Evaluating Reliability and Availability of a CO_2-Selective Membrane Testing Unit Using Monte Carlo Simulation

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The urgency of mitigating climate change has intensified the search for effective CO_2 sequestration technologies, with membrane-based separation emerging as a promising solution for natural gas treatment due to its energy efficiency and compact footprint. To achieve large-scale viability, such technologies must demonstrate not only technical performance but also high operational and maintenance (O&M) standards to ensure economic competitiveness and sustained throughput. However, estimating O&M performance during early development stages remains challenging, particularly for novel systems with limited real-world operational data. In this context, a Reliability, Availability, and Maintainability (RAM) analysis was conducted for an Advanced Membrane Testing Skid designed to support accelerated membrane qualification. The system comprises 59 mechanical, thermal, and instrumentation elements, grouped into three functional subsystems. Over a planned six-month (4000 h) testing campaign, the analysis—based on fault tree modeling and Monte Carlo simulation using OREDA failure data—revealed a mission reliability of 6.1% and a mean availability of 98.56%, corresponding to an estimated loss of approximately 90 out of 5190 membrane test cycles. Importance measures were computed to identify key failure contributors, with the electric heater AE-001 emerging as the dominant component affecting system availability. A sensitivity analysis demonstrated that a ten-fold reduction in the Mean Time To Failure (MTTF) of critical components would lower availability to 93.44%, while a ten-fold improvement would raise it to 99.1%. These findings highlight the importance of component-level design improvements, redundancy strategies, and predictive maintenance in enhancing skid uptime and supporting faster membrane technology deployment.
Keywords: Membrane reliability assessment. Monte Carlo modelling. CO_2 capture membranes. Natural gas skid.
Abbreviations: MTTF, Mean time to failure. O&M, Operational and Maintenance. RAM, Reliability Availability and Maintainability, STMA, Advanced Membrane Testing Skid.

1. Introduction

Global warming and climate change rank among the most urgent challenges of our time, and reducing CO_2 emissions from industrial processes is critical for both environmental preservation and regulatory compliance. Membrane separation has emerged as a particularly attractive technology for CO_2 capture, offering scalability, low energy consumption and the ability to operate under the high-temperature, high-pressure conditions typical of natural gas processing.

To rigorously assess membrane performance and reliability in realistic service environments, we developed the Advanced Membrane Testing Skid (STMA). The STMA is capable of evaluating a variety of advanced polymeric and inorganic membranes under controlled flow, temperature and pressure regimes, enabling precise measurement of separation efficiency, throughput and operational stability.

In this paper, we present a comprehensive Reliability, Availability, and Maintainability (RAM) analysis of the STMA, utilizing a robust statistical method based on Monte Carlo simulation. The analysis identifies critical components, evaluates their impact on overall system performance, and provides insights for optimizing asset management and maintenance strategies. Furthermore, sensitivity analyses assess how variations in critical parameters influence the reliability and availability of the system, enabling targeted improvements.

The subsequent sections of this paper include a detailed description of the STMA's functionality, followed by a clear presentation of the adopted methodology. Results from the RAM analysis, including critical system insights and practical recommendations, are thoroughly discussed. Finally, key conclusions and implications for enhancing the reliability and operational effectiveness of advanced membrane testing processes are summarized.

2. Advanced Membrane Testing SKID (STMA)

The Advanced Membrane Testing SKID (STMA) is engineered to quantify the performance of membrane vessels in removing CO_2 from natural gas. Its operation is organized into three distinct subsystems—Separation, Regeneration and Data Transmission—each with clearly defined boundaries to support targeted reliability and availability analyses.

- **Separation subsystem:** Responsible for the core function of isolating CO_2, it comprises feed, permeate, residue and depressurization lines, control valves, an electric heater, cartridge filters, membrane vessels and an online gas chromatograph. The chromatograph continuously measures CO_2 breakthrough, providing real-time separation efficiency data.
- **Regeneration subsystem:** Activated after each separation cycle, it restores membrane permeability and selectivity. This loop mirrors the Separation layout—control valves, heater, cartridge filter and membrane vessels—but adds a cooler to condition the gas stream and prevent membrane overheating.
- **Data Transmission subsystem:** Encompasses all pressure, flow and temperature sensors, transmitters and indicators (excluding the depressurization branch). It continuously relays operational parameters to the control system and enforces safety interlocks and alarms in the event of abnormal conditions.

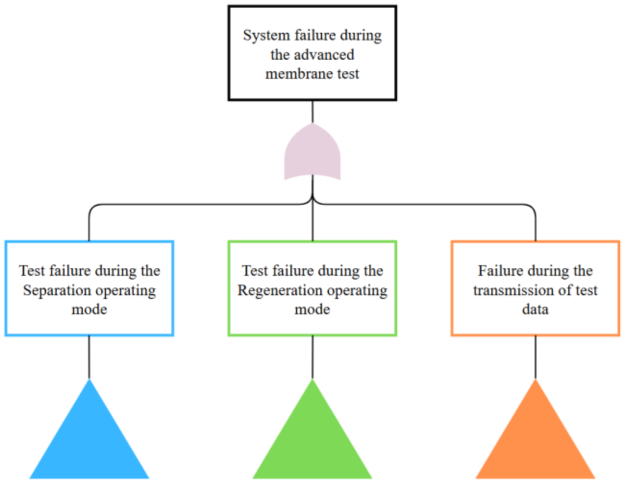
For reliability modeling, we constructed a Functional Tree to map system workflows and a complementary Fault Tree Analysis (FTA) to pinpoint how individual component failures propagate to system-level test interruptions. Key elements—such as control valves, sensors and the electric heater—emerged as high-criticality items whose unavailability directly halts the membrane test.

Figure 1 illustrates a simplified Fault Tree for the STMA. The top event, “System failure during the advanced membrane test,” is driven by an OR gate combining three intermediate events:

1. Test failure during the Separation mode
2. Test failure during the Regeneration mode
3. Failure in the transmission of test data

This structured decomposition ensures comprehensive identification of failure modes and supports the development of focused maintenance and design improvements to maximize STMA uptime and data quality.

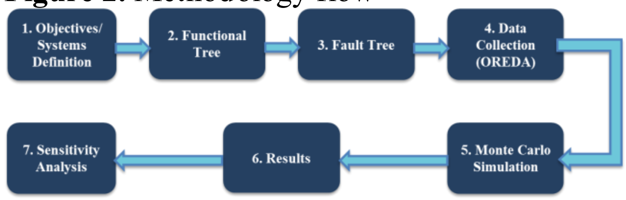
Figure 1. Simplified Fault Tree of the STMA



3. Methodology

The methodology applied to effectively analyze the advanced membrane testing skid involves identifying and understanding its individual components and compiling them into a Fault-Tree Analysis (FTA) to calculate the overall system reliability [1]. Each subsystem contributes to the overall reliability, and the subsystem with the lowest reliability is considered the most critical. To accurately evaluate these parameters under realistic operational conditions, Monte-Carlo simulation is employed. The statistical distributions adopted for failure and repair times—as well as their parameter estimates—were taken directly from the Offshore Reliability Data [2], ensuring industry-validated input data for the simulation. This approach captures complex interactions and stochastic behaviors, providing precise estimations of reliability, maintainability and availability [3]. Figure 2 illustrates the overall methodology employed in this study.

Figure 2. Methodology flow



Combining Monte Carlo simulation with Reliability, Availability, and Maintainability (RAM) analysis results in a powerful tool. This combination enables an accurate understanding of system performance, supports informed decision-making, and facilitates targeted improvements to enhance reliability.

Specifically, RAM analysis quantitatively evaluates:

- Reliability: the probability that a system operates without failures over a defined period, often modeled using an exponential distribution based on Mean Time to Failure (MTTF).
- Availability: the proportion of time the system remains operational, considering both failures and repair times.
- Maintainability: the ease and speed at which a system can be restored to operational status after a failure, typically modeled using the Mean Time to Repair (MTTR).

Due to the inherent complexity of calculating reliability analytically in systems comprising multiple components arranged in series, parallel, or k/n configurations, Monte Carlo simulation is utilized. This method performs repeated random sampling from statistical distributions representing component failure and repair times, thereby enabling a comprehensive assessment of the system's stochastic behavior. The reliability estimates become increasingly accurate with the number of simulations, in accordance with the Law of Large Numbers.

Following simulation, importance measures are calculated to pinpoint critical components. Two key metrics used are Fussel-Vesely Importance (FVI) and Risk Reduction Worth (RRW):

Fussel-Vesely Importance (FVI) quantifies the probability that a specific component contributes to the overall system failure as presented in equation (1).

$$FVI_i = \frac{P(System\ fails\ caused\ by\ i)}{P(System\ fails)} \qquad (1)$$

A higher FVI indicates a greater contribution to system unreliability, highlighting the criticality of improving or closely monitoring that component.

Equation (2) presents the Risk Reduction Worth (RRW) which evaluates the potential increase in system reliability if a component is assumed to be perfectly reliable (zero probability of failure).

$$RRW_i = 1 - \frac{P(System\ fails)}{P(System\ fails|R_i = 1)} \qquad (2)$$

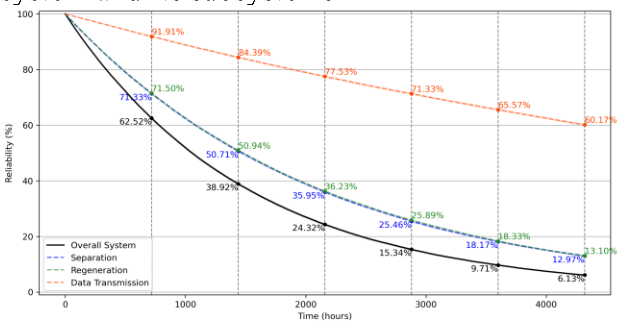
A higher RRW means that significantly improving the reliability of the component would notably enhance the system's overall reliability.

Finally, a Sensitivity Analysis, following NASA's Handbook guidelines [4], employs an Error Factor (EF) applied to critical parameters such as MTTF. This analysis evaluates how significant parameter changes affect system reliability and availability, clearly identifying the components with the highest impact and offering actionable guidance for future optimization.

4. Results and discussion

In the combined plot of reliability, **Erro! Fonte de referência não encontrada.**, and availability, Figure 4, for the STMA skid and its subsystems over the six-month mission, two contrasting behaviors become immediately apparent. The reliability curves for all elements—including the overall system and each of the three subsystems—begin at 100% and then descend continuously as failures accumulate. In stark contrast, the availability curves also start at 100%, but rather than collapsing, they plateau at high values, reflecting the system's capacity for rapid repair and return to service.

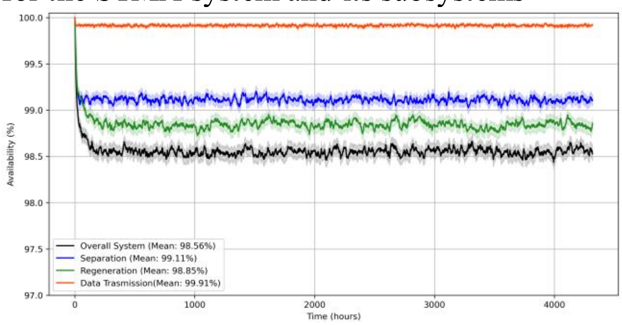
Figure 3. Reliability curves of the STMA system and its subsystems



The complete system's reliability plunges most dramatically: within the first month, it loses over one-third of its “all-good” probability, dropping from perfect operation to just 62.5%, and by mission’s end it has virtually no chance (6.1%) of having run without interruption. This steep decline is a direct consequence of having 59 components predominantly arranged in series—each additional element raises the likelihood of some failure. Yet, when viewed through the lens of availability, the story is more encouraging: the system sustains an average availability of 98.56% (95% CI: 98.48–98.63%), meaning that despite multiple failures, the skid spends less than 1.5% of its time offline.

Delving into the subsystems, Data Transmission exhibits the gentlest reliability decay. Even though it comprises the largest count of individual transmitters and sensors, its end-of-mission reliability sits at a robust 60.17%. The high mean time to failure (MTTF) of electronic components, combined with repair times tightly clustered around 2.5–5 hours, drives its availability to 99.91% (95% CI: 99.90–99.93%). In practice, this means that data links are almost never the bottleneck in sample collection, and when they do fail, they are returned to service almost immediately.

Figure 4. Availability convergence over time for the STMA system and its subsystems



By comparison, the Separation and Regeneration subsystems both decline to roughly 13% reliability by six months, but their availability profiles diverge slightly. The Separation subsystem, free of the long-MTTR heat exchanger, maintains an average availability of 99.11% (95% CI: 99.06–99.17%).

Regeneration subsystem, on the other hand, dips to 98.85% availability (95% CI: 98.78–98.92%). Reflecting the TCR-001 exchanger’s occasional 65–80 hour overhauls. Although such extended downtimes are infrequent, their presence is sufficient to lower the subsystem’s mean availability by roughly a quarter of a percent compared to Separation.

Overlaying all four reliability curves highlights the relative resilience of Data Transmission and the vulnerability of the series-dominated architecture: the steepest fall is always the black line representing the full system, while the orange, green and blue lines of the subsystems fan out above it. Similarly, stacking the availability curves shows Data Transmission hugging the top at nearly constant 100%, Separation and Regeneration just below it, and the system total settling on the same slope as a weighted blend of the three.

From an operational standpoint, these patterns carry clear implications. Since the chromatograph collects samples every ten minutes in five-shot cycles, every minute of downtime risks an entire cycle’s loss. Under a hypothetical 100% availability scenario, 5184 cycles would be completed in six months; at

98.56% availability, roughly 75 cycles are forfeited, yielding just over 5109 valid runs. Because each failure—particularly those of long-MTTR components—can damage expensive membranes and halt testing, focusing maintenance strategies on the Regeneration exchanger and other long-repair assets promises the greatest return in preserving cycle count.

In summary, while the system as a whole is almost guaranteed to suffer failures over six months, its architecture and effective corrective maintenance ensure that those failures rarely translate into significant downtime. The combined reliability/availability plot makes one point unequivocal: to maximize valid membrane-test cycles, it is far more effective to reduce repair durations and variability—especially in the Regeneration subsystem—than to chase incremental gains in intrinsic component reliability. Continuous improvement should therefore target long-MTTR assets, refining both spare-parts logistics and predictive diagnostics, to tilt the availability curve ever closer to the ideal "flat line" at 100%.

The sensitivity analysis measures conducted in this study clearly identifies the Electric Heater (AE-001) as the most critical component within the Advanced Membrane Testing SKID (STMA), highlighting its profound impact on the system's overall reliability and availability. This conclusion was supported by the Fussel Vesely Importance (FV) and Risk Reduction Worth (RRW) metrics as show in Table 1.

Table 1. Importance measures of the components in STMA

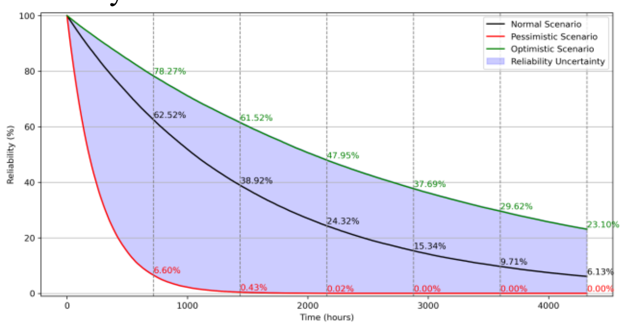
Components	Fussell-Vesely	Risk Reduction Worth
AE-001	0.6982	0.0461
TCR-001	0.0466	0.0114
FV-002	0.0635	0.0110
TV-007, PV-011, PV-015	0.0317	0.0110

Focusing exclusively on the AE-001, the Fussel Vesely measure revealed an importance score of 0.6982, significantly surpassing the second-ranked component (FV-002), which scored merely 0.0635. This considerable disparity underscores the critical role of the Electric Heater, indicating its dominant contribution to system failures. Similarly, the RRW measure reinforced this conclusion, assigning AE-001 the highest value of 0.0461, clearly demonstrating that enhancing this component's reliability could substantially reduce the overall risk of system failure.

Considering these importance metrics, a detailed sensitivity analysis was performed specifically targeting AE-001 to evaluate the impact of its reliability variations on the complete system. Two extreme scenarios were tested by applying Error Factors (EF): EF (D), where the Mean Time To Failure (MTTF) was decreased by a factor of 10, and EF (M), where the MTTF was increased by the same magnitude.

In the first scenario, EF (D), reducing AE-001's MTTF to 286 hours (compared to the original 2864 hours), the system's reliability sharply deteriorated as the Figure 5 shows, virtually reaching zero halfway through the mission duration. This highlights the severe consequences of utilizing an Electric Heater with lower reliability. Moreover, under EF (D), the system's availability drastically fell to 93.44%, reflecting substantial downtime that would severely affect operational continuity and sample collection. This scenario caused the average number of system failures to increase significantly, from 2.77 to 15.27 events during the mission period, leading directly to a reduction of approximately 341 analysis cycles.

Figure 5. Reliability over time under normal, pessimistic, and optimistic scenarios for the STMA system.



Conversely, in the improved scenario (EF (M)), where AE-001's MTTF was elevated to 28640 hours, the overall system reliability markedly improved, rising from the base case of 6.13% to 23.10% by the mission's end. Availability also improved, achieving 99.10%, translating directly into fewer interruptions and increased operational performance, allowing an additional 28 analysis cycles compared to the real scenario.

Summarizing these findings, the Sensitivity Analysis conclusively demonstrated AE-001's pivotal role within the STMA project. Its reliability directly and substantially influences the overall performance metrics of the system, particularly in availability and failure frequency. Consequently, prioritizing a highly reliable Electric Heater is essential to maximizing system uptime, operational efficiency, and safeguarding the integrity of tested membranes.

5. Conclusion

This study demonstrates that rigorous RAM analysis, underpinned by Monte Carlo simulation and importance-measure evaluation, is indispensable for qualifying the Advanced Membrane Testing SKID (STMA) as a reliable platform in the fight against industrial CO_2 emissions. Although the 59-component architecture virtually guarantees at least one failure during a six-month campaign, the system's mean availability of 98.56% shows that thoughtful design—combined with swift corrective maintenance—keeps downtime to a fraction of total operating time.

The analysis singles out the Electric Heater (AE-001) as the dominant reliability driver: its Fussell-Vesely score is an order of magnitude higher than any other component, and sensitivity tests reveal that a ten-fold drop in its MTTF would slash availability by more than five percentage points and cost hundreds of test cycles. Conversely, boosting AE-001's robustness delivers the greatest return on investment, raising system reliability almost four-fold and reclaiming dozens of otherwise lost membrane-test runs.

Subsystem behavior further clarifies upgrade priorities. Data Transmission—despite housing the highest part count—remains the most resilient thanks to short repair times, while Regeneration lags chiefly because of long-MTTR events in the TCR-001 exchanger. These findings suggest two complementary improvement paths: (i) harden AE-001 through design enhancements, redundancy, or predictive health monitoring, and (ii) target long-repair assets with condition-based maintenance and streamlined spare-parts logistics.

By translating detailed statistical insights into concrete engineering actions, the present work offers a replicable blueprint for elevating membrane-testing infrastructure from "good enough" to "mission-critical." In the broader climate-change context, every percentage-point gain in SKID availability translates directly into more reliable membrane data, faster technology maturation, and ultimately greater CO_2-capture capacity at industrial scale. Continued investment in reliability-focused design and maintenance, therefore, is not merely an operational choice but a strategic imperative for sustainable emissions abatement.

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