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Reliability analysis and optimisation of subsea compression system facing operational covariate stresses

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ABSTRACT

This paper proposes an enhanced Weibull-Corrosion Covariate model for reliability assessment of a system facing operational stresses. The newly developed model is applied to a Subsea Gas Compression System planned for offshore West Africa to predict its reliability index. System technical failure was modelled by developing a Weibull failure model incorporating a physically tested corrosion profile as stress in order to quantify the survival rate of the system under additional operational covariates including marine pH, temperature and pressure. Using Reliability Block Diagrams and enhanced Fusell-Vesely formulations, the whole system was systematically decomposed to sub-systems to analyse the criticality of each component and optimise them. Human reliability was addressed using an enhanced barrier weighting method. A rapid degradation curve is obtained on a subsea system relative to the base case subjected to a time-dependent corrosion stress factor. It reveals that subsea system components failed faster than their Mean time to failure specifications from Offshore Reliability Database as a result of cumulative marine stresses exertion. The case study demonstrated that the reliability of a subsea system can be systematically optimised by modelling the system under higher technical and organisational stresses, prioritising the critical sub-systems and making befitting provisions for redundancy and tolerances.

1. Introduction

The huge loss and sanctions experienced during the 2010 *Macondo* oil spill due to the failure of Subsea Blow-out Preventer, the 2011 *Bonga* incident and a host of recent offshore failures has sparked accelerated efforts towards improvement of reliability, risk management and asset integrity of subsea systems [1–3].

An investigation conducted by the UK Health and Safety Executive [4] indicated that nearly 80% of risk posed to offshore workers emanate from process related failures. These failures which often cause accidents, downtimes and serious economic losses emanate from the complex interaction between human and technical factors which cause approximately 70% and 30% of offshore incidents respectively [5].

With an increasing appetite for subsea processing installations, risk exposure could even be higher due to lack of standardized reliability data and the fact that underwater assets when deployed to the marine environment are exposed to additional stresses brought by dynamic influencing factors of the sea [6,7]. This justifies any study which seeks to understand the equipment failure behaviour in subsea conditions to ensure maximum uptime. The highly specialised subsea sector is not exactly known for standardized asset life cycle reliability procedures [8] because there seems to be is a lope-sided focus on the technical reliability qualification at manufacturing stages of subsea modules by several scholars; whilst appearing to neglect lifecycle asset reliability especially during the operational stages where the intertwine between human, equipment, environment is more pronounced [9].

Although, risks and failure cannot be completely eradicated from any system, they certainly can be controlled through enhanced reliability strategies throughout the lifecycle of the project. As the world's first subsea compression system – a joint industry project is currently underway at the Asgard field offshore Norway and planned to commence operations in 2015 [10,11], major concerns raised by stakeholders bother on reliability, corrosion and production assurance due to past experiences and losses encountered.

This study presents an enhancement to a concept known as

Abbreviations: API, American Petroleum Institute; BP/D, barrels per day; BORA, Barrier and Operational Risk Analysis; CAPEX, capital expenditure; DNV, Det Norske Veritas; FTA, fault tree analysis; FMECA, failure mode effects and criticality analysis; HSE, health and safety; ISO, International Standards Organisation; MTTF, mean time to failure; OPEX, operation expenditure; P/A, per annum; UK, United Kingdom.

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Accelerated Life Testing (ALT); an analysis procedure whereby basic system failure data is subjected to a high level of operational stress (covariate) and used to forecast the behaviour of a system [12]. The new approach which adopts a two-prong methodology for both technical and human reliability analysis consists of further development of the works of [13–16], where remarkable contributions were made on Weibull-based covariate relationships for technical reliability analysis and human factor analysis respectively.

Deep water production hardware is exposed to high CO_2 pressure and temperature conditions which directly affect the degradation rate and performance of such materials [17]. At temperatures below 5 °C and when pressures get much higher than 7.38 MPa, CO_2 could be in its supercritical state. In the absence of water, supercritical CO_2 is not corrosive, however, under normal deep water production operations, water is always present. When CO_2 dissolves in water, carbonic acid (H_2CO_3) is formed which significantly increases the corrosion rate of carbon steels and other materials. The mechanisms of CO_2 corrosion under supercritical conditions do not change compared to those identified at lower partial pressure [18].

The behaviour of a subsea system is better understood from a system reliability viewpoint [19] which may connote a reliability study on equipment availability times, an asset integrity assessment, a hazard and operability (HAZOP) study dealing with operability of a system or even a profitability analysis in terms of production capacity and revenue appraisal. In other contexts, it could imply Net Present Value (NPV) of a project, economic and management measures.

At the forefront of reliability analysis techniques is Monte Carlo's simulation which has been widely used over decades to quantitatively capture the realistic multi-state dynamics and stochastic behaviour of components and systems in reasonable computing times [20].

Lund [21] developed a statistics-based dynamic model for analysing offshore petroleum projects considering a number of uncertainty factors. The model incorporates several types of flexibility such as drilling options, uncertainties and capacity expansion uncertainties. A case study was carried out using the model and it shows that flexibility in capacity improves a project's economic value especially when there are many uncertainties surrounding the offshore reservoir. Unfortunately, considerations for human error estimation were not considered in the proposition.

Jablownosky et al. [22] modelled a subsea reservoir uncertainty and measured the value of flexibility of assets for various capacities that could be expanded in the future in order to maximise the project's net present value. The major deficiency of the proposed model was its lack of explicit consideration for operational safety in a subsea scenario as it largely focused on the economic aspect of the oil field. Norris et al. [23] incorporated physical parameters into risk analysis by coupling laboratory-derived probabilistic nucleation model with existing deterministic calculations for hydrate growth.

The works of Lin [24] and Lin [25] suggested flexibility models for deep water oil field systems which were simulated using Monte Carlo's model to determine the value of specified flexibilities under the uncertainty conditions of reservoir and production capacity [24,25]. The models did not address the severity of influence on CAPEX and OPEX contrary to Lee et al. [26] wherein a design procedure for offshore installations Life cycle Cost Analysis under various environmental load stresses was presented.

System failure data is usually gathered from historical performance archives, but in practice, these data are insufficient and are not always available to reflect the real operational conditions of its purposed domain [27].

In further attempts to account for these operational life conditions, a number of numerical models consisting of life-covariate relationship such as the Arrhenius model, Proportional Hazard model (PHM), Eyring model Extended Hazard Regression, Inverse Power Law had been seen to provide acceptable results [12]. Reliability analysis had been carried out using experimentally or field-sourced failure data and applying predictive models in order to extrapolate results of system reliability beyond the given data range [28–35]. For example, in PHM, the operational conditions are considered to be a covariate such that the reliability of the system is a product of time and covariates. The covariate acts multiplicatively on the threshold hazard rate by some constant [14].

The major limitation of life covariate models such as PHM is that they usually have many assumptions which are not applicable in many real world cases. It can only be applied to time-independent covariates; notwithstanding, it is still the most frequently used due to its simplicity and commercial application [15].

In a bid to enforce reliability practice across the subsea industry, ISO 20,815 standard stressed the need for representation of stochastic variations related to lifetimes and restoration times using probability distributions while AP1 17N RP provided a structured approach which organisations can adopt for management of uncertainty throughout project lifecycle [36].

Modelling complications are encountered when process variables such as temperatures, mass flows, pressures, affects the probability of occurrence of the events in resonance with human and organisational influence, thus the evolution of a subsequent scenario [23,45].

Accelerated life testing (ALT) reliability analysis is meant to help operators ascertain the difference between the reliability warranty values suggested by the manufactures and the realistic asset performance [34] being that risk influencing factors such as seabed temperature of 5 °C at 4000 m of depth, PCO_2 fugacity, and pH which are prevalent and are major agents of asset degradation at seabed. Ideally, real historical failure data are the most suitable for reliability modelling. Unfortunately, such data only become available towards the end life of a system and this justifies the use of OREDA values for MTTF in place of real field data.

OREDA is a unique data source of mean failure rates, failure mode distribution and repair times for equipment used in the offshore industry from a wide variety of geographic areas, installations, equipment types and generic operating conditions [45].

MTTF is the mean of the distribution of a product's life calculated by dividing the total operating time accumulated by a defined a group of devices within a given period of time by the total number of failures in that time period. This is based on a statistical sample and is not intended to predict a specific unit's reliability, in order words, MTTF is not a necessarily warranty statement but manufacturer's statistical prediction devoid of usage environment variations.

The model proposed in this paper was developed under the principle of time series prediction of basic failure rate with an external stress known as accelerated failure testing (AFT). In AFT, the covariates act multiplicatively with the failure time by some constant and the aim is to accelerate or decelerate failure time. This assumption provides a physical or chemical interpretation for the effect of covariates on the failure time. Hence, the AFT can be more appealing in many cases due to this direct interpretation [24]. Furthermore, unlike proportional hazards models, regression parameter estimates from AFT models are robust to omitted covariates, and they can be used to quantify the effect of time-dependent covariates.

One of the most important applications of AFT is the analyses of failure data whereby collected data is subjected to high level of operational stress (covariate) and used to predict the behaviour of