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WELLRISK - A Proposition of a Data-driven Well Integrity Management System

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In the petroleum industry, well integrity and risk management are critical concerns that must be balanced against the need for efficiency and cost reduction. The challenges of well integrity are becoming increasingly complex due to energy crises, pressure for cost reduction, and environmental considerations. To address the challenge, this paper presents a new data-driven approach to well integrity management. The proposed solution uses quantitative risk analysis that includes three figures of merit: the well integrity level, the blowout risk level, and the incremental cumulative risk. These figures of merit are used to assess the risk of well failure and their acceptance criteria guide the decision process for how long one can tolerate the failure, the mitigation measures, and the maintenance planning. The methodology is supported by advanced reliability models for the operational phase. Two case studies based on classical well integrity issues are presented to demonstrate the potential of the data-driven approach: the failure of a well barrier element and the impact of testing on the integrity of the well; and the comparison between the risk of operating in a degraded situation versus the intervention risk. The approach offers a powerful tool to mitigate risk and increase efficiency, making it a valuable tool for petroleum operators worldwide.

Keywords: Well Risk, Well Integrity, Data-driven, Risk Analysis.

1. Introduction

In the petroleum industry, well integrity and risk management are critical concerns that must be balanced against the need for efficiency and cost reduction. The challenges of well integrity are becoming increasingly complex due to energy crises, cost pressures, and environmental considerations. To address these challenges, a new data-driven approach to well integrity management is presented. The proposed solution uses quantitative risk analysis that includes three figures of merit: the well integrity level, the blowout risk level, and the incremental cumulative risk. These figures of merit are used to assess the risk of well failure and well leak and to support decision-making on how long one can tolerate a well barrier failure.

The approach is implemented in a system designed to integrate with existing data systems and to automatically update the risk of all managed wells, providing real-time insights. The methodology is supported by advanced reliability models for the operational phase and quantitative risk analysis models.

The paper explores each of the figures of merit and explains how their acceptance criteria guide the decision process, supporting the prioritization of resources.

Two case studies based on classical well integrity issues are presented to demonstrate the potential of the data-driven approach: the failure of a well barrier element and the impact of testing on the integrity of the well; and the comparison between the risk of operating in a degraded situation versus the intervention risk.

2. Well Integrity

Well integrity refers to always maintaining full control of fluids within a well to prevent unintended fluid movement or loss of containment to the environment. The well integrity operating philosophy is an important element that one should carefully consider with respect to how to manage the risk of loss of containment and overexpose oneself with additional risk by frequent well visits and interventions that brings exposure to the people and environment by doing these activities. The goal of a well integrity management system is to give transparency on how risk is managed.

The key aspect of the well integrity management system (WIMS) is the installation, monitoring, and maintenance of the well barrier elements (WBE) (NORSOK D-010). Most WIMSs used in the industry are purely qualitative, while this paper presents a quantitative approach.

2.1. *Well Reliability Model*

An operating well can be modelled as a series of cavities separated by safety barrier elements. Thus, the reliability of the system can be evaluated using a reliability graph where nodes are the cavities, and barrier elements failure modes are the edges. The directed graph starts at the reservoir (the source of the fluid with pressure) and ends at the environment. Critical paths, or cut sets, and any other system property can be obtained using graph theory. Figure 1 exemplifies the idea using a simplified well schematic and reliability graph.

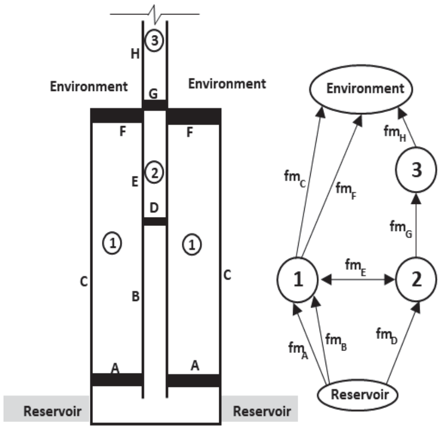

Fig. 1. Simplified well schematic and reliability graph.

Reliability characteristics of failure modes of safety barrier elements are obtained from recognized databases such as the Wellmaster and the Oreda, widely used in the petroleum industry, and from the company's own database.

System reliability is evaluated using the method proposed by Vesely (1970) and improved by Oliveira *et al.* (2022). The model calculates the risk of loss of integrity considering all the information from $t = 0$ to $t = T$ (today) and estimates the evolution of the risk for future times.

Omitting the time dependence for simplicity, the system failure probability is given by:

$$Wdt = \sum_{i=1}^{M} P[\theta_i] - \sum_{j=2}^{M} \sum_{i=1}^{j-1} P\big[\theta_j \theta_i\big] + \cdots \qquad (1)$$

where M is the number of critical paths (minimal cut sets), the first term on the right-hand side is the probability that an individual critical path occurs between t and dt, the second and subsequent terms involve the simultaneous occurrence of two or more critical paths in the same interval. All terms on the right-hand side of Eq. (1) can be rewritten as the product of a failure intensity times dt , and dt can be dropped.

And, the system unavailability, using the approximation developed by Esary and Proschan (1963), again omitting the time dependence for simplicity, is given by:

$$Q = 1 - \prod_{i=1}^{M} \left[1 - \prod_{j=1}^{N_i} q_{ij} \right] \qquad (2)$$

where, N_i is the number of failure modes of critical path i, and q_{ij} is the unavailability of the j^{th} failure mode of critical path i.

2.2. *Integration with existing data system*

Of paramount importance is the integration with existing data systems as it allows for real-time risk monitoring of all managed wells as the risk is automatically updated. Figure 2 shows a schematic of such information flow.

Fig.2. Information flow/Data system integration

Once a failure is detected or a test is performed, the model is updated, and the new information is reflected in the figures of merit so a decision on the best course of action can then be made. For an offshore well, to bring the risk down to acceptable levels in the event of a failure, this action ranges from simply changing the test schedule to sending a rig into the ocean, hundreds of miles offshore, to replace the production tubing. Repairs and replacements are also incorporated in real-time into the well integrity management system.

3. Figures of Merit

The evolution of safety within the petroleum industry involves a better understanding and better control of the risks. To that end, it is possible to express risk numerically in figures of merit to verify the safety level of a particular oil well. Different figures of merit can capture particular aspects of the risk or influence different decisions. In this work three figures of merit are proposed: the well integrity level, the blowout risk level, and the incremental cumulative risk.

3.1. *Well Integrity Level (WIL)*

WIL is a figure of merit to assess the risk of well integrity failure, regardless of whether this failure will unroll in a large leakage or no leakage at all. To calculate the WIL, all combinations of WBE failures mode that can produce a leak path between the reservoir and the environment must be considered. WIL can be computed as the conditional frequency of loss of well integrity:

$$\mathrm{WIL}(t) = \frac{W(t)}{1 - Q(t)} \tag{3}$$

where $W(t)$ is the system failure frequency and $Q(t)$ is the system unavailability, evaluated at time t. Oliveira at al. (2022) provides additional background on the computation of WIL including how to deal with tests, failures, repairs, and replacements.

3.2. *Blowout Risk Level (BRL)*

Of particular interest is the risk of an uncontrolled large oil leak to the environment throughout its lifecycle, usually referred to as a blowout. Minor leaks represent a limited threat and are not considered to be a part of a blowout flow path. A blowout flow path needs to include a combination of large barrier leaks between the reservoir and the environment. To take that into account, one can regard some of the failures as large leaks, for instance: 10% of leaks through a closed valve or 100% if it fails to close.

The Blowout Risk Level (BRL), as a figure of merit to assess the risk of a blowout, is then defined as the same way the WIL was, but only considering the large leaks:

$$\mathrm{BRL}(t) = \frac{W_L(t)}{1 - Q_L(t)} \tag{4}$$

where, $W_L(t)$ is the system failure probability for large leaks and $Q_L(t)$ is the system unavailability for large leaks, evaluated at time t.

3.3. *Incremental Cumulative Risk (ICR)*

The two previous figures of merit handle the current status of the well integrity, regarding any kind of loss of well integrity in the case of WIL and only blowout accidents in the case of BRL. There is a need for a third figure of merit that will handle the temporary chances, like the failure of a single WBE. The incremental cumulative risk (ICR) was defined to compute the additional amount of probability of having a well integrity loss accumulated after a failure is detected. This concept is similar to the incremental core damage probability from the nuclear industry.

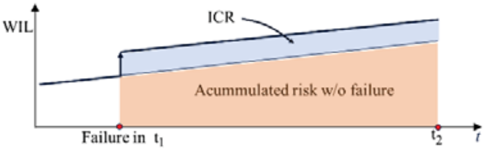

Fig. 3. Incremental Cumulative Risk (ICR)

$$\mathrm{ICR}(t_1, t_2) = \int_{t_1}^{t_2} \Delta F(t)dt \quad (5)$$

$$\Delta F(t) = \mathrm{WIL}(t) - \mathrm{WIL}_{\mathrm{nf}}(t) \quad (6)$$

where $\mathrm{WIL}_{\mathrm{nf}}$ is the "original" well integrity level before the failure. The time t_1 is the moment that the failure occurs and the time and the ICR starts to be integrated. Oliveira *et al.* (2022) provide additional background on the computation of ICR.

The PSA Applications Guide, Electric Power Research Institute (1995), presents the ICR as a figure of merit to assess the temporary increase in risk such as the occurrence of a failure. The ICR coupled with a limit criterion determines deadlines for repair.

3.4 *Limit or Acceptance Criteria*

Even in the presence of regulatory criteria to meet, the choice of criteria to help decision-making comes down to company risk tolerability, i.e., to one of the company values in terms of its safety commitment and reputation, and stakeholder perception. A discussion follows on acceptance criteria for the proposed figures of merit.

3.4.1. *WIL Acceptance Criteria*

Considering the WIL , a lower control limit (LCL) and an upper control limit (UCL) can be defined which divide the risk space in three regions, as shown in Fig. 4.

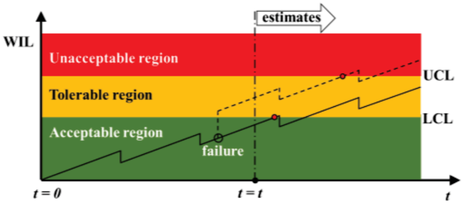

Fig. 4. Two Control Limit Well Integrity Management

In the unacceptable region, risks are intolerable and risk reduction measures are essential. In the middle region, risk reduction measures are desirable but may not be implemented if their cost is disproportionate to the benefit achieved. And, in the acceptable region, no further risk reduction measures are generally needed.

In 2018 the Norwegian Oil and Gas Association (2018) published a revision of its guideline, known as OLF-70, on recommended safety integrity level (SIL) requirements for the Norwegian Petroleum Industry. For systems to maintain a safe state operating continuously, OLF-70 establishes a relationship between SIL, and the system required probability (see Table 1).

Table 1. SIL for safety functions operating in a continuous mode.

SIL	Probability of a dangerous failure per hour – PFH
4	$\geq 10^{-9}$ to $< 10^{-8}$
3	$\geq 10^{-8}$ to $< 10^{-7}$
2	$\geq 10^{-7}$ to $< 10^{-6}$
1	$\geq 10^{-6}$ to $< 10^{-5}$

Source: OLF-70

For isolation of one subsea well function, OLF-70, in its appendix A, requires SIL 3. Using the Norwegian guideline as a reference, one may choose the WIL lower control limit ($\mathrm{LCL}_{\mathrm{WIL}}$) as $10^{-7}/\mathrm{h}$ and the WIL upper control limit ($\mathrm{UCL}_{\mathrm{WIL}}$) as $10^{-6}/\mathrm{h}$, for instance.

3.4.2. *BRL Acceptance Criteria*

A new set of lower and control limits can be defined and a plot similar to the one depicted in Figure 3, now for the BRL, can be constructed.

In 2019 IOGP, the International Association of Oil & Gas Producers (2019), published technical report 424-02 on blowout frequencies. Based on the IOGP risk assessment data directory, the report presents recommended frequencies of blowouts and well release incidents applicable to operations in the North Sea and the US Gulf of Mexico, or any operations in other regions with comparable standards of operation.

As an example, for offshore operation of North Sea standard, gas producing wells (excluding external causes) have a blowout frequency of $7.2 \times 10^{-5}/\text{year}$ or $8.2 \times 10^{-9}/\text{h}$ recommended by report 434-02. For gas producing wells, one may choose the BRL upper control limit (UCL_{BRL}) as $8 \times 10^{-9}/\text{h}$ and the BRL lower control limit (LCL_{BRL}) as $10^{-9}/\text{h}$, for instance.

3.4.1. *ICR Acceptance Criterion*

The acceptance criterion for the ICR is the one that dictates the time to respond after a failure occurs. This is called completion time in the nuclear industry and grace period in the well engineering terms. Although the concept is borrowed from the nuclear industry, its acceptance criterion is difficult to be replicate in the petroleum industry, as risks and response times are very different between the two industries.

In this work, the criterion proposed is a fraction of the total maximum allowed accumulated probability of well integrity loss, $\text{TWIL}_{\text{allowed}}$. Using Eq. 5, $\text{TWIL}_{\text{allowed}}$ can be computed as

$$\text{TWIL}_{\text{allowed}} = \int_0^T \text{LCL}_{\text{WIL}}(t)dt \qquad (7)$$

Where, T is the total mission time of the well from construction to abandonment.

Then, the limit to ICR is given by:

$$\text{ICR}_{\text{lim}} = A \times \text{TWIL}_{\text{allowed}} \qquad (8)$$

For instance, if the total mission time of a well is 30 years, LCL_{WIL} is set as the limit of SIL 3, $10^{-7}/h$; and A is 20%, results in $\text{ICR}_{\text{lim}} = 5.26 \times 10^{-3}$.

4. Case Studies

4.1. *Case study 1: The Failure of a Well Barrier Element*

Once an offshore oil well is constructed (i.e. the well drilled and completion equipment installed) and connected to a platform, the production or operational phase of the well life cycle begins. So does the well integrity monitoring, initiating plans to inspect and test well barrier elements at standardized frequency in line with industry best practices.

Throughout the well useful life, it is expected that some components fail, and in the offshore well scenario, that means a corrective maintenance, i.e., to act reactively, due to high risk and cost that entails in intervening in these wells. Therefore, if one or more barrier elements fail, it is important to assess the remaining barriers to determine whether to continue production despite the presented failure, and if so, to determine a reasonable grace period to intervene and assure barriers are reinstated.

In the proposed methodology, the well integrity is monitored in real time, or near real time, through the well integrity level (WIL).

Figure 5 shows a simulation using geometry and elements data from a real life well.

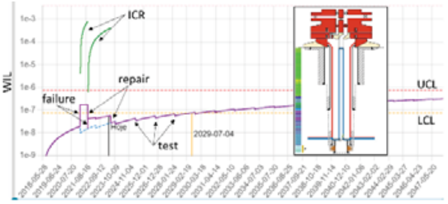

Fig. 5. WIL vs. time – Case study 1

When an element is tested or repaired or replaced; the information is incorporated to the model resulting in a reduction to the well failure rate (drop in Figure 5). And, if a failure occurs, there is an increase to the well failure rate (rise in Figure 3).

If WIL reaches the tolerable region, as a result of aging or failure of well component, the well should be assessed, and steps taken to ensure compliance to rules and regulations and so that the ALARP (As Low As Reasonably Practicable) principle is being followed. The assessment may contain different WILL progression scenarios throughout the well production phase to assist in decision making.

4.2. *Case study 2: Operating in a degraded situation versus the intervention risk*

For this case study, two scenarios are looked at:

- Scenario 1: Same as case study 1, a rig is sent to perform a heavy workover (HWO) intervention and replace the second failed equipment.
- Scenario 2: A rig is sent to perform a light workover (LWO) intervention, to restore production condition, and the well operates with a failed equipment (degraded), see Figures 6 and 7.

The goal is to compare the risk of blowout between the two scenarios where the risk during the intervention is also considered.

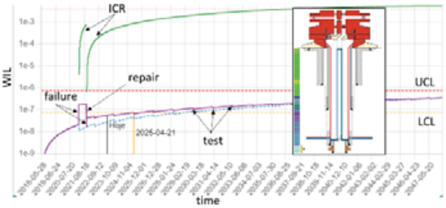

Fig. 6. WIL vs. time – Case study 2

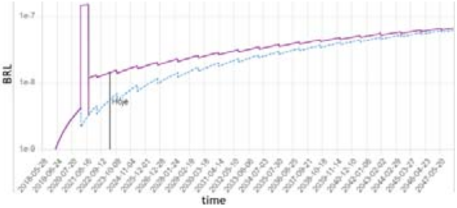

Fig. 7. BRL vs. time – Case study 2

Figure 8 shows the risk comparison between the two scenarios. Although the risk during production reduces in scenario 1, for the HWO intervention work scope considered, it is clear that scenario 1 entails more risk than scenario 2.

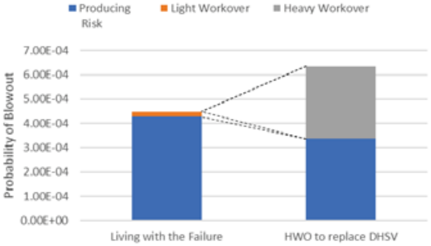

Fig. 8. Risk comparison

Both scenarios require a workover intervention on the well. However, the LWO intervention work scope is much simpler than the HWO intervention work scope. As a result, the LWO intervention requires less effort (i.e. less expensive); and has less risk of blowout than the HWO intervention. Figure 9 shows the risk and the effort required for both interventions. Additionally, because the LWO intervention is quicker than the HWO intervention there is less loss of production in scenario 2.

One should also notice that operating with a degraded status is only possible if the WILL and BRL upper control limit (UCL); and the ICR limit are not reached. Therefore, continuous monitoring of well integrity is essential.

Fig. 9. Risk vs. Effort

5. Well Integrity Charts

For an offshore well, severity can be defined in terms of potential blowout flow rates, proximity to the coast, water depth, fluid type (oil or gas) etc. Using such definition, a Severity vs. WILL plot and a Severity vs. BRL plot, or Well Integrity Charts, can be used to better present risk tolerability criteria, where two criteria lines divide the space into three regions –where risk is intolerable, where it is broadly acceptable and where it requires further assessment and risk reduction as far as is reasonably practicable, as shown in Figure 10. This is the same framework for risk tolerability shown in Figure 3.

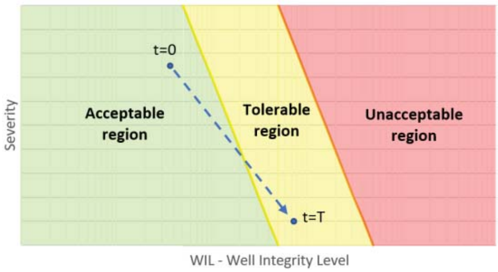

Fig. 10. Severity-WIL Well Integrity Chart

Risk tolerability criteria for all managed wells can then be presented in real time. The charts can be a powerful tool to aid decision-making, for example, in resource allocation.

Figure 10 also shows an example of a path the well follows during its producing phase, as elements age the WILL increases, and at the same time Severity reduces.

6. Final Comments

The approach main goals are to improve risk management and to reduce risk exposure by making better risk-informed decisions. However, the case studies have shown that is possible to be more efficient, save cost and increase production volume using the data-driven methodology, and thus gain substantial financial benefits at comparable risk levels.

The paper demonstrates the potential of a data-driven well integrity management system to improve decision-making and enhance well integrity in the petroleum industry. The approach offers a powerful tool to mitigate risk and to increase efficiency, making it a valuable asset for petroleum operators around the world.

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