Integrity Challenges in Harsh Environments: Lessons Learned and Potential Development Strategies

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Vast reserves in the Arctic and sub-Arctic regions have attracted interest of the oil and gas industry. However, oil and gas development in harsh environments faces significant technical and logistical challenges. A workshop on "safety and integrity management of operations in harsh environments" was organized by the Safety and Risk Engineering Group at Memorial University of Newfoundland focusing on main aspects of asset integrity. The event featured representatives from industry, regulatory authorities, and research and development institutions. Participants shared experience and lessons learned, and together developed a roadmap for achieving desired solutions.

This paper briefly reviews the lessons learned from the two-day workshop and shares recent developments and applications of risk-based approaches to degradation modeling, integrity assessment, and inspection and maintenance decision-making in harsh environments. The recently developed novel approach of risk-based winterization method is introduced. This approach helps to analyze how much winterization is sufficient to address local and regional weather loading considering operating envelop and criticality of the components or the system. A case study from the Arctic region is used for discussion.

Keywords: Harsh environment; asset integrity management; risk-based inspection; risk-based maintenance; degradation modeling.

Introduction

Development of natural resources in the Arctic and sub-Arctic regions faces huge challenges. The Arctic harsh environment is mainly characterised by a short productive season, low temperatures, extreme ice features, icebergs, permafrost and icing, extreme winds, and storms. Because of these hazardous environmental conditions, the development of vast natural resources in the Arctic encounters significant technical and operational challenges. Some of these challenges are due to complex degradation rates, unpredictable climate changes, and high uncertainty due to lack of knowledge and data. Several incidents, such as the recent one in 2012 in Beaufort Sea (Natural Resources Defense Council, 2013), have proven that the threat to the Arctic ecosystem is amplified due to lack of adequate technology or infrastructure to prevent and respond to accidents. This includes the stoppage and cleanup of hydrocarbons releases. The research report by Short et al. highlights that "the slightly weathered Exxon Valdez oil spill in 1989 persists in Gulf of Alaska beach sediments after 16 years" (Short et al., 2007). These experiences leave little doubt that to move into deeper water and more severe ice conditions, it is necessary to be as proactive as possible keeping in mind that it is very difficult to respond effectively to an accident in a harsh environment such as the Arctic.

To stimulate strategic research initiatives, with the purpose of supporting oil and gas development in harsh environments, on March 19-20, 2013, approximately 120 researchers and practitioners came together from different parts of the world for a workshop on "safety and integrity management of operations in harsh environments". This workshop was organized by the Safety and Risk Engineering Group (SREG), a research division of the Faculty of Engineering and Applied Science at Memorial University of Newfoundland. The objectives of the workshop were to identify and prioritize the risks and challenges for operations and exploration in harsh environments, strategize a plan for solutions, and disseminate knowledge and advances in safety and asset integrity in harsh environments. In a recent work, Khan et al. reported and discussed the safety challenges regarding process and occupational safety, risk assessment with scarce data, winterization, and human factors based on the workshop findings (Khan et al., 2013). This work identifies the integrity challenges in harsh environments, shares the lessons learned, and proposes potential strategies to overcome the identified challenges.

The following section aims to recap the integrity challenges identified by the workshop participants. The rest of the article shares recent developments and applications to address the integrity threats to operations in extreme conditions. In Section 3, the risk-based asset integrity management (RBIM) is introduced as an effective inspection and maintenance decision making tool to ensure safety and integrity of the facilities operating in harsh environments. Section 4 proposes a risk-based approach for the selection of winterization technologies and determination of winterization levels. A case study is used to demonstrate how the proposed approach can be applied to the identification of heating requirements a pipeline on a vessel deck. Finally, Section 5 provides conclusions and some recommendations for future work.

Integrity Challenges in Harsh Environments

Hidden degradations, such as corrosion and cracking under insulation, was identified as a major potential integrity threat in harsh environments. Pitting corrosion was listed as a significant contributor to this threat. To understand and model degradation in winterized conditions is a key challenge to address design, inspection, and maintenance of such assets. Since most of the degradation mechanisms are stochastic processes, the inspection data are also random in nature (Thodi, Khan, & Haddara, 2013). To overcome this challenge, a Bayesian approach is proposed in Section 3 that allows to incorporate the effect of uncertainty in data and model asset integrity using real-life inspection data.

Another major challenge in inspection and maintenance of assets in harsh environments is the variability in operating conditions. This, along with design and modeling uncertainties pose practical problems to decide the required sample size to represent the population. Obtaining representative samples is a problem in harsh environments due to difficulties in conducting inspection and collecting data. There are limited studies aiming to address assessment of the localized corrosion sample size. As discussed in Section 3, integration of extreme value method with Baye's theorem may help addressing this problem.

Lack of data and information in harsh environments is another serious problem in reliability modeling and decision making. Choosing appropriate data that can best represent the conditions in harsh environments is challenging. On-line monitoring will be helpful for data collection to conduct reliability modeling and to know about assets aging. However, on-line measurements are challenging as well as costly in harsh environments. Current reliability models should be adapted for harsh environments by using more conservative assumptions and enhancing criticality of analyses; utilization of the risk-based methods may also be more effective. As described by Khan et al. (2013), potential sources of information and data include:

- Expert knowledge and experience
- Input from local residents in the Arctic and sub-Arctic regions
- Data and information shared across industries that have operations in harsh environments

Therefore, technologies, infrastructure, and regulations should be developed to record, retain, and share information; however, all associated confidentiality issues should be considered.

Another issue that requires careful consideration during the design stage is the effect of unpredictable climate changes on design and operational integrity. To deal with dynamic changes in environmental factors in harsh environments, extreme parameters, such as wind speed and temperature, along with effective and efficient winter protections must be considered in design. Pre-start testing of seasonal pipelines is also required to prevent failure due to unpredictable climate change.

Load monitoring and load characterization are also identified as practical challenges of offshore operations in harsh environments. Ship sizes are becoming larger and conventional load characterization methods are not applicable due to their limitations. Modes of operation are also changing; new tankers are no more escorted by ice breakers. Traditionally, captains would have just followed the ice breakers; however, in the new mode of operations without icebreakers, they have more responsibility in navigation. Therefore, new systems are required which are less dependent on human input and have features such as the predictability of ice load to aid decision making about the best direction. Stress-based load monitoring techniques and probabilistic approaches to load characterization could address these challenges.

In summary, based on the knowledge sharing and discussion with industrial participants of the workshop, the following main integrity challenges of operations in harsh environments are identified:

- scarce information and lack of knowledge on degradation mechanism and their impact
- stochastic nature of degradation and their consideration in design
- determination of winterization requirement
- effect of unpredictable climate changes on design and operational integrity,
- ineffectiveness of conventional load monitoring and load characterization methods

Next section describes different aspects of these integrity threats and provides potential development strategies to address these challenges.

Risk-Based Integrity Management (RBIM)

Due to the high level of difficulty associated with inspection and maintenance activities in harsh environments, a holistic approach is needed for integrity management of process equipment. The integrity challenges should be considered early at the design stage to minimize inspection, maintenance, and replacement activities. Risk-based integrity management (RBIM) is a method that uses risk as a basis for inspection and maintenance decision-making to ensure safety and integrity of a system. Risk in this context (RG comment – because there are other risk definitions which are different to this e.g. consequence severity x likelihood) is a function of design limits, operating conditions, system characteristics, materials of construction, and the history of system operation. Asset integrity has a broader definition compared to reliability. In addition to functionality, it also includes the safeguarding of life and environment for the entire useful life of an asset. RBIM provides the ability to target resources to the areas where it is needed the most with the objective of minimizing business and public health risks and maximizing return on assets. It also helps to minimize the overall operational risk.

Risk-based framework for asset integrity management

Degradation mechanisms are the most critical environmentally induced asset integrity threats (Thodi, Khan, & Haddara, 2010). Cold temperatures, corrosive sea waves, excessive moisture and insulation affect corrosion and cracking mechanism in harsh environments. Winterization techniques such as steam and electric tracing introduce their own complexity, and sometimes new degradation mechanisms, into the system. Due to the stochastic nature of the degradation mechanisms, they can be best described using risk-based approaches. However, utilization of risk-based approaches, particularly quantitative methods, requires availability of input information. Due to adverse environment and geological conditions, inspection in harsh environment is physically and technically challenging. Also performing high frequency inspection in harsh environment is difficult. Therefore, lack of input information is a challenge in performing conventional risk-based techniques.

Bayesian approach is a decision making process where there is minimal information from the system. After obtaining more information from the asset service, Bayesian approach enables the combination of current understanding with additional asset information to help make informed decisions. This approach keeps updating the understanding from asset condition and its probability of failure to revise the actions whenever needed. The more information obtained from the asset, the more confidence will be gained in calculated results.

Figure 1 illustrates the general framework for RBIM, modified from Thodi et al. (2013). As can be seen in Figure 1, risk assessment has two components: stochastic degradation modeling and economic consequence analysis which are discussed in the following section.

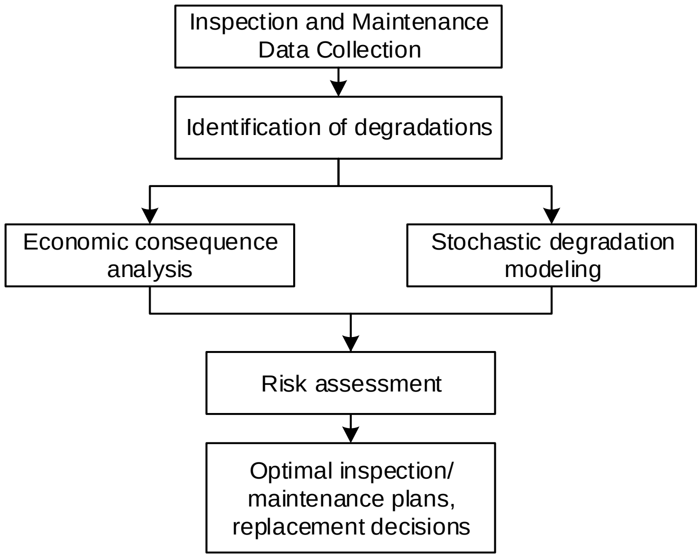

Figure 1. Risk based integrity modeling framework (modified from Thodi et al., 2013)

Probabilistic stochastic degradation modeling

To model the stochastic degradation mechanisms, the Bayesian prior-posterior analysis has been used where the prior knowledge of the system and field data are input to predict future behaviour. The Bayesian approach takes advantage of the Bayes' theorem to update the prior probabilities of variables, $p(\theta)$, given new observations, $p(y|\theta)$, rendering the updated or posterior probabilities (Thodi et al., 2010):

$$p(\theta/y) = \frac{p(\theta)p(y/\theta)}{\int p(\theta)p(y/\theta)d\theta} \quad (1)$$

The first task to apply Bayesian approach is the prior probability modeling based on the expert's prior knowledge and the inspection information such as non-destructive test (NDT) data. An estimation of the prior failure rates and probability values can be obtained by analyzing historic data from the same or other similar components. Thodi, Khan, & Haddara (2009) tested several probability distributions to develop the prior models for different corrosion mechanisms using the data extracted from the relevant literature. Once the prior probability distribution of components failure rate is determined, the inspection data is used to estimate the likelihood probability of different types of corrosion degradation. For the case of general corrosion for instance the inspection data include ultrasonic thickness measurements of a pipeline. Likelihood probability can be modeled by standard probability models using probability plot and good-of-fit methods. Finally, having known prior and likelihood functions, the posterior probability will be modeled using Bayes' theorem (Equation 1). Thodi et al. (2010) proposed four methods for computing the posterior distributions: analytical approximations, such as numerical integration techniques and Laplace approximations; data augmentation methods, such as the e-m (expectation-maximization) algorithm; Monte Carlo direct sampling and Markov chain Monte Carlo (McMC) methods, such as the M-H algorithm and Gibb's sampling. Simulation or Monte Carlo methods are required to estimate the posterior parameters if the problem under consideration does not involve a conjugate prior-likelihood pair. Interested readers are referred to Thodi et al. (2010) for the development of posterior probability models in risk-based integrity modeling.

Consequence analysis

Component failure due to degradation mechanism and subsequent loss of containment of hazardous fluids from pressurized processing equipment may result in damage to surrounding equipment, serious injury to personnel, production losses, and undesirable environmental impacts (American Petroleum Institute, 2008; CCPS, 1999; Khan & Amyotte, 2005). Harsh environmental conditions restrict the prevention and/or response activities and therefore the loss of containment from the facilities results in severe consequences. Therefore, consequence analysis is an important part of implementing RBIM in harsh environments. For the purpose of consistency in measured risk from many contributing sources, dollar unit can be used to express different consequence categories (Hashemi, Ahmed, & Khan, 2013; Thodi et al., 2013).

Thodi et al. (2013) developed an overall framework for economic consequence analysis of failure costs where the failure cost is defined as the cost associated with the loss of a facility due to structural deteriorations. The total failure cost due to degradation mechanisms, such as corrosion and cracking, is given by the sum of inspection and maintenance cost and failure cost. Cost of failure can have different elements including loss of product, loss of shutdown, spill cleanup, nature damage, and liability charges. Inspection and maintenance costs may include gaining access, surface preparation, testing and inspection, repair, and replacement. Based on the consequence category and available information, there are different methods for computing these loss elements including (American Petroleum Institute, 2008; CCPS, 1999; Hashemi et al., 2013; Khan & Amyotte, 2005). Thodi et al. (2013) proposed the consequnce analysis methods for different loss elements for the case of offshore operations. These methods need to be adopted to be applicable for hasrh environemnt conditions.

Inspection, maintenance, and replacement planning

The premise of inspection, maintenance, and replacement planning using RBIM is based on the fact that at some point in time, the risk as defined in Equations (2) exceeds an acceptable level of risk:

$$R = F\left[p\left(\theta/y\right)\right] \times COF \qquad (2)$$

where R is the risk of failure from a degradation, $F[\ p(\theta/y)]$ is the cumulative density function (CDF) of posterior probability of failure and COF is the consequences of failure in dollar (Thodi et al., 2013). An inspection and/or maintenance of the equipment is recommended when or before the risk threshold is reached. Inspecting a piece of equipment does not necessarily reduce the inherent risk associated with that piece of equipment; however, inspection does provide knowledge of the damage state of the vessel and reduces uncertainty. Therefore, the probability of failure is directly related to the amount of information that is available from inspection/maintenance and the ability to quantify that damage (American Petroleum Institute, 2008). The age-related structural degradations increase the probability of failure over time that may necessitate the replacement of components. In such a case, RBIM will assist asset integrity engineers/managers in estimating optimal replacement intervals (Thodi et al., 2013).

RBIM provides a forward looking approach for uncertain, dynamic, and highly variable situations of harsh environments. Additional research is required to adopt RBIM method to incorporate the characteristics of such environments.

Estimating sample size to assess corrosion

While there are several standards and industrial guidelines that provide recommendations for conducting inspection and determining frequency of inspections, they do not provide specific guidelines for inspection sampling. As a result, the decision on inspection sample size is left for the inspection practitioner’s judgement (Khalifa, Khan, & Haddara, 2012b). Decision making about the required sample size to ensure that the inspection sample represents the population is a practical problem (Khalifa et al., 2012a). A conservative approach to tackle this problem is to choose a larger sample size to decrease the error in the sample estimate. However, considering the cost and the difficulties associated with inspection of process components operating in harsh environment, as well as the variability and uncertainty in operating conditions, a structured framework to estimate the optimal inspection sample size is required.

Khalifa et al. (2012b) proposed a Bayesian approach-based method to determine the minimum size for inspection samples used to assess the condition of process components subjected to general corrosion. The posterior sample mean was used as a basis to assess the population mean metal loss due to general corrosion. Based on the above mentioned method, a suitable sample size should meet an acceptable margin of error in the estimate of the posterior sample mean at a given confidence level. A Bayesian updating process using current inspection data is used to update prior information.

Few studies have been done for calculating sample size to assess localized corrosion of process components. Khalifa et al. (2012a) addressed this problem by proposing a four step methodology which includes layering separation of component by assigning them into different corrosion circuits; physical sampling within each components group, bootstrap sampling to estimate standard error and confidence interval and extreme value analysis to predict the maximum localized corrosion, and finally calculation of sample size to predict the maximum localized corrosion within each group.

In a recent work, Khalifa, Khan, & Haddara (2013) addressed the inspection sampling problem for pitting corrosion and proposed a methodology to estimate the sample size by integrating the Bayesian updating approach and the extreme value method in a single framework. They used the extreme value method to predict the maximum pit size by extrapolating the inspected area (sample) to the entire area of the asset. The Bayesian updating approach is used to update prior information obtained from the previous inspection once newly obtained information is available from the current inspection. This allows using a smaller sample size with similar precision.

There is a lack of research to address the problem of inspection sampling for other common damage mechanisms such as fatigue, creep, and corrosion-fatigue-creep interaction. More research should be conducted to adapt existing inspection sampling methods for application in harsh environments.

Winterization

In harsh cold environments, many systems will be operated at or close to their design limits. This will require augmentation of normal performance monitoring of systems to prevent failures. Winterization is essential for safe and efficient operations in cold environments. The marine and offshore industries have been working on winterization for many years. However, it still remains challenging to many who wish to venture into harsh cold environments for hydrocarbon resources or shorter navigation routes. Most guidelines developed by classification societies provide prescriptive requirements for winterization, e.g., Guide for Vessels Operating in Low Temperature Environments (LTE Guide) developed by ABS (American Bureau of Shipping, 2010). Although these requirements provide comprehensive guidance, there are many situations that may require additional consideration owing to variations in systems and arrangements, environmental conditions, and operational profiles. Systems on modern vessels and offshore operation units are complex; moreover, to address new operational challenges in harsh cold environments these systems will continue to see novel concepts employed. Therefore, it becomes nearly impossible to provide a complete prescriptive guideline or rule set for winterizing an installation. Considering this, a performance-based guideline is preferable. A risk-based approach to winterization would be one way forward in this direction. The following discusses risk-based winterization with a simple example application.

Yang et al. (2013) proposed a risk-based approach to winterization. This quantitative approach is intended to provide a rational way of determining the need for winterization and its level on a case-by-case basis. In order to characterize the environmental load within the risk-based framework, a better understanding of the temperature and duration of exposure is required. Loading scenarios are defined by statistical analysis of hind cast temperature data to obtain probabilistic distributions of loadings for various durations of exposure. Risk is estimated under different loading scenarios. Based on the estimation, need for winterization is determined. The proposed risk-based approach also provides the opportunity to determine appropriate winterization levels, e.g., heating requirements. It can be estimated by setting risks after winterization equal to the acceptable level. The following example illustrates the application of this approach.

Risk-based winterization is applied to a pipeline on a vessel deck. Assume that:

a) Load (extreme temperatures for 24 hours duration 100 year return period) follows a normal distribution with mean μ_1= -45.8 and standard deviation σ_1= 1.1;

b) Operating temperature, T_{op} (the temperature to be maintained for normal operation of a system), follows a normal distribution with μ_2= 10 and σ_2= 4

c) $\left|\Delta T_{Limit}\right|$ = 25 °C = k (the maximum allowable temperature difference between the load and operating envelop of a system without winterization)

Since $\left|\Delta T_{Actual}\right|$ = $\left|L - T_{op}\right|$ (the difference between the load (L) and operating temperature), then $\left|\Delta T_{Actual}\right|$ may follow a normal distribution with μ=$\left|-45.8-10\right|$ = 55.8 and σ= $[(1.1)^2+(4)^2]^{0.5}$ = 4.14

$$\text{PoF} = \Pr\left(\left|\Delta T_{Actual}\right| > k\right) = \int_k^{\infty} f_{\Delta T_{actual}}(\Delta T_{actual})\, d\Delta T_{actual} = 1-\Phi\left(\frac{k-\mu}{\sigma}\right) = 1-\Phi\left(\frac{25-55.8}{4.1}\right) = 1.00$$

where PoF is the probability of failure. Severity levels of consequences depend on the criticality of systems. Criticality can be determined based on experts' opinions. Different criticality levels may correspond to different financial losses and injury fatalities. For simplicity, a severity value is used to represent the consequence in this example. The severity value of the consequence of failure of a pipeline on deck is assumed to be 3. Figure 2 gives an example of a risk matrix that could be used for risk estimation. According to Figure 2, the risk is considered high. Therefore, winterization methods must be applied.

Electric heat tracing combined with insulation is the appropriate winterization option for the pipeline. For illustrative purpose, dimensions and materials of pipeline and insulation were assumed and are given in **Error! Reference source not found.**. According to the risk matrix, the maximum PoF value is 0.001 if the low risk is acceptable.

Considering the same load:

$$\text{PoF} = 1-\Phi\left(\frac{k-(\mu-E)}{\sigma}\right) = 1-\Phi\left(\frac{25-(55.8-E)}{4.14}\right) = 0.001, \text{ then } \frac{25-(55.8-E)}{4.14} = 3.09, \ E = \Delta T = 43.6\ °C$$

Where E is defined as the winterization efficacy, i.e., the capacity of a winterization method to produce freezing protection effect or the capacity to reduce the temperature difference between the load and operating temperature.

Assume that the average wind speed is 20 m/s, then $h_c = 7.6v^{0.78} = 78.63$ (W)/(m^2)(°C) ,where h_c is the convective heat transfer coefficient and v is the wind speed.

The overall U (conductivity) is:

$$U = \frac{1}{\frac{1}{h_c} + \frac{x_{steel}}{k_{steel}} + \frac{x_{fiberglass}}{k_{fiberglass}}} = \frac{1}{\frac{1}{78.63} + \frac{0.006}{43} + \frac{0.025}{0.04}} = 1.57 \text{ (W)/(m}^2\text{)(°C)}$$

Where X_{steel} and $X_{fiberglass}$ represent the thickness of the steel pipe and insulation.

The heat transfer area for one-meter pipe without and with snow layers will be:

$$A = 2pl[\frac{r_{outer} - r_{inner}}{\ln(\frac{r_{outer}}{r_{inner}})}] = 2\pi \times 1 \times [\frac{0.0825 - 0.0510}{\ln(\frac{0.0825}{0.0510})}] = 0.41 \text{ m}^2$$

Where l is the length of the pipe and r_{outer} and r_{inner} represent the outer and inner radiuses of the pipe with insulation.

The heating requirement for the pipe is $Q = UA\Delta T$= 28 watt/ meter of pipe

PROBABILITY \ CONSEQUENCE	Insignificant (0-2)	Marginal (2-4)	Moderate (4-6)	Critical (6-8)	Catastrophic (8-10)
Definitely (0.1-1)	High	High	Very High	Very High	Very High
Likely (10^{-2}-10^{-1})	Medium	High	High	Very High	Very High
Occasional (10^{-3}-10^{-2})	Low	Medium	High	Very High	Very High
Seldom (10^{-4}-10^{-3})	Low	Low	Medium	High	Very High
Unlikely (<10^{-4})	Low	Low	Medium	High	High

Figure 2. Risk matrix

Table 1 Dimensions and materials of pipe and insulation

	Internal Diameter (inch)	External Diameter (inch)	Thickness (inch)	Material	K Factor (W.m/°C)
Pipe	4	4.5	0.25	Steel	43
Insulation	4.5	6.5	1	Fiberglass	0.04

Conclusions

Oil and gas exploration and production operations in low temperature environments present many challenges to the industry. These challenges include both hardware issues related directly to the design, construction, and operation of facilities, as well as those issues pertaining to the ability of plant personnel to function in a difficult environment. From this workshop, a list of identified integrity related challenges and issues was compiled and the current state of the technology to address these challenges are reviewed. Optimized winterization should be a goal. Due to uncertainty in information, variability in climate conditions, and data scarcity in harsher conditions, probabilistic approaches for load characterization, degradation modelling, and integrity modeling may be more useful than deterministic approaches. Risk-based asset integrity management (RBIM) was identified as a strategy to bridge the gap between economic and technical requirements to design, to make operational decision, and to estimate optimal replacement intervals of process components suffering stochastic degradation in harsh environments. An RBIM framework is proposed to help integrity practitioners for inspection, maintenance, and replacement decisions. Methodologies are also proposed to estimate the inspection sample size to assess general, localized corrosions (particularly under insulation). The workshop also identified that there is a need to continuously revisit the lessons learned from integrity related incidents. Specific regulations and standards need to be developed and integrity management procedures must be periodically reviewed, reassessed, and updated. Integration of safety and integrity in a holistic asset management framework and integration of human factors into risk-based asset integrity management must be recognized, acknowledged, and acted upon.

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