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Time-Dependent Reliability Analysis of Well Barrier Elements

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Abstract. The exploration and production of hydrocarbons in pre-salt ultra-deepwater environments demand robust integrity assessment methodologies due to extreme operational conditions and high intervention costs. This work proposes a time-dependent reliability framework to evaluate the structural performance of well barrier elements (WBEs) throughout the well lifecycle. The approach integrates Monte Carlo simulation, corrosion modeling, and fault logic via cut sets. Historical failure rates were combined with simulated casing corrosion to assess two critical failure modes: internal burst under formation fluid pressure (Klever-Stewart model) and collapse under full evacuation (Klever-Tamano model). Results show that accounting for time-dependent corrosion increases system failure rates and cumulative probabilities, with the KT model yielding more conservative outcomes. These findings highlight the importance of incorporating temporal degradation mechanisms into offshore well integrity management, particularly for long-life assets. The methodology allows for the estimation of remaining useful life (RUL), identification of critical degradation paths, and quantification of system reliability at any point in time.

Keywords: Well integrity, Time-dependent reliability, Well barriers, Monte Carlo simulation.

1 Introduction

Despite the progress of renewable energy sources, oil remains one of the main pillars of global energy supply. This scenario underscores the importance of structural engineering in offshore exploration, particularly in ultra-deepwater environments, where harsh operating conditions and high intervention costs demand robust solutions for risk management, structural integrity, and life extension.

Oil wells serve both structural and productive functions and must maintain satisfactory performance throughout their entire lifecycle—from design and drilling to production and abandonment. The integrity of these systems is supported by national and international regulations, such as ANP Resolution No. 46/2016 [1], NORSOK D-010 [2], and ISO 16530-1 [3], which establish the concept of Barrier Envelopes. These envelopes comprise redundant and independent arrangements of structural elements and equipment designed to prevent blowouts.

The reliability of Well Barrier Elements (WBEs)—such as tubing, casing, cementing, and valves—is directly affected by time-dependent degradation mechanisms, including corrosion, thermal fatigue, and structural collapse. As emphasized in ISO 13628-1 [4], barrier integrity assessment must account for both physical and operational aspects, as well as the stochastic nature of their failure modes.

Traditional models, based on qualitative or deterministic approaches, have shown limitations in representing the temporal evolution of reliability. Several recent studies propose more advanced methodologies: Oliveira et al. [5] recommend the adoption of probabilistic models applied to the operational phase; Almeida et al. [6] investigate

progressive failures in tubulars degraded by corrosion under combined loads; Haaland [7] introduces time-dependent reliability functions; Vesely [8] proposes the temporal evaluation of complex systems through fault trees; Colombo et al. [9, 10] present data-driven integrity management platforms; Gouveia et al. [11] assess the residual strength of corroded pipes; and Semwogerere et al. [12] discuss strategies for life extension of offshore wells.

In this context, the present work proposes a time-dependent reliability analysis methodology based on Monte Carlo simulation and the use of analytical deterministic models integrated with a structural logic grounded in the identification of minimal cut sets. The approach aims to represent the temporal evolution of WBE reliability, estimate the remaining useful life (RUL), and provide technical support for risk-based maintenance strategies, thereby optimizing the management of critical assets in offshore environments.

2 Reliability analysis applied to well barrier systems

Remaining Useful Life (RUL) analysis is a key tool for decision-making regarding the extension or abandonment of offshore wells, particularly in advanced operational environments. Physico-probabilistic methods have gained prominence due to their ability to represent the evolution of structural reliability over time by integrating failure mechanisms, stochastic variability, and normative criteria.

In this context, the deterministic strength models proposed by Klever and Stewart [13] and Klever and Tamano [14], standardized in API TR 5C3 [15], provide robust analytical equations for evaluating burst (internal pressure) and collapse (external pressure) failures in structural casings. These models incorporate geometric imperfections, strain hardening effects, and combined loading conditions, enabling the quantification of critical pressures under realistic scenarios. Implementing these equations in Monte Carlo simulations allows for the capture of uncertainties inherent in material properties, residual wall thicknesses, and loading conditions. The formulations adopted in this study follow those prescribed by API TR 5C3 [15].

2.1 Casing Strength Models

The Klever-Stewart (KS) model estimates the burst strength of casing by determining the maximum internal pressure the pipe can withstand before rupture. In scenarios involving combined loading (internal pressure along with external pressure and axial force), burst failure resistance is corrected using von Mises and Tresca failure surfaces, which represent realistic loading conditions to which tubulars are subjected throughout the productive life of the well. Accordingly, to determine the burst failure resistance at the ultimate limit state under combined loading conditions (p_{iRa}), API TR 5C3 [15] recommends the following expression:

$$p_{iRa} = p_0 + \min\left(\frac{p_M + p_{ref\,T}}{2}, p_M\right), \tag{1}$$

with:

$$p_M = p_{ref\,M}\sqrt{1 - k_R\left(\frac{F_{eff\,KS}}{F_{uts}}\right)^2}, \tag{2}$$

$$p_{ref\,M} = \left(\frac{2}{\sqrt{3}}\right)^{1+\eta}\left(\frac{1}{2}\right)^{\eta} p_{uts} = \left(\frac{2}{\sqrt{3}}\right)^{1+\eta} p_{ref\,T}, \tag{3}$$

where p_0 is the external pressure, p_M is the strength based on the von Mises failure surface, and $p_{ref\,M}$ is the von Mises burst strength without axial force. $p_{ref\,T}$ denotes the burst resistance according to the Tresca failure surface, p_{uts} is the ultimate internal pressure resistance of the pipe without imperfections, and $F_{eff\,KS}$ is the effective axial force acting on the pipe according to the KS model, calculated as:

$$F_{eff\,KS} = F_a + p_o \cdot A_s - p_M \cdot A_{tdr}. \tag{4}$$

In regimes with pronounced tensile loading, the model predicts failure by necking. Under this condition, the effective axial force should be calculated as:

$$F_{effKS} = F_{uts}\sqrt{1 - k_N\left(\frac{p_i - p_o}{p_{ref\,M}}\right)^2}. \tag{5}$$

Solving this system of equations requires an iterative procedure. To overcome this challenge, Araújo et al. [16] proposed an alternative formulation by introducing the concept of equivalent force, expressed as:

$$F_{eq} = F_a + A_s\, min(p_i, p_o), \tag{6}$$

where F_a is the axial force and A is the cross-sectional area. For further details on the methodology, see Araújo et al. [16]. The ultimate limit state equation is presented in Eq. (7), where ΔP is the differential pressure regarding the loads, in this case, formation fluid:

$$G\left(D, t, f_y, f_u, mu_{KS}\right) = R_{prob} - \Delta P. \tag{7}$$

The Klever-Tamano (KT) model describes structural failure by collapse when the external pressure exceeds the internal pressure, with the collapse resistance ($p_{0_{KT}}$) given by:

$$p_{0_{KT}} = p_i + \frac{(\Delta p_e + \Delta p_y) - \sqrt{(\Delta p_e - \Delta p_y)^2 + 4\Delta p_e \Delta p_y H_t}}{2(1 - H_t)}, \tag{8}$$

where p_i is the internal pressure, Δp_e is the elastic collapse resistance, Δp_y is the yield collapse resistance of the steel, and H_t is a decrement factor that varies according to the manufacturing properties of the steel and the pipe. The collapse resistance based on the yield limit of the steel (Δp_y) can be calculated using either the Tresca criterion (Δp_{y_T}) or the von Mises criterion (Δp_{y_M}). The ultimate limit state equation for collapse is presented in Eq. (9), where ΔP is the differential pressure associated with full evacuation loading. For further details on the formulation and solution of the problem, see API TR 5C3 [15] and Araújo et al. [16].

$$G(D, t, ov, ec, rs, mu_{KT}) = R_{prob} - \Delta P. \tag{9}$$

2.2 System Reliability

The reliability of oil wells can be modeled using coherent systems composed of barrier elements, whose failure compromises the overall system integrity. The logical structure among elements is represented by series, parallel, or mixed configurations. The reliability of each element i, denoted by $R_i(t)$, is associated with its failure rate $\lambda_i(t)$.

The barrier structure can be represented by minimal cut sets, which define combinations of simultaneous failures that lead to system failure. For hierarchically structured systems, such as the Well Barrier Schematics (WBS) defined in NORSOK D-010 [2], cut sets can be directly derived from the logic of primary and secondary barriers. The overall reliability of the well thus depends on the functional composition of the WBEs and their respective failure rates, which may be determined through empirical models, operational history, or physical simulation (as in the KS and KT models).

The instantaneous system failure rate, denoted by $\Lambda_S(t)$, represents the intensity with which the system as a whole tends to fail at time t, given that it has remained operational up to that point. This metric is calculated from the system's cumulative unreliability function ($Q_S(t)$), i.e., the probability of failure up to time t, and the failure probability density function ($W_S(t)$). Thus, the value of $\Lambda_S(t)$ is given by:

$$\Lambda_S(t) = \frac{W_S(t)}{A_S(t)} = \frac{W_S(t)}{1 - Q_S(t)}. \tag{10}$$

This expression is analogous to the hazard function used in component reliability analysis, now extended to the system level, including systems with complex topologies and dependent failures. Accurate determination of this function requires knowledge of the failure probabilities associated with the minimal cut sets and the logical architecture of the system structure, as well as the temporal evolution of the reliability functions of the individual components.

This systemic approach enables the assessment of overall integrity performance over time, allowing for the estimation of remaining useful life (RUL), identification of critical failure modes, and prioritization of interventions based on risk-based maintenance criteria, as suggested by Vesely [8] and Colombo et al. [10].

3 Methodology

Although time-dependent reliability analyses of tubulars have been proposed, few studies integrate physical models with system logic applied to actual offshore well configurations, as demonstrated in this study. Accordingly, the methodology proposed in this work is based on Monte Carlo simulations to evaluate the time-dependent reliability of well tubulars. For each simulation, random samples of resistance parameters are generated, accounting for corrosion mechanisms and the KS/KT physical models. At each time step, failure is identified when the applied load exceeds the degraded strength. The resulting failure times are then used to construct the reliability profile of the tubular. Figure 1 presents the flowchart of the proposed methodology, highlighting the simulation process, corrosion-driven strength reduction, failure detection, reliability estimation, and subsequent integration into system reliability through failure rate analysis and cut set evaluation.

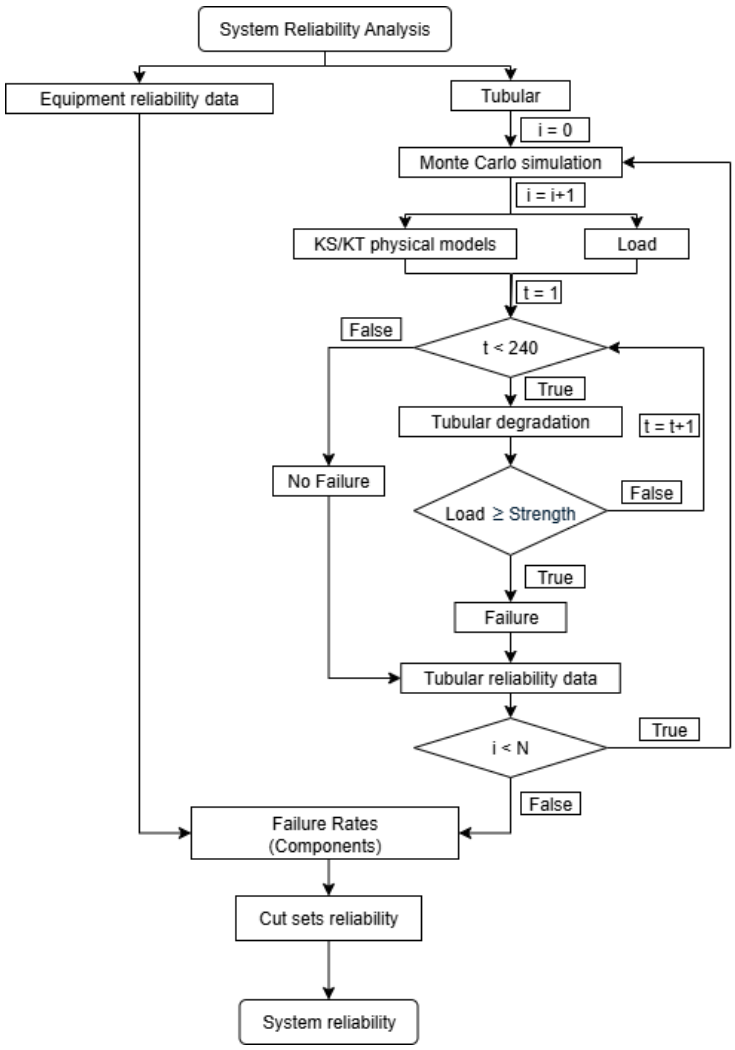


Figure 1. Flowchart of the proposed methodology

To represent the temporal corrosion of tubular strength, this study adopts a triangular probability distribution to model wall thickness reduction induced by corrosion. This probabilistic formulation enables the incorporation of epistemic uncertainty commonly associated with long-term deterioration processes in subsea environments. The triangular distribution is defined by three parameters: a, b, and c, corresponding respectively to the minimum, most probable, and maximum values of the corrosion factor applied to the original wall thickness. For the production phase, which is typically characterized by more stable operating conditions, the corrosion multipliers range from $a = 0.9980$ to $c = 0.9997$, with the mode at $b = 0.9990$, as reported by Haaland [7].

3.1 Case study

The well analyzed in this study was modeled based on the architecture described by Colombo [17], representing a typical deepwater vertical well equipped with a subsea Christmas tree (XT) and completed with production tubing, casings, and safety valves. From the well configuration, the critical Well Barrier Elements (WBEs) responsible for flow containment during the production phase were identified. These elements were grouped according to their function within the Barrier Envelopes, and the minimal cut sets were derived from a logical dependency matrix (DF) among components, representing potential integrity loss scenarios.

Based on the previous modeling, the methodology presented in Fig. 1 was applied to estimate the time-dependent reliability of the production casing. The simulation was performed using $N = 10^7$ samples over a 240-month horizon. At each time step, failure conditions were evaluated either by ductile rupture (KS model) or collapse (KT model), with progressive wall thickness corrosion based on a predefined triangular distribution. The strength modeling of the tubulars incorporated uncertainties associated with geometric and mechanical properties as well as structural imperfections. The design variables evaluated in the present work, along with their statistical parameters, are presented in Tab. 1, in accordance with API TR 5C3 [15]:

Table 1. Random properties used in the analysis

Design Variables	Mean	COV	Distribution
Uncertainty of KS (mu_{KS})	1.01	0.036	Gaussian
Uncertainty of KT (mu_{KT})	0.9991	0.067	Gaussian
Ultimate Tensile Strength (f_u)	1.10	0.0422	Gaussian
Yield Strength (f_y)	1.10	0.0361	Gaussian
Wall Thickness (t)	1.0069	0.0259	Gaussian
Outside Diameter (D)	1.0059	0.00181	Gaussian
Ovality (ov)	0.217	0.541	Weibull
Eccentricity (ec)	3.924	0.661	Weibull
Residual Stress (rs/f_y)	-0.138	0.507	Gaussian

The estimated failure rates for the production casing were integrated with those of the other components and incorporated into the system reliability model through cut set logic, as illustrated in Fig. 1. This approach enabled the assessment of the overall well reliability over time.

4 Results and discussions

The results consider constant failure rates for completion equipment and safety valves, while failure rates for the production casing were derived through Monte Carlo simulation, incorporating uncertainty related to corrosion over time. The evaluated casing is made of API X-80 steel with an outer diameter of 14 inches, assessed under two critical scenarios: internal pressure burst (Klever-Stewart model – KS), considering formation fluid as internal load, and structural collapse (Klever-Tamano model – KT), under full evacuation.

The simulation was performed with 10^7 samples over 240 months, using triangular distributions to model progressive wall thickness loss, based on corrosion parameters proposed by Haaland [7]. The resulting monthly failure rates were integrated into the logic-based system model through cut sets, enabling time-dependent reliability assessment and identification of dominant failure modes throughout the well's service life.

As illustrated in Fig. 2, the failure rates of production casing were estimated using the time-dependent Monte Carlo simulation methodology. As expected, the failure rate increases progressively throughout the simulation horizon due to the reduction in wall thickness by corrosion. Notably, the full evacuation condition (KT model) results in higher failure rates compared to the formation fluid burst scenario (KS model), particularly in later stages of the service life.

Figure 3 illustrates the cumulative system failure probability (Q_{top}) integrating both the fixed failure rates of completion components and the variable failure rate of the casing. The curve associated with the KT model again stands out, demonstrating a significantly higher cumulative failure probability over time. This indicates that casing collapse under full evacuation is a dominant failure mode, which critically affects the overall system integrity.

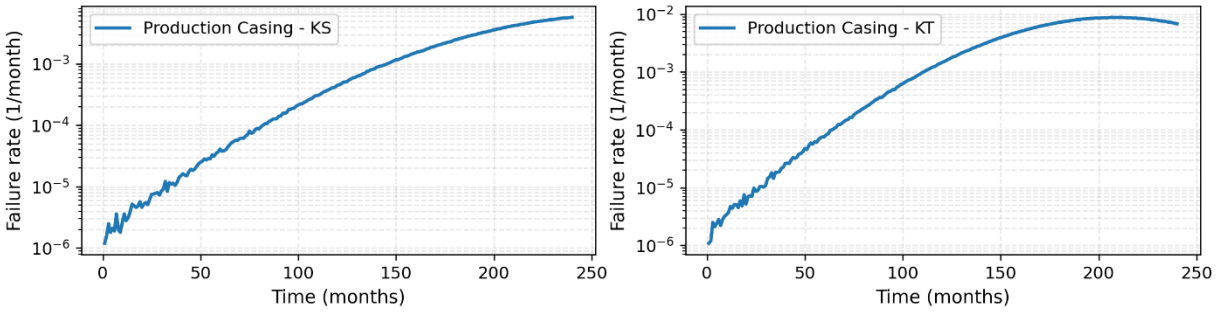


Figure 2. Time-dependent failure rate of the production casing: (left) KS model; (right) KT model.

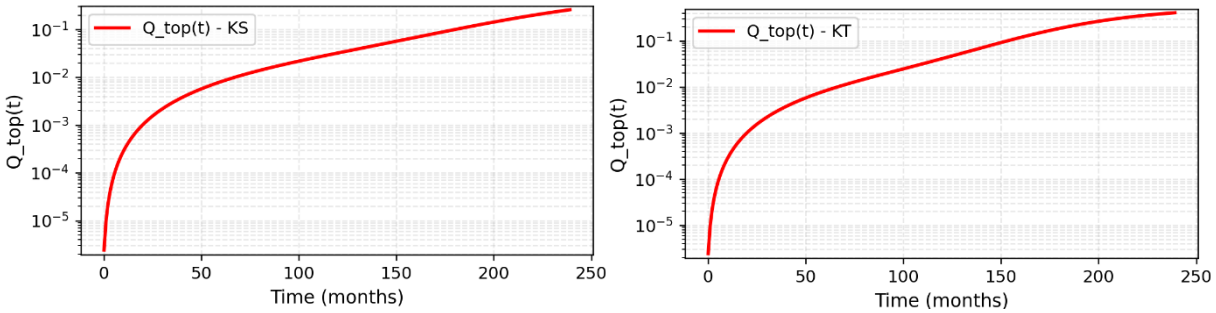


Figure 3. Time-dependent cumulative system failure probability: (left) KS model; (right) KT model.

Figure 4 presents a comparative analysis of the system-level failure rate (λ_{top}) derived from the baseline model (blue dashed line), assuming constant failure rates for all components, and the enhanced models incorporating time-dependent corrosion of the production casing (red line). The results clearly indicate that the inclusion of casing corrosion mechanisms, modeled via the KS and KT formulations, leads to a significant increase in the system failure rate over time. Notably, the KT model exhibits a steeper growth in λ_{top} after approximately 100 months, reflecting the cumulative effects of severe internal pressure collapse scenarios. This behavior highlights the critical impact of progressive material degradation on long-term system reliability and reinforces the necessity of adopting time-dependent reliability models for offshore wells subjected to aggressive operational and environmental conditions.

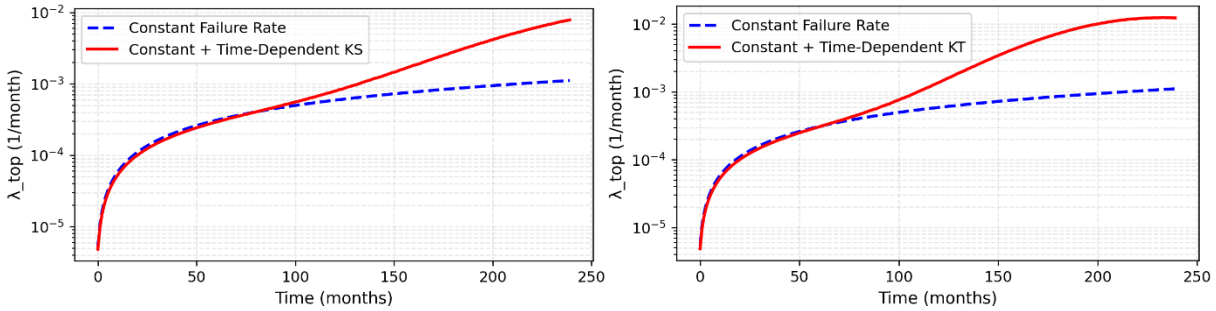


Figure 4. System failure rate with and without time-dependent casing: (left) KS model; (right) KT model.

In summary, considering time-dependent failure rates for the production casing alters the reliability of the well system. While the use of constant rates may be acceptable in short-term evaluations, the simulation results show that time-dependent corrosion, especially under critical conditions, can increase system failure rates and cumulative probabilities over extended operational periods. This time-variant modeling approach yields a more conservative estimate of well integrity, capturing corrosion effects that constant-rate models inherently overlook. These findings reinforce the importance of incorporating progressive corrosion mechanisms into offshore well integrity management frameworks.

5 Conclusions

This study introduced a time-dependent reliability methodology for evaluating the integrity of well barrier systems by integrating physical corrosion models, Monte Carlo simulation, and system-level failure logic via cut sets. The inclusion of casing corrosion effects, especially under full evacuation conditions, resulted in higher failure rates and cumulative failure probabilities compared to conventional constant-rate approaches. Among the models analyzed, the Klever-Tamano (KT) formulation yielded a more conservative reliability profile than the Klever-Stewart (KS) model. While the current use of simplified corrosion modeling provides a conservative estimate, future work should explore the implementation of more physically representative corrosion equations, incorporating parameters such as temperature, pressure, fluid composition, and flow regime to enhance the accuracy of long-term predictions. Additionally, integrating other time-dependent mechanisms, such as fatigue and wear, could further strengthen the applicability of the framework. Overall, the proposed framework offers a practical tool for identifying critical failure paths and supporting risk-informed integrity management, particularly for long-life subsea wells operating in harsh environments.

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