HEALTH, A PERFORMANCE INDICATOR FOR THE ASSESSMENT OF LIFE-SAVING APPLIANCES

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ABSTRACT

The growing number of large passenger ships has opened the door to new challenges for naval architects and marine engineers. One of these challenges is the design of suitable life-saving systems, with the capacity of allowing the massive evacuation of passengers in case of an emergency. Therefore, novel concepts of life-saving appliances have either recently emerged or are under development. However, even though these novel life-saving systems are intended to improve passengers' safety and enhance the performance of the ship abandonment, they do not systematically meet all the regulatory prescriptive requirements of the Safety Of Life At Sea (SOLAS) Convention. Nevertheless, Flag State Administrations can approve these systems under the principle that they provide at least the same safety level as the safety level provided by comparable LSAs complying with SOLAS prescriptions (like conventional lifeboats and liferafts). This principle is called safety equivalency.

When a few requirements are challenged, it is quite simple to demonstrate safety equivalency with a simplified risk analysis addressing only the specific topics covered by these requirements. However, when the design is very innovative, a global framework for the assessment of safety has to be used, that would help quantifying the ship abandonment performance. In this paper, we present a methodology for the safety performance assessment of life-saving appliances and arrangements based on passengers' health as developed in a European Union funded Framework Programme 6 (FP6) project called SAFECRAFTS [Prat et al., 2008].

Keywords: Health, Safety, Life-saving appliances, Risk assessment, Alternative design, SOLAS

NOMENCLATURE

HHS: Human Health Status = [GH MI SI D]
- GH: Good Health
- MI: Minor Injuries
- SI: Severe Injuries
- D: Deceased

IMO: International Maritime Organization
LSA: Life-Saving Appliance
LSS: Life-Saving System
SAR: Search and Rescue
SOLAS: Safety Of Life At Sea

1. INTRODUCTION

The maritime industry and the IMO have been working on improving safety at sea for years through *inter alia* the SOLAS Convention. Basically, safety means safety of people. Even with the increasing level of automation onboard, there can still be more than twenty or thirty crewmembers onboard merchant ships. It is in first instance very important to ensure their safety. However when it comes to safety onboard passenger ships, there may not only be hundreds of crewmembers but thousands of passengers which means that a major incident on such a ship has the potential to threaten the life of thousands of people. This is and has been proven to be unacceptable for the society. That is the reason why from the well known accident of the Titanic to the Herald of Free Enterprise, regulatory provisions have been adopted at an international level to make passenger ships safer. However, had an incident or an accident occurred at sea, it is sometimes preferable (if there is uncertainty on the escalation of events and the ship's survivability) or unavoidable (if there is evidence that the ships will not survive or if it does no longer provide an acceptable level of safety) to abandon the ship. Moreover, even though Life-Saving Appliances (LSA) are fully covered by regulations, the evacuation of a passenger ship is never a risk-free operation. Even when there is no catastrophic event, passengers can be injured during the process and this has been seen even during evacuation drills exercises at berth.

2. SAFETY OF LIFE-SAVING APPLIANCES

2.1 LSAS AND SAFETY OF PASSENGER SHIPS

The whole life-saving system and in particular the Life-Saving Appliances (LSAs) play a major role in the success of a passenger ship evacuation since they have to be boarded very quickly in case of an emergency, be able to be launched in certain list and trim conditions and provide protection to their passengers in bad weather conditions until they are

recovered through the Search And Rescue (SAR) operations. Moreover, passenger ships are getting increasingly bigger, which means, more lives threatened at the same time, had an incident occurred, which can be interpreted as a higher risk. Manufacturers and ship owners are therefore constantly trying to make their LSAs safer by improving existing LSAs as well as developing new concepts.
Nevertheless, novel life-saving systems, even if they provide a higher level of safety than the 'conventional' lifeboats and liferafts, are likely not to match the conventional prescriptive regulatory requirements from the SOLAS Convention.

2.2 REGULATORY REQUIREMENTS

SOLAS regulatory requirements have mainly been developed for conventional lifeboats, liferafts and rescue boats. The main international texts are SOLAS Chapter III [IMO, SOLAS Convention] and the LSA Code [IMO, LSA Code]. At a European level, the European Marine Equipment Directive (MED) [EC, MED Directive] deals with requirements for the approval of some types of LSAs. When designing novel concepts of LSA and arrangements, some of these requirements are no longer relevant and therefore cannot be fulfilled. These LSAs and arrangements would, a priori, not be accepted by Administrations.

2.2 (a) Safety Equivalence

However, SOLAS Chapter I Regulation 5 on Equivalents opens the door to the acceptance of appliances not fully complying with SOLAS requirements on a particular ship, provided that these appliances are demonstrated to be at least as effective as the 'conventional' appliance.

2.2 (b) Alternative Design

The equivalency principle is implicitly referred to in SOLAS III 38; the novel LSA or arrangement not fully complying with SOLAS requirements is called 'alternative design':

"*Life-saving appliances and arrangements may deviate from the requirements set out in part B* [of SOLAS Chapter III]*, provided that the alternative design and arrangements meet the intent of the requirements concerned and provide an equivalent level of safety. […] When alternative design or arrangements deviate from the prescriptive requirements of Part B, an engineering analysis evaluation and approval of the design and arrangements shall be carried out in accordance with this regulation".*

The engineering analysis should be carried out according to the IMO MSC Circ. 1212 [IMO MSC Circ.1212] "*Guidelines on alternative design and arrangements for SOLAS Chapter II-1 and III*".

2.3 THE APPROVAL PROCESS BASED ON SAFETY ASSESSMENT

As regards to the regulations in force, for demonstrating the safety equivalence of an alternative design or arrangement of life-saving appliance, the two following points need to be carefully addressed. First, it is necessary and crucial to clearly define the intent of the requirements not complied with. Secondly, the safety performance of life-saving appliances needs to be somehow assessed against the criteria derived from the requirements' intent.

2.4 HEALTH, A PERFORMANCE INDICATOR FOR SAFETY

In our case, safety of LSA can be assessed through their performance in achieving their purpose: allow the massive and quick evacuation of passengers while keeping them alive and in good health. It is therefore logical to look at the evolution of the health of passengers from the moment they start mustering when the General Emergency Signal (GES) is sounded to the moment they are recovered by the SAR services, by a passing vessel or reach the shore by their own means.

3. ASSESSING PASSENGERS' HEALTH DEGRADATION

3.1 OBSTACLES ALONG THE ROUTE TO SHIP EVACUATION AND RESCUE

Disembarking a ship at danger encompasses several phases, which all together can be referred to as the rescue route, which includes the Life Saving System as described further in section 4. When using life boats lowered by davits this route includes moving to the embarkation stations, embarking the lifeboat and finding a seat, withstanding impacts of the lifeboat against the ship's hull and water when the boat is lowered, surviving seasickness, dehydration and cold when the boat floats or sails freely at sea and finally embarking the rescuing ship by, e.g., a pilot ladder. In case of using liferafts, these are generally deployed overboard first, while the passengers disembark the ship via Marine Evacuation Systems (e.g. chutes). These phases all have their own particular effects on the health of the passengers, and these effects may also differ for, e.g., different age categories, i.e., older people generally being more vulnerable to physical threats than younger people. For example, the age distribution on cruise ships may peak at about 70. Health threats *per se* that have been taken into account here are those caused by injuries due to certain impacts and being tossed around, by seasickness and dehydration, and by hypothermia.

3.2 THE EFFECTS OF SHOCKS AND ACCELERATIONS ON PASSENGERS' HEALTH

3.2 (a) Assessment of Injuries

Injuries will take place if impacts deform the human body beyond a tolerable limit. The anatomical structures will be damaged and/or their function will be altered. Well-known classification scales are the Abbreviated Injury Scale [AAAM, 1998] and the Injury Severity Score (ISS) or the New ISS [Osler, 1997]. The AIS was developed to provide researchers with a simple numerical method for ranking and comparing single injuries by severity (minor to fatal), and to standardise the terminology. The ISS or NISS is a generally accepted approach for rating multiple injuries. Because such detail is not available for the current assessment, a more general approach is followed here, focusing on mobility. One reason for doing so is the assumption that passengers will generally spend less than 24 hours at sea without further medical assistance, which they are likely to survive in most cases, if at least they can (be) move(d) off the ship at danger into the lifeboat or liferaft and out again onto the rescuing ship. Injury then degrades mobility and, the other way round, poor mobility increases the risk of injury. We here took into account the effect of age and mobility on risks of falling/collisions and injuries, the general risk of falling, and the consequences of these falls. In most cases demographic data have been used to specify the risks at issue. For specific impacts such as those caused by impacts of the lifeboat against the ship's hull, these data have been amended with calculations using a multi-body/finite element software package developed for vehicle occupant responses [TNO, 2003]. For analyzing the likelihood of being tossed around, data from tests undergone during the Safecrafts project have been used [Bos et al., 2010].

3.2 (b) Assessment of Seasickness

There is general agreement that seasickness is an issue in survival craft. Nevertheless there is little information about the effects of seasickness on survival [Light and Coleshaw, 1993]. It is stated, however, that "the physical and mental condition of the occupants is critical", and for totally enclosed motor propelled survival craft "most, if not all, occupants will become seasick shortly after launch, unless the sea is extremely calm". Though seasickness is a real discomfort, discomfort by itself is not lethal in most cases. Yet, there are two specific conditions under which seasickness becomes a threat to life. The main threat is vomiting. Abundant and repeated vomiting deprives the body of fluids (dehydration) and of electrolytes, especially if blood is thrown up (violent vomiting) and there is diarrhea. Autonomic nervous system dysfunction may further increase the risk of vomiting. Vomiting (abundant) also precludes effective drinking and effective oral medication, and suffocation by the expelled puke is yet another risk especially when people are apathic or even comatose. The loss of will to survive anyhow also contributes significantly to the risks of injuries, hypothermia, and any action the afflicted person should take (e.g., climbing a pilot ladder). Although lethality due to vomiting may be marginally within 48 hours (with the exceptions of heart block and suffocation), vomiting strongly undermines the physical fitness, and increases the risks of injuries and hypothermia. Based on data from the literature and by expert assessment, a number of ensuing risks has been quantified. To assess the incidence of sickness, hydrodynamic models were used to calculate the craft motion given a number of sea states, and an extended ISO-model (i.e., including horizontal motion, habituation, and age) was used to calculate the incidences at issue given the craft motion [ISO-2631-1, 1997] [Bos et al, 2007] [Turan et al, 2005].

3.3 HYPOTHERMIA

Hypothermia is a loss of body heat. Persons who fall into cold water can be affected within minutes. Out of the water hypothermia develops more slowly. Hypothermia reduces muscle capacity, starting from the extremities (hands, feet), then arms and legs. The severely affected persons lose consciousness and may die. During disembarkation passengers can become wet during their wait at the embarkation station (precipitation, spray water, wind) and have reduced mobility because of the cold. Inside the lifeboat passengers are assumed not to get wet any further. Water inside the liferaft, however, is an insidious danger. Here we assume that the passengers absorb this water in their clothing when they fall, when they crawl, when they sit on the floor, and when they shift from one position to another to find more comfort. In this respect it is also important to consider the chain of rafts mutually connected during disembarkation of the ship at danger, while the chute is only connected to one, thus requiring the passengers to crawl from that raft to another. Hypothermia may occur because passengers sit on a cold floor. The floor generally consists of two layers separated by an air space of 20-30cm. The lower layer is in contact with the water and has the temperature of the sea water; the upper layer (where the passengers sit upon) has a temperature barely 2-3 degrees Celsius higher. In other words, the passengers sit upon a floor that is almost as cold as the sea. If the floor became wet during embarkation, the passengers sit upon a cold and wet floor. Hypothermia is furthermore expected to develop over time. Any bodily fluids (see also seasickness above) will get cold within an hour, thus contributing to the effects described above. To calculate the effects of hypothermia on health, we used the Cold Exposure Survival Model [Tikuisis & Keefe, 2005].

3.4 HARDWARE FAILURE

In addition to the numerous obstacles described in the previous sections, that each individual will have to go through and that are likely to impact their health, there are also obstacles threatening the life of all passengers of a same LSA. Indeed, depending on their design, the LSAs can suffer from a certain number of failures during the embarking, launching and navigation phases so that passengers may be injured and die from their injuries. A certain number of accidents have already pointed out some of these failures. Some typical examples of failures having occurred during the last decades are identified in a report published by the UK Marine Accident Investigation Branch [MAIB, 2001]. The most common one is: during the embarking phase, the on-load release hook of a lifeboat, if not fitted with a hook disengaging gear capable of being operated both on and off-load, might suffer from a failure and cause the lifeboat to directly fall at sea while being increasingly loaded, potentially causing very severe injuries and the death of passengers. Other failure modes were identified through expert meetings. Two of them are presented hereafter: during the launching phase of a lifeboat, in heavy weather, the roll motions of the ship may cause violent impacts of the lifeboat against the hull. The LSA might not withstand such shocks and break in two, causing people severely injured, people falling at sea and fatalities. Finally, when at sea in heavy weather, a liferaft may be progressively flooded with green water and finally sink, causing the death of its trapped occupants.

4. QUANTIFYING THE PERFORMANCE OF THE LIFE-SAVING SYSTEM

4.1 THE ASSESSMENT SCENARIOS

It is crucial to determine the evaluation scenarios so that critical points for safety are addressed in the performance assessment. This means that first of all, a study such as a Hazard Identification needs to be carried out. This study aims to put forward, as far as possible, 1) the critical situations in terms of safety during the evacuation and rescue and 2) all the situations where the novel life-saving appliance may perform differently from the conventional ones. Once the hazards have been identified, they need to be evaluated. Finally, since all the scenarios integrating these hazards cannot be reasonably adopted for further analysis, only the most critical assessment scenarios should be selected. This early selection will depend on the criteria used for ranking the hazards and has very important implications for the rest of the process for quantifying the Life-Saving System's performance. Therefore it needs to be agreed upon with all the parties, in particular with the Flag State Administration.

4.2 FORMALIZING THE ABANDONMENT AND RESCUE PROCESSES

The concept underpinning the safety assessment of alternative LSA designs and arrangements is the one of 'obstacle race'. It is based on the fact that passengers will have to go through numerous obstacles before they can be considered to have reached a safe place (ashore or onboard a rescuing ship). Therefore the 'track' or abandonment and rescue route can be split into different phases, themselves divided into steps and finally the third level of detail is composed of obstacles. Obviously, if the obstacles themselves are intrinsically determined by the technical characteristics of the Life-Saving System (LSS), the intensity of these obstacles depend on the assessment scenarios. The concept of abandonment and rescue route is illustrated in figure 1 and table 1 below:

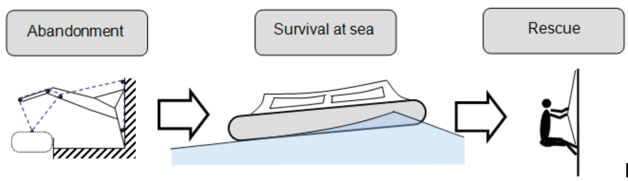

Figure 1: A Life-Saving System (LSS)

Table 1: Break-down of the phase "leaving the vessel" into elements and obstacles

Phases	Elements	Obstacles
Leaving the vessel using a lifeboat	Deployment	Malfunction
		Fail to start engine
	Boarding	Mobility failure
	Lowering	Premature release
		Failure /impact hull
		Injuries / impact hull
	Release	Fail to release
		Injuries / Slamming

There is one 'abandonment and rescue route' made of a succession of obstacles for each Life-Saving System (LSS); a LSS being defined as the association of different types of LSAs and arrangements (typically davit-launched lifeboats and liferafts associated with MES chutes). Consequently, alternative LSA design and arrangements may give birth to obstacles very different from those usually encountered with conventional lifeboats, liferafts and rescue boats or may just prevent passengers from conventional obstacles.

4.3 THE CONCEPT OF HUMAN HEALTH STATUS

The Human Health Status (HHS) is an example of an indicator that can be used to monitor the evolution of passengers and crewmembers' health during the abandonment and rescue phases. Both injuries and the mobility of people need to be reflected in the HHS. Thus, every obstacle along the abandonment and rescue route is likely to decrease the HHS of passengers. One could choose to describe the health and mobility of people with four states:

-Good health (GH): Good physical and mental health and good mobility
-Minor Injuries (MI): Moderate bleeding, no fracture, no trauma and/or impaired mobility
-Severe injuries (SI): Fractures, trauma, and/or mobility requiring assistance
-Deceased (D): Fatal injury and/or no mobility

These categories are irrespective of the age of people. This means for example that an elderly passenger who has health problems and some difficulties for walking alone properly but not requiring assistance is in the MI category and someone unable to walk by him/herself in the SI category. With such a categorization, the HHS can be described as a vector providing the probabilities of having a passenger in each state at a given time 't' as shown on the vector representing the Human Health Status (HSS) below.

$$\begin{bmatrix} \alpha \\ \beta \\ \chi \\ \delta \end{bmatrix}$$

α *Probability to be in the GH category*
β *Probability to be in the MI category*
χ *Probability to be in the SI category*
δ *Probability to be in the D category*

The HHS vector represents the probability of a person to be in each of the four states (GH, MI, SI or D), the sum of its components is always equal to 1.

4.4 ASSESSING THE OBSTACLES

Each obstacle along the abandonment and rescue route is likely to degrade the health and mobility of people so that at the end, when the rescue is deemed to be completed, from all passengers and crewmembers that were initially on the ship, some of them will be injured, severely injured or deceased. The concept of health and mobility degradation is risk-based: what is the probability that given obstacle is going to degrade the HHS in a certain extent.

4.4 (a) Local Degradation Functions

We consider that each obstacle corresponds to a local degradation function that will act on the HHS. Therefore, the degradation is a four-dimensional application that is applied to the HHS vector presented in section 4.2. These applications can be represented as four by four matrices. The matrices are defined so that for each column of a matrix, the coefficients from top to down describe how the health of a passenger in each state is likely to be degraded into GH to D states as explained below.

$$\begin{bmatrix} x_{11} & x_{12} & x_{13} & x_{14} \\ x_{21} & x_{22} & x_{23} & x_{24} \\ x_{31} & x_{32} & x_{33} & x_{34} \\ x_{41} & x_{42} & x_{43} & x_{44} \end{bmatrix} * \begin{bmatrix} \alpha_{input} \\ \beta_{input} \\ \chi_{input} \\ \delta_{input} \end{bmatrix} = \begin{bmatrix} \alpha_{output} \\ \beta_{output} \\ \chi_{output} \\ \delta_{output} \end{bmatrix}$$

With

x_{11} *Probability that somebody in GH stays in GH*
x_{21} *Probability that somebody in GH becomes MI*
x_{31} *Probability that somebody in GH becomes SI*
x_{41} *Probability that somebody in GH becomes D*

Moreover, the matrices have a certain number of particularities derived from the assumptions adopted:
- By definition the sum of coefficients in column have to be equal to one
- A person cannot get healthier in the course of the abandonment and rescue process. Consequently, the matrices have to be triangular
- The totality of deceased persons will remain deceased so the coefficients of the fourth column are nil but the one on the fourth line which is equal to one

The shape of the matrix is finally:

$$\begin{bmatrix} a & 0 & 0 & 0 \\ b & f & 0 & 0 \\ c & g & m & 0 \\ d & h & n & 1 \end{bmatrix} \quad \text{With} \quad \begin{cases} a+b+c+d=1 \\ f+g+h=1 \\ m+n=1 \end{cases}$$

The coefficients of the matrices depend on a certain number of factors. First of all, they are derived from analyses, test, experiments and other studies required to model and assess the effects of obstacles on the health and mobility degradation of people. These analyses can be mechanical simulations of the LSA motions providing the likely accelerations and shocks coupled with biomechanical simulations used for assessing the loads applied to passengers and crewmembers' bodies and the resulting injuries (see section 3.2). Then, these numerous analyses being carried out for different assessment scenarios (see section

4.1), their results may be dependent on the scenarios and so will the matrix coefficients. Finally, results of the analyses may significantly depend on the age of passengers. This means that there may be several matrices required to describe the health and mobility degradation resulting from a single obstacle.

4.4 (b) Global Degradation Functions

The abandonment and rescue route is composed of successive obstacles. The final HHS is obtained by calculating successively the HHS after each obstacle. Practically the final HHS is obtained by multiplying the initial HHS by the matrix associated to the first obstacle, then multiplying the resulting HHS by the matrix of the second obstacle and so on until the last obstacle. The product of matrices being associative it is possible to simplify the expression. The health and mobility degradation due to the whole abandonment and rescue process can be described as the degradation due to a global degradation function resulting from the multiplication of the matrices associated to all the local degradation functions (one per obstacle). The final HHS subsequently simply results from the multiplication of the global degradation matrix by the initial HHS. Here again, there may be several different global degradation matrices depending on the assessment scenario and the age category of people focused on.

4.5 THE PERFORMANCE INDEX

A performance index can be derived from the final HHS of passengers and crewmembers in order to demonstrate that the alternative design is at least as safe as a conventional design. First of all, the index would aggregate the different age categories. This can be simply done through a weighted sum of HHS vectors of the different age categories, the weighting coefficients being derived from the description of the ship's population demographics:

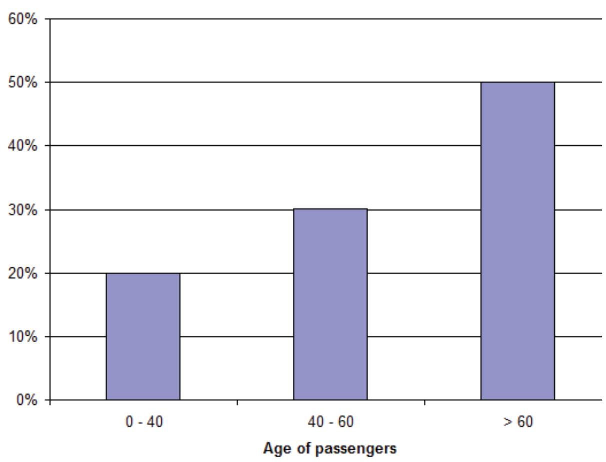

Figure 2: Example of passengers' demographic description

Such an index could be based on the comparison between the initial and the final HHS of passengers. It could integrate the fact that minor and severe injuries, even if they are not as catastrophic as fatalities, can also be important if they are numerous as shown in the formula presented below.

$$PI_k = \frac{1-\left(\delta_{N,k} + 0.1\cdot\chi_{N,k} + 0.01\cdot\beta_{N,k}\right)}{1-\left(\delta_{0,k} + 0.1\cdot\chi_{0,k} + 0.01\cdot\beta_{0,k}\right)}$$

With

k: the assessment scenario number
N: the number of the last obstacle
PI_k: the performance index calculated for the assessment scenario 'k'
δ_k, χ_k, and β_k respectively the probabilities for a passenger to be in the D, SI and MI health categories after the rescue, for the assessment scenario 'k'

This formulation assumes that having a passenger with severe injuries is ten times more unacceptable than having a passenger with minor injuries and that a fatality is a hundred times more unacceptable than a passenger suffering from minor injuries. This scale can obviously be discussed regarding the way health categories are defined and depending on the societal risk acceptance criteria (can be agreed with the Flag State Administration to whom the alternative design is submitted). It is very important to note that such a performance index does not provide the number of fatalities resulting from the abandonment of the ship. It has to be interpreted only as an indicator of the risk for persons to be injured during the abandonment and rescue process. This index is not an absolute value but should be used for comparisons only.

Table 2: Acceptance criteria for different scenarios

Assessment scenario	Acceptance criteria
Scenario 1	$PI_1(AD) \geq PI_1(CD)$
Scenario 2	$PI_2(AD) \geq PI_2(CD)$
…	…
Scenario k	$PI_k(AD) \geq PI_k(CD)$

With
AD: the Alternative Design
CD: the Conventional Design

Finally, the performance index needs to be specific to a given scenario since the acceptance criteria is that the alternative design or arrangement has to be at least as safe as a conventional one for all the assessment scenarios (as referred to MSC Circ. 1212). Then, the validation of the alternative LSA design and/or arrangement can be done by translating the acceptance criteria "at least as safe (or effective) as the conventional design" into the condition “for each scenario, a performance index equal or superior to the performance index calculated for the conventional design” as shown in table 2 above.

5. CONCLUSIONS

When dealing with new systems, it is very important to take into account human factors and to adopt safety criteria that are related to the potential impact of the systems on human health if the word ‘safety’ addresses implicitly safety of life. Studies bringing in detailed risk-based methodologies such as the one presented in this paper can reasonably not be systematically used. Indeed, they are very likely to require substantial effort for setting up an expert group, exchanging information with the Administration and the different actors, carrying out specific analyses, tests, trials, simulations, etc. However, for projects with very innovative LSA concepts, assessing safety through performance indicators based on the health of crewmembers and passengers is a relevant generic way of having a system validated by an Administration for its installation onboard a particular ship. It is presented in more detail in a Guidance Document published in March 2010 for Alternative design and arrangement of LSAs [BV, 2010].

DISCLAIMER

The opinions expressed in this paper are those of the authors and under no circumstances should they be interpreted as the policy of Bureau Veritas or TNO.

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