Safety initiatives from the SNAME ad hoc RO RO Safety Panel

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SUMMARY

This paper describes the work of the SNAME ad hoc panel. The panel was charged with reviewing the safety of North American ferries and making recommendations for improvement. It also includes a description of the analytical methods and experimental results used to validate the findings of the panel.

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SAFETY INITIATIVES FROM THE SNAME AD HOC RO RO SAFETY PANEL

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1. INTRODUCTION

Over the past fourteen years, 44 RO RO vessels have capsized. The capsize of most of these ships can be traced to a common phenomenon: the accumulation of water on the open RO RO cargo spaces causing the vessel to assume a large angle of list and capsize. Notable examples include:

- The *European Gateway*, which collided with the *Speedlink Vanguard* off Harwich/Felixstowe in the English Channel with the loss of 6 lives in 1982. This is perhaps the best real-world prototype accident illustrating the classic collision, followed by flooding of the RO RO space, followed by capsize.

- The *Herald of Free Enterprise*, which capsized outside Zeebrugge harbor in 1987 with the loss of 193 lives. The vessel had left the pier with the bow door open in order promote ventilation of exhaust fumes. The ship's crew failed to close the door as she left harbor, thus allowing water to enter the RO RO deck.

- The *Estonia* whose capsize in the Baltic on September 28, 1994 resulted in the loss of over 900 lives. The cause of the accident was failure of the bow visor locking mechanisms in heavy seas. In addition, the inner watertight barrier was too far forward and not structurally independent of bow visor. Thus, as the bow visor became detached, it dislodged the inner ramp from its closed position, allowing the ingress of water which lead to the subsequent capsize and sinking.

The tragic sinking of the *Estonia*, coupled with the previous RO RO casualties, demanded that the international community take action to significantly improve the safety of RO RO passenger vessels. The International Maritime Organization (IMO) led the efforts to address these issues by creating a Panel of Experts (POE) to conduct a thorough review of RO RO ferry safety. This paper documents the parallel efforts of the Society of Naval Architects and Marine Engineers to assess the safety of RO RO ferries in Canada and the United States and to further the understanding of the fundamental mechanics of water accumulation on deck and associated capsize phenomena.

2. FORMATION OF THE SNAME AD HOC PANEL AND ITS MISSION

The Society of Naval Architects and Marine Engineers (SNAME) established an Ad Hoc Panel on RO RO Safety in response to the capsizes and sinkings of RO RO passenger vessels in recent years, and in particular the tragic loss of the *Estonia*. SNAME's leadership recognized the potential need for changes to national and international standards to minimize the likelihood of future occurrences of this nature and formed the Ad Hoc Panel in order to take the lead in identifying important technical issues with respect to RO RO passenger ferries and to ensure that appropriate discussion and debate were initiated. The Ad Hoc Panel membership represented a wide range of perspectives and included regulatory agencies, a classification society, owners, operators, designers, universities, naval architects, and safety officials from both Canada and the United States.

The Ad Hoc Panel was charged with assessing the safety of the Canadian and United States RO RO ferry fleets and providing recommendations to improve their level of safety. Specific tasks included:

- Assess the Canadian and United States RO RO ferry fleets from both a stability and overall safety perspective.
- Review the existing research on RO RO ferries such as the numerous studies undertaken following the *Herald of Free Enterprise* accident.
- Recommend areas requiring additional research or refinement.

- Provide recommendations for improving RO RO ferry safety which are suitable for use by the Canadian and United States governments in their formulation of policy. The recommendations should also be suitable for use by the International Maritime Organization (IMO).

The work of the Ad Hoc Panel was closely coordinated with the schedule of the IMO's Panel of Experts so that timely recommendations could be provided to the Canadian and United States administrations. Numerous tasks were completed by the Panel to support their recommendations as well as to contribute to the technical basis of the Panel of Experts' decision-making process. The most significant technical work is described in this paper and includes the water-on-deck analytical studies and model tests on freeing ports and bow scooping. Additionally, the Panel reviewed the extensive list of recommendations made by the IMO Panel of Experts, providing comments and recommendations to the Canadian and United States administrations and completed an operator survey which is discussed herein. The Panel is scheduled to be dissolved in the late Spring of 1996, following completion of its final report.

The authors of this technical paper are all members of the SNAME Ad Hoc RO RO Safety Panel. Bruce Hutchison is Chairman and Patrick Little is Secretary of the SNAME Ad Hoc Panel. Additionally, David Molyneux was an active participant in all of the model testing at IMD, and Peter Noble was involved with the bow scooping model tests at B.C. Research. Bruce Hutchison was the principal investigator for the SNAME Ad Hoc Panel's analytical studies. Both Patrick Little and Robert Tagg have participated as members of the U.S. delegation to SLF, and Robert Tagg has also participated on the U.S. SOLAS working group on stability.

3. THE U.S. AND CANADIAN FERRY FLEETS

The significance of RO RO passenger ferries in the transportation network of the United States and Canada is seldom highlighted, although by international standards these services are significant. Over 80 million passengers are carried on routes accumulating over 1 billion passenger miles. By way of comparison, Washington State Ferries and British Columbia Ferry Corporation each carry more passengers annually than all the ferries of the four nations operating on the English Channel, and more than double the passengers carried on the Sweden-Finland Baltic routes.

Figure 1 compares the annual passenger traffic volume of the U.S. and Canadian ferry services to that of two heavily trafficked European routes.

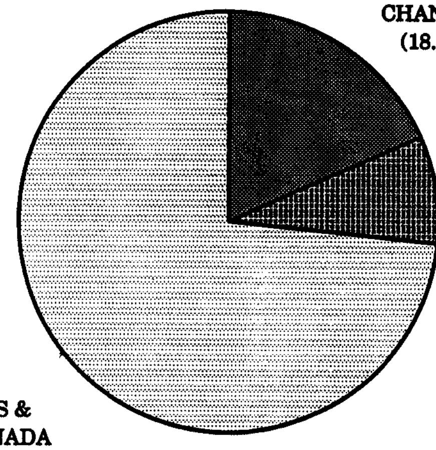

FIGURE 1
Annual Passenger Traffic Volume

In contrast to many European routes most of the North American ferry services are operating in domestic rather than international trade. Further most North American routes are in relatively protected waters such as Delaware Bay, Galveston Bay, Puget Sound or the Straits of Georgia. The majority of RO RO passenger vessels in the U.S. and Canada operate in wave climatologies characterized by 90th percentile significant wave heights of less than 1.5m.

Many of these vessels have open or partially enclosed RO RO vehicle decks, rather than fully enclosed RO RO decks commonly found on large European ferries. Ferries operating in areas such as Alaska, the North Coast of British Columbia, and between Nova Scotia and Newfoundland are, however, designed with fully enclosed RO RO decks, and are similar to vessels found in Europe.

4. ANALYTICAL STUDIES BY THE SNAME AD HOC RO RO SAFETY PANEL

The SNAME Ad Hoc Panel believes that it is necessary to develop requirements that address the hazard posed by water on the decks of vessels such as fully enclosed RO RO passenger ferries. The Panel believes that any proposal to address the water-on-deck hazard should be rationally based on:

- The operating environment
- The freeboard at the point of assumed damage
- The means to remove water from the vehicle deck

One way the SNAME Ad Hoc RO RO Safety Panel has addressed the problem of water accumulation on deck has been using time domain simulation and integral methods based on the Gaussian distribution of wave elevations. It is this research by the Panel that is the subject of sections 4 through 8 of this paper.

The primary focus of the Ad Hoc Panel's analytical research has been to determine the asymptotic average water-on-deck burden that a vessel must withstand without capsize or progressive flooding.

Stationary Ship Model

The SNAME Ad Hoc Panel investigated a highly simplified model for the accumulation of water on the deck of a damaged RO RO vessel, which is nonetheless believed to encompass the salient features of the problem. A stationary ship was assumed, with a flat deck and side damage represented by a rectangular opening of unlimited vertical extent beginning at the deck. The assumed stationarity corresponds to no vessel motion in response to flooding (i.e., no sinkage, trim or heel) or waves (i.e., not sway, heave or roll), resulting in a fixed elevation, f, of the deck at the point of assumed side damage (see Figure 2). The treatment of essential fluid flow processes in the stationary ship model is two-dimensional.

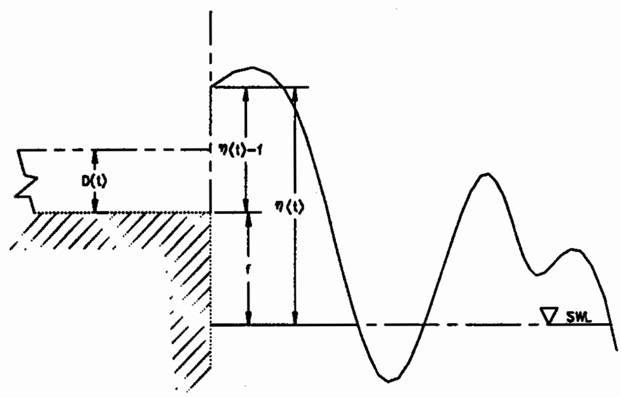

FIGURE 2

Definition Sketch

A partial rationale for the stationary ship approach is that, once new rules are implemented, the burden of water on deck is supposed to be limited to a quantity that the vessel can survive without capsize. This argument helps to explain why it may be possible to ignore sinkage, trim and heel. It remains to be established from experiments whether relative motion effects, hydrodynamic interaction between the hull and the waves, or internal dynamics of the accumulated water pool, lead to excessive departures from the expectations based on the stationary ship concept. However, as will be shown later in this synoptic paper, encouraging agreement has been found between predictions based on the stationary ship concept and model test data obtained using a free floating model at IMD.

Independent Parameters

Given the assumption of a stationary ship, the independent problem parameters are reduced to:

- A — area of the deck subject to flooding
- f — freeboard at the point of assumed damage
- W — the width of the damage opening measured normal to the direction of wave travel
- H_S — significant wave height

Objectives

The primary objective was to develop simple mathematical relationships for the following, as functions of the independent parameters:

- $\overline{Q}_{IN}$ — average in-flow rate onto the flooding deck
- $\overline{Q}_{OUT}$ — average out-flow rate for water draining off the deck through the assumed damage opening
- $\overline{D}$ — asymptotic average water depth on deck
- $\overline{V}$ — asymptotic average water volume on deck, (i.e., $\overline{V} = A\,\overline{D}$)

The Two Phases of the Analytical Research

In order to appreciate the following presentation of results obtained by the SNAME Ad Hoc Panel it is necessary to understand that its analytical work has proceeded through two phases. The first phase encompasses all work accomplished through 28 February 1995 and culminated in the submission of references [1,2]* to the IMO Panel of Experts. The second phase comprises that work accomplished since 28 February 1995.

The work accomplished during the first phase of the SNAME Panel's analytical research was grounded on a weir flow equation embodying a velocity superposition principle. The second phase of analytical research made use of a more exact pressure head form of the weir flow equation. Though the pressure head form of the weir flow equation is acknowledged to be more correct, it is demonstrated that the differences in water-on-deck accumulations between these two formulations are not of practical significance.

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* Numbers in square brackets [ ] refer to references at end of paper.

5. FIRST PHASE OF ANALYTICAL RESEARCH

During the first phase of analytical research a weir flow equation embodying a velocity superposition principle such that the instantaneous differential flow rate, dQ, at any elevation, is given by:

$$dQ = K\left\{\sqrt{h_{OUT}} - \sqrt{h_{IN}}\right\} dA \qquad (1)$$

where: K is an empirical weir flow coefficient.

h_{IN} is the instantaneous head measured on the inside of the flux plane at any specified elevation above the deck ($\eta(t) - f$ in Figure 1).

h_{OUT} is the instantaneous head measured on the outside of the flux plane at any specified elevation above the deck ($D(t)$ in Figure 1).

dA is the differential element of flow area in the flux plane at the specified elevation, $dA = W\,dz$, where W is the width of the damage opening and dz is a differential element of elevation

The motivation for exploring the velocity superposition was, and remains, the ability to separate in-flow and out-flow processes. This is much more conducive to a regulatory strategy wherein a basic water-on-deck burden would be determined based on residual freeboard, f, and significant wave height, H_S. The separation of in-flow and out-flow processes then makes it possible to determine a reduction in the water-on-deck burden in a separate regulatory step based on independent calculations of the actual out-flow potential. This procedure is outlined in reference [2].

Velocity Superposition Results

Results were obtained both from time domain simulations and from probability domain integrals during the first phase of the SNAME analytical research. The probability domain integrals were based on the Gaussian distribution of wave elevation in an irregular sea. References [1,3] provide greater detail regarding the simulation procedures and the development of the Gaussian integrals. A total of 252 time domain simulations were performed.

Figure 3 shows an example time domain simulation record. After approximately 125 seconds the water depth may be seen to attain an average value about which the time domain depth record oscillates thereafter.

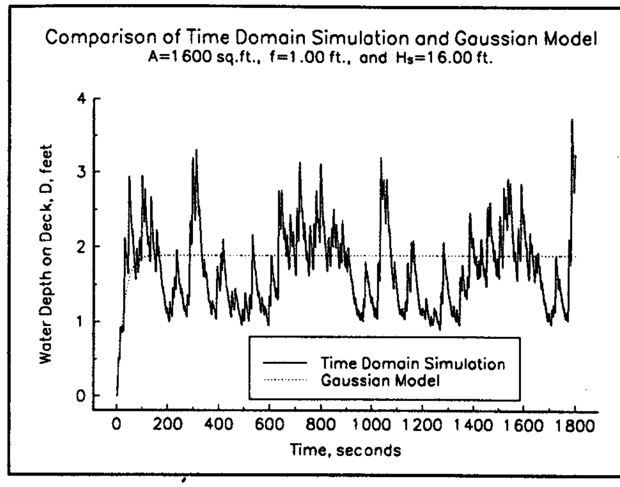

FIGURE 3

Example of Simulated Time Domain Record of Water Depth on Deck

Average In-Flow Rate

When the velocity superposition principle is applied, it is possible to define an average in-flow rate, $\overline{Q}_{IN}$. As may be seen in Figure 4, both the time domain results and the Gaussian model collapse to a single nondimensional functional relationship for $\overline{Q}_{IN}$. The agreement between the Gaussian model and the samples obtained from the time domain simulation is excellent.

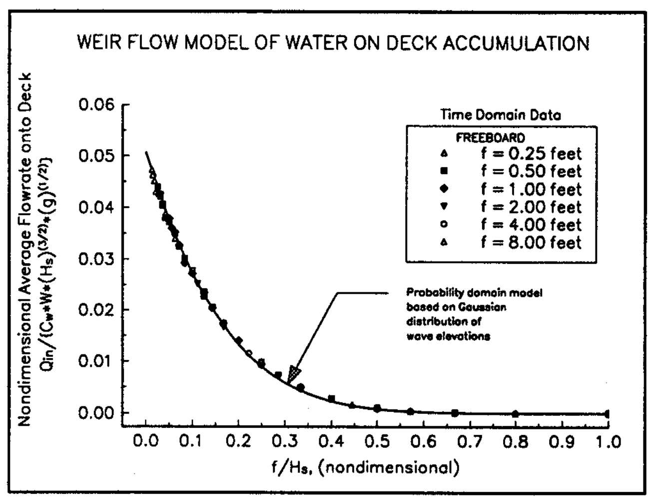

FIGURE 4

Nondimensional In-Flow Rate versus f/H_S

Asymptotic Average Water Depth

Under the assumed velocity superposition principle it is possible to determine the asymptotic average water depth accumulated on deck from the observation that the average in-flow and the average out-flow are equal when the asymptotic average water depth is achieved. Based on this observation, the following equation for the asymptotic average water depth was obtained:

$$W\, C_W \left(\tfrac{2}{3}\right) \sqrt{2\,g}\, \overline{D}^{3/2} = \overline{Q}_{OUT} = \overline{Q}_{IN} \qquad (2)$$

which has as a solution:

$$\overline{D} = \left[\frac{\overline{Q}_{IN}}{W\, C_W \left(\tfrac{2}{3}\right) \sqrt{2\,g}} \right]^{2/3} \qquad (3)$$

Figure 5 presents, in nondimensional form, a comparison between the asymptotic average water depth on deck determined from the Gaussian model, with the sample average values obtained from the time domain simulations. As may be seen in Figure 5 both the time domain results and the Gaussian model collapse to a single nondimensional functional relationship. The agreement between the Gaussian model and the samples obtained from the time domain simulation is excellent.

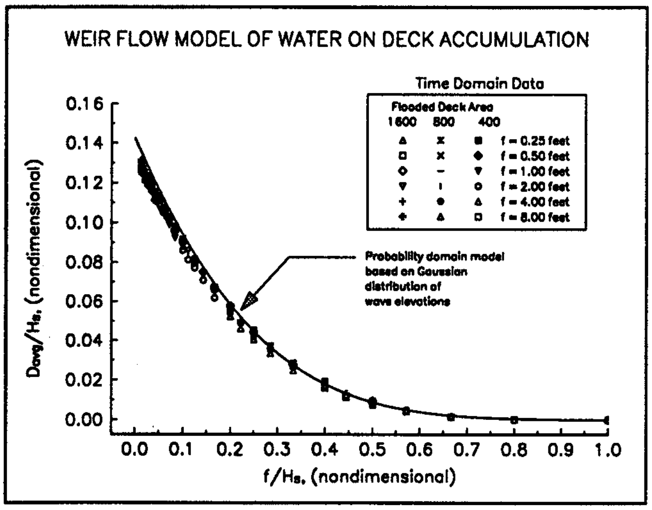

FIGURE 5

Nondimensional Asymptotic Average Water Depth on Deck versus f/H_S

Expected Build-Up Time

As detailed in references [1,3], it is possible to derive a closed form expression for the expected value of the water depth as a function of time, in terms of the flooded deck area, A, the width of the damage opening, W, and the average in-flow rate, $\overline{Q}_{IN}$. Since $\overline{Q}_{IN}$ is a function of residual freeboard, f, significant wave height, H_S, and damage width, W, the expected water depth as a function of time depends on A, W, f and H_S.

The dotted line shown in Figures 3 and 6 shows the expected build-up process for water on deck (labeled Gaussian model). As illustrated by Figures 3 and 6 the agreement is excellent between the expected trend and the mean trend of the simulated time domain data.

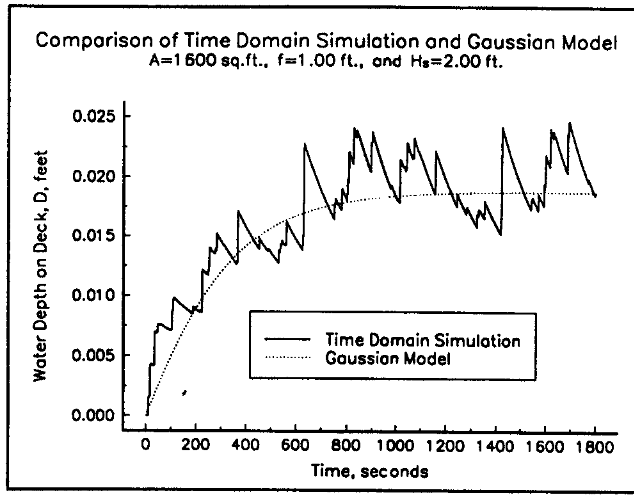

FIGURE 6

Example of Simulated Time Domain Record of Water Depth on Deck, Showing Comparison With the Expected Build-Up Model

Figures 7 and 8 compare the expected (i.e., average) time required to build up to 99% of the asymptotic average water depth with the build-up time required for the first passage above the asymptotic average water depth, as determined from the sample time domain record. Figure 7 is for a flooded deck area of 1,600 square feet while Figure 8 is for a flooded deck area of 400 square feet. The damage width is constant for all cases at W = 10 feet.

The flooded deck area in Figure 7 is four times that in Figure 8 and consequently the build-up time is longer for the cases portrayed in Figure 7 than for the cases in Figure 8.

The build-up time may be seen to be strongly dependent on the value of the asymptotic average water depth on deck. Excepting those cases where the asymptotic average water depth on deck is quite small, the build-up time is quite short. The importance of this finding is that all the most hazardous cases are achieved with great rapidity; it is only the (most likely) inconsequential cases, where only small average water depths are achieved, that build up slowly.

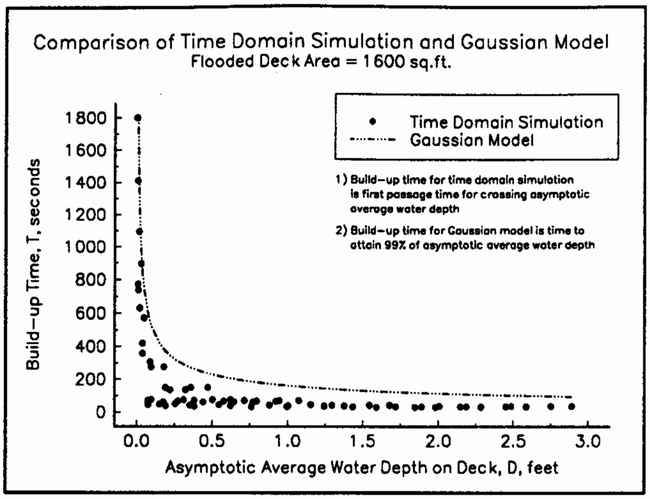

FIGURE 7

Comparison of Build-Up Times Between Time Domain Simulation and Expected Build-Up Model (Labeled Gaussian Model)

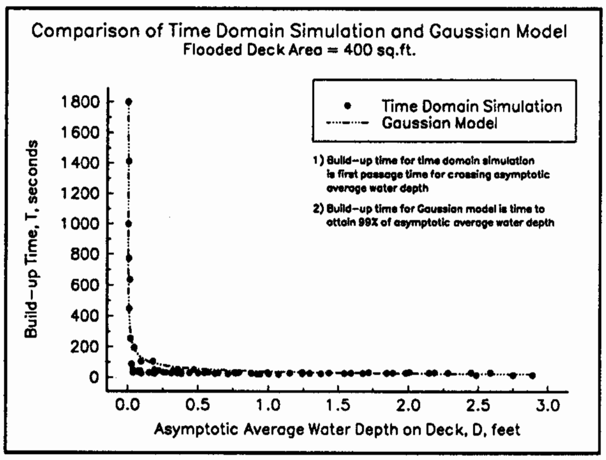

FIGURE 8

Comparison of Build-Up Times Between Time Domain Simulation and Expected Build-Up Model (Labeled Gaussian Model)

Probability Density and Cumulative Probability Distributions

Certain results regarding the stochastic water-on-deck process can be obtained only in the time domain.

Among results that can be obtained from the time domain are sample values for the probability density and cumulative probability distributions for the water depth on deck. Examples of these are shown in Figures 9 and 10.

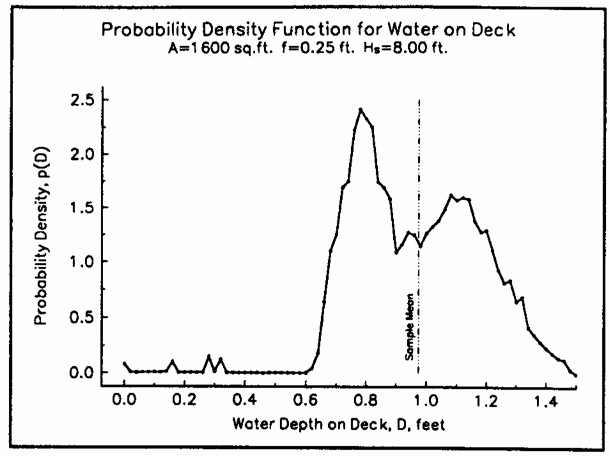

FIGURE 9

Example, Sample Probability Density Function for Water Depth on Deck

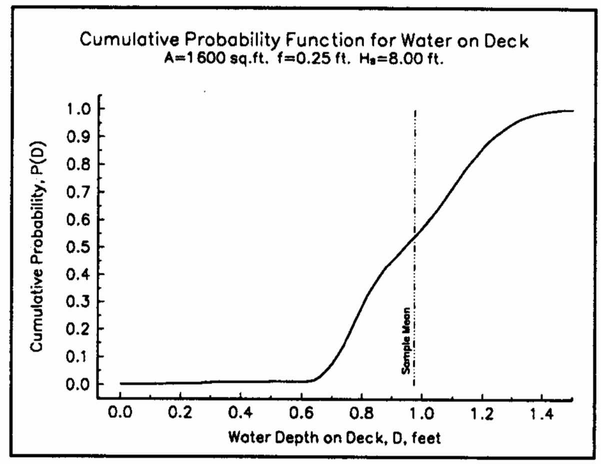

FIGURE 10

Example, Sample Cumulative Probability Distribution of Water Depth on Deck

One of the interesting features is the bi-modal character of the probability density distribution shown in Figure 9. This bi-modal character was observed in many, though certainly not all, of the cases simulated.

Persistence

Another interesting probability result that may be obtained from the time domain simulations is sample values for the persistence of the water depth process. The persistence measures the average duration of the stochastic water depth process above (or below) any specified threshold value. Figure 11 depicts an example of persistence functions sampled in the time domain.

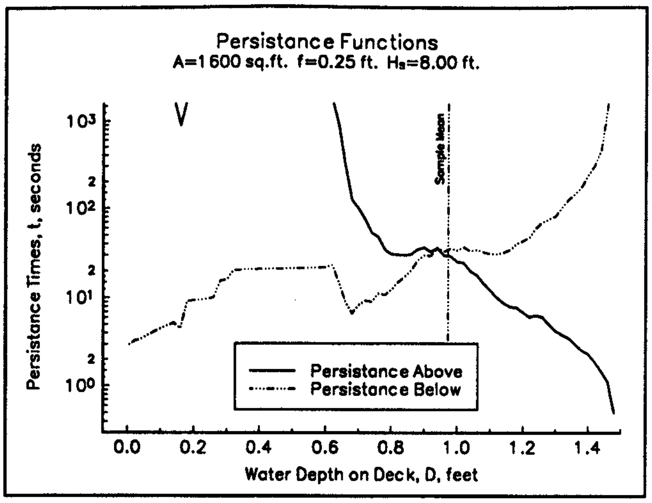

FIGURE 11

Example, Sample Persistence Functions for Water Depth on Deck

Figure 11 indicates that the water depth in this example case persists at or above the asymptotic average water level (sample mean) for an average duration of about 17.5 seconds, and that it persists below that average level for a period of time which averages approximately 20 seconds. The average recurrence interval for process upcrossings of the asymptotic average water depth is the sum of the persistences above and below that threshold, or approximately 37.5 seconds.

The water level in this example case persists at or above a 1.2 foot depth for approximately 7.0 seconds and below this level for approximately 45 seconds.

A study of the dependency trends of persistence with respect to the independent process parameters such as flooded deck area, freeboard, significant wave height and the width of the assumed damage opening, has not been completed at this time.

6. PRESSURE HEAD FORMULATION OF WEIR FLOW EQUATION RESULTS

Subsequent to the 28 February 1995 submission of references [1,2] to the IMO Panel of Experts, and prompted by correspondence with Dr. Vassalos of the University of Strathclyde, the SNAME Ad Hoc Panel investigated the application of the pressure head weir flow, equation 4, throughout. On theoretical grounds the pressure head form of the weir flow equation is regarded as more correct and accurate than the velocity superposition form applied during the first phase of the SNAME analytical studies, but the disadvantage is the loss of separation between in-flow and out-flow processes.

$$dQ = K\,\mathrm{sign}(h_{OUT} - h_{IN})\sqrt{|h_{OUT} - h_{IN}|}\;dA \quad (4)$$

In those regions where instantaneously either $h_{IN} = 0$ or $h_{OUT} = 0$, equation 4 is equivalent to the velocity superposition expression, equation 1. Equations 1 and 4 give differing results only in those regions (elevations) where water exists on both sides of the flux plane.

The method of Gaussian integral equations may be also applied when using the pressure head formulation of the weir flow equation, and the final results differ by only a small amount from those obtained using the velocity superposition method. Thus, for the purposes of regulation and rule making it may suffice to adopt the velocity superposition method and gain the advantages associated with the separation of in-flow and out-flow processes.

It should also be noted that, for the purposes of scientific investigation and engineering, but probably not for the purposes of regulation and rule making, the method of Gaussian integral equations may be applied to cases based entirely on the pressure head formulation of the weir flow equation, and including additional outflow devices such as flow biased freeing ports and deck drains.

The fundamental idea behind the analysis that follows is that the average net volume flux is zero once equilibrium has been established between the in-flow and out-flow processes.

Figure 12 is similar to Figure 5. Figure 12 shows two curvilinear lines, one marked "Weir Flow Model, Based on Velocity Superposition" and the other marked "Weir Flow Model, Based on Pressure Head." Also shown is a straight line approximation suggested by the SNAME Ad Hoc RO RO Safety Panel to the IMO Panel of Experts, and data from the IMD model tests (which will be discussed in a subsequent section of this synoptic paper).

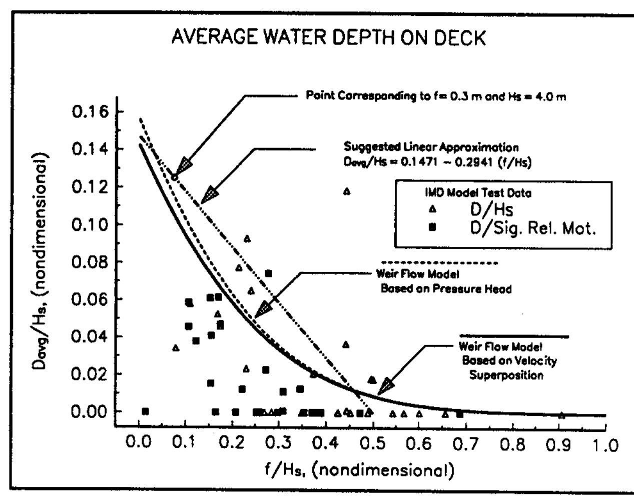

FIGURE 12

Comparison of Asymptotic Average Water Depth on Deck As Estimated by Pressure Head and Velocity Superposition Forms of the Weir Flow Equation

The curve marked "Weir Flow Model, Based on Pressure Head" was obtained using the Gaussian integral approach by solving the following equation for unknown asymptotic average water depth, D:

$$\overline{Q}_{NET} = 0 = \int_{f+D}^{\infty} N(0,\sigma,\eta)\left\{K\,W\left(\tfrac{2}{3}\right)(\eta - f - D)\sqrt{(\eta - f - D)}\right\} d\eta$$

$$+ \int_{f+D}^{\infty} N(0,\sigma,\eta)\left\{K\,W\,D\sqrt{(\eta - f - D)}\right\} d\eta$$

$$+ \int_{f}^{f+D} N(0,\sigma,\eta)\left\{K\,W\left(\tfrac{2}{3}\right)(f + D - \eta)\sqrt{(f + D - \eta)}\right\} d\eta$$

$$+ \int_{f}^{f+D} N(0,\sigma,\eta)\left\{K\,W(\eta - f)\sqrt{(f + D - \eta)}\right\} d\eta$$

$$+ \int_{-\infty}^{f} N(0,\sigma,\eta)\left\{K\,W\left(\tfrac{2}{3}\right)D\sqrt{D}\right\} d\eta \qquad (5)$$

where:

- K is a dimensional flooding coefficient.
- W is the width of the damage opening.
- f is the freeboard.
- H_S is the significant wave height.
- η is the wave elevation.
- σ is the standard deviation of the wave elevation process, $\sigma = H_S / 4$.

and

$N(0,\sigma,\eta)$ is the Gaussian (normal) probability density function with zero mean and standard deviation, σ.

$$N(0,\sigma,\eta) = \frac{e^{-\left\{\eta^2/2\sigma^2\right\}}}{\sigma\sqrt{2\pi}}$$

Note that the factor K W is a common factor which may be factored out of equation 5 (which means that the asymptotic average depth of water does not depend on either the weir flow coefficient, K, or the damage width, W).

The equation for D has been solved using a numerical root finding procedure. The result is the curve shown in Figure 12 labeled "Weir Flow Model, Based on Pressure Head" and graphed using a short dashed line. As shown in Figure 12, the pressure head equations lead to a slightly greater predicted depth of water on deck at low freeboard values when compared with the corresponding results obtained from the velocity superposition equations, but the difference is not large. At values of f/H_S greater than 0.45, the difference is negligible.

Overall, there is excellent agreement between the *pressure head* and *velocity superposition* weir flow models. The advantage which the SNAME Ad Hoc Panel finds with the velocity superposition method is the ability to de-couple the in-flow and out-flow processes, which greatly facilitates the process of evaluating out-flow credits for freeing ports and deck drains, as was done in references [2,3].

7. OUTFLOW THROUGH FREEING PORTS

Freeing Port Performance in the Time Domain

During the first phase of the SNAME Ad Hoc Panel's analytical studies a limited number of time domain simulations were performed that included freeing ports. Figure 13 compares the water-on-deck time history, with and without freeing ports, for an example case with a freeboard of 0.25 feet (0.076 m), a significant wave height of 8.0 feet (2.44 m) and a flooded deck area of 1,600 sq. ft. (149 m^2). The freeing port modeled in this time domain case had an aggregate width of 20 feet and a height of 1.0 foot. The width of the assumed damage was 10 feet. Thus the ratio of the freeing port width to the assumed damage width was $W_{FP}/W = 2.0$, and the ratio of the freeing port height to the significant wave height was $h/H_S = 0.125$.

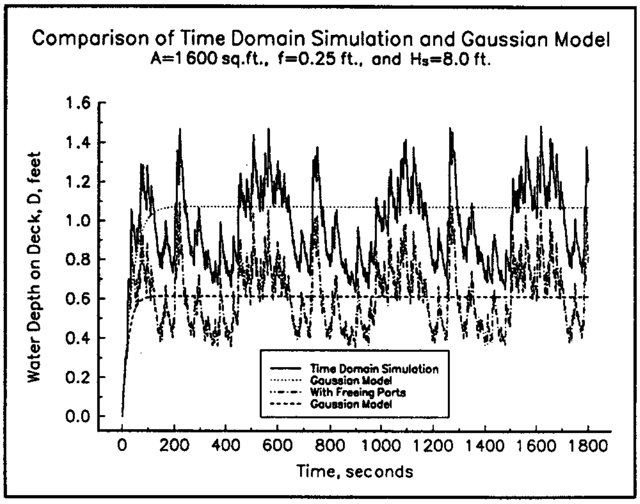

FIGURE 13

Time History of Water Depth on Deck Comparison Case With and Without Freeing Ports

Figure 14 shows the sample probability density functions for the same comparison case, with and without freeing ports.

It may be seen in both Figures 13 and 14 that the general character of the water-on-deck process is preserved, but that it occurs about a lower mean value when freeing ports are provided. For the example shown the ratio of the average water depth with freeing ports to that without freeing ports is about 0.57.

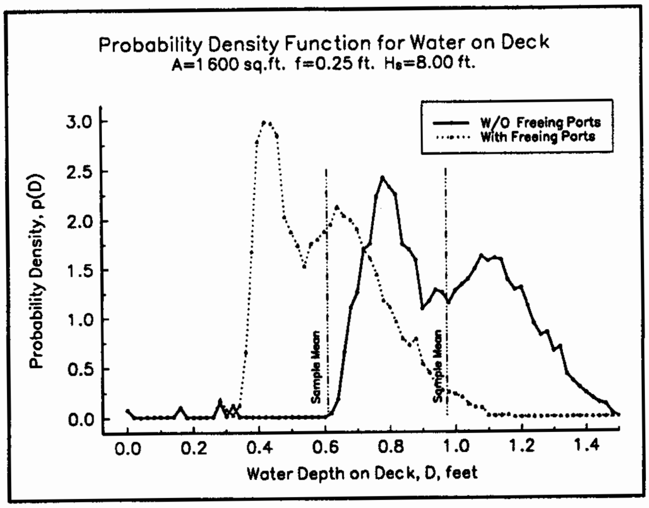

FIGURE 14

Sample Probability Density Functions for Water Depth on Deck Comparison Case with and Without Freeing, with Head Loss of $H_L/H_S = 0.01$ and Freeing Port Height $h/H_S = 0.200$

References [2,3] contain discussion and examples of how out-flow credits could be applied in a simple and practical procedure suitable for inclusion in a regulatory framework.

One final result obtained based on the pressure head formulation of the weir flow equation using the method of Gaussian integral equations is presented in Figure 15 without development.

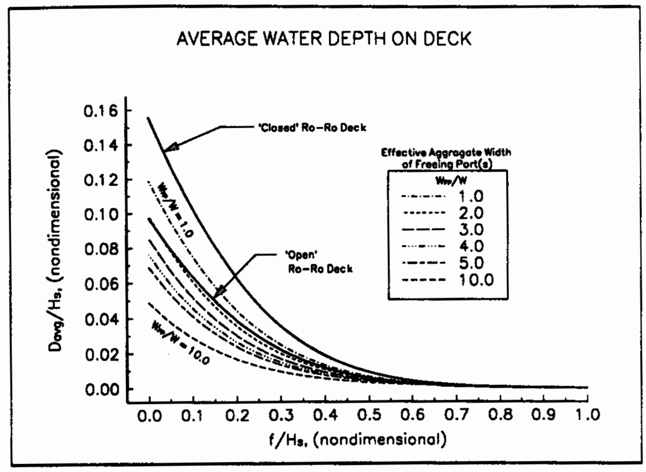

FIGURE 15

Freeing Port Performance Obtained Based on Pressure Head Formulation of Weir Flow Equations Using the Method of Gaussian Integral Equations

The curve in Figure 15 labeled " 'Closed' RO RO Deck" corresponds to the curve in Figure 12 labeled "Weir Flow Model, Based on Pressure Head." Six curves are shown in Figure 15 for freeing ports with a height ratio of $h/H_S = 0.125$, corresponding to freeing port aggregate width ratios, W_{FP}/W, of: 1.0, 2.0, 3.0, 4.0, 5.0 and 10.0. Also shown is a curve labeled " 'Open' RO RO Deck," which was obtained for the stationary ship by permitting out-flow both through the damage opening and through a permanent opening of width, W, on the leeward side of the vessel (and assuming no waves on the leeward side).

Figure 15 indicates that, for the case of the stationary ship, flow biased freeing ports ($h/H_S = 0.125$) with an aggregate width twice the width of damage at the deck edge are as effective as a completely open deck. Flow biased freeing ports with an aggregate width four times the width of damage will result in a reduction to approximately 50% of that obtained without freeing ports.

Other Outflow Issues

Reference [2] may be consulted for details of the development of the freeing port outflow and also for similar development regarding outflow through deck drains (scuppers). Other issues discussed in reference [2] include the effect of casings on outflow processes, the attenuation of the significant wave height on the lee side of the vessel, and the effect of freeing port height on the general effectiveness of freeing ports.

It should be noted that in the first phase of the SNAME research, freeing ports and deck drains (scuppers) were shown to be complementary. Freeing ports are most effective in removing large volumes of water from the deck, but lose their effectiveness when the water depth on deck becomes small. Deck drains are not particularly effective in removing large volumes of water, but, because of the suction head in the deck drain tailpipe, deck drains are more effective than freeing ports in removing small residual depths of water from the deck.

8. DEPENDENCIES INDICATED BY MATHEMATICAL MODEL

The dependence of the main dependent variables examined in this paper on the independent parameters, is summarized in the following table.

TABLE 1

Dependence of Dependent Variables on Independent Parameters

Dependent Variables		Independent Parameters				
		f	Hs	W	A	Cw
Average In-Flow Rate	$\bar{Q}_{IN}$	YES	YES	YES	NO	YES
Average Out-Flow Rate	$\bar{Q}_{OUT}$	YES	YES	YES	NO	YES
Asymptotic Average Water Depth	$\bar{D}$	YES	YES	NO	NO	NO
Average Build-Up Time	t	YES	YES	YES	YES	YES

The most important result is that, under the assumptions of these analytical studies, the asymptotic average water depth is independent of the width of the assumed damage opening, the flooded deck area, and the weir flow coefficient. The only dependencies for the asymptotic average water depth of the stationary ship are freeboard and significant wave height.

9. MODEL EXPERIMENTS AT IMD

Prior to the formation of the SNAME Ad Hoc Panel, Transport Canada had commissioned a series of experiments to investigate the adequacy of the SOLAS 90 regulations for RO RO passenger ships. The experiments were carried out at the Institute for Marine Dynamics (IMD) in St. John's, Newfoundland between June 1993 and September 1994. The possible benefits of flapped freeing ports for ferries with centerline casings were a major aspect of the study, the results of which are described in detail in reference [4].

After the formation of the IMO Panel of Experts and the SNAME Ad Hoc Panel, Transport Canada commissioned an additional series of experiments carried out in August 1995 to investigate the effects of permanently open freeing ports on survivability. This research gave a comparison between a fully enclosed deck, permanently open freeing ports, and flapped freeing ports – all at the same ship stability conditions.

The initial proposal for new regulations from the IMO Panel of Experts focused on the appropriate level of water on the deck of the damaged ferry. The Transport Canada model experiments had included detailed measurements of the water build-up on the deck as a function of time. These data were investigated to support the analytical model developed as part of the SNAME Ad Hoc committee work described above. This section of the paper describes the model experiments and summarizes the results.

Two Dimensional Physical Model Used at IMD

The model used for this study was a simplified representation of a large RO RO ferry. The hull had a constant cross-section over its length as shown in Figure 16. An exploded view of the model is shown in Figure 17. The result of the simplification, was to reduce the dynamics of the hull to two dimensions and factors such as change of trim with flooding were not considered. The basic dimensions of the model are given in Table 2.

TABLE 2

Basic Parameters, Intact Model

	Model	Prototype
Scale	20	1.00
Length o.a. (m)	8.000	160.00
Beam o.a. (m)	1.330	26.60
Draft, intact, (m)	0.250	5.00
Beam, w.l. (m)	1.023	20.47
Displacement (cu. m)	1.458	11667
Displacement (kg f.w./tonnes s.w.)	1457	11382
KM (m)	0.645	12.909

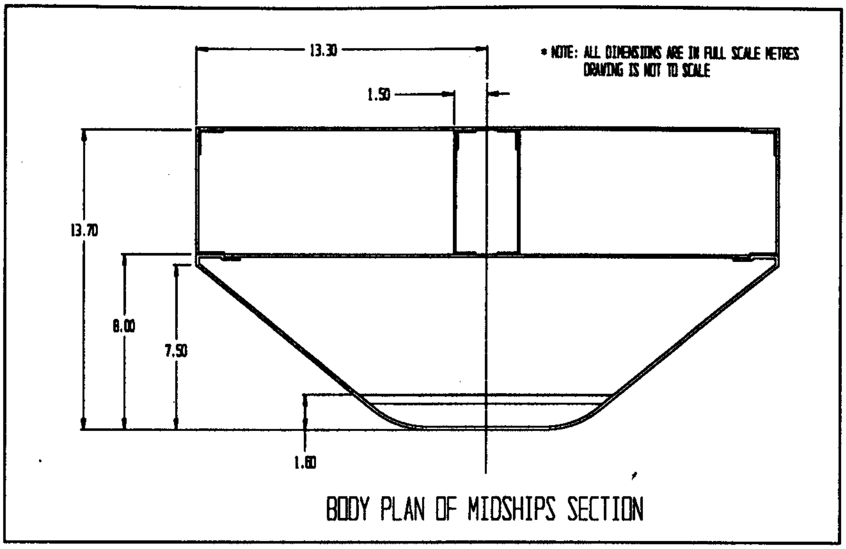

FIGURE 16

Midship Section of Two-Dimensional Physical Model Used for Tests at IMD

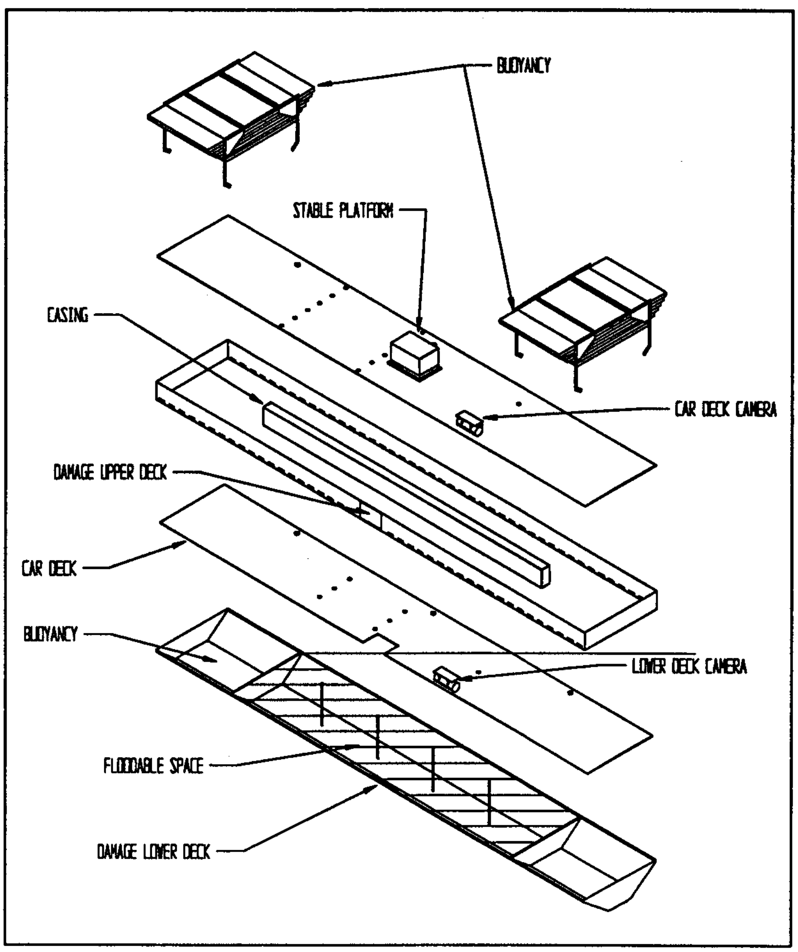

FIGURE 17

Exploded View of Physical Model Used in Tests at IMD

The study was carried out for a range of heights for the center of gravity at residual freeboards of 0.5, 1.0, 1.5 and 2.0 meters. Damage to the ship was represented by holes in the side of the model, covered with sliding trap doors. The extent of the idealized damage to the hull and deck was set using the relationships given by the International Convention for the Safety of Life at Sea, reference [5].

All the damage holes were idealized as rectangles. The length of the damage to the hull corresponded to 3 meters plus 3% of the length of the ship (7.8 meters). The penetration of the deck corresponded to 20% of the beam at the deck (5.32 meters). The midpoint of the damage was located at midships. The double bottom shown in Figure 16 was not damaged since it was more than B/5 from the edge of the deck.

Total freeing port area (A_{FP}, per side), was varied between zero and 0.3L, where L is the length of the deck. Two types of freeing port arrangement were studied. One type had permanently open ports and the other type had ports fitted with flaps that allowed water to drain off the deck, but prevented wave action flooding the deck through the port. Testing was carried out with various combinations of vertical center of gravity (KG), freeing port area and presence or absence of a centerline casing.

The freeing port dimensions were 1.2 meters by 0.6 meters, with the long side close to the deck. The flaps were made as light as possible using Plexiglas and hinged along the top edge. The flaps had three operational positions: locked shut, working flaps and locked open.

Before testing, the intact metacentric height was checked with an inclining experiment. The model was then flooded and the residual freeboard and trim were confirmed in that condition. If the model was heeled or trimmed in the flooded condition, this was corrected and the modified weight distribution was used in the intact condition. For all the experiments the model had the same intact displacement and the residual freeboard was set by varying the length of the hull that could be flooded. Details of the length of flooding are given in Table 3.

TABLE 3

Residual Freeboard and Flooded Length

Residual Freeboard (m)	Flooded Length (m)
0.5	85.88
1.0	75.52
1.5	62.88
2.0	47.02

The tests described in this report were carried out in irregular waves equivalent to the steepest waves likely to be encountered for a given significant wave height. All sea states were generated using JONSWAP spectra with g of 3.3. A summary of the significant wave heights and modal periods used during the testing is given in Table 4.

TABLE 4

Wave Heights and Modal Periods Used in Irregular Wave Experiments

Nominal Significant Wv. Ht. (m)	Modal Period (sec)	Measured Significant Wv. Ht. (m)	$H_s / (g T_0^2)$ x 1000
0.5	5.0	0.590	2.406
1.0	5.5	1.255	4.229
1.5	6.0	1.688	4.780
2.0	6.5	1.957	4.722
3.0	7.0	2.780	5.783
4.0	7.5	3.774	6.839
5.0	8.0	4.633	7.379
6.0	8.5	5.020	7.083
7.0	9.0	6.110	7.689

In order to calculate the volume of water on the deck as a function of time, the model was fitted with an array of 14 wave probes. The model was also instrumented to measure roll, heave and relative motion between the deck and the wave surface. Wave probe signals for water level inside and outside the hull were set to zero for the intact, dry calm water condition, which was recorded at the start of each run. Also four video cameras recorded the motion of the ship and the build-up of water on the car deck.

The model was tested in the IMD towing tank (200m x 12m x 7m), with the model's centerline parallel to the wave crests, and the damage side into the waves. Data acquisition began in the calm water period before the wave train reached the model. Once the 'steady' wave height had developed, the model was released and allowed to drift with the waves. Both damage doors were then opened simultaneously and the hull allowed to flood. The model was kept parallel to the incident waves by a small tug on guiding lines, fitted along the centerline of the hull. These lines were carefully handled so as to minimize any motions other than yaw. In the cases when the model did not capsize, the full scale equivalent time corresponded to approximately 40 minutes.

The design of the model and the experiment techniques are described in more detail in Reference [8].

10. EXPERIMENTAL RESULTS AT IMD

Average Depth of Water on Deck

The data selected for this analysis came from all of the experiments which did not result in a capsize. Wave height, relative motion and volume of water on deck were calculated from the time histories of data recorded during the experiments. The starting times were selected based on an estimate of when a steady state wave action on the car deck had built up, and the stopping time was taken as the end of the run. The freeboard was corrected from the nominal values to an average value for the actual test condition, using the hydrostatic data for the model and the average volume of water on the deck.

Figure 18 shows average water depth on the deck, normalized by significant wave height (D_{avg}/H_S) plotted against residual freeboard, normalized by significant wave height (f/H_S). It can be seen that the numerical model presents a reasonably realistic method for predicting the upper limit of depth of water on the car deck. There are only five experimental observations higher than the predictions.

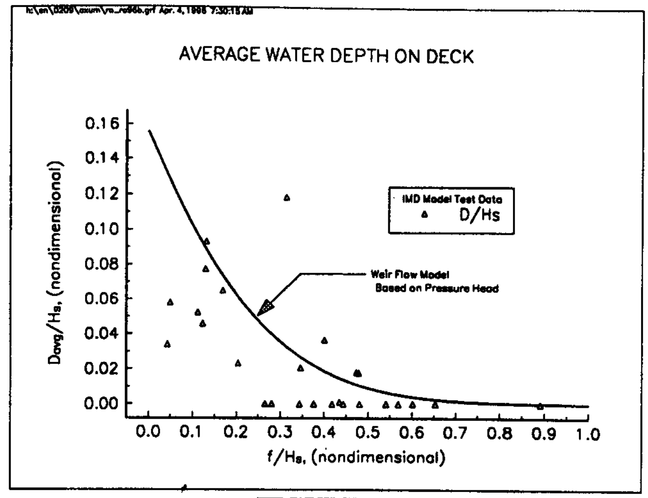

FIGURE 18

Accumulated depth of water on deck, using significant waveheight

The hull in the simulation is fixed in space and does not represent the actual test conditions for the experiments where the hull is free to heave, roll and sway with the wave forces. Relative motion between the deck edge and the water surface was on average 1.46 times the wave height. For the stationary assumptions in the simulation, the relative motion was the same as the wave height. Figure 19 shows the model data plotted with relative motion as the normalizer, rather than wave height. This shows slightly less scatter in the experiment results, but the line is more conservative than the observed data.

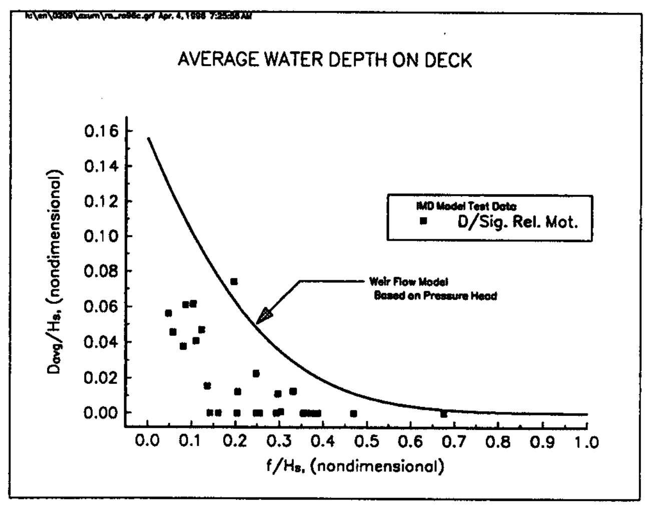

FIGURE 19

Accumulated Depth of Water on Deck, using Significant Relative Motion

The measured data confirm the predictions that above a certain ratio of freeboard to wave height there is very little water on the deck. The predicted line tends to overestimate the observed amount of water on deck at low values of freeboard to wave height ratio. These conditions were very difficult to measure on a dynamic model, since they were the most prone to capsizing or sinking and this may be part of the reason for the discrepancy.

An interesting observation was that even at relatively low values of f/H_S there were some cases when there were very low volumes of water on the deck. Although the instrumentation in the model was not designed to measure very low depths of water, video records of the experiments confirmed that the volume of water on the deck in these cases was negligible. From the video tapes, it was seen that below a critical value of wave height, a lot of the water was coming onto the deck through the damage in the deck and not through the side. In these cases it was very easy for the water to drain back out through the hole in the deck, without flooding it.

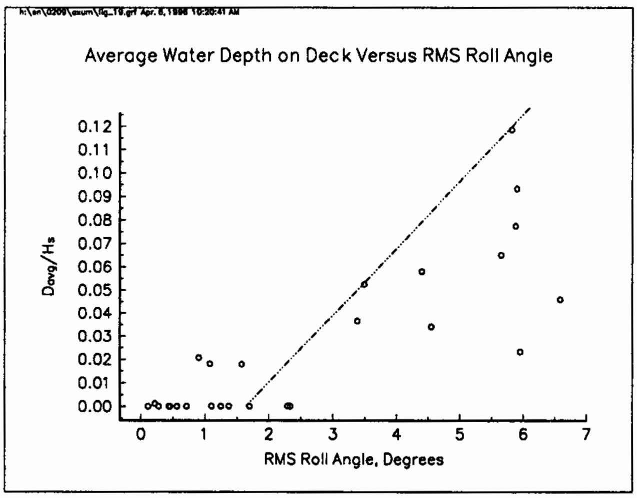

FIGURE 20

D/H_S against RMS Roll Angle

The other factor that has to be considered is the relationship between relative motion and roll angle. The flow of water onto the deck did not become significant until the roll angle exceeded a critical value. For small roll angles, the water remained relatively static and easily drained off the deck. For higher roll angles, a wave system built up on the deck which affected the drainage rates. Figure 20 shows average depth of water on deck, divided by significant waveheight, against RMS roll angle. It can be seen from this figure that the RMS roll angle had to be greater than approximately 2 degrees before there was a significant depth of water accumulated on the deck.

Effect of Residual Freeboard and Freeing Ports on Survivability

An important conclusion determined from the experiments was that permanently open freeing ports are of no benefit to the survivability of the vessel, and in some cases they have a detrimental impact. The ability of the freeing ports to drain the deck is severely compromised by the water flooding in through the permanently open port. Flapped ports, however, do not allow the ingress of water to the vehicle deck but do permit drainage. Their effect is to introduce a progressive benefit to the vessel in terms of survivability when freeing port area is increased. In all cases, the use of flapped freeing ports either maintained the level of survivability of the fully enclosed hull or improved it.

For the vessel in the fully enclosed condition, at least 2 meters of residual freeboard was necessary to ensure survival in waves with a significant height of 4 meters. At this residual freeboard only very small volumes of water entered the car deck through the damage. As the residual freeboard was reduced, then survivability was achieved by increasing the area under the GZ curve above the minimum requirement of 0.015 meter-radians required by SOLAS 90.

With the freeing ports permanently open at $A_{FP}/L=0.3$, the vessel required 2 meters of residual freeboard to survive waves with a significant height of 4 meters. With flapped freeing ports of the same area, the vessel survived the same waveheight with 1 meter of residual freeboard.

The research also showed that the centerline casing had a slight detrimental effect on survivability of the fully enclosed deck. When the casing was removed, there was often a tendency for the hull to heel away from the damage, increasing the freeboard on the side of the incoming waves. When the flapped freeing ports were used, the water on the deck could drain off through freeing ports on both sides, whereas when the casing was fitted, the water tended only to drain off through the ports on the side of the damage. The removal of the centerline casing caused a significant increase in survivability when flapped freeing ports were used. However, when permanently open freeing ports were used, the casing did not influence the survivability. Water flowing in through the ports caused a heel towards the damage and the benefits of the increase in freeboard due to heel could not be obtained.

Limiting Waveheights for Flapped Freeing Ports

The limiting waveheights for different areas of freeing ports fitted with flaps are given in Table 5. The table gives the stability condition for the ship, after damage, together with the limiting waveheight that the model would survive interpolated from the test data. These data are given in full in reference [4].

Results are given for two residual freeboards, 0.5m and 1m. The data given include the vertical center of gravity above the keel, KG, the residual freeboard in calm water with no water on the deck, the area of the GZ curve (meter-radians) and the range for positive righting moment, GZ, in degrees. For each freeing port area, A_{FP}/L, the limiting significant waveheight, in meters, is given. A_{FP} is the total area of freeing ports on one side of the ship, in square meters and L is the length of the floodable deck in meters.

All results are given for the model with the centerline casing included. Typical KG heights for this size of ship are approximately 10.6 m.

The highly flared hull, which is typical of many North American ferries, meant that the constraints for SOLAS 90, in terms of GZ area and GZ range did not occur simultaneously. For this reason, the range and the area have been included in the summary of the results.

Also, since the data were derived from a prismatic hull form, they may not necessarily apply directly to real hull shapes.

TABLE 5

Limiting significant waveheight that the simplified ferry would survive after damage (interpolated from experiments)

KG, m	7.809	9.765	10.890	9.755	10.830	12.430
Residual Freeboard, m	0.50	050	0.50	1.00	1.00	1.00
GZ area, m-radians	0.067	0.027	0.015	0.071	0.041	0.015
GZ range, deg	15.1	9.2	7.1	15.0	12.0	8.7
Limiting Significant Wave Height, m						
$A_{FP}/L = 0$	> 4	1.6	1.4	> 4	2.3	1.8
$A_{FP}/L = 0.075$	-	1.9	-	-	3.1	1.6
$A_{FP}/L = 0.150$	-	2.2	1.4	-	> 4	2.9
$A_{FP}/L = 0.300$	-	> 4	1.9	-	> 4	> 4

11. BOW SCOOPING MODEL TESTS

Two recent RO RO ferry accidents (the *Estonia* and the *Herald Of Free Enterprise*) have occurred when large quantities of water have accumulated on the vehicle deck from being forced aboard by the ship being driven with significant forward speed. The discussions on how to deal with this problem focused around ways of minimizing the chance of such ingress of water by ensuring the efficiency of the watertight bow closures and even by having further subdivision on the vehicle deck to limit over the bow flooding to the forward end of the ship. The majority of large ferries operated by the British Columbia Ferry Corporation have relatively high freeboard and non-watertight superstructures covering their vehicle decks, and any requirement to make this superstructure watertight or to subdivide the car decks was not seen as necessary to maintain a proper level of safety. In order to verify this position it was decided to undertake a number of model tests and analyses to investigate the relationship between initial freeboard, wave conditions, vessel trim and vessel speed.

Two existing models of BC Ferry vessels were used for the experiments which were conducted at the Ocean Engineering Facilities of BC Research Inc., in Vancouver, B.C. The larger model was of the *Queen of New Westminster*, a 5950 MT displacement single ended, twin screw vessel, while the smaller vessel was a generic double ended ferry of 3800 MT displacement. Both these vessels were tested over a range of speeds, initial freeboards and wave conditions. In addition, tests were also conducted varying the area of freeing ports fitted.

Since the principle purpose of these tests was to indicate whether these types of ferries would have any bow scooping problems, the data were analyzed in a way to compare initial freeboard with the likelihood of bow scooping. Figure 21 shows the initial static freeboard at the bow, normalized by the significant wave height plotted against the instantaneous freeboard at the bow, again normalized by the significant wave height.

Reviewing the data it is clear that the instantaneous freeboard at the bow is always positive for an initial static freeboard to significant wave height ratio of 2.5 or larger. Since these type of ferries, as designed and operated in the U.S. and Canada, generally have minimum static freeboard in excess of 3.0 times the wave height, it is felt that the experimental data support that operation of this type vessel can be safely continued without special requirements for watertight bow closures or subdivision of the car deck.

In those two tests where bow scooping occurred, large quantities of water came aboard very quickly due to the forward motion of the vessel and due to the fact that the additional weight of water accumulating on the bow further lowered the bow freeboard exacerbating the problem. The tests conducted with various freeing port areas showed that once a bow scooping incident is commenced freeing ports have little effect. In fact the only way to avoid serious consequences appears to be to slow down or stop the ship quickly to causing the water on deck to flow out through the bow opening.

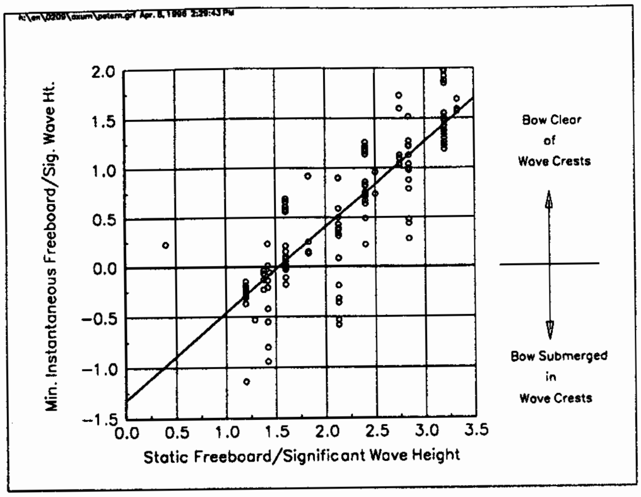

FIGURE 21

Minimum Instantaneous
Freeboard vs. Static Freeboard
(Both normalized by Significant Wave Height)

12. RO RO FERRY HUMAN PERFORMANCE

The SNAME Ad Hoc Panel, in assessing the risks faced by the Canadian and United States ferry fleets, recognized that the human element is a vital part of RO RO ferry safety. Clearly, the loss of the Estonia involved failures in human performance, both in shoreside management and aboard the vessel. In order to evaluate the risks founded in human performance and management practices, the SNAME Ad Hoc Panel developed a questionnaire based upon the IMO's International Ship Management (ISM) Code. The survey was distributed to all the RO RO ferry operators in Canada and the United States. Responses were received on approximately 30% of the vessels surveyed. This section summarizes some of the survey's key findings.

The first part of the survey was designed to profile the vessels in the fleet. Approximately 70% of the respondents operate on short, dedicated routes in partially protected waters where service is provided 24 hours a day in a mass transit-type operation with no overnight service. All of the vessels submitting responses operate in waters where the sea temperature can go below 50° F and were originally built as RO RO ferries. A majority of the vessels were fitted with centerline casings. None are fitted with vehicle deck flooding alarms or transverse bulkheads. All of the operators reported no significant problems with ventilation on the vehicle deck, however, only a few tested for carbon monoxide.

Most of the operators are able to maintain an experienced core of well trained crew members year round. During peak periods of operation with the associated high passenger loads, some of the operators supplement their crews with inexperienced personnel. Basic emergency training is provided to the crew members in the following priority order:

1) First Aid
2) Basic Fire Fighting
3) CPR
4) Man Overboard
5) Damage Control
6) Advanced Fire Fighting

The crews do not receive any special training on the operational risks pertaining to the RO RO ferry fleet nor has a risk analysis been done to determine which elements of shipboard emergencies associated with RO RO ferry operations are critical to the safety of passengers and the survival of the vessel. Most operators agreed that special qualifications are needed for their crews in handling large numbers of passengers in routes of short duration, but no such training presently exists.

Most operators do not have written contingency plans for dealing with catastrophic events which may occur during RO RO ferry operations. However, they are developing emergency plans to comply with the intent of the ISM Code. There was agreement among the operators that providing a safety briefing to passengers was difficult because of the large number of passengers on short duration voyages. Most operators perform the safety brief by showing videos in the terminal or on the vessel. Passengers are not typically involved in the drills.

Very few operators felt that security was a problem on their vessels. They consider their typical monitoring methods of roving security patrols, reliable internal communications and closed circuit television, sufficient. Bridge mimic panels indicating the status of all hull opening closure devices are not common.

Language barriers between crew members and passengers are not a problem. Foreign tour groups usually have a translator and the ship's crew generally pay special attention to these groups.

The biggest concern in vessel operation was special route hazards, the most prevalent being ice and extreme tidal ranges.

13. CONCLUSIONS

The work of the SNAME Ad Hoc Panel provides a strong basis for understanding the fundamentals of water accumulation on the deck of a RO RO ferry due to two mechanisms: 1) a collision induced damage opening; and 2) bow scooping. For clarity, the conclusions are grouped to the specific study which supports them.

Water on deck after damage

The volume of water accumulated on deck is a complex dynamic phenomena, depending greatly upon the relative motion of the vessel in the water and the vessel freeboard. However, a simplified mathematical model has been developed to predict the accumulation of water on deck, and results were compared to physical tests of a two-dimensional ship model. We believe that correlation between these methods is reasonably good and that this mathematical model provides a practical method for analyzing the phenomena of water-on-deck accumulation.

In many (though not all) of the physical model experiments, the resulting average depth of water falls within the upper bound predicted by the mathematical model. Taken together, the results of the analytical work and model tests clearly show the relationship between the depth of water accumulation, to both freeboard and wave height. The following generalizations can be made from these studies:

- The depth of water that accumulates on the deck of a damaged ship is primarily a function of freeboard in way of the damaged opening and significant wave height.
- The depth of water is independent of the width of the damage opening and the flooded deck area.
- For freeboard to significant wave height ratios of greater than about 0.5, there is little or no accumulation of water on deck.
- For the minimum damaged freeboards permitted in the SOLAS regulations (0.3 meters), at significant wave height seas of 4 meters, the resulting water accumulation on deck closely correlates with the 0.5 meter value originally suggested by the IMO Panel of Experts.
- Where combinations of residual freeboard and significant wave height correspond to potentially dangerous asymptotic average depths of water-on-deck, these quantities of water are likely to build up very quickly.

In addition to the water on deck analysis for closed deck RO RO ships, the effects of freeing ports on the depth of water was also investigated. Again, the results of the analytical work and model tests show reasonable correlation and can be summarized by the following generalizations:

- Permanently open freeing ports do not increase the survivability of a damaged RO RO vessel in waves, and in some cases they may even reduce survivability. The ability of water to enter the car deck through the open freeing ports offsets the ability for it to subsequently drain from them.
- The use of flow biased freeing ports can effectively reduce the average depth of water accumulation on deck and increase capsize safety. The effectiveness of the freeing ports is primarily based on the residual freeboard, the depth of water on deck, and the area of the freeing ports.
- For maximum effectiveness, flow biased freeing ports should be as low as possible to the deck and have a height greater than 0.25 m. Freeing port heights exceeding 0.5 m provide little additional benefit.
- Freeing ports are most effective when coupled with residual freeboards of 1 meter or more.
- The effectiveness of freeing ports may be diminished by the presence of a casing.

Water on deck from bow scooping

The experimental studies on the model of the *Queen of New Westminster* demonstrate that the accumulation of water on deck from bow scooping is a realistic scenario and depends on vessel freeboard at the bow, forward speed, significant wave height and wave period. In general, no water on deck accumulation is observed when the bow freeboard is more than 2.5 times the significant wave height. Freeing ports are ineffective in reducing the volume of water associated with bow scooping due to the large volumes of water involved and the practical limitations on sizing the freeing ports. When bow scooping does occur, potentially dangerous quantities of water are taken aboard very quickly. These events develop so rapidly that there may be little that can be accomplished operationally to prevent or mitigate the adverse consequences.

User surveys

The North American RO RO ferry fleet contains a wide variety of vessel types, ranging from small, river-crossing barges to large, European style vessels operating in the North Atlantic and Gulf of Alaska. As such, these vessels are a significant portion of the world RO RO ferry fleet.

The user surveys revealed that Canadian and United States RO RO ferry operators place an appropriate emphasis on basic crew training. Additional emphasis should be placed on identifying emergency scenarios which are particular to RO RO ferry vessels, developing contingency plans to deal with these types of emergencies and ensuring adequate crew training for dealing with these situations. It appears the IMO's ISM Code will help facilitate the development of such action.

14. RECOMMENDATIONS

The SNAME Ad Hoc RO RO Safety Panel concurred with and endorsed many of the recommendation by the IMO Panel of Experts [7]. Some of the POE's conclusions endorsed by the SNAME Ad Hoc Panel are:

- Water-on-deck is a realistic and demonstrable phenomena which is not adequately accounted for in the current SOLAS damage stability regulations.
- The accumulation of water-on-deck is primarily a function of the damaged freeboard and the significant wave height at the time of the casualty.
- Biased flow freeing ports can be effective in reducing the amount of water accumulation on deck.
- Capsize is primarily a hydrostatic phenomena, occurring once a critical volume of water on deck is reached. This can lead to practical proposed regulations based primarily on existing analysis methods of evaluating damage stability with the additional burden of water-on-deck.

The 1995 SOLAS conference was unable to reach consensus to incorporate the recommendations of the IMO Panel of Experts (regarding water-on-deck) into new international regulations. As a consequence of this outcome of the 1995 SOLAS conference, a group of North West European countries (Sweden, Norway, Finland, Denmark, Germany, United Kingdom, Ireland and France), acting under the provisions of Resolution 14 of the 1995 SOLAS Conference, are in the process of adopting a regional agreement to implement these recommendations of the IMO Panel of Experts in their national waters for all new and existing RO RO passenger vessels.

Having generally supported the efforts and recommendations of the POE, the authors of this paper finds this lack of international consensus regrettable, and applauds the efforts and initiative of the North West European Countries.

The authors of this paper make the following short- and long-term recommendations for which we will be seeking endorsement by the full SNAME Ad Hoc RO RO Safety Panel:

1) Apply the SOLAS 95 Resolution 14 (i.e., satisfy SOLAS 90 residual stability standards with water-on-deck) to new construction of U.S. and Canadian RO RO Passenger vessels.
2) Phase in the application of the SOLAS 95 Resolution 14 to existing U.S. and Canadian RO RO passenger vessels, based on a timetable initially considering ships most susceptible to this phenomenon (i.e. low damaged freeboards and operation in high sea state areas) and with the lowest existing safety levels (based on IMO A.265 survivability index.).
3) The U.S. and Canadian delegations to IMO should continue to press for broader international acceptance of the IMO Panel of Experts type water-on-deck criteria.
4) The U.S. and Canadian delegations to IMO should support the continued development of harmonized probabilistic damage stability regulations to include the effects of water-on-deck for all ships with large open type compartments located near the damaged waterline.

The first recommendation given above has already been adopted voluntarily by U.S. and Canadian owners for their current new construction projects. This includes the Alaska Marine Highway System's new Ocean Class vessel and B.C. Ferry Corporation's new Century Class vessels.

The new Alaska Ocean Class vessel is a 116 m vessel intended for unrestricted ocean service in the Gulf of Alaska. It is worthy of note that the design of the new Ocean Class vessel satisfies the IMO Panel of Experts recommendations regarding stability with water-on-deck without the necessity of any subdivision of the RO RO vehicle deck. The residual freeboard necessary to satisfy the IMO Panel of Experts recommendations has been achieved in the case of the new Ocean Class vessel through the introduction of watertight longitudinal bulkheads located a distance of B/5 inboard of the sides below the subdivision deck. The resulting wing void tanks are cross-connected port and starboard to ensure symmetric flooding in a damaged condition.

Recommendation for further research which could lead to practical refinements of the proposed damaged stability and water-on-deck criteria are as follows:

- More model testing for vessels with open sterns and/or with bulwarks only, particularly in relation to the effectiveness of flapped freeing ports.
- The use of various other deck drainage approaches should be addressed to evaluate their effectiveness in comparison with the performance of the vertical flaps tested to this point.
- Test programs similar to that conducted by IMD should be carried out using hull forms more representative of the trim behavior of a true vessels when flooded, so that extrapolation of the results to regulatory efforts is more applicable to real ships.
- The existing stationary ship analytical model should be expanded and extended to include ship motions, and relative motion with respect to the local wave surface.

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