Commentary on “Bayesian Estimation of Ammonia Leak Frequency for Risk Assessment of Ammonia-Fueled Vessels”

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1. INTRODUCTION

This article presents a commentary on the paper by Kojima et al. (2025) [1] mentioned in the title. For details and attached materials, please refer to the References. In particular, due to the limitations of space, we have omitted the methods of measuring the prior distribution and likelihood setting method and sensitivity analysis for the first updating, which are discussed in the following, and presented the parameters used in the estimation and the estimation results only for flanges as an example.

Reducing greenhouse gases (GHG) is an urgent global challenge, and requires industrial activities in harmony with the environment. Maritime transportation is not an exception to this trend. Although the International Maritime Organization (IMO) initially aimed to achieve zero emissions in ocean-going vessels by 2100 [2], this target was moved up to 2050 in 2023 [3]. Historically, heavy oil was the main fuel used in ocean-going vessels, but in recent years, the use of alternative fuels such as liquefied natural gas (LNG), methanol, etc. has increased, as these fuels have low GHG emissions [4].

Ammonia is positioned as a decarbonization fuel for the transition period to a hydrogen society in the “Green Growth Strategy through Achieving Carbon Neutrality in 2050” [5] developed by Japan’s Ministry of Economy, Trade and Industry in cooperation with related ministries and agencies. Use of ammonia fuel in vessels is also continuing to attract increasing attention as one feasible option [6), 7), 8]. Compared with the above-mentioned LNG, methanol and other alternative fuels, ammonia has the advantage of a high gravimetric and volumetric energy density and is compatible with the existing storage and transport infrastructure [10], which supports annual global production of 150 million tons in 2019 [9]. Ammonia is also practical in terms of its physical properties, as it is easily liquefied at atmospheric pressure and has a narrow flammability range. By 2050, ammonia is projected to comprise approximately 44 % of total vessel fuel demand [3], accounting 30 % of total ammonia demand [8]. On the other hand, ammonia is a toxic substance and can irritate the eyes and damage the respiratory tract at a certain exposure level [11]. In addition, it may also cause stress corrosion cracking in materials such as high-strength steel, zinc, copper and brass [12].

The International Convention for the Safety of Life at Sea (SOLAS) [13] requires a risk assessment for vessel design of vessels using alternative fuels, regardless of the type of liquefied gas fuel to be used. An assessment of the risk during usage, storage and bunkering (fuel supply) in both ports and offshore environments is necessary.

Quantitative risk assessment (QRA) is a representative assessment methodin which the consequence of an event (damage an event might cause) and the probability (frequency or likelihood of that event) are estimated (referred to hereinafter as “consequence assessment” and “frequency assessment,” respectively), and the mathematical product of the two estimates is quantified as the risk [14]. Many examples of risk assessments for LNG-fueled vessels have been reported, including examples of assessment of the engine room [15] and LNG floating production, storage and offloading systems [16], various types of vessels, such as LNG-fueled tankers, including full-bore events [17] and LNG-fueled ore and bulk carriers [18]. The primary sources of information such as the leakage frequency and accident probability, occurrence rate, etc. used in these examples are the Health and Safety Executive (HSE) Hydrocarbon Releases System (HCR) in the UK [19), 20], the Guidelines for Quantitative Risk Assessment (so-called “Purple Book”) [21] of the Committee for the Prevention of Disasters (CPR) in the Netherlands and the database of the International Association of Oil and Gas Producers (IOGP) [22), 23]. However, it must be noted that these information sources are not specific to LNG or ammonia.

Although the number of risk assessments for ammonia is limited in comparison with LNG, QRAs for ammonia fuel have also been carried out in recent years. Since accidents and the spread of ammonia during bunkering of ammonia fuel are a particularly large concern, several risk assessments for port and harbor areas are available [24), 25]. However, as one issue in these assessments, the consequence assessment is carried out based on the characteristics of ammonia, but in the frequency assessment, the

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component-specific leak frequencies (LFs for each type of component equipment) are estimated based on data for LNG or hydrocarbon fuels. Thus, QRAs that adequately reflect the unique characteristics of incidents involving ammonia leaks are limited.

Moon et al. [26] estimated the potential leak frequency of the ammonia fuel supply system by analyzing the data on ammonia leak incidents in tankers transporting liquid ammonia. Based on a comparison of the estimated LFs for ammonia and the IOGP frequency data, they concluded that IOGP frequency data can be used in risk assessments of ammonia-fueled vessels. However, they also noted the limitations of their dataset due to the lack of leakage frequency data by leak size and component type. Since increased use of ammonia-fueled vessels is anticipated, accurate, reliable QRAs are expected to be required. Therefore, it was suggested that component-specific LFs that are applicable to QRAs for ammonia-fueled vessels will be indispensable.

Based on these issues, in our research, we estimated the leak size-specific and component-specific leak frequencies (hereinafter, LFs) of ammonia leaks considering the characteristics of ammonia and the characteristics of the component equipment used in ammonia-fueled vessels. Fig. 1 shows the framework for estimating the LFs of ammonia-fueled vessels. First, we developed a Bayesian model based on the methodologies of LaChance et al. [27], Groth et al. [28] and Kihara et al. [29]. For the first updating, we incorporated the leak frequency data for LNG-fueled vessels obtained from Davies and Fort [30]. However, for the second updating, we prepared component-specific LFs for ammonia-using facilities by analyzing 18 945 accident cases spanning a period of 57 years in the Japanese High Pressure Gas Accident Cases database (HPGAC) [31], and used these LFs as the likelihood of accidents. The component-specific leak frequency (LF) in ammonia-fueled vessels was estimated as the result of the second updating. A sensitivity analysis of the likelihood was also conducted to examine the indeterminacy of the results.

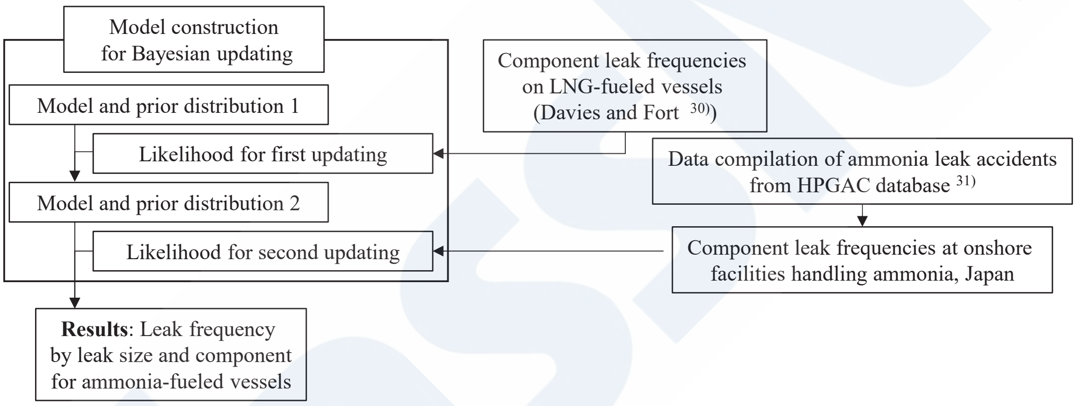

Fig. 1　Framework for estimating ammonia leak frequency from ammonia-fueled vessels

2. METHODOLOGY

2.1 Bayesian Theorem

The basic formula derived from the Bayesian theorem is expressed as shown in (1) [29].

$$\textit{Posterior distribution} \propto \textit{Likelihood x Prior distribution} \tag{1}$$

The posterior distribution is proportional to the product of the likelihood and the prior distribution. The prior distribution can be derived from objective information or assumed based on subjective information such as the experience or judgment of experts. It is sometimes uniformly distributed as a non-informative distribution. The posterior distribution can be estimated by incorporating new evidence or data as the likelihood. A new posterior distribution is then calculated by using this posterior distribution as the new prior distribution and incorporating supplementary accumulated data. This iterative process is known as Bayesian updating.

As strengths of Bayesian updating, it is possible to combine data from multiple information sources and reliability is enhanced by continuously incorporating new evidence and data. For these reasons, Bayesian updating is utilized to derive probability distributions with a certain level of objectivity and reproducibility, even in fields where prediction by empirical models is difficult and the data tends to be insufficient, as in the case of fuel ammonia.

2.2 Construction and Implementation of the Hierarchical Bayesian Model Using FLA

In this paper, we referred to the component-specific LF estimation model for leaks in hydrogen fueling facilities developed by the Sandia National Laboratory (SNL model) in the United States [27), 28)].

First, the concepts of this model will be organized. The SNL model begins from the assumption that a linear relationship exists between the leak frequency (LF; unit: /year) and the logarithm of the fractional leak area (FLA). The FLA represents the ratio of a leak area to the cross-sectional area of equipment such as piping, etc. This assumption is consistent with the intuitive feeling that the frequency of large-area leaks is low, and conversely, small leaks occur with a higher frequency. The concept of the FLA is derived based on the results of an analysis of accident data from the chemical processing, compressed gas, nuclear power plant and offshore petroleum industries, and a similar tendency has also been confirmed in other past research (e.g., Spouge [32)], IOGP [22)]).

The model equation can be simplified to (3) by taking the logarithms of both sides of (2), and further simplified to (4) by substituting a constant for the intercept of (3) and changing the logarithm base. The size of the FLAs shown in Table 1 can be understood intuitively because the FLA output is converted to negative integers (-4, -3, -2, -1, 0) by changing the base. Next, the SNL model assumed that the logarithm of $LF(I)$, where I represents the size of leaks divided into the five categories shown in Table 1, follows the normal distribution expressed by (5).

The leak size was categorized as described here because the leak sizes reported in the information sources of the data for incorporation in the model were not consistent. That is, when handling the leak size continuously, the database frequently contains only one accident of a certain leak size. As a result, the probability data used as the likelihood cannot be prepared and Bayesian estimation becomes impossible. To avoid this situation, we collected accident cases where it was possible to judge the size of a similar leak and created a procedure for calculating the LF for that size. Considering the diversity of the contents of accident reports, the authors strongly recognized the necessity of this categorization procedure, even in the leak size classification work carried out in 2.6.2.

Returning to the description of the model equation, when the logarithm of $LF(I)$ follows the normal distribution in (5), (2) can be written as the logarithmic linear model in (6) having an intercept α_1 and a slope α_2. At this time, a natural conjugate distribution (conjugate prior distribution) is set for α_1, α_2 and ${\sigma^2}_{LF(I)}$, which are the parameters used in the estimations in (5) and (6), and (7) and (8) are assumed to have a normal distribution, while an inverse gamma distribution is assumed for (9). That is, we assumed a hierarchical Bayesian model where $\mu_{LF(I)}$ has a distribution in which α_1 and α_2 are variables, and furthermore, α_1 and α_2 also have respective distributions.

The LFs of components can be estimated by using this procedure by converting various combinations of the component cross-sectional areas (pipe diameters) and leak sizes derived from accident data to FLA, and incorporating the FLA in a Bayesian model. Here, we constructed a model for estimating the leak frequency distribution in ammonia-fueled vessels by incorporating the LFs of components used in ammonia facilities. Although the SNL model used WinBUGS [33)] as the tool for Bayesian updating, we used the R package jagsUI [34)].

$$LF = A_1 \times FLA^{A_2} \tag{2}$$
$$\ln LF = \log A_1 + A_2 \cdot \ln FLA \tag{3}$$
$$\ln LF = \alpha_1 + \alpha_2 \cdot \log_{10} FLA \tag{4}$$
$$\ln\big(LF(I)\big) \sim Normal\big(\mu_{LF(I)}, {\sigma^2}_{LF(I)}\big) \tag{5}$$
$$\mu_{LF(I)} = \alpha_1 + \alpha_2 \cdot \log_{10} FLA_I \tag{6}$$
$$\alpha_1 \sim Normal\big(\mu_{\alpha_1}, {\sigma^2}_{\alpha_1}\big) \tag{7}$$
$$\alpha_2 \sim Normal\big(\mu_{\alpha_2}, {\sigma^2}_{\alpha_2}\big) \tag{8}$$
$${\sigma^2}_{LF(I)} \sim InvGamma(a_I, b_I) \tag{9}$$

I: leak size (Table 1);
$LF(I)$: component leak frequency at leak size I;
A_1, A_2: parameters for the FLA;
α_1, α_2: intercept and slope parameters for the exponential function $\log_{10} FLA$ and μ_{LF}, respectively;
$\mu_{\alpha_1}, {\sigma^2}_{\alpha_1}$: mean and variance of the normal distribution for α_1, respectively;

μ_{α_2}, ${\sigma^2}_{\alpha_2}$: mean and variance of normal distribution for α_2, respectively;
$\mu_{LF(I)}$: mean of the recorded leak frequency;
${\sigma^2}_{LF(I)}$: variance of the recorded leak frequency; and
a_I, b_I: shape and scale parameters of the inverse gamma distribution for ${\sigma^2}_{LF(I)}$, respectively.

Table 1 Coefficients corresponding to the categories of leak size and FLA

Leak size (I)		FLA[a]
1	Very small	0.0001
2	Minor	0.001
3	Medium	0.01
4	Major	0.1
5	Rupture	1

[a] FLA: Fractional Leak Area. The ratio of the leak area to the total cross-sectional flow area of the equipment (pipe). For example, the leak category "very small" refer to a leak area that is 0.0001 (= 0.01 %) of the total flow area.

2.3 Target Components of Leak Frequency Estimation

Table 2 shows the categories of the components for the prior distribution and the two likelihoods for the first and second updating required in the estimation reported in the respective sources referenced in this study. In this paper, the targets of the estimations of leak frequency were limited to components for which information was available in all three information sources, namely, Flanges, Joints, Pipes, Valves (actuated) and Valves (manual). For compressors, Davies and Fort [30] categorize the centrifugal type and reciprocating type separately, but LaChance et al. [27] and Japan's High Pressure Gas Accident Cases database (HPGAC database) [31] do not distinguish between the two types. Therefore, Compressors were excluded, considering the mechanical differences between the two types.

Table 2 Categories of components reported in each data source and their correspondence

Components in LaChance et al. [27] as prior distribution	Components in Davies and Fort [30] as likelihood for first updating	Component in HPGAC database [31] as likelihood for second updating
Flanges	**Flanges**	**Flanges**
Joints	**Instrument connections** [a]	**Joints**
Pipes	**Pipes**	**Pipes**
Valves	**Valves (actuated)**	**Valves**
	Valves (manual)	
Compressors	Compressors (centrifugal)	Compressors
	Compressors (reciprocating)	
Cylinders		
Filters		
Hoses		Hoses
	Pressure vessel	
	Refrigerated ambient pressure vessel	
Instruments	-	Others [b]

*Blank spaces indicate components that were not reported in the source.
[a] Davies and Fort [30] noted that "Instrument connections include flanges within the given release frequency." In the following, these are denoted as "Joints" unless specially noted otherwise.
[b] "Others" include Storage tanks, Heat exchangers, Pumps, Chillers, Measuring Instruments, etc.

2.4 Prior Distribution

The LFs used in the prior distribution of the first updating were the LFs of general components [27] estimated from accident data in various fields, including chemical processing, compressed gas, nuclear power plants, offshore petroleum, etc.

2.5 Likelihood for the First Updating: LFs from LNG Fueling Systems in Davies and Fort [30]

In the first updating, the LFs from LNG fueling systems estimated by Davies and Fort [30] were converted to correspond to the FLAs in Table 1, and the results were incorporated in the likelihood. These LFs are referenced in the risk assessment guidelines for LNG-fueled vessels (IGF Code) [35] and are considered to have a certain degree of reliability.

2.6 Likelihood for the Second Updating: Likelihood Estimated from the HPGAC Database [31]

2.6.1 Extraction of Ammonia Leak Accident Cases at Facilities Using Ammonia by Leak Size

Since ammonia-fueled vessels are currently in the research and design stage, accident cases and an accident database are still lacking. In this situation, use of data from onshore ammonia production and consumption facilities as alternative data has been suggested [12]. In this paper, the leak frequency for the likelihood in the second updating was estimated from leak accident cases involving ammonia at onshore facilities in Japan, referring to the above-mentioned HPGAC database [31], which is managed by the High Pressure Gas Safety Institute of Japan.

The HPGAC database contains 18 945 accident records spanning the period from 1965 to 2022. Businesses that handle high pressure gases, including ammonia, are required to report accidents under Japan's High Pressure Gas Safety Act. These reports contain a total of 28 fields for each accident, including identifying information, the time and location of the accident, the number of injuries and fatalities, the substance involved, the characteristics of the leak or blowout (degree, component involved, etc.), the cause and an overview of the accident[*1].

From these 18 945 accident cases, 927 cases containing the word "ammonia" in the "Substance" field or "Accident overview" field were extracted. Next, 610 records[*2] related to ammonia refrigeration were excluded from the 927 cases. Those cases were excluded because refrigeration systems circulate ammonia in a closed loop, and do not produce or consume ammonia [36], and their characteristics are considered to be different from those of combustion systems which continuously supply and consume ammonia. The remaining 317 cases were limited to the components selected as the evaluation targets in Table 2, i.e., Flanges, Joints, Pipes and Valves. As a result, the dataset was narrowed to 215 cases.

2.6.2 Categorization of the Leak Size of Ammonia Leak Accidents

The sizes of the leaks in the 215 cases obtained were determined following the flowchart in Fig. 2. First, in cases where it was possible to calculate the FLA directly from the degree or place of the leak, the leak size was set corresponding to that FLA. Next, accidents that could be judged easily from descriptors in the accident overview were classified as "Rupture" or "Very small." For example, accidents with descriptors such as "fracture," "disconnection" or "rupture" were classified as "Rupture," while those described by terms such as "negligible," "keep normal operation" or "steady operation" were classified as "Very small." In accidents where the leak rate could be estimated from the description in the overview or information concerning the leak, the leak size was classified according to that flow rate. For other cases, two researchers estimated the leak size separately. When the two estimates agreed, that leak size was used, and when the estimates did not coincide, the leak size was determined through consultation. It was possible to categorize the leak size for 109 cases by the procedure up to this point.

Since the remaining 106 cases contained little or none of the information necessary for classifying the leak size, those cases were distributed proportionally based on the number of accident cases classified as Very small, Minor, Medium and Major up to this point. Rupture was not included in this proportional distribution because detailed information is generally available for large accidents classified as Rupture, while other accidents are described briefly. Very small was included in the distribution considering the possibility that some very small leaks might have been undetected or unreported. The results obtained are shown in Table 3, which provides a breakdown of the number of ammonia leak accidents before and after the proportional distribution.

[*1] However, complete reports including all fields were only available for 28 cases (0.1 %) of the 18 945 cases.

[*2] Cases in which the "type of industry," "facility category" or "accident overview" field in the accident report contained the terms "refrigeration," "freezing," "ice making," "food," "fishing" or "fisheries" were excluded.

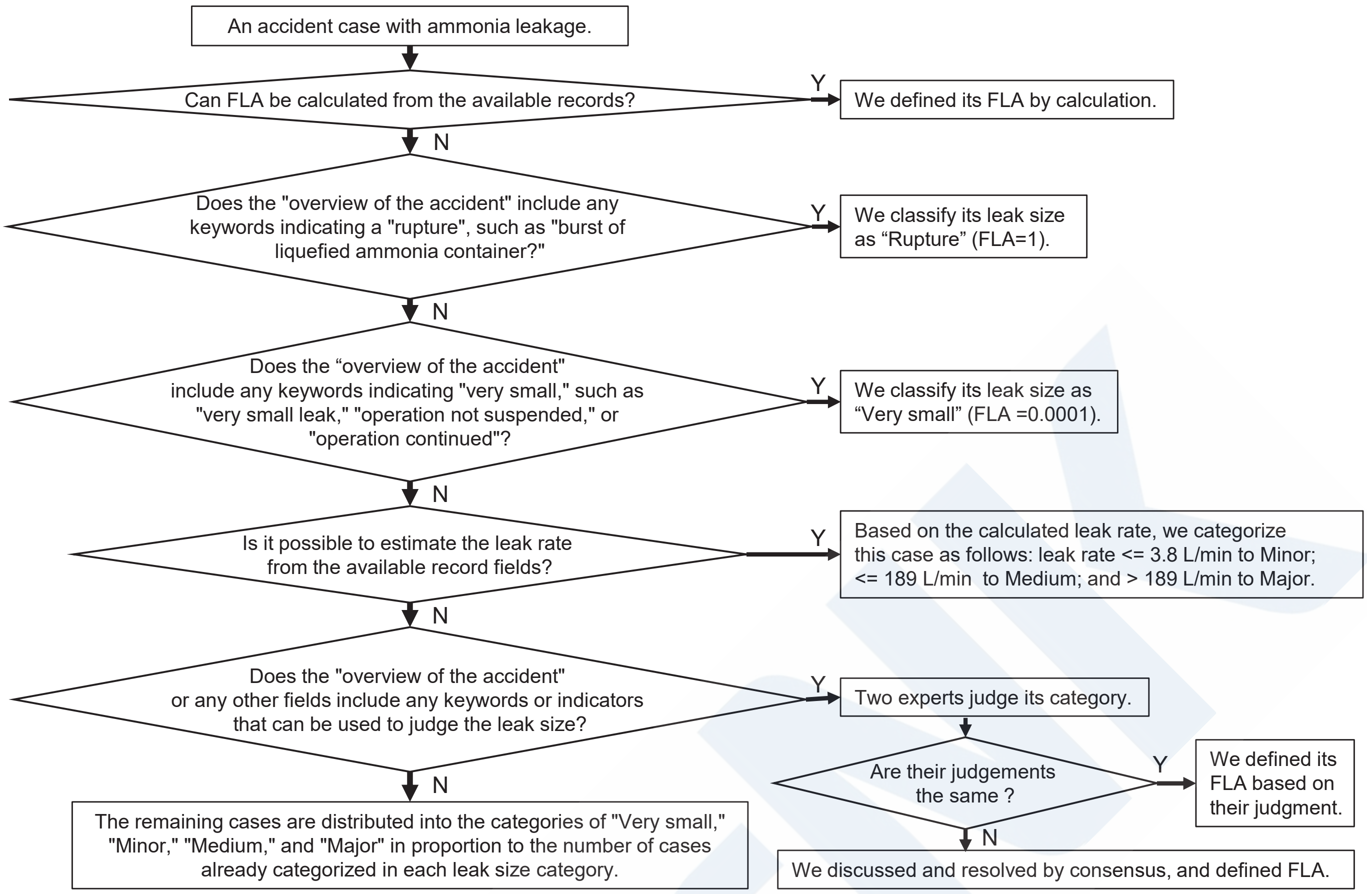

Fig. 2　Flowchart for determining leak size of ammonia leak accidents obtained from HPGAC database

Table 3　Component-specific number of ammonia leak accident cases by leak size

Component	Number of accidents by leak size						
		Very small	Minor	Medium	Major	Rupture	Unknown
Flanges	Before proportional distribution	14	1	1	0	1	18
	After proportional distribution	30	2	2	0	1	

2.6.3　Conversion from Number of Accident Cases to Accident Frequency (Likelihood)

In order to estimate the annual leak frequency (annual LF) per unit length (per meter for pipes) from the number of accidents by leak size estimated in 2.6.2, the number of leak cases after proportional distribution in Table 3 was divided by the total number of components (component count) and the total operational time of the component concerned. The total component count is estimated by multiplying the number of facilities by the average number of components in a facility.

$$LF(I)_j = \frac{LC(I)_j}{Period \times N_F \times N_{C,j}} \tag{10}$$

$LF(I)_j$ (cases/year/number): annual LF per unit (per meter in pipes) for component j in leak size category I

$LC(I)_j$ (cases): number of ammonia leak accidents for component j in leak size category I

$Period$ (years): total operational time, assumed to be 57 years from the period of the HPGAC database (1965 to 2022)

N_F (facilities): total number of ammonia-related facilities in Japan

$N_{C,j}$ (number/facilities): number of components per ammonia-related facility for component j in Japan

The total number of ammonia-related facilities (N_F) and the number of component j per ammonia-related facility ($N_{C,j}$) were estimated based on the information in the respective references, as these numbers were not available from the HPGAC database or the statistics tabulated by trade associations or the government.

For N_F, Suzuki [37] reported that the number of general facilities handling Class I gases (which include ammonia) under Japan's High Pressure Gas Safety Act was 12 428 as of March 1996 and 21 438 as of March 2015. Based on the discussion in 2.6.1, the ratio of ammonia-related accidents (927) to all accidents (18 945) is 4.9 % (= 927/18 945), and when limited to non-refrigeration ammonia accidents (317), the ratio is 1.7 % (317/18 945). Based on these calculations, the number of ammonia-related facilities is considered to be in the range from 211 (≒12 428 x 1.7 %) to 1 050 (≒21 438 x 4.9 %). Therefore, the "most likely" number of ammonia-related facilities N_F from 1965 to 2022 was estimated to be 500.

The number of components per facility $N_{C,j}$ for component j was estimated referring to the number of components per facility for estimation of the leak frequency of hydrogen gas set by Japan's National Institute of Advanced Industrial Science and Technology (AIST) [38]. That reference assumed that compressed natural gas (CNG) facilities are representative of high pressure gas facilities and gasoline fueling stations are representative of facilities handling hazardous substances, and used the typical component counts of the respective facilities in estimation of the leak frequency of hydrogen gas. Based on the same thinking, in this paper, the component count was estimated on the assumption that ammonia facilities are similar to CNG stations. As a result, the numbers of component j per facility ($N_{C,j}$) were Flanges = 10, Pipes = 48, Joints = 40 and Valves = 8.

The LFs estimated from these results are shown in Table 4. The range of the LFs was from 10^{-5} to 10^{-4}, and showed a lower tendency that of the LFs of LNG-fueled vessels.

Table 4　Leak frequency (likelihood) of flanges in ammonia facilities estimated from HPGAC database

FLA	Leak frequency, LF (/year)
0.0001	1.05E-04
0.001	7.02E-06
0.01	7.02E-06
0.1	Not available
1	3.51E-06

2.6.4　Sensitivity Analysis: Study of the Effect of Assumptions for LFs Based on the HPGAC Database on Estimation Results

The proportional distribution method, which was applied to accidents when the leak size was "Unknown," and the estimation methods for N_F and $N_{C,j}$ discussed in sections 2.6.1 to 2.6.3 include subjective judgments and assumptions. Therefore, a sensitivity analysis was conducted as an effective technique [39] for understanding how the judgments and assumptions applied to the data affect the estimation results. In this paper, the values adopted up to now were assumed to represent the case with the highest validity ("most likely" case). The results obtained under different assumptions were compared with those values, and the difference was considered. We also conducted a sensitivity analysis of the effect on the analysis results when the LFs reported by Davies and Fort [30] were converted to FLAs, but the effect was slight. For details, please refer to the reference.

In the sensitivity analysis for the proportional distribution of accidents with an "Unknown" leak size in section 2.6.2, accidents with "Unknown" leak sizes were distributed proportionally to Very small to Rupture, Minor to Major, and Minor to Rupture, and the LFs were estimated based on those distributions and compared with the results for the proportional distribution to Very small to Major ("most likely" case).

Regarding the number of ammonia-related facilities N_F in Japan, in section 2.6.3, N_F = 500 was adopted based on the estimated range of approximately 211 to 1 050. Referring to this estimated range, in the sensitivity analysis, 100 was adopted as the N_F for the Lower bound case, and 1 000 was adopted for the Upper bound case (Table 5). In the sensitivity analysis for the number of components per facility $N_{C,j}$, the $N_{C,j}$ adopted as alternative cases were set referring to the values for CNG fueling stations and gasoline fuelling stations (Table 6).

Combining the three cases in Table 5 and the three case in Table 6, the five cases in Table 7 were set for the sensitivity analysis.

Table 5 Total number of facilities (N_F) in Japan in each case

Parameter	Lower bound	Most likely	Upper bound
N_F (facility): total number of ammonia-handling facilities.	100	500	1,000

Table 6 Number of components per facility ($N_{C,j}$) in each case

Parameter	Component (j)	Lower bound	Most likely	Upper bound
$N_{C,j}$ (number/facility): number of components per facility for component j.	Flanges	5	10	48

Table 7 Five cases used in sensitivity analysis for estimation of LFs of flanges in ammonia-handling facilities

Case No.	1	2	3	4	5
Cases of N_F	Most likely	Lower bound	Upper bound	Most likely	Most likely
Cases of $N_{C,j}$	Most likely	Most likely	Most likely	Lower bound	Upper bound
FLA					
0.0001	1.1E-04	5.3E-03	5.3E-05	2.1E-04	2.1E-05
0.001	7.0E-06	3.5E-04	3.5E-06	1.4E-05	1.4E-06
0.01	7.0E-06	3.5E-04	3.5E-06	1.4E-05	1.4E-06
0.1	NA	NA	NA	NA	NA
1	3.5E-06	1.8E-04	1.8E-06	7.0E-06	7.0E-07

3. RESULTS

3.1 Estimation Results of LF by Leak Size in Ammonia-Fueled Ships

Rhat, which is an indicator for diagnosis of convergence in Bayesian updating, was less than 1.1 for all parameters in all cases. Convergence and its plot were also confirmed, indicating that valid solutions were obtained in all cases, including the sensitivity analysis.

The results of the leak frequency estimation for ammonia-fueled vessels are shown in Fig. 3. The values of the plots and the confidence intervals are given in the Supplementary material of this paper. Compared with the LFs of LNG-fueled vessel, at the first updating (shown by the black dots/black lines in Fig. 3), the LFs of the ammonia-fueled vessels at the second updating (shown by the red dots/red lines) were relatively lower. This means that, when the LFs for LNG-fueled vessels are used in a QRA for ammonia-fueled vessels, the quantitative risk of the latter is overestimated by a factor of 1 to 10 times. In this case, it was suggested that a safer (more conservative) assessment result is obtained, but on the other hand, stricter risk management and more expensive measures may be required. The reason for this difference in the LFs will be considered in Chapter 4.

Regarding the confidence interval of the LFs, the 90 % uncertainty interval (spanning the 5th to 95th percentiles of the mean) was within a range of about 1/10 to 10 times the mean. This confidence interval represents the uncertainty that invariably accompanies estimation results, and must be considered when making risk assessments.

Comparing the LF estimation results for actuated (automatic) valves and manual valves, in the first updating, the LFs of manual valves were approximately 10 times higher than those of actuated valves, reflecting the fact that the LF (likelihood) of leaks in manual valves was roughly 10 times higher than that of actuated values in the report by Davies and Fort [30]. However, at the second updating, the same likelihood obtained from the HPGAC database was used for both types of vessels, and substantially the same LF estimation results were obtained, in spite of the difference in the prior distributions. These results were obtained because the LF estimation results (LF distribution) are determined by a limited number of data points and the inflexible linear model defined by (3). Although an immediate response to these issues will be difficult, it may be possible to obtain results that more accurately reflect the characteristics of accidents in each component by enhancing the accident database or applying more flexible modelling approach (e.g., Kaneko and Yuzui [40]).

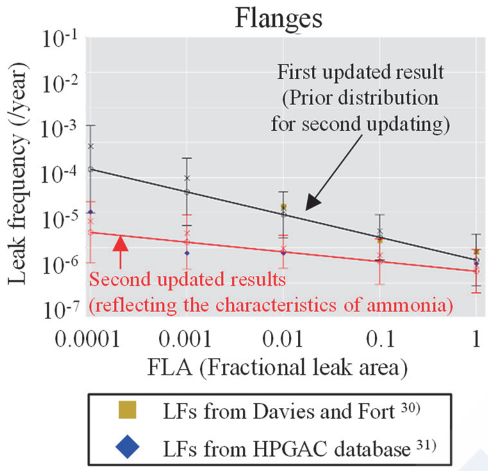

Fig. 3 Results of LF estimation for ammonia-fueled vessels

3.2 Results of Sensitivity Analysis

This section discusses the results of the sensitivity analysis for the likelihood in the second update, using Flanges as an example, as in the discussion until now (Fig. 4, Fig. 5). The results for other components can be found in the Supplemental material.

First, we will discuss the sensitivity analysis results of the proportional distribution method for accidents for which the leak size is “Unknown.” In the Very small to Major case adopted as the “most likely” approach, the LF estimation results for ammonia-fueled vessels showed that LF decreased as the leak size increased. Although this tendency was also the same for Minor to Major and Very small to Rupture, the slopes of the LFs were more moderate. However, Minor to Rupture showed a positive slope, which was a counterintuitive result, as the leak frequency became larger as the leak size increased. In addition, while there were differences in the 90 % confidence interval depending on the leak size and the component, the difference in the estimated mean was within the range of 1/10 to 10 times the mean. As a result, it can be concluded that Very small to Major gave a distribution which is suitable for the most conservative assessment.

Next, we will discuss the sensitivity analysis results for the number of ammonia facilities N_F and the number of components per facility $N_{C,j}$, as shown in Fig. 5. Since the only difference in the five graphs in Fig. 5 is these two parameters, which are both in the denominator in (10), and the likelihood (LF) increases or decreases in (10) independent of the leak size category, the five estimation results (straight red lines) in Fig. 5 have substantially identical slopes, and only the intercept (LF on the y-axis) is different. Regarding the mean of the estimated LF distribution, when compared against the “Most likely and Most likely” case (upper left), the values for the other cases are within a range of roughly 1/10 to 10 times of that case. The difference in the means is particularly wide depending on the assumption N_F, indicating that the influence of N_F was larger than that of the proportional distribution method for Unknown cases described above. With the exception of the Lower bound case of N_F, the results of the mean LF estimations of the Lower bound and the Upper bound for almost all components and leak sizes were generally within the confidence interval of the Most likely case. As a reason for the deviation of the Lower bound case of N_F, it is suggested that the setting of N_F = 100 was excessively small. The value of 100 was set because the lower end of the range of ammonia-related accidents was 211 (12 428 facilities x 1.7 %), and experts judged this good number as a boundary line.

Although assumptions always contain a certain bias, the distribution of the leak frequency estimated as the most likely case is considered to be within an acceptable range, even with limited information.

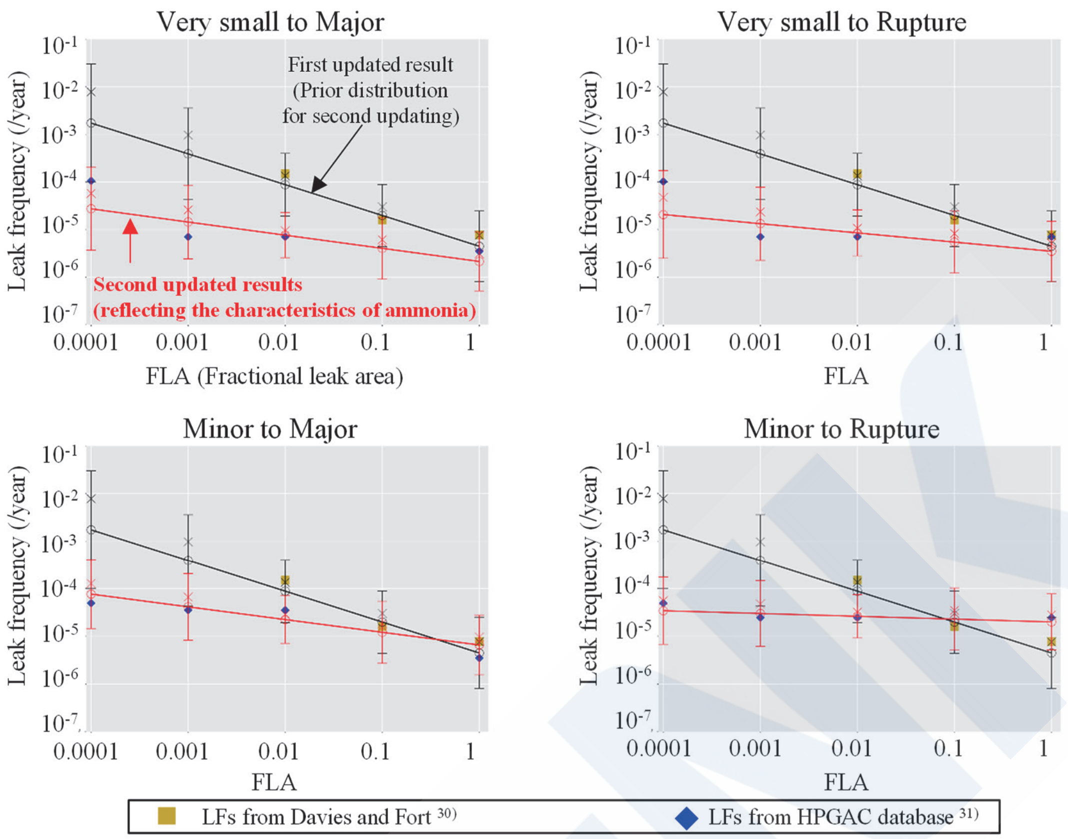

Fig. 4 Results of sensitivity analysis for proportional distribution of cases with “Unknown” leak size

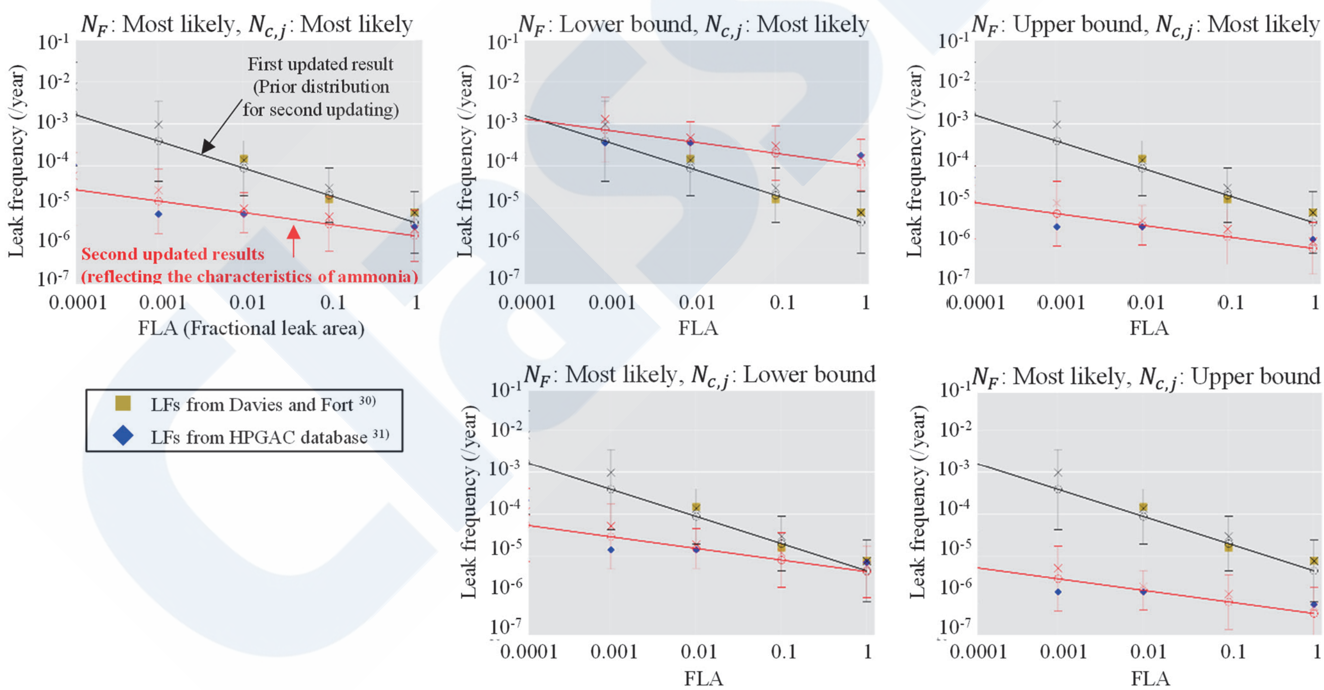

Fig. 5 Result of sensitivity analysis for number of facilities handling ammonia and number of components per facility

4. DISCUSSION

4.1 Comparison of Leak Frequencies of Ammonia-Fueled Ships and Other-Fueled Ships

In this research, the component-level leak frequency LF of ammonia-fueled vessels was estimated, and the results were compared with the estimation results reported by Moon et al. [26]. It should be noted that a direct comparison was difficult due to the limited amount of research reflecting the unique characteristics of accidents involving ammonia in the leak frequency, other than the above-mentioned study. Moon et al. [26] estimated that the system-level leak frequency of an ammonia-fueled vessel as a whole is 2.40 x 10^{-2}, which is equivalent to 77 % of LF of a conventional LPG tanker (3.10 x 10^{-2}). Because the system-level LF of the total vessel is not estimated in the present research, a direct comparison is not possible, but comparing the LF of ammonia-fueled vessels and the component-level LF of LNG-fueled vessels used as the likelihood, the tendency was similar. It is thought that the LF of ammonia-fueled vessel is lower than that of LNG-fueled vessel because comparatively strict controls are applied to ammonia, since ammonia, unlike hydrocarbon fuels, is both flammable and toxic. On the other hand, the difference in the LFs of LNG-fueled vessels and the ammonia-fueled vessels estimated by the authors was larger than the 77 % reported by Moon et al. [26]. In explaining this difference, it may be noted that Moon et al. [26] derived their results for both fuels from data sources for maritime accidents, while our results were larger because we compared the likelihoods derived from onshore systems and LFs derived from offshore systems.

4.2 Qualitative Discussion of Elements Influencing the Uncertainty of Leak Frequency Estimation

As noted in section 4.1, the previous research is inadequate for a full discussion of whether the leak frequency estimated in this paper is overestimated or underestimated. Here, however, we will arrange the elements that influence the uncertainty of LF estimations within the range possible.

First, as already discussed, the likelihood incorporated in the second Bayesian updating reflects the condition of operation and control of onshore ammonia facilities in Japan extracted from the HPGAC database. Because this database includes accidents dating from 1965, the use of the LFs estimated in this paper may result in a QRAs on the safe side, considering the progress of materials science, construction technology, and operation and management up to the present in 2025. On the other hand, in comparison with onshore systems, the external loads acting on offshore systems are generally larger, and since this element is not considered in the LF, the QRA may be on the dangerous side.

Thus, because only the likelihoods from the HPGAC database were used in this study, there are several elements that could not be considered, and this is a problem. As described in Chapter 1, since accidents involving ammonia have not been arranged systematically in existing databases, some type of ingenuity is required when incorporating the data in a Bayesian estimation. In this connection, although LaChance et al. [27] incorporated the likelihoods obtained from multiple databases as the data point cloud, some cases showed expanded 90 % confidence interval when the data point cloud were widely dispersed. This point must also be noted.

Reporting bias should also be considered. Mulcahy et al. [39] pointed out that the estimated results may diverge from the actual condition because the leak frequency of very small leak sizes is difficult to detect and report. They also noted that the results of predictions of the leak frequency should be interpreted cautiously, as extrapolations to small leaks may contain bias, and the direction of that bias is not clear; this suggests that simply adding additional data may not reduce uncertainty.

4.3 Correspondence of Definitions of Components

When referring to the leak frequencies estimated in this paper, it is important to consider the nominal meaning and the actual situation of the component parts. As mentioned in connection with Table 2, the indicated range of components may differ depending on the source.

Although Joint, Flange and Instrumental connection are similar terms, there are presumably cases where these terms indicate different components. In fact, when we referred to the Japanese HPGAC database, we were unable to differentiate these terms based solely on the information provided in the database. Likewise, Davies and Fort [30] noted that "Instrument connections include flanges within the given release frequency," suggesting a similar difficulty exists in this case.

Judgments in safety assessments of pipes also differ depending on whether the pipe is single-walled or double-walled. In Japan, the High Pressure Gas Safety Act requires that double-walled pipes be used for pipes handling toxic substances, including ammonia, but permits single-walled pipes if measures have been taken to prevent the diffusion of leaked gas. Since most facilities have taken preventive measures, single-walled piping is generally used. Based on this background, we assumed that all pipes in the HPGAC database are single-walled. Similarly, in Davies and Fort [30], after mentioning the number of walls of pipes, they also suggested that single-walled pipes are generally used. Therefore, we adopted assumptions consistent with that observation as a methodology.

4.4 Applicability of Estimated Leak Frequency

It is possible to update QRAs [24), 25] by using the leak frequences derived to date from hydrocarbon fuels [20), 22] by LFs that reflect the unique characteristics of accidents involving ammonia estimated in this paper. This makes it possible to support QRAs for ammonia-fueled vessels that better reflect the characteristics of ammonia. Since the leak frequencies for ammonia-fueled vessels estimated in this research represent an initial study with the aim of reflecting the distinctive characteristics of ammonia leak accidents, significant improvement of the accuracy and reliability in the coming decades is a realistic possibility.

5. CONCLUSION

In this research, we constructed a Bayesian updating model and proposed a component-specific estimation method of leak frequencies for various types of components (Flanges, Joints, Pipes, Valves) in ammonia-fueled vessels, even though only limited data is currently available. In particular, the likelihoods used in the second Bayesian updating phase was estimated based on accident cases in onshore ammonia facilities in Japan, and the unique characteristics of ammonia were reflected by incorporating the results in the Bayesian updating model. Uncertainties regarding the estimated leak frequencies were considered through a process of comparing the LFs of ammonia-fueled vessels and LNG-fueled vessels in a sensitivity analysis and the previous research, and arranging the characteristics of ammonia-related accidents in a database of accident cases as the likelihood for the second updating phase. The estimation results obtained in this process indicated that the leak frequency of ammonia-fueled vessels is lower than that of existing LNG-fueled vessels, reflecting the stricter control of ammonia. Since the proposed approach utilizes estimated leak size-specific and component-specific leak frequencies, this approach is considered suitable for integration into quantitative risk management frameworks, supporting regulatory compliance, and enhancing operational safety standards for ammonia-fueled vessels.

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