesian	-	4.48E-08	3.94E-09	8.76E-08
Facility A	SD-OP-M3-model B	Operational only	4.62E-07	-	2.17E-07	8.68E-07
Facility A	SD-SOP-M6-model D	Bayesian	-	2.95E-07	1.51E-08	8.84E-07
Facility A	SD-OP-M4-model C	Bayesian	-	1.83E-07	9.41E-09	5.49E-07
Facility A	SD-ION-M4-model E	Bayesian	-	4.90E-07	2.51E-08	1.47E-06
Facility B	SD-OP-M6-model A	Bayesian	-	3.48E-08	1.79E-09	1.04E-07
Facility B	SD-ION-M4-model E	Bayesian	-	7.51E-08	3.85E-09	2.25E-07
Facility B	SD-ION-M6-model G	Bayesian	-	3.52E-07	1.80E-08	1.05E-06
Facility C	SD-SOP-M6-model D	Bayesian	-	3.49E-08	1.79E-09	1.05E-07
Facility C	SD-OP-M4-model C	Bayesian	-	4.89E-07	2.51E-08	1.46E-06
Facility C	SD-ION-M4-model F	Bayesian	-	4.73E-07	2.42E-08	1.42E-06
Facility D	SD-SOP-M6-model D	Operational only	2.84E-07	-	1.12E-07	5.96E-07
Facility D	SD-OT-M11-model I	Bayesian	-	4.68E-07	2.40E-08	1.40E-06
Facility E	SD-SOP-M6-model D	Bayesian	-	1.36E-07	6.96E-09	4.07E-07
Facility F	SD-OP-M6-model A	Operational only	4.18E-07	-	2.27E-07	7.09E-07
Facility F	SD-SOP-M6-model D	Bayesian	-	2.56E-07	1.32E-08	7.68E-07
Facility F	SD-IR-M10-model H	Bayesian	-	4.73E-07	2.43E-08	1.42E-06
Facility F	SD-ION-M6-model G	Bayesian	-	4.86E-07	2.49E-08	1.46E-06
Facility G	SD-OP-M6-model A	Operational only	1.93E-07	-	7.62E-08	4.07E-07
Facility H	SD-OP-M6-model A	Bayesian	-	3.88E-08	3.41E-09	7.58E-08
Facility H	SD-OP-M3-model B	Operational only	5.93E-07	-	3.22E-07	1.01E-06
Facility H	SD-OP-M4-model C	Bayesian	-	4.71E-07	2.41E-08	1.41E-06
Facility I	SD-SOP-M6-model D	Bayesian	-	5.40E-08	2.77E-09	1.62E-07
Facility J	SD-OP-M6-model A	Bayesian	-	8.93E-08	4.58E-09	2.68E-07
Facility J	SD-OP-M3-model B	Bayesian	-	2.44E-07	2.89E-08	3.86E-07
Facility K	SD-OP-M6-model A	Bayesian	-	3.69E-07	3.24E-08	7.21E-07
Facility K	SD-SOP-M6-model D	Bayesian	-	1.14E-07	1.00E-08	2.23E-07
Facility K	SD-OP-M4-model C	Operational only	1.17E-06	-	5.49E-07	2.20E-06
Facility L	SD-SOP-M6-model D	Bayesian	-	4.26E-07	2.19E-08	1.28E-06

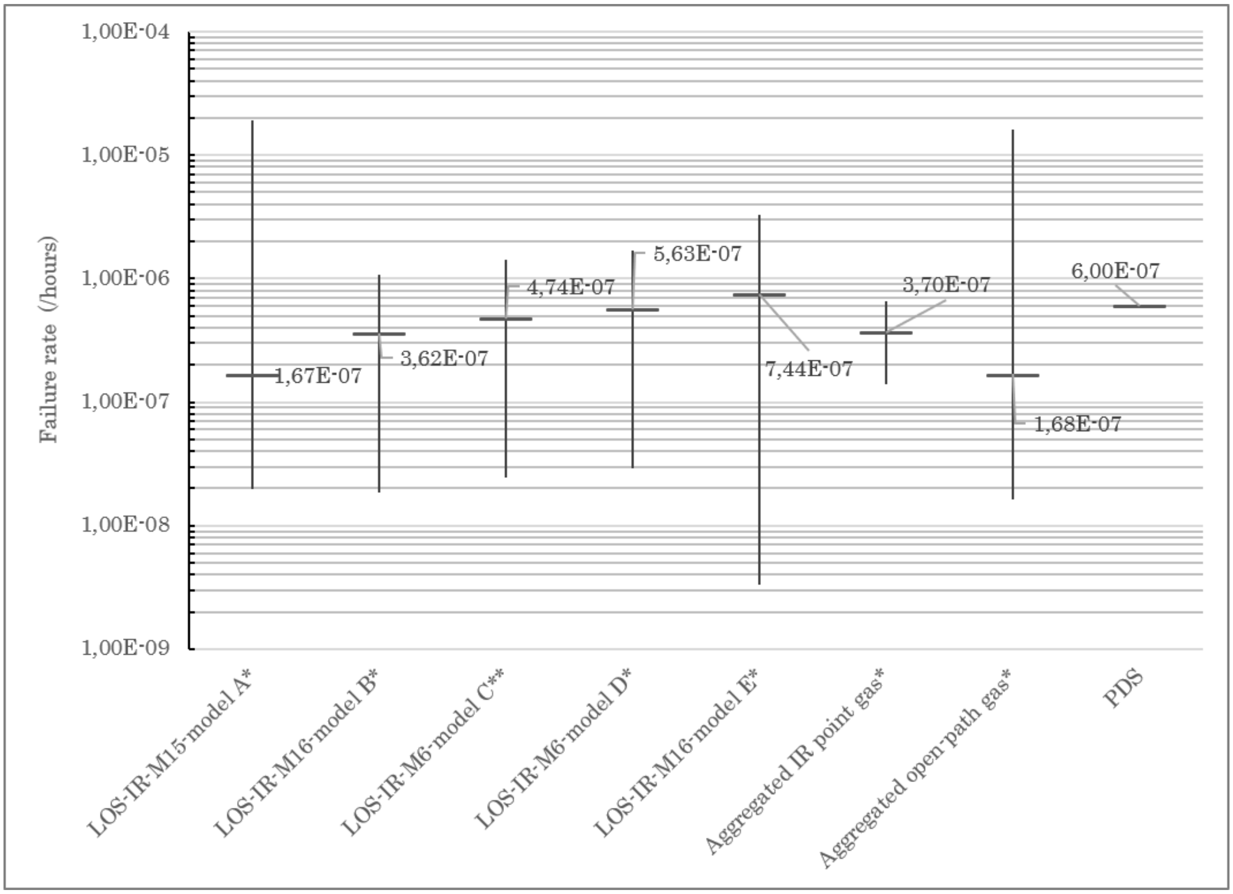
4.2.4 Failure Rate for Aspirating Smoke Detector

The aspirating smoke detector is one of the latest technologies of smoke detection systems. The detector consists of a central detection unit and a tubing unit that draws air from a room into the detector. The detector usually is equipped with a flow transmitter with a low alarm to alert the operator when the air is not sucked into the smoke detector. A room is only required to have one of the aspirating type smoke, and hence, the quantity data available for this detector is limited. In the observed data, there are four facilities use the aspirating smoke detector. The aspirating smoke detectors are supplied by the manufacturer 6 and the manufacturer 7. The number of aspirating smoke detectors is presented in Table 4.11 below.

Table 4.11: Aspirating smoke detectors quantity

Facilitiy	**Measurement**	**Manufacturer**	**Model**	**Quantity**	**Operation Time (hour)**	**DU**
Facility A	Aspirating system	Manufacturer 6	ASD-AS-M6-model A	8	336768	0
Facility A	Flow monitoring	Manufacturer 6	ASD-FT-M13-model D	8	336768	2
Facility C	Aspirating system	Manufacturer 6	ASD-AS-M6-model B	1	19416	0
Facility J	Aspirating system	Manufacturer 6	ASD-AS-M6-model B	3	103680	0
Facility J	Aspirating system	Manufacturer 7	ASD-AS-M7-model C	27	933120	7
Facility H	Aspirating system	Manufacturer 6	ASD-AS-M6-model A	5	208800	0
Facility H	Flow monitoring	Manufacturer 6	ASD-FT-M13-model D	5	208800	4

The DU failure is mainly observed at ASD-AS-M7-model C and the flow switch ASD-FT-M13-model D. Figure 4.7 shows the failure rate for each model.



*failure rate is calculated using OREDA Multi-Sample (θ^*)

**failure rate is calculated using Bayesian approach ($\lambda_{\ddot{DU}}$)

Figure 4.7: Aspirating detector failure rate for each model

The aggregated failure rate of aspirating smoke detector is significantly higher than the conventional smoke detector. From the aggregated data, the failure rate of smoke detector is 1.34×10^{-8} per hour, while aspirating smoke detector is 8.19×10^{-6} per hour. DU failures are mainly coming from the flow transmitters. The typical DU failure for the flow transmitter is that it is not indicating alarm when the tubing is blocked or leaked. The leak or blockage issues are observed during a functional test or preventive maintenance only. The failure rate of aspirating detector is significantly higher than the failure rate of a smoke detector in PDS data handbook, 5×10^{-7} per hour. The use of this type of detector shall be further evaluated in the future facility due to the fact that it has low reliability. An effective method for detecting tubing leakage or tubing blockage should be further evaluated. Table 4.12 shows the failure rate for aspirating smoke detectors in each facility.

Table 4.12: The failure rate of the aspirating smoke detectors in all facilities

Facility	**Model**	**Method**	$\hat{\lambda_{DU}}(h^{-1})$	$\ddot{\lambda_{DU}}(h^{-1})$	**90% CI low** (h^{-1})	**90% CI up** (h^{-1})
Facility A	ASD-AS-M6-model A	Bayesian	-	4.27E-07	2.15E-08	1.28E-06
Facility A	ASD-FT-M13-model D	Bayesian	-	1.28E-06	1.52E-07	2.03E-06
Facility C	ASD-AS-M6-model B	Bayesian	-	4.95E-07	2.54E-08	1.48E-06
Facility J	ASD-AS-M6-model B	Bayesian	-	4.75E-07	2.43E-08	1.42E-06
Facility J	ASD-AS-M7-model C	Operational only	7.51E-06	-	3.52E-06	1.41E-05
Facility H	ASD-AS-M6-model A	Bayesian	-	4.52E-07	2.32E-08	1.35E-06
Facility H	ASD-FT-M13-model D	Operational only	1.91E-05	-	6.54E-06	4.38E-05

Facility H has the highest failure rate for the flow transmitter. The failure rate of the flow transmitter is higher than the aspirating smoke detector.

4.2.5 Failure Rate for Point Type Infrared Gas Detector

There are enormous numbers of infrared point type gas detectors installed in the 12 observed facilities. Details of the infrared gas detectors quantity for each facility is presented in Table 4.13 below.

Table 4.13: Gas detectors quantity

Facility	**Measurement**	**Manufacturer**	**Model**	**Quantity**	**Operation Time (hour)**	**DU**
Facility A	Infrared, point type	Manufacturer 14	GD-IR-M14-model A	450	18943200	3
Facility B	Infrared, point type	Manufacturer 14	GD-IR-M14-model A	271	11408016	3
Facility C	Infrared, point type	Manufacturer 14	GD-IR-M14-model A	434	6687624	7
Facility D	Infrared, point type	Manufacturer 14	GD-IR-M14-model A	233	8052480	0
Facility D	Infrared, point type	Manufacturer 6	GD-IR-M6-model C	4	138240	0
Facility E	Infrared, point type	Manufacturer 14	GD-IR-M14-model A	123	2105544	0
Facility F	Infrared, point type	Manufacturer 14	GD-IR-M14-model A	147	4230072	3
Facility G	Infrared, point type	Manufacturer 14	GD-IR-M14-model A	343	8882328	2
Facility H	Infrared, point type	Manufacturer 14	GD-IR-M14-model A	541	22592160	9
Facility I	Infrared, point type	Manufacturer 14	GD-IR-M14-model A	287	9918720	3
Facility J	Infrared, point type	Manufacturer 14	GD-IR-M14-model A	156	5210208	3
Facility J	Infrared, point type	Manufacturer 14	GD-IR-M14-model B	68	181152	0
Facility K	Infrared, point type	Manufacturer 14	GD-IR-M14-model A	111	3836160	3
Facility K	Infrared, point type	Manufacturer 6	GD-IR-M6-model C	6	207360	0

Table 4.13: Gas detectors quantity

Facility	**Measurement**	**Manufacturer**	**Model**	**Quantity**	**Operation Time (hour)**	**DU**
Facility L	Infrared, point type	Manufacturer 14	GD-IR-M14-model A	40	1382400	0

Approximately 98% gas detector is supplied by Manufacturer 14 with GD-IR-M14-model. The comparison of operational hour of each model can be seen in Figure 4.8 below.

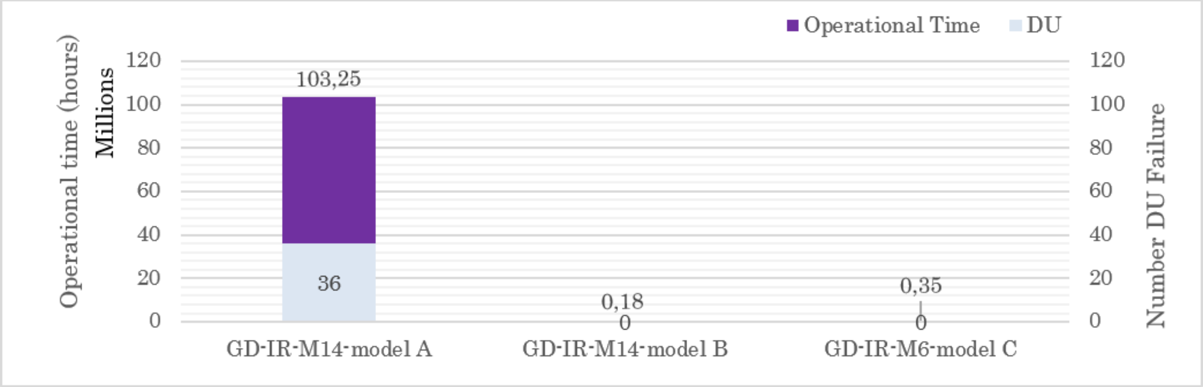
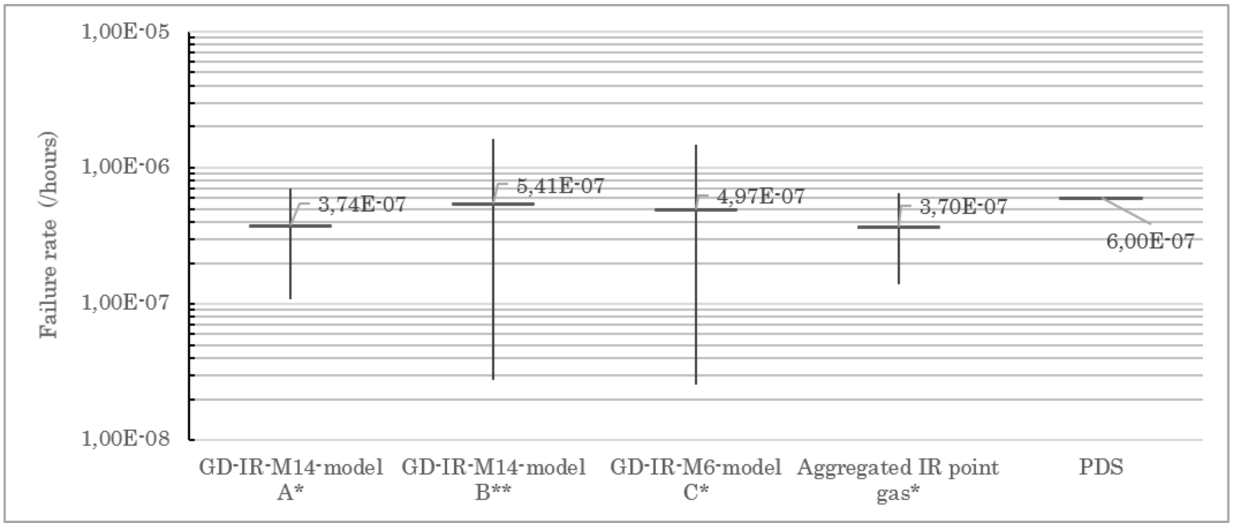


Figure 4.8: Infrared gas detector model: operational time and DU failures

There are only a small number of operating hour of GD-IR-M14-model B and GD-IR-M14-model C compared to GD-IR-M14-model A. The operating hour of GD-IR-M14-model B and GD-IR-M14- model C is not statically enough for making a conclusion. The failure rates for each detector is shown in Figure 4.9 below.



*failure rate is calculated using OREDA Multi-Sample (θ^*)

**failure rate is calculated using Bayesian approach ($\ddot{\lambda}_{DU}$)

Figure 4.9: Infrared point gas detector failure rate for each model

In general, the failure rate of infrared point gas detectors from operational data is lower than the failure rate stated by PDS. Based on the 90% confident interval failure, statistically, the failure rate obtained is vigorous as the confident interval range is narrow. It can also be seen that the detector operating hours are 103 million hours. Equinor can update the failure rate of infrared point gas detector from 6 $\times 10^{-7}$ per hour (PDS data handbook) to 3.7 $\times 10^{-7}$ per hour based on the aggregated operational data. Table 4.14 shows the failure rate for the infrared gas detector in each of the facility. Facility C has the highest failure rate of the GD-IR-M14-model A.

Table 4.14: The failure rate of the gas detectors in all facilities

Facility	**Model**	**Method**	$\hat{\lambda}_{DU}(h^{-1})$	$\ddot{\lambda}_{DU}(h^{-1})$	**90% CI low** (h^{-1})	**90% CI up** (h^{-1})
Facility A	GD-IR-M14-model A	Operational only	1.58E-07	-	4.32E-08	4.09E-07
Facility B	GD-IR-M14-model A	Operational only	2.63E-07	-	7.17E-08	6.80E-07
Facility C	GD-IR-M14-model A	Operational only	1.05E-06	-	4.91E-07	1.97E-06
Facility D	GD-IR-M14-model A	Bayesian	-	1.03E-07	5.28E-09	3.08E-07
Facility D	GD-IR-M6-model C	Bayesian	-	5.54E-07	2.84E-08	1.66E-06
Facility E	GD-IR-M14-model A	Bayesian	-	2.65E-07	1.36E-08	7.94E-07
Facility F	GD-IR-M14-model A	Operational only	7.09E-07	-	1.93E-07	1.83E-06
Facility G	GD-IR-M14-model A	Bayesian	-	2.84E-07	3.37E-08	4.50E-07
Facility H	GD-IR-M14-model A	Operational only	3.98E-07	-	2.08E-07	6.95E-07
Facility I	GD-IR-M14-model A	Operational only	3.02E-07	-	8.24E-08	7.82E-07
Facility J	GD-IR-M14-model A	Operational only	5.76E-07	-	1.57E-07	1.49E-06
Facility J	GD-IR-M14-model B	Bayesian	-	5.41E-07	2.78E-08	1.62E-06
Facility K	GD-IR-M14-model A	Operational only	7.82E-07	-	2.13E-07	2.02E-06
Facility K	GD-IR-M6-model C	Bayesian	-	5.34E-07	2.74E-08	1.60E-06
Facility L	GD-IR-M14-model A	Bayesian	-	3.28E-07	1.68E-08	9.83E-07

4.2.6 Failure Rate for Aspirating Gas Detector

The aspirating gas detector is required for the ventilation ducting as it is not possible to install the point type gas detector into it. Aspirating accessories are installed to allow detection. The gas detector is located outside the ducting and the tubing penetrates the ducting for sucking the air into the detector. A flow switch is installed inside the tubing. The purpose of installing the flow switch is to alert the operator when the air is not flowing into the detector. The quantity of aspirating type detectors in the facilities is presented in Table 4.15.

Table 4.15: Aspirating gas detectors quantity

Facility	**Measurement**	**Manufacturer**	**Model**	**Quantity**	**Operation Time (hour)**	**DU**
Facility A	Aspirated HC point	Manufacturer 14	AGD-IR-M14-model A	5	210480	0
Facility A	Flow monitoring	Manufacturer 12	AGD-FT-M12-model B	5	210480	0
Facility B	Aspirated HC point	Manufacturer 14	AGD-IR-M14-model A	3	126288	0
Facility B	Flow monitoring	Manufacturer 12	AGD-FT-M12-model B	3	126288	3
Facility C	Aspirated HC point	Manufacturer 14	AGD-IR-M14-model A	4	78240	0
Facility H	Aspirated HC point	Manufacturer 14	AGD-IR-M14-model A	90	3758400	1

Table 4.15: Aspirating gas detectors quantity

Facility	**Measurement**	**Manufacturer**	**Model**	**Quantity**	**Operation Time (hour)**	**DU**
Facility H	Flow monitoring	Manufacturer 12	AGD-FT-M12-model B	90	3758400	16
Facility I	Aspirated HC point	Manufacturer 14	AGD-IR-M14-model A	7	241920	0

The AGD-IR-M14-model A is the same gas detector model GD-M1-model A with aspirating accessories. The operating hour and quantity of DU failure is shown in Figure 4.10.

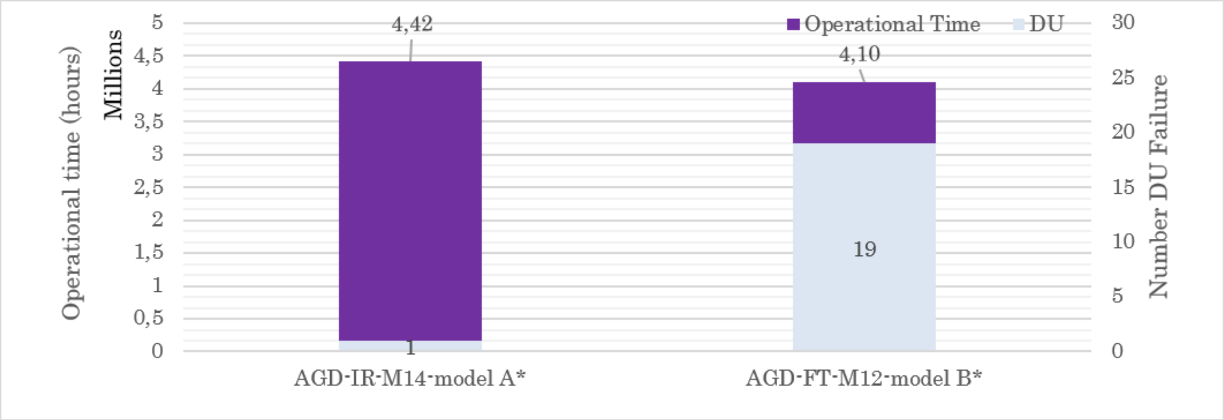
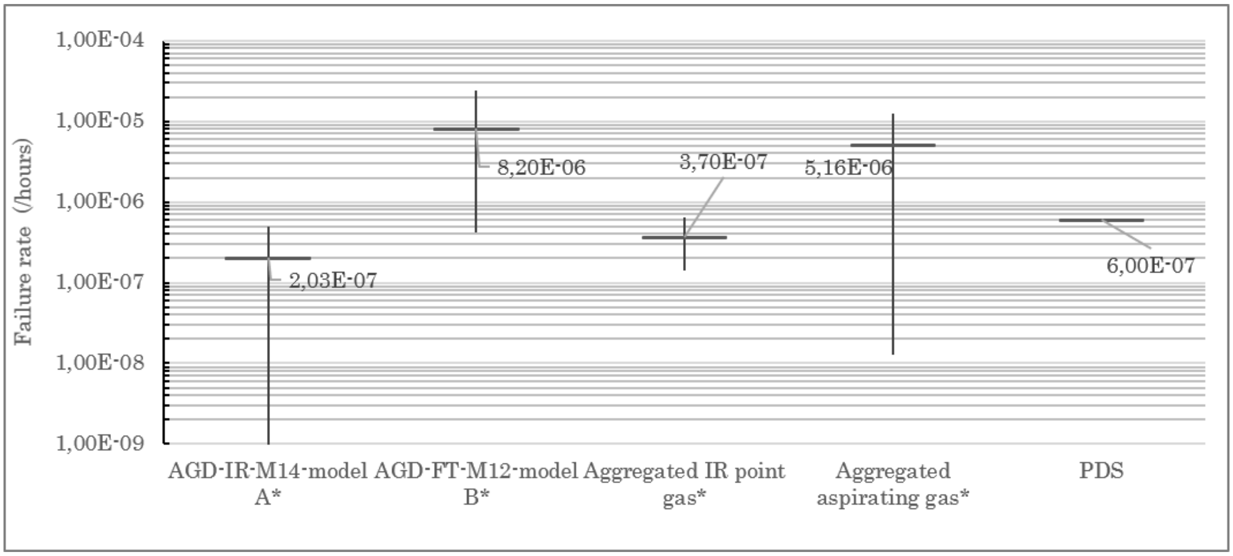


Figure 4.10: Aspirating detector model: operational time and DU failures

The DU failures are mainly observed for flow switch. The failure rates of each detector and the flow switch is presented in Figure 4.11.



*failure rate is calculated using OREDA Multi-Sample (θ^*)

**failure rate is calculated using Bayesian approach ($\ddot{\lambda}_{DU}$)

Figure 4.11: Aspirating point gas detector failure rate for each model

The aggregated failure rate of aspirating gas detector is 5.16 × 10^{-6} per hour. This failure is 10× higher the failure rate of point type infrared gas detector, 3.7 × 10^{-7} per hour. The main failure contributor is the flow switch, which is 8.2 × 10^{-6} per hour. The main reason is that the tubing can be blocked or leaking without the flow switch is initiating the alarm. The failure rate of the aspirating detector is also higher than PDS failure rate 6 × 10^{-7} per hour. A practical method to detect tubing leakage or tubing blockage should be further evaluated. Besides, the set point of flow switch should be evaluated to detect leakage effectively. Table 4.16 shows the failure rate for the infrared gas detectors in each facility.

Table 4.16: The failure rate of the gas detectors in all facilities

Facility	**Model**	**Method**	$\hat{\lambda}_{DU}(h^{-1})$	$\ddot{\lambda}_{DU}(h^{-1})$	**90% CI low** (h^{-1})	**90% CI up** (h^{-1})
Facility A	AGD-IR-M14-model A	Bayesian	-	5.33E-07	2.73E-08	1.60E-06
Facility A	AGD-FT-M12-model B	Bayesian	-	5.33E-07	2.73E-08	1.60E-06
Facility B	AGD-IR-M14-model A	Bayesian	-	5.58E-07	2.86E-08	1.67E-06
Facility B	AGD-FT-M12-model B	Operational only	2.38E-05	-	6.47E-06	6.14E-05
Facility C	AGD-IR-M14-model A	Bayesian	-	5.73E-07	2.94E-08	1.72E-06
Facility H	AGD-IR-M14-model A	Bayesian	-	3.69E-07	3.24E-08	7.20E-07
Facility H	AGD-FT-M12-model B	Operational only	4.26E-06	-	2.67E-06	6.47E-06
Facility I	AGD-IR-M14-model A	Bayesian	-	5.24E-07	2.69E-08	1.57E-06

4.2.7 Failure Rate for Open Path Gas Detector

There are various model open path gas detector in the observed data. Details of open path gas detector quantity for each facility is presented in Table 4.17 below.

Table 4.17: Open path gas detector quantity

Facility	**Measurement**	**Manufacturer**	**Model**	**Quantity**	**Operation Time (hour)**	**DU**
Facility A	Line of sight-optical	Manufacturer 15	LOS-IR-M15-model A	128	2694144	0
Facility A	Line of sight-optical	Manufacturer 16	LOS-IR-M16-model E	10	210480	0
Facility B	Line of sight-optical	Manufacturer 15	LOS-IR-M15-model A	98	2062704	1
Facility C	Line of sight-optical	Manufacturer 15	LOS-IR-M15-model A	254	2737272	0
Facility D	Line of sight-optical	Manufacturer 15	LOS-IR-M15-model A	51	1762560	1
Facility E	Line of sight-optical	Manufacturer 16	LOS-IR-M16-model B	128	1094832	0
Facility F	Line of sight-optical	Manufacturer 15	LOS-IR-M15-model A	436	6273168	20
Facility F	Line of sight-optical	Manufacturer 16	LOS-IR-M16-model E	30	517968	1
Facility G	Line of sight-optical	Manufacturer 15	LOS-IR-M15-model A	326	4221048	0
Facility H	Line of sight-optical	Manufacturer 15	LOS-IR-M15-model A	216	4510080	0
Facility I	Line of sight-optical	Manufacturer 15	LOS-IR-M15-model A	94	1624320	0
Facility I	Line of sight-optical	Manufacturer 15	LOS-IR-M15-model A	6	69120	0
Facility I	Line of sight-optical	Manufacturer 6	LOS-IR-M6-model D	32	108672	0
Facility I	Line of sight-optical	Manufacturer 6	LOS-IR-M6-model C	32	444288	0
Facility J	Line of sight-optical	Manufacturer 15	LOS-IR-M15-model A	68	1175040	0
Facility K	Line of sight-optical	Manufacturer 15	LOS-IR-M15-model A	16	380160	7

Table 4.17: Open path gas detector quantity

Facility	**Measurement**	**Manufacturer**	**Model**	**Quantity**	**Operation Time (hour)**	**DU**
Facility K	Line of sight-optical	Manufacturer 16	LOS-IR-M16-model B	44	725760	7
Facility L	Line of sight-optical	Manufacturer 15	LOS-IR-M15-model A	4	69120	0
Facility L	Line of sight-optical	Manufacturer 16	LOS-IR-M16-model E	32	552960	0

The LOS-IR-M15-model A is mainly used in the facility, it is approximately 85% from detector quantity. The DU failure quantity of each model is depicted in the Figure 4.12.

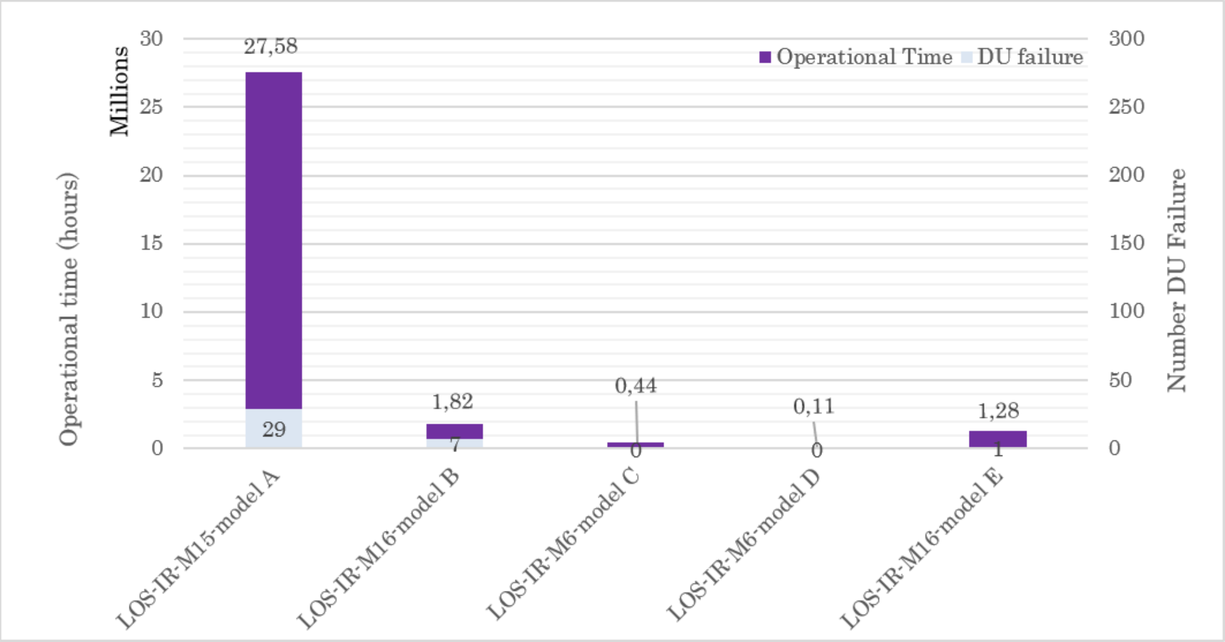
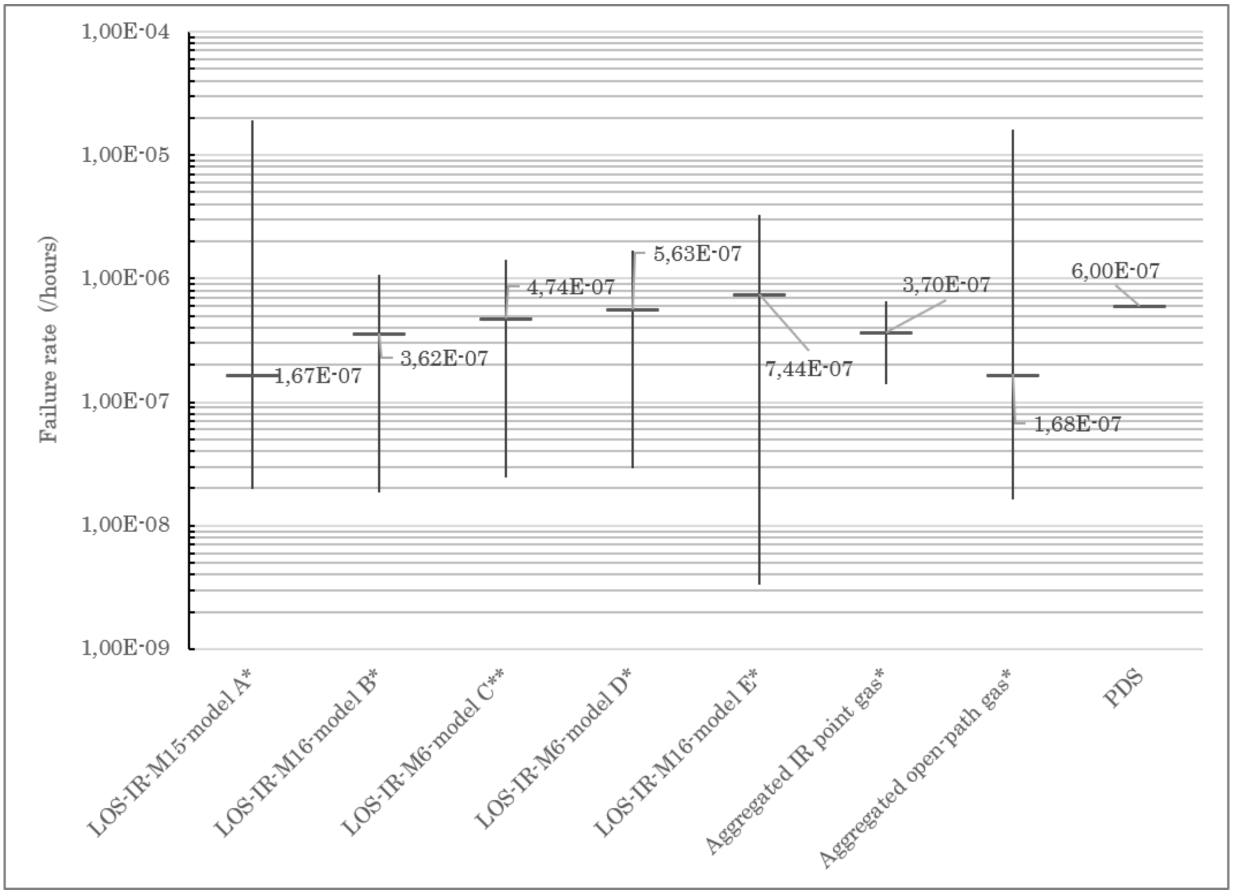


Figure 4.12: Open path gas detector model: operational time and DU failures

Facility K is experiencing a very high number of DU failures compared to the operational time. The LOS-IR-M15-model A is having 7 DU failures from 44 detectors and the LOS-IR-M16-model B is having 7 DU failures from 16 detectors. The failure rate is high, and it is increasing the overall failure rate significantly. The DU failure of this facility is the domineering number of DU failures in the other facilities, and hence, it is not included in the overall failure rate calculation. The aggregated failure rate of each model by removing DU failure of facility K is depicted in Figure 4.13.

The overall aggregated failure rate of open path gas detector, 1.68×10^{-7} per hour, is smaller than the failure rate defined by the PDS data handbook, 6×10^{-7} per hour. The operational failure rate of LOS-IR-M15-model A, 1.67×10^{-7} per hour, it is almost similar to the failure rate of the aggregated all open path detectors as 85% of the detector models is LOS-IR-M15-model A. The total number of detector operating hours for model LOS-IR-M15-model A and LOS-IR-M16-model B are more than 29 million hours. It is indicating, statistically, that the data is adequate enough to conclude that the detector is having a better reliability than the stated failure rate in PDS data handbook.



*failure rate is calculated using OREDA Multi-Sample (θ^*)

**failure rate is calculated using Bayesian approach ($\ddot{\lambda}_{DU}$)

Figure 4.13: Open path gas detector failure rate for each model

Table 4.18 shows the failure rate for the open path gas detector in each facility. The failure rate of LOS-IR-M15-model A in facility K is 1.84 × 10^{-5} per hour and the failure rate of LOS-IR-M16-model B in facility K for 9.65 × 10^{-6} per hour. These failure rates are higher compared to the failure rate for other detectors, and hence, it is excluded from the aggregated data calculation.

Table 4.18: The failure rate of the open path gas detector in all facilities

Facility	**Model**	**Method**	$\hat{\lambda}_{DU}(h^{-1})$	$\ddot{\lambda}_{DU}(h^{-1})$	**90% CI low** (h^{-1})	**90% CI up** (h^{-1})
Facility A	LOS-IR-M15-model A	Bayesian	-	2.29E-07	1.18E-08	6.87E-07
Facility A	LOS-IR-M16-model E	Bayesian	-	5.33E-07	2.73E-08	1.60E-06
Facility B	LOS-IR-M15-model A	Bayesian	-	5.36E-07	4.72E-08	1.05E-06
Facility C	LOS-IR-M15-model A	Bayesian	-	2.27E-07	1.16E-08	6.80E-07
Facility D	LOS-IR-M15-model A	Bayesian	-	5.83E-07	5.13E-08	1.14E-06
Facility E	LOS-IR-M16-model B	Bayesian	-	3.62E-07	1.86E-08	1.08E-06

Table 4.18: The failure rate of the open path gas detector in all facilities

Facility	**Model**	**Method**	$\hat{\lambda}_{DU}(h^{-1})$	$\ddot{\lambda}_{DU}(h^{-1})$	**90% CI low** (h^{-1})	**90% CI up** (h^{-1})
Facility F	LOS-IR-M15-model A	Operational only	3.19E-06	-	2.11E-06	4.63E-06
Facility F	LOS-IR-M16-model E	Bayesian	-	9.15E-07	8.05E-08	1.79E-06
Facility G	LOS-IR-M15-model A	Bayesian	-	1.70E-07	8.71E-09	5.09E-07
Facility H	LOS-IR-M15-model A	Bayesian	-	1.62E-07	8.30E-09	4.85E-07
Facility I	LOS-IR-M15-model A	Bayesian	-	3.04E-07	1.56E-08	9.10E-07
Facility I	LOS-IR-M15-model A	Bayesian	-	5.76E-07	2.96E-08	1.73E-06
Facility I	LOS-IR-M6-model D	Bayesian	-	5.63E-07	2.89E-08	1.69E-06
Facility I	LOS-IR-M6-model C	Bayesian	-	4.74E-07	2.43E-08	1.42E-06
Facility J	LOS-IR-M15-model A	Bayesian	-	3.52E-07	1.81E-08	1.05E-06
Facility K	LOS-IR-M15-model A	Operational only	1.84E-05	-	8.64E-06	3.46E-05
Facility K	LOS-IR-M16-model B	Operational only	9.65E-06	-	4.53E-06	1.81E-05
Facility L	LOS-IR-M15-model A	Bayesian	-	5.76E-07	2.96E-08	1.73E-06
Facility L	LOS-IR-M16-model E	Bayesian	-	4.51E-07	2.31E-08	1.35E-06

4.2.8 Failure Rate for Catalytic Gas Detector

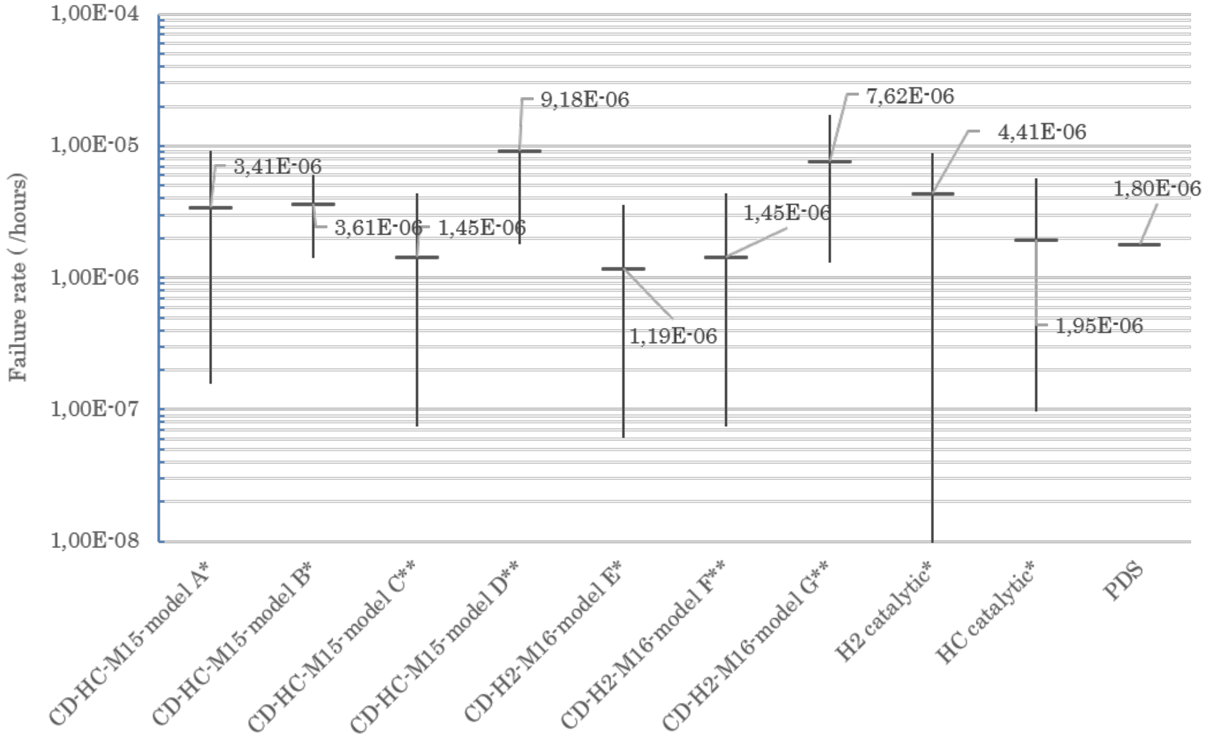
The catalytic gas detector is used to detect hydrocarbon gas or hydrogen gas. The hydrogen gas is commonly located inside the battery room or in the analyzer package. The battery releases hydrogen gas during charging. The number of the catalytic gas detector for detecting hydrogen gas in the data collection is very limited compares to the catalytic gas detector for detecting hydrocarbon gas. Table 4.19 shows number of detectors in each of the facility.

Table 4.19: Catalytic gas detectors quantity

Facility	**Measurement**	**Manufacturer**	**Model**	**Quantity**	**Operation Time (hour)**	**DU**
Facility A	HC catalytic	Manufacturer 15	CD-HC-M15-model A	238	9976752	11
Facility B	H2 Catalytic	Manufacturer 16	CD-H2-M16-model E	6	252576	0
Facility C	HC catalytic	Manufacturer 15	CD-HC-M15-model B	58	797040	4
Facility C	HC catalytic	Manufacturer 15	CD-HC-M15-model C	31	132048	0
Facility D	HC catalytic	Manufacturer 15	CD-HC-M15-model B	7	241920	0
Facility E	H2 Catalytic	Manufacturer 16	CD-H2-M16-model F	8	136464	0
Facility F	H2 Catalytic	Manufacturer 16	CD-H2-M16-model G	6	172656	3
Facility G	H2 Catalytic	Manufacturer 16	CD-H2-M16-model G	5	129480	0
Facility H	H2 Catalytic	Manufacturer 16	CD-H2-M16-model G	9	375840	2
Facility K	HC catalytic	Manufacturer 15	CD-HC-M15-model A	176	6082560	35
Facility K	HC catalytic	Manufacturer 15	CD-HC-M15-model D	6	207360	6
Facility L	H2 Catalytic	Manufacturer 16	CD-H2-M16-model E	1	34560	0

The DU failures occur mainly to the catalytic hydrocarbon detector. The facility K has 35 DU failures from the total number of 176 detectors, which is significantly higher than the number of DU failures in the other facilities. The number of DU failure in facility A is also higher than the other facilities. Both facilities are the main contributor to DU failures for the catalytic detector.

That is understandable as the operating hours in both facilities also are significantly higher. There are only 2 DU failures observed at the catalytic gas detector to detect hydrogen gas. The operating hour of the catalytic hydrogen detector is low, and statistically, the data may not be adequate to present a good observation. The DU failure rate for each gas detector model is presented in Figure 4.14.



*failure rate is calculated using OREDA Multi-Sample

**failure rate is calculated using Bayesian approach

Figure 4.14: Catalytic gas detector failure rate for each model

The failure rate of the catalytic gas detector during operational time is generally higher than the failure rate of the catalytic gas detector stated in the PDS data handbook. Table 4.20 shows the failure rate for the catalytic gas detector in each facility.

Table 4.20: The failure rate of the catalytic gas detector in all facilities

Facility	**Model**	**Method**	$\hat{\lambda}_{DU}(h^{-1})$	$\ddot{\lambda}_{DU}(h^{-1})$	**90% CI up** (h^{-1})	**90% CI up** (h^{-1})
Facility A	CD-HC-M15-model A	Operational only	1.10E-06	-	6.18E-07	1.82E-06
Facility B	CD-H2-M16-model E	Bayesian	-	1.24E-06	6.35E-08	3.71E-06
Facility C	CD-HC-M15-model B	Operational only	5.02E-06	-	1.71E-06	1.15E-05
Facility C	CD-HC-M15-model C	Bayesian	-	1.45E-06	7.46E-08	4.36E-06
Facility D	CD-HC-M15-model B	Bayesian	-	1.25E-06	6.43E-08	3.76E-06
Facility E	CD-H2-M16-model F	Bayesian	-	1.45E-06	7.41E-08	4.33E-06

Table 4.20: The failure rate of the catalytic gas detector in all facilities

Facility	**Model**	**Method**	$\hat{\lambda}_{DU}(h^{-1})$	$\ddot{\lambda}_{DU}(h^{-1})$	**90% CI up** (h^{-1})	**90% CI up** (h^{-1})
Facility F	CD-H2-M16-model G	Operational only	1.74E-05	-	4.74E-06	4.49E-05
Facility G	CD-H2-M16-model G	Bayesian	-	1.46E-06	7.49E-08	4.37E-06
Facility H	CD-H2-M16-model G	Bayesian	-	3.22E-06	3.82E-07	5.09E-06
Facility K	CD-HC-M15-model A	Operational only	5.75E-06	-	4.25E-06	7.63E-06
Facility K	CD-HC-M15-model D	Operational only	2.89E-05	-	1.26E-05	5.71E-05
Facility L	CD-H2-M16-model E	Bayesian	-	5.88E-07	3.02E-08	1.76E-06

The hydrocarbon catalytic detector operational failure rate in all facilities is higher than the failure rate of hydrocarbon point type IR detector. The reliability of this detector is lower than the hydrocarbon point type IR detector. Use of this type detector shall be limited, and it shall be only in the area where hydrocarbon point type IR detector is not practical, such as an enclosure with too high operating temperature.

4.3 Failure Rate Discussion

IEC 61508 requires every SIF component to be follow-up during the operational phase. The equipment failure rate is one of the critical parameters to ensure the PFDavg requirement is full-filled. According to the guideline for SIS follow-up, the failure rate can be calculated based on the operational failure data only, or it can be calculated by combining with a priory failure rate., λ_{DU}, through Bayesian method.

The purpose of this section is to investigate a different approach to calculate the Bayesian failure rate. Typically. the PDS data handbook failure rate is used as a priory failure rate, λ_{DU}, and in this master thesis, the possibility of using aggregated operational failure rate is reviewed. The reason is that the operational failure rate has up to date data. At first, this section discusses the required criteria, and hence, the operational data is considered sufficient. Then the discussion continues with the possibility to use the aggregated operational failure rate as a priory failure rate, λ_{DU}. Lastly, it is comparing the aggregated operational failure rate and the PDS data handbook failure rate as a priory failure rate, λ_{DU}. The summary calculation is presented in this chapter and the full result in Appendix D.

4.3.1 The Sufficient Operational Experience Criteria

Hauge and Lundteigen (2008) in SINTEF guideline for SIL follow-up actions defines the operational data is adequate if the upper 95% percentile of the operational failure rate, $\hat{\lambda}_{DU}$, is approximately three times the mean value or lower. Based on the calculated result from the observed data, the requirement is fulfilled when there are more than 2 DU failures during the operational time interval. Table 4.21 shows the summary of the sufficient operational experience criteria calculation.

Table 4.21: The operational data based on 95% Confident Interval (CI) criteria

Facilities	**Model**	**Operational time (hours)**	**DU**	$\hat{\lambda}_{DU}(h^{-1})$	**3×(h^{-1})**	**95% CI up** (h^{-1})	**Data adequate**
Facility A	SD-OP-M6-model A	4.26E+07	1	2.35E-08	7.04E-08	1.11E-07	No
Facility B	FD-IR3-M1-model A	9.51E+06	2	2.10E-07	6.31E-07	6.62E-07	No
Facility H	SD-OP-M6-model A	4.95E+07	1	2.02E-08	6.06E-08	9.58E-08	No
Facility J	SD-OP-M3-model B	1.03E+07	2	1.94E-07	5.83E-07	6.11E-07	No
Facility K	SD-SOP-M6-model D	1.55E+07	1	6.44E-08	1.93E-07	3.06E-07	No
Facility B	CD-H2-M16-model G	1.14E+07	3	2.63E-07	7.89E-07	6.80E-07	Yes
Facility F	GD-IR-M14-model A	1.73E+05	3	1.74E-05	5.21E-05	4.49E-05	Yes

*CI = Confident interval

CD-H2-M16-model G in facility B with 3 DU failures with approximately 10 million operating hours has fulfilled the criteria of sufficient operational data. Meanwhile, FD-IR3-M1-model A in facility B with 2 DU failures, and it is approximately similar operational hours with the previous model, it will not fulfill the same criteria. This criterion is considered fair when there are more than 2 DU failures. The operational data shall be used because it can be considered conservative enough. Two DU failures are considered too small for making a decision. When the failure is two or less, the data is not considered statistically adequate to make the decision, and hence, it is suggested to calculate failure rate by combining with the more conservative failure rate, such as failure rate in PDS data method using the Bayesian approach to ensure that the obtained failure rate is not too optimistic.

A study also performed to investigate what is the impact if the requirement of sufficient operational experience criteria is reduced into 75% upper limit confident interval or it is increased into 99% upper limit confident interval instead of the 95% upper limit confident interval. The result is indicating that the operational experience is considered as sufficient data if the DU failure is more than 1 for the 75% upper limit confident interval and the DU failure is more than 3 for the 99% upper limit confident interval. The approach proposes by SINTEF guideline is considered as a right approach as it has 95% confidence level, and it is including approximately 20% from the operational failure notification data that is considered to have adequate operational experience. The requirement is in line with IEC 61508 standard that the failure rate shall have minimum 90% confident interval with the range is 5% lower limit confident interval and 95% upper limit confident interval.

Hauge and Lundteigen (2008) is not establishing the requirement on minimum operational time data in the SINTEF guideline. As a result, the calculated failure rate can be too conservative. Table 4.22 shows the detector model, which has low operational time; however, it is considered having adequate operational experience data as it has 3 DU failures or more.

Table 4.22: Low operational time and sufficient operational data

Facility	**Model**	**time (hours)**	**DU**	$\hat{\lambda}_{DU}(h^{-1})$	**3**$\hat{\lambda}_{DU}(h^{-1})$	**90% CI up** (h^{-1})	**Data**	**PDS** $\lambda_{DU}(h^{-1})$
Facility A	FD-UV-M1-model D	8.00E+05	3	3.75E-06	1.13E-05	9.69E-06	OK	5.00E-07
Facility C	CD-HC-M15-model B	7.97E+05	4	5.02E-06	1.51E-05	1.15E-05	OK	1.80E-06
Facility F	CD-H2-M16-model G	1.73E+05	3	1.74E-05	5.21E-05	4.49E-05	OK	1.80E-06

*CI = Confident interval

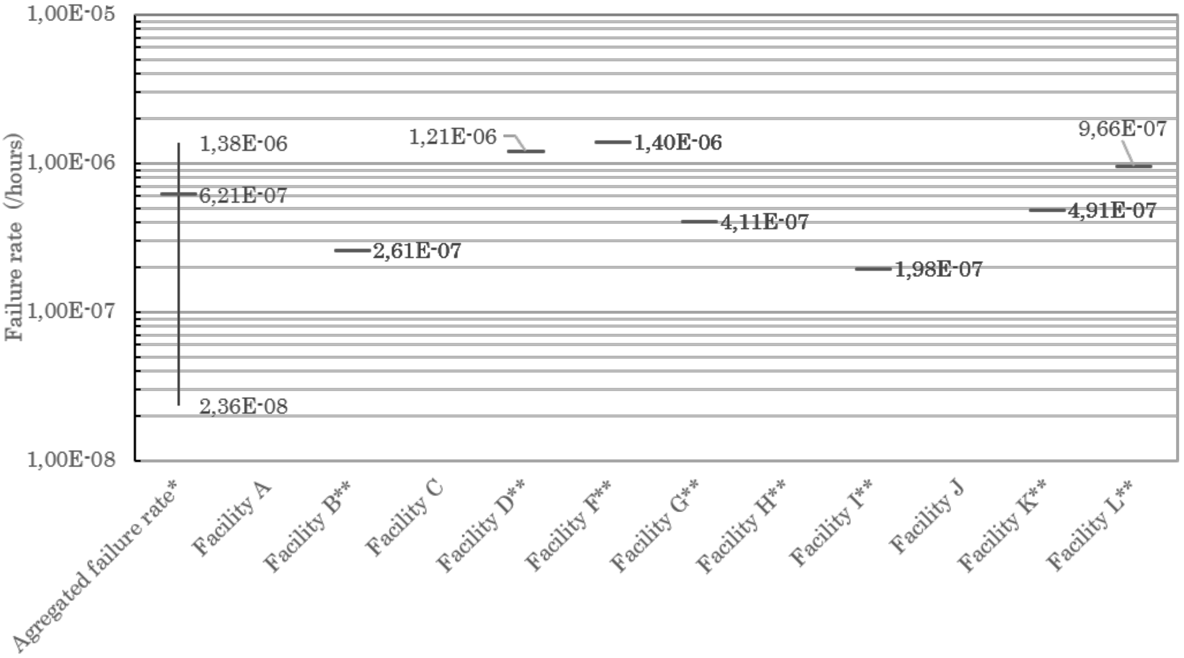
The operational failure rate of the model in Table 4.22 is significantly higher than the failure rate stated in the PDS data handbook. It may sound too conservative in deciding to increase the test interval based on the low operational time data only. The possibility to limit the minimum operational time should be further investigated. The observed data is not adequate to draw any conclusion as there is not much data with the operational failure rate is significantly higher than the PDS data handbook failure rate. The minimum operational time can reduce the possibility of over-pessimistic operational failure rate. The further investigation valuable to determine the number of operational time to ensure the data is statistically adequate, and narrow confidence interval.

4.3.2 Selection of A Priory Failure Rate

This section describes the possibility of using aggregated operational failure rate as a priory failure rate, λ_{DU}. The reason is that the aggregated failure rate represent current technology and the particular use of a component SIS more accurate than the general failure rate available in PDS data handbook. Equinor operates for more than 20 years, and hence, the company has adequate data to calculate its operational failure rate. The author uses the OREDA Multi-Sample method to calculate the aggregated failure rate from the operational phase. The calculated aggregation failure rate is the mean distribution of the failure rate for each facility. Figure 4.15 and Figure 4.16 are indicating a comparison of the calculated aggregation failure rate with the failure rate for each facility for a detector mode.

In general, the failure rate for each facility is within 90% confident interval limit of the aggregated failure rate calculated by OREDA Multi-Sample. Figure 4.15 is having wider confident interval range compare to Figure 4.16. The main reason is due to the failure rate distribution of the FD-IR3-M1-model A is wider than the failure rate distribution of GD-IR-M14-model A. This is proving the effectiveness of OREDA Multi-Sample method.

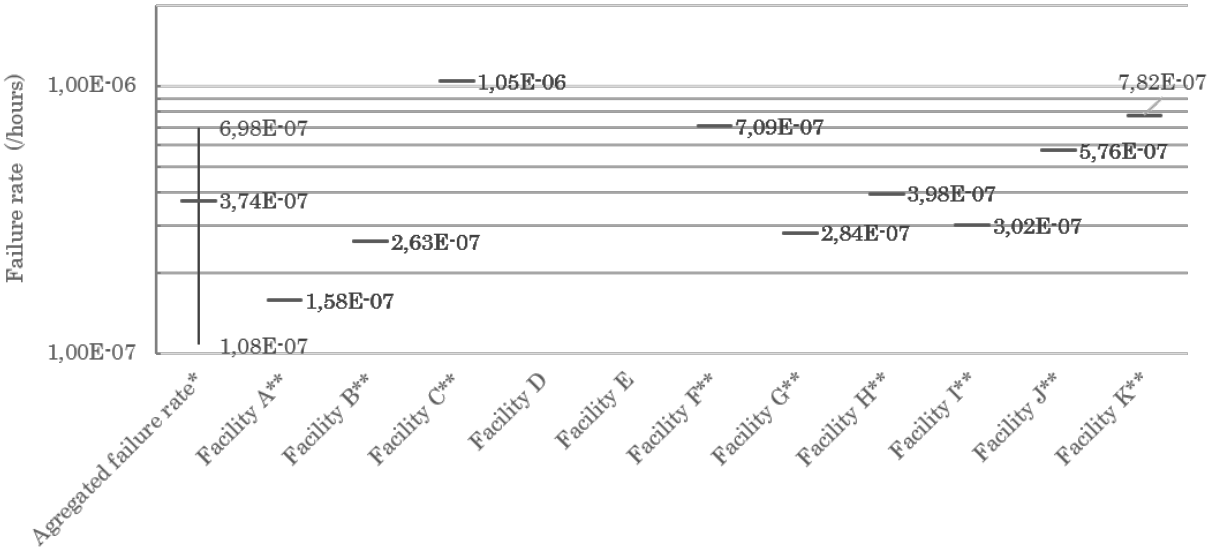
GD-IR-M14-model A in facility C is having the operational failure rate higher than the upper limit 95% confident interval of gas detector GD-IR-M14-model A. This result may indicates that further investigation may be required in the facility as the failure rate is significantly higher than other facilities. A systematic failure may be the cause of the failure, and further failure analysis maybe required the facility C. The 90% confident interval of a detector model can be used to decide if the detector in an installation is behaving in the same manner with the other installation. It is possible to use this approach to evaluate the performance of the detector failure rate.



*failure rate is calculated using OREDA Multi-Sample (θ^*)

**Operational failure rate only (λ_{DU})

Figure 4.15: Comparison aggregated failure rate between OREDA Multi-Sample and failure rate for each facility (FD-IR3-M1-model A)



*failure rate is calculated using OREDA Multi-Sample (θ^*)

**Operational failure rate only (λ_{DU})

Figure 4.16: Comparison aggregated failure rate between OREDA Multi-Sample and failure rate for each facility (GD-IR-M14-model A)

In this research the calculated aggregation failure rate by using OREDA Multi-Sample is also compared with the failure rate generally used in the SRS from PDS data handbook and the failure rate claimed by manufacturer. As general knowledge the operational failure rate is likely higher than the failure rate in SIL certification. The same result is also drawn from this research, for all detectors. Figure 4.17 shows the comparison of the failure rate. In general, the aggregated operational failure calculated is having almost similar failure rate for each detector type with the failure rate presented in PDS data handbook.

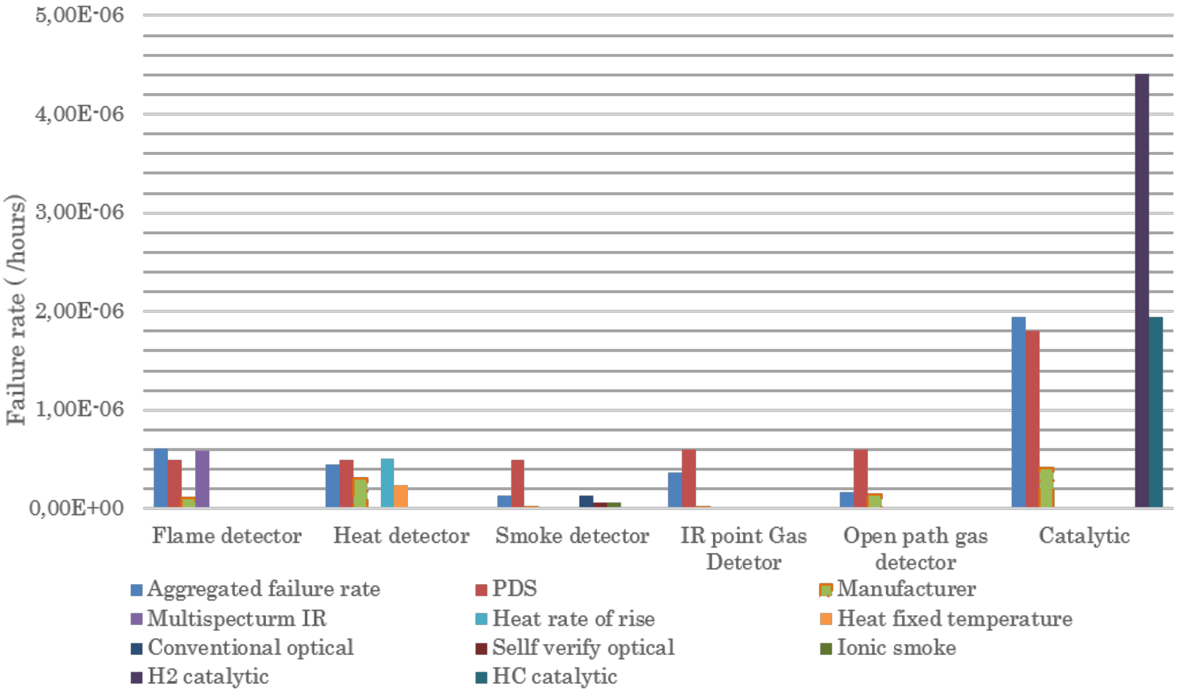


Figure 4.17: Comparison operational failure rate, PDS failure rate, and supplier data

The experienced failure rate during operational time is significantly higher than the failure rate stated in the manufacturer certification such as Safety Analysis Report (SAR) and the reason may be due to the fact that there is systematic failure included in the failure rate calculation meanwhile the failure rate in certification considers random hardware failure only. One of the concerns is when using the failure rate from the manufacturer certificate to calculate PFD during SIS verification, the result can be overoptimistic. The requirement to use the operational data failure rate or industrial database such as PDS data handbook for SIS verification may be valuable as the proof that the systematic failure cannot be avoided in practice. van Beurden and Goble (2015) combines the operational failure rate with the industrial database for SIS verification calculation. It can be beneficial for the company to have its database based on operational failure data for SIS verification calculation in the future project.

The aggregated operational failure rate, θ^*, of flame detectors, heat detectors, IR point gas detectors and catalytic gas detectors are almost same with the failure rate at PDS data handbook.

The aggregated operational failure rate, θ^*, of smoke detectors, is considerably lower than the PDS data handbook failure rate. One of the reason is a new technology that has good diagnostic coverage, and hence, the DU failure number becomes smaller. It may be valuable for PDS to update the failure rate of smoke detectors as the technology is improving. Besides, it may be valuable for PDS data handbook to define more specific detector measurement principle. One of the examples is the aggregated operational failure rate of heat detector rate of rise that is higher than the failure rate of the heat detector fixed temperature or the aggregated failure rate of the aspirator gas detector is higher than the aggregated failure rate of regular gas detector.

The aggregated operational failure calculated with OREDA Multi-Sample method has almost similar failure rate for each detector type with the failure rate presented in PDS data handbook. This can be one of the reasons that it is possible to use the aggregated failure rate during operational time as a priory failure rate for the Bayesian approach, the further evaluation is detailed in the subsection below.

4.3.3 Comparison Calculated Bayesian Failure Rate $\ddot{\lambda}_{DU}$ based on Different A Priory Failure Rate λ_{DU}

The Bayesian method has been widely used to combine different data from different data sources. Kvam and Martz (1995) states that the Bayesian approach can be used to calculate when the observed failure is too small compared to failure in the standard data. As a general case for an SIS component, as the component should have high reliability and integrity, the number of failures is too small or no failure observed. However, there is a disadvantage of the Bayesian approach as the Bayesian failure rate approach depends on the value of a priory data used. This issue leads to the controversy of this method between researchers.

In this master thesis, the author reviews the impact of using different a priory failure rate for calculating the Bayesian failure rate, $\ddot{\lambda}_{DU}$. A priory failure rate can be the failure rate used from the expert judgment, which typically is PDS method data handbook. In the master thesis, others a priory data is used. The other a priory data is based on the aggregated failure rate from the operational phase. Two types of aggregated operational failure rates are used. They are the aggregated failure rate of the model and the aggregated failure rate of the detector type. The result is three different calculated failure rates with the Bayesian approach as listed below:

- Case A: the Bayesian approach failure rate where a priory failure rate is PDS data handbook failure rate
- Case B: the Bayesian approach failure rate where a priory failure rate is the OREDA Multi-Sample failure rate for the detector type
- Case C: the Bayesian approach failure rate where a priory failure rate is the OREDA Multi-Sample failure rate for the detector model

The result is indicating that a priory failure rate is impacting the failure rate of a component in the facility. The impact of a priory failure rate can be seen in Table 4.23 below.

Table 4.23: Comparison of the $\ddot{\lambda}_{DU}$ with a different priory λ_{DU}

Facility	**Model**	**Time -hour**	**DU**	**Case A** (h^{-1})		**Case B** (h^{-1})		**Case C** (h^{-1})	
				$\lambda_{DU,A}$	$\ddot{\lambda}_{DU,A}$	$\lambda_{DU,B}$	$\ddot{\lambda}_{DU,B}$	$\lambda_{DU,C}$	$\ddot{\lambda}_{DU,C}$
Facility A	SD-SOP-M6-model D	1389168	0	5E-07	2.95E-07	1.35E-07	5.65E-08	6.67E-08	6.10E-08
Facility E	SD-SOP-M6-model D	5366112	0	5E-07	1.36E-07	1.35E-07	2.13E-08	6.67E-08	4.91E-08
Facility F	SD-SOP-M6-model D	1899216	0	5E-07	2.56E-07	1.35E-07	4.66E-08	6.67E-08	5.92E-08
Facility L	SD-SOP-M6-model D	345600	0	5E-07	4.26E-07	1.35E-07	1.00E-07	6.67E-08	6.52E-08
Facility K	SD-OP-M6-model A	3421440	1	5E-07	3.69E-07	1.35E-07	2.56E-07	1.24E-07	1.75E-07
Facility F	CD-H2-M16-model G	172656	3	2E-06	5.49E-06	4.41E-06	1.00E-05	7.62E-06	1.32E-05
Facility G	CD-H2-M16-model G	129480	0	2E-06	1.46E-06	4.41E-06	2.81E-06	7.62E-06	3.84E-06
Facility L	CD-H2-M16-model E	34560	0	2E-06	5.88E-07	4.41E-06	3.83E-06	4.41E-06	3.83E-06
Facility A	LOS-IR-M15-model A	2694144	0	6.00E-07	2.29E-07	1.68E-07	6.03E-08	1.67E-07	5.98E-08
Facility I	HD-ROR-M8-model B	276480	0	5E-07	4.39E-07	5.11E-07	4.47E-07	2.12E-07	2.00E-07
Facility A	FD-IR3-M1-model A	20963808	0	5E-07	4.35E-08	6.07E-07	4.42E-08	6.21E-07	4.43E-08
Facility F	GD-IR-M14-model A	4230072	3	6E-07	7.09E-07	3.70E-07	7.09E-07	3.74E-07	7.09E-07
Facility G	GD-IR-M14-model A	8882328	2	6E-07	2.84E-07	3.70E-07	2.59E-07	3.74E-07	2.60E-07

This result is consistent with the existing agreement that the Bayesian approach is biased with the value of a priory data. Table 4.23 clearly shows that Bayesian failure rate, $\ddot{\lambda}_{DU}$, is increased if a priory failure rate, λ_{DU}, is increasing. The $\ddot{\lambda}_{DU}$ different value is obvious for smoke detector and open path gas detector. It is due to the aggregated operational failure rate both detectors are significantly lower than the failure rate in PDS data handbook. On the other hand, the failure rate of the flame detector and the gas detector is almost the same as both detectors operational failure rate calculated by OREDA Multi-Sample method is almost the same with the failure rate in PDS data handbook.

Table 4.23 indicates it is critical to use the correct priory failure rate for calculating $\ddot{\lambda}_{DU}$. As generally the aggregated operational failure rate for detector type and the PDS data handbook failure rate is almost similar, the author suggests that the aggregated failure rate for the detector can be used as a priory failure rate for the Bayesian approach. The aggregated failure rate for OREDA Multi-Sample can be associated with the expert judgment as this is mean failure rate for all the facilities.

The Bayesian failure rate method in the guideline for SIS follow-up stated that a priory failure rate, λ_{DU}, is the original assumed of DU failure rates during design. The author proposes Equinor to define its failure rate value based on the operational experience for their basis and use it as a priory failure rate in the Bayesian method. The main reason is Equinor has adequate data statistically to calculate the failure rate and the aggregated operational failure rate is associated with the facility and the company performance of the detector. This failure rate is related to systematic failure rate aside from the random failure rate. The calculated $\ddot{\lambda}_{DU}$ by using the aggregated OREDA value, it provides more specific and up to date result compared to the use of PDS data handbook as a priory failure rate. The company can revise the aggregated failure rate based on its requirements without waiting for PDS data handbook new revision. If the aggregated operation failure rate is used as a priory failure rate, Equinor shall use this failure rate for the design also.

Most of the detector model does not have enough data to be used for a priory failure rate. There are many detector models in the facility, and hence, in real operation situation, it is not practical to use the aggregated failure rate based on the model for the failure rate calculation. It will be too many a priory failure rate. The aggregated failure rate based on the detector type is considered to be representative enough to calculate the failure rate based on the Bayesian approach has already explained in the previous paragraph. The possibility to use aggregated failure rate based on the measurement principle should also be evaluated in further research. There will be enough data, and there are not too many variations of the measurement principle.

The application Bayesian approach is also using the maximum conservative estimate failure rate (λ_{DU-CE}) to prevent the failure rate is over-optimistic. Hauge and Lundteigen (2008) stated that there is a lower limit of λ_{DU-CE}, which is 5×10^{-7} as they never believe that any piece of equipment in the field is having better value than 5×10^{-7}. However, the smoke detector in the field with sufficient operational time and sufficient DU failure has proved that the failure rate is 1.35×10^{-7}. The impact of changing λ_{DU-CE} to calculated failure rate is also investigated in this project. The comparison is performed when $\lambda_{DU-CE} = 5 \times 10^{-7}$ or $\lambda_{DU-CE} = 2\times\lambda_{DU}$, where $\lambda_{DU} = 1.35 \times 10^{-7}$ as a priory failure rate for smoke detector (aggregated failure rate by OREDA Multi-Sample) is used and the result is presented in Table 4.24.

Table 4.24: Comparison of the failure rate by using the Bayesian approach with a different conservative estimate failure rate

Facility	**Model**	**Time (hours)**	**DU**	$\lambda_{DU}(h^{-1})$	λ_{DU-CE} $= \mathbf{5} \times \mathbf{10}^{-7}(h^{-1})$	$\ddot{\lambda}_{DU}(h^{-1})$	$\lambda_{DU-CE}(h^{-}$ $= \mathbf{2}\times\lambda_{DU}$	$\ddot{\lambda}_{DU}(h^{-1})$
Facility A	SD-OP-M6-model A	42626592	1	1.35E-07	5.00E-07	2.60E-08	2.69E-07	4.00E-08
Facility A	SD-OP-M3-model B	15154560	7	1.35E-07	5.00E-07	4.42E-07	2.69E-07	3.54E-07
Facility A	SD-SOP-M6-model D	1389168	0	1.35E-07	5.00E-07	5.65E-08	2.69E-07	1.13E-07
Facility A	SD-OP-M4-model C	3451872	0	1.35E-07	5.00E-07	3.04E-08	2.69E-07	9.19E-08
Facility A	SD-ION-M4-model E	42096	0	1.34E-07	5.00E-07	1.28E-07	2.69E-07	1.34E-07
Facility B	SD-OP-M6-model A	26730960	0	1.35E-07	5.00E-07	4.88E-09	2.69E-07	2.93E-08
Facility B	SD-ION-M4-model E	11323824	0	1.34E-07	5.00E-07	1.08E-08	2.69E-07	5.33E-08
Facility B	SD-ION-M6-model G	841920	0	1.34E-07	5.00E-07	7.25E-08	2.69E-07	1.21E-07
Facility C	SD-SOP-M6-model D	26666184	0	1.35E-07	5.00E-07	4.90E-09	2.69E-07	2.93E-08

Table 4.24: Comparison of the failure rate by using the Bayesian approach with a different conservative estimate failure rate

Facility	**Model**	**Time (hours)**	**DU**	$\lambda_{DU}(h^{-1})$	λ_{DU-CE} $\mathbf{= 5 \times 10^{-7}}(h^{-1})$	$\ddot{\lambda}_{DU}(h^{-1})$	$\lambda_{DU-CE}(h^{-}$ $\mathbf{= 2}\times\lambda_{DU}$	$\ddot{\lambda}_{DU}(h^{-1})$
Facility C	SD-OP-M4-model C	45432	0	1.35E-07	5.00E-07	1.29E-07	2.69E-07	1.34E-07
Facility C	SD-ION-M4-model F	116328	0	1.34E-07	5.00E-07	1.20E-07	2.69E-07	1.32E-07
Facility D	SD-SOP-M6-model D	17625600	5	1.35E-07	5.00E-07	2.76E-07	2.69E-07	2.39E-07
Facility D	SD-OT-M11-model I	138240	0	1.34E-07	5.00E-07	1.17E-07	2.69E-07	1.32E-07
Facility E	SD-SOP-M6-model D	5366112	0	1.35E-07	5.00E-07	2.13E-08	2.69E-07	7.81E-08
Facility F	SD-OP-M6-model A	23935944	10	1.35E-07	5.00E-07	4.06E-07	2.69E-07	3.51E-07
Facility F	SD-SOP-M6-model D	1899216	0	1.35E-07	5.00E-07	4.66E-08	2.69E-07	1.07E-07
Facility F	SD-IR-M10-model H	115104	0	1.34E-07	5.00E-07	1.20E-07	2.69E-07	1.32E-07
Facility F	SD-ION-M6-model G	57552	0	1.34E-07	5.00E-07	1.26E-07	2.69E-07	1.33E-07
Facility G	SD-OP-M6-model A	25844208	5	1.35E-07	5.00E-07	1.91E-07	2.69E-07	1.80E-07
Facility H	SD-OP-M6-model A	49541616	1	1.35E-07	5.00E-07	2.25E-08	2.69E-07	3.51E-08
Facility H	SD-OP-M3-model B	16871040	10	1.35E-07	5.00E-07	5.67E-07	2.69E-07	4.53E-07
Facility H	SD-OP-M4-model C	125280	0	1.35E-07	5.00E-07	1.20E-07	2.69E-07	1.32E-07
Facility I	SD-SOP-M6-model D	16519680	0	1.35E-07	5.00E-07	7.73E-09	2.69E-07	4.17E-08
Facility J	SD-OP-M6-model A	9192960	0	1.35E-07	5.00E-07	1.33E-08	2.69E-07	6.01E-08
Facility J	SD-OP-M3-model B	10298880	2	1.35E-07	5.00E-07	1.89E-07	2.69E-07	1.69E-07
Facility K	SD-OP-M6-model A	3421440	1	1.35E-07	5.00E-07	2.56E-07	2.69E-07	1.84E-07
Facility K	SD-SOP-M6-model D	15517440	1	1.35E-07	5.00E-07	6.87E-08	2.69E-07	8.71E-08
Facility K	SD-OP-M4-model C	5978880	7	1.35E-07	5.00E-07	1.02E-06	2.69E-07	5.96E-07
Facility L	SD-SOP-M6-model D	345600	0	1.35E-07	5.00E-07	1.00E-07	2.69E-07	1.29E-07

Table 4.24 shows that the impact can be significant when the conservative failure is changed. In general, when there is no DU failure observed, the failure rate is increased when the λ_{DU-CE} is lower than 5×10^{-7} per hour. The reason is due to the Bayesian parameters are increased significantly. While when the DU failure is more than one, then the failure rate is decreased as long as λ_{DU-CE} is lower than 5×10^{-7} per hour as the Bayesian parameters are increased and it reduces the impact of the operational failure rate. It is recommended to evaluate the limitation of λ_{DU-CE} to 5×10^{-7} as the diagnostic coverage technology is improved and it is possible to have a failure rate less than 5×10^{-7}. Removing the maximum requirement will bring the Bayesian failure rate result, $\ddot{\lambda}_{DU}$, closer to a priory failure rate.

4.4 Test Interval Calculation Result

IEC 61508 requires a functional test to be performed to reveal dangerous undetected failures as the low demand does not normally function during normal operation. The functional test is performed during a certain time interval and it is required human intervention during execution and to restore the system into its original condition or as good as new. The functional test is also expected to reveal all the failure that may be associated with the equipment. The SIF component shall be evaluated during SIS follow-up to ensure its integrity. The evaluation is performed by comparing the operational failure rate and the assumption failure rate (a priory failure rate) during design. If the failure rate is higher than a priory failure rate, it is possible to decrease the test interval and vice versa. In this master thesis, the approach by Hauge and Lundteigen (2008) as detailed in chapter 2.5 of this report, is used. This method is also recommended by NOGA guideline 070 in Appendix F. The method is using a conservative approach where the maximum test interval can only be increased into doubled or decreased into halved of the original test interval. The table 4.25 shows the result updating test interval for the selected facility and model. The result in this section is only summary, the full result and calculation example is in Appendix E.

Table 4.25: The test interval update based on the operational failure rate

Facility	**Model**	**Time (hours)**	**DU**	$\hat{\lambda}_{DU}(h^{-1})$	$\lambda_{DU}(h^{-1})$	$\ddot{\lambda}_{DU}(h^{-1})$	$\lambda_{DU}/\ddot{\lambda}_{DU}$	τ*	$\ddot{\tau}$*
Facility A	FD-IR3-M1-model A	2.10E+07	0	0.00E+00	5.00E-07	4.35E-08	11.48	12	24
Facility G	FD-IR3-M1-model A	7.30E+06	3	4.11E-07	5.00E-07	1.00E-06	1.16	12	12
Facility B	FD-IR3-M1-model A	9.51E+06	2	2.10E-07	5.00E-07	2.61E-07	1.92	12	18
Facility I	FD-IR3-M1-model A	8.12E+06	1	1.23E-07	5.00E-07	1.98E-07	2.53	12	18
Facility A	HD-ROR-M5-model A	1.09E+06	0	0.00E+00	5.00E-07	3.23E-07	1.55	12	18
Facility K	HD-ROR-M8-model B	6.19E+06	1	1.62E-07	5.00E-07	2.44E-07	2.05	12	18
Facility A	SD-OP-M6-model A	4.26E+07	1	2.35E-08	5.00E-07	4.48E-08	11.16	12	24
Facility D	SD-SOP-M6-model D	1.76E+07	5	2.84E-07	5.00E-07	3.06E-07	1.64	12	18
Facility E	SD-SOP-M6-model D	5.37E+06	0	0.00E+00	5.00E-07	1.36E-07	3.68	12	24
Facility G	SD-OP-M6-model A	2.58E+07	5	1.93E-07	5.00E-07	2.15E-07	2.32	12	24
Facility J	SD-OP-M3-model B	1.03E+07	2	1.94E-07	5.00E-07	2.44E-07	2.05	12	18
Facility A	GD-IR-M14-model A	1.89E+07	3	1.58E-07	6.00E-07	1.94E-07	3.09	12	24
Facility B	GD-IR-M14-model A	1.14E+07	3	2.63E-07	6.00E-07	3.06E-07	1.96	12	18
Facility G	GD-IR-M14-model A	8.88E+06	2	2.25E-07	6.00E-07	2.84E-07	2.11	12	18
Facility A	LOS-IR-M15-model A	2.69E+06	0	0.00E+00	6.00E-07	2.29E-07	2.62	12	18
Facility H	LOS-IR-M15-model A	4.51E+06	0	0.00E+00	6.00E-07	1.62E-07	3.71	12	24
Facility B	CD-H2-M16-model E	2.53E+05	0	0.00E+00	1.80E-06	1.24E-06	1.45	6	6
Facility F	CD-H2-M16-model G	1.73E+05	3	1.74E-05	1.80E-06	5.49E-06	0.33	6	3
Facility K	CD-HC-M15-model A	6.08E+06	35	5.75E-06	1.80E-06	5.42E-06	0.33	6	3
Facility K	CD-HC-M15-model D	2.07E+05	6	2.89E-05	1.80E-06	9.18E-06	0.20	6	3
Facility L	CD-H2-M16-model E	3.46E+04	0	0.00E+00	1.80E-06	1.69E-06	1.06	6	6
Facility B	FD-UV-M1-model D	8.00E+05	3	3.75E-06	5.00E-07	1.00E-06	0.35	12	6
Facility F	FD-IR3-M2-model C	6.79E+06	9	1.33E-06	5.00E-07	1.00E-06	0.44	12	6
Facility K	SD-OP-M4-model C	5.98E+06	7	1.17E-06	5.00E-07	1.00E-06	0.50	12	6
Facility F	LOS-IR-M15-model A	6.27E+06	20	3.19E-06	6.00E-07	1.20E-06	0.23	12	6
Facility K	LOS-IR-M15-model A	3.80E+05	7	1.84E-05	6.00E-07	1.20E-06	0.15	12	6

*the test interval in months

Equinor uses the method on the guideline for SIS follow-up activities by SINTEF to update the test interval (Hauge and Lundteigen, 2008). The increasing of the test interval into doubled and decreasing into halved is only applicable when the data statistically adequate. Based on the observed data. the test interval is doubled when there is no DU failure for 3.5 million operating hours. 1 DU failure for approximately 10 million operating hours, 3 DU failures for approximately 18 million operating hours and 5 DU failures for approximately 20 million operating hours. It is required that a vast number of operating hours before the test interval can be doubled. It is indicated that the approach is conservative enough before doubling the test interval. However, the approach for halving the failure rate is not conservative enough, because the halving is performed when the ratio of λ_{DU} and $\ddot{\lambda}_{DU}$ is less than 0.45. The approach is not conservative, but it is proposed to make the test interval calculation near to the initial test interval. The test interval update based on SINTEF guidelines is conservative enough for doubling the test interval, but it is more optimistic for halving the test interval. That is understandable because the method would like to bring the test interval into the initial value.

4.5 Test Interval Calculation Evaluation

The master thesis evaluates the possibility to update the existing method proposed by the guideline for SIS follow-up by SINTER to calculate the "allowed" change of test interval. It is allowable to change the test interval based on the ratio of $\lambda_{DU}/\ddot{\lambda}_{DU}$. The new test interval value is the result of multiplying $\lambda_{DU}/\ddot{\lambda}_{DU}$ and the initial test interval.

At first, the impact of different λ_{DU} value is discussed. The main reason is that no specific requirement in the guideline of this value. Then the author discusses the impacts of changing $\ddot{\lambda}_{DU}$ to $\hat{\lambda}_{DU}$ when the operation data is adequate as it is fairer to use the operational failure rate, $\hat{\lambda}_{DU}$. Lastly, it is comparing using the confident interval or credibility interval for doubling or halving requirement as the approach is using Bayesian failure rate, and hence, it is fairer to use credibility interval. The result in this section is only summary, the full result is in Appendix E.

4.5.1 Modification A Priory Failure Rate λ_{DU}

The basic approach of SINTEF method is by calculating the ratio of $\lambda_{DU}/\ddot{\lambda}_{DU}$ and estimate the new test interval based on the ratio. If the ratio is more than 1, it is allowed to increase the test interval. While if the ratio is less than 1, it may require to decrease the test interval. In the guideline, λ_{DU} is defined as the assumed rate of dangerous undetected failure. This definition is vague. The value of λ_{DU} can be interpreted as the original failure estimate which is used during SIL calculation and stated in SRS (a priory failure rate such as PDS method data), or it can also be interpreted as the maximum allowable failure rate to achieve the SIL requirement. The failure rate to achieve SIL is calculated as follow.

$$\lambda_{DU-SIL} = \frac{2 \times PFD_t}{\tau_i} \tag{4.1}$$

Where PFD_t is the target probability failure on demand and τ_i is the initial test interval. For fire and gas detector equipment, the requirement is to achieve SIL 2. The maximum PFD for SIL 2 is 0.01. The fire and gas detection SIF is consists of the detector and the logic solver. For conservative result, the allocation of PFD for the detector sets as half of the PFD, which is 0.005. Tabel 4.26 shows the impact of the different assumption failure rate as numerator part of the ratio section in the test interval update as follows.

Table 4.26: The comparison of calculated test interval based on the different λ_{DU}

Facility	**Model**	**Time (hour)**	**DU**	τ_{init}*	**PDS** $\lambda_{DU-PDS}(h^{-1})$	$\ddot{\tau}$*	**Required SIL** $\lambda_{DU-SIL}(h^{-1})$	$\ddot{\tau}$*
Facility B	FD-UV-M1-model D	799824	3	12	5.00E-07	6	1.14E-05	9
Facility D	FD-IR3-M1-model A	483840	2	12	5.00E-07	6	1.14E-05	12
Facility D	FD-IR3-M3-model G	5529600	6	12	5.00E-07	9	1.14E-05	12
Facility F	FD-IR3-M1-model A	2848824	4	12	5.00E-07	9	1.14E-05	12
Facility F	FD-IR3-M2-model B	201432	1	12	5.00E-07	9	1.14E-05	12
Facility F	FD-IR3-M2-model C	6791136	9	12	5.00E-07	6	1.14E-05	12
Facility L	FD-IR3-M1-model A	1105920	2	12	5.00E-07	9	1.14E-05	12
Facility B	HD-FT-M6-model G	589344	1	12	5.00E-07	9	1.14E-05	12
Facility D	HD-ROR-M5-model A	518400	2	12	5.00E-07	6	1.14E-05	12
Facility K	SD-OP-M4-model C	5978880	7	12	5.00E-07	6	1.14E-05	12
Facility C	GD-IR-M14-model A	6687624	7	12	6.00E-07	9	1.14E-05	12
Facility F	LOS-IR-M16-model E	517968	1	12	6.00E-07	9	1.14E-05	12
Facility F	CD-H2-M16-model G	172656	3	6	1.80E-06	3	2.28E-05	6
Facility K	CD-HC-M15-model A	6082560	35	6	1.80E-06	3	2.28E-05	6
Facility K	CD-HC-M15-model D	207360	6	6	1.80E-06	3	2.28E-05	6
Facility H	HD-ROR-M8-model B	28062720	7	12	5.00E-07	18	1.14E-05	24

*the test interval in months

The changing of the assumption failure rate λ_{DU} from the failure rate used in the design (a priory failure rate), e.g., PDS data handbook failure rate into the maximum failure rate based on the SIL requirement has a quite noticeable impact. This approach is less conservative, but it is not impacting the safety of the system due to the SIL requirement is still achieved. The disadvantage with the approach is that the test interval will double faster because of the fewer data than when the λ_{DU} in the ratio $\lambda_{DU}/\ddot{\lambda}_{DU}$ is the failure rate used in the design (a priory failure rate.

The recommendation is to use the λ_{DU} from the required SIL allocation when the operational failure rate is higher than a priory failure rate to prevent decreasing test interval unnecessarily, which leads to additional operational cost. Then use the λ_{DU} from the PDS data handbook or other a priory failure rate source when the operational failure rate is lower than the priory failure rate, and hence it is not too optimistic when doubling the test interval. When λ_{DU} in the ratio $\lambda_{DU}/\ddot{\lambda}_{DU}$ based on the SIL requirement is used to decrease the test interval, the halving requirement based on the confident interval (as stated in Section 2.5) should be removed as the safety of the system may be compromised if the halving is delayed.

4.5.2 Modification $\ddot{\lambda}_{DU}$ into $\hat{\lambda}_{DU}$ in ratio $\lambda_{DU}/\ddot{\lambda}_{DU}$

SINTEF guideline calculating the failure rate based on the ratio between $\lambda_{DU}/\ddot{\lambda}_{DU}$, where $\ddot{\lambda}_{DU}$ is the calculated failure rate based on the Bayesian method. In this part, the impact of changing $\ddot{\lambda}_{DU}$ into $\hat{\lambda}_{DU}$, the operational failure rate only is investigated. The reason as it is fairer to compare with the operational failure rate when the DU failure and operational time are sufficient, and the result is presented in Table 4.27.

Table 4.27: The comparison of calculated test interval by changes $\ddot{\lambda}_{DU}$ into $\hat{\lambda}_{DU}$

Facility	**Model**	**Time (hours)**	**DU**	τ_{init}*	**Bayesian**		**Operational**	
					$\ddot{\lambda}_{DU}$	$\ddot{\tau}$*	$\hat{\lambda}_{DU}$	$\ddot{\tau}$*
Facility F	FD-IR3-M2-model C	6791136	9	12	1.14E-06	6	1.33E-06	6
Facility G	FD-IR3-M1-model A	7302672	3	12	4.30E-07	12	4.11E-07	12
Facility H	HD-ROR-M8-model B	28062720	7	12	2.66E-07	18	2.49E-07	24
Facility A	SD-OP-M3-model B	15154560	7	12	4.66E-07	12	4.62E-07	12
Facility D	SD-SOP-M6-model D	17625600	5	6	3.06E-07	18	2.84E-07	18
Facility C	GD-IR-M14-model A	6687624	7	12	9.58E-07	9	1.05E-06	9
Facility F	GD-IR-M14-model A	4230072	3	12	6.78E-07	12	7.09E-07	12
Facility H	GD-IR-M14-model A	22592160	9	12	4.12E-07	12	3.98E-07	18
Facility I	GD-IR-M14-model A	9918720	3	12	3.45E-07	18	3.02E-07	18
Facility J	GD-IR-M14-model A	5210208	3	12	5.82E-07	12	5.76E-07	12
Facility K	GD-IR-M14-model A	3836160	3	12	7.27E-07	12	7.82E-07	12
Facility F	LOS-IR-M15-model A	6273168	20	12	2.64E-06	6	3.19E-06	6
Facility K	LOS-IR-M15-model A	380160	7	12	3.91E-06	6	1.84E-05	6
Facility K	LOS-IR-M16-model B	725760	7	12	3.34E-06	6	9.65E-06	6

*the test interval is in months

In general. there is no impact by changing the Bayesian failure rate into the operational failure rate. as the operational failure rate value and the Bayesian failure rate is almost the same. From the observed data, the impact may occur when the ratio of $\lambda_{DU}/\hat{\lambda}_{DU}$ is near to two. The Bayesian failure rate is a more appropriate method since the test interval update is calculated by using the ratio of $\lambda_{DU}/\ddot{\lambda}_{DU}$ (λ_{DU}= a priory failure rate), and the Bayesian failure rate is including a priory failure rate, while the operational failure is not.

4.5.3 Confident Interval Changes into Credibility Interval

The SINTEF guideline for follow-up of SIS in the operational phase provides restriction to doubled or halved the test interval by considering the 90% confident interval. This approach is a good approach when the operational data is considered sufficient due to the operational failure rate is used ($\hat{\lambda}_{DU}$). This master thesis evaluates if the credibility interval as defined in Equation 2.7 should be used for evaluating the restriction to doubled or halved the test interval during the operational data is not sufficient because the failure rate is defined as the Bayesian failure rate, $\ddot{\lambda}_{DU}$. The result is presented in Table 4.28 below.

Table 4.28: The comparison of calculated test interval based on confident interval and credibility interval

Facility	Model	Time-hour	DU	$\tau_{init}*$	Confident interval			Credibility interval		
					90% CI low (h^{-1})	90% CI up (h^{-1})	$\ddot{\tau}*$	90% CI low (h^{-1})	90% CI up (h^{-1})	$\ddot{\tau}*$
Facility B	FD-UV-M1-model D	799824	3	12	1.38E-06	8.35E-06	6	2.87E-07	1.64E-06	9
Facility D	FD-IR3-M1-model A	483840	2	12	1.10E-06	1.10E-05	6	2.14E-07	1.56E-06	9
Facility F	FD-IR3-M1-model A	2848824	4	12	6.12E-07	2.80E-06	6	2.27E-07	1.09E-06	9
Facility F	FD-IR3-M2-model C	6791136	9	12	8.00E-07	2.09E-06	6	3.17E-07	9.824E-07	9
Facility J	FD-IR3-M3-model G	3386880	0	12	0.00E+00	6.79E-07	18	1.95E-08	4.27E-07	24
Facility D	HD-ROR-M5-model A	518400	2	12	1.03E-06	1.02E-05	6	2.11E-07	1.54E-06	9
Facility K	HD-ROR-M8-model B	6186240	1	12	1.70E-08	6.28E-07	18	3.56E-08	3.81E-07	24
Facility A	SD-OP-M4-model C	3451872	0	12	0.00E+00	6.67E-07	18	1.93E-08	4.22E-07	24
Facility J	SD-OP-M3-model B	10298880	2	12	5.16E-08	5.16E-07	18	4.32E-08	3.16E-07	24
Facility K	SD-OP-M4-model C	5978880	7	12	6.51E-07	1.96E-06	6	2.61E-07	9.20E-07	9
Facility A	LOS-IR-M15-model A	2694144	0	12	0.00E+00	8.54E-07	18	2.41E-08	5.28E-07	24
Facility C	LOS-IR-M15-model A	2737272	0	12	0.00E+00	8.41E-07	18	2.39E-08	5.22E-07	24
Facility C	CD-HC-M15-model B	797040	4	6	2.19E-06	1.00E-05	3	8.14E-07	3.93E-06	6
Facility F	CD-H2-M16-model G	172656	3	6	6.38E-06	3.86E-05	3	1.10E-06	6.34E-06	6

*The test interval in months

The upper limit and the lower limit of the credibility interval is lower than the upper limit and the lower limit of the confident interval. Because the Bayesian failure rate ($\ddot{\lambda_{DU}}$) is lower than the operational ($\hat{\lambda_{DU}}$) in general. Table 4.28 indicates that if the credibility interval criteria are used, the doubling and the halving requirement is less conservative.

The 90% upper limit credibility interval is lower than 90% upper limit confident interval, and hence, it allows the doubling faster with less operational time. The 90% lower limit credibility interval is lower than 90% lower limit confident interval, and hence, it delays the halving longer. In order to achieve an inherently safer design, the author recommends maintaining the existing approach by using the confident interval regardless of the adequacy of the operational data. The doubling and the halving by using confident interval as stated in section 2.5 provides a more conservative result.

4.5.4 Halving and Doubling Criteria

The SINTEF guideline for follow-up of SIS in the operating phase provides restriction for doubling or halving the test interval by considering the 90% confident interval is used. The requirement of halved and doubled is using a similar requirement. It is interesting to investigate if the possibility to stringent the requirement by using 70% for halving the test interval and hence the halving is not delayed too long and by using 95% for doubling the test interval, and hence the doubling has more data. The result is presented in Table 4.29.

Table 4.29: The comparison of calculated test interval based on different doubling and halving approach

Facility	**Model**	**Time hour**	**DU**	τ_{init}*	**SINTEF approach**			**New approach**		
					90% CI low (h^{-1})	**90% CI up** (h^{-1})	$\ddot{\tau}$*	**70% CI low** (h^{-1})	**95% CI up** (h^{-1})	$\ddot{\tau}$*
Facility C	FD-IR3-M2-model C	4864416	0	12	0.00E+00	4.73E-07	24	0.00E+00	9.47E-07	18
Facility F	FD-IR3-M1-model A	2848824	4	12	6.12E-07	2.81E-06	9	5.52E-07	3.60E-06	6
Facility E	SD-SOP-M6-model D	5366112	0	12	0.00E+00	4.29E-07	24	0.00E+00	8.58E-07	18
Facility G	LOS-IR-M15-model A	4221048	0	12	0.00E+00	5.46E-07	24	0.00E+00	1.09E-06	18
Facility H	LOS-IR-M15-model A	4510080	0	12	0.00E+00	5.11E-07	24	0.00E+00	1.02E-06	18
Facility C	CD-HC-M15-model B	797040	4	6	2.19E-06	1.00E-05	6	1.97E-06	1.28E-05	3

*The test interval is in months

When the requirement for increasing the test interval into doubling the initial test interval is changed from 90% upper limit confident interval into 95% upper limit confident interval, the test interval doubling is required more operating time, and in the other word, the doubling is delayed.

When the requirement for decreasing the test interval into halving the initial test interval is changed from 90% lower limit confident interval into 70% lower limit confident interval, the test interval halving is required less operating time, and in the other word, it prevents delay of the halving of the test interval. An additional concern is that the halving test interval may require to consider the SIL requirement. It is suggested to check the new failure rate impact to the SIL requirement. When the SIL requirement is not achieved, the test interval should be halving without delay. A further study on the approach for halving the test interval may be valuable to the industry, as the current approach is not conservative enough.

Chapter 5

Summary and Recommendations for Further Work

This last chapter's objective is to present the summary of the result, discussion if the objective is achieved and discuss recommendations for further works. First summary and conclusion of what the author has performed throughout the report are presented. Afterwards, discussions of the findings are presented before possible paths for further work are presented in the last section.

5.1 Summary and Conclusion

The main objective of the master thesis is to investigate the use of maintenance notification data to monitor integrity level of a SIS component, with fire and gas detectors as the study case. The master thesis uses the guideline for SIS follow-up during operational phase by SINTEF as the main guidance.

The author performs two main activities during the master thesis, which are data quality checking and failure analysis by calculating the failure rate and test interval. The data quality checking consumes most of the research time, approximately 70%. The purpose of data quality checking is to ensure that the equipment properties has the correct input in the database, and the failure attribute is correctly addressed into the equipment properties.

One of the findings during the master thesis is the management of changes is crucial for SIS follow-up activities. It is critical to ensure that the changes are recorded correctly in the CMMS. One of the examples of this observation is that a detector is recorded as an IR point type gas detector in the database, but after further investigation, the detector was a catalytic gas detector during the observation period. The changes from a catalytic gas detector into IR point type gas detector is not properly recorded. It leads to the failure attributes being addressed to the wrong detector type.

The equipment failure in failure notification data is classified into the IEC 61508 failure class, which is DU, DD, SU, and SS. The author proposed to use the simplified Failure Mode Effect and Diagnostic Analysis (FMEDA) to classify the failure notification data into IEC 61508 failure class. The FMEDA approach has been identified as this can be used for failure classification given that the failure mode, failure mechanism, and detection methods are classified correctly. Training into ISO 14224 is required to ensure that the maintenance personnel is able to classify the mentioned parameters correctly. The simplified FMEDA method is expected to reduce the time consumed to classify failure into the IEC 61508 failure class.

Based on the number of DU failures and the operating time, the failure rate of the equipment is calculated by assuming that the failure rate is following the exponential distribution. The detector properties such as detector type, measurement principle, and model have an impression on the failure rate. This finding is harmonious with the Håbrekke et al. (2018) that indicates detector type and measurement principle properties contribute to the failure rate. The IR point type gas detector has a smaller failure rate compared to the catalytic detector. The difference is quite significant for the two sensor types. The result of the failure rate of each detector type, measurement principle, and models is presented in Section 4.2 of this report. The summary of detector failure rate is presented in Table 5.1.

Table 5.1: The failure rates of the detector result

Detector type	**Measurement principle**	θ^* **(h^{-1})**
Flame detectors	Infrared	6,07E-07
Flame detectors	Multi-sensor Infrared	5,85E-07
Heat detectors	Rate of Rise	5,11E-07
Heat detectors	Fixed Temperature	2,40E-07
Smoke detectors	Optical	1,35E-07
Smoke detectors	Ionization	6,95E-08
Gas detector - point	Infrared	3,70E-07
Gas detector - open path	Infrared	1,68E-07
Catalytic detectors	Hydrocarbon	1,95E-06
Catalytic detectors	Hydrogen	4,41E-06

The OREDA Multi-Sample method is used to calculate the failure rate in Table 5.1. The OREDA Multi-Sample method is found valid to calculate the non-homogeneous failure rate as 90% confident interval data will cover most of the individual failure rates and the calculated mean failure rate is located near the different samples means as indicated in Figure 4.16. The Maximum Likelihood Event (MLE) for exponential distribution is used to calculate the failure rate for a detector model in a facility when the operating data is sufficient, and it is called an operational failure rate, $\hat{\lambda}_{DU}$. The operating data is sufficient if there are more than 2 DU failures observed during the operation time. If the operating data is not sufficient, the failure rate is calculated by using the Bayesian approach, and it is called a Bayesian failure rate, $\ddot{\lambda}_{DU}$. The Bayesian failure rate has weakness because it depends on a priory failure rate, and hence, the correct a priory failure rate is essential, and this weakness has been well known.

The calculated failure rate is used to update the test interval. It is allowable to change the test interval based on the ratio of $\lambda_{DU}/\ddot{\lambda}_{DU}$. The new test interval value is the result of multiplying $\lambda_{DU}/\ddot{\lambda_{DU}}$ and the initial test interval. The test interval could be increased (doubled as maximum) or decreased (halved as a minimum) with a strict criteria prior doubling the test interval or halving the test interval. The criteria used by SINTEF in the guideline for SIS follow-up during the operational phase is found practical and useful. However, a few improvements could be valuable. One of the proposals is to use maximum allowable failure rate to achieve the SIL requirement instead of a priory failure rate, λ_{DU}, in ratio $\lambda_{DU}/\ddot{\lambda_{DU}}$ (Equation 2.18) when the operational failure rate is higher than a priory failure rate to prevent decreasing test interval unnecessarily. If this approach is used the halving criteria based on the confident interval should not be used because it is comprised the safety if the halving is delayed. The other proposal of improvement is updating the halving and doubling criteria into more strict requirement such as use 70% lower limit confident interval before allowing halving the test interval and use 95% upper limit confident interval before allowing doubling the test interval. The last proposal is to use the aggregated failure rate of a component as a priory failure rate, λ_{DU}, for updating the test interval in the second time.

5.2 Discussion

The purposes of this master thesis are assisting Equinor to perform SIS follow-up activities by using the failure notification data of fire and gas detector and evaluating the guideline of SIS follow-up during operational phase by SINTEF as the guideline has not been updated for ten years. The author achieves the main objective, but the final task for improving the existing guideline is not completed due to time constraint. The failure rate and the test interval are calculated for the fire and gas detector for 12 facilities. Some possibilities for improvement of the guideline are studied, but there is no significant input for improvement the guideline that can be drawn.

The first task is to provide systematic guidance on the classification of Dangerous Undetected (DU) failures and the proposed guidance is simplified FMEDA. The FMEDA approach is a feasible method to decide the IEC failure classification given that failure mode, failure mechanism, and detection method are classified correctly. During the observation, when the failure mode is recorded correctly, the need for "long text" information to decide the critically of failure can be minimized and less time consuming.

DU failure from failure classification is used to calculate the failure rate. The aggregated failure rate for a detector type and detector model is calculated by using the OREDA Multi-Sample, and failure rate for each model in a facility is calculated by the Bayesian method. The Bayesian method is required a priory failure rate as prior knowledge. It has investigated that the aggregated failure rate for detector type can be used as a priory failure rate for the Bayesian method. One of the observation during the analysis is the limitation of λ_{DU-CE} to 5×10^{-7} for calculating the Bayesian method should be evaluated as the diagnostic coverage technology is improved and it is possible to have a failure rate less than 5×10^{-7}. The change of λ_{DU-CE} has a significant impact on the calculate Bayesian failure rate, $\ddot{\lambda_{DU}}$.

The final task is for improving the existing method proposed by SINTEF guideline to update the test interval of SIS Component, but this task is not completed. However, some approaches have been investigated. The first one is changing the nominator in $\lambda_{DU}/\ddot{\lambda}_{DU}$ from a priory failure rate into the maximum allowable failure rate to achieve the SIL requirement. The changing of assumption failure rate λ_{DU} from a priory data to the failure rate based on the SIL requirement has a quite noticeable impact. The recommendation is to use the λ_{DU} in $\lambda_{DU}/\ddot{\lambda}_{DU}$ ratio from required SIL when the operational failure rate is higher than a priory failure rate to prevent decreasing the test interval unnecessary. If the operational failure rate is lower than a priory failure rate to use the λ_{DU} in $\lambda_{DU}/\ddot{\lambda}_{DU}$ ratio from the PDS or other a priory failure rate , and hence it is not too optimistic when doubling the failure rate. The second approach is changing the denominator from $\ddot{\lambda}_{DU}$ into $\hat{\lambda}_{DU}$. There is no impact by changing the Bayesian failure rate into the operational failure rate, as the operational failure rate value, and the Bayesian failure rate is almost the same.

One of the criteria for doubling the test interval is the entire estimated 90% confident interval for the $\hat{\lambda}_{DU}$ is below the priory λ_{DU}. The possibility to change the requirement from 90% confident interval to 90% credibility interval is studied in section 4.5.3, and it recommends maintaining the existing approach by using the confident interval as this result is more conservative. Besides the possibility to change from 90% confident interval to 95% confident interval is also studied, this approach provides more strict criteria than the existing method. It is also suggested to change the requirement of halving from 90% confident interval to 70% confident interval. The halving will be faster, and it is a safer result.

5.3 Recommendation for Further Works

The research is far from perfect; further works are required to improve the result. Several options are available to develop the research.

First, Appendix B demonstrated that the simplified FMEDA approach is a feasible method for classifying failure notification data into IEC 61508 failure class given that the failure mode, failure mechanism, and detection method is classified correctly. The evaluation is only performed to fire and gas detectors. The simplified FMEDA approach can be tested into different equipment to ensure the possibility to use in further work. A clear definition of failure mode is required for every equipment.

Second, during the master thesis, there is much time consumed for data quality audit. The main reason is the small modification such as the model, or detector type changes is not properly recorded. The guideline for SIS follow-up activities has included the management of changes, but it is too general, and it does not specify how details management of change required. It indicates that further research in data collection is required to improve the failure notification data recording.

Third, the existing guideline for SIS follow-up activities states that the operational data is adequate if the upper 95% percentile of the operational failure rate, $\hat{\lambda}_{DU}$, is approximately three times the mean value or lower. However, it is not indicating the minimum operating time. The further investigation valuable to determine the length of operational time and hence, the failure rate is not unrealistically high.

Fourth, the conservative failure rate λ_{DU-CE} is one of the parameters to calculate the Bayesian failure rate, $\ddot{\lambda}_{DU}$. The conservative failure rate is defined as the maximum value between operational failure rate, database failure rate, or deterministic value of 5×10^{-7}. 5×10^{-7} is the lower limit failure rate as Hauge and Lundteigen (2008) never believe that any piece of equipment in the field is having better value than 5×10^{-7}. However, the smoke detector with a lot of operational time has proved that the failure rate is 1.35×10^{-7}. Further investigation to evaluate the applicability on limitation of λ_{DU-CE} to 5×10^{-7} may be required as it may not be relevant anymore.

Fifth, the existing guideline for SIS follow-up activities discussed in the test interval update from initial design to the first follow-up activities. There is no discussion yet if it is allowable or not to update the test interval after it was updated from the initial test interval. The time required to update the test interval can also be investigated.

Sixth, the smoke detector with a lot of operational time has proved that the failure rate is 1.35×10^{-7}. However, the test interval cannot be updated more than doubling due to the restriction. The possibility to increase the test interval of SIS component to more than double the initial test interval when the prior use of the data has proven that the operational failure is always low, should be further investigated. The approach used by Zhu and Liyanage (2018b) can be a valuable input.

Seventh, the possibility to use machine learning to calculate the failure rate can be studied as a lot of notification data is available. Xie et al. (2019) uses operational data to calculate the failure rate by data-driven prediction.

Appendix A

Example FMEDA Failure Classification

Table A.1: The IEC 61508 failure classification for OREDA failure mode by using FMEDA

Unit identification		**Description of Unit**		**Description of failure**			**Failure Effect**	**Failure analysis**		**Fail class**	**Remarks**
Not no.	**Tag**	**Part**	**Function**	**Failure mode**	**Failure mechanism**	**Detection method**		**Cons**	**Diagnos**		
fail-001	GD-01	Sensor	detect gas	Failure to function on demand	no signal	During demand	No detection	D	No	DU	
fail-002	GD-02	Sensor	detect gas	no output	no signal	Functional test	No detection	D	No	DU	
fail-003	GD-03	Sensor	detect gas	no output	no signal	Condition monitoring	No detection	D	Yes	DD	
fail-004	GD-04	Sensor	detect gas	eractic output	instrument failure	Condition monitoring	Detection when no gas	S	Yes	SD	
fail-005	GD-05	Sensor	detect gas	eractic output	instrument failure	Functional test	unsifficient detection	D	No	DU	
fail-006	GD-06	Sensor	detect gas	Low output	faulty signal	Functional test	No detection	D	No	DU	
fail-007	GD-07	Sensor	detect gas	Low output	faulty signal	Condition monitoring	No detection	D	No	DD	
fail-008	GD-08	Sensor	detect gas	Low output	faulty signal	Condition monitoring	No detection	D	No	DD	
fail-009	GD-09	Sensor	detect gas	High output	faulty signal	Condition monitoring	Detection when no gas	S	Yes	SD	
fail-010	GD-10	Sensor	detect gas	spurious	faulty signal	Condition monitoring	Detection when no gas	S	Yes	SD	

Appendix B

FMEDA Failure Classification

Table B.1: The IEC 61508 failure classification for observed data by using FMEDA

Unit Not. No	Tag	Unit Desc.		Description of failure			Failure Effect	Failure analysis		class	Remarks
		Part	Functic	Mode	Mech	Det Method		Cons	Diagnos		
A001	FD01	lens	to detect fire	other	not identified	PM	No fire detection	D	No	DU	The lens is covered by mud
A002	FD02	sensor	to detect fire	other	not identified	Casual obs.	No fire detection	D	No	DU	The detector is indicating fault alarm but there is no information in control room
A003	FD03	lens	to detect fire	other	not identified	inspection	No fire detection	D	No	DU	The detector view is blocked due to new installation
A004	FD04	sensor	to detect fire	other	not identified	Cond Monitor	No fire detection	D	Yes	DD	The detector indicates it has low sensitivity and providing alarm
A005	FD05	sensor	to detect fire	other	not identified	Cond Monitor	No fire detection	D	Yes	DD	The detector indicates it has low sensitivity and providing alarm
A006	FD06	sensor	to detect fire	other	not identified	FT	No fire detection	D	No	DU	The detector is pointing downward, it is not seeing the equipment
A007	FD07	sensor	to detect fire	low output	Instrument failure	Cond Monitor	No fire detection	D	Yes		The detector is sending alarm and it is indicating there is failure in the detector
A008	FD08	sensor	to detect fire	no signal	Instrument failure	FT	No fire detection	D	No	DU	The detector sensitivity is lowered. It take more than 3x testing to set alarm
A009	FD09	sensor	to detect fire	no signal	Instrument failure	FT	No fire detection	D	No	DU	The detector is not indicating alarm
A010	FD10	sensor	to detect fire	other	not identified	PM	No fire detection	D	No	DU	The detector is not working during maintenance testing

Table B.1 continued from previous page

Unit		Unit Desc.		Description of failure				Failure analysis			
Not. No	Tag	Part	Functic	Mode	Mechanism	Det Method	Failure Effect	Cons	Diagnos	class	Remarks
A011	FD11	sensor	to detect fire	no signal	Instrument failure	FT	No fire detection	D	No	DU	The detector is dirty but the fault alarm is not working
A012	FD12	sensor	to detect fire	no signal	Instrument failure	FT	No fire detection	D	No	DU	The detector is not working
A013	FD13	sensor	to detect fire	no signal	Instrument failure	FT	No fire detection	D	No	DU	The detector is not indicating alarm
A014	FD14	sensor	to detect fire	other	not identified	Cond Monitor	No fire detection	D	Yes	DD	The detector active failure alarm due to the lens is dirty
A015	FD15	sensor	to detect fire	no signal	not identified	FT	No fire detection	D	No	DU	The detector is not working
A016	FD16	sensor	to detect fire	other	not identified	FT	No fire detection	D	No	DU	The detector is not indicating alarm during FT
A017	FD17	sensor	to detect fire	no signal	Instrument failure	FT	No fire detection	D	No	DU	The detector is not indicating alarm
A018	FD18	sensor	to detect fire	no signal	Instrument failure	FT	No fire detection	D	No	DU	The detector is not indicating alarm
A019	FD19	lens	to detect fire	other	not identified	Casual obs.	No fire detection	D	No	DU	The detector view is blocked due to new installation
A020	FD20	lens	to detect fire	Erractic output	not identified	FT	No fire detection	D	No	DU	The detector sensitivity is lowered. It take several times test to set alarm
A021	FD21	sensor	to detect fire	no signal	Instrument failure	FT	No fire detection	D	No	DU	The detector is not working
A022	FD22	sensor	to detect fire	no signal	not identified	FT	No fire detection	D	No	DU	The detector is not indicating alarm

Table B.1 continued from previous page

Unit		Unit Desc.		Description of failure				Failure analysis			
Not. No	Tag	Part	Functic	Mode	Mechanism	Det Method	Failure Effect	Cons	Diagnos	class	Remarks
A023	FD23	sensor	to detect fire	other	not identified	FT	No fire detection	D	No	DU	The detector is not working
A024	FD24	sensor	to detect fire	no signal	not identified	FT	No fire detection	D	No	DU	The detector is not indicating alarm
A025	HD01	sensor	to detect fire	other	not identified	FT	No fire detection	D	No	DU	The detector is not working
A026	HD02	sensor	to detect fire	no signal	Instrument failure	FT	No fire detection	D	No	DU	The detector is not indicating alarm
A027	HD11	sensor	to detect fire	no signal	not identified	FT	No fire detection	D	No	DU	The detector is broken
A028	HD12	sensor	to detect fire	no signal	not identified	FT	No fire detection	D	No	DU	The detector is not working
A029	HD13	sensor	to detect fire	no signal	Instrument failure	FT	No fire detection	D	No	DU	The detector is not indicating alarm
A030	HD14	sensor	to detect fire	no signal	not identified	FT	No fire detection	D	No	DU	The detector is not indicating alarm
A031	HD15	sensor	to detect fire	no signal	not identified	FT	No fire detection	D	No	DU	The detector is not indicating alarm
A032	HD16	sensor	to detect fire	no signal	not identified	FT	No fire detection	D	No	DU	The detector is not working, but it might be due to the wrong loop location
A033	HD17	sensor	to detect fire	no signal	not identified	FT	No fire detection	D	No	DU	The detector is not working, but it might be due to the wrong loop location
A034	HD18	sensor	to detect fire	no signal	not identified	PM	No fire detection	D	No	DU	The detector is not working

Table B.1 continued from previous page

Unit		Unit Desc.		Description of failure				Failure analysis			
Not. No	**Tag**	**Part**	**Functio**	**Mode**	**Mechanism**	**Det Method**	**Failure Effect**	**Cons**	**Diagnos**	**class**	**Remarks**
A035	HD19	sensor	to detect fire	no signal	not identified	FT	No fire detection	D	No	DU	The detector is covered by painting
A036	HD20	sensor	to detect fire	no signal	not identified	FT	No fire detection	D	No	DU	The detector is not working
A037	SD01	sensor	to detect smoke	low output	not identified	FT	No fire detection	D	No	DU	The detector sensitivity is reduced
A038	SD02	sensor	to detect smoke	low output	not identified	Cond Monitor	No fire detection	D	Yes	DD	The detector is giving alarm that it is in fault condition
A039	SD03	sensor	to detect smoke	low output	not identified	CM	No fire detection	D	No	DU	The detector is not indicating alarm
A040	SD04	sensor	to detect fire	no signal	not identified	FT	No fire detection	D	No	DU	The detector is not working
A041	SD05	sensor	to detect fire	no signal	not identified	FT	No fire detection	D	No	DU	The detector is not working
A042	SD06	sensor	to detect fire	no signal	not identified	FT	No fire detection	D	No	DU	The detector is not working
A043	SD07	sensor	to detect fire	no signal	not identified	FT	No fire detection	D	No	DU	The detector is not working
A044	SD08	sensor	to detect fire	no signal	not identified	FT	No fire detection	D	No	DU	The detector is not working
A045	SD09	sensor	to detect fire	no signal	not identified	FT	No fire detection	D	No	DU	The detector is not working
A046	SD10	sensor	to detect smoke	low output	not identified	FT	No fire detection	D	No	DU	The detector is not indicating alarm

Table B.1 continued from previous page

Unit		Unit Desc.		Description of failure				Failure analysis			
Not. No	**Tag**	**Part**	**Functic**	**Mode**	**Mechanism**	**Det Method**	**Failure Effect**	**Cons**	**Diagnos**	**class**	**Remarks**
A047	SD11	sensor	to detect fire	no signal	not identified	FT	No fire detection	D	No	DU	The detector is not working
A048	SD12	sensor	to detect fire	no signal	not identified	FT	No fire detection	D	No	DU	The detector is not working
A049	SD13	sensor	to detect fire	no signal	not identified	FT	No fire detection	D	No	DU	The detector is not working
A050	SD14	sensor	to detect fire	no signal	not identified	FT	No fire detection	D	No	DU	The detector is not working
A051	SD15	sensor	to detect fire	no signal	not identified	FT	No fire detection	D	No	DU	The detector is not working
A052	SD16	sensor	to detect fire	no signal	not identified	FT	No fire detection	D	No	DU	The detector is not working
A053	SD17	sensor	to detect fire	no signal	not identified	FT	No fire detection	D	No	DU	The detector is not working
A054	SD18	sensor	to detect smoke	low output	not identified	FT	No fire detection	D	No	DU	The detector is not indicating alarm
A055	SD19	sensor	to detect smoke	low output	not identified	FT	No fire detection	D	No	DU	The detector sensitivity is reduced. It is taking several time before it is get the failure
A056	SD20	sensor	to detect smoke	low output	Electrical failure	FT	No fire detection	D	No	DU	The detector sensitivity is reduced. It is taking several time before it is get the failure
A057	SD21	sensor	to detect fire	no signal	Instrument failure	PM	No fire detection	D	No	DU	The detector is not working

Table B.1 continued from previous page

Unit Not. No	Tag	Unit Desc. Part	Functic	Description of failure Mode	Mechanism	Det Method	Failure Effect	Failure analysis Cons	Diagnos	class	Remarks
A058	SD22	sensor	to detect fire	no signal	Instrument failure	PM	No fire detection	D	No	DU	The failure of the I/O card
A059	SD23	sensor	to detect fire	faulty signal	Instrument failure	PM	No fire detection	D	No	DU	The failure of the I/O card
A060	SD24	sensor	to detect fire	no signal	Instrument failure	PM	No fire detection	D	No	DU	The detector is not indicating alarm
A061	SD25	sensor	to detect fire	no signal	Instrument failure	FT	No fire detection	D	No	DU	The detector is not indicating alarm
A062	SD26	sensor	to detect fire	no signal	Instrument failure	FT	No fire detection	D	No	DU	The detector is not working
A063	SD27	sensor	to detect fire	no signal	Instrument failure	FT	No fire detection	D	No	DU	The detector is not working
A064	SD28	sensor	to detect fire	no signal	Instrument failure	PM	No fire detection	D	No	DU	The detector is not working
A065	SD29	sensor	to detect fire	faulty signal	Instrument failure	PM	No fire detection	D	No	DU	The detector is not working
A066	SD30	sensor	to detect fire	low output	not identified	Cond Monitor	No fire detection	D	Yes	DD	The detector is giving alarm that it is in fault condition
A067	SD31	sensor	to detect fire	other	not identified	inspection	The detector is not functioning as intended	D	No	DU	Wrong type of detector is installed
A068	SD32	sensor	to detect fire	no signal	Instrument failure	FT	No fire detection	D	No	DU	The detector is not working
A069	SD33	sensor	to detect fire	no signal	Instrument failure	FT	No fire detection	D	No	DU	The detector is not working

Table B.1 continued from previous page

Unit		Unit Desc.		Description of failure				Failure analysis			
Not. No	Tag	Part	Functi	Mode	Mechanism	Det Method	Failure Effect	Cons	Diagnos	class	Remarks
A070	HSD1	sensor	to detect fire	other	not identified	FT	No fire detection	D	No	DU	The detector is not working
A071	HSD2	sensor	to detect fire	other	not identified	FT	No fire detection	D	No	DU	The detector is not working
A072	HSD3	sensor	to detect fire	other	not identified	FT	No fire detection	D	No	DU	The detector is not working
A073	HSD4	sensor	to detect fire	no signal	not identified	FT	No fire detection	D	No	DU	The detector is not working
A074	HSD5	sensor	to detect fire	no signal	Instrument failure	other	No fire detection	D	No	DU	The detector is not working
A075	ASD1	aspirator tubing	ensure flow to detector	other	Instrument failure	inspection	No fire detection	D	No	DU	The tubing is blocked
A076	ASD2	aspirator tubing	ensure flow to detector	other	Instrument failure	PM	No fire detection	D	No	DU	The tubing is blocked
A077	ASD3	aspirator tubing	ensure flow to detector	faulty signal	Instrument failure	inspection	No fire detection	D	No	DU	The tubing is broken
A078	ASD4	aspirator tubing	ensure flow to detector	Natural degradation	Material failure	CM	No fire detection	D	No	DU	The tubing is blocked
A079	ASD5	aspirator tubing	ensure flow to detector	Breakage	Material failure	other	No fire detection	D	No	DU	The tubing is blocked

Table B.1 continued from previous page

Unit		Unit Desc.		Description of failure				Failure analysis			
Not. No	**Tag**	**Part**	**Functio**	**Mode**	**Mechanism**	**Det Method**	**Failure Effect**	**Cons**	**Diagnos**	**class**	**Remarks**
A080	ASD6	aspirator tubing	ensure flow to detector	General	Material failure	inspection	No fire detection	D	No	DU	The tubing is broken
A081	ASD7	aspirator tubing	ensure flow to detector	other	not identified	other	No fire detection	D	No	DU	The tubing is blocked
A082	ASD8	aspirator tubing	ensure flow to detector	other	not identified	other	No fire detection	D	No	DU	The tubing is broken
A083	GD1	sensor	to detect gas release	faulty signal	not identified	FT	No gas detection	D	No	DU	The detector is not working
A084	GD2	sensor	to detect gas release	other	not identified	PM	No gas detection	D	No	DU	The detector is broken
A085	GD3	sensor	to detect gas release	low output	not identified	FT	No gas detection	D	No	DU	The detector is reading 25% LFL when it is tested with 50% LF gas
A086	GD4	sensor	to detect gas release	faulty signal	Instrument failure	FT	No gas detection	D	No	DU	The detector is reading 22% LFL when it is tested with 50% LF gas. Not reach H alarm of 30%

Table B.1 continued from previous page

Unit		Unit Desc.		Description of failure			Failure Effect	Failure analysis		class	Remarks
Not. No	**Tag**	**Part**	**Functic**	**Mode**	**Mechanism**	**Det Method**		**Cons**	**Diagnos**		
A087	GD5	sensor	to detect gas release	other	not identified	FT	No gas detection	D	No	DU	I/O card failure and leads to no alarm to 6 gas detectors
A088	GD6	sensor	to detect gas release	low output	not identified	FT	No gas detection	D	No	DU	Reduce sensitivity of the gas detector. The detector fails to exceed High alarm limit.
A089	GD7	sensor	to detect gas release	no signal	not identified	Casual obs.	No gas detection	D	No	DU	The detector is not working
A090	GD8	sensor	to detect gas release	other	not identified	PM	reduce possibility of gas detection	D	No	DU	The detector is located in the wrong location
A091	GD9	sensor	to detect gas release	low output	not identified	FT	No gas detection	D	No	DU	Reduce sensitivity of the gas detector.
A092	GD10	sensor	to detect gas release	other	Instrument failure	FT	No gas detection	D	No	DU	The detector is reading 22% LFL when it is tested with 50% LF gas. Not reach H alarm of 30%

Table B.1 continued from previous page

Unit		Unit Desc.		Description of failure				Failure analysis			
Not. No	**Tag**	**Part**	**Functic**	**Mode**	**Mechanism**	**Det Method**	**Failure Effect**	**Cons**	**Diagnos**	**class**	**Remarks**
A093	GD11	sensor	to detect gas release	no signal	Instrument failure	FT	No gas detection	D	No	DU	The detector reading is no more than 27%LEL
A094	GD12	sensor	to detect gas release	no signal	Instrument failure	PM	No gas detection	D	No	DU	The detector reading is no more than 16%LEL
A095	GD13	sensor	to detect gas release	no signal	not identified	FT	No gas detection	D	No	DU	The detector is defect
A096	GD14	sensor	to detect gas release	no signal	not identified	FT	No gas detection	D	No	DU	The detector is defect
A097	GD15	sensor	to detect gas release	no signal	not identified	FT	No gas detection	D	No	DU	The detector is defect
A098	GD16	sensor	to detect gas release	low output	not identified	FT	No gas detection	D	No	DU	The detector is not indicating alarm

Table B.1 continued from previous page

Unit Not. No	Tag	Unit Desc. Part	Functic	Description of failure Mode	Mechanism	Det Method	Failure Effect	Failure analysis Cons	Diagnos	class	Remarks
A099	GD17	sensor	to detect gas release	no signal	Instrument failure	FT	No gas detection	D	No	DU	The detector is not indicating alarm
A100	GD18	sensor	to detect gas release	other	not identified	FT	No gas detection	D	No	DU	Reduce sensitivity of the gas detector.
A101	GD19	sensor	to detect gas release	other	not identified	FT	No gas detection	D	No	DU	Reduce sensitivity of the gas detector.
A102	GD20	sensor	to detect gas release	low output	not identified	Cond Monitor	No gas detection	D	Yes	DD	Reduce sensitivity of the gas detector.
A103	GD21	Earth cable	ATEX atmosphere protection	Earth fault	Electrical failure	Casual obs.	No ATEX atmosphere protection, can be source of ignition	NR	No	NC	Earthing cable failure
A104	GD22	Earth cable	ATEX atmosphere protection	Earth fault	Electrical failure	Casual obs.	No ATEX atmosphere protection, can be source of ignition	NR	No	NC	Earthing cable failure

Table B.1 continued from previous page

Unit Not. No	Tag	Unit Desc.		Description of failure			Failure Effect	Failure analysis		class	Remarks
		Part	Functic	Mode	Mechanism	Det Method		Cons	Diagnos		
A105	GD23	Earth cable	ATEX atmosphere protection	Earth fault	Electrical failure	Casual obs.	No ATEX atmosphere protection, can be source of ignition	NR	No	NC	Earthing cable failure
A106	GD24	sensor	to detect gas release	low output	not identified	FT	No gas detection	D	No	DU	The detector reading is no more than 6%LEL
A107	GD25	sensor	to detect gas release	low output	not identified	FT	No gas detection	D	No	DU	The detector only goes up to 12.9% LEL, it is above the Low alarm but below the high alarm.
A108	GD26	sensor	to detect gas release	no signal	Instrument failure	FT	No gas detection	D	No	DU	The detector is defect
A109	GD27	sensor	to detect gas release	no signal	Instrument failure	FT	No gas detection	D	No	DU	The detector is reading 25% LFL when it is tested with 50% LF gas. Not reach H alarm of 30%
A110	GD28	sensor	to detect gas release	low output	not identified	FT	No gas detection	D	No	DU	The detector is reading 30% LFL when it is tested with 50% LF gas

Table B.1 continued from previous page

Unit		Unit Desc.		Description of failure				Failure analysis			
Not. No	**Tag**	**Part**	**Functic**	**Mode**	**Mechanism**	**Det Method**	**Failure Effect**	**Cons**	**Diagnos**	**class**	**Remarks**
A111	GD29	sensor	to detect gas release	other	not identified	FT	No gas detection	D	No	DU	The detector reading is no more than 10%LEL
A112	GD30	sensor	to detect gas release	other	not identified	PM	No gas detection	D	No	DU	The detector reading is no more than 19%LEL
A113	GD31	sensor	to detect gas release	Out of adjustment	Instrument failure	FT	No gas detection	D	No	DU	The detector is reading 33% LFL during testing
A114	GD32	sensor	to detect gas release	General	Instrument failure	PM	No gas detection	D	No	DU	The detector reading is no more than 19%LEL
A115	GD33	sensor	to detect gas release	other	not identified	PM	No gas detection	D	No	DU	The detector reading is no more than 15%LEL
A116	GD34	sensor	to detect gas release	other	not identified	FT	No gas detection	D	No	DU	The detector reading is no more than 5%LEL

Table B.1 continued from previous page

Unit		Unit Desc.		Description of failure				Failure analysis			
Not. No	**Tag**	**Part**	**Functic**	**Mode**	**Mechanism**	**Det Method**	**Failure Effect**	**Cons**	**Diagnos**	**class**	**Remarks**
A117	GD35	sensor	to detect gas release	General	Instrument failure	PM	No gas detection	D	No	DU	The detector is not indicating alarm
A118	GD36	sensor	to detect gas release	Out of adjustment	Instrument failure	PM	No gas detection	D	No	DU	The detector reading is no more than 19%LEL
A119	GD37	sensor	to detect gas release	high output	not identified	Cond Monitor	Gas detection when there is no gas	S	Yes	SD	The detector is going into alarm
A120	GD38	sensor	to detect gas release	high output	not identified	Cond Monitor	Gas detection when there is no gas	S	Yes	SD	The detector reading is 9% LEL when there is no gas
A121	GD39	sensor	to detect gas release	high output	not identified	Cond Monitor	Gas detection when there is no gas	S	Yes	SD	Gas detector is reading 7.5 LEL when there is no gas
A122	GD40	sensor	to detect gas release	high output	not identified	Cond Monitor	Gas detection when there is no gas	S	Yes	SD	The detector reading is 40% LEL when there is no gas

Table B.1 continued from previous page

Unit Not. No	**Tag**	**Unit Desc.**		**Description of failure**		**Det Method**	**Failure Effect**	**Failure analysis**		**class**	**Remarks**
		Part	**Functi**	**Mode**	**Mechanism**			**Cons**	**Diagnos**		
A123	GD41	sensor	to detect gas release	high output	not identified	Cond Monitor	Gas detection when there is no gas	S	Yes	SD	Gas detector is indicating too high value
A124	GD42	sensor	to detect gas release	high output	not identified	Cond Monitor	Gas detection when there is no gas	S	Yes	SD	Gas detector is indicating too high value
A125	GD43	sensor	to detect gas release	high output	not identified	Casual obs.	Gas detection when there is no gas	S	No	SU	Detector shows value above 8% without gas in area.
A126	AGD1	aspirator tubing	ensure flow to detector	other	not identified	Cond Monitor	No gas detection	D	Yes	DD	The aspirator tube was blocked by oil
A127	AGD2	aspirator flow swith	to detect if there is flow into gas detector	no signal	not identified	Casual obs.	No gas flow to gas detector	D	No	DU	The filter in flow switch transmitter is defect

Table B.1 continued from previous page

Unit Not. No	Tag	Unit Desc. Part	Functio	Description of failure Mode	Mechanism	Det Method	Failure Effect	Failure analysis Cons	Diagnos	class	Remarks
A128	AGD3	aspirator flow swith	to detect if there is flow into gas detector	no signal	not identified	FT	No gas flow to gas detector	D	No	DU	The flow switch is not working
A129	AGD4	aspirator flow swith	to detect if there is flow into gas detector	no signal	not identified	FT	No gas flow to gas detector	D	No	DU	The flow switch is not working
A130	AGD5	aspirator flow swith	to detect if there is flow into gas detector	no signal	not identified	FT	No gas flow to gas detector	D	No	DU	The flow switch is not working

Table B.1 continued from previous page

Unit Not. No	Tag	Unit Desc.		Description of failure			Failure Effect	Failure analysis		class	Remarks
		Part	Functi	Mode	Mechanism	Det Method		Cons	Diagnos		
A131	AGD6	aspirator flow swith	to detect if there is flow into gas detector	no signal	not identified	FT	No gas flow to gas detector	D	No	DU	The flow switch is not working
A132	AGD7	aspirator flow swith	to detect if there is flow into gas detector	no signal	not identified	Casual obs.	No gas flow to gas detector	D	No	DU	The flowswitch is not indicating alarm
A133	AGD8	aspirator tubing	ensure flow to detector	no signal	not identified	PM	No gas flow to gas detector	D	No	DU	The aspirator tube was blocked
A134	AGD9	aspirator flow swith	to detect if there is flow into gas detector	no signal	not identified	FT	No gas flow to gas detector	D	No	DU	The flowswitch is not indicating alarm

Table B.1 continued from previous page

Unit Not. No	Tag	Unit Desc. Part	Functi	Description of failure Mode	Mechanism	Det Method	Failure Effect	Failure analysis Cons	Diagnos	class	Remarks
A135	AGD10	aspirator flow swith	to detect if there is flow into gas detector	no signal	not identified	FT	No gas flow to gas detector	D	No	DU	The flowswitch is not indicating alarm
A136	AGD11	aspirator tubing	ensure flow to detector	no signal	not identified	Casual obs.	No gas flow to gas detector	D	No	DU	The aspirator tube was blocked
A137	AGD12	aspirator flow swith	to detect if there is flow into gas detector	other	not identified	FT	No gas flow to gas detector	D	No	DU	The flowswitch is not indicating alarm
A138	AGD13	aspirator flow swith	to detect if there is flow into gas detector	no signal	not identified	PM	No gas flow to gas detector	D	No	DU	The flowswitch is not indicating alarm

Table B.1 continued from previous page

Unit Not. No	Tag	Unit Desc. Part	Functio	Description of failure Mode	Mechanism	Det Method	Failure Effect	Failure analysis Cons	Diagnos	class	Remarks
A139	AGD14	aspirator flow swith	to detect if there is flow into gas detector	other	not identified	FT	No gas flow to gas detector	D	No	DU	The flowswitch is not indicating alarm
A140	AGD15	aspirator flow swith	to detect if there is flow into gas detector	no signal	not identified	PM	No gas flow to gas detector	D	No	DU	The flow switch is not working
A141	AGD16	aspirator flow swith	to detect if there is flow into gas detector	no signal	not identified	PM	No gas flow to gas detector	D	No	DU	The flow switch is not working

Table B.1 continued from previous page

Unit Not. No	Tag	Unit Desc. Part	Unit Desc. Functic	Description of failure Mode	Description of failure Mechanism	Det Method	Failure Effect	Failure analysis Cons	Failure analysis Diagnos	class	Remarks
A142	AGD17	aspirator flow swith	to detect if there is flow into gas detector	no signal	not identified	FT	No gas flow to gas detector	D	No	DU	The flow switch is not working
A143	OGD1	sensor	to detect gas release	Out of adjustment	Instrument failure	PM	No gas detection	D	No	DU	The detector only goes up to 0.5 LELm, it is below the high alarm.
A144	OGD2	sensor	to detect gas release	no signal	Instrument failure	FT	No gas detection	D	No	DU	The detector is not indicating alarm
A145	OGD3	sensor	to detect gas release	Misc external cause	Extranal	FT	No gas detection	D	No	DU	The detector lens must be cleaned
A146	OGD4	sensor	to detect gas release	Misc external cause	Extranal	FT	No gas detection	D	No	DU	The detector lens must be cleaned
A147	OGD5	sensor	to detect gas release	no signal	Instrument failure	FT	No gas detection	D	No	DU	The detector is not indicating alarm

Table B.1 continued from previous page

Unit		Unit Desc.		Description of failure				Failure analysis			
Not. No	**Tag**	**Part**	**Functic**	**Mode**	**Mechanism**	**Det Method**	**Failure Effect**	**Cons**	**Diagnos**	**class**	**Remarks**
A148	OGD6	sensor	to detect gas release	Misc external cause	Extranal	FT	No gas detection	D	No	DU	The detector lens must be cleaned
A149	OGD7	sensor	to detect gas release	no signal	not identified	Casual obs.	No gas detection	D	No	DU	The detector is not indicating alarm
A150	OGD8	sensor	to detect gas release	no signal	not identified	FT	No gas detection	D	No	DU	The detector is indicating 0 LEL during testing
A151	OGD9	sensor	to detect gas release	Misc external cause	Extranal	FT	No gas detection	D	No	DU	The detector lens must be cleaned
A152	OGD10	sensor	to detect gas release	no signal	not identified	FT	No gas detection	D	No	DU	The detector is indicating 0 LEL during testing
A153	OGD11	sensor	to detect gas release	low output	not identified	FT	No gas detection	D	No	DU	The detector is reduced function. It works after lens cleaned

Table B.1 continued from previous page

Unit		Unit Desc.		Description of failure				Failure analysis			
Not. No	**Tag**	**Part**	**Functic**	**Mode**	**Mechanism**	**Det Method**	**Failure Effect**	**Cons**	**Diagnos**	**class**	**Remarks**
A154	OGD12	sensor	to detect gas release	low output	not identified	FT	No gas detection	D	No	DU	The detector is reduced function. It works after lens cleaned
A155	OGD13	sensor	to detect gas release	low output	not identified	FT	No gas detection	D	No	DU	The detector is reduced function.
A156	OGD14	sensor	to detect gas release	other	not identified	FT	No gas detection	D	No	DU	The detector is installed in the wrong location
A157	OGD15	sensor	to detect gas release	low output	not identified	FT	No gas detection	D	No	DU	The detector is reduced function. It is worked after cleaning and callibration
A158	OGD16	sensor	to detect gas release	low output	not identified	FT	No gas detection	D	No	DU	The detector is reduced function. It is worked after cleaning and callibration
A159	OGD17	sensor	to detect gas release	no signal	Instrument failure	FT	No gas detection	D	No	DU	The detector is not indicating alarm

Table B.1 continued from previous page

Unit Not. No	Tag	Unit Desc. Part	Functic	Description of failure Mode	Mechanism	Det Method	Failure Effect	Failure analysis Cons	Diagnos	class	Remarks
A160	OGD18	sensor	to detect gas release	no signal	not identified	FT	No gas detection	D	No	DU	The detector is not indicating alarm
A161	OGD19	sensor	to detect gas release	no signal	Instrument failure	FT	No gas detection	D	No	DU	The detector lens must be cleaned
A162	OGD20	sensor	to detect gas release	no signal	Instrument failure	FT	No gas detection	D	No	DU	The detector lens must be cleaned
A163	OGD21	sensor	to detect gas release	no signal	not identified	FT	No gas detection	D	No	DU	The detector lens must be cleaned
A164	OGD22	sensor	to detect gas release	no signal	not identified	FT	No gas detection	D	No	DU	The detector lens must be cleaned
A165	CD01	sensor	to detect gas release	no signal	not identified	FT	No gas detection	D	No	DU	The detector has very slow response

Table B.1 continued from previous page

Unit Not. No	Tag	Unit Desc. Part	Functic	Description of failure Mode	Mechanism	Det Method	Failure Effect	Failure analysis Cons	Diagnos	class	Remarks
A166	CD02	sensor	to detect gas release	other	not identified	PM	No gas detection	D	No	DU	The detector is not indicating alarm
A167	CD03	sensor	to detect gas release	other	not identified	PM	No gas detection	D	No	DU	The detector is not working
A168	CD04	sensor	to detect gas release	no signal	not identified	FT	No gas detection	D	No	DU	The detector is not working
A169	CD05	sensor	to detect gas release	no signal	not identified	FT	No gas detection	D	No	DU	The detector reading is 17% LEL when test with 50% LFL gas
A170	CD06	sensor	to detect gas release	other	not identified	FT	No gas detection	D	No	DU	I/O card failure and leads to no alarm to 6 gas detectors
A171	CD07	sensor	to detect gas release	no signal	not identified	FT	No gas detection	D	No	DU	I/O card failure and leads to no alarm to 6 gas detectors

Table B.1 continued from previous page

Unit Not. No	Tag	Unit Desc.		Description of failure			Failure Effect	Failure analysis		class	Remarks
		Part	Functic	Mode	Mechanism	Det Method		Cons	Diagnos		
A172	CD08	sensor	to detect gas release	no signal	not identified	FT	No gas detection	D	No	DU	I/O card failure and leads to no alarm to 6 gas detectors
A173	CD09	sensor	to detect gas release	no signal	not identified	FT	No gas detection	D	No	DU	I/O card failure and leads to no alarm to 6 gas detectors
A174	CD10	sensor	to detect gas release	other	not identified	FT	No gas detection	D	No	DU	I/O card failure and leads to no alarm to 6 gas detectors
A175	CD11	sensor	to detect gas release	no signal	not identified	FT	No gas detection	D	No	DU	I/O card failure and leads to no alarm to 6 gas detectors
A176	CD12	sensor	to detect gas release	faulty signal	Instrument failure	FT	No gas detection	D	No	DU	The detector is reduced function and must be calibrated
A177	CD13	sensor	to detect gas release	faulty signal	Instrument failure	FT	No gas detection	D	No	DU	The detector is deffective

Table B.1 continued from previous page

Unit Not. No	Tag	Unit Desc. Part	Functic	Description of failure Mode	Mechanism	Det Method	Failure Effect	Failure analysis Cons	Diagnos	class	Remarks
A178	CD14	sensor	to detect gas release	no signal	Instrument failure	FT	No gas detection	D	No	DU	The detector reading is 9% LEL when test with 50% LFL gas
A179	CD15	sensor	to detect gas release	faulty signal	Instrument failure	FT	No gas detection	D	No	DU	The detector reading is 14% LEL when test with 50% LFL gas
A180	CD16	sensor	to detect gas release	other	not identified	FT	No gas detection	D	No	DU	The detector reading is 35% LEL when test with 50% LFL gas
A181	CD17	sensor	to detect gas release	no signal	not identified	FT	No gas detection	D	No	DU	The detector reading is 4% LEL when test with 50% LFL gas
A182	CD18	sensor	to detect gas release	no signal	Instrument failure	FT	No gas detection	D	No	DU	The detector is defect
A183	CD19	sensor	to detect gas release	no signal	Instrument failure	PM	No gas detection	D	No	DU	The detector is not indicating alarm

Table B.1 continued from previous page

Unit Not. No	Tag	Unit Desc.		Description of failure				Failure analysis		class	Remarks
		Part	Functic	Mode	Mechanism	Det Method	Failure Effect	Cons	Diagnos		
A184	CD20	sensor	to detect gas release	no signal	not identified	FT	No gas detection	D	No	DU	The detector is not indicating alarm
A185	ASD1	sensor	to detect gas release	no signal	not identified	FT	No gas detection	D	No	DU	The detector has very slow response
A186	ASD2	sensor	to detect gas release	no signal	not identified	FT	No gas detection	D	No	DU	The detector is not working
A187	ASD3	sensor	to detect gas release	no signal	Instrument failure	FT	No gas detection	D	No	DU	The detector is defect
A188	ASD4	aspirator flow swith	to detect if there is flow into gas detector	no signal	not identified	PM	No gas detection	D	No	DU	The flow switch is not working

Table B.1 continued from previous page

Unit Not. No	**Tag**	**Unit Desc.**		**Description of failure**			**Failure Effect**	**Failure analysis**		**class**	**Remarks**
		Part	**Functio**	**Mode**	**Mechanism**	**Det Method**		**Cons**	**Diagnos**		
A189	ASD5	aspirator flow swith	to detect if there is flow into gas detector	no signal	not identified	FT	No gas detection	D	No	DU	The flow switch is defect
A190	ASD6	aspirator flow swith	to detect if there is flow into gas detector	no signal	not identified	FT	No gas detection	D	No	DU	The flow switch is not working
A191	ASD7	aspirator tubing	ensure flow to detector	no signal	not identified	FT	No gas detection	D	No	DU	There is no air coming into the flowswitch
A192	ASD8	aspirator tubing	ensure flow to detector	no signal	not identified	FT	No gas detection	D	No	DU	There is a leakage in the tubing
A193	ASD9	aspirator tubing	ensure flow to detector	no signal	not identified	FT	No gas detection	D	No	DU	There is no air coming into the flowswitch

Appendix C

Failure Rate Calculation Example

C.1 OREDA Multi-Sample

OREDA Multi sample method is used to calculate the aggregated the failure rate of each detector model. This Appendix C provides example for calculating the aggregated failure rate. The SD-SOP-M6-model D data is used in this calculation and the input data is shown in Table C.1 below.

Table C.1: SD-SOP-M6-model D summary for each facility

Facility Name	Number of SD-SOP-M6-model D	Total time period	Number of DU failure
Facility A	33	1389168	0
Facility C	1208	26666184	0
Facility D	510	17625600	5
Facility E	783	5366112	0
Facility F	66	1899216	0
Facility I	478	16519680	0
Facility K	449	15517440	1
Facility L	10	345600	0

To calculate Multi-Sample OREDA estimator, the following procedure is used:

- the number of the facilities, k = 8
- A initial estimate of the mean failure rate by pooling the data

$$\hat{\theta}_1 = \frac{\sum_{i=1}^{k} n_i}{\sum_{i=1}^{k} \tau_i} = 7.03 \times 10^{-08}$$

(C.1)

- calculate the statistical coefficient

$$S_1 = \sum_{i=1}^{k} \tau_i = 8.53 \times 10^{07} \tag{C.2}$$

$$S_2 = \sum_{i=1}^{k} \tau_i^2 = 1.57 \times 10^{15} \tag{C.3}$$

$$V = \sum_{i=1}^{k} \frac{\left(n_i - \hat{\theta}_1\right)^2}{\tau_i} = \sum_{i=1}^{k} \frac{n_i^2}{\tau_i} - \hat{\theta}_1^{\,2} S_1 = 1.06 \times 10^{-06} \tag{C.4}$$

- calculate an estimate for variance between sample

$$\hat{\sigma}^2 = \frac{V - (k-1)\hat{\theta}_1}{S_1^2 - S_2} \times S_1 = 8.5 \times 10^{-15} \tag{C.5}$$

when the result is greater than 0, otherwise

$$\hat{\sigma}^2 = \sum_{i=1}^{k} \frac{\left[\frac{n_i}{\tau_i} - \hat{\theta}_1\right]^2}{k-1} = 9.22 \times 10^{-08} \tag{C.6}$$

- calculate the mean failure rate

$$\theta^* = \frac{1}{\sum_{i=1}^{k} \frac{1}{\frac{\hat{\theta}_1}{\tau_i} + \hat{\sigma}^2}} \sum_{i=1}^{k} \left[\frac{1}{\frac{\hat{\theta}_1}{\tau_i} + \hat{\sigma}^2} \times \frac{n_i}{\tau_i}\right] = 6.67 \times 10^{-08} \tag{C.7}$$

- calculate the gamma distribution parameter $\hat{\alpha}$ and $\hat{\beta}$

$$\hat{\alpha} = \hat{\beta} \times \theta^* = 0.52 \tag{C.8}$$

$$\hat{\beta} = \frac{\theta^*}{\hat{\sigma}^2} = 7.85 \times 10^{06} \tag{C.9}$$

- calculate the confident interval

$$\left(\frac{1}{2\hat{\beta}} z_{0.95,2\hat{\alpha}}, \frac{1}{2\hat{\beta}} z_{0.05,2\hat{\alpha}}\right) = \left(2.51 \times 10^{-10}, 2.45 \times 10^{-07}\right) \tag{C.10}$$

C.2 Bayesian Approach

Bayesian approach is used to calculate the failure rate of a detector model in a facility when the operational data is not adequate such as the failure is not found during the observation time. The SD-SOP-M6-model D data at facility C is used in this calculation. The operational time is 26666184 hours with no DU failure. A priory failure rate, λ_{DU}, of smoke detector is 5×10^{-07} based on PDS data handbook.

The Bayesian parameter as follow.

$$\alpha = \frac{\lambda_{DU}}{[\lambda_{DU-CE} - \lambda_{DU}]^2} = \frac{5 \times 10^{-07}}{[1 \times 10^{-06} - 5 \times 10^{-07}]^2} = 1 \tag{C.11}$$

$$\gamma = \alpha . \lambda_{DU} = 5 \times 10^{-07} \tag{C.12}$$

The Bayesian failure rate as follow.

$$\ddot{\lambda}_{DU} = \frac{\gamma + x}{\alpha + t_n} = 3.49 \times 10^{-08} \tag{C.13}$$

The credibility interval for the $\ddot{\lambda}_{DU}$ as follow.

$$\left(\frac{1}{2(\alpha + t)} z_{0.95,2(\gamma+n)}, \frac{1}{2(\alpha + t)} z_{0.05,22(\gamma+n)} \right) = \left(1.79 \times 10^{-09}, 1.05 \times 10^{-07} \right) \tag{C.14}$$

Appendix D

Failure Rate Calculation Result

D.1 The Sufficient Operational Experience Criteria

Table D.1: Low operational time and sufficient operational data

Facility	**Model**	**time (hours)**	**DU**	$\hat{\lambda}_{DU}(h^{-1})$	**3**$\hat{\lambda}_{DU}(h^{-1})$	**90% CI up** (h^{-1})	**Data**
Facility A	FD-IR3-M1-model A	2.10E+07	0	0.00E+00	0.00E+00	1.43E-07	NO
Facility B	FD-IR3-M1-model A	9.51E+06	2	2.10E-07	6.31E-07	6.62E-07	NO
Facility B	FD-UV-M1-model D	8.00E+05	3	3.75E-06	1.13E-05	9.69E-06	YES
Facility C	FD-IR3-M1-model A	3.13E+05	0	0.00E+00	0.00E+00	9.58E-06	NO
Facility C	FD-IR3-M2-model B	1.68E+06	0	0.00E+00	0.00E+00	1.78E-06	NO
Facility C	FD-IR3-M2-model C	4.86E+06	0	0.00E+00	0.00E+00	6.16E-07	NO
Facility D	FD-IR3-M1-model A	4.84E+05	2	4.13E-06	1.24E-05	1.30E-05	NO
Facility D	FD-IR3-M3-model G	5529600	6	1.09E-06	3.26E-06	2.14E-06	YES
Facility E	FD-IR3-M2-model C	1921920	0	0.00E+00	0.00E+00	1.56E-06	NO
Facility F	FD-IR3-M1-model A	2848824	4	1.40E-06	4.21E-06	3.21E-06	YES
Facility F	FD-IR3-M2-model B	201432	1	4.96E-06	1.49E-05	2.36E-05	NO
Facility F	FD-IR3-M2-model C	6.79E+06	9	1.33E-06	3.98E-06	2.31E-06	YES
Facility G	FD-IR3-M1-model A	7.30E+06	3	4.11E-07	1.23E-06	1.06E-06	YES
Facility G	FD-IR3-M2-model B	2.15E+06	1	4.65E-07	1.40E-06	2.21E-06	NO
Facility H	FD-IR3-M1-model A	2.42E+06	0	0.00E+00	0.00E+00	1.24E-06	NO
Facility H	FD-IR-M1-model E	3.13E+06	1	3.19E-07	9.58E-07	1.51E-06	NO
Facility I	FD-IR3-M1-model A	8.12E+06	1	1.23E-07	3.69E-07	5.84E-07	NO
Facility J	FD-IR3-M1-model A	2.42E+05	0	0.00E+00	0.00E+00	1.24E-05	NO
Facility J	FD-IR3-M3-model G	3386880	0	0.00E+00	0.00E+00	8.85E-07	NO
Facility K	FD-IR3-M1-model A	4112640	2	4.86E-07	1.46E-06	1.53E-06	NO
Facility K	FD-IR3-M4-model H	34560	0	0.00E+00	0.00E+00	8.67E-05	NO
Facility K	FD-UI-M1-model F	230832	0	0.00E+00	0.00E+00	1.30E-05	NO
Facility L	FD-IR3-M1-model A	1105920	2	1.81E-06	5.43E-06	5.69E-06	NO
Facility A	HD-ROR-M5-model A	1094496	0	0.00E+00	0.00E+00	2.74E-06	NO
Facility A	HD-FT-M6-model G	1052400	0	0.00E+00	0.00E+00	2.85E-06	NO
Facility B	HD-ROR-M5-model A	336768	0	0.00E+00	0.00E+00	8.90E-06	NO

Table D.1: Low operational time and sufficient operational data

Facility	**Model**	**time (hours)**	**DU**	$\hat{\lambda_{DU}}(h^{-1})$	$3\hat{\lambda_{DU}}(h^{-1})$	**90% CI up** (h^{-1})	**Data**
Facility B	HD-FT-M6-model G	589344	1	1.70E-06	5.09E-06	8.05E-06	NO
Facility C	HD-ROR-M5-model A	77568	0	0.00E+00	0.00E+00	3.86E-05	NO
Facility C	HD-FT-M6-model E	193056	0	0.00E+00	0.00E+00	1.55E-05	NO
Facility C	HD-FT-M6-model F	251568	0	0.00E+00	0.00E+00	1.19E-05	NO
Facility D	HD-ROR-M5-model A	518400	2	3.86E-06	1.16E-05	1.21E-05	NO
Facility D	HD-FT-M6-model F	1175040	1	8.51E-07	2.55E-06	4.04E-06	NO
Facility E	HD-FT-M6-model F	205920	0	0.00E+00	0.00E+00	1.45E-05	NO
Facility F	HD-ROR-M5-model A	345312	0	0.00E+00	0.00E+00	8.68E-06	NO
Facility F	HD-FT-M6-model G	797232	0	0.00E+00	0.00E+00	3.76E-06	NO
Facility G	HD-ROR-M5-model A	388440	0	0.00E+00	0.00E+00	7.71E-06	NO
Facility G	HD-FT-M6-model G	1139424	0	0.00E+00	0.00E+00	2.63E-06	NO
Facility G	HD-LN-M7-model I	258960	0	0.00E+00	0.00E+00	1.16E-05	NO
Facility H	HD-ROR-M8-model B	28062720	7	2.49E-07	7.48E-07	4.69E-07	YES
Facility I	HD-FT-M6-model F	1002240	0	0.00E+00	0.00E+00	2.99E-06	NO
Facility I	HD-ROR-M8-model B	276480	0	0.00E+00	0.00E+00	1.08E-05	NO
Facility J	HD-FT-M6-model D	32952	0	0.00E+00	0.00E+00	9.09E-05	NO
Facility J	HD-ROR-M5-model A	381768	0	0.00E+00	0.00E+00	7.85E-06	NO
Facility J	HD-FT-M6-model G	241920	0	0.00E+00	0.00E+00	1.24E-05	NO
Facility J	HD-ROR-M3-model C	138240	0	0.00E+00	0.00E+00	2.17E-05	NO
Facility K	HD-ROR-M8-model B	6186240	1	1.62E-07	4.85E-07	7.67E-07	NO
Facility K	HD-FT-M9-model H	172800	0	0.00E+00	0.00E+00	1.73E-05	NO
Facility L	HD-FT-M6-model F	103680	0	0.00E+00	0.00E+00	2.89E-05	NO
Facility A	SD-OP-M6-model A	42626592	1	2.35E-08	7.04E-08	1.11E-07	NO
Facility A	SD-OP-M3-model B	15154560	7	4.62E-07	1.39E-06	8.68E-07	YES
Facility A	SD-SOP-M6-model D	1389168	0	0.00E+00	0.00E+00	2.16E-06	NO
Facility A	SD-OP-M4-model C	3451872	0	0.00E+00	0.00E+00	8.68E-07	NO
Facility A	SD-ION-M4-model E	42096	0	0.00E+00	0.00E+00	7.12E-05	NO
Facility B	SD-OP-M6-model A	26730960	0	0.00E+00	0.00E+00	1.12E-07	NO
Facility B	SD-ION-M4-model E	11323824	0	0.00E+00	0.00E+00	2.65E-07	NO
Facility B	SD-ION-M6-model G	841920	0	0.00E+00	0.00E+00	3.56E-06	NO
Facility C	SD-SOP-M6-model D	26666184	0	0.00E+00	0.00E+00	1.12E-07	NO
Facility C	SD-OP-M4-model C	45432	0	0.00E+00	0.00E+00	6.59E-05	NO
Facility C	SD-ION-M4-model F	116328	0	0.00E+00	0.00E+00	2.58E-05	NO
Facility D	SD-SOP-M6-model D	17625600	5	2.84E-07	8.51E-07	5.96E-07	YES
Facility D	SD-OT-M11-model I	138240	0	0.00E+00	0.00E+00	2.17E-05	NO
Facility E	SD-SOP-M6-model D	5366112	0	0.00E+00	0.00E+00	5.58E-07	NO
Facility F	SD-OP-M6-model A	23935944	10	4.18E-07	1.25E-06	7.09E-07	YES
Facility F	SD-SOP-M6-model D	1899216	0	0.00E+00	0.00E+00	1.58E-06	NO
Facility F	SD-IR-M10-model H	115104	0	0.00E+00	0.00E+00	2.60E-05	NO
Facility F	SD-ION-M6-model G	57552	0	0.00E+00	0.00E+00	5.21E-05	NO
Facility G	SD-OP-M6-model A	25844208	5	1.93E-07	5.80E-07	4.07E-07	YES
Facility H	SD-OP-M6-model A	49541616	1	2.02E-08	6.06E-08	9.58E-08	NO
Facility H	SD-OP-M3-model B	16871040	10	5.93E-07	1.78E-06	1.01E-06	YES
Facility H	SD-OP-M4-model C	125280	0	0.00E+00	0.00E+00	2.39E-05	NO

Table D.1: Low operational time and sufficient operational data

Facility	**Model**	**time (hours)**	**DU**	$\hat{\lambda}_{DU}(h^{-1})$	**3**$\hat{\lambda}_{DU}(h^{-1})$	**90% CI up** (h^{-1})	**Data**
Facility I	SD-SOP-M6-model D	16519680	0	0.00E+00	0.00E+00	1.81E-07	NO
Facility J	SD-OP-M6-model A	9192960	0	0.00E+00	0.00E+00	3.26E-07	NO
Facility J	SD-OP-M3-model B	10298880	2	1.94E-07	5.83E-07	6.11E-07	NO
Facility K	SD-OP-M6-model A	3421440	1	2.92E-07	8.77E-07	1.39E-06	NO
Facility K	SD-SOP-M6-model D	15517440	1	6.44E-08	1.93E-07	3.06E-07	NO
Facility K	SD-OP-M4-model C	5978880	7	1.17E-06	3.51E-06	2.20E-06	YES
Facility L	SD-SOP-M6-model D	345600	0	0.00E+00	0.00E+00	8.67E-06	NO
Facility A	GD-IR-M14-model A	18943200	3	1.58E-07	4.75E-07	4.09E-07	YES
Facility B	GD-IR-M14-model A	11408016	3	2.63E-07	7.89E-07	6.80E-07	YES
Facility C	GD-IR-M14-model A	6687624	7	1.05E-06	3.14E-06	1.97E-06	YES
Facility D	GD-IR-M14-model A	8052480	0	0.00E+00	0.00E+00	3.72E-07	NO
Facility D	GD-IR-M6-model C	138240	0	0.00E+00	0.00E+00	2.17E-05	NO
Facility E	GD-IR-M14-model A	2105544	0	0.00E+00	0.00E+00	1.42E-06	NO
Facility F	GD-IR-M14-model A	4230072	3	7.09E-07	2.13E-06	1.83E-06	YES
Facility G	GD-IR-M14-model A	8882328	2	2.25E-07	6.75E-07	7.09E-07	NO
Facility H	GD-IR-M14-model A	22592160	9	3.98E-07	1.20E-06	6.95E-07	YES
Facility I	GD-IR-M14-model A	9918720	3	3.02E-07	9.07E-07	7.82E-07	YES
Facility J	GD-IR-M14-model A	5210208	3	5.76E-07	1.73E-06	1.49E-06	YES
Facility J	GD-IR-M14-model B	181152	0	0.00E+00	0.00E+00	1.65E-05	NO
Facility K	GD-IR-M14-model A	3836160	3	7.82E-07	2.35E-06	2.02E-06	YES
Facility K	GD-IR-M6-model C	207360	0	0.00E+00	0.00E+00	1.44E-05	NO
Facility L	GD-IR-M14-model A	1382400	0	0.00E+00	0.00E+00	2.17E-06	NO
Facility A	LOS-IR-M15-model A	2694144	0	0.00E+00	0.00E+00	1.11E-06	NO
Facility A	LOS-IR-M16-model E	210480	0	0.00E+00	0.00E+00	1.42E-05	NO
Facility B	LOS-IR-M15-model A	2062704	1	4.85E-07	1.45E-06	2.30E-06	NO
Facility C	LOS-IR-M15-model A	2737272	0	0.00E+00	0.00E+00	1.09E-06	NO
Facility D	LOS-IR-M15-model A	1762560	1	5.67E-07	1.70E-06	2.69E-06	NO
Facility E	LOS-IR-M16-model B	1094832	0	0.00E+00	0.00E+00	2.74E-06	NO
Facility F	LOS-IR-M15-model A	6273168	20	3.19E-06	9.56E-06	4.63E-06	YES
Facility F	LOS-IR-M16-model E	517968	1	1.93E-06	5.79E-06	9.16E-06	NO
Facility G	LOS-IR-M15-model A	4221048	0	0.00E+00	0.00E+00	7.10E-07	NO
Facility H	LOS-IR-M15-model A	4510080	0	0.00E+00	0.00E+00	6.64E-07	NO
Facility I	LOS-IR-M15-model A	1624320	0	0.00E+00	0.00E+00	1.84E-06	NO
Facility I	LOS-IR-M15-model A	69120	0	0.00E+00	0.00E+00	4.33E-05	NO
Facility I	LOS-IR-M6-model D	108672	0	0.00E+00	0.00E+00	2.76E-05	NO
Facility I	LOS-IR-M6-model C	444288	0	0.00E+00	0.00E+00	6.74E-06	NO
Facility J	LOS-IR-M15-model A	1175040	0	0.00E+00	0.00E+00	2.55E-06	NO
Facility K	LOS-IR-M15-model A	380160	7	1.84E-05	5.52E-05	3.46E-05	YES
Facility K	LOS-IR-M16-model B	725760	7	9.65E-06	2.89E-05	1.81E-05	YES
Facility L	LOS-IR-M15-model A	69120	0	0.00E+00	0.00E+00	4.33E-05	NO
Facility L	LOS-IR-M16-model E	552960	0	0.00E+00	0.00E+00	5.42E-06	NO
Facility A	CD-HC-M15-model A	9976752	11	1.10E-06	3.31E-06	1.82E-06	YES
Facility B	CD-H2-M16-model E	252576	0	0.00E+00	0.00E+00	1.19E-05	NO
Facility C	CD-HC-M15-model B	797040	4	5.02E-06	1.51E-05	1.15E-05	YES

Table D.1: Low operational time and sufficient operational data

Facility	**Model**	**time (hours)**	**DU**	$\hat{\lambda}_{DU}(h^{-1})$	**3**$\hat{\lambda}_{DU}(h^{-1})$	**90% CI up** (h^{-1})	**Data**
Facility C	CD-HC-M15-model C	132048	0	0.00E+00	0.00E+00	2.27E-05	NO
Facility D	CD-HC-M15-model B	241920	0	0.00E+00	0.00E+00	1.24E-05	NO
Facility E	CD-H2-M16-model F	136464	0	0.00E+00	0.00E+00	2.20E-05	NO
Facility F	CD-H2-M16-model G	172656	3	1.74E-05	5.21E-05	4.49E-05	YES
Facility G	CD-H2-M16-model G	129480	0	0.00E+00	0.00E+00	2.31E-05	NO
Facility H	CD-H2-M16-model G	375840	2	5.32E-06	1.60E-05	1.68E-05	NO
Facility K	CD-HC-M15-model A	6082560	35	5.75E-06	1.73E-05	7.63E-06	YES
Facility K	CD-HC-M15-model D	207360	6	2.89E-05	8.68E-05	5.71E-05	YES
Facility L	CD-H2-M16-model E	34560	0	0.00E+00	0.00E+00	8.67E-05	NO

D.2 Comparison Calculated Bayesian Failure Rate $\ddot{\lambda}_{DU}$ based on Different A Priory Failure Rate λ_{DU}

Table D.2: Comparison of the $\ddot{\lambda}_{DU}$ with a different priory λ_{DU}

Facility	**Model**	**Time -hour**	**DU**	**Case A** (h^{-1})		**Case B** (h^{-1})		**Case C** (h^{-1})	
				$\lambda_{DU,A}$	$\ddot{\lambda}_{DU,A}$	$\lambda_{DU,B}$	$\ddot{\lambda}_{DU,B}$	$\lambda_{DU,C}$	$\ddot{\lambda}_{DU,C}$
Facility A	FD-IR3-M1-model A	20963808	0	5.00E-07	4.35E-08	6.07E-07	4.42E-08	6.21E-07	4.43E-08
Facility B	FD-IR3-M1-model A	9513696	2	5.00E-07	2.61E-07	6.07E-07	2.69E-07	6.21E-07	2.70E-07
Facility B	FD-UV-M1-model D	799824	3	5.00E-07	1.43E-06	6.07E-07	1.63E-06	6.07E-07	1.63E-06
Facility C	FD-IR3-M1-model A	312840	0	5.00E-07	4.32E-07	6.07E-07	5.10E-07	6.21E-07	5.20E-07
Facility C	FD-IR3-M2-model B	1680000	0	5.00E-07	2.72E-07	6.07E-07	3.01E-07	1.11E-06	3.88E-07
Facility C	FD-IR3-M2-model C	4864416	0	5.00E-07	1.46E-07	6.07E-07	1.54E-07	4.96E-07	1.45E-07
Facility D	FD-IR3-M1-model A	483840	2	5.00E-07	1.21E-06	6.07E-07	1.41E-06	6.21E-07	1.43E-06
Facility D	FD-IR3-M3-model G	5529600	6	5.00E-07	9.30E-07	6.07E-07	9.75E-07	6.07E-07	9.64E-07
Facility E	FD-IR3-M2-model C	1921920	0	5.00E-07	2.55E-07	6.07E-07	2.80E-07	4.96E-07	2.54E-07
Facility F	FD-IR3-M1-model A	2848824	4	5.00E-07	1.03E-06	6.07E-07	1.11E-06	6.21E-07	1.12E-06
Facility F	FD-IR3-M2-model B	201432	1	5.00E-07	9.08E-07	6.07E-07	1.08E-06	1.11E-06	1.82E-06
Facility F	FD-IR3-M2-model C	6791136	9	5.00E-07	1.14E-06	6.07E-07	1.19E-06	4.96E-07	1.14E-06

Table D.2: Comparison of the $\ddot{\lambda}_{DU}$ with a different priory λ_{DU}

Facility	**Model**	**Time -hour**	**DU**	**Case A** (h^{-1})		**Case B** (h^{-1})		**Case C** (h^{-1})	
				$\lambda_{DU,A}$	$\ddot{\lambda}_{DU,A}$	$\lambda_{DU,B}$	$\ddot{\lambda}_{DU,B}$	$\lambda_{DU,C}$	$\ddot{\lambda}_{DU,C}$
Facility G	FD-IR3-M1-model A	7302672	3	5.00E-07	4.30E-07	6.07E-07	4.47E-07	6.21E-07	4.49E-07
Facility G	FD-IR3-M2-model B	2149368	1	5.00E-07	4.82E-07	6.07E-07	5.27E-07	1.11E-06	6.57E-07
Facility H	FD-IR3-M1-model A	2422080	0	5.00E-07	2.26E-07	6.07E-07	2.46E-07	6.21E-07	2.48E-07
Facility H	FD-IR-M1-model E	3132000	1	5.00E-07	3.90E-07	6.07E-07	4.19E-07	6.07E-07	4.19E-07
Facility I	FD-IR3-M1-model A	8121600	1	5.00E-07	1.98E-07	6.07E-07	2.05E-07	6.21E-07	2.06E-07
Facility J	FD-IR3-M1-model A	241920	0	5.00E-07	4.46E-07	6.07E-07	5.29E-07	6.21E-07	5.40E-07
Facility J	FD-IR3-M3-model G	3386880	0	5.00E-07	1.86E-07	6.07E-07	1.99E-07	6.07E-07	1.95E-07
Facility K	FD-IR3-M1-model A	4112640	2	5.00E-07	4.91E-07	6.07E-07	5.21E-07	6.21E-07	5.24E-07
Facility K	FD-IR3-M4-model H	34560	0	5.00E-07	4.92E-07	6.07E-07	5.95E-07	6.07E-07	5.95E-07
Facility K	FD-UI-M1-model F	230832	0	5.00E-07	4.48E-07	6.07E-07	5.33E-07	6.07E-07	5.33E-07
Facility L	FD-IR3-M1-model A	1105920	2	5.00E-07	9.66E-07	6.07E-07	1.09E-06	6.21E-07	1.10E-06
Facility A	HD-ROR-M5-model A	1094496	0	5.00E-07	3.23E-07	5.11E-07	3.28E-07	6.55E-07	3.82E-07
Facility A	HD-FT-M6-model G	1052400	0	5.00E-07	3.28E-07	2.40E-07	1.91E-07	2.91E-07	2.23E-07
Facility B	HD-ROR-M5-model A	336768	0	5.00E-07	4.28E-07	5.11E-07	4.36E-07	6.55E-07	5.37E-07
Facility B	HD-FT-M6-model G	589344	1	5.00E-07	7.72E-07	2.40E-07	4.20E-07	2.91E-07	4.97E-07
Facility C	HD-ROR-M5-model A	77568	0	5.00E-07	4.81E-07	5.11E-07	4.91E-07	6.55E-07	6.23E-07
Facility C	HD-FT-M6-model E	193056	0	5.00E-07	4.56E-07	2.40E-07	2.29E-07	2.40E-07	2.29E-07
Facility C	HD-FT-M6-model F	251568	0	5.00E-07	4.44E-07	2.40E-07	2.26E-07	4.91E-07	4.37E-07
Facility D	HD-ROR-M5-model A	518400	2	5.00E-07	1.19E-06	5.11E-07	1.21E-06	6.55E-07	1.47E-06
Facility D	HD-FT-M6-model F	1175040	1	5.00E-07	6.30E-07	2.40E-07	3.74E-07	4.91E-07	6.23E-07

Table D.2: Comparison of the $\ddot{\lambda}_{DU}$ with a different priory λ_{DU}

Facility	**Model**	**Time -hour**	**DU**	**Case A** (h^{-1})		**Case B** (h^{-1})		**Case C** (h^{-1})	
				$\lambda_{DU,A}$	$\ddot{\lambda}_{DU,A}$	$\lambda_{DU,B}$	$\ddot{\lambda}_{DU,B}$	$\lambda_{DU,C}$	$\ddot{\lambda}_{DU,C}$
Facility E	HD-FT-M6-model F	205920	0	5.00E-07	4.53E-07	2.40E-07	2.28E-07	4.91E-07	4.46E-07
Facility F	HD-ROR-M5-model A	345312	0	5.00E-07	4.26E-07	5.11E-07	4.34E-07	6.55E-07	5.34E-07
Facility F	HD-FT-M6-model G	797232	0	5.00E-07	3.57E-07	2.40E-07	2.01E-07	2.91E-07	2.36E-07
Facility G	HD-ROR-M5-model A	388440	0	5.00E-07	4.19E-07	5.11E-07	4.26E-07	6.55E-07	5.22E-07
Facility G	HD-FT-M6-model G	1139424	0	5.00E-07	3.19E-07	2.40E-07	1.88E-07	2.91E-07	2.19E-07
Facility G	HD-LN-M7-model I	258960	0	5.00E-07	4.43E-07	4.46E-07	4.00E-07	4.46E-07	4.00E-07
Facility H	HD-ROR-M8-model B	28062720	7	5.00E-07	2.66E-07	5.11E-07	2.66E-07	2.12E-07	2.44E-07
Facility I	HD-FT-M6-model F	1002240	0	5.00E-07	3.33E-07	2.40E-07	1.93E-07	4.91E-07	3.29E-07
Facility I	HD-ROR-M8-model B	276480	0	5.00E-07	4.39E-07	5.11E-07	4.47E-07	2.12E-07	2.00E-07
Facility J	HD-FT-M6-model D	32952	0	5.00E-07	4.92E-07	2.40E-07	2.38E-07	2.40E-07	2.38E-07
Facility J	HD-ROR-M5-model A	381768	0	5.00E-07	4.20E-07	5.11E-07	4.27E-07	6.55E-07	5.24E-07
Facility J	HD-FT-M6-model G	241920	0	5.00E-07	4.46E-07	2.40E-07	2.27E-07	2.91E-07	2.72E-07
Facility J	HD-ROR-M3-model C	138240	0	5.00E-07	4.68E-07	5.11E-07	4.77E-07	5.11E-07	4.77E-07
Facility K	HD-ROR-M8-model B	6186240	1	5.00E-07	2.44E-07	5.11E-07	2.46E-07	2.12E-07	1.83E-07
Facility K	HD-FT-M9-model H	172800	0	5.00E-07	4.60E-07	2.40E-07	2.30E-07	2.40E-07	2.30E-07
Facility L	HD-FT-M6-model F	103680	0	5.00E-07	4.75E-07	2.40E-07	2.34E-07	4.91E-07	4.68E-07
Facility A	SD-OP-M6-model A	42626592	1	5.00E-07	4.48E-08	1.35E-07	2.60E-08	1.24E-07	2.55E-08
Facility A	SD-OP-M3-model B	15154560	7	5.00E-07	4.66E-07	1.35E-07	4.42E-07	4.45E-07	4.60E-07

Table D.2: Comparison of the $\ddot{\lambda}_{DU}$ with a different priory λ_{DU}

Facility	**Model**	**Time -hour**	**DU**	**Case A** (h^{-1})		**Case B** (h^{-1})		**Case C** (h^{-1})	
				$\lambda_{DU,A}$	$\ddot{\lambda}_{DU,A}$	$\lambda_{DU,B}$	$\ddot{\lambda}_{DU,B}$	$\lambda_{DU,C}$	$\ddot{\lambda}_{DU,C}$
Facility A	SD-SOP-M6-model D	1389168	0	5.00E-07	2.95E-07	1.35E-07	5.65E-08	6.67E-08	6.10E-08
Facility A	SD-OP-M4-model C	3451872	0	5.00E-07	1.83E-07	1.35E-07	3.04E-08	6.32E-07	1.99E-07
Facility A	SD-ION-M4-model E	42096	0	5.00E-07	4.90E-07	1.35E-07	1.28E-07	1.34E-07	1.33E-07
Facility B	SD-OP-M6-model A	26730960	0	5.00E-07	3.48E-08	1.35E-07	4.88E-09	1.24E-07	2.88E-08
Facility B	SD-ION-M4-model E	11323824	0	5.00E-07	7.51E-08	1.35E-07	1.08E-08	1.34E-07	5.32E-08
Facility B	SD-ION-M6-model G	841920	0	5.00E-07	3.52E-07	1.35E-07	7.25E-08	1.34E-07	1.20E-07
Facility C	SD-SOP-M6-model D	26666184	0	5.00E-07	3.49E-08	1.35E-07	4.90E-09	6.67E-08	2.40E-08
Facility C	SD-OP-M4-model C	45432	0	5.00E-07	4.89E-07	1.35E-07	1.29E-07	6.32E-07	6.14E-07
Facility C	SD-ION-M4-model F	116328	0	5.00E-07	4.73E-07	1.35E-07	1.20E-07	1.34E-07	1.32E-07
Facility D	SD-SOP-M6-model D	17625600	5	5.00E-07	3.06E-07	1.35E-07	2.76E-07	6.67E-08	1.84E-07
Facility D	SD-OT-M11-model I	138240	0	5.00E-07	4.68E-07	1.35E-07	1.17E-07	1.35E-07	1.31E-07
Facility E	SD-SOP-M6-model D	5366112	0	5.00E-07	1.36E-07	1.35E-07	2.13E-08	6.67E-08	4.91E-08
Facility F	SD-OP-M6-model A	23935944	10	5.00E-07	4.24E-07	1.35E-07	4.06E-07	1.24E-07	3.44E-07
Facility F	SD-SOP-M6-model D	1899216	0	5.00E-07	2.56E-07	1.35E-07	4.66E-08	6.67E-08	5.92E-08
Facility F	SD-IR-M10-model H	115104	0	5.00E-07	4.73E-07	1.35E-07	1.20E-07	1.35E-07	1.32E-07
Facility F	SD-ION-M6-model G	57552	0	5.00E-07	4.86E-07	1.35E-07	1.26E-07	1.34E-07	1.33E-07
Facility G	SD-OP-M6-model A	25844208	5	5.00E-07	2.15E-07	1.35E-07	1.91E-07	1.24E-07	1.77E-07
Facility H	SD-OP-M6-model A	49541616	1	5.00E-07	3.88E-08	1.35E-07	2.25E-08	1.24E-07	3.47E-08
Facility H	SD-OP-M3-model B	16871040	10	5.00E-07	5.83E-07	1.35E-07	5.67E-07	4.45E-07	5.75E-07
Facility H	SD-OP-M4-model C	125280	0	5.00E-07	4.71E-07	1.35E-07	1.20E-07	6.32E-07	5.86E-07
Facility I	SD-SOP-M6-model D	16519680	0	5.00E-07	5.40E-08	1.35E-07	7.73E-09	6.67E-08	3.17E-08
Facility J	SD-OP-M6-model A	9192960	0	5.00E-07	8.93E-08	1.35E-07	1.33E-08	1.24E-07	5.80E-08

Table D.2: Comparison of the $\ddot{\lambda}_{DU}$ with a different priory λ_{DU}

Facility	**Model**	**Time -hour**	**DU**	**Case A** (h^{-1})		**Case B** (h^{-1})		**Case C** (h^{-1})	
				$\lambda_{DU,A}$	$\ddot{\lambda}_{DU,A}$	$\lambda_{DU,B}$	$\ddot{\lambda}_{DU,B}$	$\lambda_{DU,C}$	$\ddot{\lambda}_{DU,C}$
Facility J	SD-OP-M3-model B	10298880	2	5.00E-07	2.44E-07	1.35E-07	1.89E-07	4.45E-07	2.39E-07
Facility K	SD-OP-M6-model A	3421440	1	5.00E-07	3.69E-07	1.35E-07	2.56E-07	1.24E-07	1.75E-07
Facility K	SD-SOP-M6-model D	15517440	1	5.00E-07	1.14E-07	1.35E-07	6.87E-08	6.67E-08	6.55E-08
Facility K	SD-OP-M4-model C	5978880	7	5.00E-07	1.00E-06	1.35E-07	1.02E-06	6.32E-07	1.06E-06
Facility L	SD-SOP-M6-model D	345600	0	5.00E-07	4.26E-07	1.35E-07	1.00E-07	6.67E-08	6.52E-08
Facility A	GD-IR-M14-model A	18943200	3	6.00E-07	1.58E-07	3.70E-07	1.58E-07	3.74E-07	1.58E-07
Facility B	GD-IR-M14-model A	11408016	3	6.00E-07	2.63E-07	3.70E-07	2.63E-07	3.74E-07	2.63E-07
Facility C	GD-IR-M14-model A	6687624	7	6.00E-07	1.05E-06	3.70E-07	1.05E-06	3.74E-07	1.05E-06
Facility D	GD-IR-M14-model A	8052480	0	6.00E-07	1.03E-07	3.70E-07	9.29E-08	3.74E-07	9.32E-08
Facility D	GD-IR-M6-model C	138240	0	6.00E-07	5.54E-07	3.70E-07	3.52E-07	3.70E-07	3.52E-07
Facility E	GD-IR-M14-model A	2105544	0	6.00E-07	2.65E-07	3.70E-07	2.08E-07	3.74E-07	2.09E-07
Facility F	GD-IR-M14-model A	4230072	3	6.00E-07	7.09E-07	3.70E-07	7.09E-07	3.74E-07	7.09E-07
Facility G	GD-IR-M14-model A	8882328	2	6.00E-07	2.84E-07	3.70E-07	2.59E-07	3.74E-07	2.60E-07
Facility H	GD-IR-M14-model A	22592160	9	6.00E-07	3.98E-07	3.70E-07	3.98E-07	3.74E-07	3.98E-07
Facility I	GD-IR-M14-model A	9918720	3	6.00E-07	3.02E-07	3.70E-07	3.02E-07	3.74E-07	3.02E-07
Facility J	GD-IR-M14-model A	5210208	3	6.00E-07	5.76E-07	3.70E-07	5.76E-07	3.74E-07	5.76E-07
Facility J	GD-IR-M14-model B	181152	0	6.00E-07	5.41E-07	3.70E-07	3.46E-07	3.70E-07	3.46E-07
Facility K	GD-IR-M14-model A	3836160	3	6.00E-07	7.82E-07	3.70E-07	7.82E-07	3.74E-07	7.82E-07
Facility K	GD-IR-M6-model C	207360	0	6.00E-07	5.34E-07	3.70E-07	3.43E-07	3.70E-07	3.43E-07
Facility L	GD-IR-M14-model A	1382400	0	6.00E-07	3.28E-07	3.70E-07	2.45E-07	3.74E-07	2.47E-07
Facility A	LOS-IR-M15-model A	2694144	0	6.00E-07	2.29E-07	1.68E-07	6.03E-08	1.67E-07	5.98E-08
Facility A	LOS-IR-M16-model E	210480	0	6.00E-07	5.33E-07	1.68E-07	1.62E-07	7.44E-07	6.44E-07

Table D.2: Comparison of the $\ddot{\lambda}_{DU}$ with a different priory λ_{DU}

Facility	**Model**	**Time -hour**	**DU**	**Case A** (h^{-1})		**Case B** (h^{-1})		**Case C** (h^{-1})	
				$\lambda_{DU,A}$	$\ddot{\lambda}_{DU,A}$	$\lambda_{DU,B}$	$\ddot{\lambda}_{DU,B}$	$\lambda_{DU,C}$	$\ddot{\lambda}_{DU,C}$
Facility B	LOS-IR-M15-model A	2062704	1	6.00E-07	5.36E-07	1.68E-07	2.49E-07	1.67E-07	2.48E-07
Facility C	LOS-IR-M15-model A	2737272	0	6.00E-07	2.27E-07	1.68E-07	1.15E-07	1.67E-07	1.15E-07
Facility D	LOS-IR-M15-model A	1762560	1	6.00E-07	5.83E-07	1.68E-07	2.59E-07	1.67E-07	2.58E-07
Facility E	LOS-IR-M16-model B	1094832	0	6.00E-07	3.62E-07	1.68E-07	1.42E-07	1.68E-07	1.42E-07
Facility F	LOS-IR-M15-model A	6273168	20	6.00E-07	2.64E-06	1.68E-07	1.72E-06	1.67E-07	1.71E-06
Facility F	LOS-IR-M16-model E	517968	1	6.00E-07	9.15E-07	1.68E-07	3.08E-07	7.44E-07	1.07E-06
Facility G	LOS-IR-M15-model A	4221048	0	6.00E-07	1.70E-07	1.68E-07	9.81E-08	1.67E-07	9.79E-08
Facility H	LOS-IR-M15-model A	4510080	0	6.00E-07	1.62E-07	1.68E-07	9.54E-08	1.67E-07	9.52E-08
Facility I	LOS-IR-M15-model A	1624320	0	6.00E-07	3.04E-07	1.68E-07	1.32E-07	1.67E-07	1.31E-07
Facility I	LOS-IR-M15-model A	69120	0	6.00E-07	5.76E-07	1.68E-07	1.66E-07	1.67E-07	1.65E-07
Facility I	LOS-IR-M6-model D	108672	0	6.00E-07	5.63E-07	1.68E-07	1.65E-07	1.68E-07	1.65E-07
Facility I	LOS-IR-M6-model C	444288	0	6.00E-07	4.74E-07	1.68E-07	1.56E-07	1.68E-07	1.56E-07
Facility J	LOS-IR-M15-model A	1175040	0	6.00E-07	3.52E-07	1.68E-07	1.40E-07	1.67E-07	1.40E-07
Facility K	LOS-IR-M15-model A	380160	7	6.00E-07	3.91E-06	1.68E-07	1.26E-06	1.67E-07	1.26E-06
Facility K	LOS-IR-M16-model B	725760	7	6.00E-07	3.34E-06	1.68E-07	1.19E-06	1.68E-07	1.19E-06
Facility L	LOS-IR-M15-model A	69120	0	6.00E-07	5.76E-07	1.68E-07	1.66E-07	1.67E-07	1.65E-07
Facility L	LOS-IR-M16-model E	552960	0	6.00E-07	4.51E-07	1.68E-07	1.53E-07	7.44E-07	5.27E-07
Facility A	CD-HC-M15-model A	9976752	11	1.80E-06	1.14E-06	1.95E-06	1.14E-06	3.41E-06	1.17E-06
Facility B	CD-H2-M16-model E	252576	0	1.80E-06	1.24E-06	4.41E-06	2.09E-06	4.41E-06	2.09E-06
Facility C	CD-HC-M15-model B	797040	4	1.80E-06	3.70E-06	1.95E-06	3.81E-06	3.61E-06	4.66E-06
Facility C	CD-HC-M15-model C	132048	0	1.80E-06	1.45E-06	1.95E-06	1.55E-06	1.95E-06	1.55E-06
Facility D	CD-HC-M15-model B	241920	0	1.80E-06	1.25E-06	1.95E-06	1.32E-06	3.61E-06	1.93E-06

Table D.2: Comparison of the $\ddot{\lambda}_{DU}$ with a different priory λ_{DU}

Facility	**Model**	**Time -hour**	**DU**	**Case A** (h^{-1})		**Case B** (h^{-1})		**Case C** (h^{-1})	
				$\lambda_{DU,A}$	$\ddot{\lambda}_{DU,A}$	$\lambda_{DU,B}$	$\ddot{\lambda}_{DU,B}$	$\lambda_{DU,C}$	$\ddot{\lambda}_{DU,C}$
Facility E	CD-H2-M16-model F	136464	0	1.80E-06	1.45E-06	4.41E-06	2.75E-06	4.41E-06	2.75E-06
Facility F	CD-H2-M16-model G	172656	3	1.80E-06	5.49E-06	4.41E-06	1.00E-05	7.62E-06	1.32E-05
Facility G	CD-H2-M16-model G	129480	0	1.80E-06	1.46E-06	4.41E-06	2.81E-06	7.62E-06	3.84E-06
Facility H	CD-H2-M16-model G	375840	2	1.80E-06	3.22E-06	4.41E-06	4.98E-06	7.62E-06	5.92E-06
Facility K	CD-HC-M15-model A	6082560	35	1.80E-06	5.42E-06	1.95E-06	5.46E-06	3.41E-06	5.65E-06
Facility K	CD-HC-M15-model D	207360	6	1.80E-06	9.18E-06	1.95E-06	9.71E-06	1.95E-06	9.71E-06
Facility L	CD-H2-M16-model E	34560	0	1.80E-06	5.88E-07	4.41E-06	3.83E-06	4.41E-06	3.83E-06

Appendix E

Test Interval Calculation Result

E.1 Test Interval Based on SINTEF Guideline

The test interval is updated by using the method in guidelines for SIS follow-up activities as described in section 2.5. One of example test interval calculation is below:

FD-IR3-M1-model A in facility A has no failure in 20963808 hour. The Bayesian failure rate is 4.35×10^{-08} with the 90% lower limit is 0 and 90% upper limit is 1.43×10^{-07}. The a prior failure rate, λ_{DU},for flame detector is 5×10^{-07}. The estimate new test interval

$$\ddot{\tau} = \frac{\lambda_{DU}}{\ddot{\lambda}_{DU}} \times \tau = \frac{5 \times 10^{-07}}{4.35 \times 10^{-08}} \times 12 = 138 month \tag{E.1}$$

The operational failure rate is 0, and hence $\hat{\lambda}_{DU} < \lambda_{DU}$. The 90% upper limit confident interval is also less than λ_{DU}. That indicates that the doubling criteria is fulfilled. The new test interval is 24 months. The result is presented in Table E.1.

Table E.1: The test interval update based on the operational failure rate (all result)

Facility	**Model**	**Time (hours)**	**DU**	$\hat{\lambda}_{DU}(h^{-1})$	$\lambda_{DU}(h^{-1})$	$\ddot{\lambda}_{DU}(h^{-1})$	$\lambda_{DU} / \ddot{\lambda}_{DU}$	τ*	$\ddot{\tau}$*
Facility A	FD-IR3-M1-model A	20963808	0	0.00E+00	5.00E-07	4.35E-08	11.48	12	24
Facility B	FD-IR3-M1-model A	9513696	2	2.10E-07	5.00E-07	2.61E-07	1.92	12	18
Facility B	FD-UV-M1-model D	799824	3	3.75E-06	5.00E-07	1.43E-06	0.35	12	6
Facility C	FD-IR3-M1-model A	312840	0	0.00E+00	5.00E-07	4.32E-07	1.16	12	12
Facility C	FD-IR3-M2-model B	1680000	0	0.00E+00	5.00E-07	2.72E-07	1.84	12	18
Facility C	FD-IR3-M2-model C	4864416	0	0.00E+00	5.00E-07	1.46E-07	3.43	12	18
Facility D	FD-IR3-M1-model A	483840	2	4.13E-06	5.00E-07	1.21E-06	0.41	12	6
Facility D	FD-IR3-M3-model G	5529600	6	1.09E-06	5.00E-07	9.30E-07	0.54	12	9
Facility E	FD-IR3-M2-model C	1921920	0	0.00E+00	5.00E-07	2.55E-07	1.96	12	18
Facility F	FD-IR3-M1-model A	2848824	4	1.40E-06	5.00E-07	1.03E-06	0.48	12	6

Table E.1: The test interval update based on the operational failure rate (all result)

Facility	**Model**	**Time (hours)**	**DU**	$\hat{\lambda}_{DU}(h^{-1})$	$\lambda_{DU}(h^{-1})$	$\ddot{\lambda}_{D_U}(h^{-1})$	$\lambda_{DU}/\ddot{\lambda}_{D_U}$	$\tau*$	$\ddot{\tau}*$
Facility F	FD-IR3-M2-model B	201432	1	4.96E-06	5.00E-07	9.08E-07	0.55	12	9
Facility F	FD-IR3-M2-model C	6791136	9	1.33E-06	5.00E-07	1.14E-06	0.44	12	6
Facility G	FD-IR3-M1-model A	7302672	3	4.11E-07	5.00E-07	4.30E-07	1.16	12	12
Facility G	FD-IR3-M2-model B	2149368	1	4.65E-07	5.00E-07	4.82E-07	1.04	12	12
Facility H	FD-IR3-M1-model A	2422080	0	0.00E+00	5.00E-07	2.26E-07	2.21	12	18
Facility H	FD-IR-M1-model E	3132000	1	3.19E-07	5.00E-07	3.90E-07	1.28	12	12
Facility I	FD-IR3-M1-model A	8121600	1	1.23E-07	5.00E-07	1.98E-07	2.53	12	18
Facility J	FD-IR3-M1-model A	241920	0	0.00E+00	5.00E-07	4.46E-07	1.12	12	12
Facility J	FD-IR3-M3-model G	3386880	0	0.00E+00	5.00E-07	1.86E-07	2.69	12	18
Facility K	FD-IR3-M1-model A	4112640	2	4.86E-07	5.00E-07	4.91E-07	1.02	12	12
Facility K	FD-IR3-M4-model H	34560	0	0.00E+00	5.00E-07	4.92E-07	1.02	12	12
Facility K	FD-UI-M1-model F	230832	0	0.00E+00	5.00E-07	4.48E-07	1.12	12	12
Facility L	FD-IR3-M1-model A	1105920	2	1.81E-06	5.00E-07	9.66E-07	0.52	12	9
Facility A	HD-ROR-M5-model A	1094496	0	0.00E+00	5.00E-07	3.23E-07	1.55	12	18
Facility A	HD-FT-M6-model G	1052400	0	0.00E+00	5.00E-07	3.28E-07	1.53	12	18
Facility B	HD-ROR-M5-model A	336768	0	0.00E+00	5.00E-07	4.28E-07	1.17	12	12
Facility B	HD-FT-M6-model G	589344	1	1.70E-06	5.00E-07	7.72E-07	0.64	12	9
Facility C	HD-ROR-M5-model A	77568	0	0.00E+00	5.00E-07	4.81E-07	1.03	12	12
Facility C	HD-FT-M6-model E	193056	0	0.00E+00	5.00E-07	4.56E-07	1.09	12	12
Facility C	HD-FT-M6-model F	251568	0	0.00E+00	5.00E-07	4.44E-07	1.12	12	12
Facility D	HD-ROR-M5-model A	518400	2	3.86E-06	5.00E-07	1.19E-06	0.41	12	6
Facility D	HD-FT-M6-model F	1175040	1	8.51E-07	5.00E-07	6.30E-07	0.79	12	12
Facility E	HD-FT-M6-model F	205920	0	0.00E+00	5.00E-07	4.53E-07	1.10	12	12
Facility F	HD-ROR-M5-model A	345312	0	0.00E+00	5.00E-07	4.26E-07	1.17	12	12
Facility F	HD-FT-M6-model G	797232	0	0.00E+00	5.00E-07	3.57E-07	1.39	12	12
Facility G	HD-ROR-M5-model A	388440	0	0.00E+00	5.00E-07	4.19E-07	1.19	12	12
Facility G	HD-FT-M6-model G	1139424	0	0.00E+00	5.00E-07	3.19E-07	1.56	12	18
Facility G	HD-LN-M7-model I	258960	0	0.00E+00	5.00E-07	4.43E-07	1.12	12	12
Facility H	HD-ROR-M8-model B	28062720	7	2.49E-07	5.00E-07	2.66E-07	1.87	12	18
Facility I	HD-FT-M6-model F	1002240	0	0.00E+00	5.00E-07	3.33E-07	1.50	12	18
Facility I	HD-ROR-M8-model B	276480	0	0.00E+00	5.00E-07	4.39E-07	1.13	12	12
Facility J	HD-FT-M6-model D	32952	0	0.00E+00	5.00E-07	4.92E-07	1.01	12	12
Facility J	HD-ROR-M5-model A	381768	0	0.00E+00	5.00E-07	4.20E-07	1.19	12	12
Facility J	HD-FT-M6-model G	241920	0	0.00E+00	5.00E-07	4.46E-07	1.12	12	12
Facility J	HD-ROR-M3-model C	138240	0	0.00E+00	5.00E-07	4.68E-07	1.06	12	12
Facility K	HD-ROR-M8-model B	6186240	1	1.62E-07	5.00E-07	2.44E-07	2.04	12	18
Facility K	HD-FT-M9-model H	172800	0	0.00E+00	5.00E-07	4.60E-07	1.08	12	12
Facility L	HD-FT-M6-model F	103680	0	0.00E+00	5.00E-07	4.75E-07	1.05	12	12
Facility A	SD-OP-M6-model A	42626592	1	2.35E-08	5.00E-07	4.48E-08	11.15	12	24
Facility A	SD-OP-M3-model B	15154560	7	4.62E-07	5.00E-07	4.66E-07	1.07	12	12
Facility A	SD-SOP-M6-model D	1389168	0	0.00E+00	5.00E-07	2.95E-07	1.69	12	18
Facility A	SD-OP-M4-model C	3451872	0	0.00E+00	5.00E-07	1.83E-07	2.72	12	18
Facility A	SD-ION-M4-model E	42096	0	0.00E+00	5.00E-07	4.90E-07	1.021	12	12

Table E.1: The test interval update based on the operational failure rate (all result)

Facility	**Model**	**Time (hours)**	**DU**	$\hat{\lambda}_{DU}(h^{-1})$	$\lambda_{DU}(h^{-1})$	$\ddot{\lambda}_{DU}(h^{-1})$	λ_{DU} $/\ddot{\lambda}_{DU}$	$\tau*$	$\ddot{\tau}*$
Facility B	SD-OP-M6-model A	26730960	0	0.00E+00	5.00E-07	3.48E-08	14.36	12	24
Facility B	SD-ION-M4-model E	11323824	0	0.00E+00	5.00E-07	7.51E-08	6.66	12	24
Facility B	SD-ION-M6-model G	841920	0	0.00E+00	5.00E-07	3.52E-07	1.42	12	12
Facility C	SD-SOP-M6-model D	26666184	0	0.00E+00	5.00E-07	3.49E-08	14.33	12	24
Facility C	SD-OP-M4-model C	45432	0	0.00E+00	5.00E-07	4.89E-07	1.02	12	12
Facility C	SD-ION-M4-model F	116328	0	0.00E+00	5.00E-07	4.73E-07	1.05	12	12
Facility D	SD-SOP-M6-model D	17625600	5	2.84E-07	5.00E-07	3.06E-07	1.63	12	18
Facility D	SD-OT-M11-model I	138240	0	0.00E+00	5.00E-07	4.68E-07	1.06	12	12
Facility E	SD-SOP-M6-model D	5366112	0	0.00E+00	5.00E-07	1.36E-07	3.68	12	18
Facility F	SD-OP-M6-model A	23935944	10	4.18E-07	5.00E-07	4.24E-07	1.17	12	12
Facility F	SD-SOP-M6-model D	1899216	0	0.00E+00	5.00E-07	2.56E-07	1.94	12	18
Facility F	SD-IR-M10-model H	115104	0	0.00E+00	5.00E-07	4.73E-07	1.05	12	12
Facility F	SD-ION-M6-model G	57552	0	0.00E+00	5.00E-07	4.86E-07	1.02	12	12
Facility G	SD-OP-M6-model A	25844208	5	1.93E-07	5.00E-07	2.15E-07	2.32	12	24
Facility H	SD-OP-M6-model A	49541616	1	2.02E-08	5.00E-07	3.88E-08	12.88	12	24
Facility H	SD-OP-M3-model B	16871040	10	5.93E-07	5.00E-07	5.83E-07	0.85	12	12
Facility H	SD-OP-M4-model C	125280	0	0.00E+00	5.00E-07	4.71E-07	1.06	12	12
Facility I	SD-SOP-M6-model D	16519680	0	0.00E+00	5.00E-07	5.40E-08	9.25	12	24
Facility J	SD-OP-M6-model A	9192960	0	0.00E+00	5.00E-07	8.93E-08	5.59	12	24
Facility J	SD-OP-M3-model B	10298880	2	1.94E-07	5.00E-07	2.44E-07	2.04	12	18
Facility K	SD-OP-M6-model A	3421440	1	2.92E-07	5.00E-07	3.69E-07	1.35	12	12
Facility K	SD-SOP-M6-model D	15517440	1	6.44E-08	5.00E-07	1.14E-07	4.37	12	24
Facility K	SD-OP-M4-model C	5978880	7	1.17E-06	5.00E-07	1.00E-06	0.49	12	6
Facility L	SD-SOP-M6-model D	345600	0	0.00E+00	5.00E-07	4.26E-07	1.17	12	12
Facility A	GD-IR-M14-model A	18943200	3	1.58E-07	6.00E-07	1.94E-07	3.09	12	24
Facility B	GD-IR-M14-model A	11408016	3	2.63E-07	6.00E-07	3.06E-07	1.96	12	18
Facility C	GD-IR-M14-model A	6687624	7	1.05E-06	6.00E-07	9.58E-07	0.62	12	9
Facility D	GD-IR-M14-model A	8052480	0	0.00E+00	6.00E-07	1.03E-07	5.83	12	24
Facility D	GD-IR-M6-model C	138240	0	0.00E+00	6.00E-07	5.54E-07	1.08	12	12
Facility E	GD-IR-M14-model A	2105544	0	0.00E+00	6.00E-07	2.65E-07	2.26	12	18
Facility F	GD-IR-M14-model A	4230072	3	7.09E-07	6.00E-07	6.78E-07	0.88	12	12
Facility G	GD-IR-M14-model A	8882328	2	2.25E-07	6.00E-07	2.84E-07	2.10	12	18
Facility H	GD-IR-M14-model A	22592160	9	3.98E-07	6.00E-07	4.12E-07	1.45	12	12
Facility I	GD-IR-M14-model A	9918720	3	3.02E-07	6.00E-07	3.45E-07	1.73	12	18
Facility J	GD-IR-M14-model A	5210208	3	5.76E-07	6.00E-07	5.82E-07	1.031	12	12
Facility J	GD-IR-M14-model B	181152	0	0.00E+00	6.00E-07	5.41E-07	1.10	12	12
Facility K	GD-IR-M14-model A	3836160	3	7.82E-07	6.00E-07	7.27E-07	0.82	12	12
Facility K	GD-IR-M6-model C	207360	0	0.00E+00	6.00E-07	5.34E-07	1.12	12	12
Facility L	GD-IR-M14-model A	1382400	0	0.00E+00	6.00E-07	3.28E-07	1.82	12	18
Facility A	LOS-IR-M15-model A	2694144	0	0.00E+00	6.00E-07	2.29E-07	2.61	12	18
Facility A	LOS-IR-M16-model E	210480	0	0.00E+00	6.00E-07	5.33E-07	1.1	12	12
Facility B	LOS-IR-M15-model A	2062704	1	4.85E-07	6.00E-07	5.36E-07	1.11	12	12
Facility C	LOS-IR-M15-model A	2737272	0	0.00E+00	6.00E-07	2.27E-07	2.64	12	18

Table E.1: The test interval update based on the operational failure rate (all result)

Facility	Model	Time (hours)	DU	$\hat{\lambda}_{DU}(h^{-1})$	$\lambda_{DU}(h^{-1})$	$\ddot{\lambda}_{D_U}(h^{-1})$	$\lambda_{DU} / \ddot{\lambda}_{D_U}$	$\tau*$	$\ddot{\tau}*$
Facility D	LOS-IR-M15-model A	1762560	1	5.67E-07	6.00E-07	5.83E-07	1.02	12	12
Facility E	LOS-IR-M16-model B	1094832	0	0.00E+00	6.00E-07	3.62E-07	1.65	12	18
Facility F	LOS-IR-M15-model A	6273168	20	3.19E-06	6.00E-07	2.64E-06	0.22	12	6
Facility F	LOS-IR-M16-model E	517968	1	1.93E-06	6.00E-07	9.15E-07	0.65	12	9
Facility G	LOS-IR-M15-model A	4221048	0	0.00E+00	6.00E-07	1.70E-07	3.53	12	18
Facility H	LOS-IR-M15-model A	4510080	0	0.00E+00	6.00E-07	1.62E-07	3.70	12	18
Facility I	LOS-IR-M15-model A	1624320	0	0.00E+00	6.00E-07	3.04E-07	1.97	12	18
Facility I	LOS-IR-M15-model A	69120	0	0.00E+00	6.00E-07	5.76E-07	1.04	12	12
Facility I	LOS-IR-M6-model D	108672	0	0.00E+00	6.00E-07	5.63E-07	1.06	12	12
Facility I	LOS-IR-M6-model C	444288	0	0.00E+00	6.00E-07	4.74E-07	1.26	12	12
Facility J	LOS-IR-M15-model A	1175040	0	0.00E+00	6.00E-07	3.52E-07	1.70	12	18
Facility K	LOS-IR-M15-model A	380160	7	1.84E-05	6.00E-07	3.91E-06	0.15	12	6
Facility K	LOS-IR-M16-model B	725760	7	9.65E-06	6.00E-07	3.34E-06	0.17	12	6
Facility L	LOS-IR-M15-model A	69120	0	0.00E+00	6.00E-07	5.76E-07	1.04	12	12
Facility L	LOS-IR-M16-model E	552960	0	0.00E+00	6.00E-07	4.51E-07	1.33	12	12
Facility A	CD-HC-M15-model A	9976752	11	1.10E-06	1.80E-06	1.14E-06	1.57	6	9
Facility B	CD-H2-M16-model E	252576	0	0.00E+00	1.80E-06	1.24E-06	1.45	6	6
Facility C	CD-HC-M15-model B	797040	4	5.02E-06	1.80E-06	3.70E-06	0.48	6	3
Facility C	CD-HC-M15-model C	132048	0	0.00E+00	1.80E-06	1.45E-06	1.23	6	6
Facility D	CD-HC-M15-model B	241920	0	0.00E+00	1.80E-06	1.25E-06	1.43	6	6
Facility E	CD-H2-M16-model F	136464	0	0.00E+00	1.80E-06	1.45E-06	1.24	6	6
Facility F	CD-H2-M16-model G	172656	3	1.74E-05	1.80E-06	5.49E-06	0.32	6	3
Facility G	CD-H2-M16-model G	129480	0	0.00E+00	1.80E-06	1.46E-06	1.23	6	6
Facility H	CD-H2-M16-model G	375840	2	5.32E-06	1.80E-06	3.22E-06	0.55	6	6
Facility K	CD-HC-M15-model A	6082560	35	5.75E-06	1.80E-06	5.42E-06	0.33	6	3
Facility K	CD-HC-M15-model D	207360	6	2.89E-05	1.80E-06	9.18E-06	0.19	6	3
Facility L	CD-H2-M16-model E	34560	0	0.00E+00	1.80E-06	1.69E-06	1.06	6	6

E.2 Modification A Priory Failure Rate λ_{DU}

Table E.2: The comparison of calculated test interval based on the different λ_{DU}

Facility	Model	Time (hour)	DU	$\tau_{init}*$	PDS		Required SIL	
					$\lambda_{DU-PDS}(h^{-1})$	$\ddot{\tau}*$	$\lambda_{DU-SIL}(h^{-1})$	$\ddot{\tau}*$
Facility A	FD-IR3-M1-model A	20963808	0	12	5.00E-07	24	1.14E-05	24
Facility B	FD-IR3-M1-model A	9513696	2	12	5.00E-07	18	1.14E-05	18
Facility B	FD-UV-M1-model D	799824	3	12	5.00E-07	6	1.14E-05	9
Facility C	FD-IR3-M1-model A	312840	0	12	5.00E-07	12	1.14E-05	18
Facility C	FD-IR3-M2-model B	1680000	0	12	5.00E-07	18	1.14E-05	18
Facility C	FD-IR3-M2-model C	4864416	0	12	5.00E-07	18	1.14E-05	24

Table E.2: The comparison of calculated test interval based on the different λ_{DU}

Facility	**Model**	**Time (hour)**	**DU**	τ_{init}^*	**PDS**		**Required SIL**	
					$\lambda_{DU-PDS}(h^{-1})$	$\ddot{\tau}^*$	$\lambda_{DU-SIL}(h^{-1})$	$\ddot{\tau}^*$
Facility D	FD-IR3-M1-model A	483840	2	12	5.00E-07	6	1.14E-05	12
Facility D	FD-IR3-M3-model G	5529600	6	12	5.00E-07	9	1.14E-05	12
Facility E	FD-IR3-M2-model C	1921920	0	12	5.00E-07	18	1.14E-05	18
Facility F	FD-IR3-M1-model A	2848824	4	12	5.00E-07	6	1.14E-05	12
Facility F	FD-IR3-M2-model B	201432	1	12	5.00E-07	9	1.14E-05	12
Facility F	FD-IR3-M2-model C	6791136	9	12	5.00E-07	6	1.14E-05	12
Facility G	FD-IR3-M1-model A	7302672	3	12	5.00E-07	12	1.14E-05	18
Facility G	FD-IR3-M2-model B	2149368	1	12	5.00E-07	12	1.14E-05	18
Facility H	FD-IR3-M1-model A	2422080	0	12	5.00E-07	18	1.14E-05	18
Facility H	FD-IR-M1-model E	3132000	1	12	5.00E-07	12	1.14E-05	18
Facility I	FD-IR3-M1-model A	8121600	1	12	5.00E-07	18	1.14E-05	18
Facility J	FD-IR3-M1-model A	241920	0	12	5.00E-07	12	1.14E-05	18
Facility J	FD-IR3-M3-model G	3386880	0	12	5.00E-07	18	1.14E-05	18
Facility K	FD-IR3-M1-model A	4112640	2	12	5.00E-07	12	1.14E-05	18
Facility K	FD-IR3-M4-model H	34560	0	12	5.00E-07	12	1.14E-05	18
Facility K	FD-UI-M1-model F	230832	0	12	5.00E-07	12	1.14E-05	18
Facility L	FD-IR3-M1-model A	1105920	2	12	5.00E-07	9	1.14E-05	12
Facility A	HD-ROR-M5-model A	1094496	0	12	5.00E-07	18	1.14E-05	18
Facility A	HD-FT-M6-model G	1052400	0	12	5.00E-07	18	1.14E-05	18
Facility B	HD-ROR-M5-model A	336768	0	12	5.00E-07	12	1.14E-05	18
Facility B	HD-FT-M6-model G	589344	1	12	5.00E-07	9	1.14E-05	12
Facility C	HD-ROR-M5-model A	77568	0	12	5.00E-07	12	1.14E-05	18
Facility C	HD-FT-M6-model E	193056	0	12	5.00E-07	12	1.14E-05	18
Facility C	HD-FT-M6-model F	251568	0	12	5.00E-07	12	1.14E-05	18
Facility D	HD-ROR-M5-model A	518400	2	12	5.00E-07	6	1.14E-05	12
Facility D	HD-FT-M6-model F	1175040	1	12	5.00E-07	12	1.14E-05	18
Facility E	HD-FT-M6-model F	205920	0	12	5.00E-07	12	1.14E-05	18
Facility F	HD-ROR-M5-model A	345312	0	12	5.00E-07	12	1.14E-05	18
Facility F	HD-FT-M6-model G	797232	0	12	5.00E-07	12	1.14E-05	18
Facility G	HD-ROR-M5-model A	388440	0	12	5.00E-07	12	1.14E-05	18
Facility G	HD-FT-M6-model G	1139424	0	12	5.00E-07	18	1.14E-05	18
Facility G	HD-LN-M7-model I	258960	0	12	5.00E-07	12	1.14E-05	18
Facility H	HD-ROR-M8-model B	28062720	7	12	5.00E-07	18	1.14E-05	24
Facility I	HD-FT-M6-model F	1002240	0	12	5.00E-07	18	1.14E-05	18
Facility I	HD-ROR-M8-model B	276480	0	12	5.00E-07	12	1.14E-05	18
Facility J	HD-FT-M6-model D	32952	0	12	5.00E-07	12	1.14E-05	18
Facility J	HD-ROR-M5-model A	381768	0	12	5.00E-07	12	1.14E-05	18
Facility J	HD-FT-M6-model G	241920	0	12	5.00E-07	12	1.14E-05	18
Facility J	HD-ROR-M3-model C	138240	0	12	5.00E-07	12	1.14E-05	18
Facility K	HD-ROR-M8-model B	6186240	1	12	5.00E-07	18	1.14E-05	18
Facility K	HD-FT-M9-model H	172800	0	12	5.00E-07	12	1.14E-05	18
Facility L	HD-FT-M6-model F	103680	0	12	5.00E-07	12	1.14E-05	18
Facility A	SD-OP-M6-model A	42626592	1	12	5.00E-07	24	1.14E-05	24

Table E.2: The comparison of calculated test interval based on the different λ_{DU}

Facility	**Model**	**Time (hour)**	**DU**	τ_{init}*	**PDS**		**Required SIL**	
					$\lambda_{DU-PDS}(h^{-1})$	$\ddot{\tau}$*	$\lambda_{DU-SIL}(h^{-1})$	$\ddot{\tau}$*
Facility A	SD-OP-M3-model B	15154560	7	12	5.00E-07	12	1.14E-05	18
Facility A	SD-SOP-M6-model D	1389168	0	12	5.00E-07	18	1.14E-05	18
Facility A	SD-OP-M4-model C	3451872	0	12	5.00E-07	18	1.14E-05	18
Facility A	SD-ION-M4-model E	42096	0	12	5.00E-07	12	1.14E-05	18
Facility B	SD-OP-M6-model A	26730960	0	12	5.00E-07	24	1.14E-05	24
Facility B	SD-ION-M4-model E	11323824	0	12	5.00E-07	24	1.14E-05	24
Facility B	SD-ION-M6-model G	841920	0	12	5.00E-07	12	1.14E-05	18
Facility C	SD-SOP-M6-model D	26666184	0	12	5.00E-07	24	1.14E-05	24
Facility C	SD-OP-M4-model C	45432	0	12	5.00E-07	12	1.14E-05	18
Facility C	SD-ION-M4-model F	116328	0	12	5.00E-07	12	1.14E-05	18
Facility D	SD-SOP-M6-model D	17625600	5	12	5.00E-07	18	1.14E-05	18
Facility D	SD-OT-M11-model I	138240	0	12	5.00E-07	12	1.14E-05	18
Facility E	SD-SOP-M6-model D	5366112	0	12	5.00E-07	18	1.14E-05	24
Facility F	SD-OP-M6-model A	23935944	10	12	5.00E-07	12	1.14E-05	18
Facility F	SD-SOP-M6-model D	1899216	0	12	5.00E-07	18	1.14E-05	18
Facility F	SD-IR-M10-model H	115104	0	12	5.00E-07	12	1.14E-05	18
Facility F	SD-ION-M6-model G	57552	0	12	5.00E-07	12	1.14E-05	18
Facility G	SD-OP-M6-model A	25844208	5	12	5.00E-07	24	1.14E-05	24
Facility H	SD-OP-M6-model A	49541616	1	12	5.00E-07	24	1.14E-05	24
Facility H	SD-OP-M3-model B	16871040	10	12	5.00E-07	12	1.14E-05	18
Facility H	SD-OP-M4-model C	125280	0	12	5.00E-07	12	1.14E-05	18
Facility I	SD-SOP-M6-model D	16519680	0	12	5.00E-07	24	1.14E-05	24
Facility J	SD-OP-M6-model A	9192960	0	12	5.00E-07	24	1.14E-05	24
Facility J	SD-OP-M3-model B	10298880	2	12	5.00E-07	18	1.14E-05	18
Facility K	SD-OP-M6-model A	3421440	1	12	5.00E-07	12	1.14E-05	18
Facility K	SD-SOP-M6-model D	15517440	1	12	5.00E-07	24	1.14E-05	24
Facility K	SD-OP-M4-model C	5978880	7	12	5.00E-07	6	1.14E-05	12
Facility L	SD-SOP-M6-model D	345600	0	12	5.00E-07	12	1.14E-05	18
Facility A	GD-IR-M14-model A	18943200	3	12	6.00E-07	24	1.14E-05	24
Facility B	GD-IR-M14-model A	11408016	3	12	6.00E-07	18	1.14E-05	18
Facility C	GD-IR-M14-model A	6687624	7	12	6.00E-07	9	1.14E-05	12
Facility D	GD-IR-M14-model A	8052480	0	12	6.00E-07	24	1.14E-05	24
Facility D	GD-IR-M6-model C	138240	0	12	6.00E-07	12	1.14E-05	18
Facility E	GD-IR-M14-model A	2105544	0	12	6.00E-07	18	1.14E-05	18
Facility F	GD-IR-M14-model A	4230072	3	12	6.00E-07	12	1.14E-05	12
Facility G	GD-IR-M14-model A	8882328	2	12	6.00E-07	18	1.14E-05	18
Facility H	GD-IR-M14-model A	22592160	9	12	6.00E-07	12	1.14E-05	18
Facility I	GD-IR-M14-model A	9918720	3	12	6.00E-07	18	1.14E-05	18
Facility J	GD-IR-M14-model A	5210208	3	12	6.00E-07	12	1.14E-05	18
Facility J	GD-IR-M14-model B	181152	0	12	6.00E-07	12	1.14E-05	18
Facility K	GD-IR-M14-model A	3836160	3	12	6.00E-07	12	1.14E-05	12
Facility K	GD-IR-M6-model C	207360	0	12	6.00E-07	12	1.14E-05	18
Facility L	GD-IR-M14-model A	1382400	0	12	6.00E-07	18	1.14E-05	18

Table E.2: The comparison of calculated test interval based on the different λ_{DU}

Facility	**Model**	**Time (hour)**	**DU**	$\tau_{init}*$	**PDS**		**Required SIL**	
					$\lambda_{DU-PDS}(h^{-1})$	$\ddot{\tau}*$	$\lambda_{DU-SIL}(h^{-1})$	$\ddot{\tau}*$
Facility A	LOS-IR-M15-model A	2694144	0	12	6.00E-07	18	1.14E-05	18
Facility A	LOS-IR-M16-model E	210480	0	12	6.00E-07	12	1.14E-05	18
Facility B	LOS-IR-M15-model A	2062704	1	12	6.00E-07	12	1.14E-05	18
Facility C	LOS-IR-M15-model A	2737272	0	12	6.00E-07	18	1.14E-05	18
Facility D	LOS-IR-M15-model A	1762560	1	12	6.00E-07	12	1.14E-05	18
Facility E	LOS-IR-M16-model B	1094832	0	12	6.00E-07	18	1.14E-05	18
Facility F	LOS-IR-M15-model A	6273168	20	12	6.00E-07	6	1.14E-05	6
Facility F	LOS-IR-M16-model E	517968	1	12	6.00E-07	9	1.14E-05	12
Facility G	LOS-IR-M15-model A	4221048	0	12	6.00E-07	18	1.14E-05	24
Facility H	LOS-IR-M15-model A	4510080	0	12	6.00E-07	18	1.14E-05	24
Facility I	LOS-IR-M15-model A	1624320	0	12	6.00E-07	18	1.14E-05	18
Facility I	LOS-IR-M15-model A	69120	0	12	6.00E-07	12	1.14E-05	18
Facility I	LOS-IR-M6-model D	108672	0	12	6.00E-07	12	1.14E-05	18
Facility I	LOS-IR-M6-model C	444288	0	12	6.00E-07	12	1.14E-05	18
Facility J	LOS-IR-M15-model A	1175040	0	12	6.00E-07	18	1.14E-05	18
Facility K	LOS-IR-M15-model A	380160	7	12	6.00E-07	6	1.14E-05	6
Facility K	LOS-IR-M16-model B	725760	7	12	6.00E-07	6	1.14E-05	6
Facility L	LOS-IR-M15-model A	69120	0	12	6.00E-07	12	1.14E-05	18
Facility L	LOS-IR-M16-model E	552960	0	12	6.00E-07	12	1.14E-05	18
Facility A	CD-HC-M15-model A	9976752	11	6	1.80E-06	9	2.28E-05	12
Facility B	CD-H2-M16-model E	252576	0	6	1.80E-06	6	2.28E-05	9
Facility C	CD-HC-M15-model B	797040	4	6	1.80E-06	3	2.28E-05	6
Facility C	CD-HC-M15-model C	132048	0	6	1.80E-06	6	2.28E-05	9
Facility D	CD-HC-M15-model B	241920	0	6	1.80E-06	6	2.28E-05	9
Facility E	CD-H2-M16-model F	136464	0	6	1.80E-06	6	2.28E-05	9
Facility F	CD-H2-M16-model G	172656	3	6	1.80E-06	3	2.28E-05	6
Facility G	CD-H2-M16-model G	129480	0	6	1.80E-06	6	2.28E-05	9
Facility H	CD-H2-M16-model G	375840	2	6	1.80E-06	6	2.28E-05	6
Facility K	CD-HC-M15-model A	6082560	35	6	1.80E-06	3	2.28E-05	6
Facility K	CD-HC-M15-model D	207360	6	6	1.80E-06	3	2.28E-05	3
Facility L	CD-H2-M16-model E	34560	0	6	1.80E-06	6	2.28E-05	9

E.3 Modification $\ddot{\lambda}_{DU}$ into $\hat{\lambda}_{DU}$ in ratio $\lambda_{DU}/\ddot{\lambda}_{DU}$

Table E.3: The comparison of calculated test interval by changes $\ddot{\lambda}_{DU}$ into $\hat{\lambda}_{DU}$

Facility	**Model**	**Time (hours)**	**DU**	$\tau_{init}*$	**Bayesian**		**Operational**	
					$\ddot{\lambda}_{DU}$	$\ddot{\tau}*$	$\hat{\lambda}_{DU}$	$\ddot{\tau}*$
Facility A	FD-IR3-M1-model A	20963808	0	12	4.35E-08	24	0.00E+00	24
Facility B	FD-IR3-M1-model A	9513696	2	12	2.61E-07	18	2.10E-07	18
Facility B	FD-UV-M1-model D	799824	3	12	1.43E-06	6	3.75E-06	6

Table E.3: The comparison of calculated test interval by changes $\ddot{\lambda}_{DU}$ into $\hat{\lambda}_{DU}$

Facility	**Model**	**Time (hours)**	**DU**	τ_{init}*	**Bayesian**		**Operational**	
					$\ddot{\lambda}_{DU}$	$\ddot{\tau}$*	$\hat{\lambda}_{DU}$	$\ddot{\tau}$*
Facility C	FD-IR3-M1-model A	312840	0	12	4.32E-07	12	0.00E+00	12
Facility C	FD-IR3-M2-model B	1680000	0	12	2.72E-07	18	0.00E+00	18
Facility C	FD-IR3-M2-model C	4864416	0	12	1.46E-07	18	0.00E+00	24
Facility D	FD-IR3-M1-model A	483840	2	12	1.21E-06	6	4.13E-06	6
Facility D	FD-IR3-M3-model G	5529600	6	12	9.30E-07	9	1.09E-06	9
Facility E	FD-IR3-M2-model C	1921920	0	12	2.55E-07	18	0.00E+00	18
Facility F	FD-IR3-M1-model A	2848824	4	12	1.03E-06	6	1.40E-06	9
Facility F	FD-IR3-M2-model B	201432	1	12	9.08E-07	9	4.96E-06	9
Facility F	FD-IR3-M2-model C	6791136	9	12	1.14E-06	6	1.33E-06	6
Facility G	FD-IR3-M1-model A	7302672	3	12	4.30E-07	12	4.11E-07	12
Facility G	FD-IR3-M2-model B	2149368	1	12	4.82E-07	12	4.65E-07	12
Facility H	FD-IR3-M1-model A	2422080	0	12	2.26E-07	18	0.00E+00	18
Facility H	FD-IR-M1-model E	3132000	1	12	3.90E-07	12	3.19E-07	12
Facility I	FD-IR3-M1-model A	8121600	1	12	1.98E-07	18	1.23E-07	18
Facility J	FD-IR3-M1-model A	241920	0	12	4.46E-07	12	0.00E+00	12
Facility J	FD-IR3-M3-model G	3386880	0	12	1.86E-07	18	0.00E+00	18
Facility K	FD-IR3-M1-model A	4112640	2	12	4.91E-07	12	4.86E-07	12
Facility K	FD-IR3-M4-model H	34560	0	12	4.92E-07	12	0.00E+00	12
Facility K	FD-UI-M1-model F	230832	0	12	4.48E-07	12	0.00E+00	12
Facility L	FD-IR3-M1-model A	1105920	2	12	9.66E-07	9	1.81E-06	9
Facility A	HD-ROR-M5-model A	1094496	0	12	3.23E-07	18	0.00E+00	18
Facility A	HD-FT-M6-model G	1052400	0	12	3.28E-07	18	0.00E+00	18
Facility B	HD-ROR-M5-model A	336768	0	12	4.28E-07	12	0.00E+00	12
Facility B	HD-FT-M6-model G	589344	1	12	7.72E-07	9	1.70E-06	9
Facility C	HD-ROR-M5-model A	77568	0	12	4.81E-07	12	0.00E+00	12
Facility C	HD-FT-M6-model E	193056	0	12	4.56E-07	12	0.00E+00	12
Facility C	HD-FT-M6-model F	251568	0	12	4.44E-07	12	0.00E+00	12
Facility D	HD-ROR-M5-model A	518400	2	12	1.19E-06	6	3.86E-06	6
Facility D	HD-FT-M6-model F	1175040	1	12	6.30E-07	12	8.51E-07	12
Facility E	HD-FT-M6-model F	205920	0	12	4.53E-07	12	0.00E+00	12
Facility F	HD-ROR-M5-model A	345312	0	12	4.26E-07	12	0.00E+00	12
Facility F	HD-FT-M6-model G	797232	0	12	3.57E-07	12	0.00E+00	12
Facility G	HD-ROR-M5-model A	388440	0	12	4.19E-07	12	0.00E+00	12
Facility G	HD-FT-M6-model G	1139424	0	12	3.19E-07	18	0.00E+00	18
Facility G	HD-LN-M7-model I	258960	0	12	4.43E-07	12	0.00E+00	12
Facility H	HD-ROR-M8-model B	28062720	7	12	2.66E-07	18	2.49E-07	24
Facility I	HD-FT-M6-model F	1002240	0	12	3.33E-07	18	0.00E+00	18
Facility I	HD-ROR-M8-model B	276480	0	12	4.39E-07	12	0.00E+00	12
Facility J	HD-FT-M6-model D	32952	0	12	4.92E-07	12	0.00E+00	12
Facility J	HD-ROR-M5-model A	381768	0	12	4.20E-07	12	0.00E+00	12
Facility J	HD-FT-M6-model G	241920	0	12	4.46E-07	12	0.00E+00	12
Facility J	HD-ROR-M3-model C	138240	0	12	4.68E-07	12	0.00E+00	12
Facility K	HD-ROR-M8-model B	6186240	1	12	2.44E-07	18	1.62E-07	18

Table E.3: The comparison of calculated test interval by changes $\ddot{\lambda}_{DU}$ into $\hat{\lambda}_{DU}$

Facility	**Model**	**Time (hours)**	**DU**	τ_{init}*	**Bayesian**		**Operational**	
					$\ddot{\lambda}_{DU}$	$\ddot{\tau}$*	$\hat{\lambda}_{DU}$	$\ddot{\tau}$*
Facility K	HD-FT-M9-model H	172800	0	12	4.60E-07	12	0.00E+00	12
Facility L	HD-FT-M6-model F	103680	0	12	4.75E-07	12	0.00E+00	12
Facility A	SD-OP-M6-model A	42626592	1	12	4.48E-08	24	2.35E-08	24
Facility A	SD-OP-M3-model B	15154560	7	12	4.66E-07	12	4.62E-07	12
Facility A	SD-SOP-M6-model D	1389168	0	12	2.95E-07	18	0.00E+00	18
Facility A	SD-OP-M4-model C	3451872	0	12	1.83E-07	18	0.00E+00	18
Facility A	SD-ION-M4-model E	42096	0	12	4.90E-07	12	0.00E+00	12
Facility B	SD-OP-M6-model A	26730960	0	12	3.48E-08	24	0.00E+00	24
Facility B	SD-ION-M4-model E	11323824	0	12	7.51E-08	24	0.00E+00	24
Facility B	SD-ION-M6-model G	841920	0	12	3.52E-07	12	0.00E+00	12
Facility C	SD-SOP-M6-model D	26666184	0	12	3.49E-08	24	0.00E+00	24
Facility C	SD-OP-M4-model C	45432	0	12	4.89E-07	12	0.00E+00	12
Facility C	SD-ION-M4-model F	116328	0	12	4.73E-07	12	0.00E+00	12
Facility D	SD-SOP-M6-model D	17625600	5	12	3.06E-07	18	2.84E-07	18
Facility D	SD-OT-M11-model I	138240	0	12	4.68E-07	12	0.00E+00	12
Facility E	SD-SOP-M6-model D	5366112	0	12	1.36E-07	18	0.00E+00	24
Facility F	SD-OP-M6-model A	23935944	10	12	4.24E-07	12	4.18E-07	12
Facility F	SD-SOP-M6-model D	1899216	0	12	2.56E-07	18	0.00E+00	18
Facility F	SD-IR-M10-model H	115104	0	12	4.73E-07	12	0.00E+00	12
Facility F	SD-ION-M6-model G	57552	0	12	4.86E-07	12	0.00E+00	12
Facility G	SD-OP-M6-model A	25844208	5	12	2.15E-07	24	1.93E-07	24
Facility H	SD-OP-M6-model A	49541616	1	12	3.88E-08	24	2.02E-08	24
Facility H	SD-OP-M3-model B	16871040	10	12	5.83E-07	12	5.93E-07	12
Facility H	SD-OP-M4-model C	125280	0	12	4.71E-07	12	0.00E+00	12
Facility I	SD-SOP-M6-model D	16519680	0	12	5.40E-08	24	0.00E+00	24
Facility J	SD-OP-M6-model A	9192960	0	12	8.93E-08	24	0.00E+00	24
Facility J	SD-OP-M3-model B	10298880	2	12	2.44E-07	18	1.94E-07	18
Facility K	SD-OP-M6-model A	3421440	1	12	3.69E-07	12	2.92E-07	12
Facility K	SD-SOP-M6-model D	15517440	1	12	1.14E-07	24	6.44E-08	24
Facility K	SD-OP-M4-model C	5978880	7	12	1.00E-06	6	1.17E-06	6
Facility L	SD-SOP-M6-model D	345600	0	12	4.26E-07	12	0.00E+00	12
Facility A	GD-IR-M14-model A	18943200	3	12	1.94E-07	24	1.58E-07	24
Facility B	GD-IR-M14-model A	11408016	3	12	3.06E-07	18	2.63E-07	18
Facility C	GD-IR-M14-model A	6687624	7	12	9.58E-07	9	1.05E-06	9
Facility D	GD-IR-M14-model A	8052480	0	12	1.03E-07	24	0.00E+00	24
Facility D	GD-IR-M6-model C	138240	0	12	5.54E-07	12	0.00E+00	12
Facility E	GD-IR-M14-model A	2105544	0	12	2.65E-07	18	0.00E+00	18
Facility F	GD-IR-M14-model A	4230072	3	12	6.78E-07	12	7.09E-07	12
Facility G	GD-IR-M14-model A	8882328	2	12	2.84E-07	18	2.25E-07	18
Facility H	GD-IR-M14-model A	22592160	9	12	4.12E-07	12	3.98E-07	18
Facility I	GD-IR-M14-model A	9918720	3	12	3.45E-07	18	3.02E-07	18
Facility J	GD-IR-M14-model A	5210208	3	12	5.82E-07	12	5.76E-07	12
Facility J	GD-IR-M14-model B	181152	0	12	5.41E-07	12	0.00E+00	12

Table E.3: The comparison of calculated test interval by changes $\ddot{\lambda}_{DU}$ into $\hat{\lambda}_{DU}$

Facility	**Model**	**Time (hours)**	**DU**	τ_{init}*	**Bayesian**		**Operational**	
					$\ddot{\lambda}_{DU}$	$\ddot{\tau}$*	$\hat{\lambda}_{DU}$	$\ddot{\tau}$*
Facility K	GD-IR-M14-model A	3836160	3	12	7.27E-07	12	7.82E-07	12
Facility K	GD-IR-M6-model C	207360	0	12	5.34E-07	12	0.00E+00	12
Facility L	GD-IR-M14-model A	1382400	0	12	3.28E-07	18	0.00E+00	18
Facility A	LOS-IR-M15-model A	2694144	0	12	2.29E-07	18	0.00E+00	18
Facility A	LOS-IR-M16-model E	210480	0	12	5.33E-07	12	0.00E+00	12
Facility B	LOS-IR-M15-model A	2062704	1	12	5.36E-07	12	4.85E-07	12
Facility C	LOS-IR-M15-model A	2737272	0	12	2.27E-07	18	0.00E+00	18
Facility D	LOS-IR-M15-model A	1762560	1	12	5.83E-07	12	5.67E-07	12
Facility E	LOS-IR-M16-model B	1094832	0	12	3.62E-07	18	0.00E+00	18
Facility F	LOS-IR-M15-model A	6273168	20	12	2.64E-06	6	3.19E-06	6
Facility F	LOS-IR-M16-model E	517968	1	12	9.15E-07	9	1.93E-06	9
Facility G	LOS-IR-M15-model A	4221048	0	12	1.70E-07	18	0.00E+00	24
Facility H	LOS-IR-M15-model A	4510080	0	12	1.62E-07	18	0.00E+00	24
Facility I	LOS-IR-M15-model A	1624320	0	12	3.04E-07	18	0.00E+00	18
Facility I	LOS-IR-M15-model A	69120	0	12	5.76E-07	12	0.00E+00	12
Facility I	LOS-IR-M6-model D	108672	0	12	5.63E-07	12	0.00E+00	12
Facility I	LOS-IR-M6-model C	444288	0	12	4.74E-07	12	0.00E+00	12
Facility J	LOS-IR-M15-model A	1175040	0	12	3.52E-07	18	0.00E+00	18
Facility K	LOS-IR-M15-model A	380160	7	12	3.91E-06	6	1.84E-05	6
Facility K	LOS-IR-M16-model B	725760	7	12	3.34E-06	6	9.65E-06	6
Facility L	LOS-IR-M15-model A	69120	0	12	5.76E-07	12	0.00E+00	12
Facility L	LOS-IR-M16-model E	552960	0	12	4.51E-07	12	0.00E+00	12
Facility A	CD-HC-M15-model A	9976752	11	6	1.14E-06	9	1.10E-06	9
Facility B	CD-H2-M16-model E	252576	0	6	1.24E-06	6	0.00E+00	6
Facility C	CD-HC-M15-model B	797040	4	6	3.70E-06	3	5.02E-06	6
Facility C	CD-HC-M15-model C	132048	0	6	1.45E-06	6	0.00E+00	6
Facility D	CD-HC-M15-model B	241920	0	6	1.25E-06	6	0.00E+00	6
Facility E	CD-H2-M16-model F	136464	0	6	1.45E-06	6	0.00E+00	6
Facility F	CD-H2-M16-model G	172656	3	6	5.49E-06	3	1.74E-05	3
Facility G	CD-H2-M16-model G	129480	0	6	1.46E-06	6	0.00E+00	6
Facility H	CD-H2-M16-model G	375840	2	6	3.22E-06	6	5.32E-06	6
Facility K	CD-HC-M15-model A	6082560	35	6	5.42E-06	3	5.75E-06	3
Facility K	CD-HC-M15-model D	207360	6	6	9.18E-06	3	2.89E-05	3
Facility L	CD-H2-M16-model E	34560	0	6	1.69E-06	6	0.00E+00	6

E.4 Confident Interval Changes into Credibility Interval

Table E.4: The comparison of calculated test interval based on confident interval and credibility interval

Facility	Model	Time-hour	DU	$\tau_{init}*$	Confident interval			Credibility interval		
					90% CI low (h^{-1})	90% CI up (h^{-1})	$\ddot{\tau}*$	90% CI low (h^{-1})	90% CI up (h^{-1})	$\ddot{\tau}*$
Facility A	FD-IR3-M1-model A	20963808	0	12	0.00E+00	1.10E-07	24	0.00E+00	2.20E-07	24
Facility B	FD-IR3-M1-model A	9513696	2	12	5.59E-08	5.59E-07	18	4.71E-08	7.59E-07	18
Facility B	FD-UV-M1-model D	799824	3	12	1.38E-06	8.35E-06	6	1.21E-06	1.10E-05	6
Facility C	FD-IR3-M1-model A	312840	0	12	0.00E+00	7.36E-06	12	0.00E+00	1.47E-05	12
Facility C	FD-IR3-M2-model B	1680000	0	12	0.00E+00	1.37E-06	18	0.00E+00	2.74E-06	18
Facility C	FD-IR3-M2-model C	4864416	0	12	0.00E+00	4.73E-07	24	0.00E+00	9.47E-07	18
Facility D	FD-IR3-M1-model A	483840	2	12	1.10E-06	1.10E-05	6	9.27E-07	1.49E-05	6
Facility D	FD-IR3-M3-model G	5529600	6	12	5.70E-07	1.90E-06	9	5.26E-07	2.36E-06	9
Facility E	FD-IR3-M2-model C	1921920	0	12	0.00E+00	1.20E-06	18	0.00E+00	2.40E-06	18
Facility F	FD-IR3-M1-model A	2848824	4	12	6.12E-07	2.81E-06	9	5.52E-07	3.60E-06	6
Facility F	FD-IR3-M2-model B	201432	1	12	5.23E-07	1.93E-05	9	3.87E-07	2.77E-05	9
Facility F	FD-IR3-M2-model C	6791136	9	12	8.00E-07	2.09E-06	6	7.51E-07	2.52E-06	6
Facility G	FD-IR3-M1-model A	7302672	3	12	1.51E-07	9.15E-07	12	1.33E-07	1.20E-06	12
Facility G	FD-IR3-M2-model B	2149368	1	12	4.90E-08	1.81E-06	12	3.63E-08	2.59E-06	12
Facility H	FD-IR3-M1-model A	2422080	0	12	0.00E+00	9.51E-07	18	0.00E+00	1.90E-06	18
Facility H	FD-IR-M1-model E	3132000	1	12	3.36E-08	1.24E-06	12	2.49E-08	1.78E-06	12
Facility I	FD-IR3-M1-model A	8121600	1	12	1.30E-08	4.79E-07	18	9.60E-09	6.86E-07	18
Facility J	FD-IR3-M1-model A	241920	0	12	0.00E+00	9.52E-06	12	0.00E+00	1.90E-05	12
Facility J	FD-IR3-M3-model G	3386880	0	12	0.00E+00	6.80E-07	18	0.00E+00	1.36E-06	18
Facility K	FD-IR3-M1-model A	4112640	2	12	1.29E-07	1.29E-06	12	1.09E-07	1.76E-06	12

Table E.4: The comparison of calculated test interval based on confident interval and credibility interval

Facility	Model	Time-hour	DU	$\tau_{init}*$	Confident interval			Credibility interval		
					90% CI low (h^{-1})	90% CI up (h^{-1})	$\ddot{\tau}*$	90% CI low (h^{-1})	90% CI up (h^{-1})	$\ddot{\tau}*$
Facility K	FD-IR3-M4-model H	34560	0	12	0.00E+00	6.66E-05	12	0.00E+00	1.33E-04	12
Facility K	FD-UI-M1-model F	230832	0	12	0.00E+00	9.98E-06	12	0.00E+00	2.00E-05	12
Facility L	FD-IR3-M1-model A	1105920	2	12	4.81E-07	4.81E-06	9	4.06E-07	6.53E-06	9
Facility A	HD-ROR-M5-model A	1094496	0	12	0.00E+00	2.10E-06	18	0.00E+00	4.21E-06	18
Facility A	HD-FT-M6-model G	1052400	0	12	0.00E+00	2.19E-06	18	0.00E+00	4.38E-06	18
Facility B	HD-ROR-M5-model A	336768	0	12	0.00E+00	6.84E-06	12	0.00E+00	1.37E-05	12
Facility B	HD-FT-M6-model G	589344	1	12	1.79E-07	6.60E-06	9	1.32E-07	9.45E-06	9
Facility C	HD-ROR-M5-model A	77568	0	12	0.00E+00	2.97E-05	12	0.00E+00	5.94E-05	12
Facility C	HD-FT-M6-model E	193056	0	12	0.00E+00	1.19E-05	12	0.00E+00	2.39E-05	12
Facility C	HD-FT-M6-model F	251568	0	12	0.00E+00	9.15E-06	12	0.00E+00	1.83E-05	12
Facility D	HD-ROR-M5-model A	518400	2	12	1.03E-06	1.03E-05	6	8.65E-07	1.39E-05	6
Facility D	HD-FT-M6-model F	1175040	1	12	8.97E-08	3.31E-06	12	6.63E-08	4.74E-06	12
Facility E	HD-FT-M6-model F	205920	0	12	0.00E+00	1.12E-05	12	0.00E+00	2.24E-05	12
Facility F	HD-ROR-M5-model A	345312	0	12	0.00E+00	6.67E-06	12	0.00E+00	1.33E-05	12
Facility F	HD-FT-M6-model G	797232	0	12	0.00E+00	2.89E-06	12	0.00E+00	5.78E-06	12
Facility G	HD-ROR-M5-model A	388440	0	12	0.00E+00	5.93E-06	12	0.00E+00	1.19E-05	12
Facility G	HD-FT-M6-model G	1139424	0	12	0.00E+00	2.02E-06	18	0.00E+00	4.04E-06	18
Facility G	HD-LN-M7-model I	258960	0	12	0.00E+00	8.89E-06	12	0.00E+00	1.78E-05	12

Table E.4: The comparison of calculated test interval based on confident interval and credibility interval

Facility	Model	Time-hour	DU	$\tau_{init}*$	Confident interval			Credibility interval		
					90% CI low (h^{-1})	90% CI up (h^{-1})	$\ddot{\tau}*$	90% CI low (h^{-1})	90% CI up (h^{-1})	$\ddot{\tau}*$
Facility H	HD-ROR-M8-model B	28062720	7	12	1.39E-07	4.19E-07	18	1.29E-07	5.14E-07	18
Facility I	HD-FT-M6-model F	1002240	0	12	0.00E+00	2.30E-06	18	0.00E+00	4.59E-06	18
Facility I	HD-ROR-M8-model B	276480	0	12	0.00E+00	8.33E-06	12	0.00E+00	1.67E-05	12
Facility J	HD-FT-M6-model D	32952	0	12	0.00E+00	6.99E-05	12	0.00E+00	1.40E-04	12
Facility J	HD-ROR-M5-model A	381768	0	12	0.00E+00	6.03E-06	12	0.00E+00	1.21E-05	12
Facility J	HD-FT-M6-model G	241920	0	12	0.00E+00	9.52E-06	12	0.00E+00	1.90E-05	12
Facility J	HD-ROR-M3-model C	138240	0	12	0.00E+00	1.67E-05	12	0.00E+00	3.33E-05	12
Facility K	HD-ROR-M8-model B	6186240	1	12	1.70E-08	6.29E-07	18	1.26E-08	9.01E-07	18
Facility K	HD-FT-M9-model H	172800	0	12	0.00E+00	1.33E-05	12	0.00E+00	2.67E-05	12
Facility L	HD-FT-M6-model F	103680	0	12	0.00E+00	2.22E-05	12	0.00E+00	4.44E-05	12
Facility A	SD-OP-M6-model A	42626592	1	12	2.47E-09	9.13E-08	24	1.83E-09	1.31E-07	24
Facility A	SD-OP-M3-model B	15154560	7	12	2.57E-07	7.77E-07	12	2.39E-07	9.52E-07	12
Facility A	SD-SOP-M6-model D	1389168	0	12	0.00E+00	1.66E-06	18	0.00E+00	3.32E-06	18
Facility A	SD-OP-M4-model C	3451872	0	12	0.00E+00	6.67E-07	18	0.00E+00	1.33E-06	18
Facility A	SD-ION-M4-model E	42096	0	12	0.00E+00	5.47E-05	12	0.00E+00	1.09E-04	12
Facility B	SD-OP-M6-model A	26730960	0	12	0.00E+00	8.61E-08	24	0.00E+00	1.72E-07	24
Facility B	SD-ION-M4-model E	11323824	0	12	0.00E+00	2.03E-07	24	0.00E+00	4.07E-07	24
Facility B	SD-ION-M6-model G	841920	0	12	0.00E+00	2.73E-06	12	0.00E+00	5.47E-06	12

Table E.4: The comparison of calculated test interval based on confident interval and credibility interval

Facility	Model	Time-hour	DU	$\tau_{init}*$	Confident interval			Credibility interval		
					90% CI low (h^{-1})	90% CI up (h^{-1})	$\ddot{\tau}*$	90% CI low (h^{-1})	90% CI up (h^{-1})	$\ddot{\tau}*$
Facility C	SD-SOP-M6-model D	26666184	0	12	0.00E+00	8.63E-08	24	0.00E+00	1.73E-07	24
Facility C	SD-OP-M4-model C	45432	0	12	0.00E+00	5.07E-05	12	0.00E+00	1.01E-04	12
Facility C	SD-ION-M4-model F	116328	0	12	0.00E+00	1.98E-05	12	0.00E+00	3.96E-05	12
Facility D	SD-SOP-M6-model D	17625600	5	12	1.38E-07	5.26E-07	18	1.26E-07	6.62E-07	18
Facility D	SD-OT-M11-model I	138240	0	12	0.00E+00	1.67E-05	12	0.00E+00	3.33E-05	12
Facility E	SD-SOP-M6-model D	5366112	0	12	0.00E+00	4.29E-07	24	0.00E+00	8.58E-07	18
Facility F	SD-OP-M6-model A	23935944	10	12	2.60E-07	6.44E-07	12	2.45E-07	7.68E-07	12
Facility F	SD-SOP-M6-model D	1899216	0	12	0.00E+00	1.21E-06	18	0.00E+00	2.42E-06	18
Facility F	SD-IR-M10-model H	115104	0	12	0.00E+00	2.00E-05	12	0.00E+00	4.00E-05	12
Facility F	SD-ION-M6-model G	57552	0	12	0.00E+00	4.00E-05	12	0.00E+00	8.00E-05	12
Facility G	SD-OP-M6-model A	25844208	5	12	9.41E-08	3.59E-07	24	8.60E-08	4.51E-07	24
Facility H	SD-OP-M6-model A	49541616	1	12	2.13E-09	7.85E-08	24	1.57E-09	1.12E-07	24
Facility H	SD-OP-M3-model B	16871040	10	12	3.69E-07	9.13E-07	12	3.48E-07	1.09E-06	12
Facility H	SD-OP-M4-model C	125280	0	12	0.00E+00	1.84E-05	12	0.00E+00	3.68E-05	12
Facility I	SD-SOP-M6-model D	16519680	0	12	0.00E+00	1.39E-07	24	0.00E+00	2.79E-07	24
Facility J	SD-OP-M6-model A	9192960	0	12	0.00E+00	2.50E-07	24	0.00E+00	5.01E-07	24
Facility J	SD-OP-M3-model B	10298880	2	12	5.16E-08	5.17E-07	18	4.35E-08	7.02E-07	18
Facility K	SD-OP-M6-model A	3421440	1	12	3.08E-08	1.14E-06	12	2.28E-08	1.63E-06	12
Facility K	SD-SOP-M6-model D	15517440	1	12	6.79E-09	2.51E-07	24	5.02E-09	3.59E-07	24
Facility K	SD-OP-M4-model C	5978880	7	12	6.51E-07	1.97E-06	6	6.06E-07	2.41E-06	6
Facility L	SD-SOP-M6-model D	345600	0	12	0.00E+00	6.66E-06	12	0.00E+00	1.33E-05	12

Table E.4: The comparison of calculated test interval based on confident interval and credibility interval

Facility	Model	Time-hour	DU	$\tau_{init}*$	Confident interval			Credibility interval		
					90% CI low (h^{-1})	90% CI up (h^{-1})	$\ddot{\tau}*$	90% CI low (h^{-1})	90% CI up (h^{-1})	$\ddot{\tau}*$
Facility A	GD-IR-M14-model A	18943200	3	12	5.82E-08	3.53E-07	24	5.12E-08	4.63E-07	24
Facility B	GD-IR-M14-model A	11408016	3	12	9.66E-08	5.86E-07	18	8.51E-08	7.69E-07	18
Facility C	GD-IR-M14-model A	6687624	7	12	5.82E-07	1.76E-06	9	5.41E-07	2.16E-06	9
Facility D	GD-IR-M14-model A	8052480	0	12	0.00E+00	2.86E-07	24	0.00E+00	5.72E-07	24
Facility D	GD-IR-M6-model C	138240	0	12	0.00E+00	1.67E-05	12	0.00E+00	3.33E-05	12
Facility E	GD-IR-M14-model A	2105544	0	12	0.00E+00	1.09E-06	18	0.00E+00	2.19E-06	18
Facility F	GD-IR-M14-model A	4230072	3	12	2.61E-07	1.58E-06	12	2.29E-07	2.07E-06	12
Facility G	GD-IR-M14-model A	8882328	2	12	5.99E-08	5.99E-07	18	5.05E-08	8.13E-07	18
Facility H	GD-IR-M14-model A	22592160	9	12	2.40E-07	6.29E-07	12	2.26E-07	7.56E-07	12
Facility I	GD-IR-M14-model A	9918720	3	12	1.11E-07	6.74E-07	18	9.79E-08	8.84E-07	18
Facility J	GD-IR-M14-model A	5210208	3	12	2.12E-07	1.28E-06	12	1.86E-07	1.68E-06	12
Facility J	GD-IR-M14-model B	181152	0	12	0.00E+00	1.27E-05	12	0.00E+00	2.54E-05	12
Facility K	GD-IR-M14-model A	3836160	3	12	2.87E-07	1.74E-06	12	2.53E-07	2.29E-06	12
Facility K	GD-IR-M6-model C	207360	0	12	0.00E+00	1.11E-05	12	0.00E+00	2.22E-05	12
Facility L	GD-IR-M14-model A	1382400	0	12	0.00E+00	1.67E-06	18	0.00E+00	3.33E-06	18
Facility A	LOS-IR-M15-model A	2694144	0	12	0.00E+00	8.55E-07	18	0.00E+00	1.71E-06	18
Facility A	LOS-IR-M16-model E	210480	0	12	0.00E+00	1.09E-05	12	0.00E+00	2.19E-05	12
Facility B	LOS-IR-M15-model A	2062704	1	12	5.11E-08	1.89E-06	12	3.78E-08	2.70E-06	12
Facility C	LOS-IR-M15-model A	2737272	0	12	0.00E+00	8.41E-07	18	0.00E+00	1.68E-06	18
Facility D	LOS-IR-M15-model A	1762560	1	12	5.98E-08	2.21E-06	12	4.42E-08	3.16E-06	12
Facility E	LOS-IR-M16-model B	1094832	0	12	0.00E+00	2.10E-06	18	0.00E+00	4.21E-06	18

Table E.4: The comparison of calculated test interval based on confident interval and credibility interval

Facility	Model	Time-hour	DU	$\tau_{init}*$	Confident interval			Credibility interval		
					90% CI low (h^{-1})	90% CI up (h^{-1})	$\ddot{\tau}*$	90% CI low (h^{-1})	90% CI up (h^{-1})	$\ddot{\tau}*$
Facility F	LOS-IR-M15-model A	6273168	20	12	2.32E-06	4.31E-06	6	2.23E-06	4.92E-06	6
Facility F	LOS-IR-M16-model E	517968	1	12	2.03E-07	7.51E-06	9	1.51E-07	1.08E-05	9
Facility G	LOS-IR-M15-model A	4221048	0	12	0.00E+00	5.46E-07	24	0.00E+00	1.09E-06	18
Facility H	LOS-IR-M15-model A	4510080	0	12	0.00E+00	5.11E-07	24	0.00E+00	1.02E-06	18
Facility I	LOS-IR-M15-model A	1624320	0	12	0.00E+00	1.42E-06	18	0.00E+00	2.84E-06	18
Facility I	LOS-IR-M15-model A	69120	0	12	0.00E+00	3.33E-05	12	0.00E+00	6.66E-05	12
Facility I	LOS-IR-M6-model D	108672	0	12	0.00E+00	2.12E-05	12	0.00E+00	4.24E-05	12
Facility I	LOS-IR-M6-model C	444288	0	12	0.00E+00	5.18E-06	12	0.00E+00	1.04E-05	12
Facility J	LOS-IR-M15-model A	1175040	0	12	0.00E+00	1.96E-06	18	0.00E+00	3.92E-06	18
Facility K	LOS-IR-M15-model A	380160	7	12	1.02E-05	3.10E-05	6	9.52E-06	3.79E-05	6
Facility K	LOS-IR-M16-model B	725760	7	12	5.37E-06	1.62E-05	6	4.99E-06	1.99E-05	6
Facility L	LOS-IR-M15-model A	69120	0	12	0.00E+00	3.33E-05	12	0.00E+00	6.66E-05	12
Facility L	LOS-IR-M16-model E	552960	0	12	0.00E+00	4.16E-06	12	0.00E+00	8.33E-06	12
Facility A	CD-HC-M15-model A	9976752	11	6	7.04E-07	1.66E-06	9	6.66E-07	1.97E-06	9
Facility B	CD-H2-M16-model E	252576	0	6	0.00E+00	9.12E-06	6	0.00E+00	1.82E-05	6
Facility C	CD-HC-M15-model B	797040	4	6	2.19E-06	1.00E-05	6	1.97E-06	1.28E-05	3
Facility C	CD-HC-M15-model C	132048	0	6	0.00E+00	1.74E-05	6	0.00E+00	3.49E-05	6
Facility D	CD-HC-M15-model B	241920	0	6	0.00E+00	9.52E-06	6	0.00E+00	1.90E-05	6
Facility E	CD-H2-M16-model F	136464	0	6	0.00E+00	1.69E-05	6	0.00E+00	3.37E-05	6
Facility F	CD-H2-M16-model G	172656	3	6	6.38E-06	3.87E-05	3	5.62E-06	5.08E-05	3
Facility G	CD-H2-M16-model G	129480	0	6	0.00E+00	1.78E-05	6	0.00E+00	3.56E-05	6

Table E.4: The comparison of calculated test interval based on confident interval and credibility interval

Facility	Model	Time-hour	DU	$\tau_{init}*$	Confident interval			Credibility interval		
					90% CI low (h^{-1})	90% CI up (h^{-1})	$\ddot{\tau}*$	90% CI low (h^{-1})	90% CI up (h^{-1})	$\ddot{\tau}*$
Facility H	CD-H2-M16-model G	375840	2	6	1.41E-06	1.42E-05	6	1.19E-06	1.92E-05	6
Facility K	CD-HC-M15-model A	6082560	35	6	4.55E-06	7.21E-06	3	4.42E-06	8.00E-06	3
Facility K	CD-HC-M15-model D	207360	6	6	1.52E-05	5.08E-05	3	1.40E-05	6.30E-05	3
Facility L	CD-H2-M16-model E	34560	0	6	0.00E+00	6.66E-05	6	0.00E+00	1.33E-04	6

E.5 Halving and Doubling Criteria

Table E.5: The comparison of calculated test interval based on different doubling and halving approach

Facility	**Model**	**Time hour**	**DU**	$\tau_{init}*$	**SINTEF approach**			**New approach**		
					90% CI low (h^{-1})	**90% CI up** (h^{-1})	$\ddot{\tau}*$	**70% CI low** (h^{-1})	**95% CI up** (h^{-1})	$\ddot{\tau}*$
Facility A	FD-IR3-M1-model A	20963808	0	12	0.00E+00	1.10E-07	24	4.59E-09	1.00E-07	24
Facility B	FD-IR3-M1-model A	9513696	2	12	5.59E-08	5.59E-07	18	4.62E-08	3.38E-07	18
Facility B	FD-UV-M1-model D	799824	3	12	1.38E-06	8.35E-06	6	2.88E-07	1.65E-06	9
Facility C	FD-IR3-M1-model A	312840	0	12	0.00E+00	7.36E-06	12	4.56E-08	9.96E-07	12
Facility C	FD-IR3-M2-model B	1680000	0	12	0.00E+00	1.37E-06	18	2.86E-08	6.26E-07	18
Facility C	FD-IR3-M2-model C	4864416	0	12	0.00E+00	4.73E-07	24	1.53E-08	3.35E-07	24
Facility D	FD-IR3-M1-model A	483840	2	12	1.10E-06	1.10E-05	6	2.14E-07	1.57E-06	9
Facility D	FD-IR3-M3-model G	5529600	6	12	5.70E-07	1.90E-06	9	2.32E-07	8.87E-07	9
Facility E	FD-IR3-M2-model C	1921920	0	12	0.00E+00	1.20E-06	18	2.69E-08	5.87E-07	18
Facility F	FD-IR3-M1-model A	2848824	4	12	6.12E-07	2.81E-06	6	2.27E-07	1.10E-06	9
Facility F	FD-IR3-M2-model B	201432	1	12	5.23E-07	1.93E-05	9	1.33E-07	1.42E-06	9
Facility F	FD-IR3-M2-model C	6791136	9	12	8.00E-07	2.09E-06	6	3.17E-07	9.83E-07	9

Table E.5: The comparison of calculated test interval based on different doubling and halving approach

Facility	**Model**	**Time hour**	**DU**	τ_{init}*	**SINTEF approach**			**New approach**		
					90% CI low (h^{-1})	**90% CI up** (h^{-1})	$\ddot{\tau}$*	**70% CI low** (h^{-1})	**95% CI up** (h^{-1})	$\ddot{\tau}$*
Facility G	FD-IR3-M1-model A	7302672	3	12	1.51E-07	9.15E-07	12	8.66E-08	4.96E-07	12
Facility G	FD-IR3-M2-model B	2149368	1	12	4.90E-08	1.81E-06	12	7.04E-08	7.53E-07	12
Facility H	FD-IR3-M1-model A	2422080	0	12	0.00E+00	9.51E-07	18	2.38E-08	5.21E-07	18
Facility H	FD-IR-M1-model E	3132000	1	12	3.36E-08	1.24E-06	12	5.69E-08	6.09E-07	12
Facility I	FD-IR3-M1-model A	8121600	1	12	1.30E-08	4.79E-07	24	2.89E-08	3.09E-07	24
Facility J	FD-IR3-M1-model A	241920	0	12	0.00E+00	9.52E-06	12	4.70E-08	1.03E-06	12
Facility J	FD-IR3-M3-model G	3386880	0	12	0.00E+00	6.80E-07	18	1.96E-08	4.27E-07	24
Facility K	FD-IR3-M1-model A	4112640	2	12	1.29E-07	1.29E-06	12	8.70E-08	6.36E-07	12
Facility K	FD-IR3-M4-model H	34560	0	12	0.00E+00	6.66E-05	12	5.18E-08	1.13E-06	12
Facility K	FD-UI-M1-model F	230832	0	12	0.00E+00	9.98E-06	12	4.72E-08	1.03E-06	12
Facility L	FD-IR3-M1-model A	1105920	2	12	4.81E-07	4.81E-06	9	1.71E-07	1.25E-06	9
Facility A	HD-ROR-M5-model A	1094496	0	12	0.00E+00	2.10E-06	18	3.40E-08	7.44E-07	18
Facility A	HD-FT-M6-model G	1052400	0	12	0.00E+00	2.19E-06	18	3.45E-08	7.54E-07	18
Facility B	HD-ROR-M5-model A	336768	0	12	0.00E+00	6.84E-06	12	4.51E-08	9.85E-07	12
Facility B	HD-FT-M6-model G	589344	1	12	1.79E-07	6.60E-06	9	1.13E-07	1.21E-06	9
Facility C	HD-ROR-M5-model A	77568	0	12	0.00E+00	2.97E-05	12	5.07E-08	1.11E-06	12
Facility C	HD-FT-M6-model E	193056	0	12	0.00E+00	1.19E-05	12	4.80E-08	1.05E-06	12
Facility C	HD-FT-M6-model F	251568	0	12	0.00E+00	9.15E-06	12	4.68E-08	1.02E-06	12
Facility D	HD-ROR-M5-model A	518400	2	12	1.03E-06	1.03E-05	6	2.11E-07	1.54E-06	9

Table E.5: The comparison of calculated test interval based on different doubling and halving approach

Facility	**Model**	**Time hour**	**DU**	τ_{init}*	**SINTEF approach**			**New approach**		
					90% CI low (h^{-1})	**90% CI up** (h^{-1})	$\ddot{\tau}$*	**70% CI low** (h^{-1})	**95% CI up** (h^{-1})	$\ddot{\tau}$*
Facility D	HD-FT-M6-model F	1175040	1	12	8.97E-08	3.31E-06	12	9.20E-08	9.84E-07	12
Facility E	HD-FT-M6-model F	205920	0	12	0.00E+00	1.12E-05	12	4.78E-08	1.04E-06	12
Facility F	HD-ROR-M5-model A	345312	0	12	0.00E+00	6.67E-06	12	4.49E-08	9.82E-07	12
Facility F	HD-FT-M6-model G	797232	0	12	0.00E+00	2.89E-06	12	3.77E-08	8.23E-07	12
Facility G	HD-ROR-M5-model A	388440	0	12	0.00E+00	5.93E-06	12	4.41E-08	9.64E-07	12
Facility G	HD-FT-M6-model G	1139424	0	12	0.00E+00	2.02E-06	18	3.36E-08	7.33E-07	18
Facility G	HD-LN-M7-model I	258960	0	12	0.00E+00	8.89E-06	12	4.66E-08	1.02E-06	12
Facility H	HD-ROR-M8-model B	28062720	7	12	1.39E-07	4.19E-07	18	6.93E-08	2.44E-07	18
Facility I	HD-FT-M6-model F	1002240	0	12	0.00E+00	2.30E-06	18	3.51E-08	7.67E-07	18
Facility I	HD-ROR-M8-model B	276480	0	12	0.00E+00	8.33E-06	12	4.63E-08	1.01E-06	12
Facility J	HD-FT-M6-model D	32952	0	12	0.00E+00	6.99E-05	12	5.18E-08	1.13E-06	12
Facility J	HD-ROR-M5-model A	381768	0	12	0.00E+00	6.03E-06	12	4.42E-08	9.67E-07	12
Facility J	HD-FT-M6-model G	241920	0	12	0.00E+00	9.52E-06	12	4.70E-08	1.03E-06	12
Facility J	HD-ROR-M3-model C	138240	0	12	0.00E+00	1.67E-05	12	4.93E-08	1.08E-06	12
Facility K	HD-ROR-M8-model B	6186240	1	12	1.70E-08	6.29E-07	18	3.57E-08	3.82E-07	24
Facility K	HD-FT-M9-model H	172800	0	12	0.00E+00	1.33E-05	12	4.85E-08	1.06E-06	12
Facility L	HD-FT-M6-model F	103680	0	12	0.00E+00	2.22E-05	12	5.01E-08	1.09E-06	12

Table E.5: The comparison of calculated test interval based on different doubling and halving approach

Facility	**Model**	**Time hour**	**DU**	τ_{init}*	**SINTEF approach**			**New approach**		
					90% CI low (h^{-1})	**90% CI up** (h^{-1})	$\ddot{\tau}$*	**70% CI low** (h^{-1})	**95% CI up** (h^{-1})	$\ddot{\tau}$*
Facility A	SD-OP-M6-model A	42626592	1	12	2.47E-09	9.13E-08	24	6.55E-09	7.00E-08	24
Facility A	SD-OP-M3-model B	15154560	7	12	2.57E-07	7.77E-07	12	1.21E-07	4.28E-07	12
Facility A	SD-SOP-M6-model D	1389168	0	12	0.00E+00	1.66E-06	18	3.11E-08	6.79E-07	18
Facility A	SD-OP-M4-model C	3451872	0	12	0.00E+00	6.67E-07	18	1.93E-08	4.22E-07	24
Facility A	SD-ION-M4-model E	42096	0	12	0.00E+00	5.47E-05	12	5.16E-08	1.13E-06	12
Facility B	SD-OP-M6-model A	26730960	0	12	0.00E+00	8.61E-08	24	3.67E-09	8.01E-08	24
Facility B	SD-ION-M4-model E	11323824	0	12	0.00E+00	2.03E-07	24	7.91E-09	1.73E-07	24
Facility B	SD-ION-M6-model G	841920	0	12	0.00E+00	2.73E-06	12	3.71E-08	8.10E-07	12
Facility C	SD-SOP-M6-model D	26666184	0	12	0.00E+00	8.63E-08	24	3.68E-09	8.03E-08	24
Facility C	SD-OP-M4-model C	45432	0	12	0.00E+00	5.07E-05	12	5.15E-08	1.13E-06	12
Facility C	SD-ION-M4-model F	116328	0	12	0.00E+00	1.98E-05	12	4.98E-08	1.09E-06	12
Facility D	SD-SOP-M6-model D	17625600	5	12	1.38E-07	5.26E-07	18	7.22E-08	3.06E-07	18
Facility D	SD-OT-M11-model I	138240	0	12	0.00E+00	1.67E-05	12	4.93E-08	1.08E-06	12
Facility E	SD-SOP-M6-model D	5366112	0	12	0.00E+00	4.29E-07	24	1.43E-08	3.13E-07	24
Facility F	SD-OP-M6-model A	23935944	10	12	2.60E-07	6.44E-07	12	1.22E-07	3.58E-07	12
Facility F	SD-SOP-M6-model D	1899216	0	12	0.00E+00	1.21E-06	18	2.70E-08	5.91E-07	18
Facility F	SD-IR-M10-model H	115104	0	12	0.00E+00	2.00E-05	12	4.98E-08	1.09E-06	12
Facility F	SD-ION-M6-model G	57552	0	12	0.00E+00	4.00E-05	12	5.12E-08	1.12E-06	12
Facility G	SD-OP-M6-model A	25844208	5	12	9.41E-08	3.59E-07	24	5.09E-08	2.16E-07	24
Facility H	SD-OP-M6-model A	49541616	1	12	2.13E-09	7.85E-08	24	5.67E-09	6.06E-08	24
Facility H	SD-OP-M3-model B	16871040	10	12	3.69E-07	9.13E-07	12	1.67E-07	4.91E-07	12

Table E.5: The comparison of calculated test interval based on different doubling and halving approach

Facility	**Model**	**Time hour**	**DU**	τ_{init}*	**SINTEF approach**			**New approach**		
					90% CI low (h^{-1})	**90% CI up** (h^{-1})	$\ddot{\tau}$*	**70% CI low** (h^{-1})	**95% CI up** (h^{-1})	$\ddot{\tau}$*
Facility H	SD-OP-M4-model C	125280	0	12	0.00E+00	1.84E-05	12	4.96E-08	1.08E-06	12
Facility I	SD-SOP-M6-model D	16519680	0	12	0.00E+00	1.39E-07	24	5.69E-09	1.24E-07	24
Facility J	SD-OP-M6-model A	9192960	0	12	0.00E+00	2.50E-07	24	9.41E-09	2.06E-07	24
Facility J	SD-OP-M3-model B	10298880	2	12	5.16E-08	5.17E-07	18	4.32E-08	3.16E-07	24
Facility K	SD-OP-M6-model A	3421440	1	12	3.08E-08	1.14E-06	12	5.39E-08	5.77E-07	12
Facility K	SD-SOP-M6-model D	15517440	1	12	6.79E-09	2.51E-07	24	1.67E-08	1.78E-07	24
Facility K	SD-OP-M4-model C	5978880	7	12	6.51E-07	1.97E-06	6	2.61E-07	9.20E-07	9
Facility L	SD-SOP-M6-model D	345600	0	12	0.00E+00	6.66E-06	12	4.49E-08	9.82E-07	12
Facility A	GD-IR-M14-model A	18943200	3	12	5.82E-08	3.53E-07	24	3.91E-08	2.24E-07	24
Facility B	GD-IR-M14-model A	11408016	3	12	9.66E-08	5.86E-07	18	6.16E-08	3.53E-07	18
Facility C	GD-IR-M14-model A	6687624	7	12	5.82E-07	1.76E-06	9	2.49E-07	8.79E-07	9
Facility D	GD-IR-M14-model A	8052480	0	12	0.00E+00	2.86E-07	24	1.08E-08	2.37E-07	24
Facility D	GD-IR-M6-model C	138240	0	12	0.00E+00	1.67E-05	12	5.84E-08	1.28E-06	12
Facility E	GD-IR-M14-model A	2105544	0	12	0.00E+00	1.09E-06	18	2.79E-08	6.10E-07	18
Facility F	GD-IR-M14-model A	4230072	3	12	2.61E-07	1.58E-06	12	1.37E-07	7.83E-07	12
Facility G	GD-IR-M14-model A	8882328	2	12	5.99E-08	5.99E-07	24	5.04E-08	3.69E-07	24
Facility H	GD-IR-M14-model A	22592160	9	12	2.40E-07	6.29E-07	12	1.15E-07	3.56E-07	12
Facility I	GD-IR-M14-model A	9918720	3	12	1.11E-07	6.74E-07	18	6.95E-08	3.99E-07	18
Facility J	GD-IR-M14-model A	5210208	3	12	2.12E-07	1.28E-06	12	1.17E-07	6.72E-07	12
Facility J	GD-IR-M14-model B	181152	0	12	0.00E+00	1.27E-05	12	5.70E-08	1.25E-06	12
Facility K	GD-IR-M14-model A	3836160	3	12	2.87E-07	1.74E-06	12	1.46E-07	8.39E-07	12

Table E.5: The comparison of calculated test interval based on different doubling and halving approach

Facility	**Model**	**Time hour**	**DU**	τ_{init}*	**SINTEF approach**			**New approach**		
					90% CI low (h^{-1})	**90% CI up** (h^{-1})	$\ddot{\tau}$*	**70% CI low** (h^{-1})	**95% CI up** (h^{-1})	$\ddot{\tau}$*
Facility K	GD-IR-M6-model C	207360	0	12	0.00E+00	1.11E-05	12	5.62E-08	1.23E-06	12
Facility L	GD-IR-M14-model A	1382400	0	12	0.00E+00	1.67E-06	18	3.46E-08	7.55E-07	18
Facility A	LOS-IR-M15-model A	2694144	0	12	0.00E+00	8.55E-07	18	2.42E-08	5.28E-07	24
Facility A	LOS-IR-M16-model E	210480	0	12	0.00E+00	1.09E-05	12	5.61E-08	1.23E-06	12
Facility B	LOS-IR-M15-model A	2062704	1	12	5.11E-08	1.89E-06	12	7.83E-08	8.38E-07	12
Facility C	LOS-IR-M15-model A	2737272	0	12	0.00E+00	8.41E-07	18	2.39E-08	5.23E-07	24
Facility D	LOS-IR-M15-model A	1762560	1	12	5.98E-08	2.21E-06	12	8.52E-08	9.11E-07	12
Facility E	LOS-IR-M16-model B	1094832	0	12	0.00E+00	2.10E-06	18	3.82E-08	8.34E-07	18
Facility F	LOS-IR-M15-model A	6273168	20	12	2.32E-06	4.31E-06	6	8.84E-07	1.94E-06	6
Facility F	LOS-IR-M16-model E	517968	1	12	2.03E-07	7.51E-06	9	1.34E-07	1.43E-06	9
Facility G	LOS-IR-M15-model A	4221048	0	12	0.00E+00	5.46E-07	24	1.79E-08	3.91E-07	24
Facility H	LOS-IR-M15-model A	4510080	0	12	0.00E+00	5.11E-07	24	1.71E-08	3.73E-07	24
Facility I	LOS-IR-M15-model A	1624320	0	12	0.00E+00	1.42E-06	18	3.20E-08	7.00E-07	18
Facility I	LOS-IR-M15-model A	69120	0	12	0.00E+00	3.33E-05	12	6.07E-08	1.33E-06	12
Facility I	LOS-IR-M6-model D	108672	0	12	0.00E+00	2.12E-05	12	5.93E-08	1.30E-06	12
Facility I	LOS-IR-M6-model C	444288	0	12	0.00E+00	5.18E-06	12	4.99E-08	1.09E-06	12
Facility J	LOS-IR-M15-model A	1175040	0	12	0.00E+00	1.96E-06	18	3.71E-08	8.10E-07	18
Facility K	LOS-IR-M15-model A	380160	7	12	1.02E-05	3.10E-05	6	1.02E-06	3.59E-06	6
Facility K	LOS-IR-M16-model B	725760	7	12	5.37E-06	1.62E-05	6	8.71E-07	3.07E-06	6
Facility L	LOS-IR-M15-model A	69120	0	12	0.00E+00	3.33E-05	12	6.07E-08	1.33E-06	12
Facility L	LOS-IR-M16-model E	552960	0	12	0.00E+00	4.16E-06	12	4.75E-08	1.04E-06	12

Table E.5: The comparison of calculated test interval based on different doubling and halving approach

Facility	**Model**	**Time hour**	**DU**	τ_{init}^{*}	**SINTEF approach**			**New approach**		
					90% CI low (h^{-1})	**90% CI up** (h^{-1})	$\ddot{\tau}$*	**70% CI low** (h^{-1})	**95% CI up** (h^{-1})	$\ddot{\tau}$*
Facility A	CD-HC-M15-model A	9976752	11	6	7.04E-07	1.66E-06	9	3.34E-07	9.41E-07	9
Facility B	CD-H2-M16-model E	252576	0	6	0.00E+00	9.12E-06	6	1.30E-07	2.85E-06	6
Facility C	CD-HC-M15-model B	797040	4	6	2.19E-06	1.00E-05	3	8.15E-07	3.93E-06	6
Facility C	CD-HC-M15-model C	132048	0	6	0.00E+00	1.74E-05	6	1.53E-07	3.35E-06	6
Facility D	CD-HC-M15-model B	241920	0	6	0.00E+00	9.52E-06	6	1.32E-07	2.89E-06	6
Facility E	CD-H2-M16-model F	136464	0	6	0.00E+00	1.69E-05	6	1.52E-07	3.33E-06	6
Facility F	CD-H2-M16-model G	172656	3	6	6.38E-06	3.87E-05	3	1.11E-06	6.34E-06	6
Facility G	CD-H2-M16-model G	129480	0	6	0.00E+00	1.78E-05	6	1.54E-07	3.36E-06	6
Facility H	CD-H2-M16-model G	375840	2	6	1.41E-06	1.42E-05	6	5.71E-07	4.18E-06	6
Facility K	CD-HC-M15-model A	6082560	35	6	4.55E-06	7.21E-06	3	2.00E-06	3.64E-06	3
Facility K	CD-HC-M15-model D	207360	6	6	1.52E-05	5.08E-05	3	2.29E-06	8.76E-06	3
Facility L	CD-H2-M16-model E	34560	0	6	0.00E+00	6.66E-05	6	1.79E-07	3.90E-06	6

Appendix F

Abbreviation, Definition and Symbol

F.1 Abbreviation

CCF Common Cause Failure

CMMS Computerized Maintenance Management System

DD Dangerous Detected

DU Dangerous Undetected

E/E/PE Electrical, Electronic or Programmable E lectronic

FMEDA Failure Mode and Effect Diagnostic Analysis

FMMEA Failure Mode, Mechanism and Effect Analysis

EUC Equipment Under Control

IEC International Electrotechnical Commission

IR Infra-red

ISO International Standard Organization

LEL Lower Explosion Limit

LELm Lower Explosion Limit meter

LFL Low Flammable Limit

NFPA National Fire Protection Association

NONC Non-critical

OREDA Offshore Reliability Data

PFD Probability of failure on demand

PFDavg Probability of failure on demand avarage

PFH Probability of dangerous failure per hour

PSA Process Safety Authority

RAMS Reliability, Availability, Maintainability and Safety

RRF Risk Reduction Factor

SFF Safe Failure Fraction

SIF Safety Instrumented Functions

SD Safe detected

SIL Safety Integrated Level

SIS Safety Instrumented System

SRS Safety Requirement Specification

SU safe undetected

UV Ultra-violet

F.2 Definition

Dangerous failure Failure of a component that prevents a safety function from operating when required or causes a safety function to fail such that the Equipment Under Control (EUC) is put into a hazardous state

DD failure Failure is a dangerous failure that can be detected by automatic diagnostic testing or personnel self-test

DU failure Failure is a dangerous failure that can not be detected by the diagnostic test, operator intervention or through normal operation

Detection method Method or activity by which a failure is discovered

Failure A condition when an equipment is not able to perform its function

Failure mode Manner in failure is manifesting into the system

Failure mechanism The process of the failure induced into the component

Failure notification data Data characterizing the failure such as failure description, failure cause, and details descriptions

Failure on demand Failure likely to be observed when a demand occurs

Failure rate Conditional probability per unit of time that the item fails between t and t + dt, provided that it has been working over 0, t

Failure root cause The basic cause of failure

Hidden failure Failure that is not immediately evident to operations and maintenance personnel

IEC 61508 failure class Failure classification into DU, DD, SU, and SD

Modification Combination of all technical and administrative actions intended to change an item

NONC failure Failure that is not affected by the main equipment ability to perform the intended function, but it may gradually develop into a critical failure

Operating time Time interval during which an item is in an operating state

Random failure Failure that is related to the physical of the equipment such as aging

Safe failure Failure that affects the safety function but does not have the potential to put the EUC in a hazardous or fail-to-function state

SD failure A spurious failure that can be detected by automatic diagnostic testing or personnel self-test

SU failure A safe failure that cannot be detected by the diagnostic test, operator intervention or through normal operation

Systematic failure Failure related to the non-physical failure

F.3 Symbol

x The number of components in the population of comparable

t_n Total aggregated time in operation (hour)

$\lambda\hat{_{DU}}$ Operational failure rate (per hour)

$z_{0.95}$ 5% lower limit confident interval

$z_{0.05}$ 95 % upper limit confident interval

τ Test interval (months)

n The number of DU failures

λ_{DU} A priory failure rate (per hour)

λ_{DU-CE} The conservative failure rate (per hour)

α The Bayesian parameter

γ The Bayesian parameter

$\ddot{\lambda}_{DU}$ The Bayesian failure rate

θ^* The aggregated failure rate by OREDA Multi-Sample

$\ddot{\tau}$ The updated test interval

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