Current Science
CS 5 (2), 1604-1617 *(2025)*
Received 10 **Dec** 2024 | **Revised 22 Jan** 2024 | **Accepted 20 Feb**. 2024 | **Online Available 18 March** 2025
https://doi.org/ 10.52845/CS/2025-5-2-25

Current Science

Current Science

OPEN ACCESS

ISSN(O)2795-8639

ORIGINAL ARTICLE

Risk Analysis of Offshore Test Process for Ultra High Temperature and High Pressure Wellhead Equipment System Based on FMECA

Hongyan Wang[a,b], Shenyu Liu[a], Jinzhu Tian[c], Jiwei Li[d], Zhenyu Xiong[d], Chao Liu[a,b*], Wenbo Zhao[a], Junguo Cui[b*]

[a]College of Electromechanical Engineering, Qingdao University of Science & Technology, Qingdao 266061, China

[b]National Engineering Research Center of Marine Geophysical Prospecting and Exploration and Development Equipment, China University of Petroleum (East China), Qingdao 266580, China

[c]China offshore Engineering & Technology Co., Ltd， Certification and Consulting Department

[d]Sinopec Offshore Oil and Gas Branch, China Petrochemical Co., Ltd

[*]Corresponding Author: Chao Liu & Junguo Cui

Abstract

The wellhead equipment system is a cornerstone of offshore oil and gas operations, playing a pivotal role in ensuring both operational safety and efficiency. However, the offshore testing process for these systems is fraught with significant risks, which, if not meticulously managed, can lead to catastrophic failures, environmental damage, and substantial economic losses. To address these challenges, this study employs Failure Mode, Effects, and Criticality Analysis (FMECA), a systematic and structured methodology, to identify, assess, and prioritize potential failure modes during the offshore testing of ultra-high-temperature and high-pressure wellhead equipment. By integrating historical failure data, expert judgment, and quantitative risk assessment, a comprehensive risk analysis framework is developed. This framework not only identifies the most critical failure modes but also evaluates their potential impacts across multiple dimensions, including safety, environmental sustainability, and operational efficiency. The results of the analysis reveal key failure modes such as pressure testing anomalies, seal failures, and structural deformations, which pose the highest risks to the integrity of the wellhead equipment system. Based on these findings, targeted mitigation strategies are proposed, including enhanced monitoring systems, material upgrades, and procedural improvements. These strategies aim to reduce the likelihood of failures and mitigate their consequences, thereby enhancing the overall reliability and safety of the offshore testing process. This research contributes a robust and practical methodology for improving the safety and reliability of offshore wellhead equipment testing. By proactively addressing potential risks, the study provides valuable insights for reducing operational hazards, preventing environmental disasters, and ensuring the long-term sustainability of offshore oil and gas operations. The findings underscore the importance of a proactive and data-driven approach to risk management in high-stakes industrial environments.

Keywords: Wellhead equipment system, Offshore test process, Ultra-high-temperature and high-pressure, FMECA, Reliability

Introduction

With the continuous depletion of onshore oil and gas resources, the global energy industry has increasingly shifted its focus to offshore exploration and production. As a result, major oil companies have intensified their efforts to develop offshore oil and gas resources, leading to a rapid surge in demand for advanced offshore oil extraction equipment [1][2]. Among these critical components, the wellhead equipment system plays a pivotal role as it serves as the essential interface connecting surface facilities and the wellbore during oil and gas development. This system is primarily responsible for controlling wellhead pressure, regulating inflow, ensuring effective sealing, and providing structural support. Its reliability is of paramount importance, as it directly impacts the safety, operational efficiency, and environmental sustainability of oil and gas wells.

Despite advancements in technology, safety incidents caused by the failure of wellhead equipment systems remain a significant concern. Notable examples include the catastrophic 2010 Deepwater Horizon accident in the U.S. Gulf of Mexico [3], where the sealing failure of the wellhead equipment system triggered a massive blowout, resulting in severe environmental pollution and economic losses. Similarly, in 2016, a wellhead equipment system failure in an Alaskan oil field led to a crude oil spill [4], causing long-term ecological damage to the local environment. These incidents underscore the critical reliability challenges faced by wellhead equipment systems, particularly under the demanding conditions of high pressure, high temperature, and complex operational environments.

As the exploration and development of oil and gas resources extend into deeper waters, ultra-deep wells, and unconventional reserves, wellhead equipment systems are subjected to even more extreme geological conditions, higher pressures, and more volatile temperatures. Consequently, ensuring the reliability of these systems has become a focal point for the industry [5][6]. Although significant progress has been made in the design and manufacturing technologies of wellhead equipment systems, persistent issues such as stress concentration, material degradation, and sealing performance deterioration continue to pose risks. These potential failure modes highlight the need for ongoing research and innovation to enhance system durability and performance. In this context, conducting reliability analysis research on wellhead equipment systems is of profound significance. Such studies can help uncover the underlying failure mechanisms, optimize design structures, extend equipment service life, and formulate effective preventive maintenance strategies [7][8]. Moreover, the integration of modern techniques such as digital twin technology, finite element analysis, and fault tree analysis offers promising avenues for achieving accurate modeling and dynamic assessment of wellhead equipment system reliability 9[10]. These advanced methodologies enable real-time monitoring, predictive maintenance, and data-driven decision-making, thereby providing a scientific foundation for ensuring the safe and efficient operation of oil and gas field development [11][12]. In summary, as the oil and gas industry ventures into increasingly challenging environments, the reliability of wellhead equipment systems remains a critical concern. By leveraging cutting-edge technologies and conducting in-depth reliability analyses, the industry can mitigate risks, enhance operational safety, and ensure sustainable resource development in the face of evolving challenges.

In the field of engineering, the assessment of system reliability is a critical process that relies on three primary analytical strategies: qualitative risk analysis, quantitative risk analysis, and semi-quantitative risk analysis [13][14]. Each of these approaches offers unique advantages and is applied based on the specific requirements and complexities of the system under evaluation.

Qualitative risk analysis is primarily based on the professional judgment and expert insights of researchers to evaluate the likelihood of failure events and their contributing factors. This approach employs methods such as the Hazard Checklist Method, Hazard and Operability Analysis (HAZOP), and Failure Mode and Effects Analysis (FMEA) [15][16]. These techniques are particularly useful in identifying potential risks and failure modes during the early stages of system design or operation, providing a foundational understanding of system vulnerabilities. Quantitative risk analysis, on the other hand, focuses on constructing reliability models using system failure statistics. Through these models, precise reliability metrics are calculated to assess system performance. Common methods include Fault Tree Analysis (FTA) [17][18], Reliability Block Diagrams (RBD) [19], Markov Analysis [20], Bayesian Networks [21], Monte Carlo Simulation [22], GO methods [23], Petri nets [24], and Potential Failure Mode and Effects Criticality Analysis (FMECA) [25]. These quantitative techniques enable engineers to predict system behavior under various conditions, quantify risks, and prioritize mitigation efforts based on data-driven insights. Semi-quantitative risk analysis bridges the gap between qualitative and quantitative approaches by combining elements of both. Methods such as Event Tree Analysis (ETA) [26] and Facility Risk View (FRR) [27] are often employed in this strategy. These methods allow for a more nuanced assessment of risks by incorporating both expert judgment and statistical data, making them particularly useful in scenarios where complete quantitative data may be unavailable or difficult to obtain.

Among these methodologies, the FMECA (Failure Mode, Effects, and Criticality Analysis) method has gained significant traction in the reliability analysis of wellhead equipment systems. FMECA is a systematic approach that identifies potential failure modes, assesses their effects, and evaluates their criticality in terms of system performance and safety. For instance, Liu et al. applied FMECA to analyze the failure modes of the control system in a subsea production system. Their study classified equipment failures and developed a risk matrix, providing valuable insights for enhancing the safety and reliability of wellhead equipment systems [28]. Similarly, Joanna et al. utilized FMEA to investigate failures in flow valve equipment, offering a reliability reference for wellhead equipment system risk analysis [29]. Their findings highlighted that FMECA not only identifies critical failure modes but also serves as an effective tool for prioritizing maintenance activities, ensuring that components requiring frequent attention are adequately addressed.

These studies underscore the importance of the FMECA methodology in the reliability assessment of wellhead equipment systems. By systematically identifying and evaluating failure modes, FMECA not only aids in preventing potential failures but also supports the optimization of maintenance strategies29. This, in turn, enhances the overall reliability and safety of wellhead equipment systems, which are critical to the safe and efficient operation of oil and gas exploration and production activities. As the oil and gas industry continues to operate in increasingly challenging environments, the adoption of these advanced analytical techniques will be essential for mitigating risks, ensuring operational safety, and maintaining the integrity of critical infrastructure.

The FMECA method is used to analyze the failures of wellhead equipment system with the following four significant advantages:

(1) Systematic and Comprehensive Analysis: The FMECA method systematically identifies and evaluates all potential failure modes of the wellhead equipment system, ensuring no critical failure points are overlooked. This enhances the comprehensiveness and accuracy of the analysis.

(2) Preventive Maintenance: FMECA analysis identifies weak links in the wellhead equipment system that could lead to serious failures, enabling the implementation of preventive maintenance measures. This reduces both the likelihood and impact of failures.

(3) Design Optimization: The results of FMECA analysis provide a critical foundation for design improvements in the wellhead equipment system. This helps engineers optimize design schemes, thereby enhancing the reliability and safety of the equipment.

(4) Enhanced Safety: By detailing failure modes and their impacts, FMECA facilitates the formulation of effective risk control measures. This significantly improves the operational safety of the wellhead equipment system and reduces the risk of accidents.

In summary, FMECA offers a robust framework for analyzing the reliability of complex systems. It provides a thorough understanding of failure modes, their causes, and their effects on system-level reliability. This integrated approach supports better decision-making, efficient resource allocation, and improved system design optimization.

The remaining sections of this study are organized as follows. Section 2 presents an overview of the wellhead equipment system for this test as well as the test procedure. Section 3 describes the use of the FMCEA methodology and the principles of its use. Section 4 performs a risk analysis of the wellhead equipment system. Section 5 presents the conclusions.

1. Wellhead equipment system and test procedure

2.1 Wellhead equipment system

The wellhead equipment system is a critical component in oil and gas drilling operations, serving as the primary interface between the wellbore and surface facilities. Its primary functions include controlling fluid flow at the wellhead, monitoring key parameters such as pressure and temperature, and facilitating the collection and injection of fluids. Typically installed at the wellhead of drilling or production wells, this system plays a vital role in maintaining well integrity, controlling pressure and flow rates, and preventing hydrocarbon leaks, which are essential for ensuring safe and efficient operations.

The wellhead equipment system comprises a complex assembly of valves, pipes, measuring instruments, and blowout prevention equipment. Key components include flow control valves, pressure protection valves, safety valves, and oil recovery/injection valves. These elements work in concert to regulate wellbore conditions and mitigate potential hazards. Additionally, modern wellhead systems are often equipped with advanced automatic monitoring and remote control systems. These systems provide real-time feedback on downhole conditions, enabling operators to make informed decisions and maintain the safety and stability of the production process.

During the production phase, the wellhead equipment system facilitates the extraction of oil and gas, while during the shut-in phase, it ensures a secure seal at the wellhead to prevent blowouts or other dangerous incidents. Given its pivotal role, the design, installation, and maintenance of the wellhead equipment system are of utmost importance. Properly engineered and well-maintained systems are essential for safeguarding drilling operations, optimizing production efficiency, and ensuring the long-term integrity of the well.

The test equipment used in this study, the Ultra-High Temperature High-Pressure Wellhead Equipment System, was developed by Gem Machinery. This system is specifically designed to withstand extreme conditions encountered in deepwater and ultra-deepwater drilling operations. It supports the weight of multiple casing strings through casing hangers, which are integral to oil and gas exploration and development. Additionally, it forms a reliable pressure seal between inner and outer casing columns, ensuring wellbore integrity under high-pressure and high-temperature (HPHT) conditions.

The main components of the ultra-high temperature and high-pressure wellhead equipment system include:

① 20” inverted kava assembly

② Casing head 20×21 1/4-10M

③ Mandrel-type suspension 21 1/4×13 3/8

④ Casing tee 21 1/4-10M×13 5/8-20M

⑤ Mandrel-type suspension 13 3/8×9 5/8

⑥ Flat plate valve PFFA78-140

⑦ Metal-to-metal seals

⑧ Metal sealing gaskets

Supporting equipment for this system includes kava suspensions, anti-friction sleeves, test pressure tools, and conversion flanges, among others. These components collectively ensure the system's robustness and reliability under demanding operational conditions. A schematic of the test wellhead installation is illustrated in Fig. 1, providing a visual representation of the system's configuration and key components.

In summary, the wellhead equipment system is an indispensable part of oil and gas operations, ensuring safety, efficiency, and environmental protection. The development of advanced systems like the Ultra-High Temperature High-Pressure Wellhead Equipment System by Gem Machinery represents a significant step forward in addressing the challenges posed by extreme drilling environments. By leveraging cutting-edge technology and robust engineering, these systems enhance the reliability and performance of wellhead operations, contributing to the sustainable development of oil and gas resources.

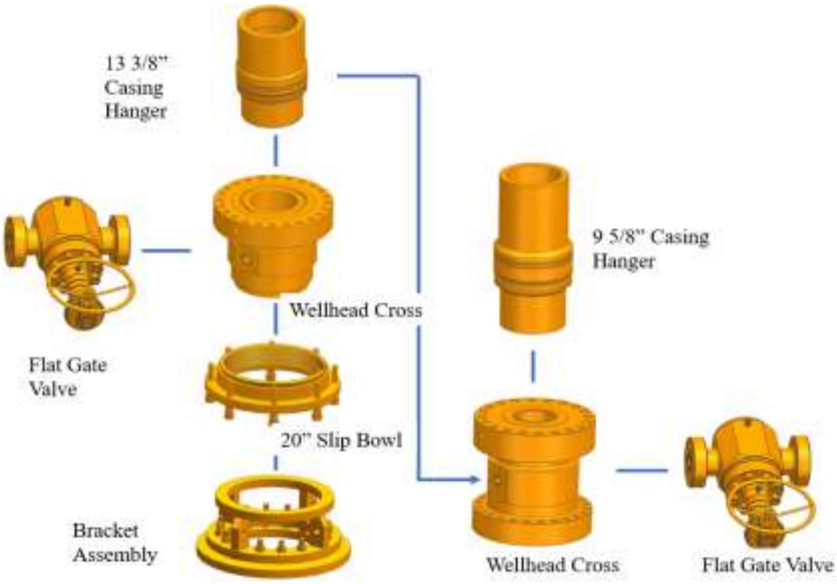

Figure 1 Ultra-high temperature and high-pressure platform wellhead installation diagram

2.2 Sea trial test process

(1) Lifting from Quay to Transportation Vessel

The process begins with the use of a shipyard crane and specialized lifting locks to carefully transport the equipment and packing boxes from the quay to the transportation vessel. During this operation, it is crucial to arrange the wooden boxes in a stable and level manner to prevent collisions or shifting during transit. Attention must be paid to the crane's load capacity to avoid overloading, and appropriate protective measures, such as padding and securing the cargo, should be implemented to safeguard the equipment from damage.

(2) Lifting the Equipment from the Transportation Vessel to the Platform

Once the transportation vessel reaches its destination, the equipment is lifted onto the platform deck in a predetermined sequence. A skidder is then employed to move the equipment to its designated assembly position. This step requires precision to ensure that the equipment is handled smoothly and positioned correctly for subsequent assembly.

(3) Assembly of the Whole Machine Platform

During the unpacking phase, the integrity of each box must be verified before opening. Specialized tools are used to unpack the equipment to prevent accidental damage. The main body of the wellhead equipment system and its accessories are then transported to the assembly area. Key components, such as sealing rings and metal sealing vices, are installed onto their corresponding parts with care to ensure proper fit and functionality.

(4) Testing During Operation

Prior to installation, the platform must be equipped with all necessary lifting equipment, tools, cleaning materials, and safety and firefighting gear. A thorough inspection is conducted to verify the integrity of all components, and personnel with expertise in installation techniques should be present. Coordination with the drilling team is essential to align on the installation program and quality standards. During installation, it is critical to ensure that the dimensions and height of the watertight conduit and the wellhead casing meet design specifications. Adequate installation space must be available on the platform, and appropriate lifting methods should be employed to prevent damage to sealing surfaces. Additionally, the edges of the casing must be polished according to regulations before lifting.

(5) Grouping and Checking During Dismantling of the Whole Machine

The dismantling process follows the reverse order of the sea trial program. Each component, including the casing head, casing tee, casing suspender, and metal seals, is inspected for damage, and findings are documented. The parts are then cleaned, lubricated, and treated with protective oil to prevent corrosion. Finally, the equipment is stored in a dry environment, elevated to avoid contact with stagnant water, ensuring its preservation.

(6) Packaging

After the sea trial is completed, all parts are carefully repacked into their original packing boxes. The packaging must be stable and secure, with additional protective measures implemented to safeguard the equipment during transit. This step is crucial to prevent damage and ensure the equipment arrives at its next destination in optimal condition.

(7) Lifting the Platform to the Transportation Vessel

Using lifting locks and a platform skid, the equipment is moved to the platform deck. It is then lifted onto the transportation vessel, taking into account the vessel's deck space and load capacity. The wooden boxes must be leveled and secured with fastening mechanisms to prevent movement during transport. Protective measures, such as padding and strapping, are applied to minimize the risk of damage.

(8) Lifting the Transportation Vessel to the Quay

Upon arrival at the destination port, the equipment is lifted from the transportation vessel to the quay using lifting locks and the shipyard crane. This step requires careful coordination to ensure the safe and efficient transfer of the equipment, completing the cycle of transportation and installation.

This comprehensive process highlights the meticulous planning, coordination, and execution required to handle, transport, and assemble wellhead equipment systems, ensuring their integrity and functionality throughout the lifecycle of oil and gas operations.

2. Failure analysis using FMECA

3.1 Analysis process of FMECA

In this study, the FMECA (Failure Mode, Effects, and Criticality Analysis) method is employed to systematically analyze the risks associated with ultra-high-temperature and high-pressure drilling operations and sea trial tests. The FMECA approach is a structured and comprehensive methodology that enables the identification, evaluation, and prioritization of potential failure modes and their impacts on safety, environmental sustainability, and economic performance. The analysis is conducted through the following key steps:

① Layer (sea trial process) division;

② Identify the failure modes generated in each sub-sea trial process;

③ Selection of a failure mode, identification of typical failure causes, and evaluation of the safety, environmental, and economic consequences of the failure;

④ Evaluate whether the initial risk of the failure mode meets acceptable criteria, including the likelihood of failure and the consequences of failure;

⑤ For failure modes with an initial risk in the medium/high risk category, identify existing control measures;

⑥ Repeat the above steps until all subunits have been analyzed.

By following this structured approach, the FMECA method provides a robust framework for identifying and mitigating risks in ultra-high-temperature and high-pressure drilling and sea trial operations. It not only highlights critical failure modes but also supports the development of targeted risk mitigation strategies, ultimately enhancing the safety, reliability, and efficiency of the system. This methodology is particularly valuable in high-stakes environments where failures can have severe consequences, making it an essential tool for risk management in the oil and gas industry.

3.2 Principles of classification related to FMECA

Fault occurrence degree is the likelihood of a fault occurring, and the occurrence degree is categorized into five levels, C5, C4, C3, C2, and C1, as shown in Table 1.

Table 1. Severity Classification

Level	**Consequence Category**		
	Safety	**Environmental protection**	**Property damage**

C5	Multiple fatalities on-site fatality off-site Multiple permanent disabilities off-site.	More than 100 tons of hydrocarbons and hazardous substances spilled, with long-term impacts off-site.	Completely dysfunctional, needing to be taken out of the water surface for replacement.
C4	One fatality on-site Multiple permanent disabilities among on-site personnel One permanent disability off-site Multiple temporary disabilities off-site.	Spillage of 10-100 tons of hydrocarbons and hazardous substances, with long-term impacts in certain areas off-site.	Complete loss of functionality and need to be taken out of the water for submerged repairs.
C3	Permanent disability of one person on-site One or more people on-site unable to work for lost time injury One person off-site unable to work for a period of time.	Uncontrolled spill of 1~10 tons, long-term impact on site, no long-term impact on areas off-site.	Loss of function or large error, but underwater repairs can be made on-line without affecting production.
C2	Light injury to one or more on-site personnel Minor injury to one person off-site Recordable minor injury to one person off-site.	Uncontrolled spill of 0.1 to 1, no long term impact on off-site area.	Single component damage, loss of backup, but does not affect overall equipment functionality.
C1	First aid or less does not affect off-site personnel.	Spills of less than 0.1 tons, hazardous material leaks do not affect off-site areas, minor damage, can be quickly removed.	No, or minor, effects.

Failure severity is the severity of the impact of the failure mode. The failure severity is divided into 5 levels, which are F5, F4, F3, F2, F1, as shown in Table 2.

Table 2. Classification of Occurrence

Grade	**Likelihood Description**
F5	Frequent: Several times per year in the eastern part of the South China Sea.
F4	Likely: several times per year within the GOOS.
F3	Likely to occur: Occurs within the CNOOC system.
F2	Rarely occurs: Industry has heard of it.
F1	Largely unlikely to occur: never heard of in the industry.

The risk level of the failure mode is divided into five levels, which are low risk, medium-low risk, medium risk, medium-high risk, and high risk, as shown in Table 3 which is also known as the Risk Matrix Table, with the horizontal axis being the five levels of failure severity (C1-C5), and the vertical axis being the five levels of failure occurrence (F1-F5).

Table 3. Risk matrix table

Risk Martic Table					
F5		High		High	
F4	Medium	Medium	To		Risk
F3		To	Risk	High	
F2	Low		Low		Risk

F1	🟩	🟩 Risk	🟩	🟧 Risk	🟧
	C1	**C2**	**C3**	**C4**	**C5**

3. FMECA analysis of wellhead equipment system

On the basis of extensive research, through several communications and exchanges with the relevant technical staff of Shanghai Bureau, the possible risks, sources of danger, their locations and main consequences were analyzed and determined, and the expert survey method was used to obtain the occurrence and severity data, as shown in Table 4, which provided strong support for the subsequent research.

Table 4. Risk values

No.	**Reason for failure**	**Degree of occurrence**	**Severity**	**Risk value**
1	Inadequate matching of lifting locks and cranes	3	2	6
2	Operators are unskilled, inexperienced, do not strictly follow operating procedures or are fatigued.	2	1	2
3	Failure to keep wooden crates containing equipment level during lifting	2	5	10
4	Collision of wooden crates containing equipment with hard objects during lifting	3	1	3
5	Insufficient hull space	4	5	20
6	Unreasonable transportation fastening guards and measures	5	1	5
7	Failure of hoist, electrical system or hydraulic system; breakage of wire rope or spreader	3	1	3
8	Excessive wind speed, extreme weather, etc.	3	1	3
9	Operators are unskilled, inexperienced, do not strictly follow operating procedures or are fatigued	2	1	2
10	There is a structural defect or quality problem with the wellhead equipment system itself	4	1	4
11	Inadequate matching of lifting locks and cranes	3	1	3
12	Failure of the platform transfer skid	5	5	25
13	Failure of hoist, electrical system, or hydraulic system; breakage of wire rope	3	1	3
14	Excessive wind speed, rough sea conditions, tidal changes, etc.	2	2	4
15	Inexperienced operators or operational errors.	3	1	3
16	There is a structural defect or quality problem with the wellhead equipment	4	1	4
17	Inversion during handling or storage	5	4	20
18	Shock or crushing during transportation or storage	3	2	6
19	Workers not equipped with or not using specialized tools	4	2	8
20	Use violent opening methods such as hammering	3	4	12
21	Lack of attention to the position of the nails during disassembly	3	1	3
22	Packaging boxes are left lying around or discarded	3	2	6
23	Failure to properly position or improper handling during installation	3	2	6
24	Wrong choice of seal specification or substandard quality	2	1	2

No.	**Reason for failure**	**Degree of occurrence**	**Severity**	**Risk value**
25	Unclean assembly environment or improper storage of seals	2	2	4
26	Incomplete tightening or inaccurate positioning during installation	2	1	2
27	Improper sealing materials or methods used	3	4	12
28	Physical damage to equipment during transportation or handling	3	4	12
29	Failure to follow standard operating procedures during installation operations	3	2	6
30	Inadequate component machining accuracy resulting in poor assembly	4	1	4
31	Inadequate installation tools or equipment	4	4	16
32	Transportation control	4	5	20
33	Operator error	4	1	4
34	Accidents such as falling objects during cross work	4	1	4
35	Failure of the overhead crane, turntable, and wellhead equipment system to reach the three points of contact	2	2	4
36	Failure of lifting equipment, electrical systems or tools; quality of components; poor adaptation of equipment	4	4	16
37	Excessive wind speed, rough sea conditions, weather changes, etc.	3	4	12
38	Inexperienced operators or operational errors	3	2	6
39	Structural defects or quality problems in the component itself	4	1	4
40	Inadequate or improperly handled sanding tools	1	2	2
41	Inadequate control of the sanding process or insufficient sanding time	2	2	4
42	Failure to check the position of the top wire before installation	3	4	12
43	Improper operation of the top wire or top wire jamming	2	4	8
44	Inaccurate calculation processes or lack of valid measurement tools	3	4	12
45	Failure of the operator to double-check the position of the pressure test plugs	3	4	12
46	Improper operation or inaccurate force control of the ejector wire	4	4	16
47	Defective material or design of the wear protection sleeve	5	1	5
48	Failure to regularly check wear on the anti-friction sleeve	2	2	4
49	Insufficient quality or accelerated wear of the wear protection sleeve	4	4	16
50	Deteriorated or damaged seals; loose or improperly installed connections	3	2	6
51	Wear or jamming of internal mechanical parts of the valve; malfunction of the control system	3	4	12
52	Secondary seal does not seal sleeve or secondary seal is damaged	4	4	16
53	Loose bolts or gasket seal failure	5	2	10
54	Weather	4	2	8

No.	Reason for failure	Degree of occurrence	Severity	Risk value
55	Deteriorated or rusted components	4	4	16
56	Operator error	3	4	12
57	Inadequate disassembly tools	4	1	4
58	Wear and tear of components due to prolonged use	4	4	16
59	Environmental factors causing corrosion	4	4	16
60	Check for equipment or personnel operating errors	4	2	8
61	Wear or corrosion caused by prolonged use; damage caused by operational errors or environmental factors	4	4	16
62	Deteriorated or damaged seals; poor sealing due to improper installation.	4	4	16
63	Inappropriate cleaning tools or methods	4	4	16
64	Wrong choice of lubricant or improper application rate	2	2	4
65	Improper selection or placement of lifting equipment	4	4	16
66	Poor room humidity control	4	4	16
67	Inadequate preservative treatment; unsealed packaging leading to moisture ingress.	4	4	16
68	Insufficient shockproof materials or poor fixation; strong vibration during transportation	3	4	12
69	Inadequate or insufficient packaging materials; careless handling during cartoning	4	4	16
70	Incomplete labeling of the outside of the box; incomplete documentation of the packing process	4	5	20
71	Inadequate matching of lifting locks and cranes	3	4	12
72	Failure of the platform transfer skid	4	4	16
73	Failure of hoist, electrical system or hydraulic system; breakage of wire rope or spreader	4	2	8
74	Excessive wind speed, rough sea conditions, tidal changes, etc.	3	2	6
75	Inexperienced operators or operational errors	3	2	6
76	There is a structural defect or quality problem with the wellhead equipment	3	4	12
77	Inadequate matching of lifting locks and cranes	3	4	12
78	Operators are unskilled, inexperienced, do not strictly follow operating procedures or are fatigued	2	1	2
79	Failure to keep wooden crates containing equipment level during lifting	3	4	12
80	Collision of wooden crates containing equipment with hard objects during lifting	2	5	10
81	Insufficient hull space	4	5	20
82	Unreasonable transportation fastening guards and measures	4	4	16
83	Failure of hoist, electrical system or hydraulic system; breakage of wire rope or spreader	4	2	8
84	Excessive wind speed, extreme weather, etc.	4	4	16
85	Operators are unskilled, inexperienced, do not strictly follow operating procedures or are fatigued.	4	4	16
86	There is a structural defect or quality problem with the wellhead equipment system itself	4	2	8

In accordance with the sea trial program and process, based on the risk matrix method, the risk level is divided into 19 types of low risk, 18 types of medium-low risk, 7 types of medium risk, 17 types of medium-high risk and 25 types of high-risk. As shown in risk matrix Table 4.

Table 4. Risk matrix table

Risk Matrix Table					
F5	2	1	0	1	1
F4	7	6	0	19	4
F3	7	9	0	14	0
F2	5	6	0	1	2
F1	0	1	0	0	0
	C1	C2	C3	C4	C5

According to the calculation results the risk values for each fault can be obtained as shown in Fig.2.

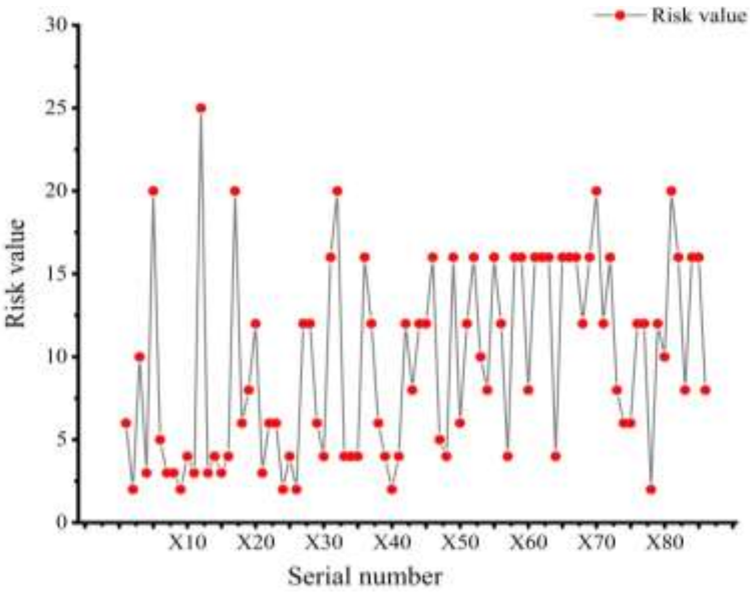

Figure 2 Risk matrix table

As illustrated in Fig. 2, the failure mode with the highest risk score is X12 (Platform Transport Skid Failure), scoring 25 points, which categorizes it as a high-level risk. This indicates that platform transport skid failure poses a significant threat to the success of the sea trial experiment and requires immediate attention. Other notable failure modes, each scoring 20 points, include:X5 (Insufficient Space in the Hull), X17 (Inversion During Handling or Storage), X32 (Transportation Control Issues), X70 (Poor Labeling Outside of the Box; Incomplete Record-Keeping During the Packing Process), X81 (Insufficient Space in the Hull). These failure modes also represent substantial risks that could compromise the integrity and success of the sea trial experiment. Therefore, it is imperative to prioritize protective measures and mitigation strategies for these specific processes. Key actions include:

① Enhancing Transport Skid Reliability: Implementing regular inspections, maintenance, and load testing to prevent skid failures during transportation.

② Optimizing Space Allocation: Ensuring adequate space within the hull to avoid operational constraints and potential damage to equipment.

③ Improving Handling and Storage Protocols: Establishing strict guidelines to prevent inversion or mishandling of equipment during storage and transportation.

④ Strengthening Transportation Control: Utilizing advanced monitoring systems and trained personnel to oversee transportation activities and address issues promptly.

⑤ Ensuring Proper Labeling and Documentation: Implementing standardized labeling practices and maintaining comprehensive records during the packing process to avoid misplacement or loss of critical components.

By addressing these high-risk failure modes proactively, the likelihood of operational disruptions can be significantly reduced, ensuring the successful execution of the sea trial experiment. This targeted approach not only enhances the safety and reliability of the process but also contributes to the overall efficiency and effectiveness of the operation.

4. Conclusion

This study underscores the significant effectiveness of the FMECA (Failure Mode, Effects, and Criticality Analysis) methodology in identifying, assessing, and mitigating risks associated with the offshore testing process for wellhead equipment systems. By systematically analyzing potential failure modes and evaluating their criticality, the proposed framework offers a robust and structured approach to enhancing operational safety, reliability, and efficiency. The integration of historical data, expert judgment, and quantitative risk assessment ensures a comprehensive and multi-dimensional evaluation of risks, enabling stakeholders to prioritize mitigation efforts effectively and allocate resources where they are most needed. The results of the analysis reveal the most critical failure modes, including pressure testing anomalies, seal failures, and structural deformations, which pose significant risks to the integrity and performance of wellhead equipment systems. To address these risks, targeted mitigation strategies are proposed. These findings highlight the importance of adopting a proactive approach to risk management in offshore operations. By identifying potential failures before they occur and implementing preventive measures, the likelihood of accidents, downtime, and environmental damage can be significantly reduced, ultimately safeguarding both personnel and assets.

Looking ahead, future research should focus on integrating advanced technologies such as machine learning (ML) and the Internet of Things (IoT) to further enhance the accuracy, predictive capabilities, and real-time applicability of FMECA. For instance, machine learning algorithms could be employed to analyze vast datasets and identify patterns that may indicate emerging risks, while IoT-enabled sensors could provide continuous, real-time monitoring of equipment conditions. These innovations would enable a more dynamic and adaptive risk management framework, capable of responding to changing operational conditions and emerging threats. Moreover, the proposed FMECA framework can be extended to other offshore systems and components, such as subsea production systems, drilling rigs, and pipeline networks. By applying this methodology across the broader oil and gas infrastructure, the industry can achieve a more holistic approach to risk management, contributing to the overarching goals of improving safety, reliability, and operational efficiency.

In conclusion, this study not only validates the effectiveness of FMECA in addressing risks associated with wellhead equipment systems but also paves the way for future advancements in risk management practices. By leveraging cutting-edge technologies and expanding the scope of application, the oil and gas industry can continue to enhance its resilience and sustainability in the face of increasingly complex and challenging operational environments.

References

1. Mechanisms and capacity of high-pressure soaking after hydraulic fracturing in tight/shale oil reservoirs[J]. Petroleum Science, 2021, 18: 546-564.
2. Zhang Z G, Liu Y B, Sun H T, et al. An alternative approach to match field production data from unconventional gas-bearing systems[J]. Petroleum Science, 2020, 17(5): 1370-1388.
3. Slater D.H. Was the Deepwater Horizon incident a "Normal" accident? [J]. Safety Science, 2023, 168: 106290.
4. W J S, M J M. A Quantitative Comparison of

Oil Sources on Shorelines of Prince William Sound, Alaska, 17 Years After the Exxon Valdez Oil Spill[J]. Archives of environmental contamination and toxicology, 2023, 85(2):140-146.

5. Liu, C., Wu, L., Huang, X.D., Xiao, W.S. Improved dynamic adaptive ant colony optimization algorithm to solve pipe routing design [J]. Knowledge-based systems, 2022, 237: 107846.
6. Liu, C., Wu, L., Xiao, W.S., et al. An improved heuristic mechanism ant colony optimization algorithm for solving path planning[J]. Knowledge-Based Systems, 20 23, 271: 110540.
7. Liu, C., Wu, L., Li, G.X., H, Zhang, Xiao, W.S, Xu, D.P., Guo, J.J. Improved multi-search strategy A* algorithm to solve three-dimensional pipe routing design [J]. Expert Systems with Applications, 240 (2024), Article 122313.
8. Liu C, Wu L, Li G, et al. AI-based 3D pipe automation layout with enhanced ant colony optimization algorithm[J]. Automation in Construction, 2024, 167: 105689.
9. Xiao W, Wu L, Tian X, et al. Applying a new adaptive genetic algorithm to study the layout of drilling equipment in semisubmersible drilling platforms[J]. Mathematical Problems in Engineering, 2015, 2015(1): 146902.
10. Li G.X, Liu C., Xiao W.S, et al. A mixing algorithm of ACO and ABC for solving path planning mobile robot [J]. Applied Soft Computing Journal.2023, 148: 110868.
11. Xiao W.S, Li G.X., Liu C., et al. A novel chaotic and neighborhood search-based artificial bee colony algorithm for solving optimization problems [J]. Scientific Reports, 2023, 13(1): 20496.
12. Cui J, Wu L, Huang X, et al. Multi-strategy adaptable ant colony optimization algorithm and its application in robot path planning[J]. Knowledge-Based Systems, 2024, 288: 111 4 59.
13. Xie C, Huang L, Wang R, et al. Research on quantitative risk assessment of fuel leak of LNG-fuelled ship during lock transition process[J]. Reliability Engineering & System Safety, 2022, 221: 108368.
14. Hu X, Zhou C, Duan M, et al. Reliability analysis of marine risers with narrow and long corrosion defects under combined loads[J]. Petroleum Science, 2014, 11: 139-146.
15. Hosseini S, Ivanov D, Dolgui A. Review of quantitative methods for supply chain resilience analysis[J]. Transportation Research Part E: Logistics and Transportation Review, 2019, 125: 285-307.
16. Khadem M M R K, Piya S, Shamsuzzoha A. Quantitative risk management in gas injection project: a case study from Oman oil and gas industry[J]. Journal of Industrial Engineering International, 2018, 14(3): 637-654.
17. Davis E H, Velez J O, Russell B J, et al. Evaluation of Whatman FTA cards for the preservation of yellow fever virus RNA for use in molecular diagnostics[J]. PLOS Neglected Tropical Diseases, 2022, 16(6): e0 010487.
18. Ramezanifar E, Gholamizadeh K, Mohammadfam I, et al. Risk assessment of methanol storage tank fire accident using hybrid FTA-SPA[J]. PLoS one, 2023, 18(3): e0282657.
19. Kumar A, Sangeeta P, Ram M. Complex system reliability analysis and optimization[M]//Advanced Mathematical Techniques in Science and Engineering. River Publishers, 2022: 185-199.
20. Yesantharao P S, Lee E, Klifto K, et al. A Markov Analysis of Surgical vs Medical Management of Chronic Migraines[J]. Journal of the American College of Surgeons, 2021, 233(5): S195.
21. Yu Q, Teixeira Â P, Liu K, et al. An integrated dynamic ship risk model based on Bayesian Networks and Evidential Reasoning[J]. Reliability Engineering & System Safety, 2021, 216: 107993.
22. Luo C, Keshtegar B, Zhu S P, et al. Hybrid enhanced Monte Carlo simulation coupled with advanced machine learning approach for accurate and efficient structural reliability analysis[J]. Computer Methods in Applied Mechanics and Engineering, 2022, 388: 114 218.
23. Li J, Lu Y, Liu X, et al. Reliability analysis of cold-standby phased-mission system based on GO-FLOW methodology and the universal generating function[J]. Reliability Engineering & System Safety, 2023, 233: 10 9125.
24. Yu Y X, Gong H P, Liu H C, et al.

Knowledge representation and reasoning using fuzzy Petri nets: a literature review and bibliometric analysis[J]. Artificial Intelligence Review, 2023, 56(7): 6241-6265.

25. Yang Y J, Huang C, Zhong Q Y, et al. A case study on safety integrity level analysis for shale gas station[J]. Journal of Mechanical Science and Technology, 2021, 35(12): 5445-5452.
26. Abad F, Naeni L M. A hybrid framework to assess the risk of change in construction projects using fuzzy fault tree and fuzzy event tree analysis[J]. International Journal of Construction Management, 2022, 22(12): 2385-2397.
27. Singh A K, Kumar R S, Pusti A. Consequence Analysis of Most Hazardous Initiating Event in Electrical Energy Storage Systems Using Event Tree Analysis[J]. Journal of Failure Analysis and Prevention, 2022, 22(4): 1646-1656.
28. Liu, C., Zhou, C., Tan, L., Cui, J., Xiao, W., Liu, J., Wang, H., & Wang, T. (2024). Reliability analysis of subsea manifold system using FMECA and FFTA. Scientific Reports, 14(1), 22873.
29. Fabis-Domagala J., Momeni H., Domagala M., et al. Matrix FMEA Analysis of the Flow Control Valve[J]. Quality Production Improvement - QPI,2019,1(1):590-595.
30. Liu C, Li G, Xiao W, et al. Reliability analysis of subsea control system using FMEA and FFTA[J]. Scientific Reports, 2024, 14(1): 1-21.