

Original Article



Integrated LEC Risk Assessment and Reliability Enhancement for Downhole Tools in Ultra-High Temperature and High-Pressure Offshore Environments

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Abstract:

The reliability of downhole tool systems is critical to ensuring the safety and efficiency of offshore oil and gas operations. However, the marine testing phase of these systems involves significant risks, which, if mismanaged, may result in severe accidents. This study employs Job Hazard Analysis (JHA) to establish a systematic risk evaluation framework aimed at comprehensively identifying, assessing, and prioritizing potential failure modes during the sea trials of ultra-high-temperature and high-pressure downhole tools. By integrating multi-source data—including historical failure databases, expert knowledge, and quantitative assessment models—a data-driven risk analysis system was developed. The research outcomes accurately pinpoint high-risk failure modes and their cascading effects, while proposing targeted risk mitigation measures encompassing both technical enhancements and management optimizations. The methodologies and practical strategies presented in this study provide a scientific foundation for improving the safety and reliability of downhole tool testing in offshore environments. These contributions hold substantial theoretical and practical implications for reducing operational risks, preventing environmental incidents, and advancing the sustainable development of marine oil and gas resources.

Keywords: Downhole tools, offshore testing processes, ultra-high temperature and pressure, reliability, LEC

Introduction

In recent years, easily accessible, low-cost onshore oil and gas resources have gradually diminished, forcing companies to shift their focus to developing unconventional onshore resources such as low-permeability and high-viscosity reservoirs, or to invest in higher-cost exploration of deep, hidden oil and gas reservoirs. This has led to a significant increase in the technical

barriers and capital investment required for exploration and development. To maintain resource reserves and production scale, companies have no choice but to shift their exploration and development focus to marine areas (such as deep-sea and ultra-deep-sea regions) as well as polar and remote regions that have previously been less developed. This

requires adapting to more complex extraction environments, placing higher demands on equipment, technology, and management capabilities [1, 2]. The reliability of downhole tools is a core factor in ensuring safety, efficiency, and economic viability throughout the entire lifecycle of oil and gas wells, from drilling to production. However, in recent years, safety incidents caused by downhole tool failures have occurred frequently, resulting in severe economic losses and environmental risks. For example, in 2010, a well blowout occurred in the Gulf of Mexico due to downhole tool failure, resulting in an explosion and fire on the platform that killed 11 people and injured 17 others [3]. The oil spill, which lasted 87 days, released approximately 4.9 million barrels of crude oil, contaminating 1,600 kilometers of coastline along the U.S. state of Louisiana and causing long-term damage to the Gulf of Mexico ecosystem. In the same year, a Norwegian oil platform experienced a leakage accident due to well tool failure, resulting in the emergency shutdown of the platform and the evacuation of 90 people. Production was suspended for nearly two months to repair the well control barrier, resulting in approximately \$120 million in lost production capacity. These cases clearly demonstrate that under complex operating conditions such as high temperature and pressure, the reliability of well tools plays a decisive role in the safety of oil and gas field development and operational continuity.

Currently, the development of oil and gas resources is gradually expanding into challenging areas such as deepwater, ultra-deep wells, and unconventional oil and gas reservoirs. The geological conditions faced by downhole tools are becoming increasingly complex, and the pressure and temperature gradients in their operating environments are significantly increasing. The reliability bottleneck of these tools has become a key bottleneck constraining development efficiency [4, 5]. Although the design and

manufacturing technology of downhole tools has been continuously iterated, potential failure factors such as manufacturing and assembly precision deviations in certain components and performance degradation under extreme conditions have not yet been systematically eliminated. Therefore, conducting reliability analysis research on downhole tools holds multi-dimensional support value for strengthening the safety barrier of oil and gas development, reducing engineering risks, promoting technological innovation, and enhancing development economics. It is a foundational topic for ensuring the safe, efficient, and sustainable development of the oil and gas industry [6-8]. Meanwhile, by leveraging modern analytical methods such as fault tree analysis and multi-state Bayesian models [9, 10], it is possible to achieve precise modeling and dynamic assessment of downhole tool reliability, providing quantitative decision support for the safe and efficient operation of oil and gas field development [11].

In current reliability research, researchers primarily conduct qualitative risk analysis through typical methods such as Failure Mode and Effects Analysis (FMEA) and Hazard and Operability Analysis (HAZOP), relying on professional judgment and expert experience to identify event failure probabilities and influencing factors [12, 13]. Additionally, researchers employ Bayesian networks [14], fault tree analysis (FTA) [15, 16], failure mode and effects criticality analysis (FMECA) [17], reliability block diagrams (RBD) [18], Markov analysis [19], and Monte Carlo simulation [20] to conduct quantitative risk analysis of system reliability. Finally, semi-quantitative risk analysis combines the advantages of qualitative and quantitative analysis. Event tree analysis (ETA) [21], facility risk view (FRR) [22], and Likelihood-exposure-consequence (LEC) method are typical methods [23, 24].

The LEC method is widely applied in reliability analysis. Fu *et al.* employed the LEC method to conduct risk analysis on bridge maintenance

accidents. This model utilizes long-term accumulated hazard data to reflect the current risk level during the maintenance phase, providing a referenceable approach for applying the LEC method to risk analysis of underground tools [25-28]. Zhao et al. developed a safety risk analysis model for the construction of concrete gravity dams in cold regions based on fuzzy VIKOR-LEC, analyzing the management of construction safety risks. Their findings provide reliable references for risk analysis of underground tools [29-33]. The aforementioned studies confirm the significance of the LEC method in reliability analysis, as it balances assessment accuracy and implementation costs through its semi-quantitative characteristics, expands the dimensions of reliability analysis from a “human-machine-environment” coupled perspective, and provides operational and targeted tool support for reliability optimization of complex systems through risk quantification and rapid screening functions [34-39]. Additionally, the LEC method's close integration with engineering practice grants it strong flexibility in dynamic risk assessment, particularly in addressing the complex and variable operational environments underground, enabling it to swiftly respond to newly emerging risk sources and provide real-time support for safety management [40-45].

The use of the LEC method for reliability analysis of downhole tools offers the following four significant advantages:

(1) Comprehensive Analysis

The LEC method incorporates exposure frequency (E) into the assessment system, covering both the service life of the tool under extreme environmental conditions and the frequency of human operation and maintenance. This enables a comprehensive reflection of the synergistic effects of multiple factors on failures, overcoming the limitation of focusing solely on the tool's performance and making failure analysis more aligned with on-site realities.

(2) Efficiency of Analysis

The LEC method calculates the risk value (D) to rank fault risks, enabling rapid identification of critical faults with high D values (e.g., blowout preventer shear failure, packer sleeve aging, etc.). This avoids over-allocating analytical resources to low-risk faults, significantly enhancing the targeting and efficiency of fault analysis.

(3) Applicability of Analysis

The LEC method uses a semi-quantitative grading of likelihood (L), exposure frequency (E), and consequence severity (C) to quantify risks based on expert experience and limited field data, without relying on large-scale failure statistics. This effectively addresses the pain point of “insufficient data for quantitative assessment” in downhole tool fault analysis.

(4) Analysis Intuitiveness

The LEC method outputs risk levels through risk value (D) grading, facilitating the formulation of targeted prevention and control measures. It can convert the abstract risk of downhole tool failures into concrete decision-making basis, enabling more reasonable allocation of prevention and control resources based on different risk levels.

The remaining sections of this study are arranged as follows: Section 2 introduces the sea trial of the downhole tool. Section 3 introduces risk analysis based on the LEC method and related grading principles. Section 4 conducts risk analysis on the downhole tool. Section 5 presents the conclusions.

2. MWD Sea Trial

2.1 Test Equipment

The MWD system can be further classified into two technical approaches based on the structural morphology of the pulse generator: the upper suspension-type pulse generator integrated system and the lower seat-type pulse generator integrated system. Both systems utilize the pulsator as the core unit for signal transmission, coupled with

directional measurement probes to achieve real-time monitoring of downhole parameters. The system demonstrates outstanding performance in key technical indicators: in terms of environmental adaptability, it can operate stably under extreme conditions of 200°C high temperature and 206 MPa ultra-high pressure; in terms of measurement accuracy, the measurement error of well inclination angle is controlled within

the high-precision range of $\pm 0.1^\circ$; and both azimuth angle and tool face angle measurement errors are maintained within $\pm 1.0^\circ$. By establishing a high-precision inertial navigation measurement system, the system provides reliable wellbore parameter sensing and transmission support for the exploration and development of deep oil and gas resources.



Fig.1 Schematic diagram of key equipment for ultra-high temperature and pressure downhole tools

2.2 Target Marine Environment and Test Procedure

The target wells of this experiment are located near the central bottom incision zone in the northern part of the NH Sea, where the crust has been subjected to many times of strong tension since the Cenozoic era, with rapid basin subsidence, large sediment thickness, and complex temperature and pressure systems. The

target layers of several hundreds of billions of square meters of atmospheric fields discovered in the previous period around this block are mainly located in the above 3500 meters, and most of them are high-temperature and high-pressure wells, and the flow chart of the experiment is shown in Fig.2.

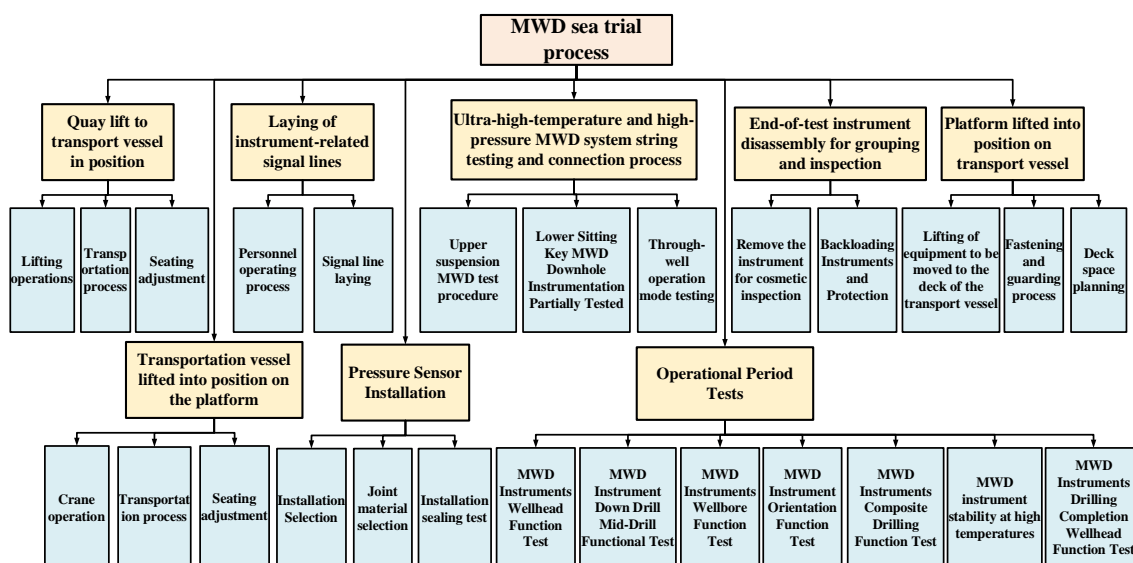


Fig. 2 MWD sea trial process

(1) Lifting From the Dock to the Transportation Vesseli Position

Use the shipyard crane and lifting rigging to lift the special instrument lifting box from the shipyard to the transportation vessel. According to the deck space of the ship and the sequence of the subsequent lifting platform, arrange the instruments to the deck reasonably.

(2) Lifting the Instruments from the Transportation Vessel to the Platform in Position.

According to the requirements of sea transportation, the instrument lifting box is placed in the safe position on both sides of the runway under the drilling platform to ensure the convenience of instrument taking out and assembling.

(3) Laying of Instrument-Related Signal Lines

According to the safety requirements of the platform, lay the pump pressure line and the division display line: pump pressure line: the plug of the pressure sensor end is placed in the mud high-pressure pipeline to connect to the sensor, and the decoder box end is placed in the working room of the drilling platform instrument.

Division display line: placed in the drilling platform drilling room and the decoding box connected to the place. Ensure that the signal line and the power supply cable are not parallel or intersecting, in order to avoid electromagnetic interference.

(4) Pressure Sensor Installation

Determine the installation location of the pressure sensor and make sure it is far away from the mud pump when installing. If there is no suitable location, provide connectors for installation.

(5) Ultra-High-Temperature and High-Pressure MWD System String Test and Connection

a. Upper Suspension MWD Test Process:

Take out the instrument bracket, clamp and

supporting tools from the special instrument lifting box; connect the ultra-high-temperature and high-pressure pulser assembly, battery assembly and probe tube assembly in sequence; connect the assemblies with braided wire and use the special test software to monitor the data; carry out percussion and vibration test to confirm that the pulser is rotating and the data are normal; tighten the connecting parts to ensure that there is no looseness and install the tail vertebrae; install the suspension of the non-magnetic short section to the drilling tool; hoist and adjust the position of the instrument string and then fix the instrument. and adjust the position of the instrument string and then fix the instrument.

b. Test the MWD downhole instruments:

Take out the relevant instrument components from the special lifting box and connect them in turn; carry out percussion and vibration test to ensure that the downhole seating key pulser and data are normal; adjust the connection parts to ensure that there is no looseness, and the salvage head has been installed; carry out the angular difference measurement and the rotation adjustment of the instrument string.

(6) Test During Operation Period

Conduct various tests during the operation period to ensure that the data and pulser waveforms are normal; test the functions of wellhead, midway downhole, bottoming, directional, compound drilling, etc.; test the stability under high temperature; test the function of the wellhead of the start and finish drilling.

(7) Grouping and Inspection of Disassembled Instruments at the End of the Test

After the end of the test, carry out appearance inspection and take photos for record; use special packing box and instrument transportation box to reassemble the instruments and ensure that protective measures are in place.

(8) Lift the Platform to the Transportation Ship

and Put it Into Position.

According to the deck space, lift the equipment to be transported to the deck of the transportation ship, and carry out fastening and protection.

3. Risk analysis based on the LEC method

3.1 Overview of the LEC Method

The LEC method is a risk assessment method based on semi-quantitative analysis. Its core principle is to construct a risk evaluation model by quantifying the probability of an accident occurring, the frequency of personnel exposure to hazardous environments, and the severity of accident consequences, thereby enabling a graded assessment of the hazards of an operational system. The assessment logic of this method can be broken down into the following three key steps:

First, parameter definition and quantitative grading. The LEC method decomposes risk assessment elements into three core parameters:

(1) Accident occurrence probability (L): This represents the probability of an accident occurring under specific hazardous conditions. It is typically graded based on historical data and expert experience, with specific grading criteria refined according to industry characteristics.

(2) Exposure frequency (E): Describes the duration or frequency of personnel exposure to hazardous work environments, generally categorized into six levels (0.5–10 points). For example, “less than one exposure per year” is scored as 0.5 points, “continuous exposure during daily working hours” is scored as 6 points, and “constant exposure to hazardous environments” is scored as 10 points, reflecting the intensity of personnel contact with hazardous factors.

(3) Consequence severity (C): This encompasses the multi-dimensional consequences of an accident, including potential casualties, property damage, and environmental impact, typically categorized into 6 levels (1–100 points). For

example, “minor injuries” are scored as 1 point, “multiple deaths or significant property damage” as 40 points, and “mass casualties or catastrophic environmental damage” as 100 points. The grading must consider both legal regulations and industry-accepted risk tolerance standards.

Second, the risk value calculation model. The comprehensive risk value (D) is obtained through the product of three parameters. The LEC method's formula is:

$$D = L \times E \times C \quad (3-1)$$

Where: L — probability of the accident occurring;

E — frequency of personnel being in a hazardous work environment;

C — consequences that the risk accident may cause;

D — risk value.

This model converts qualitative descriptions into comparable quantitative indicators, achieving a transformation from “fuzzy judgment” to “numerical representation” of risk.

Third, hazard classification determination. Based on the magnitude of the risk value (D), the hazard level of the work system is classified into several grades (e.g., “negligible risk,” “acceptable risk,” “risk requiring control,” “unacceptable risk,” etc.). Using a typical grading standard as an example: $D < 20$ is “negligible risk,” $20 \leq D < 70$ is “acceptable risk,” $70 \leq D < 160$ is “risk requiring improvement,” $160 \leq D < 320$ is “high risk,” and $D \geq 320$ is “extreme risk.” Through this classification, risk levels can be intuitively determined, and the priority of preventive measures can be established, providing clear decision-making criteria for operational safety management.

The LEC method process is shown in Fig .3:

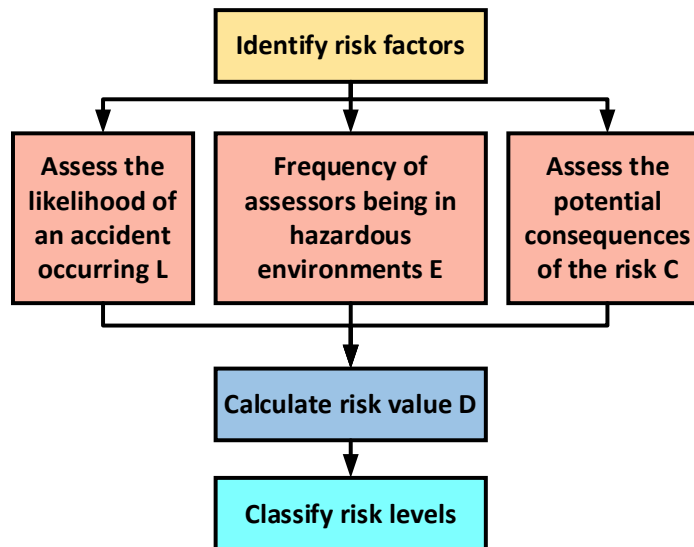


Fig.3 LEC method analysis flow chart

The LEC method is widely used in industrial system risk assessment due to its clear logic, ease of operation, and ability to combine qualitative and quantitative analysis. It is particularly suitable for rapid risk screening and classification management in complex operating environments.

3.2 Principles for Classification of LEC Levels

The likelihood of an accident occurring (L) describes the probability of an accident occurring.

Typically, the probability of an inevitable accident is set to 1, with a score of 10. Considering that events that are inevitably unlikely to occur do not exist in actual engineering construction processes, the score for accidents that are actually impossible to occur is set to 0.1. Other corresponding situations are then assigned scores between 0.1 and 10, as shown in Tab 1.

Tab 1 Accident Occurrence Probability (L) Score Classification

Score value	Likelihood of Accident
10	Risky accidents that can be anticipated
6	Risks that are very likely to occur
3	Likely, but infrequent risk incidents
1	Risk incident with low likelihood of occurrence, totally unexpected
0.5	Risk incident that can be envisioned but is very unlikely to occur
0.2	Risk incident that is highly unlikely to occur
0.1	Risk incident that is practically impossible

Exposure frequency (E) is a parameter that describes the amount of time or frequency with which personnel are exposed to hazardous work environments. In construction work environments, the severity of hazards faced by workers is typically positively correlated with the duration and frequency of their exposure to

hazardous conditions. Generally speaking, the longer workers are exposed to hazardous environments during construction processes and the higher the frequency of such exposure, the greater the likelihood of them being harmed in such environments. For the E value, situations where workers are continuously exposed to hazardous environmental conditions are assigned

a score of 10, while extremely rare situations are assigned a score of 0.5. Other situations are

assigned scores between 0.5 and 10, as shown in Table 2.

Tab 2 Frequency of Exposure to Hazardous Environments (E) Score Classification

Score	Frequency of exposure to hazardous environments
10	Continuity
6	During working hours
3	Weekly or occasional
2	Once a month
1	Several times a year
0.5	Rarity

The severity of consequences (C) encompasses the multidimensional consequences of an accident, including casualties, property damage, and environmental impact. Considering the wide range of fluctuations in the number of casualties caused by accidents, the C value is set between 1

and 100 points. For minor injuries, the C value is set at 1, while for major engineering accidents resulting in 10 or more deaths or 50 or more serious injuries, the C value is set at 100, as shown in Tab 3.

Tab 3 Possible consequences of an accident (C)

Score value	Likely consequences of a risk incident
100	Major accidents occurring, resulting in 10 or more deaths or 50 or more serious injuries
40	Major accidents resulting in 3-9 deaths or 10-49 serious injuries
15	General accidents resulting in 1-2 deaths or 6-9 serious injuries
7	General accident resulting in 3-5 serious injuries
3	General accident resulting in less than 2 serious injuries
1	Accident caused concern to management and minor injuries to operators

Using the calculation formula (3-1) of the LEC method, the risk values of various potential hazard sources during engineering construction can be calculated. The magnitude of the D value is positively correlated with the risk level of the potential hazard source, meaning that the larger the D value, the higher the risk level of the hazard source, and the corresponding risk grade is also higher. In practical application, it is necessary to first classify the hazard scores of each risk source

into grades, clearly define the D value ranges corresponding to different risk grades, then determine the risk grade of a specific hazard source by comparing its D value with the corresponding range, and based on this, formulate targeted risk prevention measures to ensure the safety of the construction process. The detailed classification of D value hazard scores is shown in Table 4.

Tab 4 Risk Value (D) Classification Table

Hazard Score	Risk level	Risk level
<20	Low risk, acceptable	1
20~70	General risk, need to be concerned	2
70~160	Medium risk, need to be rectified	3
160~320	High risk, need to be rectified immediately	4

>320	Extremely dangerous situation, need to stop work and rectification	5
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Currently, while the LEC evaluation method has established a widely accepted risk grading standard, it is important to note that this standard is derived from expert experience and thus inevitably carries some subjective limitations. Therefore, when determining the specific value ranges for each hazard level in practical engineering applications, it is essential to make targeted adjustments based on the unique characteristics of the specific project. Additionally, the classification threshold values are not fixed but should be dynamically adjusted based on the actual conditions of the project at different stages to ensure alignment with the objective reality of project safety risks, thereby achieving continuous optimization of risk management.

According to the classification in Table 4, we classify risks of levels 4–5 as unacceptable risks and risks of levels 1–3 as acceptable risks.

4. MWD Risk Analysis Based on the LEC Method

4.1 Evaluation of Core Parameters

To perform LEC analysis on the downhole tool system, it is necessary to first quantify and

classify the three core parameters—likelihood of occurrence (L), exposure frequency (E), and severity of consequences (C)—based on the failure scenarios. This grading process must closely align with the unique operational environment of downhole tools (such as high-temperature, high-pressure, high-sulfur, and deep-sea conditions) and their failure mode characteristics (such as seal failure, structural fracture, and functional jam), to establish a quantitative standard tailored to oil and gas development scenarios. Based on extensive research, through multiple communications and exchanges with field test technical personnel, potential risks, hazard sources, their locations, and primary consequences were analyzed and identified. The expert survey method was used to collect detailed data on the likelihood of an accident occurring (L), the frequency of personnel being in a hazardous work environment (E), and the consequences of a risk accident (C), providing strong support for subsequent research. Table 5 presents the key L, E, and C data for downhole tools, derived from literature reviews, field surveys, and expert evaluations by multiple frontline sea trial experts.

Tab.5 LEC Expert Scoring Table

Serial number	Reason for failure	L	E	C
1	Personnel falling into water	0.5	15	3
2	Inadequate fall prevention hoist and life jacket	3	15	3
3	Deteriorated or damaged lifting rigging or crane equipment not inspected in time	3	7	3
4	Insufficient load-bearing lifting equipment, overloaded operation	3	15	3
5	Inexperienced hoisting personnel or failure to operate in accordance with specifications	3	15	3
6	Poor communication during lifting, command and operation not coordinated	6	1	6
7	Inadequate consideration of deck space, hull balance and lifting sequence	6	1	3

Serial number	Reason for failure	L	E	C
8	Mismatch between lifting position and subsequent operations, affecting workflow	1	1	6
9	Suddenly encountered bad weather during the lifting process, affecting operational safety	3	2	2
10	Failure to consider the actual space and safety requirements of the drill floor and the lower runway	3	2	2
11	Improper placement, affecting subsequent operation or safety	3	1	3
12	Improper placement of lift box resulting in damage to equipment or personnel	3	1	3
13	Lift box placed without protective measures	3	3 1	3 1
14	Lift box not secured after placement, resulting in movement or tilting of the box	1	2	6
15	Fixtures do not meet the requirements and are not securely fastened	3	1	6
16	Environmental conditions affecting placement and stabilization of lift box	3	1	6
17	Presence of disturbances in the environment affecting placement	3	1	6
18	Personnel selection errors	3	1	6
19	Operator error	3	7	3
20	Failure to consider pipeline location and environmental factors during placement	3	7	3 7
21	Division display line is not installed according to the specified position	3	1	3
22	Layout does not take into account the location and connection of the drill hall and the instrumentation room.	3	1	3
23	Signal and power supply cables do not comply with the relative position requirements	3	1	6
24	Failure to consider the effects of electromagnetic interference when placing	3	1	6
25	Failure to secure cables after placement, resulting in looseness or displacement	3	1	6
26	Improperly selected or poorly installed fixtures	1	1	6
27	Placement does not take into account the impact of environmental factors such as temperature and humidity	1	1	6
28	Environmental conditions causing physical damage or interference to cables	3	1	6
29	Inadequate communication between technician and construction technician, inaccurate confirmation of installation location	3	1	6
30	Mud pump and pipeline locations and space requirements were not considered during the confirmation process	3	1	6
31	Mud pump impact not considered during installation, resulting in improper installation	3	1	6
32	Technician did not follow technical requirements or did not investigate on site	3	1	6
33	Improper mounting position may result in incorrectly installed connectors	3	1	6
34	Possible problems with the selection and installation of	3	1	6

Serial number	Reason for failure	L	E	C
	specialized connectors			
35	Failure to follow strict specifications during installation, resulting in poor sealing	3	1	6
36	Failure of well team technician to perform adequate inspection and testing	3	1	6
37	Improper handling when removing instrument holders and toolboxes, falling or bumping equipment	3	1	6
38	Placement without using proper tools or equipment, resulting in equipment damage	0.5	1	6
39	Missing or incomplete tools in kit	3	1	6
40	Toolbox not scrutinized and inadequately prepared	3	1	6
41	Improper handling when removing the assembly, resulting in damage to the assembly	3	1	6
42	The assembly may be damaged if it is not placed gently and in the right order.	3	3 1	6
43	Connect pigtail wires out of order or not securely connected	3	1	6
44	Failure to set up the software correctly or improper procedure during testing	3	1	6
45	Connections not tightened, resulting in loose instruments	3	1	6
46	Unstable installation of the tailbone, affecting the stability of the instrument	3	15	6
47	Improper operation may result in damage to the holder, clamp or toolbox	3	7	6
48	Placement does not meet safety requirements and equipment is unstable	1	7	6
49	Improper removal of the assembly, resulting in damage to the assembly	1	7	6
50	The assemblies were not placed in the right order and collided with each other.	1	1	1 1
51	Connecting pigtail wires in wrong order or not securely connected	1	1	3
52	Failure to set up the software correctly or improper procedure during testing	1	1	3
53	Inaccurate tapping force or position, affecting test results	1	7	6
54	Failure to read or record test parameters correctly	1	2	6
55	Connection not tightened, resulting in loose instrumentation	1	7	6
56	Unstable installation of the salvage head, affecting the stability of the equipment	1	7	6
57	Measurement of the pilot slope position is not adjusted or the angle difference data is wrong	1	7	6
58	Poor connection of the special test cable, affecting the data reading	3	7	6
59	Abnormal well instrumentation, resulting in construction stoppage	3	7	6
60	Well entry tool breakage, fish fall at bottom of well	3	7	6
61	MWD measurement data distorted	3	15	6
62	Problems with compatibility or installation of equipment to be tested and through-hole drilling tools	6	7	3
63	Data transmission system failure or wiring problems	3	15	2

Serial number	Reason for failure	L	E	C
64	Borehole conditions or drilling fluid circulation affecting the test environment	3	15	1
65	Sensor failure or inaccurate calibration	3	7	1
66	Data transmission line problems	3	7	1
67	Damaged or improperly adjusted pulser assembly	3	2	2
68	Vibration or shock effect when the instrument is down drilling	1	7	1
69	Sensor or pulser failure	1	15	1
70	High pressure or temperature affects instrument performance	3	7	2
71	Wellbore environment interferes with data transmission	3	7	1
72	Directional sensor failure or improper calibration	3	15	1
73	Data processing system problems	10	7	3
74	Instrument response problems in composite drilling mode	3	7	3
75	Unstable or incorrect data transmission	1	7	2
76	High temperatures affecting instrument components	1	7	2
77	Poor heat dissipation causes instrument overheating	1	7	1
78	Effect of vibration or shock during drilling of the instrument	1	7	1
79	Problems with equipment or data transmission	6	7	2
80	Incomplete inspection, missing problems	6	7	2
81	Poor quality of photographs or incomplete records	3	2	2
82	Parts not returned in original packaging	3	2	2
83	Packaging protection not in place	3	1	3
84	Damaged or improperly packed packaging materials	3	1	2
85	Lifting equipment faulty or not suitable for the weight of the equipment	3	1	3
86	Inadequate maintenance or improper operation of lifting equipment	3	1	3
87	Inadequate or poorly secured fixtures	3	1	3
88	Insufficient protective material to effectively protect the equipment	1	1	3
89	Insufficient deck space or equipment not reasonably located	3	7	2
90	Failure to consider the effect of equipment size and lifting sequence	3	7	2

4.2 Calculation of Risk Values

The calculation of the LEC risk value (D) is a core component of semi-quantitative risk assessment. The process involves applying standardized parameters and logical operations based on the previously determined accident occurrence probability (L), exposure frequency (E), and consequence severity (C) grading criteria to generate quantifiable results for risk level determination. For underground tool systems, the calculation of LEC risk values must incorporate detailed data on the likelihood of accidents (L), the frequency of personnel being exposed to

hazardous working environments (E), and the potential consequences of risk incidents (C), which were collected through expert surveys as described earlier. These values are then substituted into the standardized formula (3-1), with dynamic adjustments and case validation to ensure that the results not only quantify the risk level but also provide actionable decision-making criteria for risk management of underground tools. The final calculated hazard scores and risk levels corresponding to each serial number are shown in Table 6. Figures 4 and 5 are line charts plotted based on the risk values.

Tab.6 Hazard Score and Risk Level Table

Serial number	Hazard score	Level	Serial number	Hazard score	Level	Serial number	Hazard score	Level
1	22.5	2	31	18	1	61	270	4
2	135	3	32	18	1	62	126	3
3	63	2	33	18	1	63	90	3
4	135	3	34	18	1	64	45	2
5	135	3	35	18	1	65	21	2
6	36	2	36	18	1	66	21	2
7	18	1	37	18	1	67	12	1
8	6	1	38	3	1	68	7	1
9	12	1	39	18	1	69	15	1
10	12	1	40	18	1	70	42	2
11	9	1	41	18	1	71	21	2
12	9	1	42	18	1	72	45	2
13	9	1	43	18	1	73	210	4
14	12	1	44	18	1	74	63	2
15	18	1	45	18	1	75	14	1
16	18	1	46	270	4	76	14	1
17	18	1	47	126	3	77	7	1
18	18	1	48	42	2	78	7	1
19	63	2	49	42	2	79	84	3
20	63	2	50	3	1	80	84	3
21	9	1	51	3	1	81	12	1
22	9	1	52	3	1	82	12	1
23	18	1	53	42	2	83	9	1
24	18	1	54	12	1	84	6	1
25	18	1	55	42	2	85	9	1
26	6	1	56	42	2	86	9	1
27	6	1	57	42	2	87	9	1
28	18	1	58	126	3	88	3	1
29	18	1	59	126	3	89	42	2
30	18	1	60	126	3	90	42	2

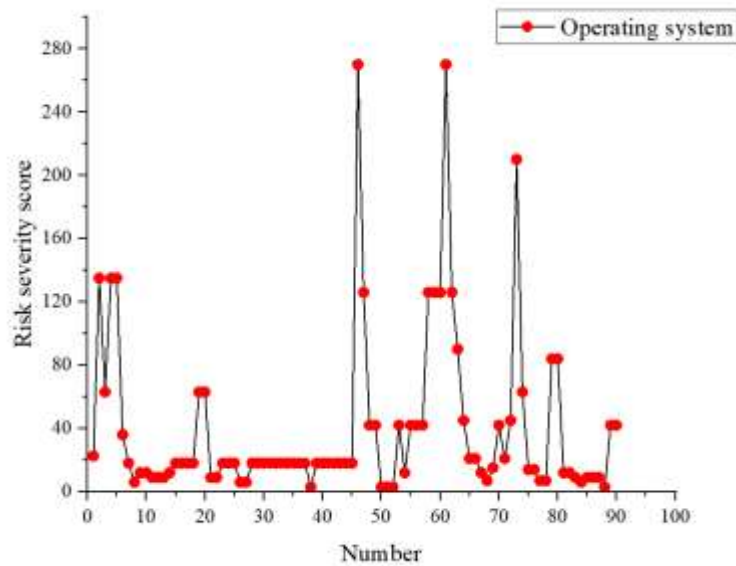


Fig. 4 Line chart showing the hazard scores for each serial number

As shown in Table 4, the highest risk level is Level 4, corresponding to serial numbers 46 (unstable tailbone installation affecting instrument stability), 61 (distorted MWD measurement data), and 73 (data processing system issues). Their hazard scores are 270 points, 270 points, and 210 points, respectively, classified as uncontrollable risks requiring immediate rectification. Additionally, item number 2 (incomplete fall arrest hoists or life jackets), item number 4 (insufficient load-bearing capacity of lifting equipment, overloading operations), item number 5 (lack of experience among lifting personnel or failure to follow operational procedures), item 47 (improper operation may cause damage to supports, clamps, or toolboxes), and item 59 (abnormal well entry instruments causing construction delays) are classified as Level 3 risks, with hazard scores ranging from 84 to 135. These risks are manageable but have relatively high risk levels and hazard scores, making them

moderate risks that require rectification. Item 1 (personnel falling into the water) and 20 other items are classified as Level 2 risks, with hazard scores ranging from 21 to 63. These are general risks that require increased attention. The remaining 55 items are classified as Level 1 risks, with hazard scores all below 18 points, which are low-level risks and acceptable. Therefore, during sea trial experiments, priority should be given to protecting against the above medium-to-high-risk failure modes to prevent failures from occurring. At the same time, during routine maintenance, general risks and low-risk incidents should be promptly addressed and resolved to ensure the smooth conduct of sea trial experiments.

5. Conclusion

This chapter uses the LEC method to classify the risk levels of downhole tools MWD. According to the LEC analysis data, there are a total of 90 risks associated with MWD in sea trials, and the risk levels are shown in Fig.5.

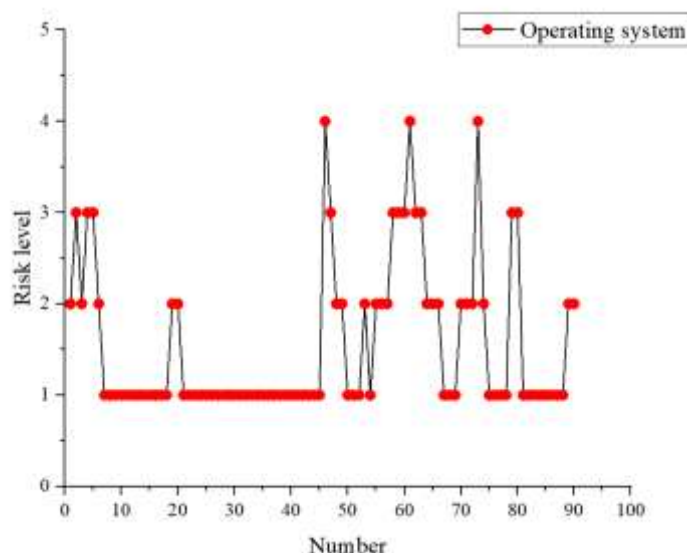


Fig.5 Line chart showing risk levels for each serial number

Among these, there are 55 items classified as Level 1 risk (accounting for 61.1%), 21 items as Level 2 risk (23.3%), 11 items as Level 3 risk (12.2%), and 3 items as Level 4 risk. There are no

Level 5 risks. The overall risk profile is dominated by lower-level risks, but Level 3 and Level 4 risks still require attention. It is recommended to implement targeted preventive measures to mitigate potential impacts and ensure

the safety of sea trials.

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