International Gas Union Research Conference 2011

PREDICTING HUMAN ERROR PROBABILITIES FOR MUSTER ACTIONS DURING LNG TANKER EMERGENCIES

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ABSTRACT

A key component of the liquefied natural gas (LNG) value chain is LNG shipping. The safe design for the storing and transport of LNG is of utmost importance, in particular to coastal areas. The LNG industry has an excellent safety record over the last 40 years but due to ever increasing demands and expansion the risks associated with transport activities may be increasing. Innovations to improve safety and the economics of LNG transport are continuous and include progress in the areas of shipping capacity, cargo designs, cargo handling systems and propulsion systems.

The prediction of human error probabilities and their consequences for LNG tanker musters, in emergency situations, through an expert judgment technique, provides a proactive approach for the inclusion of human factors in risk assessments. Due to the lack of human error databases the Success Likelihood Index Methodology (SLIM) was adopted as a vehicle to predict human error probabilities for credible LNG tanker muster scenarios of varying severity. SLIM is a rating orientated model originally developed with the support of the U.S. Nuclear Regulatory Commission and has been applied to other industries including chemical and transport. The SLIM technique is intended to be applied to tasks at any level of detail, making it adaptable to range of muster scenarios such as man overboard, gas release and fires.

A description of how human error probability (HEP) data from an expert judgment technique may be utilized in developing a Human Error Probability Index (HEPI) specifically for the emergency scenarios considered, is provided. Such an index can be a useful tool to bring human error assessment into the general vernacular of risk determination. The framework of SLIM has universal application throughout the LNG value chain providing a human factors tool to engineers, operators and health and safety personnel.

1. INTRODUCTION

The study of human factors is a scientific discipline that involves the systematic approach of information regarding human characteristics and behaviour to improve the performance of man-machine systems. Much of the past work in human error prediction has emanated from the nuclear industry through the development of expert judgment techniques such as THERP (Technique for Human Error Prediction) (1) and SLIM (Success Likelihood Index Methodology) (2). The need for expert judgment techniques arose from the lack of human error data and the severe consequences that may occur from nuclear accidents. Analogously, the Piper Alpha, Ocean Ranger and most recently the Deepwater Horizon, have generated a greater awareness of the impact from human error in an offshore environment. The Ocean Odyssey disaster is an example how a breakdown in the muster sequence can lead directly to fatalities (3).

Liquefied Natural Gas (LNG) shipping emergencies have significant potential for severe ramifications and present a challenging scenario for human error prediction and reduction. Operational safety has improved in the areas of training, procedures, regulations and operating experience, but there still exists credible scenarios in the offshore industry that could result in a loss of containment and serious consequences such as gas release and fire and explosion. While there has been an extensive amount of work on the consequences for such events (4) (5) (6) and (7), there is a general lack of research in human factors as related to risks associated with human error during the muster sequence for these events. The LNG shipping industry has an exceptional safety record with no incidents resulting in loss of containment. Though expectations for musters are clearly defined for the shipping industry by the International Convention for Safety of Life at Sea (8) there is still opportunity to reduce risk from human error during this phase of these events.

2. HUMAN ERROR

Due to the relatively slow progress in the field of human reliability quantification, there is a need to advance this area of research and provide a technique that employs human factors in a risk assessment environment. A central issue is the concept of human error and the lack of consistency with regards to definition and application. An improvement in the understanding of human error and its consequences can be realized through the application of human error identification models. In order to achieve this, human error can be placed within a systems perspective. The factors that can influence human error, through a systems perspective, can be identified and managed, in a tangible manner, to reduce the overall risk associated within that system.

Human error often can play a significant role in accident causation. Human error from a systems perspective can be treated as a natural consequence arising from a discontinuity between human capabilities and the demands of processes and procedures. The human error potential of a system is a function of the properties of the system which includes human and machine components.

Changes that increase the disorder in that system can increase the probability of human error and the severity of its consequences. Systems must strive to be error tolerant and provide predictive and reactive measures to mitigate the risk from human error. Though there is a wide variation in data associated with losses resulting from human error as a causal factor, it has been reported to be significant (9). Despite this, it is not unreasonable to state that human error plays a significant role in accidents through either inadequate design or direct human action.

Applying a consistent definition for human factors and human error may help reduce confusion when assessing human error potential and generate more consistent human reliability assessments. Human error in this study is defined as follows:

Environmental and organizational and job factors, system design, task attributes and human characteristics that influence behaviour and affect health and safety (10).

A definition for human error whether it is unintentional or intentional is as follows:

Any human action or lack thereof, that exceeds or fails to achieve some limit of acceptability, where limits of human performance are defined by the system (11).

Human factors play a major role in offshore platform musters and their successful outcomes (12). Analogously, human factors are equally important in LNG tanker operations. The importance of human factors in the offshore has been recognized through previous works that range from human error probability prediction to the assessment of human factors in safety critical tasks (13), (14). On a regulatory basis there remains a lack of clear definition or specific requirement for the inclusion of human error considerations in management systems or risk assessments. A method that incorporates the identification and assessment of human error, within a system, can be a used as means of applying human factors to risk assessments. The SLIM technique applied within the framework of a human error probability index (HEPI) provides a methodology to assess the risk from human error under a variety of muster scenarios.

Human error probabilities are based on features that affect human performance also known as performance shaping factors (PSFs). These PSFs are weighted and rated utilizing the SLIM technique to develop a success likelihood index (SLI) for each human action in a muster sequence from which the probability of success (POS) and the human error probability (HEP) are estimated.

3. DEVELOPMENT OF HUMAN ERROR PROBABILITY DATA AND ANALYSIS

This work concerns itself with the actions at the start of the muster and ends with the tasks performed at the life boat station (safe muster location) (Figure 1) and precedes the actions associated with possible evacuation of the facility. The first three phases of a muster entail awareness, evaluation and egress. These phases are brief in relation to the total time of muster (approximately 10 to 30%), but it is during these phases that individuals may have their greatest exposure to the effects of the muster initiator (e.g. blast wave, heat, toxic gases). It is also during these phases that psychological stress will also be at peak levels effecting judgment and decision making while the tenability of an individual's surrounding may be degrading rapidly.

The tenability of one surroundings is a measure of the quality of one's egress path and the surrounding environment and has been used in the modeling of human behavior during building fires (15). This concept of tenability applies well to LNG tanker muster scenarios as a factor influencing the POS for each task in the muster sequence.

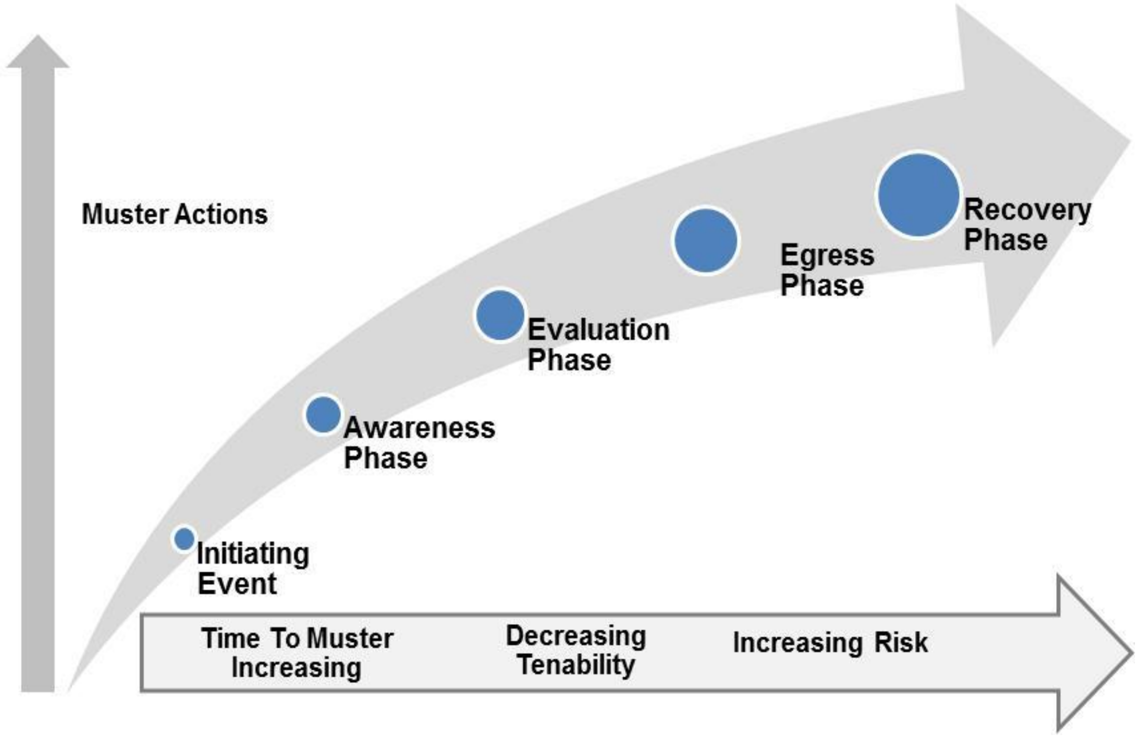

Figure 1: Graphical representation of a muster sequence

The general lack of HEP data, in the offshore industry and in particular for LNG tanker musters, is a driver for employing an expert judgment technique to estimate the probability of success associated with the muster steps. The tasks that make up a muster sequence for an LNG tanker involve essentially the same steps as those employed for fixed platforms (16). The probabilities previously estimated, through SLIM, for fixed platforms is applied for the same muster scenario on an LNG tanker.

The SLIM technique, as applied by DiMattia (17), involves a core review team (CRT) of experienced personnel who work in the offshore oil and gas industry. The CRT chose a set of muster scenarios that represent a range of severity to the personnel on board (POB). The scenarios selected are man overboard (MO), gas release (GR), and fire and explosion (FE) and are detailed in DiMattia (17). In addition the CRT performed a hierarchical task analysis (HTA) to generate a generic muster sequence (Table 1) that is adapted to LNG carriers, and developed a set of performance shaping factors that influence the probability of completing a muster action successfully. The muster tasks are common to each muster scenario.

3.1 Behavior Modes

Each action within the muster sequence is classified by the type of behavior which governs its action. These modes of behavior are known as skill (S), rule (R) and knowledge (K) based and form what is referred to as the SRK model (18). This model describes the error mechanisms based on level of conscious effort required to complete a task successfully. For example, with skill based actions an individual operates in what is referred to as an unconscious mode where the likely error mechanism is a slip due to inattention. In this behaviour mode individuals are typically highly skilled in relation to the task requirements and do not expend any significant amount of mental energy to successfully complete the task. In rule based mode individuals need to apply a known rule to complete the action and requires a greater level of consciousness. Finally, in knowledge based mode individuals are faced with a task for which they may be unfamiliar with and lack adequate knowledge or training. In this behavior mode individuals may gather data, formulate new rules and apply them in attempt to complete the task successfully. In this mode individuals are considered to be fully conscious. It is difficult for individuals to operate for extended periods in this behavioural mode as mental fatigue may set-in relatively quickly generating more errors.

Understanding the different modes of behavior associated with each action can aid in the development of more meaningful measures to help increase the probability of success of completing a task. Table 1 lists the behavior mode for each muster task within the three muster scenarios. As muster severity increases certain actions (e.g. move along egress route) require a higher degree of

No.	Muster Action	MO	GR	FE
Awareness Phase				
1	Detect Alarm	S	S	S
2	Identify Alarm	R	R	R
3	Act Accordingly	S	S	S
Evaluation Phase				
4	Ascertain if danger is imminent	K	K	K
5	Muster if in imminent danger	R	R	R
6	Return process equipment to safe state, if conditions allow	R	K	K
7	Make workplace as safe as possible in limited time	R	K	K
Egress Phase				
8	Listen and follow PA announcements	R	K	K
9	Evaluate potential egress paths and choose route	K	K	K
10	Move along egress route	R	K	K
11	Assess quality of egress route while moving to muster station	K	K	K
12	Choose alternate route if egress path is not tenable	K	K	K
13	Collect personal survival suit if in accommodations at time of muster	R	R	R
14	Assist others, if needed or as directed	K	K	K
Recovery Phase				
15	Register at muster location	R	R	R
16	Provide pertinent feedback attained while enroute to muster station	K	K	K
17	Don personal or muster station survival suit if instructed to do so	R	R	R
18	Follow instructions	R	R	R

Table 1: Muster actions broken down by muster phase (17)

consciousness due to the unfamiliar circumstances, moving behaviors into the knowledge based zone.

3.2 Performance Shaping Factors

Performance shaping factors are parameters that influence the ability of an individual to successfully complete a given task. The number of PSFs that may influence an individual for any given task is numerous. The degree for which any PSF influences each individual also varies. A list of key PSFs for each muster task is provided in Table 2. These PSFs are common to all individuals involved in the muster and are deemed to have the greatest influence on the POS for each task.

PSF	Description
Stress	PSF affecting the completion of actions as quickly as possible to effectively muster in a safe manner. This is essentially the effect of the muster initiator on the consequences of not completing a task successfully.
Complexity	PSF that affects the likelihood of a task being completed successfully because of the intricacy of the action and any sub-actions. Combined with a high level of stress, actions that are typically simplistic in nature become complicated. This PSF may cause individuals to take shortcuts to perform tasks quickly or to skip a task.
Training	PSF that directly relates to an individual's familiarity of performing musters under various scenarios. Training quality may provide a complacency factor as individuals may lack a sense of urgency because of the repetitiveness of the training.
Experience	PSF related to real musters. Experience in real musters and the stress that it generates may generate strong biases and influence decision making when working through the muster sequence.
Event Factors	PSF that is directly related to the muster initiator and the location of the individual relative to the initiator. Event factors that may affect the POS of completing a muster task include smoke, heat, fire, pressure wave and noise.
Weather	PSF that includes environmental factors such as wind, rain, snow or sleet that may affect manual dexterity, hearing, eyesight and make egress paths hazardous when moving quickly.

Table 2: Performance shaping factor descriptions (17)

3.2.1 Weighting of Performance Shaping Factors

For each action a PSF weight is determined ranging from 0 to 100, with a value of 100 representing a maximum PSF weight. A complete list of weights, for each muster task's PSF can be found in DiMattia (17). The mean PSF weights for each muster scenario are provided in Figure 2. Training and experience have consistently the greatest weights of all the PSFs for all three musters. Stress, complexity and event factor PSF weights increase with muster severity while the weather PSF weight does not vary appreciably with muster scenario and drops off with increasing severity.

3.2.2 Rating of Performance Shaping Factors

The rating of the PSFs is a measure of their quality. The optimal rating for any given PSF is 100 and a 0 value is the minimum value or in other terms the quality of the PSF is low as the rating approaches 0. Table 3 shows the PSF rating scales for each muster action. Using this scale each PSF was given a rating based on the individual muster sequences. Figure 3 summarizes the mean PSF rating for each of the three muster scenarios. In all three muster scenarios the quality of the PSF drops off markedly with increasing muster severity.

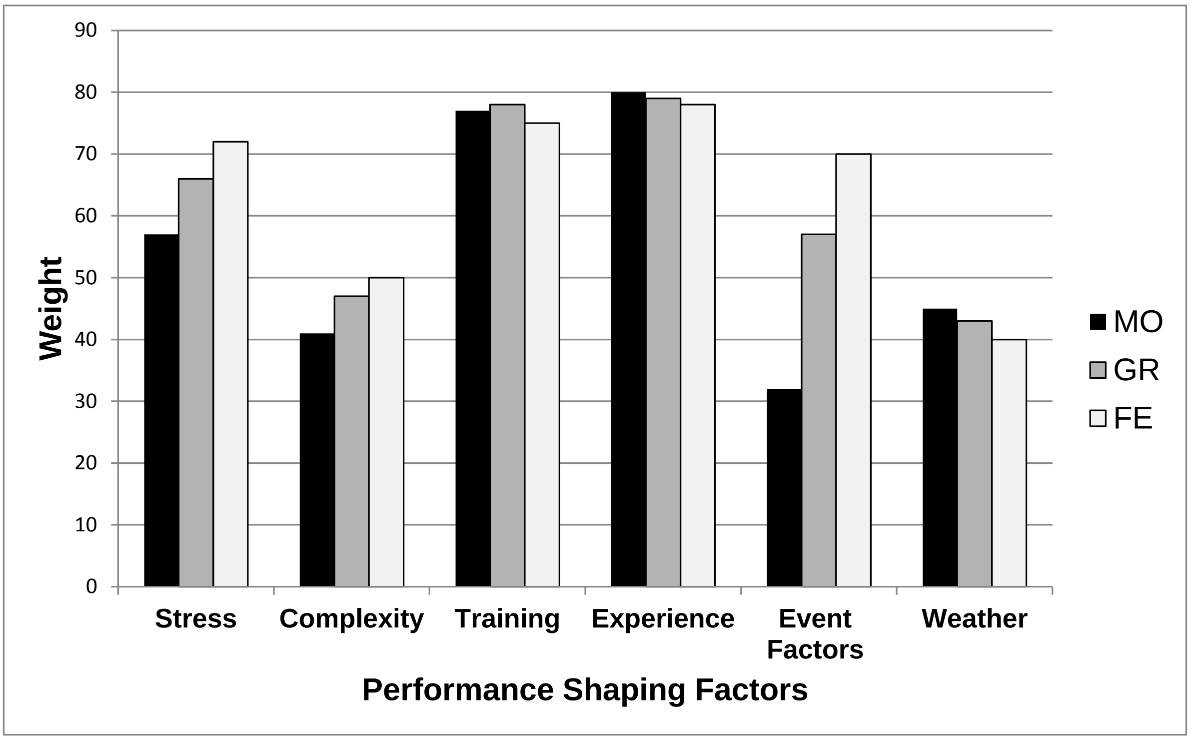

Figure 2: Mean PSF weights for all actions and muster initiators (17)

Rating Scale	Performance Shaping Factors					
	Stress	Complexity	Training	Experience	Event Factors	Atmospheric Factors
100	No stress	Not complex	Highly trained	Very experienced	No effect	No effect
50	Some stress	Somewhat complex	Some training	Somewhat experienced	Some effect	Some effect
0	Highly stressed	Very complex	No training	No experience	Large effect	Large effect

Table 3: PSF rating scales for each muster action (17)

3.2.3 Human Error Probabilities:

The determination of the human error probabilities (HEPs) follows the SLIM protocol for which the details can be found in DiMattia (17). The steps taken to calculate the HEPs are summarized as follows:

- For a given muster action the weight of each PSF is normalized by dividing the weight by the sum of all the PSF weights for that action. This is termed the n-weight.
- The product of the n-weight and the rating provides the success likelihood index (SLI) for a given PSF.

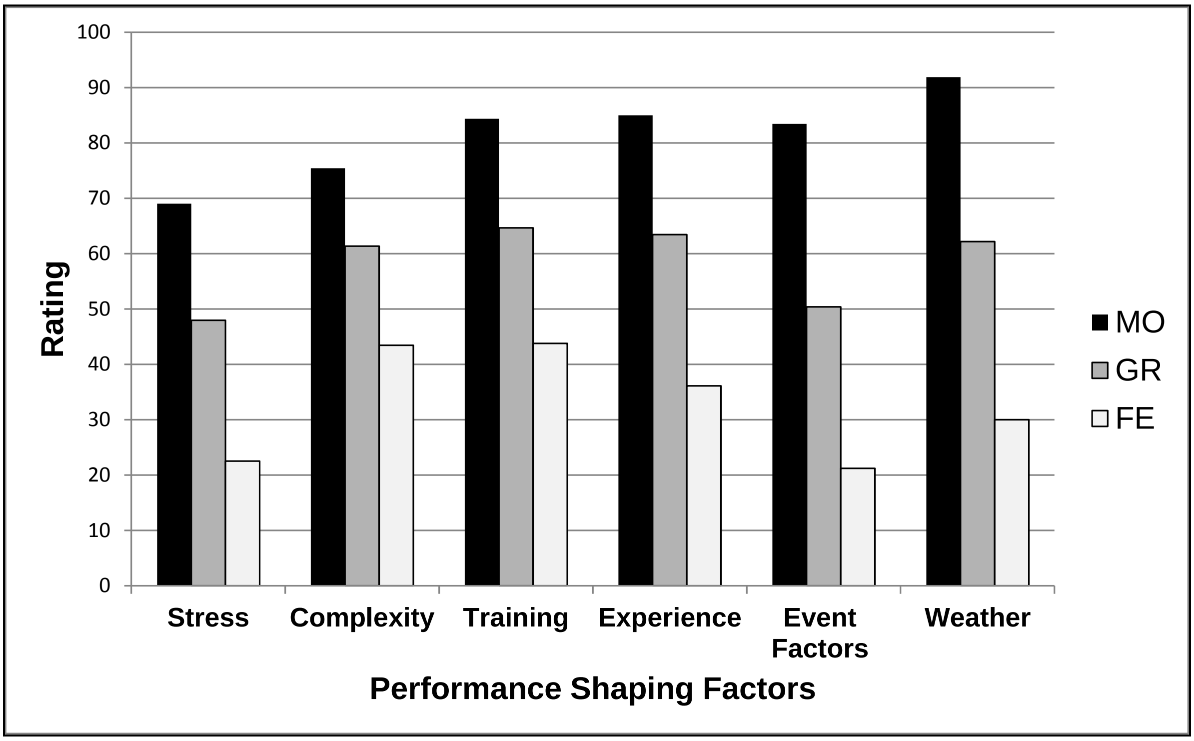

Figure 3: Mean ratings for all actions and muster initiators (17)

- The SLI values for the PSFs are summed to yield the total SLI or simply the SLI for a given action.

The greater the SLI, the greater the probability of successfully completing a task. A summary of the SLI values for each muster scenario can be seen in Table 4. The table illustrates the following trends:

- The difference in severities (tenability) between these muster scenarios is significant enough such that there is a clear distinction between each scenario with no cross-over in SLI values between each scenario.
- The FE scenario actions in general have the lowest SLI values are the least likely to be completed successfully.
- The SLI for the awareness, evaluation and egress phases are lowest for the GR and FE scenarios while for the MO scenario similar SLIs are associated for each action

The probability of success (POS) for each action is determined by the correlation first stipulated by Pontecorvo (19). The correlation is the foundation of the SLIM methodology and is represented as follows:

$$\log POS_i = a(SLI_{i,m}) + b \qquad (1)$$

No.	Muster Action	MO	GR	FE
Awareness Phase				
1	Detect Alarm	83	66	31
2	Identify Alarm	85	66	32
3	Act Accordingly	83	59	26
Evaluation Phase				
4	Ascertain if danger is imminent	80	52	24
5	Muster if in imminent danger	82	53	29
6	Return process equipment to safe state, if conditions allow	78	51	23
7	Make workplace as safe as possible in limited time	77	50	21
Egress Phase				
8	Listen and follow PA announcements	83	56	29
9	Evaluate potential egress paths and choose route	80	51	23
10	Move along egress route	84	53	30
11	Assess quality of egress route while moving to muster station	81	51	27
12	Choose alternate route if egress path is not tenable	78	45	20
13	Collect personal survival suit if in accommodations at time of muster	n/a	n/a	n/a
14	Assist others, if needed or as directed	76	56	35
Recovery Phase				
15	Register at muster location	89	71	48
16	Provide pertinent feedback attained while enroute to muster station	79	62	41
17	Don personal or muster station survival suit if instructed to do so	83	68	48
18	Follow instructions	83	68	47

Table 4: Success Likelihood Index values for each muster scenario (17)

where

POS_i = probability of success for action i = 1 – HEP_i

$SLI_{i,m}$ = arithmetic mean of success likelihood index values for action i

a, b = constants

The determination of the constants a and b is performed by an evaluation of the human error probabilities for the muster actions that have the highest and lowest SLI value. These two HEPs are referred to as based human error probabilities that permit the solution of the constants, a and b. Once these constants are determined the remaining HEPs are calculated for each muster action. The muster action with the maximum SLI (SLI_{max}) for all three muster scenarios is action 15 (register at muster location). The task which has the lowest SLI for the MO scenario is action 14 (assist others if needed or as directed) and for the GR and the FE scenarios action 12 (choose alternate route if egress path is not tenable) has the minimum SLI. Three approaches may be used to calculate the constants, a and b, and are as follows:

- empirical human error data
- elicitation of human error data from a set of experienced individuals
- estimated from THERP data (1)

THERP data provides adequate rigor to calculate the HEPs for the remaining muster actions for each scenario. Table 5 provides a summary of the predicted HEPs and illustrates how increasing muster severity significantly impacts success likelihood in a negative manner. A list of possible error mechanisms with examples are listed in DiMattia (17). Through an understanding of the error type one is in a better position to suggest more effective mitigation measures. These mitigation measures may take the form of enhanced training (e.g. more realistic muster exercises at varying times), improved procedures and management systems (e.g. preventative maintenance program) and better design and application of equipment (e.g. alarm systems, lighting).

Though an understanding of how the probability of human error varies with muster severity has usefulness it of itself, combining the probability with a consequence evaluation allows for a risk determination of human error. The consequence table as provided by DiMattia (17) has been adapted for LNG tankers and is provided in Table 6. Applying a risk matrix (17) based on consequence and probability is a common method of communicating risk in the process industries. The application of mitigating measures can then be used to reassess the probability and consequence associated for a given action.

4. HUMAN PROBABILITY INDEX (HEPI)

A human error probability index provides a novel approach for the inclusion of human factors in risk assessments. HEPI provides a methodology for the identification, assessment and mitigation of risk due to human error as applied here to muster scenarios aboard LNG tankers. Through the use of such a methodology, error reduction recommendations in areas such as training, procedures, management systems and equipment are brought forward to help reduce the risk from human error. Since the muster scenarios were set up to cover a range of severity in terms of the chosen PSFs, the development of a set of a reference graphs for each PSF's weight and rating permits the assessment of other muster scenarios through interpolation. These reference graphs represent the generalization of the generated HEP data and are the foundation of the index.

No.	Muster Action	MO	GR	FE
Awareness Phase				
1	Detect Alarm	0.00499	0.0308	0.396
2	Identify Alarm	0.00398	0.0293	0.386
3	Act Accordingly	0.00547	0.0535	0.448
Evaluation Phase				
4	Ascertain if danger is imminent	0.00741	0.0765	0.465
5	Muster if in imminent danger	0.00589	0.0706	0.416
6	Return process equipment to safe state, if conditions allow	0.00866	0.0782	0.474
7	Make workplace as safe as possible in limited time	0.00903	0.0835	0.489
Egress Phase				
8	Listen and follow PA announcements	0.00507	0.0605	0.420
9	Evaluate potential egress paths and choose route	0.00718	0.0805	0.476
10	Move along egress route	0.00453	0.0726	0.405
11	Assess quality of egress route while moving to muster station	0.00677	0.0788	0.439
12	Choose alternate route if egress path is not tenable	0.00869	0.1000	0.500
13	Collect personal survival suit if in accommodations at time of muster	n/a	n/a	n/a
14	Assist others, if needed or as directed	0.01010	0.0649	0.358
Recovery Phase				
15	Register at muster location	0.00126	0.0100	0.200
16	Provide pertinent feedback attained while enroute to muster station	0.00781	0.0413	0.289
17	Don personal or muster station survival suit if instructed to do so	0.00517	0.0260	0.199
18	Follow instructions	0.00570	0.0208	0.210

Table 5: Human error probabilities values for each muster scenario (17)

Each muster action has a set of six reference curves, one for each PSF, to determine the respective weights and ratings. This results in a two graphs for PSF weights and ratings, for each muster action. These reference graphs provide the normalized PSF weight (n-weight) and rating based on a ranking value for the given action. An overview of development of HEPI is provided by DiMattia et al. (20) and Khan et al. (13) and a detailed description of HEPI and the inclusive reference graphs can be found in DiMattia (17). The following steps summarize the HEPI framework and are graphically represented by Figure 4.

- Develop a muster scenario. Through the use of a ranking questionnaire a rank for each of the given PSF is determined. The questionnaire provides a means of

Severity	Ability to Egress	Other POB	Muster Initiator	Health
Critical	Can no longer reach muster station or any other safe refuge	Prevents others from reaching muster station or any other safe refuge	Raise severity where muster is no longer possible	Loss of life
High	Can no longer reach muster station	Prevents others from reaching muster station	Raises severity where muster is in jeopardy	Significant physical injury
Medium	Moderate to significant delay in arriving at muster station	Moderate to significant delay for others in arriving at muster station	Raises severity producing moderate to long delays in reaching muster station	Minor to moderate injuries.
Low	No to minor delay in reaching muster station	No to minor delay for others reaching muster station	No to minor increase in severity of muster	No to minor injury

Table 6: Consequence table (17)

comparing muster scenarios relative to the three base scenarios.

- Rank PSFs. Performance shaping factors are ranked by summing the values obtained from the questionnaire. Each PSF rank is then used to calculate the normalized weights and ratings for each muster action.
- Determine PSF weights and ratings. Through the use of the reference graphs and rankings determined from the questionnaire the n-weights and ratings are interpolated and recorded.
- Determine the SLI values. The SLI values are calculated for each muster action, as shown in Eq. (2).

$$\text{SLI } (\pi) = \text{n-weight } (\mu) * \text{rating } (\alpha) \qquad (2)$$

The total SLI (β) for a muster action is the sum of the SLIs for the given PSFs are shown in Eq. (3).

$$\beta = \sum \pi \qquad (3)$$

- Determine the human error probability values. The log of the probability of success (POS) is determined for each muster action from one of three SLI reference graphs. These reference graphs cover the range of SLI values for each muster scenario. The probability of success for any given muster action is the inverse of the log POS. The human error probability (HEP) is simply calculated by the following equation:

$$\text{HEP} = 1 - \text{POS} \qquad (4)$$

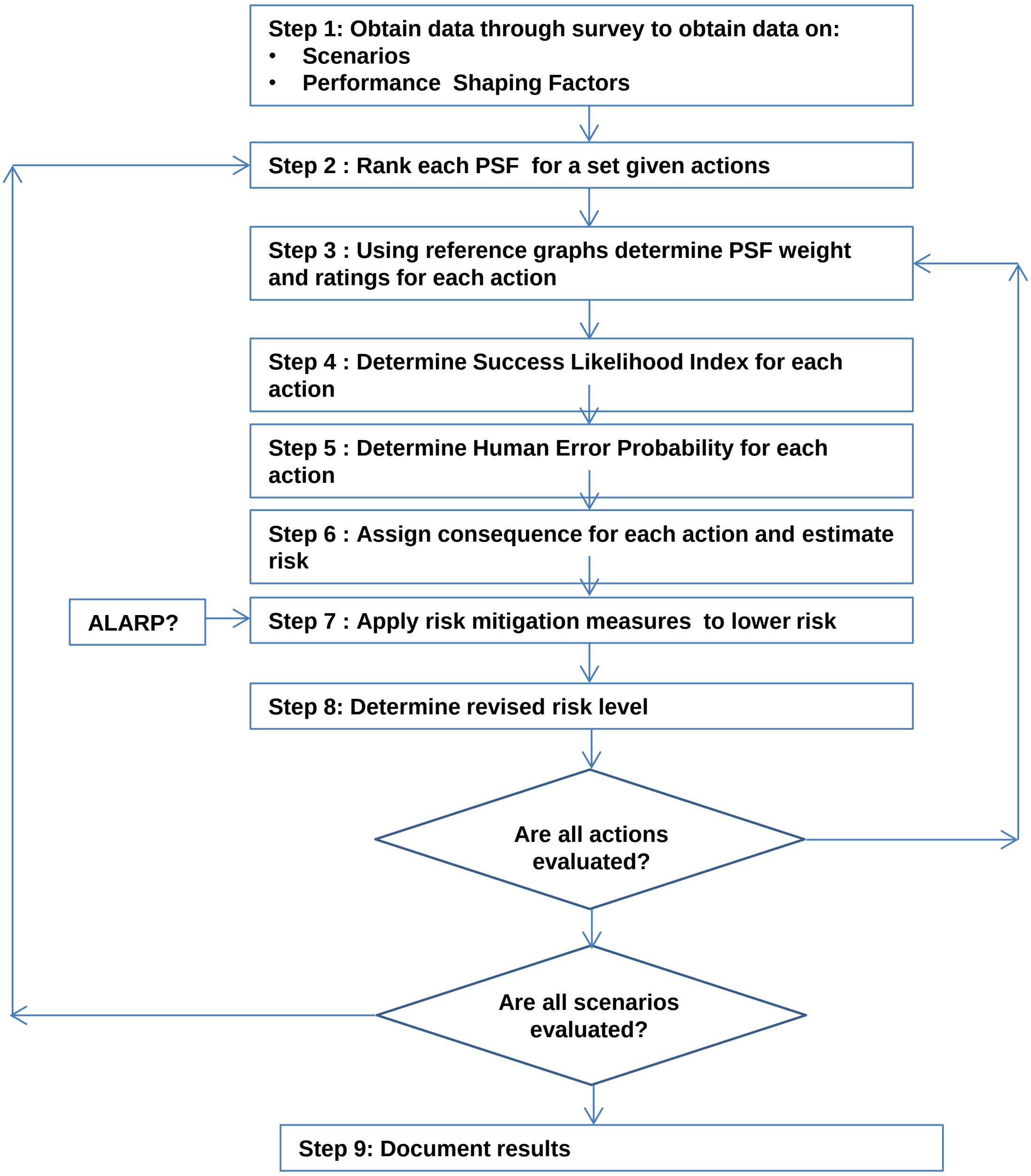

Figure 4: HEPI Methodology (17)

- Assign consequences and estimate risk level. In order to characterize the risk associated with human error a consequence is assigned for each action. The consequence table is based on different levels of severity for the following factors:
    - ability to egress (capacity to reach the muster location)
    - impact on other personnel (influence on other personnel mustering)
    - muster initiator (potential to escalate event that caused muster)
    - health of individual (potential level of injury sustained by individual)

- Application of risk mitigation measures. A table of risk mitigation measures may be provided in a formal table, as in Kennedy (12), or provided through a risk assessment team discussion. Based on the risk mitigation measures new PSF ratings are established and subsequently revised HEP and consequences are determined.

- Determine revised risk level. The PSF n-weights represent the importance of each PSF for each muster action. Hence the PSF n-weights are not recalculated. Mitigation measures do enhance the quality of the PSFs and therefore the ratings are recalculated. The level of improvement of the rating may be given a percentage value based on the difference between the calculated rating and the optimal value (maximum rating) for a given action. The new, higher rated, PSF is now used to determine the revised risk ranking.

An example of the application of HEPI is conducted in a case study, detailed in DiMattia (17) and summarized in Khan et al. (13).

5. CONCLUSIONS

A human error probability index has been proposed that applies the estimated probability of failure for a set of muster actions associated with LNG tanker emergencies through a series of reference graphs. The HEPI method helps promote a consistent approach to the assessment of human factors in offshore environments and has wide application beyond LNG tankers and offshore fixed platforms. The index employs a consequence table and risk matrix to assess the ramifications of human error for a wide range of muster severities. Applying risk mitigation measures permits a re-evaluation of risk. The application of these HEP predictions in the form of an index brings forward a human reliability assessment tool that is practical and does not require human factors expertise.

The ability to adequately prepare for severe muster scenarios is achievable through advancements in procedures, training, equipment and management systems. No system can be free of human error but through better preparation, systems can become more error tolerant and will help lower risk from human error. Tools such as HEPI can help bring forward a common understanding of human error and its mechanisms. The collection of human error data through drills and actual events can lead to improving the quality of HEP predictions and risk mitigation measures.

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