Application of Reliability Testing in Completion Equipment in the Oil and Gas Industry: A Reliability Design Test (RDT) Approach

Marco Aurelio Pestana[1*], Arthur Rios de Azevedo[1], Luiz Flávio da Silva[1], Vinicius Airão Barros[2]
[1] *SENAI CIMATEC, Oil & Gas Department, Salvador, Bahia, Brazil*
[2] *PETROBRAS, Centro de Pesquisas (CENPES), Rio de Janeiro, Brazil*
**Corresponding author: SENAI CIMATEC; Av. Orlando Gomes, 1845 - Piatã, Salvador - BA, 41650-010; marco.pestana@fieb.org.br*

Abstract: The reliability of completion equipment is essential for the safe and economic performance of offshore wells. This paper presents the application of Reliability Design Tests (RDTs) as a tool to estimate and validate the reliability of critical components during the development phase. After contextualizing the operational challenges in the oil and gas industry, the fundamentals of RDTs are described, followed by a hypothetical case study on an Inflow Control Valve (ICV). The study demonstrates how the methodology enables early failure detection, uncertainty reduction, and supports design and maintenance decisions. Results indicate that RDTs, when applied systematically, significantly contribute to risk reduction, asset lifecycle optimization, and compliance with industry technical standards.
Keywords: reliability. completion equipment. design testing. inflow control valve. oil and gas.
Abbreviations: ICV, Inflow Control Valve. IEC, International Electrotechnical Commission. ISO, International Organization for Standardization. MTBF, Mean Time Between Failures.
MTTF, Mean Time to Failure. RCM, Reliability-Centered Maintenance. RDT, Reliability Design Test.

1.Introduction

The oil and gas industry operates in highly complex and hostile environments, particularly in subsea systems and deep wells such as those in the pre-salt. In this context, completion equipment plays a critical role in maintaining well control and ensuring long-term integrity under extreme conditions including high pressures and temperatures (HPHT), corrosive fluids, and mechanical loads[1]. Failures in components like safety valves, packers, sensors, and control lines can lead to significant consequences, including production shutdowns, costly interventions, and environmental hazards. Therefore, close collaboration with suppliers is essential to develop equipment with the functionality and reliability required to withstand such demanding operational environments [2].

In the pre-salt environment, these technical challenges are further compounded by high completion costs driven by factors such as well depth, HPHT conditions, and demanding logistics. This economic pressure, especially during periods of low oil prices, has led to the development of new technologies and best practices aimed at improving project feasibility[3]. In this scenario, advances such as optimized completion designs, application of reliability engineering to completion systems, MPD-assisted workovers, and completion drill-through techniques have proven essential for cost control and operational efficiency.[1]

Reliability estimation of completion equipment has therefore become a key enabler, not only to support risk-based maintenance and enhance safety, but also to optimize lifecycle cost management and ensure economic viability in challenging offshore environments. However, the application of traditional reliability tests faces limitations in offshore operations, where destructive testing or long-term field campaigns may be impractical or economically prohibitive.

In this scenario, Reliability Design Tests (RDTs) emerge as a promising alternative for early-stage reliability estimation. RDTs allow the assessment of critical components under controlled and accelerated conditions, enabling the identification of failure modes and quantification of reliability before field deployment [4]. This paper aims to discuss the fundamentals of RDTs and their practical application in estimating the reliability of completion equipment in the oil and gas industry.

2.Reliability of Well Completion Equipment

Completion equipment is responsible for isolating production zones, controlling fluid flow, monitoring process variables, and ensuring well integrity over its service life. Since these components are generally installed in inaccessible environments after completion — such as the wellbore or subsea control lines — reliability becomes a key requirement for the technical and economic viability of offshore operations.

In engineering, reliability is defined as the probability that an item will perform its intended function without failure for a specified period under stated conditions[5]. Common metrics include:

MTTF (Mean Time to Failure): average time to failure, used for non-repairable systems;

MTBF (Mean Time Between Failures): average time between failures, used for repairable systems;

Failure rate (λ): frequency of failure occurrences in a given interval;

Reliability function $R(t)$: probability of operating without failure up to time t.

Subsea wells are exposed to harsh environments, with pressures above 10,000 psi, temperatures exceeding 150 °C, presence of CO_2 and H_2S, plus vibration and thermal cycling accelerate failure mechanisms such as fatigue, stress corrosion cracking, elastomer degradation, and welding or sealing failures[6].

Given the high costs and complexity of corrective maintenance in subsea wells, reliability must be incorporated into the design phase through robust engineering methods, modeling, and laboratory validation.

3.Types of Reliability Testing

Reliability validation can be performed using various methods, depending on the component's criticality, operating conditions, and lifecycle stage:

- Accelerated Life Testing (ALT): exposing equipment to harsher-than-normal conditions to induce failures faster, then extrapolating life expectancy statistically;

- Highly Accelerated Life Testing (HALT): identifying operational limits quickly, often destructively, without necessarily producing statistically significant life data;
- Field or simulated service testing: monitoring equipment in real or representative environments, often requiring long observation times.

While widely used, these methods have limitations in the offshore context:

- Cost and time: long test durations can be prohibitively expensive for complex prototypes;
- Reproducibility: real subsea well conditions are difficult to replicate in the laboratory;
- Low statistical power: highly reliable components may fail so rarely during testing that data significance is compromised.

These limitations create the need for more design-oriented approaches, such as RDTs, which enable earlier and more statistically robust reliability assessments.

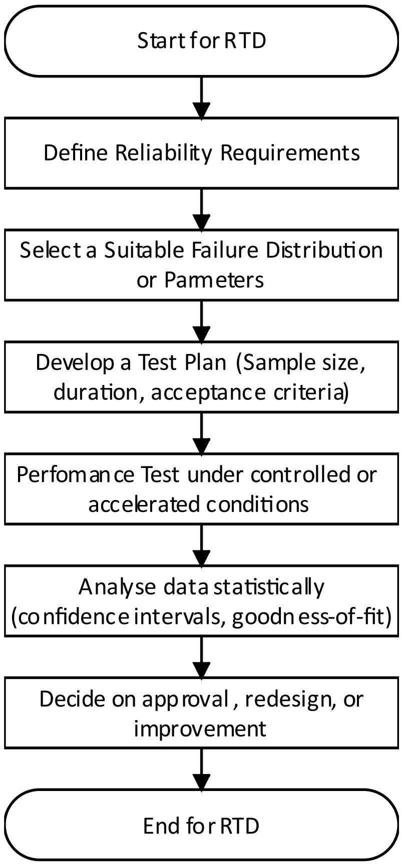
4.Reliability Design Test (RDT): Fundamentals and Applications

RDTs are structured, design-integrated reliability tests conducted early in product development. Unlike conventional testing, which often occurs late in the lifecycle, RDTs aim to verify whether components meet predefined reliability requirements using statistically valid test plans.

4.1. Steps in an RDT

The reliability assessment follows a structured process comprising six steps: definition of reliability requirements (e.g., MTTF, $R(t)$); selection of an appropriate failure distribution (e.g., Weibull, lognormal); development of a test plan (sample size, duration, acceptance criteria); execution of tests under controlled or accelerated conditions; statistical analysis of the data (confidence intervals, goodness-of-fit); and, finally, decision-making regarding approval, redesign, or improvement. This process is illustrated in Figure 1.

Figure 1. An RDT process flow



4.2. Advantages in Completion Systems

In completion systems, the adoption of structured reliability testing and analysis offers significant advantages. One of the key benefits is the early identification of potential design or material weaknesses, enabling corrective actions before field deployment. This approach also contributes to reducing test duration and associated costs by optimizing test planning and leveraging accelerated testing techniques. Furthermore, reliability assessments can be effectively integrated with other risk analysis tools such as Failure Modes and Effects Analysis (FMEA), Fault Tree Analysis (FTA), and Monte Carlo[7][8] [9]simulations, providing a more comprehensive evaluation of system performance under uncertainty[5][7][8][9]. These practices align with international standards and industry guidelines, supporting compliance with API 17N, ISO 13628, and IEC 61508, and enhancing the overall robustness and safety of subsea completion operations[10][11][12].

5. RDT on an Inflow Control Valve (ICV) – A Hypothetical Case Study

Inflow Control Valves (ICVs) play a vital role in intelligent completions by enabling precise zonal control of oil and gas production. Over the past two decades, technological advancements have greatly enhanced the reliability of ICVs, resulting in longer operational lifespans and lower failure rates across applications from ultra-deepwater to unconventional reservoirs[13] . In the present hypothetical case study, an electro-hydraulic ICV, rated for operations at 3,000 m depth, 10,000 psi, and 130 °C, was evaluated under accelerated conditions.

The reliability demonstration test (RDT) was structured to verify whether the ICV could achieve a five-year reliability target of

$R \geq 0.95$ with 90% confidence, assuming a non-repairable system. Failure behavior was modeled by a Weibull distribution with a shape parameter $\beta = 1.5$, a value indicative of wear-out failure mechanisms typical of mechanical components.

A zero-failure acceptance test plan was adopted, which requiring all 9 units to be tested simultaneously for a total of 2,000 hours—an accelerated equivalent to five years of operation. Testing was conducted within a hydrothermal loop, featuring pressure cycling from 0 to 10,000 psi and temperature cycling between 30 and 150 °C to mimic operational stressors.

Throughout the testing campaign, key performance indicators were closely monitored, including actuation time, sealing integrity, power consumption, and hydraulic integrity, to ensure coverage of both functional performance and long-term reliability requirements.

6. Results

No failures were observed across all nine electro-hydraulic ICV units during 2,000 hours of accelerated hydrothermal testing. Implementing a zero-failure acceptance test based on the Weibull distribution ($\beta = 1.5$), statistical analysis confirms—at a 90% confidence level—that the five-year reliability target ($R \geq 0.95$) is achieved or exceeded. This underscores the reliability under the simulated extreme operational conditions

7.Discussion

A hypothesis-driven sensitivity assessment reveals how the reliability projections would shift under alternative modeling assumptions and testing limitations. If the Weibull shape parameter were lower, approximating β=1.2 (reflecting more random failure tendencies), the five-year reliability estimate would moderately decrease (e.g., within the range of $R \approx 0.92–0.94$).

Conversely, a more pronounced wear-out behavior represented by β=2.5 would yield a more notable reliability decline (e.g.,$R \approx 0.88$). Such sensitivity to β aligns with known properties of the Weibull distribution, where small changes in the shape parameter can significantly affect hazard dynamics and reliability outcomes

Moreover, reducing the number of test units (for instance, to six samples) would inevitably widen confidence bounds and weaken statistical assurance that the reliability requirement is met. Similarly, shortening the test duration to 1,200 hours, while maintaining identical Weibull assumptions. would likely lower the extrapolated reliability (e.g., $R \approx 0.90$), demonstrating the trade-off between test duration and statistical power, as also reflected in reliability test design literature.

Additionally, employing less aggressive environmental stress conditions (i.e., narrower pressure or temperature cycling profiles) would likely mask performance degradation mechanisms, risking overly optimistic or non-conservative reliability estimates.

Together, these insights emphasize that the original test design, entailing nine units, 2,000 hours of stress testing, and a zero-failure acceptance criterion, offers a compellingly conservative demonstration of reliability under the assumed Weibull paradigm. However, the sensitivity analysis highlights the critical importance of carefully selecting β, sample size, test duration, and stress levels to maintain rigor in reliability claims. In real-world engineering deployment, supplementary testing, conservative assumptions, and validation under operational conditions are advisable to mitigate overconfidence and ensure robustness in reliability projections.

This hypothetical case study demonstrates the feasibility and tangible benefits of applying a Reliability Demonstration Test (RDT) to critical completion equipment like Inflow Control Valves (ICVs). By implementing early, accelerated testing under controlled yet challenging conditions, the methodology enables the anticipation of potential failure modes, thereby reducing the need for costly redesigns and significantly increasing confidence in system reliability. Such proactive assessment aligns with the overarching objective in completion-system engineering: maximizing operational uptime and reliability over extended service life, and avoiding the "infant mortality" and wear-out phases of the reliability bathtub curve

Nonetheless, several limitations must be acknowledged. The accuracy of the mission profile: such as depth, pressure, and temperature cycles, affects the validity of reliability extrapolations. The high cost of establishing and operating testing laboratories able to reproduce the harsh environments encountered in subsea wells may limit broader adoption. Moreover, RDTs may overlook latent or rare failure mechanisms that emerge only over longer operational timelines or under untested transients, underscoring the continued need for complementing these tests with field data and condition-based monitoring strategies

Despite these caveats, RDT adoption within oil and gas projects offers a powerful means of mitigating operational risks and optimizing lifecycle costs. Early identification of vulnerabilities and performance degradation not only guides more informed design decisions but also underpins reliability-centered maintenance and proactive degradation management, thereby enabling safer and more cost-efficient well completion operations.

8.References

[1] Fernandes FB, Sthel ASO, Amorin Martins DE, Siqueira CYS, Rezende FHG, Dos Santos ER. Drilling and Completion Technologies for Pre-Salt Developments. 55th U.S. Rock Mechanics / Geomechanics Symposium 2021, vol. 5, 2021.

[2] Beltrao RL, Sombra C, Lage A, Fagundes Netto J, Henriques C. Challenges and New Technologies for the Development of the Pre-Salt Cluster, Santos Basin, Brazil, Society of Petroleum Engineers (SPE); 2009. https://doi.org/10.4043/otc-19880-ms.

[3] Vigano GC. Methodology to a feasibility study to implement an oil/water subsea separation. Offshore Technology Conference Brasil 2019, OTCB 2019, 2020. https://doi.org/10.4043/29895-ms.

[4] Chen WH, Gao L, Pan J, Qian P, He QC. Design of Accelerated Life Test Plans—Overview and Prospect. Chinese Journal of Mechanical Engineering (English Edition) 2018;31. https://doi.org/10.1186/s10033-018-0206-9.

[5] Modarres M, Kaminskiy MP, Krivtsov V. Reliability engineering and risk analysis a practical gide. 2016. https://doi.org/10.1201/9781315382425.

[6] DeBruijn G, Skeates C, Greenaway R, Harrison D, Parris M, James S, Mueller F, Ray S, Riding M, Temple L, Wutherich K. High-pressure, high-temperature technologies. Oilfield Review 2008;20.

[7] US Department of Defence. MIL-P-1629A: Military Standard, Procedures for Performing a Failure Mode, Effects and Criticality Analysis 1949.

[8] Stamatelatos M, Caraballo MJ, Vesely W, Dugan J, Fragola J, Minarick J, Railsback J. Fault tree handbook with aerospace applications. 2002.

[9] Zio E, Baraldi P, Patelli E. Assessment of the availability of an offshore installation by

Monte Carlo simulation. International Journal of Pressure Vessels and Piping 2006;83:312–20. https://doi.org/10.1016/j.ijpvp.2006.02.010.

[10] Strutt J, Wells D. API 17N – Recommended Practise for Subsea Production System Reliability, Technical Risk & Integrity Management. Offshore Technology Conference, OTC; 2014. https://doi.org/10.4043/25412-MS.

[11] International Electrotechnical Commission. IEC 61508 : Functional safety of electrical/electronic/ programmable electronic safety-related systems. 1st IEE Automotive Electronics Conference 2005.

[12] ISO 13628. BS EN ISO 13628-1-2005 Petroleum and natural gas industries — Design and operation of subsea production systems —Part 1 General requirements and recommendations. vol. 3. 2003.

[13] Joubran J. Intelligent completions: Design and reliability of interval control valves in the past, present, and future. Proceedings of the Annual Offshore Technology Conference, vol. 5, 2018. https://doi.org/10.4043/28917-ms.