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Development and implementation of an online integrated well integrity and risk assessment management process for onshore gas wells

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Well integrity is a critical component of safe and sustainable onshore gas production. A thorough understanding is required of the risks that can cause undesirable events such as loss of containment, human and environmental safety hazards, and loss of production for the successful management of well integrity. Specifically, well integrity entail the application of technical, operational and organizational solutions to reduce the risk of uncontrolled releases of hazardous substances and well fluids throughout the life cycle of the well. In this paper, we present the development of an online integrated well integrity and risk assessment process (WIRAP) for managing well integrity across the life cycle of the well. The online application integrates various well integrity and risk assessment methods, including fault tree and well barrier analysis, reliability modeling, online process modeling, consequence modeling and final risk assessment. The online application is built on data from physical well head inspections and real time data from the plant historian to perform model scoring and predictive analytics for early fault detection and diagnostic analysis. The application provides the capability of identifying high-risk wells through statistical comparisons based on probabilistic modeling and well health indices. It is shown how the online WIRAP methodology is implemented throughout the company for in-time decision making by operations and management.

Keywords: Online web-based platform, onshore gas wells, risk assessment, well integrity.

1. Introduction

History reveals many incidents of oil and gas well-related accidents and disasters, such as Piper Alpha disaster in 1988 in the North Sea, the Montara blow-out in 2009 in Australia and the BP Deep Water Horizon disaster in 2010 in the Gulf of Mexico. These incidents resulted in the loss of many lives, severe environmental impact, and significant financial losses due to equipment damages, reputational damage and loss in production. Therefore, over the last few decades, these incidents have necessitated not only the need to gain a better understanding of the risks posed by these facilities but also to fully comprehend the mechanisms and levers in place to manage these risks effectively and sustainably. Yakoot et al. (2021) reported that 30-45% of active wells world-wide have some kind of integrity issue. The main problems are related to sustained annulus pressure, which implies a persistent release of hazardous substances from the feed source to the surface. Well integrity concerns may also occur due to other failures or malfunctions, such as failures of safety critical equipment, deficiency of installed components, corrosion failure, wellhead and X-tree valves (Yakoot et al., 2021). Although it might not be possible to reduce the risk of a major incident to zero, significant reductions can be achieved by reducing the likelihood and consequence of such an event to ensure the risk is managed within the tolerable range (ALARP). Jaculli et al. (2022) provided a review on the past, present and future of well safety and integrity evaluation of offshore wells. Yakoot et al. (2021) provided a state-of-the-art review for well integrity management in mature fields. Kiran et al. (2017) provided a review on the identification and evaluation of well integrity and causes of failure of well integrity barriers.

There is a need for the development and implementation of a risk-based approach to well integrity and risk assessment process (WIRAP) to enhance decision-making for prioritizing and synchronizing well integrity management and production demands. Oil and gas companies face major challenges in developing and implementing WIRAP. These challenges include, but not limited to fragmented inspection and operational data due to the lack of digitalization and inefficient cloud/ETL technology, reactive maintenance due to limited real-time insights, reduced or no visibility of asset health due to the lack of data-driven analytics, too much manual data and manual work flows which limits in-time reporting and decision-making, risk assessment of equipment failures and barriers that might be compromised due to data gaps and lack of advanced engineering intelligence and data analytics. Therefore, the industry requires guidance and leadership in how to tackle and overcome these challenges. In this paper, we discuss the development and implementation of an integrated WIRAP management process for onshore wells, based on industry best practices, methodologies and standards (API RP 90 (API RP-90, 2006), NORSOK D-10 (NORSOK D-010, 2013)). The WIRAP process is online, which embeds digitalization and integrates various well integrity and risk assessment methods.

2. Integrated WIRAP management platform

2.1. *WIRAP process overview*

Well integrity and risk assessment management is a process where integrity analysis, risk analysis and health status of the well are integrated. The general steps required in performing a well integrity and risk assessment entails: well family classification and well status, well integrity analysis, leak path and barrier analysis, risk assessment, prioritization & mitigations and risk summary & reporting. The technical and modeling components implemented in the integrated WIRAP platform are depicted in Figure 1.

Fig. 1. Technical components of the integrated WIRAP platform.

2.2. *WIRAP components*

In this section we discuss briefly each of the components in Figure 1.

2.2.1. *Digitalization*

WIRAP digitizes and automates the data collection and integration of various data from source, including inspection data, annular pressures, operating variables and history, into one source of truth. The data is extracted through a secure API and tagged with meta-data (timestamp, well ID, source, etc.). Integrating and merging different data sources into one source of truth allows for advanced engineering, machine learning and statistical analysis to pro-actively identify well integrity concerns, risk assessments, mitigation and maintenance recommendations. In addition, key performance indicators such as annular pressures and other process variables are available for process health monitoring, which entails model building and deployment, model scoring, condition monitoring and fault or anomaly detection in real time.

2.2.2. *Well status and integrity analysis*

Well integrity must be continuously assessed and reported to ensure production stability and no safety or environmental impacts (Yakoot et al., 2021). For continuous monitoring of well status and health, a well head index is defined based on inspection data on safety critical equipment. To specify a health index, the inspection data is categorised into three categories: 1=Low, 2=Medium and 3=High. For example, the maximum for the TRSCSSV leak rate (SCF/hr) is 900 SCF/hr, and any value above 900 SCF/hr will be classified as high and assigned a value of 3. The ranges for the low and medium categories can be specified according to the distribution of historical data or user specified. This is done for all the inspections on safety critical equipment. The values obtained are then summed over all the inspection variables to yield one health index for each well; the higher the value the lower is the health and integrity of the well.

The index is unit free, which allows for the comparison across wells and prioritization. The index is continuously updated with new inspection data, which also enables the visualization of the health of the well across time. Figure 2 shows an example of the index for a number of wells. The index is color coded where high values are red and low values are green for quick comparison across the wells. The gaps in the heatmap illustrate the lack of data due to either new wells brought into production or inspections not being done. From the heatmap it is quick to identify wells of immediate concern and wells whose integrity may be deteriorating over time. Therefore, it is an effective way to rank the wells in terms of integrity concerns.

2.2.3. *Leak path and well barrier analysis*

Yakoot et al. (2021) mentioned three types of risk assessment in well integrity i.e., qualitative risk assessment, quantitative risk assessment

Fig. 2. Well head risk heatmap across years for various wells.

and failure mode, effects and criticality analysis (FMECA). Quantitative risk assessment entails the computation of the failure probability of individual barrier components along with an overall reliability based on the well configuration. First, a well schematic overview must be drawn, which shows the primary and secondary well barriers (Colombo et al., 2022). Specifically, a well barrier is a pressure-containing envelope that prevents fluids and gasses from flowing unintentionally from the formation into another formation or the atmosphere. The prime well barrier is aimed at containing the fluids and gasses under load conditions during the well's life cycle, and the secondary well barrier should contain the fluids and gasses in the event of a breach of the primary barrier. Key well barrier elements must be specified in the well schematic overview, which establishes the baseline integrity of the well.

All leak paths consisting of one or more barrier elements must be established that indicates how hazardous material may potentially breach the primary and secondary barriers. The individual leak paths are combined into a consolidated leak path diagram, which is used for the fault tree analysis and probability of failure calculations. The determination of failure probabilities requires knowledge of equipment specific failure rates or mean-time-to-failure (MTTF) as well as the failure distribution (e.g., exponential or Weibull distribution

(Barlow and Proschan, 1975)). In the event where site specific MTTF or failure rates are not available, it can be substituted with generic failure rates (Colombo et al., 2022; OREDA Participants and SINTEF Industrial Management, 2002). Note, however, that the use of generic failure rates could either grossly underestimate or overestimate the final failure frequency if the necessary caution is not applied.

The probability of failure is represented by the cumulative distribution function (CDF), which is the probability that the random variable, time, denoted as T, does not exceed time t:

$$F(t) = P(T \leq t) = \int_{-\infty}^{t} f(u)du \qquad (1)$$

where $f(u)$ is the probability density function (PDF) of the failure time distribution. The reliability function $R(t)$ is defined as the probability that the component operates successfully beyond time t:

$$R(t) = 1 - F(t) = \int_{t}^{\infty} f(u)du. \qquad (2)$$

The hazard function or hazard rate, $h(t)$, represents the instantaneous failure rate as the time interval approaches zero. That is, from (1),

$$h(t) = \frac{f(t)}{R(t)}.$$

The failure rate, denoted by $\lambda(t)$, is defined as the ratio of the probability of failure within the interval $[t, t + \Delta t]$ to the product of the survival probability at t_1 and the interval length. That is,

$$\lambda(t) = \frac{R(t) - R(t + \Delta t)}{\Delta t R(t_1)}. \qquad (3)$$

The mean time to failure (MTTF) represents the expected time to failure, which is,

$$MTBF = \int_{0}^{\infty} t f(t)dt \qquad (4)$$

(Rahmoune and Hafaifa, 2017).

Let M denote the number of barrier elements in total i.e., $c_m, m = 1, 2, \ldots, M$, where each leak path can consist of different combinations of these elements. Consider the following leak path as an illustration. Hazardous substances may be released from the reservoir, through the 7” line pipe (c_1), the 7” cement (c_2), the liner hanger packer seal (c_3), the casing hanger seal (c_4) to the surroundings. For the specific leak path, the probability of failure or a leak at time t is calculated as:

$$P_l(t) = P_{c_1}(t) \times P_{c_2}(t) \times P_{c_3}(t) \times P_{c_4}(t) \quad (5)$$

where $P_{c_j}(t)$ is the probability of failure for element $c_j, j = 1, 2, \ldots, M$, and $l = 1, 2, \ldots, L$, denotes the number of leak paths. Therefore, each barrier element in the leak path must fail for the hazardous material to reach the surroundings i.e., it is a system of components in series (Rahmoune and Hafaifa, 2017). $P_{c_j}(t)$ is calculated using the appropriate reliability model. The probability of failure for the well across all leak paths are then:

$$P(t) = \sum_{l=1}^{L} P_l(t) \qquad (6)$$

and the reliability of the well is

$$R(t) = 1 - P(t).$$

Therefore, any of the leak paths may be breach to flag a concern for hazardous substances potentially being released to the surroundings.

2.2.4. *FMECA, Consequence analysis and Process Monitoring*

From Figure 1, FMECA is one of the components within the integrated WIRAP framework. It is discussed in detail by Koekemoer et al. (2026). In the current application, FMECA is implemented online and specifies a risk priority between 0 and 100% for each component. The risk priority incorporates a severity index between 1 and 7 (from less severe to most severe) in the event of a potential failure, a rating between 1 and 10 (most likely to least likely) indicating how likely it is to detect the failure, and the reliability $(1 - P_{c_j}(t))$. FMECA provides recommendations to monitor or to reduce the risk for each component. The consequence must be evaluated in the event of a loss of containment, together with the severity of the consequence. Consequence analysis is done for different scenarios and on a case-by-case bases by a suitable team of representatives. Consequence analysis and quantification are discussed in detail by Nel et al. (2026). FMECA and consequence analysis are implemented online and allows for scenario analysis and online monitoring of the risk associated with each component.

Process health and asset health entails the use of production data to monitor the operation of the well and to detect anomalies in the process. Multivariate statistical process monitoring (MSPM) provides a set of tools to monitor many process variables simultaneously and for the detection of operational anomalies or deviations (Rossouw et al., 2020). Principal component analysis (PCA) has been extensively used for process monitoring and control in industrial applications (Yu, 2012). Typical monitoring statistics derived from PCA include Hotelling's T^2-statistic and the squared prediction error (SPE), also known as the Q-statistic, which are frequently employed to detect out-of-control conditions (Ferrer, 2007). Rossouw et al. (2020) illustrated the use of MSPM for online monitor of a gas production facility and the visualization and calculation of variable contributions to process anomalies. MSPM is implemented in the integrated WIRAP framework for online monitoring of all wells using temperatures, pressures and flows. It provides the ability for early detection of anomalies in the process, and performs variable contribution analysis, which leads to proactive corrective actions and continuous improvement. Liebenberg et al. (2026) discusses MSPM and the implementation for process health and asset health monitoring within the integrated WIRAP framework.

2.2.5. *Risk assessment and analysis*

The respective risks are quantified and evaluated for personnel safety, community safety, environment impact, financial and reputational risk. Figure 3 provides an example of a process risk matrix for the analysis of the various risks. The risk is plotted on a 7 $\times$ 7 matrix where the consequence severity in the event of a leak or a loss of containment is on the y-axis and the probability of occurrence, failure or likelihood on the x-axis. Therefore, the ultimate risk is considered as the product of consequence severity $\times$ likelihood. The consequence severity is extracted from the consequence analysis and is labeled I1, I2, to I7, from lowest severity to highest severity. The likelihood is extracted from the barrier and leak path reliability analysis and is labeled P1, P2 to P7, from lowest probability to highest probability. The risk level is indicated on the matrix and is labeled L1, L2 to L6, from the highest risk level at the top right corner to the lowest risk level at the bottom left corner. The yellow colored area on the matrix indicates the region with too high risk, the white area indicates the region with marginal tolerable risk, and the green area indicates the region with acceptable risk. Note these tolerable regions were gauged for safety according to the UK Health and Safety Executive (HSE) regulations (`https://www.hse.gov.uk/index.htm`), which means they are only applicable to the personnel and community safety events. Risk tolerability for environment, financial loss and reputation must be accepted or agreed internally by executive management.

From Figure 3, the respective risks appear to the right of the risk matrix with specific descriptions for each consequence severity index. The different symbols on the risk matrix in Figure 3 indicates the specific risk level and probability of failure for the various risks. For example, the red dot shows that the safety risk to people is at a risk level L5, with a severity index of I5 and a likelihood of P3. However, the blue dot indicates that the monetary cost of the safety risk is at a risk level L2, with a severity index of I5 and a likelihood of P6, which is too high. Therefore, several scenarios needs to be considered and evaluated to reduce the risk to at least the ALARP levels, or to consider interventions to move the various risks from the yellow region to the white or even better, the green region. Corrective actions or risk reduction strategies can either lower the event frequency (e.g., improving the integrity of the well barrier elements, removing personnel from the site, etc.) or lower the consequence (e.g., early gas detection, remote shut-in, emergency procedures etc.). For example, removing or repairing a degraded barrier will improve the reliability, whereas the implementation of manual intervention or emergency procedures are considered at most to only

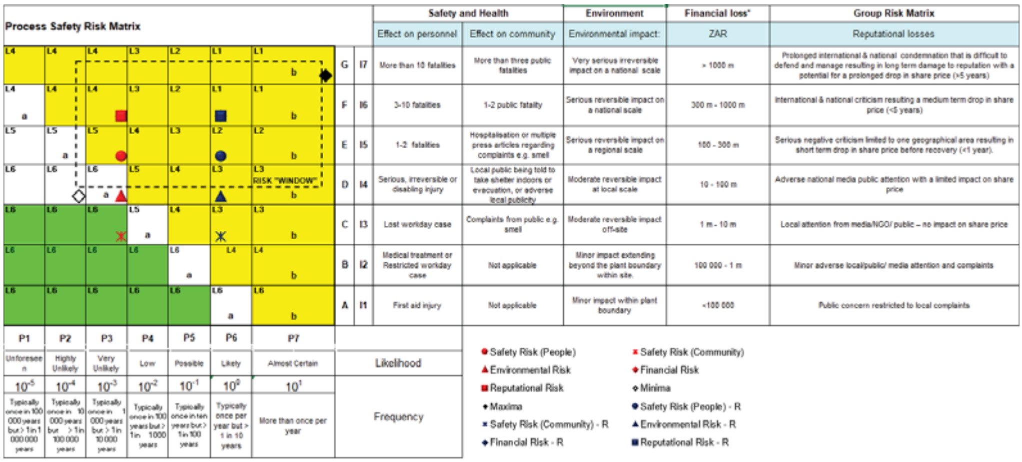

Fig. 3. Process Risk Matrix.

allow for one order of magnitude reduction in risk due to its dependence on human intervention. The FMECA must be consulted for this assessment, as well as the consequence severity and likelihood of the events must be recalculated. This process of scenario analysis and the benefits of improvement initiatives or lack thereof must be repeated several times for reducing the various risks and the overall risk. In some cases, this is not possible, and the risk assessment team needs to consider removing the well from service or turn-down production on the well operation to inevitably plug & abandon. The risk matrix is implemented online for integrated well integrity and risk analysis. Risk levels can be specified and modified directly on the web application for each scenario evaluated. The results can also be exported for reporting purposes.

Following the risk analysis using the risk matrix, well barrier and reliability analysis, consequence analysis and FMECA consideration, the risk is consolidated and summarized in a risk assessment table, which contains the following information:

- The undesirable event, and the causes for the undesirable event.
- Consequences of the event.
- A list of the compromised well barrier elements, and the remaining well barrier elements that are not compromised.
- Conditional barriers and administrative controls.
- Consequence severity index for each of the various consequences. the likelihood of the event, and the risk level.
- Risk conclusion and recommendations.

For example, an undesirable event could be the potential well blow out due to degraded integrity of well equipment resulting in a high pressure release of natural gas from the reservoir to the surroundings. Upon ignition it could result in a potential flash fire or a jet fire. A review of the latest well integrity reports must be done, including the well inspections and FMECA analysis. The compromised well barrier envelopes must be specified, and an indication which one or maybe more of the L leak paths may lead to loss of containment. Consequence analysis is performed to specify consequences of the event in terms of the personnel safety, community safety, environment impact, financial and reputational impact. Conditional barriers may include the suspension of the well, additional integrity testing, isolating the well from personnel and an emergency response plan. The consequence severity index is informed from the consequence analysis, the likelihood of the event is extracted from the well barrier analysis and the risk level is obtained from the risk analysis and the risk matrix. The risk conclusion consolidates all the information from the well integrity, consequence and risk analysis, and provides clear recommendations re the well integrity, mitigation or improvement initiatives, or to plug and abandon the well. All the modules are implemented online on a web application, providing an integrated well integrity and risk assessment process for potentially compromised wells, scenario analysis, diagnostic and FMECA analysis, but also online monitoring of the process and well health and anomaly detection for pro-active corrective actions and process improvement. Reporting on well integrity is generated on the web application and ensures transparency and credibility across the organization.

3. Online web-based WIRAP platform

The WIRAP platform combines various data sources, including operational data and manual inspections, to proactively detect well integrity issues and assess risks. It is a modular, cloud-based solution that integrates with existing systems, offering a secure and scalable environment for well lifecycle management and data-driven analysis and decisions. Figure 4 provides the schematic of the data flow from source, performing data assurance and processing, storing data on the cloud for data management and processing, as well as visualization on a web application. The solution architecture entails the following components:

- Data Ingestion: Well integrity and operational data (annular pressures, test logs, SAP PM history) are extracted from source systems via secure APIs or batch connectors. Data is validated, normalized, and tagged with metadata (timestamp, well ID, source).
- Data Analytics: Well barrier analysis and reliability models calculate the probability of failure for each barrier element and the overall well configuration. Consequence analysis estimate potential impact and severity of the various consequences. FMECA analysis is performed on all barrier elements. Process health monitoring and diagnostic analysis are conducted using MSPM. Risk analysis an assessment are performed using risk matrix and ALARP criteria.
- Visualisation & Reporting: Engineers access dashboards that visualize risk levels, leak paths, and trend evolution across wells or well families. Scenario analyses are performed and automated reports summarize high-risk wells and recommended mitigation actions.
- Continuous Improvement: User feedback, updated field data, and new diagnostic results are fed back into the system, supporting iterative model refinement and data-driven decision support.

The online integrated WIRAP platform is developed for the management of risk across the life cycle of the wells. Specifically, it improves risk-informed decision-making through data-driven analytics and engineering insights. The platform creates one source of truth for all data and information required for well integrity and risk assessment across the life cycle of the well. Therefore, it provides transparency and visibility across the organization on the actual risk for each well. Furthermore, the platform strengthens regulatory compliance and assurance.

4. Conclusions

An integrated well integrity and risk assessment methodology and framework was developed for assessing both inherent and residual risk. The WIRAP management platform integrates advanced data analytics with fundamental scientific and engineering principles. It transforms what is typically a time-consuming, expert-driven process into a scalable, repeatable, and transparent practice. Automated data ingestion and one source of truth are established for all online and offline data, used to identify and prioritize wells at risk and quantifying risk assessments and reliability of compromised barriers, and process and well-head health. It is a digital solution enabling full-scale operational and well integrity that aligns investments with operational priorities and Environmental, Social, and Governance (ESG) objectives.

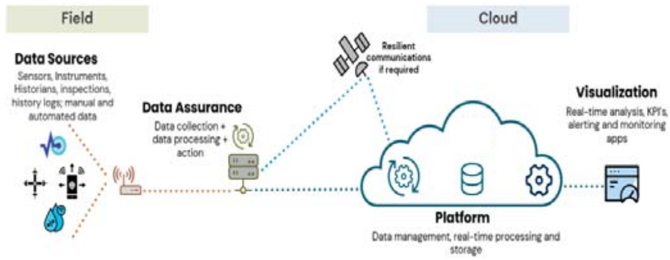

Fig. 4. WIRAP platform data flow.

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