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Original Paper

Reliability and lifetime assessment of flowmeters on LNG carriers using operational failure data and Weibull analysis

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Abstract: This study analyzed the functional life characteristics of flowmeters using ten functional failure records obtained from the failure and maintenance histories of nine LNG carriers. Functional failure was defined as the inability to provide valid flow information required for shipboard monitoring. A two-parameter Weibull model was applied to estimate the life characteristics and reliabilities at selected times since installation. The fitted Weibull distribution yielded a shape parameter of 2.37, a characteristic life of 133,000 hours, a mean life of 118,000 hours, and a B10 life of 51,300 hours. The point estimate of the shape parameter suggested an increasing tendency in the functional failure rate with time since installation. A zero-failure test duration was separately calculated for a target B10 life of 8,760 hours. Using an exponential distribution with a constant failure rate, an 80% confidence level, ten test units, and zero allowable failures, the required test duration was 13,400 hours per unit. The life-analysis results characterize the fitted life distribution based on the ten recorded functional failures, rather than the absolute reliability of the entire installed flowmeter population. The test-duration calculation provides separate statistical conditions for reliability demonstration planning during product development.

Keywords: LNG carrier, Flowmeter, Weibull analysis, B10 life, Zero-failure test duration

1. Introduction

On LNG carriers, the movement of both liquid and gaseous fluids must be continuously monitored during LNG loading and unloading operations and the handling of boil-off gas (BOG) generated during voyages. Flowmeters are installed in cargo transfer lines, vapour return lines, and BOG handling systems to measure flow rates and transferred quantities. Abnormal output or indication failures in these flowmeters can make it difficult to accurately determine the status of LNG transfer and BOG handling, thereby affecting cargo-operation monitoring and operational decision-making. In particular, flowmeters installed in BOG supply lines are used to measure the amount of gas supplied to boilers and other gas-consuming equipment and are therefore relevant to the stable management of BOG.

The International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code) provides the principal design and safety requirements for cargo tanks, cargo piping, and associated instrumentation and control systems on LNG carriers. The IGC Code requires instrumentation and automation systems supporting the safe transport and handling of cargo liquids and vapors to operate reliably under specified operating conditions **[1]**. Although the IGC Code does not prescribe quantitative reliability targets for flowmeters, it provides the regulatory context for the importance of reliable instrumentation in LNG cargo and BOG handling systems. Accordingly, characterizing the functional life of flowmeters can support the assessment and maintenance of these measurement systems.

Previous studies on flowmeters have primarily focused on measurement performance under different measurement principles and operating conditions, failure-cause analysis, and fault diagnosis. Wu *et al.* investigated the effects of material properties, temperature, pressure, zero stability, and repeatability on the measurement uncertainty of Coriolis flowmeters used for LNG mass-flow measurement under cryogenic conditions **[2]**. Zhou *et al.* analyzed major failure causes and the effects of failure modes using failure data from electromagnetic flowmeters **[3]**. Chen *et al.* proposed a fault-diagnosis method for

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distinguishing gas entrainment, wax deposition, and installation-related abnormalities in liquid ultrasonic flowmeters **[4]**. These studies have contributed to understanding flowmeter measurement uncertainty and identifying abnormal operating conditions.

Reliability and lifetime analyses have also been applied to shipboard machinery. Kimera and Nangolo analyzed failure and maintenance data for deck machinery on aging fishing vessels using Weibull and Gamma distributions to evaluate reliability and life characteristics **[5]**. Song *et al.* applied a Weibull model to in-service ship equipment to estimate characteristic life and support preventive-maintenance decisions **[6]**. However, relatively few studies have quantitatively investigated the lifetime distribution of flowmeters installed on LNG carriers. Studies that calculate the zero-failure test duration required to demonstrate a predefined reliability target for flowmeters during product development are also limited.

In this study, a two-parameter Weibull distribution was applied to ten functional-failure times obtained from flowmeters installed on nine LNG carriers. The life characteristics and reliabilities at selected times since installation of the flowmeters were subsequently evaluated. In addition, because the failure-rate behavior of the product under development could not be specified in advance, the required zero-failure test duration for demonstrating a target B10 life was calculated using an exponential distribution with a constant failure rate. This study aims to quantitatively evaluate the functional life of flowmeters and, separately, to present a procedure for calculating the zero-failure test duration required during product development.

2. Data and Analysis Methods

2.1 Dataset Construction and Functional Failure Criteria

The initial dataset comprised flowmeter failure and maintenance records provided by a shipping company for 13 LNG carriers. Of these, 4 vessels were recorded as having no flowmeter failures during the investigation period. However, the installation dates, observation end dates, and cumulative operating hours of the individual flowmeters were unavailable. Consequently, these cases could not be included as right-censored observations. A total of 12 functional abnormalities were identified across the remaining 9 vessels. Because this study focused on the life characteristics of flowmeters during normal operation, 2 cases that occurred during commissioning and initial setup were classified as belonging to a different operating phase and were excluded from the analysis. The final life analysis therefore included 10 functional failures recorded during normal operation across 9 LNG carriers.

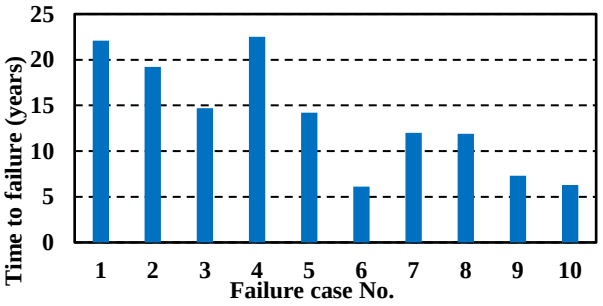

Figure 1: Time to functional failure for the flowmeters included in the analysis

Table 1: Flowmeter functional-failure records used in the life analysis

No.	Installation location	Failure effect	Failure cause	Time to failure (h)
1	Main boiler BOG supply line	Fixed flow-rate indication	Flow transmitter malfunction	191,000
2	Main boiler BOG supply line	Fixed flow-rate indication	Flow transmitter malfunction	166,000
3	Cargo gas flowmeter panel	Failure of the gas flowmeter to power on	Power-supply module failure	127,000
4	Atmospheric discharge and shore vapor return lines	Loss of gas-flow indication	Lightning-induced equipment damage	194,400
5	Shore vapor return line	No response in gas-flow indication	Flow transmitter malfunction	122,700
6	No.4 cargo tank	Continuous upward drift in gas-flow indication	Flow transmitter malfunction	52,700
7	Gas flowmeter panel	Loss of historical-data retrieval	CPU card failure	103,700
8	Boiler vapor supply line	Abnormal transmitter output response	Undetermined due to insufficient maintenance records	102,800
9	BOG supply line to the boiler	Flow indication fluctuating	Signal distortion caused by Zener-barrier failure	63,100
10	Shore vapor return line	Loss of flow indication	Differential-pressure transmitter failure	54,400

For each case, the failure time was defined as the time from installation of the flowmeter to the occurrence of a functional failure. Because cumulative running-hour records were unavailable, these values represent time since installation rather than accumulated operating hours. The resulting failure times ranged from 52,700 to 194,400 hours. **Table 1** presents the installation location, observed failure, failure cause, and time to functional failure for each case. **Figure 1** compares the failure times of the ten cases included in the analysis.

A functional failure was defined as a condition in which the flowmeter was unable to provide, display, or retrieve valid flow information required for shipboard monitoring, thereby requiring repair or replacement. Accordingly, the analysis included not only cases involving the replacement of flow transmitters but also cases involving repairs to power supply modules, CPU cards, and Zener barriers that directly affected the output or display of flow information. Case 8, for which the failure cause could not be determined from the available maintenance records, was also retained in the analysis because it satisfied the functional-failure criterion.

The life estimated in this study therefore represents the functional life over which a flowmeter provided valid flow information to the shipboard control and monitoring systems, rather than the physical life of the sensing element alone. Furthermore, because the observation times of non-failed flowmeters were unavailable, the subsequent life and reliability estimates describe the characteristics of the life distribution fitted to the ten recorded failure times. These estimates should not be interpreted as the absolute failure probability of the entire installed flowmeter population or as the warranty life of any specific manufacturer or model.

2.2 Weibull Life Distribution and Reliability Measures

The failure times in the analyzed dataset differed by a factor of approximately 3.7 between the minimum and maximum values. For data exhibiting such variability, mean life alone cannot adequately characterize the change in failure probability with time since installation or the lower-tail behavior of the life distribution. Therefore, a two-parameter Weibull distribution was applied because it can represent positive continuous-time data and describe various failure-rate behaviors through its shape parameter **[7][8]**. The Weibull distribution was applied in this study because its shape parameter allows the failure-rate behavior to be characterized directly as decreasing, constant, or increasing with time. In contrast, the exponential distribution assumes a constant failure rate, while the lognormal distribution does not provide the same direct interpretation of failure-rate behavior through a shape parameter. The probability density function $f(t)$ is expressed as **Equation (1)**.

$$f(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} e^{-\left(\frac{t}{\eta}\right)^{\beta}} \quad (1)$$

where t is the time since installation, β is the shape parameter, and η is the scale parameter, subject to $t \geq 0$, $\beta > 0$, and $\eta > 0$. A shape parameter less than 1 indicates a concentration of failures during early operation, whereas a value equal to 1 represents a constant failure rate independent of time since installation. A shape parameter greater than 1 indicates an increasing failure rate with time since installation. The scale parameter represents the characteristic life at which the cumulative failure probability reaches approximately 63.2%.

The shape and scale parameters were estimated using rank regression on X (RRX) in ReliaSoft Weibull++. The cumulative failure probability of each failure time was assigned using the median-rank method, and the parameters were estimated by minimizing the deviations between the transformed data points and the fitted line in the X-axis direction on the Weibull probability plot.

The reliability function and mean life were calculated to evaluate the probability that a flowmeter would operate without functional failure up to a specified time since installation and to determine the average level of the fitted life distribution. In addition, the B10 life, defined as the time at which the cumulative failure probability reaches 10%, was evaluated to characterize the lower-tail behavior of the life distribution. These reliability measures are expressed by **Equations (2)-(4)**.

$$R(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}} \quad (2)$$

$$E(T) = \eta\Gamma\left(1 + \frac{1}{\beta}\right) \quad (3)$$

$$B_{10} = \eta[-\ln(0.9)]^{\frac{1}{\beta}} \quad (4)$$

$R(t)$ is the probability that a flowmeter remains functional up to time since installation t. T represents the lifetime random variable, and $E(T)$ is its expected value, or mean life. $\Gamma(\cdot)$ is the gamma function. The B10 life is the 10th percentile of the life distribution, corresponding to a cumulative failure probability of 10% and a reliability of 90%.

2.3 Calculation of Zero-Failure Test Duration

Weibull life analysis characterizes the life behavior of flowmeters represented by their failure and maintenance records. However, a separate reliability demonstration test is required to determine whether a development product satisfies a specified target life. In this study, a zero-failure test allowing no failures during the test period was adopted, and the test duration required for a given number of test units and confidence level was calculated.

A zero-failure test is not intended to estimate the actual life of a product. Instead, it determines, at a specified confidence level, whether the product satisfies a target reliability or percentile life **[9][10]**. Assuming a Weibull distribution, the relationship between the target percentile life and the required zero-failure test duration per unit is expressed as **Equation (5)**.

$$t_0 = t_p \left[\frac{\ln(1-CL)}{n\ln(1-p)}\right]^{1/\beta} \quad (5)$$

where t_0 is the zero-failure test duration per unit, t_p is the target percentile life, CL is the confidence level, n is the number of test units, p is the target cumulative failure probability, and β is the shape parameter. To demonstrate a B10 life, p=0.1 is applied.

Among the input parameters required by **Equation (5)**, the confidence level was selected using the criticality-based method developed by the Reliability Evaluation Center of the Korea Institute of Machinery and Materials and presented by Kim **[11]**. The four criteria presented in **Table 2** were test unit cost, test cost, economic loss, and safety. Test unit cost was evaluated by considering the unit price and the number of test units available from the manufacturer. Test cost was assessed based on the power requirements and electrical energy consumption associated with long-duration testing. Economic loss represented the potential effect of a flowmeter failure on system operation, whereas safety represented the potential risk to human life in the event of failure. The occurrence and severity ratings in Table 2 were assigned by experts from the flowmeter manufacturer with reference to MIL-STD-1629A **[12]**. The corresponding criticality scores were determined using the criticality matrix analysis procedure presented by Kim **[11]**. Under this procedure, the occurrence–severity combination is first mapped to a criticality grade, and Grades I–V are assigned scores of 9, 7, 5, 3, and 1, respectively. Accordingly, a Medium–Medium rating corresponds to Grade III and a score of 5, while a Medium–High rating corresponds to Grade II and a score of 7. Based on these considerations, test-unit cost and test cost were rated as Medium for both occurrence and severity, resulting in a criticality score of 5 for each criterion. Economic loss and safety were rated as Medium in occurrence and High in severity because the loss of valid flow information may disrupt cargo and BOG monitoring and impair safety-related operational decisions, resulting in a score of 7 for each criterion.

Table 2: Criticality assessment for determining the confidence level

No.	Evaluation criterion	Criticality		
		Occurrence	Severity	Criticality
1	Test unit cost	Medium	Medium	5
2	Test cost	Medium	Medium	5
3	Economic loss	Medium	High	7
4	Safety	Medium	High	7
Total				24

Table 3: Confidence level according to the cumulative criticality score

Grade	Total criticality score	Confidence level, CL
I	≥ 30	95%
II	25–29	90%
III	20–24	80%
IV	15–19	70%
V	< 15	60%

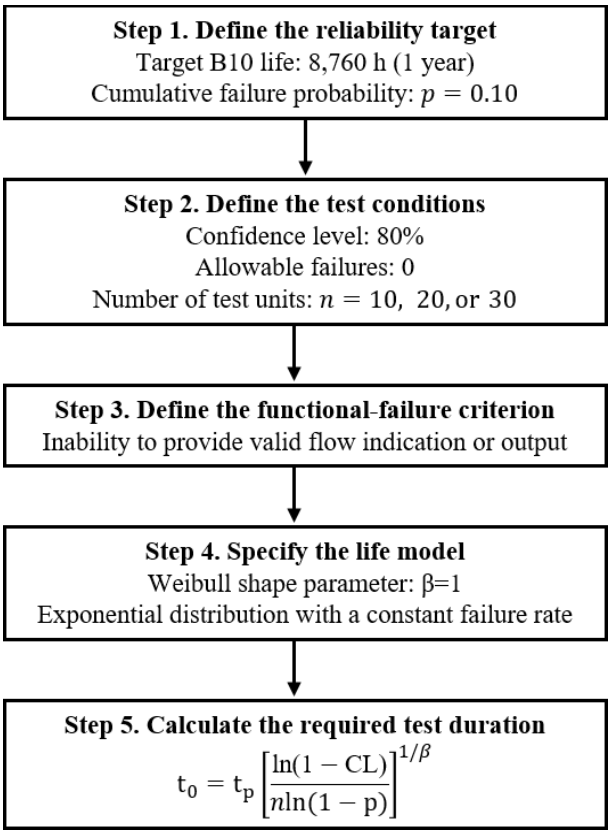

Figure 2: Procedure for calculating the required zero-failure test duration

The resulting cumulative criticality score was 24. According to the classification criteria in **Table 3**, this score corresponds to Grade III and a confidence level of 80%. Accordingly, $CL = 0.80$ was applied in **Equation (5)**. This confidence level was adopted as a study-specific test-planning criterion rather than as a universal statistical requirement.

In addition to the confidence level, calculation of the zero-failure test duration requires the target life, number of test units, functional failure criterion, and assumed life distribution to be specified. The overall calculation procedure and principal input conditions used in this study are summarized in **Figure 2**.

A functional failure during the test was defined according to the criterion established in Section 2.1, namely, a condition in which the flowmeter was unable to provide a valid flow indication or output signal. The target B10 life to be initially demonstrated during product development was set at 1 year, corresponding to 8,760 h. This value was selected as a practical initial demonstration target representing one year of continuous operation, rather than as a regulatory or field-derived service-life requirement. It was intended to provide a clear baseline for planning the zero-failure test during the early stage of product development. The confidence level was set at 80%, and zero failures were allowed. A baseline test plan using 10 test units was established, and alternative plans using 20 and 30 units were additionally evaluated to examine the effect of sample size on the required test duration. All test units were assumed to be independently tested under identical conditions, with the test duration equally allocated among the units. Unlike the field failure times, which represent time since installation, the test duration represents continuous exposure time per unit under the specified test conditions. The tests were also assumed to be conducted at the same stress level as the actual operating condition, without applying an acceleration factor.

Although a shape parameter of 2.37 was estimated from the operational failure records, this value was derived from ten functional failures with different causes. Furthermore, because the design and components of the product under development may differ from those of the existing products, the shape parameter estimated from the operational data was not directly applied to the test design. Instead, an exponential distribution with a constant failure rate was assumed by setting the Weibull shape parameter to 1. This distribution was adopted as a planning assumption for calculating the required zero-failure test duration because the failure-rate behavior of the product under development could not be specified in advance. This assumption is conservative with respect to the required test duration. When the field-estimated shape parameter of $\beta = 2.37$ is substituted into **Equation (5)**, the required test duration for 10 units is approximately 10,500 h per unit, compared with 13,400 h per unit under $\beta = 1$. Thus, the $\beta = 1$ assumption results in a longer test duration than that obtained using the field-estimated $\beta = 2.37$. This comparison does not imply that $\beta = 1$ is conservative for all possible values of the unknown shape parameter.

3. Life Analysis Results and Discussion

3.1 Functional Life Characteristics of Flowmeters

The analysis of 10 functional failures yielded a shape parameter of 2.37 and a scale parameter of 133,000 h for the two-parameter Weibull distribution. **Figure 3** shows the Weibull probability plot based on the analyzed failure-time data. In the figure, the data points represent the failure time of each case, the central solid line represents the fitted line estimated using rank regression, and the two dashed lines represent the 90% two-sided confidence bounds.

The point estimate of the shape parameter was greater than 1, suggesting an increasing tendency in the functional failure rate with time since installation. However, this tendency should be interpreted cautiously because it was estimated from only ten failure records. Because the analysis was based on failure records only, differences in the service ages of the sampled vessels may have contributed to the observed variation in failure times.

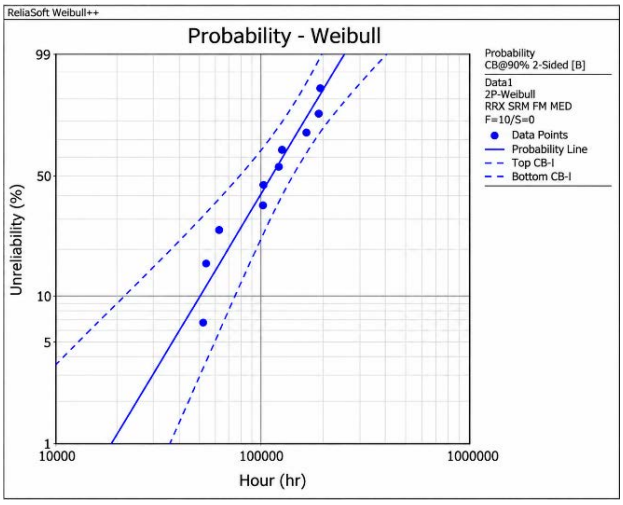

Figure 3: Weibull probability plot of flowmeter functional failure times

The functional failures included in this study arose from different components and failure causes within the flow-measurement and signal-processing chain. In addition to failures of the flow transmitter itself, the dataset included failures involving the power-supply module, CPU card, and Zener barrier. These cases were retained because they directly resulted in the loss of valid flow information and therefore satisfied the functional-failure criterion defined in Section 2.1. Case 10 also involved a differential-pressure transmitter with a different measurement principle, further contributing to the heterogeneity of the dataset.

The underlying failure mechanisms were not necessarily homogeneous. In particular, the lightning-induced failure in Case 4 was caused by an external event and may not reflect time-dependent degradation. Therefore, the Weibull parameters should be interpreted as characteristics of the overall functional-failure-time distribution rather than as representing a single physical failure mechanism.

From a maintenance perspective, these failure records indicate that condition assessment should not be limited to measurement accuracy or calibration status. Failures involving the power-supply module, CPU card, and Zener barrier directly resulted in the loss of valid flow information, while the lightning-induced case also caused complete loss of flow indication. Therefore, maintenance of long-serving flowmeters should include checks of the power supply, signal conversion and processing functions, and output stability, together with conventional calibration and measurement-performance checks.

3.2 Reliability Assessment and Zero-Failure Test Duration

The mean life, B10 life, and estimated reliabilities at different selected times since installation calculated from the fitted Weibull life distribution are summarized in **Table 4**. The mean life was estimated to be 118,000 h, corresponding to approximately 13.4 years, and the B10 life was estimated to be 51,300 h, corresponding to approximately 5.85 years. The estimated reliabilities at 1, 3, 5, and 10 years were 99.8%, 97.9%, 93.0%, and 68.8%, respectively. Under the fitted Weibull distribution, the estimated reliability was relatively high during the earlier period after installation and gradually decreased with increasing time since installation. The B10 life represents the time at which the cumulative failure probability of the fitted Weibull distribution reaches 10% and characterizes the lower-tail behavior of the life distribution. These values characterize the Weibull distribution fitted to the ten recorded functional-failure times and should not be interpreted as the absolute reliability or failure probability of the entire installed flowmeter population.

The B10 life of 51,300 h estimated from the field failure records characterizes the fitted life distribution of the existing flowmeters. In contrast, the target B10 life of 8,760 h (1 year) was established separately as an initial reliability demonstration criterion for the development product. The 1-year target was adopted as a practical initial demonstration criterion representing one year of continuous operation and was not intended to represent the expected service life of the existing flowmeters. This target was therefore independent of the field-data analysis and was not derived from the estimated B10 life of 51,300 h. Accordingly, the two values serve different purposes. The field-derived B10 value characterizes the functional life of the existing flowmeters represented by the field data, whereas the 8,760 h target defines the reliability level to be demonstrated for the development product. The required zero-failure test durations for different numbers of test units, calculated using an 80% confidence level, zero allowable failures, and a shape parameter of 1, are presented in **Table 5**.

For 10 test units, the required test duration was 13,400 h per unit, corresponding to approximately 558 days and approximately 1.53 times the target life. For the same 10-unit test plan, increasing the confidence level to 90% and 95% increased the required test duration to approximately 19,100 h and 24,900 h per unit, respectively. For comparison, substituting the field-estimated shape parameter of $\beta = 2.37$ into Equation (5) gives a required test duration of approximately 10,500 h per unit. Thus, the baseline assumption of $\beta = 1$ results in a longer test duration and is conservative with respect to test planning.

Table 4: Weibull life-analysis results for flowmeters

Life and Reliability Measure	Analysis Result
Mean life	118,000 h
Reliability at 1 year	0.998 (99.8%)
Reliability at 3 years	0.979 (97.9%)
Reliability at 5 years	0.930 (93.0%)
Reliability at 10 years	0.688 (68.8%)
B10 life	51,300 h

Table 5: Required zero-failure test duration according to sample size

Sample size, n	Test duration per unit (h)	Test duration per unit (days)
10	13,400	558
20	6,690	279
30	4,460	186

Therefore, if all 10 units are tested for 13,400 h without a functional failure, a B10 life of 8,760 h can be demonstrated at an 80% confidence level. Increasing the number of test units to 20 and 30 reduced the required test duration per unit to 6,690 h and 4,460 h, respectively. When multiple units are tested in parallel, increasing the number of test units can reduce the overall calendar duration of the test. However, under the assumed shape parameter of 1, the total accumulated test exposure remains approximately 13,400 specimen·h for all three test plans. Therefore, increasing the number of test units does not reduce the total test exposure but distributes it among a larger number of units.

4. Conclusion

This study analyzed 10 functional failures of flowmeters recorded during the normal operation of nine LNG carriers using a two-parameter Weibull model. The zero-failure test duration required to demonstrate the target B10 life of a development product was also calculated. The analysis yielded a shape parameter of 2.37 and a characteristic life of 133,000 h. The point estimate of the shape parameter was greater than 1, suggesting an increasing tendency in the functional failure rate with time since installation in the analyzed dataset.

The mean life was estimated to be 118,000 h, corresponding to approximately 13.4 years, and the B10 life was estimated to be 51,300 h, corresponding to approximately 5.9 years. Under the fitted Weibull distribution, the estimated reliabilities at 1, 3, 5, and 10 years were 99.8%, 97.9%, 93.0%, and 68.8%, respectively. The decrease in the fitted reliability from 93.0% at 5 years to 68.8% at 10 years suggests a greater likelihood of functional failure at longer elapsed times within the analyzed failure-time distribution. Therefore, when evaluating the condition of flowmeters that have been in service for extended periods, the power supply, signal conversion, and output stability should be considered together with measurement accuracy and calibration status.

Because the failure-rate behavior of the development product could not be specified in advance, an exponential distribution with a constant failure rate was assumed by setting the Weibull shape parameter to 1. For a target B10 life of 8,760 h, an 80% confidence level, 10 test units, and zero allowable failures, the required test duration was calculated to be 13,400 h per unit. Therefore, if all 10 test units operate for 13,400 h without a functional failure, a B10 life of 8,760 h can be demonstrated at an 80% confidence level. Increasing the number of test units can reduce the required test duration per unit and the calendar duration of parallel testing while maintaining the same total accumulated test exposure.

The field-data analysis provides a quantitative characterization of the life distribution fitted to the recorded functional failures of the analyzed flowmeters, while the zero-failure test calculation provides a practical basis for demonstrating the predefined B10 life of development products. Because observation times for non-failed flowmeters were unavailable, the fitted life characteristics should not be interpreted as population-level reliability estimates for all flowmeters installed on LNG carriers. Together, these results can support condition assessment and maintenance planning for long-serving flowmeters, as well as reliability-demonstration planning for products intended for shipboard application. Further accumulation of observation-time data for non-failed units and detailed failure-cause information will enable the life estimates and test criteria to be refined according to flowmeter type and installation condition.

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Author Contributions

Conceptualization, Y.H. Cho; Methodology, Y.H. Cho; Software, Y. G. Kim; Formal Analysis, J.M. Lee; Investigation, Y. G. Kim; Resources, Y. G. Kim; Data Curation J.M. Lee; Writing-Original Draft Preparation, Y. G. Kim; Writing-Review & Editing, J.M. Lee; Visualization, Y.H. Cho; Supervision, Y. G. Kim; Project Administration, Y. G. Kim; Funding Acquisition, Y. G. Kim.

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