Ageing and life extension for safety systems on offshore facilities

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ABSTRACT: A large number of facilities on the Norwegian Continental Shelf are approaching or have exceeded their design life. Many fields, however, have remaining recoverable oil and gas reserves, so that life extension can be profitable. But in order to extend operation beyond the design life of the facility it must be assured that the safety integrity is maintained throughout a life extension period. This means that it is required to investigate the condition of structure, equipment, procedures and organisation, and also the compliance with requirements etc. for the entire facility. So far, studies on ageing of offshore facilities have focused on main systems, such as structures and pipelines. The present paper in particular addresses ageing issues related to offshore safety systems, including safety instrumented systems (SIS), during a potential life extension period. Typical ageing phenomena of the safety systems and equipment are discussed, and possible challenges related to ageing of these are presented. Various analyses are required for safety systems that are subject to life extension. What equipment and which components are most safety critical? What are the degradation mechanisms and failure modes? What are the suitable models to analyse ageing of the equipment? What are the relevant mitigating measures in order to reduce risk during the life extension period? Finally, the paper identifies main challenges and concerns with respect to ageing of offshore safety systems and operation beyond design life of the facility.

1 INTRODUCTION

A large number of facilities and parts of the infrastructure on the Norwegian Continental Shelf are approaching or have exceeded their original design life. However, many fields have remaining recoverable oil and gas reserves, and it may be profitable to extend the field’s life time. From a safety point of view, the condition of systems, structures and components may not be acceptable for extended operation. Thus, formal assessments are needed to demonstrate that the facility has sufficient technical, operational and organisational integrity to continue safe operation throughout a life extension (LE). This requires detailed information on the history, the current state and prediction on the future state of the facility and its safety systems.

The paper will give an overview of and discuss various aspects of ageing related to offshore safety systems and how to deal with them in a life extension process, i.e. the basis for deciding on LE.

It is a main objective to prevent that LE will increase the probability of major hazards, such as for instance blowout, fire, explosion, ship collisions or structural collapse. To avoid major hazards, it is important to have control with the safety systems, the barriers, their state, and the risk factors influencing each barrier. Thus, to ensure the integrity of the entire facility throughout a possible life extension period, the main focus is on such systems and barriers. Each system should therefore be broken down into subsystems or components, following a barrier line of thinking. The focus is on physical barriers related to the actual equipment and barrier systems. In a complete analysis of ageing, the level of breakdown should proceed until we arrive at units with unique degradation mechanisms or to maintainable items.

The paper is mainly based on a research project carried out in the period from 2008-2010, Hokstad et al 2010). It focused on ageing challenges that relate to process risk and the risk for major hazards for various offshore systems. Safety systems are among five main offshore systems investigated in the report. The work was based on a literature survey, expert information and feedback from international reviewers; but it was limited contact with the offshore industry.

2 OFFSHORE SAFETY SYSTEMS

The standard NORSOK S-001 on technical safety describes the principles and requirements for the de-
Development of the safety design of offshore facilities for production of oil and gas. The standard covers a huge number of safety systems on an offshore facility, e.g., fire fighting system and escape and evacuation, and we suggest these to be arranged in the following set of barriers, ref. Figure 1:

1. Containment and Process Control (PC) system, including alarms and operator intervention. The PC system is in particular important in order to reduce the number of demands on the barriers below.
2. Process safety systems, such as Process Shut Down (PSD) system and Pressure Relief Valves (PSV).
3. Fire and Gas Detection (FGD) and Emergency Shut Down (ESD) system, including isolation, blowdown valves and ignition source control.
4. Active fire fighting equipment (firewater monitors, firewater pumps, ring main, deluge, etc.)
5. Passive fire protection system (firewalls, open and closed drains, etc.)
6. Escape and evacuation routes for emergency preparedness.
7. Rescue and safety equipment for emergency preparedness.

Figure 1. Safety barriers – “The onion model”

Here the barriers are introduced as “onion shells” according to when they are activated upon a demand. Note that barriers 1-3 mainly are frequency reducing barriers while 4-7 are mainly consequence reducing barriers (with respect to major accidents). The focus in this paper is on SIS (i.e., instrumented safety barrier), like PC, PSD and ESD systems. These can be broken down into barrier elements, where some main component groups are:

- Power supply
- Logics and I/O cards
- Transmitters (pressure, temperature, flow, level)
- Detectors (smoke, fire, gas, flame)
- Valves (shut down, pilot, solenoid, isolation, blowdown)
- Cabling and connectors.

So many components are similar for the different barriers, e.g., sensors, logic, and valves. This categorisation of components is also relevant for data collection, maintenance and data availability for analyses, as the failure data is usually established for components such as temperature transmitter, gas detector and shutdown valve, ref. e.g., the PDS data handbook, (Hauge & Onshus 2010).

NORSOK S-001 also refers to a number of relevant standards, in particular IEC 61508, IEC 61511 and OLF guidelines No. 070. These standards give safety requirements on various safety systems; e.g. specifying Safety Integrity Level (SIL), which impose both qualitative and quantitative requirements for a Safety Instrumented System (SIS). It will be essential for LE approval to demonstrate that these requirements are maintained during the LE period. In the analysis of safety systems we should in addition to the failure rate (probability) of a component or system include the demand rate on the safety systems (frequency of fires, leaks, spurious trips, etc.). The product of the demand rate and the Probability of Failure on Demand (PFD) corresponds to the hazard rate, which is a main parameter for safety. Both the demand rate and the PFD (based on component failure rates) may change over time/age. It should also be considered whether systems triggering demands on safety systems are affected by ageing, (such as control systems).

3 ASPECTS OF AGEING FOR SAFETY SYSTEMS

The general aspects of ageing for offshore safety systems are discussed. First some general aspects of ageing are presented.

3.1 General aspects of ageing

Figure 2 illustrates the following categorisation for different ageing issues in ageing management, (adapted from ESReDA 2006):

- Material degradation
- Obsolescence
- Organisational issues and operational needs.

When LE is considered, the main challenges of each of these three aspects of ageing must be identified, plus measures to cope with these challenges. Note that challenges are identified at different “levels”. While material degradation can be evaluated at a component, equipment and system level, the organisational issues are mostly evaluated at system or

1 The PFD is the average probability that a SIS is unable to perform its safety function upon a demand (Hauge et al 2010).
even facility level. Obsolescence will most often be addressed at system level. In this paper we mainly restrict to material degradation and obsolescence.

3.1 Material degradation (physical ageing)
Material ageing is due to e.g. material properties, operational and environmental condition (and changes in operational and environmental conditions) and maintenance practices. All types of barriers which rely on mechanical equipment will be prone to degradation over time, e.g. closing mechanisms and valves. The moving parts become worn, lubrication deteriorates with time, friction increases and corrosion appears (COWI 2003). This ageing will result in the component having an increasing failure rate at the end of “useful life”.

3.1.2 Obsolescence
Obsolescence comprises equipment that is outdated / replaced by something newer, possibly causing challenges related to availability of spare parts. It also includes the possibility of new types of operation, new types of liquid/gas, or operation itself becoming more demanding, resulting in new requirements to existing equipment design.

In addition, obsolescence includes new needs; for instance to extract oil from reservoirs located further away from the facility, new tie-ins and new types of wells are needed. This, in turn, results in a need for new technology. Modifications on the facility involving the safety systems may also cause increased failure rates or demand rates not being an inherent property of the equipment.

3.1.3 Organisational issues
Organisational issues deal with the importance of having clear responsibilities, maintaining expertise (e.g. transferring knowledge from retiring personnel) and revising documents. Operator competence may prove critical; e.g. manning being reduced and partly moved onshore.

3.2 Material degradation of safety systems
Often electronic components are experienced not to have a change in failure rate during the lifetime. Thus, often no reduction of expected residual life can be documented as a consequence of long operational time. So a common assumption in reliability analyses is no ageing effects for electrical components. This implies that the probability of failure the last year and next year are expected to be the same (during the design life). However, it should be emphasized that this is a rather general statement. Some equipment may be exposed to harsh environment (e.g. heat, corrosive atmosphere), giving increased failure rate. And (COWI 2003) states that electronic equipment consists of components with a finite life time / design life and that the performance of equipment will degrade with time and has to be replaced.

Another argument supporting limited effect of ageing is the frequent testing and replacement of these components when they are degraded. However, for subsea components the accessibility for testing and replacement is more limited. Then, material degradation is more relevant e.g. during LE. Also, some of the topside equipment like control systems are not very often replaced.

Various degradation mechanisms can occur for main barrier elements of safety systems. Field instrumentation, such as sensors and detectors, transmitters, logics, valves and power supply, may be exposed to varying temperatures, heat, high voltages, vibrations, humidity, fog, snow, salinity and various chemical substances during its life time.

Excessive heat is an important operational factor influencing the lifetime of electronic components, both surrounding temperature and heat generated by too higher than expected supply voltages. For power supplies electrolytic condensers “dry out” and must be replaced. Power supplies are also typically more seldom replaced. Some special components like electrolytic capacitors may experience increasing failure rate.

Logics are exposed mainly to excessive temperature and humidity, while the most common degradation mechanism of I/O cards is fatigue due to high number of movements/cycles (Hokstad et al 2010). On the other hand, I/O cards, processor cards and cabling in and between cabinets have relatively controlled environment during its expected lifetime.

Detectors (smoke-, fire-, gas- and flame-) can be exposed to mechanical damage and poisoned, e.g. due to dust, fog or snow causing reduced sensitivity (TWI 2007).

Typical degradation mechanisms for transmitters leading to malfunctioning are blockage (of piping connection), corrosion and fatigue (due to external vibration) (Hokstad et al 2010). One should also beware of leakage points in particular for transmitters.
Transmitter failures could also be caused by wrong impedance.

Degradation mechanisms for valves are typical wear (from several similar operations), corrosion and erosion (due to humidity, sand, hydrates, ice, etc.), fatigue (due to vibration) and contamination of the actuating medium. The latter can lead to failure to close/open or clogging of supply/return line (TWI 2007). For components with mechanical moving parts, inspection to assess degradation due to environmental stress is recommended.

Cabling and connectors may be vulnerable to vibrations, heat and chemicals, and inspection to assess degradation due to environmental stress is required. The state of cabling is particularly important as it can be the cause of CCF. Moreover, cabling is not very often replaced, and is possibly not tested as regularly as most other equipment.

In general, components have to be operated within its specified environmental limits. It is also emphasized the importance of proper registration of failures to enable follow-up, e.g. if increased number of failures is observed, more detailed analysis is necessary to establish residual life or more frequent testing is necessary to fulfill the quantitative requirements.

3.3 Obsolescence of safety systems

As a facility changes, equipment become outdated or new operations and/or new regulations require new technology. With respect to obsolescence of safety systems it is particular necessary to identify challenges related to:

- Requirements and regulations
- Spare parts.

3.3.1 Requirements, regulations, documents and assumptions

When a facility reaches the end of service life, it is likely that regulations, requirements and other documents have been revised after the facility was designed. Typical examples are requirements related to environment and spills, new safety requirements, new technical requirements for equipment and requirements regarding modifications, e.g. new/updated versions of IEC 61508 and IEC 61511. Do the various functions/systems satisfy all present regulations/requirements? All SIS related requirements, assumptions and prerequisites from the design phase (or operational phase) that may affect how the SIS is operated and maintained must be transferred to the applicable documents and responsible follow-up parties in a consistent and complete manner. An important activity will be to verify consistency between the different premises and documents from design/operation in order to ensure that the correct requirements are being passed on to the extended life.

Typical documents, containing numbers of assumptions relevant to safety systems, are the Quantitative Risk Analysis (QRA), Process and Instrument Diagrams (P&IDs), Safety Analysis Reports (SAR) and Safety Requirement Specifications (SRS). Important assumptions made in the QRA are reliability targets for SIS and response times for valves. Other relevant assumptions (made in the SIL allocation) are diagnostic coverage, fail-safe design, loop monitoring, failure rates, test intervals, activation principles, credits for alternative protection systems, independency, etc. (Hauge & Lundteigen 2008). The SAR is a report that documents that the safety instrumented functions comply with the specified SIL and reliability targets. It contains assumptions like functional test intervals and how the SIS are to be tested, maximum allowable repair times for redundant equipment, demand rates, functions that are not to be inhibited or overridden, response times, etc.

Also, recalculation of reliability analyses based on updated failure rates, configurations, equipment types etc is necessary. Assumptions made during design / previous calculation may have changed and is no longer valid. As a consequence, there may be a need to update maintenance procedures and corresponding documents.

3.3.2 Spare parts

Availability of spare parts may become a challenge for equipment being or becoming outdated, or if it was made by manufacturers who no longer exist or can give no support into the future. This is rather typical for electrical equipment, instrumentation, control systems and software.

There is a need for provision of spare parts throughout planned LE, and timely replacement of parts, long term agreements with suppliers, and development of equivalent structures or components. Availability of spare parts or replacement parts should be continually monitored and controlled (IAEA 2009). Consequences of lack of spare parts etc. are decreasing reliability (e.g. reducing voting from 1oo2 to 1oo1), and declining performance and safety of facility. There should be procedures to provide required technical support and sufficient supply of spare parts.

It is also important that spare parts are stored and maintained according to manufacturer’s specification. If spare parts or consumables could be vulnerable to degradation due to their stocking environment (e.g. temperature, moisture, chemical attack, dust accumulation), measures should be taken to ensure that they are stored in an appropriately controlled environment.
3.3.3 Operational needs and conditions for safety systems.

New operational needs can result in space challenges and will often require new equipment and changes in overall layout on the facility. More equipment may increase the complexity, turbulence, etc. such that location of e.g. detectors should be re-assessed.

Some examples of new operational needs or conditions are changing temperature and pressure of the produced oil/gas, or conversion from oil to gas production. Equipment was originally designed for other liquid types, other temperatures and pressure conditions. Consequences may be increased failure rates and material degradation resulting in lower system reliability for the new operation. Modifications and new well solutions can be required, and thus for instance well intervention or new safety equipment could be needed.

4 REQUIRED PROCESS FOR LIFE EXTENSION

In order to accept LE it will be required to carry out a set of analyses. Here we look into the required process and modelling to perform the analyses and identify compensating measures.

4.1 The LE process

When LE is considered the main question is how to perform the process for deciding whether LE can be performed without compromising safety. The length of a possible LE period depends on the facility’s ability to maintain the technical, operational and organisational integrity.

The first task is to identify all (possible) challenges related to ageing and future operation; incorporating the whole facility and all safety related systems and equipment on the facility. For instance, will there be any changes during a future operational period, resulting in challenges? Secondly, the risk related to these challenges should be analysed (for the entire LE period). Finally, a maintenance and modification plan to reduce the risk contribution from all equipment and systems must be prepared and implemented in order to maintain (or, if required, improve) the safety integrity and to comply with the current requirements.

Part of the LE assessment is to carry out analyses to identify the possible deviations of equipment, organisations and human resources, in terms of the ability to satisfy all future demands and requirements. Hokstad et al. (2010) and Håbrekke et. al. (2011) present a suggested framework for the LE process for main systems following six activities:

1. Perform a Criticality screening, to identify critical units and barriers with respect to failure consequence and probability.
2. Analysis of failures: With respect to material degradation detailed failure analyses of the most critical barriers/components is performed (e.g. lifetime prediction).
3. Analysis of challenges: With respect to obsolescence and organisational issues it is necessary to identify challenges and gaps in particular in relation to current (or known future) requirements.
4. Identification and evaluation of potential risk reducing (compensating) measures, e.g. modifications, updated test procedures and increased redundancy or diversity of units.
5. An assessment of the overall risk picture of the facility based on all aspects of ageing, given the risk reducing measures.
6. If the overall risk picture is acceptable, an LE management plan should be implemented that ensures integrity throughout the LE period and makes sure that the facility’s technical, operational and organisational integrity level is maintained during the LE. This includes maintenance and operational plans and framework for implementation of necessary risk reducing measures. If the overall risk picture is not acceptable, additional risk reducing measures must be identified.

4.2 Analysis and modelling of ageing

Normally we think of ageing as degradation over time, but not all equipment ages proportional to time, e.g. time since manufacturing or time in operation. Other relevant ways to measure ageing is by demand rate, number of performed functional tests or number of operations. E.g. I/O cards are designed for a certain number of operations, and should then be replaced. Thus “age” for these components should be given as number of operations. In general, the ability to decide the state and also replace units if required is generally rather high for safety system components. This should reduce the need for elaborate assessments of risk and LE. However, time since replacement is essential information, e.g. for logics and transmitters that are not often replaced.

In general, life time estimation should include both physical (degradation) modelling and probabilistic modelling, ref. ESReDa (2006).

To understand the process from incipient fault to propagation, to detect faults and anticipate their evolution, it is necessary to identify the degradation mechanism at work, and to have knowledge of the physical phenomena. Also design/operational/ process parameters and maintenance should be specified (present and future) to assess current and future state.
Figure 3 indicates a model for the level of degradation. In this particular case, a specific level of degradation defines “failure” (here rupture). Ageing of e.g. cabling could be modelled using physical models.

![Figure 3. Evolution of level of degradation (ESReDa 2006).](image)

Various probabilistic models are applicable:

- **Life time models**: i.e. models for the time to first failure; often expressed as a model for the failure rate. It can be a bath tub curve, constant (meaning exponential model), Weibull, etc. Examples of such failure rate models (life time models) are shown in Figure 4.

![Figure 4. Examples of failure rate (life time) models.](image)

- For repairable units we rather use ROCOF (Rate of Occurrence of failure), which is a function both of time and maintenance strategy.

- **Markov models** are applicable to model transitions between various states of degradation (e.g. perfect, degraded and failed). Ageing of valves could be modelled with Markov models comprising the three states “functioning”, “degraded” (e.g. too long closing time) and “critical” (e.g. fail to close).

- **Probability of Failure (PoF) models**, expressing PoF directly in terms of level of degradation of unit (cf. Figure 3) is also an option.

For safety systems life time models are the most applicable. An exponential distribution is good for modelling items whose failure rate changes negligibly with age and equipment whose infant mortalities have been eliminated. However, it is not always correct to use the exponential distribution, i.e. assuming that the component is “as good as new” after each test.

### 4.3 Compensating measures

Obvious measures to compensate for ageing of safety systems are:

- more complete (higher quality) testing/inspection and follow up, besides
- increased (more frequent) periodic (functional) testing.

However, other measures should be considered both to protect against and to monitor ageing and degradation of safety systems.

#### 4.3.1 Functional testing

Operator must demonstrate high quality of tests (and subsequent maintenance) to ensure technical integrity. Since safety systems are not in continuous or active use, they may have dormant failures, so functional testing of safety systems is essential. The frequency, coverage and procedures for testing (e.g. introduction of staggered testing) could be improved. Also, follow-up of failure rates of various component groups should be performed regular in order to optimise the test frequency.

#### 4.3.1 Automatic self test

Automatic self test for sensors and logics is important to detect various failures instantly (and essentially remove the effect of these, if handled effectively). Thus, high degree and frequency of diagnostic self-tests are preferred. However, frequency of self-tests should not be too high, as excessive self-testing may itself contribute to degradation of some equipment.

#### 4.3.2 Design

A way to improve the safety system is to replace or rebuild old systems, e.g. replace switches with transmitters, replace logics, valves and cabling above certain ages or introduce redundancy. Transmitters give better monitoring and for instance reduce danger of CCF.

The degree of redundancy is essential for safety systems as it increases reliability and may be required for safety valves to satisfy safety requirements (e.g. SIL and PFD requirements). A one-out-of-two (1oo2) system is much safer than two-out-of-two (2oo2), etc. Other design solutions to prevent failures are diversity and separation (in time and space). Redundancy is also relevant for monitoring.
For instance “parallel measurements” of pressure transmitters give essential information.

4.3.3 Indicators

Indicators are measurement to follow-up and monitor the risk and state of barriers or components from ageing. Typical LE activities are establishment and follow-up of such indicators, indicator targets and analysis of collected data to verify whether the performance targets are met. An example of a component indicator is closing time of valves. Valve closing more slowly, or having increased leakage in closed position, may be indicators of a degradation failure.

5 DISCUSSION AND CONCLUSION

There are various challenges related to ageing and LE of offshore facilities and their safety systems. Some of the concerns regarding safety systems are discussed below, in particular addressing topics where the state of knowledge should be increased.

5.1 Safety system hazards

It is a specific feature of the safety systems that they represent barriers for major hazardous events like fires and explosions, (by reducing probability and/or consequence). These systems themselves are seldom the cause of risk. However, it should be noted that also the safety systems themselves can be hazardous. Electric equipment in general is a well-known cause of fire. Lightening is an external hazard and a possible cause of safety system failures; also resulting in Common Cause Failure (CCF). Thus, lightening protection is an important risk reducing measure for safety systems. Consequently, lightening activity and lightening protection and changes in these during the life extension period should be considered.

Also, new hazards may arise from new firmware or new security threats.

Finally, the impact which modifications of safety systems can have on other systems should be addressed. This is also relevant the other way around, i.e. whether modifications of other systems affect the independence between safety protection layers.

5.2 Increasing PFD contributors: Failure rate, demand rate and CCF

There is a lack of knowledge about ageing and degradation mechanisms for certain equipment types. In particular ageing of electronic systems may be a challenge.

The exact degradation process and time to failure distribution is hard to assess, and new knowledge should be achieved by developing probabilistic models for state of critical components, using real offshore failure data to fit a life time distribution. In addition, not all equipment is considered in standard reliability analyses (e.g. hydraulic return lines for closure of safety valves). Cabling is not subject to the same degree of testing as most equipment, and so it can be a challenge to identify its status (remaining life).

Besides increasing failure rates due to e.g. material degradation, increasing demand frequency is important to be aware of during LE. Tripping the safety systems (either due to real demands or spurious trips) can increase as the entire facility ages.

Also, CCF are important for the life extension evaluations, in particular for redundant equipment. There are various types of dependencies, e.g. physical-, functional, location-/environmental-, plant configuration- or human dependencies. In general a CCF analysis should consider failures due to common causes/stresses.

Common ageing of various components and equipment on a facility during the LE period can possibly result in a common (sudden) increase in the failure rate. This means that the contribution from CCF, which often is the largest contributor to the total PFD compared to independent failures, may increase.

5.3 Testing procedures

It is difficult to evaluate the quality of functional testing and inspection. With respect to manual functional testing it is often assumed that these tests have coverage of 100%, i.e. all failures not covered by self-testing will be revealed during functional testing. However, in practice also these tests are imperfect. Will they become even less perfect when equipment ages? What is the actual “coverage” of the functional tests?

The common assumption that tested systems are as “good as new” should be challenged for various equipment (both mechanical and electrical). This assumption may not necessarily be valid for ageing equipment or during an LE period. One should be aware of what “as good as new” means for different components, and what actions must be taken to restore the equipment to this condition after functional testing.

Obviously, an increase of the testing frequency is one way to reduce the PFD. However, note that more frequent testing will not necessarily increase the reliability over time, as testing can also increase degradation or introduce new failures. During a functional test there is always a possibility that new failures are introduced for instance due to incorrect calibration or incorrect restoration of tested equipment.
5.4 Further research and development

The following recommendations for research and development regarding ageing and life extension of offshore safety systems have been identified in the study:

− Analyses of degradation mechanisms of critical systems, comprising modelling of the main degradation mechanisms, considering the combined effect of various degradation mechanisms, common cause failures and effect of operational conditions.
− Development of systems for data collection and use of field experience with degradation failures.
− Improving maintenance management systems for ageing and life extension of safety systems so that all three ageing aspects are being “processed” in parallel, including also e.g. combinations of old and new equipment, availability of spare parts, common cause failures and new technology.

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7 REFERENCES

HSE, Plant ageing. Management of equipment containing hazardous fluids or pressure. 2006.


8 ABBREVIATIONS & NOTATION

CCF Common Cause Failure
ESD Emergency Shut Down
FGD Fire and Gas Detection
HSE Health and Safety Executive (UK)
IAEA International Atomic Energy Agency
IEC International Electrotechnical Commission
I/O Input/Output
LE Life Extension
OLF The Norwegian Oil Industry Association
PC Process Control
P&ID Process and Instrument Diagram
PFD Probability of Failure on Demand
PoF Probability of Failure
PSA Petroleum Safety Authority, Norway
PSD Process Shut Down
QRA Quantitative Risk Analysis
ROCOF Rate of Occurrence of Failure
SAR Safety Analysis Report
SIL Safety Integrity Level
SIS Safety Instrumented System
SRS Safety Requirement Specification
SRS Safety Requirement Specification
TWI The Welding Institute