THE SAFEGUARD HEEL SCENARIO EVACUATION BENCHMARK AND RECOMMENDATIONS TO IMO TO UPDATE MSC CIRC 1238

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SUMMARY

This paper outlines new scenarios relating to heel and trim to consider for inclusion into an updated "*Guidelines for Advanced Analysis for New and Existing Passenger Ships*", currently MSC.1/Circ.1238 [1]. It describes the research undertaken as part of the EU FP7 SAFEGUARD project to develop an appropriate set of scenarios and to investigate the impact of the heel scenario on the evacuation of the ship. A wide range of data sources, including statutory regulations, casualty data, damage stability calculations and results of relevant model testing, were utilised to identify appropriate scenarios. The impact of these scenarios was also considered: the primary influence was found to be changes to the travel speeds of the persons due to the conditions experienced. Data from full scale trials in this field was utilised to create speed variation tables which were incorporated into advanced evacuation tools. The identified scenarios were tested utilising geometries from a cruise ship and a ro-pax ferry and the results of these tests are discussed. Finally, recommendations on implementing these additional scenarios into the regulations are presented.

1. INTRODUCTION

The IMO produced guidelines relating to evacuation analysis for new and existing passenger ships, IMO MSC.1 Circ.1238[1] (referred to hereafter as *the guidelines*). The guidelines specify detailed benchmarking scenarios to be considered: Case 1 (primary, night) and Case 2 (primary, day). The main vertical zone which generates the longest time is further investigated in Case 3 and Case 4 (secondary case, night and day) in Alternative 1 and Alternative 2. The two secondary cases consider a complete run of the stairways being unavailable and 50% of the population of one of the adjacent zones to move into the identified zone. As no scenarios currently consider ship motions, heel and trim, a safety factor of 1.25 is applied to the calculated assembly time (tA).

One of the aims of the EU FP7 SAFEGUARD project is to develop a benchmark scenario relating to heel. As a benchmark scenario, it was envisaged to be an idealised case suitable for testing on all vessels covered by *the guidelines*.

A three-phase approach was utilised:

Phase One – Phase One consisted of a critical review of the following:

- Casualty data compiled from accident reports. These accident reports are published by flag administrations, e.g. The Marine Accident Investigation Branch (UK) and The Bureau of Maritime Affairs (Liberia).
- Relevant rules and regulations (EC Directives, SOLAS Chapters II-1, II-2, III, etc).
- Available damage stability calculations according to SOLAS II-1 (static stability calculations for passenger ships)
- Stockholm Agreement assessment (available performance-based assessment of existing ro-pax vessels)

This review entailed identifying what likely factors (relating to the primary cause of heel - flooding) affect an evacuation process. Through analysis and judgement the representative scenarios were developed.

Phase Two - Experimental data available in public domain on the effect of heel/trim and motion on people was reviewed and quantified. Look-up tables showing speed variation factors for different persons were developed for use in advanced evacuation simulation tools.

Phase Three - The scenarios identified were tested in two advanced evacuation simulation tools: maritimeEXODUS - developed by the Fire Safety Engineering Group (FSEG) at the University of Greenwich [2-6]; and EVi – developed by Safety at Sea Ltd, Glasgow [7-8]. Utilising the geometry from both a cruise ship and a ro-pax vessels and stipulations in *the guidelines,* Case 1 - night and a Safeguard version of Case 2 - day (with passengers on outer decks) were run. One of the scenarios identified was applied to each of these cases. Comparison and discussion on the effect of these scenarios is presented, along with recommendations for implementation.

2. DEVELOPMENT OF HEEL SCENARIO

2.1 Accident Analysis

Accident reports considering collision, grounding and flooding (ingress of water due to open doors, pumps, etc.) were analysed. Relevant vessels (passenger, ro-pax, or cruise) were identified.

The casualty data corresponds to a sample of 150 vessels involved in 109 separate accidents over a 12 year period.

Potential factors affecting the ease of evacuation of vessels were identified:
Heel and Trim –The inclination of the deck upon which the occupants must move, and the ability to open, close and pass through doors.
Motions – Sea state can cause motion-induced accelerations.
Flooding extent – Flooding may impair the availability of escape routes.
Impairment of emergency systems Emergency lighting, tannoy, ventilation systems, alarm systems, damage control systems, etc may become unavailable after sustaining damage. Blackout is considered specifically.

(1) Heel and Trim

Heel experienced at sixty minutes after the occurrence of accident (for relevant vessels) is discussed. Sixty minutes was chosen as *the guidelines* require that ro-pax and passenger vessels with less than three main vertical zones be evacuated within 60 minutes. In grounding (four cases) the average heel angle was 9.4° and the maximum between 10° and 20°. For casualty vessels in a collision (one case) the heel angle was estimated to be between 5 and 10°. For flooding (one case) the heel angle was estimated to be between 5 and 10°. Taking all data for relevant vessels into account the average heel angle after 60 minutes was found to be 8.8°.

In some cases vessels were observed to capsize. In these cases the possibility of organised mustering of persons is unlikely. Flooding situations which lead to a fixed level or slow development of heel are much more likely to allow for organised mustering. It can also be observed that in these cases the flooding is unlikely to affect the escape routes available, as the flooding is restricted to below the bulkhead deck. Trim is not generally reported.

(2) Vessel Motions

The level of motions was generally not reported. As accident reports are mainly descriptive, the effects of motion were found to be difficult to quantify.

(3) Damage Extent

The damage extent will have an impact upon the decision to stay onboard or to abandon. It was observed that vessels suffering damage are often abandoned as a precautionary measure, but manage to survive.
The extent of the damage could affect the ability of passengers to muster. In two cases where progressive flooding was identified the vessel sank too quickly to be abandoned in an orderly manner (with consequent loss of life) and in one case the vessel was damaged in such a way that allowed water ingress into the passengers' accommodations.

(4) System non-availability

It was observed that after damage, propulsion and electrical systems are most likely to suffer major damage and become inoperable. It is not considered that these will affect the outcome of the mustering process.

(5) Blackout

Six cases of blackout were observed in the database and in all cases emergency electrical power was able to supply power.

2.2 Review of Design Performance

A database of vessels that have undergone design calculations was utilised to understand expectant conditions vessels may experience during an evacuation. The vessels in the design performance review come from three samples; **Sample A**: Ro-pax vessels that underwent SOLAS 90 damage (static) stability calculations and Stockholm Agreement model testing (motions). A small number (7) were designed to 1-compartment standard (mean year of build 1976). **Sample B**: Ro-pax vessels that underwent probabilistic A index value calculations (SOLAS 2010). **Sample C**: Cruise vessels that underwent probabilistic A index value (static) calculations (SOLAS 2010)

(1) SOLAS 90 [16]

SOLAS 90 refers to the amendments brought into force in 1990. SOLAS 90 rules on subdivision are based upon ensuring that the vessel survives flooding to any one or two adjacent compartments. For each damage case, the equilibrium condition is established, yielding the final heel and trim angles (static stability calculation). The following criteria are defined for the angle of heel (ϕ):

- $\phi \leq 7°$ for flooding to one-compartment;
- $\phi \leq 12°$ for flooding to two or more adjacent compartments.

(2) Stockholm Agreement [10]

Devised and implemented in the wake of the *Estonia* disaster, the Stockholm Agreement was introduced in 1997 among the north-western European nations to address damage stability of ro-ro passenger ferries. The principle is to assess the survivability of the ferry with accumulation of water on the car deck. Models are tested in the worst damage cases as identified from the SOLAS 90 calculations and are subjected to waves corresponding to the expected significant wave height for the operating area for a relevant period of time. The vessel should withstand 10 random realisations of the sea state, each of 30 minutes duration in the damaged conditions. Motions of the vessel are recorded.

(3) A – Index Calculations (SOLAS 2009) [11]

Ship damage stability has seen a distinct change from deterministic to probabilistic requirements. A probabilistic subdivision index is used as a measure of damage stability, and it is driven by the conditional probability of flooding (p-factor) and the conditional probability of survival (s-factor). The attained value of A should be not less than a required R value ($A \geq R$), which is a function of the size of the vessel and the number of persons the vessel is certified to carry. The evaluation of damage stability for each case is still based on static stability criteria, but the basis for acceptance is the so called survival factor (s-factor), estimating the probability of survival for the evaluated damage case.

(4) Safe Return to Port [11]

Since July 2010, passenger vessels are required to comply with the so called "safe return to port" requirements, implicit in SOLAS II-2. These requirements are relevant, as they specify casualty damages for which operability requirements for specific systems are defined. Flooding of a single watertight compartment is not likely to lead to any significant level of heel or trim with modern vessels.

2.3 Results of Design Performance

(1) Heel/Trim Results

Samples A (1 and 2-zone damage), B (1, 2, and 3-zone damage) and C (1, 2, and 3-zone damage) were analysed for measured heel angles. Clear in the data however is the increase in spread of values (up to 20°) from 1 through to 3 damaged zones, see Figure 1 (negative values indicate heel to starboard). .

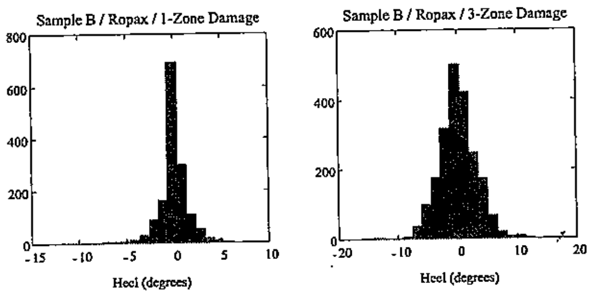

Figure 1:
Sample B – Ropax, 1 and 3 Zone Damages

Data shows that the expected trim angles are small, with the majority less than 2.5°.

(2) Ship Motions

In Stockholm Agreement testing, the vessel is tested in beam seas (wave direction is perpendicular to the vessel's longitudinal axis). Since pitch motions are normally negligible in this condition, the focus of the analysis is on roll motion. The following observations can be made:

- The angle around which the vessel rolls can be significantly higher (up to 10 times) than the calculated static heel angle.
- During transient flooding (before equilibrium is reached) very high roll angles may be experienced, which are potentially larger than the resulting heel angle after damage.

Figure 2 shows roll standard deviation (SD) against significant wave height (Hs). A conservative value of 3.5° would encompass the majority of the test runs. Assuming a Gaussian distribution with a mean of zero this can be translated into a roll amplitude value of approximately 5°.

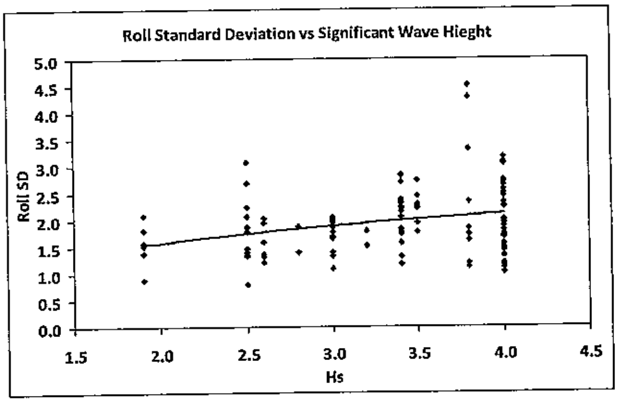

Figure 2:
Roll standard deviation vs significant wave height

From previous work [15] we can observe that the amplitude of the roll response when comparing an intact and a damaged vessel is reduced in the damaged case.

(3) Damage Extent

The key finding from reviewing current SOLAS regulation on flooding extent [9] SOLAS II-1 Reg. 7-1 is that design damages extend only to the main bulkhead deck, the maximum height of the internal subdivision. The bulkhead deck is the uppermost deck to which the internal watertight bulkheads are carried and the assembly of the passengers and crew during an evacuation is above this deck. The limits put on the evacuation by this subdivision are therefore not relevant from the point of view of MSC/Circ.1238.

(4) Other Relevant Requirements [9] [12]

SOLAS Chapter II-1, Chapter II-2 and Chapter III cover legislation of interest.

Electrical power must be provided in key named areas in the event of a main electrical power loss. Allowances endeavour to ensure power and lighting is in place for evacuation. Special reference is made to evacuation areas on board ro-pax vessels.

The EC Directive 2009/45/EC of the European Parliament and of the Council on Safety Rules and Standards for Passenger Ships covers watertight doors. It states that power-operated sliding doors shall be capable of being closed simultaneously from the central operating console at the navigating bridge in not more than 60 seconds with the ship in the upright position. The regulations detail the systems surrounding the door design and the door type. In line with the SOLAS regulations the accumulators must be able to close-open-close the doors against an **adverse list of 15°**.

Power-operated watertight doors are required to be operational for half an hour even if power is lost. Both SOLAS and the EC Directive state doors should be operational up to an angle of **15°** in the requirements governing watertight doors.

SOLAS Chapter III, Regulation 16 - Survival Craft Launching and Recovery Arrangements details SOLAS consideration for the state of the vessel at the time when the survival craft is being launched. Survival craft must be able to be launched under unfavourable conditions of a **trim of 10°** or a **list of 20°**. These figures suggest the maximum angles that SOLAS consider will be experienced aboard a vessel before mustering is completed.

3 DISCUSSION ON FINDINGS

Deck Inclination – After a casualty involving water ingress, a vessel may (i) develop a constant heel angle (after equalisation); (ii) heel at a constant rate if there is progressive flooding. If the rate of heeling is fast the vessel may capsize rapidly with little chance of abandonment. If the heeling rate is relatively slow, there may be enough time to abandon the vessel, before deck inclination is untenable for persons.

Only the cases where abandonment is possible are considered relevant cases. Taking all data for relevant vessels into account the average heel angle after 60 minutes was found to be 8.8°.

Considering all events for all categories of vessels, the average reported heel angle is found to be around **14°**.

The requirements of SOLAS chapter III are that vessels should be able to launch life saving appliances at **20°** heel and **10°** trim.

The results of design performance analysis on static damage cases indicate that the final heel angles are normally small, although extreme cases of up to **20°** were identified.

Vessel Motions – The results of the accident analysis are inconclusive as to the effect of vessel motions on evacuation process, primarily due to a dearth of detail in the accident reports in this respect. Performance analysis assist understanding of the important influencing factors (Hs, watertight arrangement, etc). For the purposes of our study the key results of the design performance work is that the amplitude of the roll motion is likely to be 5° or less.

Flooding Extent - The analysis presented indicates that, if the vessel is going to survive long enough for orderly evacuation, the flooding should not extend above the bulkhead deck. If it does extend beyond the bulkhead deck, the vessel is likely to suffer progressive flooding, or, given sufficient damage extent, to capsize quickly. Therefore, considering the extent of flooding is not required for implementation in a revised MSC.1/Circ. 1238.

Regarding the factors identified in the review, the additional scenarios can be simplified to those which involve inclinations and rotational motions of the decks.

4 RECOMMENDED SCENARIOS

Taking the factors discussed above into account, the following main candidates for the additional scenario are identified:

1. Static heel or trim from t = 0
   Heel: 20°
   Trim: 10°
2. Static heel with roll motion superimposed from t = 0
   Static heel: 15°
   Roll amplitude: 5°
   Roll period: 20 s
3. Time-varying heel with roll motion superimposed from t = 0
   Heel: linearly varying from 0° at t = 0 to15° at t = 60 minutes and then held steady
   Roll amplitude: 5°
   Roll period: 20 s

5 IMPLEMENTATION OF HEEL SCENARIO

A comprehensive research review [13] undertaken on behalf of the UK Maritime and Coastguard Agency (MCGA) was utilised to understand what the effect on the evacuation process would be as a result of the scenarios developed.

A list of factors were identified such as:
Platform attitude - Static inclination, motions;
Platform features – Stairs, doorways, width of walkways;
Facilities – Handrails, guardrails, etc;

Agent status – Gender, age, fitness/health, disabilities, group dynamics.

Only limited amount of information is readily quantifiable from the data. The platform attitude (inclination) is the only aspect that has been retained.

Among the research presented in the review [13] data presented from a team from TNO [14] on the effect of heel and trim on walking speed in open spaces and in stairs during a trial was examined more thoroughly. The trials conducted by TNO used 60 people aged between 18 and 83 on a 4m long, 2.4m wide test rig. Stair tests were conducted on a 40°, 6 step stair. The trial results were used to derive speed variation factors.

It is important to note that the data is by no means perfect, although the most appropriate among those presently available in public domain. Therefore, the recommended quantitative data should be taken only as indicative and should be updated when better datasets become available. These data sets are often the results of trials conducted with small groups of fit volunteers on a small test rig. The reality of a full scale evacuation may be very different.

Two aspects define how the data is implemented: firstly persons are defined by three age group categories (Young: 18-40, Middle aged: 41-60, Senior: 61-80); and secondly Speed Variation Factors (SVFs) were used to quantify the effects of the heel/trim for each of these age groups.

Walking speed in the data was converted to a speed variation factor (SVF) and linear trend lines representing the probable relationships between the SVFs and heel angle were established.

Using the trends thus established, the relevant speed variation factors were obtained (shown in Table 4).

The walking speed of any agent in the simulation can then be calculated by firstly defining the agent into one of the three age categories, then multiplying the original speed on that platform feature by the relevant SVF.

It must be noted that the inclination of the deck about an axis parallel to the direction of travel is termed "heel" and that about an axis at right angles to the direction of travel "trim".

It is likely that in some spaces an agent will not be walking exactly parallel or at a right angle to the axis of inclination. In those cases the lowest speed variation factor will be applied to the agent's walking speed.

Table 4:
Speed variation factors

Speed variation factors for heeled surface		
Age Range	10° heel	20° heel
Young	0.94	0.88
Middle-aged	0.92	0.84
Senior	0.90	0.80

Speed variation factors for flat terrain subjected to trim				
Age Range	-20°	-10°	10°	20°
Young	0.94	0.99	0.88	0.73
Middle aged	0.94	0.99	0.86	0.67
Senior	0.88	0.97	0.86	0.67

Speed variation factors for persons ascending/descending stairs subjected to lateral tilt				
Age Range	Ascending		Descending	
	10°	20°	10°	20°
Young	0.94	0.88	0.95	0.90
Middle-aged	0.98	0.95	0.96	0.93
Senior	0.95	0.90	0.92	0.85

Speed variation factors for persons ascending or descending stairs subjected to trim				
	Ascending			
	-20°	-10°	10°	20°
All age groups	1.02	1.03	0.84	0.68
	Descending			
	-20°	-10°	10°	20°
All age groups	0.77	0.84	1.00	0.80

6 TESTING OF HEEL SCENARIO AND RESULTS

Using the geometry of a cruise ship and a ro-pax ferry to build simulation models, the effect of heel and trim on the mustering process was assessed. The IMO night case and the Safeguard Enhanced day case were tested on the cruise vessel while the IMO day case was tested on the ro-pax. Two evacuation simulation tools: EVi [7-8] and maritimeEXODUS [2-6] were used to perform the simulations. The SAFEGUARD day case for the cruise vessel was investigated by the University of Greenwich. The IMO night case for the cruise vessel and the IMO day case for the RoPax were investigated by Safety at Sea Ltd.

6.1 Cruise Vessel

The cruise vessel has 13 decks and 7 main vertical zones (MVZ). Accommodations are located on deck 2 to 4 and 7 to 10. Public spaces and outer decks can be found on decks 5 to 6 and on decks 11 to 13. Muster stations are located on decks 5 and 6.

6.1.1 Safeguard Enhanced Day Case Results

The Safeguard Enhanced (SG) day case is similar to the IMO day case with the exception that persons can be distributed on the open decks. There are 2502 passengers and 735 modelled crew members. Passengers are randomly located in public spaces throughout the ship and are assigned a specific muster station.

Demographics and reaction times from *the guidelines* were used in the simulations and 50 runs of each scenario (SG day case, heel scenario and trim scenario) were performed.

The evacuation procedures assumed in the simulations were that passengers remain in their assigned MVZ until they reach the assembly decks (deck 5 and 6), and they then cross fire zones to reach their designated muster station.

The average mustering time in the 20° heel condition was found to be 23% longer than the average mustering time of the SG day case. The 95th percentile of the 20° heel scenario was also found to be longer than the one for the SG day case by 24%.

In trim conditions, results show an increase of 10% in the average mustering time and 13% increase for the 95th percentile mustering time.

Table 5 below gives the overall results for the SG day, heel and trim scenarios.

Table 5:
Overall results for heel and trim scenarios compared to the SG Day case

	Day case basis	Day case 10° Trim	Day case 20° Heel
Min	709	811	922
Average	879	970	1079
Max	1032	1137	1243
St Dev	74	82	87
95%ile	989	1115	1226

6.1.2 Night Case Results

In the night case 3001 passengers are located in their cabins and are assigned reaction times and demographics as per *the guidelines*. 801 crew members are also distributed throughout the ship as per *the guidelines*.

In the night case passengers are assigned muster stations according to the location of their cabins, i.e. they stay in the MVZ with some exceptions when they need to cross a fire zone to follow the escape plan.

The average mustering time in heel conditions was found to be 10% longer than the average mustering time for the night case. For the 95th percentile run the mustering time was 5.4% longer than the 95th percentile of the night case.

In trim conditions the increase in the average mustering time was found to be 6.42% longer than the average mustering time for the night case and 5.2% longer for the 95th percentile.

Table 6 below gives the overall results for the normal night, heel and trim scenarios.

Table 6:
Overall results for heel and trim scenarios compared to the Night case.

	Night Case basis	Night case 10° Trim	Night case 20° Heel
Min	1247	1331	1408
Average	1361	1449	1497
Max	1971	1792	1841
St Dev	122	91	75
95%ile	1542	1621	1625

6.2 Ro-Pax

The second ship used to assess the impact of heel and trim on the mustering time is a fast ro-pax ferry with no passenger cabins (there are cabins located on deck 9 but they are intended for lorry drivers only and not for regular passengers). Different public spaces such as business and traveller class seating areas (airline style seating), large retail and restaurant/cafeteria areas and indoor and outdoor general seating areas can be found on decks 7 to 9.

The vessel has four main vertical zones and four muster stations.

6.2.1 IMO Day Case Results

As the ship does not have passenger cabins, only the IMO day case was tested.

A total of 1781 passengers and 66 crew members were modelled with demographics and reaction times from *the guidelines*. Passengers were assigned muster stations based on their location onboard, i.e. they remain in the MVZ through the evacuation process.

50 simulation runs were performed for the IMO day case, and in heel and in trim conditions. The results are presented in table 7

Table 7:
Overall results for heel and trim scenarios compared to the Day case.

	Day Case basis	Day case 10° Trim	Day case 20° Heel
Min	418	428	442
Average	440	466	486
Max	500	531	535
St Dev	18	20	20
95%ile	467	499	518

The average mustering time in heel conditions was found to increase by 10% and for the 95th percentile the mustering time was 11% longer when compared to the day case. In trim conditions the average was found to increase by 6% and the 95th percentile was 7% longer than the day case.

7 DISCUSSION

The representative scenarios of heel and trim have been formulated after comprehensive research. The results of testing some of the scenarios show that, as expected, there is an increase in time when the scenarios are applied due to the inclination of the deck.

As only the effects of heel and trim on the walking speed have been investigated here, the impact on the total mustering time is directly linked to the speed variation factors. Indeed, as can be seen in Table 4, in trim conditions the walking speed on flat can be reduced by 0.99 to 0.86. In the stairs the variation is from 1.03 to 0.84.

This would lead to a potential increase of the mustering time by 16% to a decrease in the mustering time of 3%.

Following the same logic, the increase in the total mustering time can be estimated to vary from 5% to 33% for the heel conditions.

The results presented above are consistent with the expected increase in the mustering time, as for example in the SG day case for the cruise vessel, the average mustering time was found to increase by 23% in heel conditions and by 10% for the trim, which are within the ranges identified above.

A single safety factor has been proven to be insufficient when applying the effect of heel and trim.

The work described in this paper could only cover Scenario 1 (static heel and trim) due to lack of appropriate data. Such data may become available in due course so that the other scenarios suggested here can be implemented.

It should be noted that there are several important simplifications with the approach adopted for including the impact of heel and trim:

- The reductions in travel speed should only be considered approximate as they are based on a small number of trials, in particular the data associated with trim and were collected in a small test facility, unrepresentative of ship dimensions.
- The impact of handrails is not considered. The presence and use of handrails by persons would create a different behaviour, as persons would need to walk in a single file and their speed would be further reduced, as they would not be able to walk faster than the persons before them in the line. Although this aspect has not been investigated in SAFEGUARD project, it is anticipated that this would have a significant impact on the total mustering time.
- Other behavioural factors which may be significantly impacted by heel and trim are ignored. For example, the presence of family groups or passengers with movement disabilities may be disproportionally impacted by conditions of heel and trim. Rather than simply reducing travel speeds, movement in a particular direction may become impossible.

8 PROPOSED MODIFICATIONS TO THE IMO EVACUATION ANALYSIS GUIDELINES

The work completed shows that the heel and trim is likely to affect the time to evacuate a passenger vessel. It has been shown that the effect of heel and trim will vary depending on the type and design of each vessel. Therefore the additional heel and trim scenarios described in this paper should be considered for inclusion in the development of any new guidelines for evacuation of passenger vessels.

It is believed that a prescriptive set of scenarios may in some cases not be relevant to some ships due to their designs or intended uses.

A process of selecting relevant scenarios from a suggested list (to include heel, trim, motions, etc) would improve the whole assessment process, with useful, interesting results. The aim should be to test appropriate, justified, scenarios. Advantages of this approach include: theoretical worst cases are identified and tested; developments in ship design trends would be easily accommodated; developments in software could be utilised to allow more realistic testing of scenarios; and real areas of concern can be addressed by the owner/operator/flag administration.

9 ACKNOWLEDGMENT

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