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A NOVEL EVALUATION METHODOLOGY FOR DETERMINING I-LEVEL TEST CYCLE-TIME IN MISSILE MAINTENANCE

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ABSTRACT

The periodic testing cycle of missiles is a critical factor influencing operational readiness, reliability, and associated logistics costs, including maintenance, transportation, and testing. Despite the importance of optimizing these cycles, a clear understanding of the optimal testing intervals for different missile types remains underexplored. This study investigates the impact of various I-Level periodic testing cycles for K-type missiles, utilizing the "Important Factor Weighted Exponential Distribution Function (IFWEDF)" method to estimate and compare reliability across different intervals. A cost-benefit analysis is then conducted to evaluate the implications of extending the testing cycle. The results indicate that a three-year testing cycle optimizes reliability while minimizing costs. This paper offers a novel approach to missile maintenance strategy formulation and contributes to the existing literature by providing evidence-based recommendations for determining optimal testing cycles in missile systems. The findings of this research can inform future strategies for military maintenance planning and contribute to cost-effective operational readiness management.

Keywords: *I-Level Periodic Testing Cycle, Important Factor Weighted Exponential Distribution Function (IFWEDF)*

1. INTRODUCTION

When a missile weapon system completes development, passes verification, and enters mass production, it is officially commissioned for service. At this stage, periodic testing of the missiles becomes a necessary step to ensure they can perform their operational readiness missions effectively. These tests are designed to ensure that missiles remain in a launch-ready state. Therefore, strict implementation of maintenance and testing protocols is essential to guarantee their availability.

Missile maintenance is primarily divided into three levels: Organizational Level (O-Level), Intermediate Level (I-Level), and Depot Level (D-Level)[1][2][3]. The specific tasks for each maintenance level are detailed in Figure 1. Maintenance at the O-Level is carried out by operational units, with the main goal of ensuring that missiles can execute operational readiness missions within the full missile framework. This level of maintenance typically includes visual inspection of the missile's exterior, resistance measurement of ignition circuits, or Built-in Tests (BIT)[4][5]. BIT refers to the system's internal automatic detection and fault isolation capabilities, and its testing frequency varies depending on the missile model.

If a missile failure is detected during O-Level testing, the entire missile assembly will need to be sent to the I-Level for comprehensive testing to identify the faulty component (e.g., guidance section, warhead section) and perform module replacement or repair. For the missile system studied in this paper, each missile must be sent to the I-Level for testing and maintenance every two years. I-Level maintenance is conducted using Automatic Test Equipment (ATE) to perform comprehensive testing. When a module failure is identified, the faulty module is replaced. If the module cannot be repaired, support from the D-Level is requested, or the faulty section is sent to the D-Level for further repair.

Additionally, missiles may be damaged during transport, loading, or operational readiness due to accidental incidents (e.g., dropping, lightning strikes). In such cases, the missiles must also be sent to the D-Level for testing and repair.

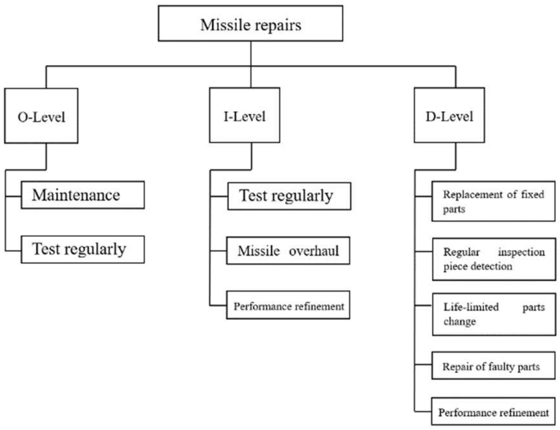

Figure 1: Tasks for Each Missile Maintenance Level

From the tasks associated with missile maintenance levels shown above, it is evident that the periodic testing cycles at the I-Level play a significant role in missile maintenance. The length of the testing cycle directly affects missile reliability. According to research, the reliability of missiles changes with their age [6], and the phenomenon of degradation is mainly caused by the test effect [7]. During testing, missiles are subjected to various stresses, effectively accelerating the aging of electronic components. Factors such as false alarms (misidentifying a functioning missile as faulty), testing procedures, and operational errors contribute to an increased missile failure rate.

Due to false alarms, missiles are often transported to the I-Level for comprehensive testing, which increases testing time. The longer the testing duration, the greater the stress imposed on internal missile modules. Additionally, the number and sequence of testing procedures significantly affect the stress experienced by the missile. A greater number of test items or improper steps can exacerbate the stress on the missile. Operational errors, often caused by insufficient familiarity with testing steps, lack of expertise, or failure to follow standard operating procedures (SOPs), may also lead to module failures.

The length of the I-Level periodic testing cycle also affects logistics and transportation costs between the O-Level and I-Level. A shorter testing cycle increases transportation frequency, resulting in higher transportation and manpower costs. However, an overly extended testing cycle may fail to ensure that missiles remain in optimal working condition. Therefore, O-Level and I-Level testing cycles should not be overly frequent to avoid adversely impacting missile reliability. Yet, without testing, it is impossible to confirm whether missiles are in proper working condition. Thus, it is crucial to study the appropriateness of I-Level periodic testing cycles.

From the above discussion, it is clear that I-Level periodic testing negatively impacts missile reliability, and shorter testing cycles increase logistics costs associated with missile transportation. This study analyzes and evaluates I-Level periodic testing cycles using relevant statistical methods, aiming to explore the feasibility of extending the I-Level testing cycle for missiles. The goal is to reduce logistics costs while enhancing missile reliability.

2. LITERATURE REVIEW

2.1. U.S. Navy Harpoon Missiles

The Harpoon Missile can be categorized into three configurations: air-launched, ship-launched, and submarine-launched [8]. The maintenance hierarchy of the Harpoon Missile is divided into three levels: Organizational Level (O-level, used by operational units), Intermediate Level (I-level, performed at maintenance facilities), and Depot Level (D-level, carried out by the manufacturer). The maintenance process is shown in Figure 2.

At the O-level maintenance tier, visual inspections of the missile's exterior and Built-In Test (BIT) are conducted. If the test results indicate a failure, the faulty missile is promptly replaced with a backup missile and sent to the I-level maintenance facility for further subsystem testing using the Missile Subsystem Test Set (MSTS) [7].

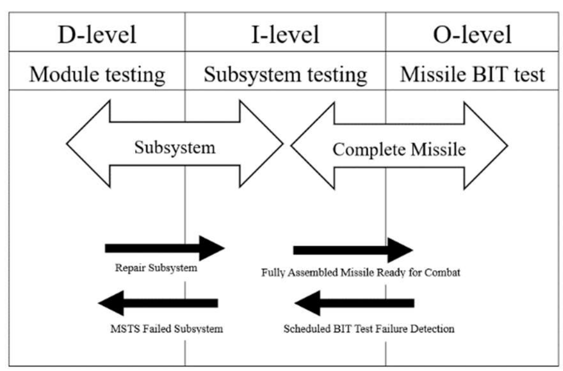

Figure.2: Harpoon Missile Maintenance Concept Diagram

Additionally, all missiles must undergo regular MSTS testing. If the BIT test indicates a missile failure, the missile will be subjected to MSTS testing. If the test results identify a failed component, it will be sent to the D-level for further repairs. The I-level maintenance facilities also assist the D-level with missile upgrade operations [11]. The D-level, managed by the original manufacturer, is responsible for repairing or replacing subassemblies. New or repaired subassemblies are reinstalled into the subsystem and returned to the I-level maintenance facility for subsystem integration and BIT testing. Once the missile passes the test, it is returned to operational units for combat readiness.

The maintenance cycle for each level is as follows: O-Level: Air-launched missiles undergo a complete BIT test during loading onto aircraft, while ship-launched and submarine-launched missiles are subjected to BIT tests every six months. I-Level and D-Level: If an failure cannot be resolved at the I-level, it is escalated to the D-level for repair.

2.2. U.S. Air Force Tactical Missiles

The periodic testing cycle for U.S. Air Force missiles at the I-level is detailed in Table 1. Prior to 1981, the U.S. Air Force mandated periodic testing every two years. As storage durations increased and failure rates did not rise, the testing interval was extended to three years between 1981 and 1986. Based on subsequent test results, the interval was further extended to five years by the end of 1986 [11].

Table 1: U.S. Air Force Missile I-Level Periodic Testing Cycle

Timeline	Level I periodic test cycles	Reasons for the extended test cycle
Before 1981	2 years	-
1981-1986	3 years	Extended Storage Duration with No Increase in Failure Rate
After 1986	5 years	Testing Interval Extended Based on Additional Test Results

2.3. Missile Failure Modes

Missiles are not solely composed of electronic equipment; they also include mechanical components (e.g., actuators, disjointed mechanisms), electronic components (e.g., navigation systems, flight controls, seekers), one-shot items (e.g., rockets), and non-mechanical life-limited components (e.g., propellant, batteries). The interfaces between these components are highly complex, and each component has unique characteristics. Notably, components such as engines, igniters, gas generators, safety arming devices, and detonators are highly sensitive to storage conditions, such as temperature and humidity [9][10]. Therefore, missiles must undergo regular inspections and testing after long-term storage and readiness missions to ensure their quality and performance [11]. The U.S. military conducted live-fire tests on a missile produced 27 years ago to confirm that the aging weapon remains reliable and operational [12]. This indicates that although missile reliability gradually degrades over time, it can still fulfill combat readiness missions.

2.4. Impact of Storage, Testing, and Transportation on Failure Rates

2.4.1. Transportation effect

According to Theunissen [13], research on Harpoon missiles reveals that vibration and shock have a far greater impact on the failure rate than temperature and humidity.

2.4.2. Testing effects

Malcolm explained: "Time itself is not a stress factor. Instead, the testing process imposes various stresses on the missile. Factors such as false alarms, testing procedures, or operational errors significantly increase the failure rate [7]". Figure 3 illustrates the impact of testing effects on failure rates. Storage conditions are not the primary cause of failures; in fact, testing effects have a more pronounced influence on failure rates [11].

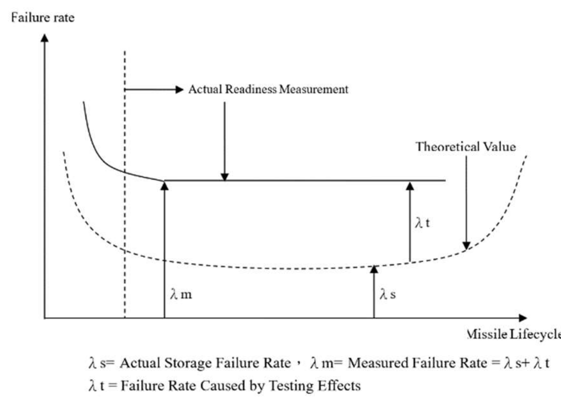

Figure.2: Illustration Of The Impact Of Testing Effects On Failure Rates

Figure 4 presents a quantitative description of the testing effect. When the storage failure rate (λs) is significantly lower than the test failure rate (λt), it indicates that the test failure rate (λt) is extremely high, suggesting that the testing process is highly inefficient. If λs is lower than λt, it indicates that the test failure rate is slightly higher, meaning that testing is not performed frequently. Conversely, when λs is significantly higher than λt, it indicates that the test failure rate (λt) is very low, reflecting a highly efficient testing process [7].

Note: N = the number of tests conducted after storing the missile for t years

F = the number of test failures
(the slope determines λs, while the y-intercept determines λt)
If λs << λt, it indicates inefficient testing.
If λs < λt, it suggests infrequent testing.

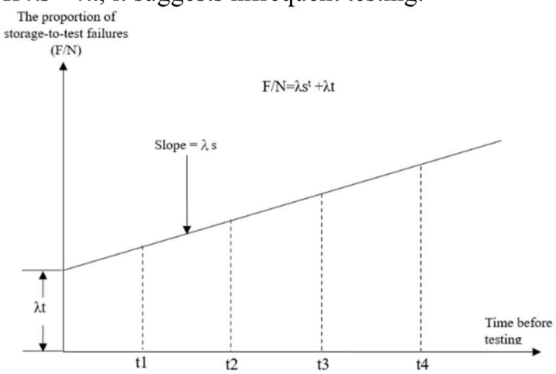

Figure.4: The Criterion For Determining The Efficiency Of Storage Testing

2.5. Storage Conditions

From the perspective of missile deployment, the stages of storage and dormancy occupy most of the missile's service life [14]. "Storage" refers to the condition where equipment is not connected to a system and is packaged and preserved in mild environmental conditions or after an extended period of storage. In contrast, "Inert storage" refers to a state where components or equipment remain connected to the system in normal operational status but experience stress or environmental conditions below normal or routine operational levels [11][15].

For missile deployment, assembled missiles on launchers and powered for readiness are considered in Inert storage, while missiles stored in depots are categorized as being in storage. This distinction highlights the significant differences in environmental stresses experienced during these two phases. From a reliability perspective, the failure rates during storage and dormancy phases also differ. Malcolm [7] conducted studies on various tactical missiles, performing flight tests after long-term storage. The results showed that the reliability of the guidance and control section did not degrade with increased storage time. For electronic equipment, the failure rate during storage was zero. Any observed degradation in missile reliability during testing was actually due to testing effects.

3. COMPREHENSIVE ANALYSIS

The primary cause of missile reliability degradation is not storage or inert storage conditions. On the contrary, environmental factors during testing and transportation processes, particularly vibration and shock, have the greatest impact on missile reliability.

3.1. General Exponential Distribution Theory

Mathematical models for reliability typically include binomial distribution, exponential distribution, Weibull distribution, and normal distribution. Among these, the exponential distribution model is commonly used for reliability estimation of electronic components due to its mathematical simplicity [16][17]. The reliability mathematical model for general components can be expressed as shown in Equation (1)

$$R_i(t) = e^{-\lambda t} \qquad (1)$$

where $R_i(t)$ is the reliability of the *i*-th component at usage time *t*, λ is the failure rate of the *i*-th component, and *t* is the usage time.
If the reliability $R_i(t)$ of each component i follows an exponential distribution with a constant failure rate λ_i, the system reliability is expressed as shown in Equation (2).

$$R_s(t) = e^{-\lambda t} = e^{-\sum_{i=1}^{N} \lambda_i t} \qquad (2)$$

3.2. Important Factor Weighted Exponential Distribution Function

This study adopts the "Important Factor Weighted Exponential Distribution Function" to estimate reliability under different periodic testing cycles. This method is an improvement based on the exponential distribution model. Through the literature review mentioned earlier, we identified the key environmental factors affecting reliability, including transportation, testing and storage.
As a result, the calculation of missile reliability takes into account the influence of these three factors, with each factor weighted according to its average failure rate. The final reliability of the missile is then determined.
The formula for calculating missile reliability is expressed as follows:

$$R = e^{(-m)} \qquad (3)$$

where $m=\Sigma K_i n_i$ =total number of failures. The greater the value of m, the lower the reliability, indicating harsher environmental conditions that significantly reduce reliability. K_i represents the average failure proportion of the missile in various environments, while n_i denotes the number of occurrences the missile experiences in each environment [18].

The K_i values are derived from empirical data obtained through actual environmental tests referenced from the literature. The n_i values are calculated based on the missile's life cycle and the number of occurrences it undergoes in each environment. The following provides an explanation of the reliability calculation method for missiles:

Assume that a K-type missile is delivered to the troops for active service, where the primary storage facilities are O-level and I-level maintenance depots. Most of the time, the missile performs combat readiness missions at aboard ships. An analysis indicates that during its service life, the missile system is exposed to various environmental factors, including transportation, testing and storage. Table 2 summarizes the impact of these three environmental factors on reliability.

For example, assume that the missile is transported from the manufacturer to the I-level maintenance depot, with a one-way distance of 400 kilometers, making the total round-trip distance 800 kilometers. After the I-level maintenance depot completes the acceptance testing, the missile is transported to various ships. The average distance between the deployment ships and the I-level maintenance depot is 400 kilometers, with a round-trip distance of 800 kilometers. Due to the higher mobility of ships, precise calculations are difficult, so the distance to deployment port is used as an estimation standard.

Table 2 Overview of the Impact of Transportation, Testing, and Storage on Missile Reliability During Service

Item	Environment	Starting Point	Endpoint	Km/Time	*K value*	*n value*
1	Transportation	Manufacturer	I-Level Maintenance Depot	Round Trip = 800 = 1600×0.5	0.025	One transportation per D-level maintenance cycle (Note1)
2		I-Level Maintenance Depot	Deployment Site	Round Trip = 800 = 1600×0.5	0.025	Depends on the maintenance cycle (Note1)
3	Testing	I-Level Maintenance Depot Conducting Full Missile Testing		Approximately Average= 2 hr	0.02	Depends on the maintenance cycle (Note1)
4		Deployment Ship Conducting Missile BIT Testing		Approximately Average= 0.2 hr	0.002	One test every six months (Note1)
5	Storage	Warehouse, Ship		NA	0.05	Note2

From the conclusions of the aforementioned literature review, it is evident that the vibration and shock effects caused by transportation and testing [6][7] have the most direct and significant impact on failure rates. Based on the existing literature, it can be concluded that every 1,000 miles (approximately 1,600 kilometers) of transportation results in a reliability decrease of about 5% (i.e., K_i= 0.05) [19]. Therefore, the round-trip distance from the manufacturer to the I-level maintenance depot, as well as the round-trip distance from the I-level depot to the deployment site, is 800 kilometers, each corresponding to a K_i value of 0.025.

The I-level maintenance depot conducts full missile testing according to the periodic testing cycle, with each test lasting approximately 2 hours. Based on the testing effect, each full missile test reduces the missile's reliability by approximately 2% (i.e., K_i = 0.02) [18].

Additionally, the O-level performs a missile BIT test every six months, with each test lasting approximately 0.2 hours. Based on the proportional relationship between the testing time and the average 2-hour full missile test at the I-level maintenance depot, the K_i for O-level testing is 0.002.

Malcolm [6] mentioned that the failure rate of electronic equipment during storage is zero. However, the K-type missile, which is the subject of this study, is mostly deployed on ships, and the impact of ship vibrations on reliability cannot be ignored. Based on actual deployment experience, the failure rate of the K-type missile is approximately 15% (i.e., 0.12). After deducting the reliability reductions caused by transportation effects (5%, Ki=0.05) and testing effects (2%, Ki=0.02), the estimated storage effect on ships is approximately 8% (Ki=0.08).

3.3. Comparison of Reliability Estimation Results for Different Periodic Testing

Based on Table 2 and Equation (3) mentioned earlier, the reliability estimation results for I-level periodic testing cycles of 2 years, 3 years, 5 years, 7 years, and 9 years were calculated and compared. Finally, a comprehensive benefit analysis and evaluation were conducted, and the optimal I-level periodic testing cycle was recommended.

4. ANALYSIS RESULTS

Based on the research design and the findings from the literature review, the reliability estimation values (R) for I-level periodic testing cycles of 2, 3, 5, 7, and 9 years were calculated. The results are explained as follows:

4.1. Two-Year I-Level Periodic Testing Cycle

The impact of transportation, testing, and storage on reliability for a 2-year I-level periodic testing cycle is assessed and summarized in Table 3. The calculation results of the reliability estimation value (R) are detailed as follows.

m=0.025+0.125+0.1+0.04+0.05≒0.34

R=exp (-m)= exp ($\Sigma n_i K_i$)=exp (-0.34)≒0.71

Table 3: Assessment of the Impact of Transportation, Testing, and Storage on Reliability for a 2-Year I-Level Periodic Testing Cycle

Item	Environment	Starting Point	Endpoint	Km/Time	*K value*	*n value*	$K_i\, n_i$
1	Transportation	Manufacturer	I-Level Maintenance Depot	Round Trip = 800 = 1600×0.5	0.025	1 (Performed once every 10 years) (Note)	0.025
2		I-Level Maintenance Depot	Deployment Site	Round Trip = 800 = 1600×0.5	0.025	5 (Performed 5 times every 10 years) (Note)	0.125
3	Testing	I-Level Maintenance Depot Conducting Full Missile Testing		Approximately Average= 2 hr	0.02	5 (Performed 5 times every 10 years) (Note)	0.1
4		Deployment Site or Ship Conducting Missile BIT Testing		Approximately Average= 0.2 hr	0.002	20 (Performed 20 times every 10 years) (Note)	0.04
5	Storage	Warehouse, Ship		NA	0.05	1(Served on a ship for 2 years)	0.05

Note: Assuming the D-level maintenance cycle is 10 years

4.2. Three-Year I-Level Periodic Testing Cycle

The impact of transportation, testing, and storage on reliability for a 3-year I-level periodic testing cycle is assessed and summarized in Table 3. The calculation results of the reliability estimation value (R) are detailed as follows.

m=0.025+0.075+0.06+0.04+0.075=0.2

R=exp (-m)= exp ($\Sigma n_i K_i$)=exp (-0.2)≒0.82

Table 4: Assessment of the Impact of Transportation, Testing, and Storage on Reliability for a 3-Year I-Level Periodic Testing Cycle

Item	Environment	Starting Point	Endpoint	Km/Time	*K value*	*n value*	$K_i\, n_i$
1	Transportation	Manufacturer	I-Level Maintenance Depot	Round Trip = 800 = 1600×0.5	0.025	1 (Performed once every 10 years) (Note1)	0.025
2		I-Level Maintenance Depot	Deployment Site	Round Trip = 800 = 1600×0.5	0.025	3 (Performed 3 times every 10 years) (Note1)	0.075
3	Testing	I-Level Maintenance Depot Conducting Full Missile Testing		Approximately Average= 2 hr	0.02	3 (Performed 3 times every 10 years) (Note1)	0.06

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4		Deployment Site or Ship Conducting Missile BIT Testing	Approximately Average= 0.2 hr	0.002	20 (Performed 20 times every 10 years) (Note1)	0.04
5	Storage	Warehouse, Ship	NA	0.05	1.5(Note2)	0.075

Note: 1.Assuming the D-level maintenance cycle is 10 years, 2.The transportation vibration stress during three years of continuous service on the ship is 1.5 times that of two years of service.

4.3. Five-Year I-Level Periodic Testing Cycle

The impact of transportation, testing, and storage on reliability for a five-year I-level periodic testing cycle is assessed and summarized in Table 3. The calculation results of the reliability estimation value (R) are detailed as follows.

m=0.025+0.05+0.04+0.04+0.125≒0.28

R=exp (-m)= exp ($\Sigma n_i K_i$)=exp (-0.28)≒0.76

Table 5: Assessment of the Impact of Transportation, Testing, and Storage on Reliability for a Five-Year I-Level Periodic Testing Cycle

Item	Environment	Starting Point	Endpoint	Km/Time	*K value*	*n value*	$K_i n_i$
1	Transportation	Manufacturer	I-Level Maintenance Depot	Round Trip = 800 = 1600×0.5	0.025	1 (Performed once every 10 years) (Note1)	0.025
2		I-Level Maintenance Depot	Deployment Site	Round Trip = 800 = 1600×0.5	0.025	2 (Performed 2 times every 10 years) (Note1)	0.05
3	Testing	I-Level Maintenance Depot Conducting Full Missile Testing		Approximately Average= 2 hr	0.02	2 (Performed 2 times every 10 years) (Note1)	0.04
4		Deployment Site or Ship Conducting Missile BIT Testing		Approximately Average= 0.2 hr	0.002	20 (Performed 20 times every 10 years) (Note1)	0.04
5	Storage	Warehouse, Ship		NA	0.05	2.5(Note2)	0.125

Note: 1.Assuming the D-level maintenance cycle is 10 years, 2.The transportation vibration stress during three years of continuous service on the ship is 2.5 times that of two years of service.

4.4. Seven-Year I-Level Periodic Testing Cycle

The impact of transportation, testing, and storage on reliability for a seven-year I-level periodic testing cycle is assessed and summarized in Table 3. The calculation results of the reliability estimation value (R) are detailed as follows.

m=0.025+0.025+0.02+0.04+0.175≒0.285

R=exp (-m)= exp ($\Sigma n_i K_i$)=exp (-0.285)≒0.75

Table 6: Assessment of the Impact of Transportation, Testing, and Storage on Reliability for a Seven-Year I-Level Periodic Testing Cycle

Item	Environment	Starting Point	Endpoint	Km/Time	*K value*	*n value*	$K_i n_i$
1	Transportation	Manufacturer	I-Level Maintenance Depot	Round Trip = 800 = 1600×0.5	0.025	1 (Performed once every 10 years) (Note1)	0.025
2		I-Level Maintenance Depot	Deployment Site	Round Trip = 800 = 1600×0.5	0.025	1 (Performed 1 times every 10	0.025

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						years) (Note1)	
3	Testing	I-Level Maintenance Depot Conducting Full Missile Testing		Approximately Average= 2 hr	0.02	1 (Performed 1 times every 10 years) (Note1)	0.02
4		Deployment Site or Ship Conducting Missile BIT Testing		Approximately Average= 0.2 hr	0.002	20 (Performed 20 times every 10 years) (Note1)	0.04
5	Storage	Warehouse, Ship		NA	0.05	3.5 (Note2)	0.175

Note: 1.Assuming the D-level maintenance cycle is 10 years, 2.The transportation vibration stress during three years of continuous service on the ship is 3.5 times that of two years of service.

4.5. Nine-Year I-Level Periodic Testing Cycle

The impact of transportation, testing, and storage on reliability for a nine-year I-level periodic testing cycle is assessed and summarized in Table 3.

The calculation results of the reliability estimation value (R) are detailed as follows.

m=0.025+0.025+0.02+0.04+0.225≒0.335

R=exp (-m)= exp ($\Sigma n_i K_i$)=exp (-0.335)≒0.72

Table 7: Assessment of the Impact of Transportation, Testing, and Storage on Reliability for a Nine-Year I-Level Periodic Testing Cycle

Item	Environment	Starting Point	Endpoint	Km/Time	*K value*	*n value*	$K_i n_i$
1	Transportation	Manufacturer	I-Level Maintenance Depot	Round Trip = 800 = 1600×0.5	0.025	1 (Performed once every 10 years) (Note1)	0.025
2		I-Level Maintenance Depot	Deployment Site	Round Trip = 800 = 1600×0.5	0.025	1 (Performed 1 times every 10 years) (Note1)	0.025
3	Testing	I-Level Maintenance Depot Conducting Full Missile Testing		Approximately Average= 2 hr	0.02	1 (Performed 1 times every 10 years) (Note1)	0.02
4		Deployment Site or Ship Conducting Missile BIT Testing		Approximately Average= 0.2 hr	0.002	20 (Performed 20 times every 10 years) (Note1)	0.04
5	Storage	Warehouse, Ship		NA	0.05	4.5(Note2)	0.225

Note: 1.Assuming the D-level maintenance cycle is 10 years, 2.The transportation vibration stress during three years of continuous service on the ship is 4.5 times that of two years of service

4.6. Comprehensive Forecast Results and Analysis

4.6.1. Comprehensive forecast results

Based on the forecast results mentioned above, the estimated R-values for the fixed measurement cycles in years 2, 3, 5, 7, and 9 are summarized in Figure 5. The figure shows that the estimated R-values for these cycles are 0.71, 0.82, 0.76, 0.75, and 0.72, respectively.

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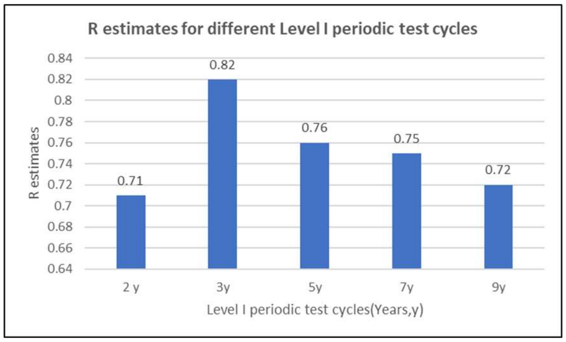

Figure 5: Estimated R-Values Of Missiles For Different Fixed Measurement Cycles

4.6.2. Comprehensive analysis

Based on the estimated R-values for the fixed measurement cycles of 2, 3, 5, 7, and 9 years, it is evident that the 3-year cycle provides the highest efficiency. According to the literature review, the U.S. Air Force has set the I-level fixed measurement cycle for missiles at 5 years. Analysis indicates that most of their missiles are stored in bunkers and are only mounted on aircraft during training exercises. Therefore, a 5-year cycle can still ensure missile reliability. However, since K-type missiles are deployed on ships, they must withstand prolonged ship vibrations and higher temperatures in their operational regions, which can accelerate aging and affect reliability. As a result, fixed measurement cycles should not be standardized across different environments.

4.7. Analysis of Actual Missile Failure Conditions in Service

If the periodic I-level test cycle is extended to three years, the current stability and quality of the missiles must be considered. According to the failure statistics of K-type missiles during deployment from P1 to P15, as shown in Table 8, the number of failures was relatively low in the early deployment stages due to the smaller quantity of missiles. However, both Segment A and Segment B experienced high failure rates in certain modules. After improvements and the installation of upgraded modules, the failure rate gradually decreased. Table 8 presents the failure data of K-type missiles, indicating that Segment A reached its failure peak during P6–P10, while Segment B peaked during P6–P9. To enhance missile reliability, it is essential to further refine, modify, and replace the A and B segments.

Table 8: Summary Of K-Type Missile Failure Counts From P1 To P15

Year	P 1	P 2	P 3	P 4	P 5	P 6	P 7	P 8	P 9	P10	P11	P12	P13	P14	P15
Segment *A*	33	10	15	23	19	41	46	36	42	49	24	27	26	27	31
Segment B	0	0	3	7	7	49	44	18	25	9	2	8	18	12	0
Total Failure Count	33	10	18	30	26	90	90	54	46	58	26	35	44	39	31

The failure data underwent statistical analysis [19][20] results indicate that the high failure rates of Segments A and B during the P6–P10 period significantly affected the reliability of K-type missiles. Therefore, based on the stable quality condition of K-type missiles after upgrading Segments A and B to enhanced modules in P10, the I-level periodic test cycle can be extended to three years.

4.8. Correlation Analysis

The Pearson correlation analysis [16][17] results, as shown in Table 9, indicate a significant correlation between K-type missile failures and failures in Segments A and B.

The regression equation [16][17] is y = -9.1 + 1.71x, with p-value = 0.000, R-Square = 69.2%, and Standardized Residual = 2.34R. The residual analysis is shown in Figure 6.

Table 9: Correlation Analysis of K-Type Missile Failures with Segments A and B Failures

Item		Segment A Failures	Segment B Failures
Failure Count	Pearson Correlation Coefficient	0.832	0.910
	p-value	0.000	0.000
Correlation		Significance	Significance

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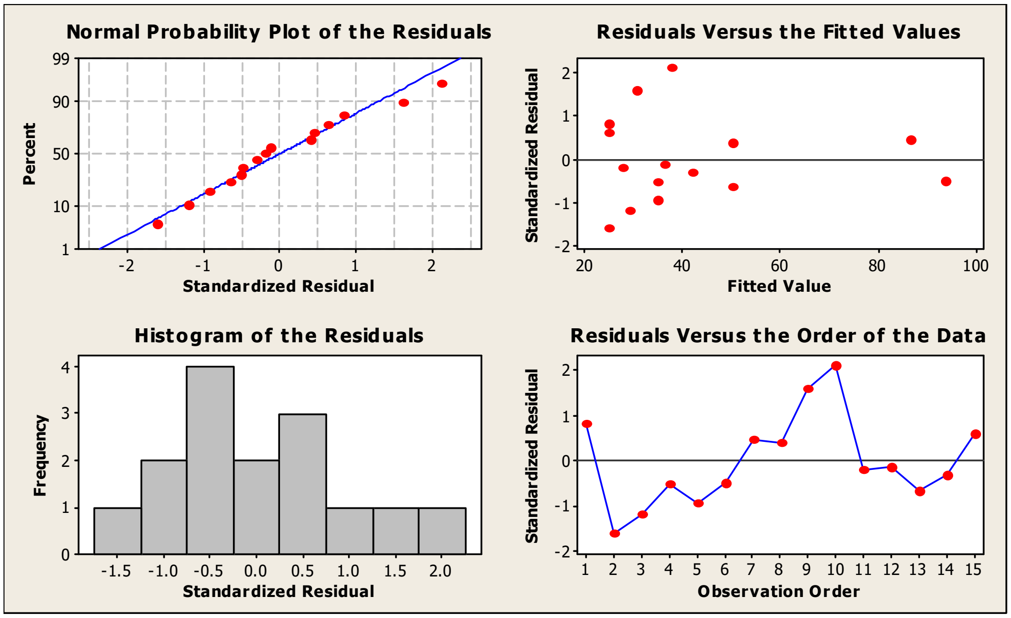

Figure 6: Residual Analysis Results For Annual Failures (Y) Vs. Segment A Failures (X)

The regression model shows that the coefficient's p-value is 0.000, indicating that at a significance level of α = 0.05, the relationship between annual failures and Segment A is significant. The R-Square (coefficient of determination) is 69.2%, suggesting that 69.2% of the variability in annual failure counts can be explained by Segment A failures, indicating a good fit of the model to the data. The 10th observation is identified as an outlier since its standardized residual value (2.34) exceeds 2, marked with the symbol "R". This indicates significant variability in annual failures and Segment A failures during the P10 period.

The regression equation is y = 25.2 + 1.39x, with p-value = 0.000, R-Square = 82.8%, and Standardized Residual = 2.11R. The residual analysis is shown in Figure 7.

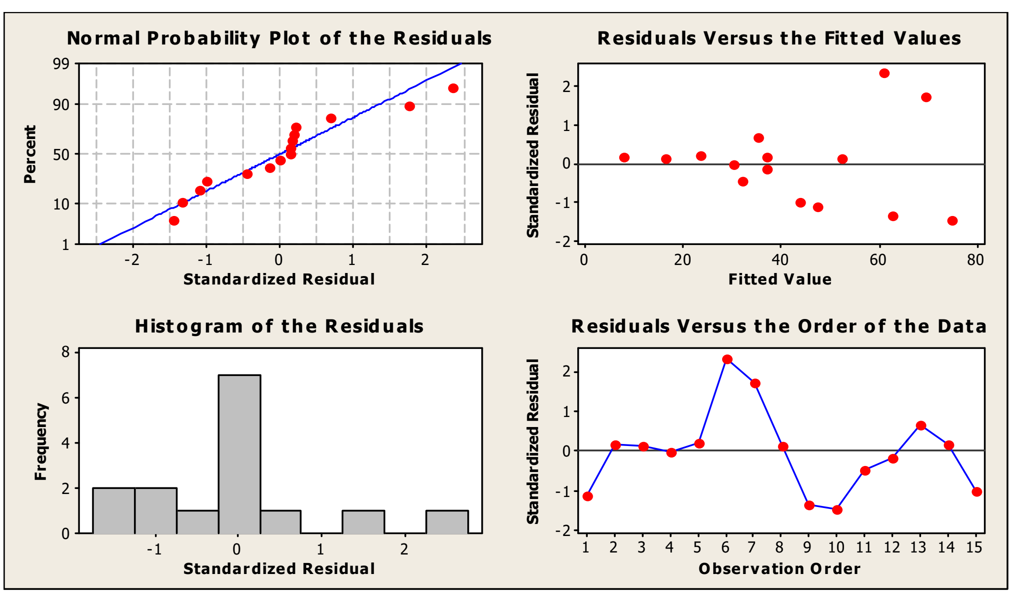

Figure 7: Residual Analysis Results For Annual Failures (Y) Vs. Segment B Failures (X)

The regression model shows that the coefficient's p-value is 0.000, which is very small. This indicates that at a significance level of $\alpha = 0.05$, the relationship between annual failures and Segment B is significant. The R-Square (coefficient of determination) is 82.8%, suggesting that 82.8% of the variability in annual failure counts can be explained by Segment B failures, demonstrating a strong explanatory power of the model. The 6th observation is identified as an outlier since its standardized residual value (2.11) exceeds 2. This phenomenon indicates an anomaly, marked with the symbol "R". It suggests that during the P6 period, there was a significant variation in annual failures and Segment B failures.

5. COST BENEFIT ANALYSIS

The following analysis evaluates the transportation, testing, and storage cost-benefit aspects of extending the I-Level periodic testing cycle from two years to three years, followed by a total cost-benefit comparison [21][22].

5.1. Transportation Cost-Benefit

Assuming a total of 5,000 missiles, when the I-Level periodic testing cycle is set at two years, 2,500 missiles must be tested annually. With a transportation capacity of two missiles per trip, this results in 1,250 trips per year. Assuming a transportation cost of $50,000 per trip, the total annual transportation cost is NT$62.5 million. Similarly, when the testing cycle is extended to three years, the transportation cost is reduced to $42 million per year. This extension results in an annual cost saving of approximately $20.5 million (around one-third). (For detailed transportation cost analysis, see Table 9.)

Table 9: Annual Transportation Cost-Benefit Analysis of Extending Level I Testing Cycle from Two Years to Three Years

Level I Testing Cycle	Number of Missiles Tested Annually	Number of Transportation Trips	Cost ($)
2 years	2500	1250 trips	62.5 million
3 years	1670	840 trips	42 million
Savings (Quantity/Cost)	830	410 trips	20.5 million

5.2. Testing Cost-Benefit

Assuming a total of 5,000 missiles, when the I-Level periodic testing cycle is set at two years, 2,500 missiles must be tested annually. Assuming a testing cost of $100,000 per test (including indirect costs), the total annual testing cost is $250 million.

Similarly, when the testing cycle is extended to three years, the total annual testing cost is reduced to $167 million. This extension results in an annual cost saving of approximately $83 million (around one-third). (For detailed testing cost analysis, see Table 10.)

Table 10: Annual Testing Cost-Benefit Analysis of Extending Level I Testing Cycle from Two Years to Three Years

Level I Testing Cycle	Number of Missiles Tested Annually	Single test cost ($)	Cost ($)
2 years	2500	100,000	250 million
3 years	1670		167 million
Savings (Quantity/Cost)	830		83 million

5.3. Storage Cost Efficiency

Assuming a total of 5,000 missiles, when the I-Level periodic inspection cycle is two years, 2,500 missiles must be temporarily stored in bunkers after each inspection cycle. If the storage cost per missile is $10,000 (including indirect costs), the total cost amounts to $25 million. Similarly, when the Level I inspection cycle is extended to three years, the storage cost is reduced to only $16.7 million. This results in an annual cost savings of approximately $8.3 million (about one-third). (For a detailed storage cost analysis, see Table 11.)

Table 11: Annual Storage Cost Efficiency Analysis of Extending the Level I Periodic Inspection Cycle from Two Years to Three Years

Level I Testing Cycle	Number of Missiles Tested Annually	Storage Quantity	Cost ($)
2 years	2500	2500	25 million
3 years	1670	1670	16.7 million
Savings (Quantity/Cost)	830	830	8.3 million

5.4. Total Cost-Benefit Analysis

Based on the cost-benefit analysis of transportation, testing, and storage mentioned above, the total annual cost savings are estimated to be NT$1,118 million (approximately one-third), calculated as NT$3,375 million - NT$2,257 million.

Table 12: Annual Total Cost-Benefit Analysis for Extending the Level I Fixed Testing Cycle from Two Years to Three Years.

Level I Testing Cycle	Transportation Cost	Testing Cost	Storage costs	Total
2 years	62.5 million	250 million	25 million	3,375 million
3 years	42 million	167 million	16.7 million	2,257 million
Save Cost	20.5 million	83 million	8.3 million	1,118 million

6. CONCLUSION

This study references the I-Level periodic test cycles established for foreign missile systems. Based on U.S. military research findings, missile failures are primarily caused by testing. Strategically, minimizing the frequency of tests is preferred. Additionally, transportation and storage are key factors affecting reliability.

Using the "Weighted Index Distribution Function for Critical Factors" method, this study considers three factors—transportation, testing and storage—to compare reliability predictions and cost-benefit analyses for different periodic test cycles. The results indicate that extending the I-Level periodic test cycle from two years to three years yields the highest reliability and reduces costs by one-third. The U.S. Air Force sets the I-Level periodic test cycle for missiles at five years, as most of their missiles are stored in underground bunkers and only mounted on aircraft during training exercises.

However, K-type missiles are deployed on ships, where they are subjected to prolonged ship vibrations. Additionally, the higher temperatures in deployment areas accelerate aging, which impacts reliability. Therefore, test cycles should not be universally applied across different environments. Based on theoretical analysis and real-world conditions, extending the I-level periodic test cycle for K-type missiles to three years is a more feasible approach to improving missile reliability.

Future Research Directions and Recommendations: (1) The "Weighted Index Distribution Function for Critical Factors" method used in this study only considers three environmental factors: transportation, testing, and storage. Future research could incorporate additional critical factors and refine the methodology. (2) Currently, the I-Level periodic test cycle for K-type missiles is set at two years. To assess the feasibility of extending it to three years, a sampling test method could be implemented. For example, assuming a total production of 5,000 missiles, a random sample of 100 missiles could be selected and tested after three years instead of two. By comparing the reliability data from the standard two-year test cycle with the results from the extended three-year test cycle, it would be possible to determine whether the extension indeed enhances reliability.

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