TP 12991E

FLOODING PROTECTION OF RO-RO FERRIES
PHASE II

Prepared for
Transportation Development Centre
Safety and Security
Transport Canada

March 1997

Submitted by:

J.H. Rousseau, P.Eng.
Polar Design Associates Ltd.
659-G Moberley Road
Vancouver, BC V5Z 4B2
Tel. (604) 873-4601
Fax (604) 874-2735
Email pda@polardesign.com

March 1997

Un sommaire français se trouve avant la table des matières.

ACKNOWLEDGEMENTS

The author would like to acknowledge the leadership and project definition efforts provided by Mr. André Taschereau as the Transportation Development Centre project officer, and Mr. Mariusz Koniecki as the Marine Safety Directorate OPI. Additional credit is due to Mr. Tom Peirce, the TDC project officer during the origination of the investigations into RO-RO capsize safety in this project, and Mr. Jacques Laframboise who was also involved in the efforts at TDC.

Acknowledgements are also due to Messrs. David Molyneux and David Cumming of the NRC Institute for Marine Dynamics, as well as to the technical and research staff at the facility. Additional assistance from Dr. Neil Bose and Mr. Dag Friis of the Memorial University of Newfoundland Ocean Engineering Research Centre is also greatly appreciated.

Transport Canada / Transports Canada

PUBLICATION DATA FORM

1. Transport Canada Publication No.	2. Project No.	3. Recipient's Catalogue No.
TP 12991E	7866	

4. Title and Subtitle	5. Publication Date
Flooding Protection of RO-RO Ferries, Phase II	March 1997
	6. Performing Organization Document No.
7. Author(s)	8. Transport Canada File No.
J.H. Rousseau	ZCD1460-319
9. Performing Organization Name and Address	10. PWGSC File No.
Polar Design Associates Ltd. 659-G Moberley Road Vancouver, B.C. V5Z 4B2	XSD91-00106-(673)
	11. PWGSC or Transport Canada Contract No.
	T8200-1-1518/01-XSD
12. Sponsoring Agency Name and Address	13. Type of Publication and Period Covered
Transportation Development Centre (TDC) 800 René Lévesque Blvd. West 6th Floor Montreal, Quebec H3B 1X9	Final
	14. Project Officer
	A. Taschereau

15. Supplementary Notes (Funding programs, titles of related publications, etc.)

Co-sponsored by Transport Canada Marine Safety Directorate. See also TP 12310E and TP 12581E.

16. Abstract

Further investigations into Roll-On/Roll-Off (RO-RO) ferry capsize safety after damage are presented, including a new set of model test data and re-analysis of the information from the earlier test programs in the project. A 1:16 scale model was derived from an existing Canadian RO-RO vessel, with modifications to simplify the shape for numerical modelling purposes (to be carried out at a later date). Construction features included a Safety Of Life At Sea (SOLAS)-compliant damage opening, flapped freeing ports and a removable centreline casing, along with variable floodable lengths to set different residual freeboards after damage.

The model was tested at the National Research Council Institute for Marine Dynamics in St. John's, Newfoundland in September of 1996. The data from these tests were analysed along with the information gathered in the earlier Phase I model tests. Conclusions were drawn with respect to the effectiveness of SOLAS regulations in providing safety, the impact of design features such as bilge keels, centreline casing, and freeing ports, and the effect of residual freeboard after damage. Various methods of presenting the data were adopted from leading research in the field, in an attempt to validate them and to contribute to the development of further knowledge especially as it relates to Canadian vessels.

17. Key Words	18. Distribution Statement
Ferries, damage, stability, model testing, freeing ports, SOLAS, safety	Limited number of copies available from the Transportation Development Centre

19. Security Classification (of this publication)	20. Security Classification (of this page)	21. Declassification (date)	22. No. of Pages	23. Price
Unclassified	Unclassified	—	xvi, 52, apps	—

CDT/TDC 79-005
Rev. 96

Canada

Transports Canada / Transport Canada

FORMULE DE DONNÉES POUR PUBLICATION

1. N° de la publication de Transports Canada TP 12991E	2. N° de l'étude 7866	3. N° de catalogue du destinataire
4. Titre et sous-titre Flooding Protection of RO-RO Ferries, Phase II		5. Date de la publication Mars 1997 6. N° de document de l'organisme exécutant
7. Auteur(s) J.H. Rousseau		8. N° de dossier - Transports Canada ZCD1460-319
9. Nom et adresse de l'organisme exécutant Polar Design Associates Ltd. 659-G Moberley Road Vancouver, B.C. V5Z 4B2		10. N° de dossier - TPSGC XSD91-00106-(673) 11. N° de contrat - TPSGC ou Transports Canada T8200-1-1518/01-XSD
12. Nom et adresse de l'organisme parrain Centre de développement des transports (CDT) 800, boul. René-Lévesque Ouest 6e étage Montréal (Québec) H3B 1X9		13. Genre de publication et période visée Final 14. Agent de projet A. Taschereau

15. Remarques additionnelles (programmes de financement, titres de publications connexes, etc.)

Coparrainé par la Direction générale de la sécurité maritime de Transports Canada.
Voir aussi TP 12310E et TP 12581E.

16. Résumé

Compte rendu des dernières recherches sur la stabilité après avarie et la tenue au chavirement d'une maquette 1:16 représentant un traversier roulier connu, travaux qui ont nécessité un réexamen de l'information tirée de recherches antérieures. La forme de la maquette avait été modifiée par rapport au navire pour en simplifier la représentation géométrique et pour en faciliter la modélisation numérique future. La maquette comportait une ouverture après avarie conforme aux critères SOLAS (Convention internationale pour la sauvegarde de la vie humaine en mer), des sabords de décharge munis de panneaux articulés, un encaissement central amovible ainsi que des compartiments inondables de longueurs variées permettant de faire varier la hauteur du franc-bord résiduel.

Les essais sur maquette ont eu lieu à l'Institut de dynamique marine à St. John's (Terre-Neuve) en septembre 1996. Les résultats ont été analysés à la lumière de ceux de la phase I du programme. Des conclusions sont tirées concernant la stabilité après avarie apportée par les critères SOLAS et l'influence sur la tenue au chavirement de dispositifs tels que quilles de roulis, encaissement central et sabords de décharge ainsi que concernant la hauteur du franc-bord résiduel. Diverses méthodes de présentation de l'information recueillie ont été adaptées de recherches éminentes dans ce domaine, dans le double but de valider ces méthodes et de contribuer à étendre la recherche, notamment par des applications à des navires canadiens.

17. Mots clés Traversiers, stabilité, essais sur maquette, sabords de décharge, convention SOLAS, sécurité	18. Diffusion Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

19. Classification de sécurité (de cette publication)	20. Classification de sécurité (de cette page)	21. Déclassification (date)	22. Nombre de pages	23. Prix
Non classifiée	Non classifiée	—	xvi, 52, ann	—

CDT/TDC 79-005
Rev. 96

Canada

SUMMARY

International efforts in studying the damage stability of roll on-roll off (RO-RO) ships have been of increasing importance on the world stage in recent years, especially following the loss of the *Herald of Free Enterprise* in 1987 and the 1994 sinking of the *Estonia*. Both provided impetus to regulatory efforts while underlining the importance of rational design and sound operating practices.

The Transportation Development Centre (TDC) and the Marine Safety Directorate (formerly Canadian Coast Guard, Ship Safety Branch) of Transport Canada sponsored an investigation in 1993-96 with a view to identifying the prime factors affecting the survivability of RO-RO passenger ferries when flooded symmetrically about amidships. The work was undertaken by Polar Design Associates Ltd. (PDA) and the National Research Council Institute for Marine Dynamics (IMD). The conclusions of the research contributed to Canada's position at international meetings of the International Maritime Organization (IMO) and its associated committees and panels.

The first phase of the research involved a model replicating the design characteristics and proportions of large Canadian flag ferries. The test program, based on Safety Of Life At Sea (SOLAS)-compliant loading conditions, took place in the clear water towing tank at IMD in St. John's.

Several interesting and important conclusions were drawn from this effort with respect to the capsize phenomenon, the effectiveness for freeing ports, the impact of a centreline casing, and the variables which seem to have some correlation with capsize survival. These included the observations that:

- capsize is the result of the accumulation of a "critical volume" of water on deck;
- accumulation of the water depends on relative motion at the damage opening;
- capsize occurs hydrostatically once the critical volume is reached; and,
- freeing ports and centreline casing have a considerable impact on the accumulation of water on deck.

An extension of this phase was commissioned to address specific issues related to enclosed, semi-enclosed and open shelterdeck configurations, and the use of flaps on the freeing ports for vehicle deck drainage, which act as "non-return" enclosures on the vehicle deck. The most important conclusion was that permanently open freeing ports give no survivability benefit to a damaged RO-RO vessel in waves.

The analyses presented in Phase I revealed the impact of some key parameters which are useful as indicators of capsize safety:

- GM and GZ in damaged condition as parameters related to the magnitude of restoring moment and consequently to the amount of water which can accumulate on the bulkhead deck before capsizing occurs;

- residual freeboard at the damage opening corresponding to a likelihood of bulkhead deck flooding due to vessel relative motion in waves;
- presence of flapped freeing ports on the RO-RO deck; and,
- presence of a centreline casing on the RO-RO deck.

The chief objective of Phase II of the research was to systematically investigate the capsize phenomenon in order to determine the nature of predictive formulations which could be applied to RO-RO ships at the design stage. This was based on the model test analyses in conjunction with a thorough examination of the state-of-the-art in RO-RO regulation and research. Any analysis would include the Phase I data as well.

Further work involved research into vessels with biased flow devices (in this case, flapped freeing ports) and centreline casings, since these items are present in several major vessels in the Canadian flag fleet. Additional work was carried out to investigate the effect of bilge keel damping and of changing sea spectrum on RO-RO safety.

The results of the Phase II model test program have provided some useful information. Freeing ports have once again demonstrated an ability to enhance the safety of the RO-RO vessel when fitted with biased flow devices (in this case, flaps).

A centreline casing seems to have a slight detrimental effect. This probably stems from the effect it seems to have upon the ability of water to flow within the RO-RO space, which despite the free surface effect can have benefits in terms of heeling away from the damage or allowing the opposite side freeing ports to help in deck drainage.

The research of Spouge, Hutchison, Pawlowski, and Vassalos has led to a probabilistic formulation which incorporates static stability, deck flooding, and sea state in leading to a calculation for survival probability, "s_i".

While freeing ports and centreline casings are not included in the combined probabilistic approach, the approach offers a valid solution to the survivability question at the present time. From the standpoint of the designer, the process begins with calculation of the angle of maximum GZ for a given damage condition in the standard manner. This is followed by determination of the critical volume of flood water on the vehicle deck which leads to a heel approximately equal to the angle of maximum GZ. This second computation is performed with the RO-RO deck considered as an intact displacer.

A relationship between head of water on the vehicle deck in this condition may then be applied, yielding an approximate safe significant wave height which may be compared with wave statistics (e.g., from a "wave atlas") for the area of operation. The survivable wave height should be in excess of the prevailing sea conditions. This excess should be applied in a probabilistic manner throughout the vessel, taking account of all damage conditions at representative loading conditions. The probabilistic formulation permits the inclusion of other factors such as the likelihood of collision, in the normal manner of these calculations. The alternative, of course, is to design for the worst case scenario, and ensure that the vessel survives in all conditions (i.e., the safe significant wave height always generously exceeds the prevailing significant wave height).

Some adjustments may be made to the survivable wave height for certain vessels, although firm values should be the subject of further study. For example, the contribution of bilge keels or flapped freeing ports may offer additional safety; the presence of a centreline casing will diminish survivability to a certain extent.

In the long term, ships meeting the criteria adopted by international convention as a result of international research efforts will provide an acceptable level of safety to the travelling public and the working crews, by ensuring that the risk of maritime disasters is reduced through rational design and in concert with human factors measures for safer operations.

The following recommendations are made for further research:

- Numerical simulation studies of the dynamic flooding problem, including the effects of inflow/outflow, sea-induced motions and internal sloshing on the buoyancy and stability of the ship.
- Additional tests and analysis to quantify the survivability impact of bilge keels, casings, and freeing ports in a form compatible with survivability formulations by expanding the database available.
- Investigations into the effect of asymmetric flooding of spaces below the vehicle deck, and asymmetry in weight distribution due to load shifting.
- Tests involving flow restriction on the RO-RO deck (i.e., as a result of vehicles).

SOMMAIRE

Les recherches mondiales sur la stabilité après avarie des traversiers rouliers se sont intensifiées au cours des dernières années. Elles ont été rendues encore plus urgentes par le naufrage en 1987 du *Herald of Free Enterprise* et par celui de l'*Estonia* en 1994. Ces deux naufrages ont montré l'urgence d'une réglementation plus adéquate et ont souligné l'importance d'une approche fondée sur des concepts rationnels et des techniques saines de mise en oeuvre.

À la demande du Centre de développement des transports et de la Direction générale de la sécurité maritime de Transports Canada (anciennement Direction, Sécurité des navires de la Garde côtière canadienne), des recherches ont été menées entre 1993 et 1996 sur les principaux facteurs influençant la tenue au chavirement des traversiers rouliers à passagers après une avarie survenue en leur tiers milieu et suivie d'un envahissement symétrique par l'eau. Elles avaient été confiées à Polar Design Associated Ltd. (PDA) et à l'Institut de dynamique marine (IDM) du Conseil national de recherches. Ces recherches ont eu un retentissement mondial, affirmant la position du Canada au sein de l'Organisation maritime internationale (OMI) et des comités mis sur pied par cet organisme.

La phase I de la recherche a été menée sur une maquette possédant les caractéristiques types des gros traversiers canadiens. Un programme d'essai conforme aux critères de stabilité en charge SOLAS (Convention internationale pour la sauvegarde de la vie humaine en mer) a été mené dans le bassin des carènes de l'IDM à St. John's, rempli d'eau libre de glaces.

Cette phase a débouché sur des résultats aussi intéressants qu'importants sur les variables régissant le chavirement, telles que les sabords de décharge, la présence ou non d'un encaissement central et toute autre caractéristique influençant la survie après avarie. Elle a permis notamment d'observer :

- que le chavirement nécessite la présence d'un volume d'eau dit critique sur le pont-garage;
- que l'accumulation d'eau dépend de l'ampleur du roulis au droit de l'avarie;
- que le chavirement se produit par effet hydrostatique une fois que le volume d'eau a atteint le point critique;
- que la présence de sabords de décharge ou d'un encaissement central modifient considérablement l'accumulation d'eau sur le pont.

La phase I a été prolongée afin d'approfondir l'effet de diverses configurations de superstructure (fermée, partiellement ouverte ou complètement ouverte), ainsi que l'influence des sabords munis d'un panneau articulé et qui agissent comme clapets de non retour sur le pont-garage. L'observation la plus probante tirée des travaux complémentaires a été que les sabords demeurant ouverts ne sont d'aucune utilité à la stabilité du navire après avarie et en présence de houle.

L'analyse des résultats de la phase I a montré l'importance de certaines variables clés dont on pourrait se servir comme indicateurs de l'imminence d'une condition de chavirement, à savoir :

- les valeurs de GM et de GZ après avarie, indicateurs de l'ampleur de la force de redressement et, par conséquent, de la quantité d'eau qui peut s'accumuler sur le pont-garage avant que la condition de chavirement ne s'amorce;
- la hauteur du franc-bord résiduel (FBR) au droit de l'avarie, indicateur de la probabilité d'un envahissement par l'eau en raison du roulis du navire provoqué par la houle;
- la présence de sabords de décharge munis d'un panneau articulé, tout le long du pont-garage;
- la présence d'un encaissement central faisant partie de ce pont.

L'objectif principal de la phase II était d'étudier systématiquement les conditions de chavirement afin de déterminer les paramètres que l'on pourrait appliquer dès l'étape de la conception des navires. Cette étude s'est appuyée sur les analyses d'essais sur maquette et sur un examen approfondi de l'état de la recherche et de la réglementation concernant les navires rouliers. Évidemment, toute nouvelle analyse devrait également porter sur les données de la phase I.

Les travaux complémentaires ont abordé la question des sabords de décharge à panneau articulé et d'un encaissement central, étant donné que les gros traversiers de la flotte canadienne sont dotés de ces éléments. Les chercheurs ont également étudié l'effet des quilles de roulis et de différents régimes de houle.

Le programme d'essais sur maquette de la phase II a produit certains résultats intéressants. Ainsi, il a été démontré que les sabords de décharge, notamment ceux munis d'un panneau articulé, donnent une meilleure tenue au chavirement.

L'existence d'un encaissement central semble avoir un effet légèrement négatif sur la stabilité après avarie, effet probablement dû au fait qu'il empêche l'eau de circuler librement à l'intérieur du pont-garage. Cette libre circulation de l'eau apporte, malgré l'effet de carène liquide, plusieurs avantages, notamment celui de faire pencher le navire sur le flanc opposé à celui où se trouve l'avarie, et de permettre à l'eau de s'évacuer par les sabords le long de ce flanc.

La recherche menée par Spouge, Hutchison, Pawlowski et Vassalos a débouché sur une méthode d'analyse de la stabilité après avarie selon une approche probabiliste, tenant compte des critères de stabilité à l'état statique, d'envahissement du pont-garage par l'eau et d'état de mer. Cette méthode permet le calcul d'un indice de sécurité $S_{i.}$.

La méthode probabiliste ne tient aucunement compte de l'effet dû à l'absence ou à la présence de sabords ou d'un encaissement central, mais elle offre pour l'heure une solution valable pour la détermination de la survivabilité. Du point de vue de l'architecte naval, cette détermination commence par le calcul, selon les méthodes habituelles, de l'angle de gîte au

GZ maximum du correspondant à un état d'avarie donné. Le concepteur doit par la suite calculer le volume critique d'eau envahissant le pont-garage auquel correspond un angle de gîte à peu près égal à celui où le GZ atteint son maximum. Ce deuxième calcul tient le pont-garage pour un volume intact.

On peut alors établir une relation entre la hauteur d'eau sur le pont-garage dans cette condition d'avarie afin d'estimer la hauteur de houle significative sécuritaire et, ainsi, de déterminer à l'aide d'un « atlas des vagues »si les états de mer dans la zone d'exploitation considérée peuvent dépasser cette valeur. Évidemment, la hauteur de houle significative sécuritaire doit être supérieure dans tous les cas. Ensuite, il faut appliquer la marge de sécurité obtenue à l'ensemble du navire selon une méthode probabiliste, prenant en compte tous les états d'avarie possibles dans des conditions de chargement représentatives. L'approche probabiliste permet d'inclure d'autres variables comme la probabilité d'une collision selon la procédure normale de calcul. L'autre possibilité est évidemment de concevoir le navire en fonction du scénario le plus défavorable et ainsi assurer la survivabilité du navire dans toutes les conditions (c.-à-d. adopter une hauteur de houle significative sécuritaire dépassant toujours par une bonne marge la hauteur de houle significative susceptible d'être rencontrée).

Pour certaines catégories de navires, des ajustements pourront être apportés à la hauteur de houle surviable, bien qu'il serait opportun de mener des études complémentaires visant à en arriver à des valeurs fermes. Par exemple, les quilles de roulis et les sabords de décharge à panneau articulé peuvent accroître le niveau de sécurité du navire alors que la présence d'un encaissement central aura pour effet de réduire la survivabilité dans une certaine mesure.

À long terme, les navires conformes aux critères adoptés par convention internationale à l'issue de travaux de recherche menés à l'échelle mondiale offriront au public voyageur et aux équipages un niveau de sécurité acceptable, résultat de la réduction des risques de catastrophes maritimes par l'application de pratiques de conception rationnelles et une organisation ergonomique du travail de nature à rehausser la sécurité des opérations.

Les chercheurs ont fait les recommandations suivantes concernant les recherches futures :

- Étudier par simulation numérique la dynamique de l'envahissement, y compris l'effet des flux entrants/sortants, des mouvements induits par la houle et du ballottement des eaux embarquées sur la flottabilité et la stabilité du navire.
- Réaliser des essais et des analyses additionnels pour quantifier en termes compatibles avec les paramètres retenus l'effet des quilles de roulis, des encaissements et des sabords de décharge sur la survivabilité du navire.
- Étudier l'effet de l'envahissement asymétrique des espaces sous le pont-garage et la distribution asymétrique du poids due au déplacement du chargement.
- Mener des essais pour étudier les effets des obstacles à la libre circulation de l'eau sur le pont-garage (les véhicules par exemple).

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

APPENDICES

GLOSSARY OF ABBREVIATIONS and IMPORTANT TERMS

B, B_{WL}	Beam: width of the vessel, maximum value or value at the waterline
C	A constant used in calculating non-dimensional wave height Hn, equal to 1.0 when damage is on the side of wave action and 0.5 when damage faces away from the incident waves
C_W	Empirical weir flow coefficient
D	Depth of water on the RO-RO deck
Draft	Submerged depth from keel to waterline
GM	Transverse metacentric height: the distance from the centre of gravity (G) to the metacentre in roll (M)
GMn	Non-dimensional GM
Freeing Port	More generally in this report, a “biased flow device”, whereby water may drain from the car (RO-RO) deck via the device but may not flow onto that deck
g	Acceleration due to gravity: 9.81 m/s^2
GZ	Righting lever at a particular angle of heel
GZ Area	Area under the stability (GZ) curve over a range of angles
h	Head of vehicle deck water above the external static waterline
Hs	Significant wave height: the average height of the 1/3 highest waves in a sea
Hn	Non-dimensional Hs
IMD	National Research Council Institute for Marine Dynamics: a hydrodynamics testing facility located in St. John’s, Newfoundland
IMO	The International Maritime Organization
KG	Vertical centre of gravity: the distance from the centre of gravity (G) to the keel (K)
L, L_{SOLAS}	Length as defined in the IMO SOLAS Conventions, between perpendiculars at the extremities of the deepest subdivision waterline

Load Line Used to denote a total freeing port area in accordance with the 1966 International Load Line Convention, using terminology of the International Maritime Organization.

MSD Marine Safety Directorate, Transport Canada

PDA Polar Design Associates Ltd.: Naval Architecture consulting firm located in Vancouver, British Columbia

Permeability The floodable volume of a space which can be occupied by sea water when opened to the environment; is less than the total geometrical volume from the ship's lines due to the volume of structure and equipment in the space

$\overline{Q}_{IN}$ Average inflow rate to the RO-RO deck (SNAME/Hutchison)

Range The extent of heel angles over which the GZ remains positive

RF Residual freeboard after damage: the distance from the waterline to the car deck at side

RO-RO A roll-on/roll-off vessel, which loads and discharges cargo and passengers via one or more large continuous vehicle decks with little or no internal subdivision; typically applied to passenger ferries

s_i Probabilistic factor used in survivability calculations; expresses the probability that a vessel in a given damage condition "i" will survive that condition

SNAME The Society of Naval Architect and Marine Engineers, a New York based technical society

SOLAS International Convention for the Safety of Life at Sea, as negotiated through the International Maritime Organization (IMO)

t Time, seconds

T Wave modal period, seconds

TDC Transportation Development Centre, Transport Canada

0.3L Denotes a combined freeing port area of 30 percent of the SOLAS length on each side of the vessel; this value was proposed by the IMO Panel of Experts

W Width of the damage opening, measured normal to the direction of wave travel

η	Wave elevation, measured vertically with respect to the mean waterline
ω	Wave circular frequency: $2\pi \div$ (modal period)
Δ	Displacement, in tonnes
∇	Volume of water on RO-RO deck, in m^3
σ_{MAX}	Angle of heel where righting lever GZ is maximum

1. INTRODUCTION

The Department of Transport in the United Kingdom initiated several studies into the damage stability of roll on-roll off (RO-RO) ships following the loss of the *Herald of Free Enterprise* in 1987 [1-4]. These efforts included model tests, full scale tests, and mathematical modelling. Additional research was performed in the areas of risk analysis, collision resistance, hull form and superstructure effects, and assessment of internal arrangements and devices.

The need to further address the safety of RO-RO ferries was highlighted by the 1994 loss of the *Estonia*, which provided additional impetus to ongoing regulatory efforts while underlining the importance of rational design and sound operating practices.

The Transportation Development Centre and the Marine Safety Directorate (formerly Canadian Coast Guard, Ship Safety Branch) of Transport Canada sponsored an investigation in 1993-96 with a view to identifying the prime factors affecting the survivability of RO-RO passenger ferries when flooded symmetrically about amidships. The work was undertaken by Polar Design Associates Ltd. (PDA) and the National Research Council Institute for Marine Dynamics (IMD). The conclusions of the research contributed to the position of Canada at international meetings of the International Maritime Organization (IMO) and its associated committees and panels. One of the most significant of these was the Panel of Experts which was formed to consider and improve constructional and operational aspects of RO-RO safety, and make recommendations for amendments to the 1990 Safety of Life at Sea (SOLAS 90) Convention.

1.1 Phase I

A comprehensive model test program was formulated to systematically investigate the effect on capsize of variations in residual freeboard, freeing ports and the presence (or absence) of the centreline casing on the vehicle deck, in waves up to 7 m significant height. This investigation formed the first phase of an effort to develop criteria for assessing RO-RO capsize safety after damage in dynamic sea conditions [5,6].

A model replicating the design characteristics and proportions of large Canadian-flag ferries was designed and used as the basis for conducting the study in SOLAS compliant loading conditions. The test program took place in the clear water towing tank at IMD.

Several interesting and important conclusions were drawn from this effort with respect to the capsize phenomenon, the effectiveness for freeing ports, the impact of a centreline casing, and the variables which seem to have some correlation with capsize survival. These included the observations that:

- capsize is the result of the accumulation of a “critical volume” of water on deck;
- accumulation of the water depends on relative motion at the damage opening;
- capsize occurs hydrostatically once the critical volume is reached; and,
- freeing ports and centreline casing have an impact on the accumulation.

1.2 Phase I - Extension

The above research was based on a model with a fully enclosed superstructure over the vehicle deck. However, many RO-RO ferries currently in operation have partially or completely open vehicle decks, and no data were available from model tests to evaluate their capsize safety. Given the need for such data, Transport Canada directed further study into this area by the performers of the previous research[3,4].

This extension of the Canadian research effort was aimed at specific investigations related to enclosed, semi-enclosed and open shelterdeck configurations, and at the use of flaps on the freeing ports for vehicle deck drainage. These devices act as "non-return" enclosures on the vehicle deck, and it was desired to determine the impact (if any) on water build-up on that deck.

The most important result derived from the Phase I Extension was the demonstration that permanently open freeing ports give no survivability benefit to a damaged RO-RO vessel in waves. The conclusions were presented to the Intersessional Working Group on RO-RO Ferry Safety at the International Maritime Organization in London in mid-October 1995.

1.3 Phase II

The analyses presented in Phase I revealed the impact of some key parameters which may be useful as indicators of capsize safety:

- GM in the damaged condition as parameters related to the magnitude of restoring moment and consequently to the amount of water which can accumulate on the bulkhead deck before capsizing occurs;
- Residual freeboard at the damage opening corresponding to a likelihood of bulkhead deck flooding due to vessel relative motion in waves;
- Presence of flapped freeing ports on the RO-RO deck; and,
- Presence of a centreline casing on the RO-RO deck.

It was considered logical to investigate these parameters further and use them in formulating the relationships reflecting the physics of capsizing in order to relate them to design variables that are quantifiable at the ship design stage. Planning therefore began for the Phase II investigations which would involve a different RO-RO vessel model.

The chief objective of the research was to systematically investigate the capsize phenomenon in order to determine the nature of predictive formulations which could be applied to RO-RO ships at the design stage. This was to be based on the model test analyses in conjunction with a thorough examination of the state of the art in RO-RO regulation and research.

This entailed the study of the SOLAS regulations themselves, to determine the physical meaning of the damage stability criteria as they relate to typical Canadian RO-RO ships and to quantify their contribution to the safety of these vessels.

It was also desired to include research into vessels with biased flow devices (in this case, flapped freeing ports) and centreline casings, since these items are present in several major vessels in the Canadian flag fleet.

An intermediate objective was to validate the findings of Phase I by demonstrating that the same parameters and data trends governed the capsize of the new vessel model, and hence can be applied widely. If different parameters were identified (e.g., maximum GZ rather than GM), re-analysis of the Phase I data would be carried out.

Some further work was to be carried out to investigate the effect of bilge keel damping on RO-RO safety, as well as the impact of changing sea spectrum on the survivability of these ships.

1.4 Phase II

Phase II was to carry on the investigations into the capsize phenomenon, both in terms of applying similar testing methods to a different ship and using the newer analysis techniques to examine the data from all phases. In addition, the data collection effort was to be planned around using the information recorded to be able to set up numerical simulations to evaluate new formulations. This would provide the possibility of faster validation (or elimination) of these methods by using available model test data, hence avoiding the need to continuously plan and set up test programs for each new theory.

In a more general sense, applying knowledge of the factors involved to a model which represents a more realistic ship form would result in a comprehensive and systematic test program which will enable definition of the degree to which key variables impact upon the capsize phenomenon for typical RO-RO vessels. Conclusions might be reached as to the merits of SOLAS 90 compliance in the damaged condition, and the required criteria which RO-RO ferries must meet in terms of geometry, arrangement and stability in order to be considered “safe”.

2. RECENT RESEARCH

Despite considerable research and intergovernmental negotiations, the regulatory recommendations of the IMO Panel of Experts with respect to stability with water on deck were not adopted in 1995. The international community had managed to reach a consensus only on the concept of regional application of proposed amendments but without incorporating them in the text of the Convention. As a result, the current stability standard for damaged RO-RO vessels remained SOLAS 90.

However, it is noteworthy that there was little comprehensive scientific support for the SOLAS 90 standard as written, especially as its development had been stimulated by a RO-RO capsizing in the intact condition due to ingress of water on the bulkhead deck. The only well-documented case of capsizing of a RO-RO ferry in a damaged condition as the result of a collision is the sinking of the *European Gateway* in December 1982 [10].

The early experiments conducted by H. Bird and R. Browne [6] are still considered to be comprehensive and reliable validation data for any theoretical approach. The collation of model test results published prior to 1993 was presented by J. Spouge [11].

A number of more recent model tests were conducted internationally to evaluate proposed amendments to the SOLAS 90 damage stability standard:

- The Italian model tests [12] done at Hamburg Ship Model Basin showed that a RO-RO ferry complying with SOLAS 90 survives the sea state corresponding to the significant wave height of 4 m when trimmed forward in damaged condition.
- The model tests conducted at DMI, Denmark and at Marintek, Norway [13] confirmed the improvement in survivability with higher residual freeboard and GM. Similar conclusions were presented by the Marine Safety Agency (MSA) of UK [14].
- The research at the Ship Research Institute of Japan [15] indicated a clear dependency of capsizing on GM at a single (0.5 m) residual freeboard.
- The experiments conducted by Canal de Experiencias Hidrodinamicas de El Pardo of Spain [16] provided supporting evidence for the above conclusions.
- In addition, theoretical work by D. Vassalos [17], identified residual freeboard and GM as key survivability parameters. This work also highlighted the importance of the “tuning” of the damaged vessel to the seas, i.e., the ratio of wave modal period to the natural roll period of the ship.

As well as pointing to the relevant variables involved, the Canadian Phase I research highlighted a need to examine a model which more truly represented a ship hull form rather than a prismatic body. This was reinforced by comments on the experimental results by representatives at IMO conferences. In addition, it was felt that new efforts should focus on lower values of residual freeboard after damage, to correspond more closely to RO-RO ships in international fleets.

As more research is done, and further analysis is undertaken of the results to date, the use of a link purely between GM and survivability has begun to lose favour among some researchers. Recent works, including those of Vassalos [18] and Pawlowski [19], attribute more of a predictive nature to the location of maximum GZ, and its link to a ship's ability to withstand water on deck. Such works lead to the definition of a "critical volume", which is the amount of water which causes the vessel to reach equilibrium with a heel angle at the location of maximum GZ. This may be described as a "point of no return" in survivability terms. This concept was to be an important part of the Phase II analysis, as the experiments attempted to validate, or contribute to refinement of, the calculation method.

Additional efforts in mathematical simulation, such as Hutchison [20], will eventually lead to a more thorough understanding of the mechanics of the capsize phenomenon. Unfortunately, such programs are still at the stage where broad assumptions are made to simplify the analyses and hence limit the applicability of the results (e.g., stationary ships, prismatic hull forms, etc.). Such was also the case with the Phase I experiments, where the numerical modelling effort was not deemed successful.

A recent joint North West European SLF submission [22] introduces a probabilistic method, and includes such elements as flooding of the RO-RO deck, loss of stability, heeling moments (e.g., cargo shifts) and downflooding. It is significant in that it attempts to address criteria from a scientific basis, and is a first step in attempting to harmonize the safety of RO-RO vessels with the probabilistic calculation method currently in use [25] under IMO Resolutions A.265(VIII) and A.266(VIII). This approach is supported by Pawlowski[19] and Vassalos[23], who are currently working on the specifics of the "s_i" factor.

While a proposal such as this would take several (4-5) years of discussion while working its way through the SLF/MSC/IMO regulatory procedures, it is a good start to eventual harmonization of the regulations. IMO working groups have already begun to make concrete efforts to analyze the proposal, including the acquisition of computer hardware and software for the purpose. Important concepts contained in the document were to be addressed where possible in the course of Phase II, to contribute to the Canadian analysis effort and also to allow informed comment on the proposals.

3. MODEL DESIGN

3.1 Configuration

The model used in the Phase II tests was based on a RO-RO ferry in Canadian service, with 85.32 m length on the waterline, 18.03 m waterline beam and an intact displacement of approximately 4400 t in the fully loaded departure condition. The scale was 1:16, a value chosen to ensure that the model was large enough in cross-section to fit all of the required equipment into the hull, while at the same time being small enough to allow the waves to be generated in scale and to enable the existing model swing to be used.

The model was to be designed to possess two planes of symmetry: centreline and midship (the bow and stern are identical, and thus yield a double-ended configuration). This would allow later numerical analysis efforts to model the hull without too much difficulty. Over a portion of the model length near midship, the cross-section had to be constant (i.e., parallel midbody) to facilitate the operation of a sliding damage door.

The initial hull form was based on the bow of the parent hull, mirrored about midship and modified to possess the parallel midbody. Following this procedure, the hydrostatics were compared to the parent hull; the results are shown in Table 1 for the 4.95 m intact design draft (similar results apply at all drafts). Since the procedure had modified the hydrostatic properties, the double ended hull form was further modified to fill out the lines and more closely match the original hydrostatics values. The result is also shown in Table 1; it is evident that the hydrostatics are much closer. Given that the model is to be derived from an existing RO-RO ferry rather than exactly matching one, the level of discrepancy is considered acceptable while still reflecting typical values.

Table 1 Hydrostatic comparison

Hull Form	Displacement (t)	Tonnes/cm	KM_T (m)	Waterplane Area (m^2)
Original Hull, bow & stern	4 438	12.05	8.41	1 176
Double Ended, Parallel Midbody	4 115	10.87	7.94	1 061
Modified Double Ended, Parallel Midbody	4 466	11.95	8.51	1 166

The geometry of the revised double ended model is depicted in Figure 1. Offsets and hydrostatics are attached in Appendix A.

Two additional hull forms were considered in the decision process in an attempt to address the initial criterion that the model be exactly SOLAS-compliant at a low residual freeboard. The first attempt represented a variant of the double ended hull, scaled to 90 percent beam. While its stability properties were closer to the desired result, it was in no way representative of a typical RO-RO ferry due to its slender plan form, and was rejected. The second version was scaled from the double ender to 90 percent beam and 90 percent depth; while achieving the desired result, this variant was rejected for straying too far from the parent hull dimensional ratios. In the end, a full analysis of the vessel stability characteristics showed that the differences in limiting KG for the SOLAS criteria at low residual freeboards are quite small in comparison with the Phase I hull form. This fact, illustrated later in this document (Figure 7), implies that the vessel may be considered as borderline SOLAS compliant over a range of freeboards as was desired in the planning stages of this phase of the project.

In the damage condition the midbody is symmetrically flooded, with residual buoyancy and stability being provided at the ends. The floodable compartments result in residual freeboards after damage of 0.2, 0.4, 0.8 and 1.2 m (to the vehicle deck), full scale.

In order to provide for successful investigation of the main capsize parameters, the design of the model included the following features:

- Robust construction in consideration of the loads placed on the model by repeated flooding and capsize;
- Foam buoyancy on top of the superstructure to avoid the stresses resulting from complete capsize;
- Two submersible pumps within the hull for fast water evacuation between tests;
- An eyebolts/pulley system to facilitate righting the model after capsize;
- Light restraining ropes to facilitate towing of the model back to the start position between tests;
- Yellow paint with black lines at the intact 4.95 m waterline and residual drafts after damage;
- A RO-RO car deck extending the full length of the model;
- A superstructure above the RO-RO deck (extended prismatically from the deck outline to a height derived from the parent ship) to constrain water on that deck after damage and hence obtain realistic water build-up;
- A Lexan superstructure top to allow visual examination of the model interior from above;
- Watertight housing to allow a camera to be fitted in the car deck space;
- Soft moorings to allow the model to be towed back up the tank for a new test run, but which were let slack to allow the model to drift freely during the tests;
- Adjustable compartment size to flood the model symmetrically to the required residual freeboards after damage;
- Ability to vary the vertical centre of gravity (KG) to simulate loading conditions at, above, or below SOLAS 90 residual damage stability criteria, with the model having been swung to set the correct radii of gyration in roll and pitch;
- Water freeing ports just above the vehicle deck, fitted with hinged flaps which can be locked in the closed position to achieve total areas corresponding to the Load Line Convention requirement and the former IMO recommendation of 0.3L per side;

- A removable centreline casing of approximately 60 percent of the car deck length, centred on midship, and with a width similar to that fitted in the parent hull;
- Removable bilge keels over 30 percent of the waterline length, placed at the turn of the bilge, constructed as flat plates 550 mm in span; and,
- A rectangular damage area at midship (in the side shell and RO-RO deck), with dimensions corresponding to SOLAS requirements [length $3+0.3L_{SOLAS}$, height from double bottom to RO-RO deck, depth $0.2B_{WL}$], complete with a sliding damage door below the car deck activated by a rope and pulley system and a removable damage door fitted into vertical slots above the car deck. Some slight flattening of the hull side was necessary to introduce this feature.

The instrumentation outfit included:

- A stationary capacitance wave probe, approximately 20 m from the wavemaker, to record wave height data;
- Capacitance probe fitted to the front (wavemaker end) of the tow carriage;
- Capacitance probe fitted to the rear (beach end) of the tow carriage, roughly opposite position of pressure transducers on model;
- Electro-mechanical gyro mounted on the superstructure centreline in a watertight casing, to measure pitch and roll angles;
- Strapdown accelerometers mounted on the superstructure centreline in a watertight casing to provide relative accelerations in heave, surge and sway;
- Capacitance probe mounted in front of the damage door and an additional probe mounted on the weather side about 0.4L from one end of the model, to measure relative motion;
- Water level probes mounted on double bottom (1 off) and car deck (20 off) to isolate time of flooding and assess water volume respectively;
- No.1 pressure transducer mounted just above the car deck facing the incident waves;
- No. 2 pressure transducer mounted just above the car deck facing inboard at roughly the same location as No.1;
- A camera in the watertight housing on the car deck, to record relevant details of flooding and motions;
- External cameras to observe the test from outside the model, one being located on a movable bracket directed at one end of the model (for the carriage operator) and another mounted on a fixed bracket looking down on the model;

The buoyancy of the shell and the deck and internal objects such as hoses and cameras are significant parameters that affect results at model scale. To take account of such factors, initial stability calculations provided for a permeability of the flooded compartment of 0.985. Final placement of the flooding bulkheads was performed by IMD to suit the calculated flooded volumes in order to ensure that the correct residual freeboards were attained.

The locations were used to develop a revised stability model, reflecting the correct permeabilities of the final arrangement. This stability model was used in the analysis phase of the project to derive the stability curves, determine the “critical volumes”, etc. The final model dimensions are as shown in Figure 2.

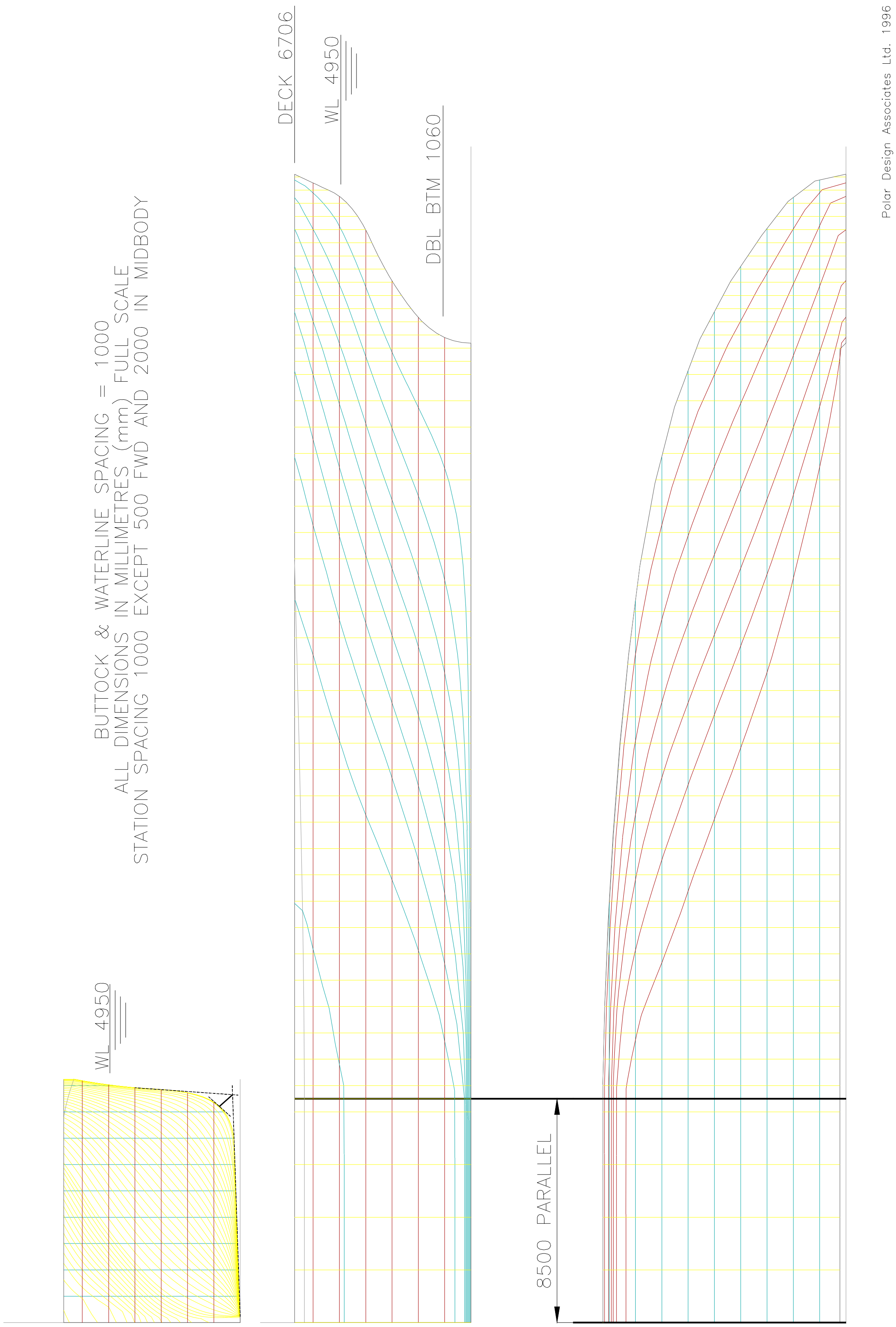

Figure 1 Model lines

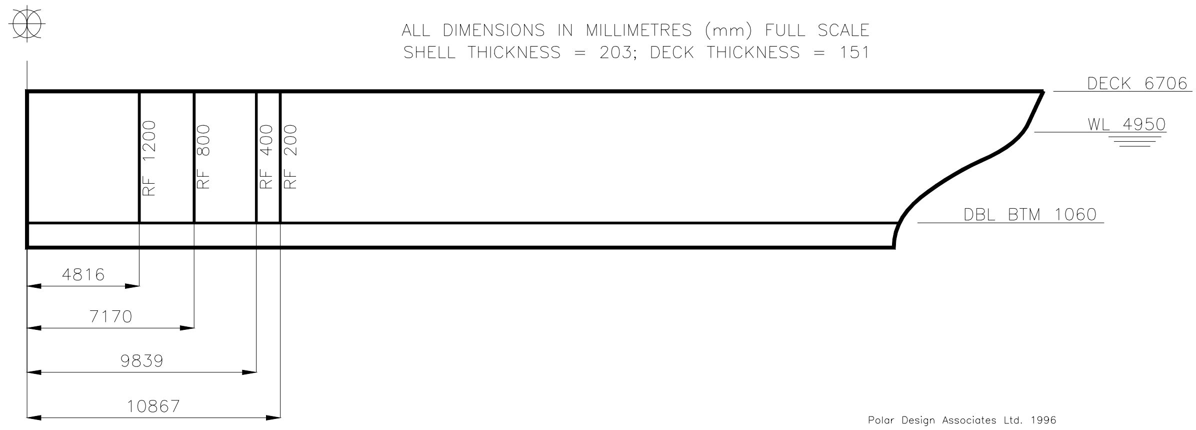

Figure 2 Floodable lengths

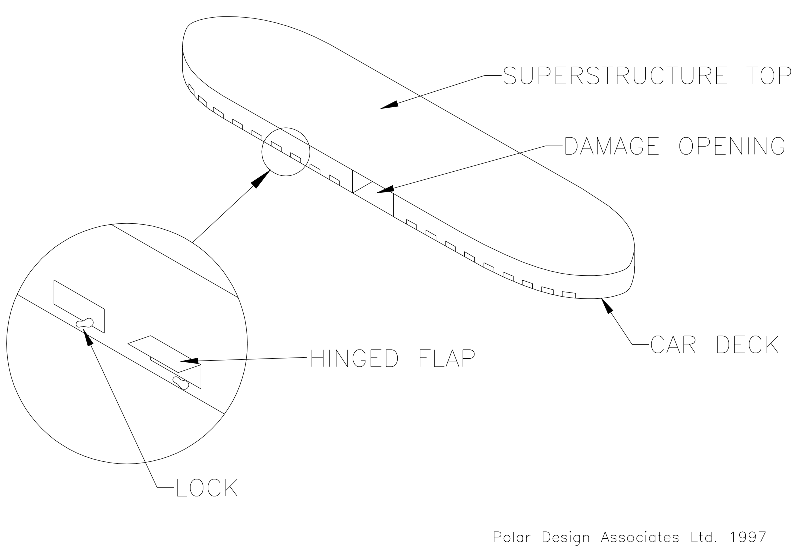

Figure 3 Arrangement of freeing ports

3.2 Freeing Ports

As in the earlier research, freeing ports were incorporated into the model on the car deck. Each opening represents a 2.0 m x 0.6 m freeing port on the full scale vessel. A locking device was fitted under each port to keep it closed. If this mechanism is not engaged, the cover is free to act as a hinged flap. There was no provision in this test series to allow the freeing ports to remain completely open as in Phase I - Extension experiments. The configuration of the freeing ports is illustrated in Figure 3.

Three conditions were established for testing as listed in Table 2. These corresponded to a fully closed condition, one condition meeting the requirements of the 1966 International Load Line Convention, and the final configuration conforming to the IMO Panel of Experts recommendation of 0.3 x L_{SOLAS} per side. The "actual" area figures which can be achieved with the freeing port arrangement as designed are shown along with the required values.

It should be noted that, throughout this report, an "open" freeing port denotes an unlocked flap, which is free to open and close as the vessel rolls.

Table 2 Freeing port configurations tested

Area Relationship	Freeing Port Configuration	Area required per side	Actual area provided
0	All Closed	0.0 m^2	0.0 m^2
Load Line	6 open per side	6.1 m^2	7.2 m^2
0.3 x L_{SOLAS}	20 open per side	24.3 m^2	24.0 m^2

3.3 Centreline Casing

The removable centreline casing to be fitted to the new model extends symmetrically over the midship point of the car deck, and is approximately 60 percent of the length of that deck. The casing is solid along its length, but water is free to move across the car deck around the forward and aft ends of the casing. The width of the casing is 1.8 metres full scale.

3.4 Bilge Keels

The model was fitted with a removable set of bilge keels. These were located at the turn of the bilge, and extended over approximately 30 percent of the waterline length (centred on the midship location). The depth of each of these appendages was 0.3 m.

The base test program was performed with these bilge keels attached. Once this primary data gathering was complete, selected conditions were repeated with the bilge keels removed to determine the effect (if any) of the roll damping effect upon motion and hence capsize behaviour.

3.5 Model Construction

The model as described above was constructed in the following manner [21]:

- One half of the model was milled out of foam using IMD's computer controlled milling machine and finished by hand prior to covering it with a light layer of glass cloth. This male plug was then used to create a female mould, which was used in turn to produce a glass reinforced plastic hull extending from the keel to the superstructure deck.
- A second identical half model was made from the female mould and joined to the first to form the final hull shape.
- A plywood double bottom concealing permanent lead ballast was then fitted and covered with glass fibre and resin. All void spaces in the double bottom were subsequently filled with closed cell foam. Transverse bulkheads extending between the double bottom and the car deck were constructed to define the limits of the available floodable length within the hull. Pumps were fitted into small sumps to ensure that the water was completely removed from beneath the car deck. The water was discharged through pipes directed at the heat sink used to cool the instrumentation box, located on top of the superstructure.
- The car deck was made from a single moulding and included watertight hatches to permit access to the hull for fitting ballast in the void spaces and to permit the installation of foam inserts to vary the floodable length.
- The damage door in the hull was designed to be opened from the tow carriage via a rope-pulley system.
- The removable centreline casing was fabricated from foam and installed to ensure a watertight barrier to transverse flow.
- Twenty freeing ports with hinged flaps and capable of being locked in the closed position were evenly distributed along each side.
- The superstructure deck was made of plywood and Lexan and permitted adequate ambient lighting for video records of water flow on the car deck.
- Foam buoyancy blocks were secured above the superstructure deck to ensure the model did not invert after a capsize.
- Bilge keels centred at amidships and fitted at the turn of the bilge, normal to the hull, were the only appendages fitted to the model. They were affixed with bolts so as to be removable.

3.6 Instrumentation

Electrical power for the ballast pumps, video camera, signal conditioning equipment and instrumentation was provided via a cable from the tow carriage. Additional signals were not collected on the model, but were also part of the data recording process (such as incident wave height from the fixed wave probe, and carriage speed).

All motion measurement instrumentation and the associated power supply, signal processing and data acquisition systems were installed in a waterproof instrumentation box mounted on top of the superstructure amidships. Provision was included for heat dissipation from this box using passive heat sinks.

Sealed pressure transducers were used to measure the external and internal hydrodynamic pressure above the freeing ports on the car deck near the damage opening.

An array of 20 capacitance probes fitted to the car deck was used to measure the level of accumulated water. Capacitance probes were also used to measure relative motion in way of the damage opening and adjacent to the pressure transducers. A stationary capacitance wave probe located 60 m from the wavemaker was used to measure the characteristics of the incident wave field. A second capacitance wave probe was fitted to the tow carriage to measure the incident wave conditions roughly opposite the location of the pressure transducers. A simple magnetic switch was mounted in the floodable segment of the hull deck and used to detect the instant the hull was flooded.

Several video records were taken for each run:

- Deckhead mounted video camera installed in a watertight enclosure to show the flooding activity on the car deck;
- An overview of the test was recorded using a video camera mounted on the tow carriage and directed down on the test area;
- A view across the tank was recorded to obtain some indication of the roll and heave of the ship as well as to view the incident waves; and,
- A hand-held video camera was directed as desired.

4. SEA CONDITIONS

The profile of representative wave conditions developed for model testing were based on coastal wave data for Canadian waters where ferry operations are routinely conducted. The resulting irregular wave patterns were characterized by the Jonswap spectrum; Table 3 below shows the attained values of significant wave height in comparison to the desired values; Figure 4 shows this graphically.

Table 3 Parameters of tested sea states (coastal spectrum)

Modal Period (sec.)	Significant Wave Ht. (m) Nominal	Attained
5.5	1.0	1.316
6.0	1.5	1.728
6.5	2.0	2.235
7.0	3.0	3.224
7.5	4.0	4.059
8.0	5.0	4.852
8.5	6.0	6.078
9.0	7.0	6.593

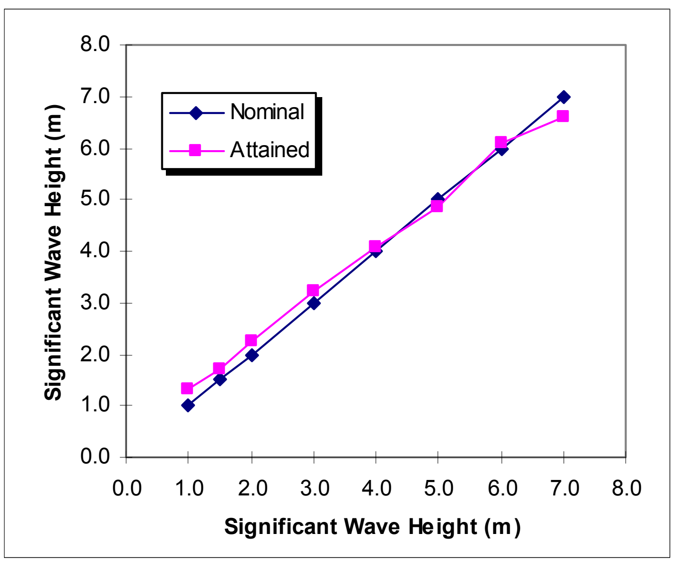

Figure 4 Nominal vs. attained sea states (coastal)

In addition to the above sea states, some testing was carried out with a variation of modal period to examine the effect of different period values and hence investigate the impact of the ship/sea "tuning" effect. The modal periods tested represented an ITTC deep ocean wave spectrum instead of the coastal Jonswap, and are detailed in Table 4 and Figure 5.

Table 4 Parameters of tested sea states (deep ocean spectrum)

Peak Period (sec.)	Significant Wave Ht. (m)	
	Nominal	Attained
8.5	2.0	1.90
10.4	3.0	2.97
12.0	4.0	3.98
14.7	6.0	6.16
15.9	7.0	7.27

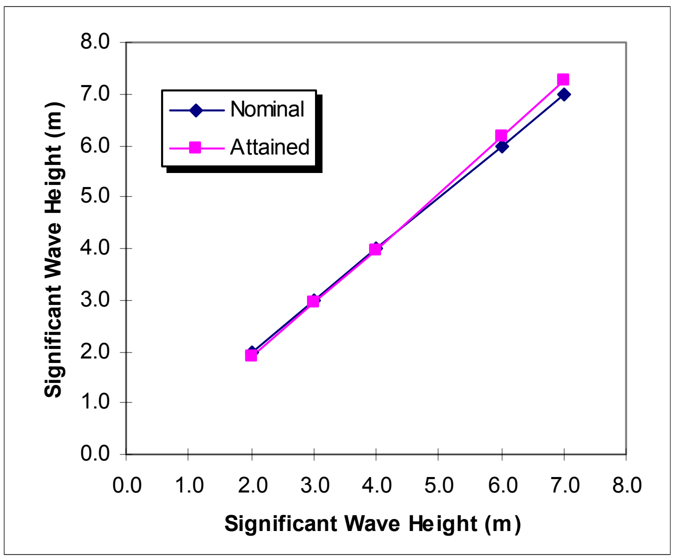

Figure 5 Nominal vs. attained sea states (deep ocean)

Additional tests were carried out in regular waves of varying period and height to provide data for easier validation of numerical models in the early stages of their formulation. The regular wave parameters were as per Table 5 below.

Table 5 Regular wave parameters

Wave Period (sec.)	Wave Heights (m)
10.0	2.0, 3.0
11.0	2.0, 3.0
12.0	2.0, 3.0
13.0	2.0, 3.0
14.0	2.0, 3.0
15.0	2.0, 3.0
16.0	2.0, 3.0

5. SCOPE OF INVESTIGATION

SOLAS 90 damage stability requirements include a minimum 0.015 m-rad dynamic stability requirement, a positive GZ range of at least 15 degrees, and a minimum 0.1 m GZ value within that range.

Extensive damage stability calculations were performed to calculate the vertical centre of gravity (KG) condition compliant with SOLAS criteria at each of the pre-selected residual freeboards. The results of these extensive calculations are contained in Appendix B to this report.

The graph in Figure 6 depicts the relationship between the residual freeboard and KG for each of the SOLAS criteria, along with the actual KG value in the full load condition of the parent RO-RO vessel. The model nears exact compliance with SOLAS 90 for the three important (non-GM) criteria at 1.2 m freeboard at a single KG. At freeboards below this point, the limiting KG curves diverge, leaving a spread between the upper and lower KG values to exactly meet each given criterion. It is interesting to note, however, that the spread is far less than that encountered in the Phase I tests, as Figure 7 reveals. This implies that the ship is in fact near exact compliance with SOLAS over a range of residual freeboards, as was desired in the formulation of the Phase II objectives.

In addition to KG and residual freeboard, testing at the suggested KG values and residual freeboards was carried out to evaluate the impact upon capsize safety of two additional variables: area of freeing ports and the presence or absence of a centreline casing.

The test program was formulated to ensure that data gathered would encompass the full range of each of the variables in question, so as to identify the trends involved (i.e., toward greater or lesser capsize safety). The graph in Figure 6 shows the actual KG test values overlaid on the residual freeboard vs. KG graph.

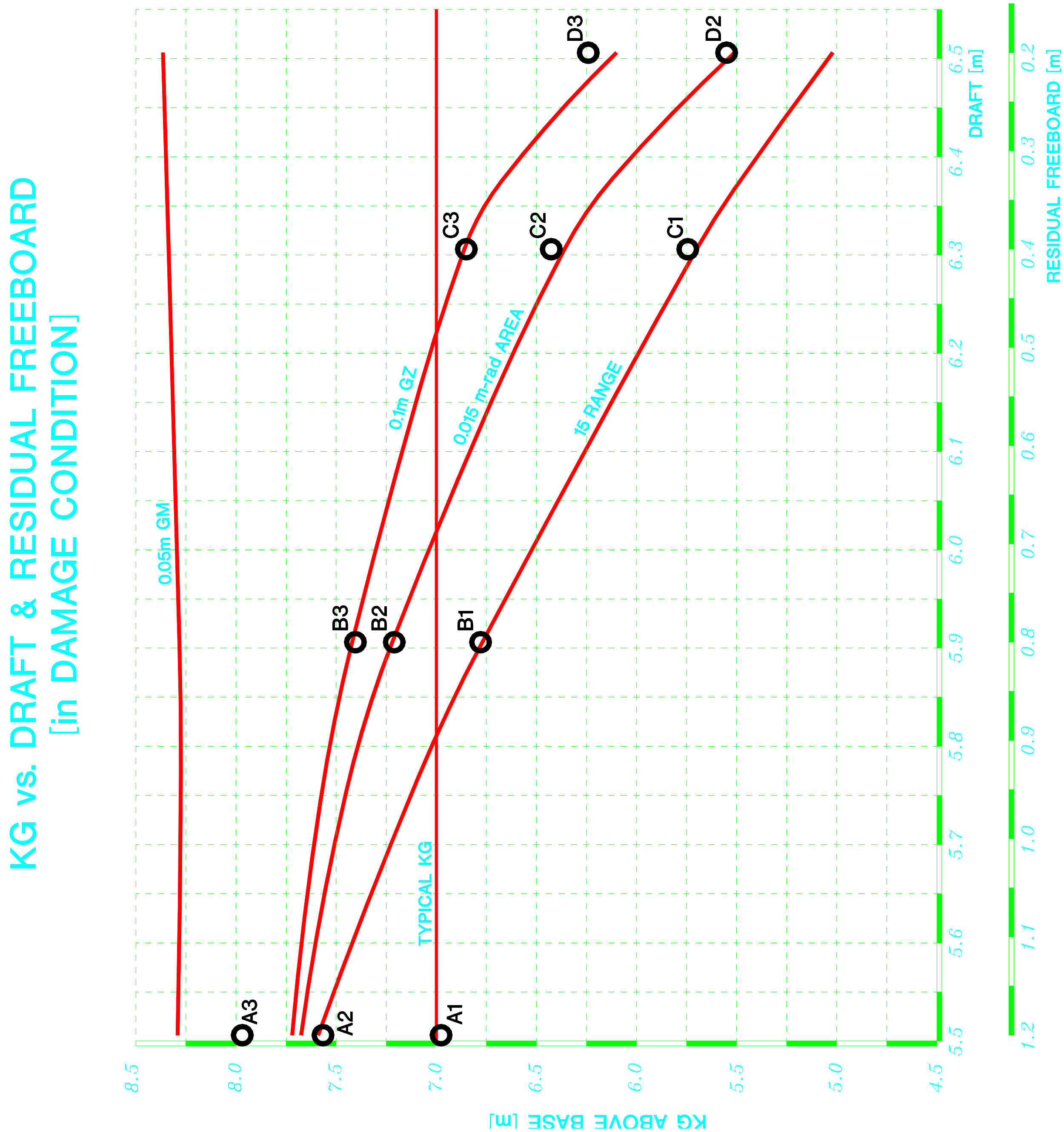

Figure 6 Tested data points with reference to KG/RF diagram

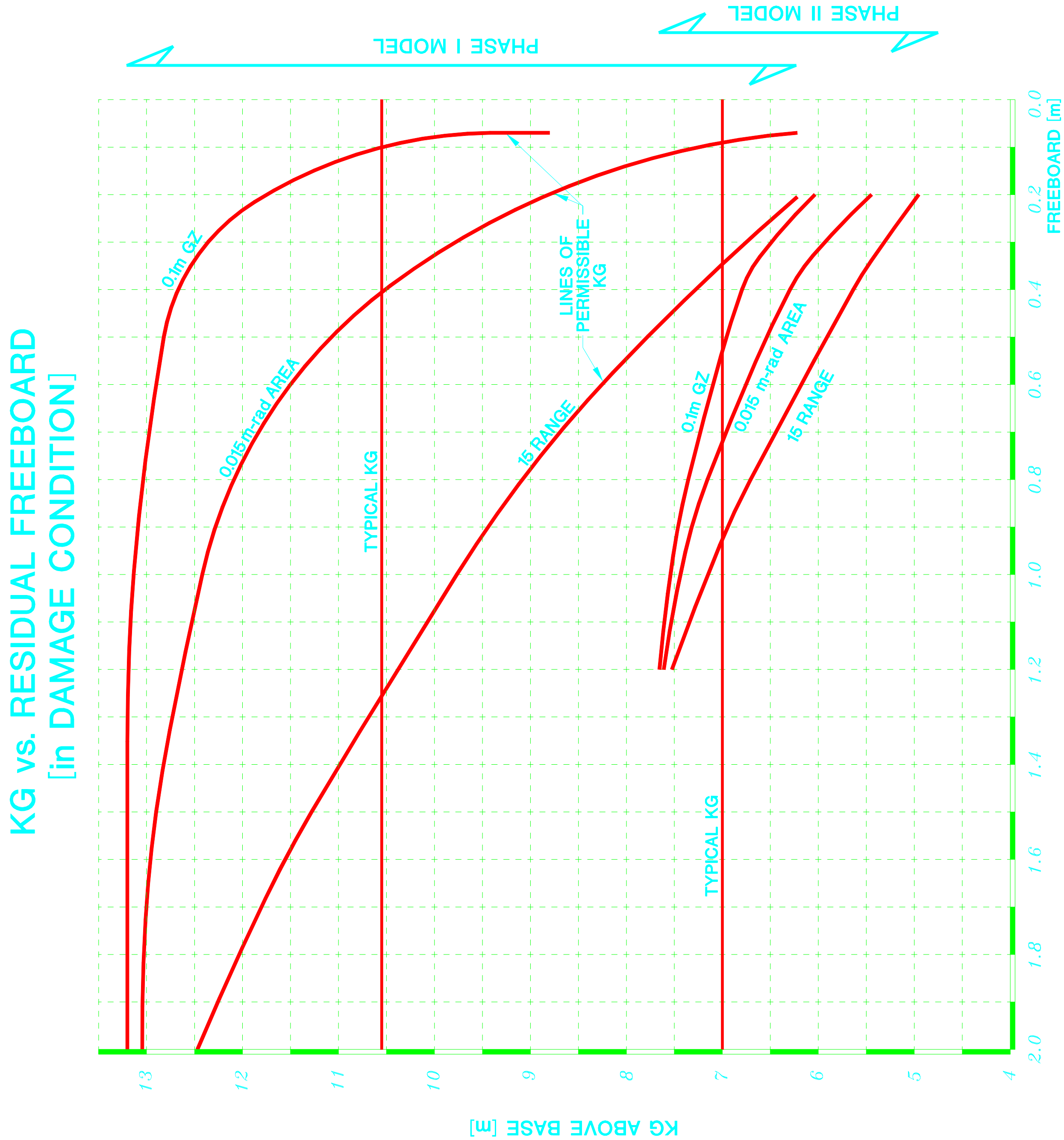

Figure 7 Comparison of Phase I and II limiting KG distributions

6. TEST METHODOLOGY

As in the earlier tests, the model was placed transversely across the clear water towing tank at IMD and allowed to drift down the tank during testing in beam seas. Systematic tests in progressively larger or smaller sea states were conducted to determine the sea states which caused a capsize to occur at each residual freeboard.

Prior to commencing the test program, the empty model was weighed and swung in air in the IMD swinging frame to determine the location of the lightship centre of gravity together with the radii of gyration in pitch and roll. This information was used to develop the ballasting plan for the model in each condition.

For each residual freeboard, tests were conducted as follows at each of the calculated KG values:

- The model was ballasted to attain the desired KG within a tolerance of ±0.1 m full scale, verified by inclining experiment.
- Roll and heave decay tests were conducted in both intact and damage conditions to determine damping coefficients and roll radius of gyration.
- The model was systematically tested in irregular waves by opening the damage and allowing the model to drift as data were collected. Individual test runs were stopped after a capsize or after approximately 40 minutes (full scale) of elapsed survival time after damage, whichever occurred first. The highest wave height tested was 7 m (full scale).
- The recorded data were put through a preliminary analysis after each test run to ensure that there has not been a loss of signal from any important sensors which might render the information incomplete; such a situation would lead to a re-test.
- At the end of a capsize run, the model was righted using a pulley system on the tow carriage.
- The damage door was closed, and the model was pumped dry using the internal pumps. It was then configured for the next experiment (e.g., freeing ports changed, casing added/removed, etc.).
- The tow carriage was returned to the start position, and the heel angle of the model was verified prior to the next run. The water was allowed to calm, and testing continued.

Early tests showed that the model was very sensitive to the static heel of the model. Even small amounts of initial heel could change the capsize wave height significantly, and so care was taken to ensure that the flooded model was on an even keel. Due to a slight asymmetry in the flooded compartment (caused by the pump recess on one side), a counterweight was used on the deck to achieve the zero heel condition when flooded. The total moment introduced was small, involving a 20 kg lead weight placed a few centimetres off centreline.

The desired result for each KG condition was a pair of data points: one representing the highest wave height in which the model remained upright, and the other representing the lowest wave height at which capsize took place. These are referred to as the *maximum upright* and *minimum capsize* wave heights. Where capsize did not occur, the latter point is indeterminate. Once these data points were determined, runs were not duplicated as the Phase I experiments showed good repeatability in results for a given condition.

In addition to the standard test series, some additional experimentation was carried out in a different wave regime (ITTC ocean spectrum instead of Jonswap coastal spectrum) in order to investigate the effect of the tuning factor between the ship and the seas. By maintaining the same significant wave height but altering the modal period of the waves, the behaviour of the model can be related to the ratio of damaged roll period to wave period. This is expected to provide further insight into the dynamics of capsize, in terms of the relative motion which leads to water build-up on the RO-RO deck.

Additional tests were carried out in regular waves, in order to facilitate the validation of numerical models at a later date. Finally, some test runs were repeated in irregular waves with the bilge keels removed from the model to investigate the effect of these roll damping devices on the motion and/or capsize behaviour of the vessel.

7. TESTS

Testing began at IMD on 22 October 1996, and was completed 15 November 1996.

7.1 Test Conditions

The test conditions are summarized in Table 6. Note that the planned "D1" condition could not be attained as the KG was too low to reach without extensive modifications.

Table 6 Summary of test conditions

Condition No.	Residual Freeboard (m)	KG (m)	
		Nominal	Actual
A1	1.2	7.00	6.976
A2	1.2	7.59	7.566
A3	1.2	8.00	7.969
B1	0.8	6.77	6.779
B2	0.8	7.22	7.210
B3	0.8	7.42	7.404
C1	0.4	5.70	5.694
C2	0.4	6.36	6.426
C3	0.4	6.86	6.850
D1	0.2	5.02	n/a
D2	0.2	5.51	5.550
D3	0.2	6.10	6.241

Selected key measurements were monitored while testing was underway, to identify directions for further study (e.g., reducing the wave height in a search for the capsize point). The majority of measurements were recorded for later manipulation and analysis.

7.2 Test Results

The results of each set of tests in a given model configuration were recorded on a condition sheet such as that shown in Figure 8.

Testing involved the collection of the requisite data from the model itself; additional post-processing by IMD resulted in additional data, such as the water on deck calculations. Summary and detailed results from all of the tests are attached at Appendix C.

The tests comprised the full scope of the test plan with respect to determining capsize limits in irregular waves with varying freeing port and casing configuration. The additional tests involving variation of modal period, use of regular waves, and removal of bilge keels were then carried out.

Capsize safety of RO-RO Ferries: #784 dd/mm/yy

Test Date	
Scale	16

Residual FB KG (nominal) Casing	in

GM nominal GM actual	
Roll period intact flooded	sec.

Nominal Hs, m	Actual Waveheight	Zero ports run #/result	Actual Waveheight	6 ports run #/result	Actual Waveheight	20 ports run #/result
1.0						
1.5						
2.0						
3.0						
4.0						
5.0						
6.0						
7.0						

Test Date	
Scale	16

Residual FB KG (nominal) Casing	out

GM nominal GM actual	
Roll period intact flooded	sec.

Nominal Hs, m	Actual Waveheight	Zero ports run #/result	Actual Waveheight	6 ports run #/result	Actual Waveheight	20 ports run #/result
1.0						
1.5						
2.0						
3.0						
4.0						
5.0						
6.0						
7.0						

Completed
Date

Checked
Date

Approved
Date

Revision#.001 Page 1

Figure 8 Sample condition summary sheet

7.2.1 Irregular Coastal Waves

The bulk of the experiments were carried out in irregular waves according to the test plan. This encompassed tests at the conditions designated “A1” through “D3”, with and without centreline casing and at the three different freeing port area values.

7.2.2 Regular Waves

The regular wave experiments were carried out at a residual freeboard of 0.8 m with a KG of 6.77 m. Tests were carried out with the bilge keels on and off in three metre waves and with the bilge keels on only in two metre waves. No capsizes were observed in the regular waves.

Regular wave data are not analyzed in this report; the numerical results are presented in Appendix C. The information was collected for later use in calibrating numerical models.

7.2.3 Irregular Deep Ocean Waves

Testing with the deep ocean (ITTC) spectrum was carried out at residual freeboards of 0.8 and 0.4 m, corresponding to the "B1" and "C1" KG conditions.

7.2.4 Effect of Bilge Keels in Irregular Waves

The effect of removing the bilge keels was investigated at residual freeboards of 0.8, 0.4 and 0.2 m, in the "B1", "C1" and "D2" configurations.

7.3 Water on Deck Calculations

Calculation of water on deck was performed after the tests were performed, using a post-processing routine on the data files. The calculation was based on calibrating a known (weighed) amount of water on the vehicle deck with the data from the internal water probes.

The calibration for water on deck had an absolute error level associated with it, rather than a percentage error. This is due to the resolution of the wave probes. The error at 95 percent confidence amounts to ±3 mm at model scale. The average static (non-rolling) error of 38.7 m^3 represents about 9 percent of the average volume to cause a capsize (420.6 m^3).

The rms value during rolling of 22.5 t gives an estimate of the accuracy of the linear interpolation. Taking the variance on this (9.1 m^3) and 95 percent confidence, the error is not expected to be better than 22.5 t ±18.2.

It is therefore expected that the uncertainty due to the linear interpolation is up to 41 m^3. The remaining part of the error can be attributed to asymmetry of the water due to trim.

There is little or no published information on estimates of uncertainty with which to compare this information.

8. ANALYSIS

8.1 Freeing Ports

As noted in the Phase I investigations, survivability of the Phase II model is generally better with biased flow devices (flapped freeing ports in this case) to facilitate car deck drainage. In light of the information gathered with respect to capsize safety being a virtually static function of water volume, and Hutchison's observations on the volume being a function of the inflow vs. outflow rates, this is not unexpected. Specific results are given in later sections, where the impact of freeing port drainage on each investigation is noted.

8.2 Casing

In most cases presented in this report, the results generally show better correlation to the various reference formulations when a casing is present, although this may be a result of the data from which they have been derived. For configurations with a higher initial stability (i.e., GM), the identified methodologies tend to underestimate survivability of the vessels when the casing is removed. One may define a non-dimensional GM [11] as shown in equation (1), using the displacement, maximum beam and length between perpendiculars:

$$GMn = \frac{\Delta \times GM}{1.025 \times L_{PP} \times B^3} \qquad (1)$$

At low values of GMn, generally less than 0.010, the influence of the casing is negligible. Above 0.010, there is a clear increase in the wave height that the vessel will survive for a given residual freeboard, although this influence reduces as the freeboard is increased. At the highest freeboards tested there was little water on the deck, and so the casing had little effect.

It is believed that the casing impedes the ability of the water to induce a heel away from the incident wave trains, thereby increasing effective freeboard and making it harder for the vehicle deck to experience significant flooding. It was observed that the low GMn cases in fact tended to heel toward the damage.

The casing also may restrict cross-flooding of the RO-RO deck to allow drainage through both banks of freeing ports. It is notable that none of the theories being studied takes this parameter (i.e., effective width of car deck flooding) explicitly into account; other means such as internal downflooding measures are similarly neglected. Specific results are given in later sections, where the impact of the casing on each investigation is noted.

8.3 Bilge Keels

Bilge keels work to increase the survivability of the vessel, depending upon the configuration, KG, etc. In general, the keels offered an increase in safety of up to 1.0 m significant wave height beyond the same condition without bilge keels, although some cases showed little or no benefit. The bilge keels never caused a degradation in performance, however. The possible increases in survivability would be due to the bilge keels' effect in reducing roll motions by damping, and hence reducing the relative motion at the damage which leads to flooding of the RO-RO deck.

8.4 Metacentric Height GM

The survivability data in Phase I were shown to be quite sensitive to the metacentric height of the vessel in a given condition[1,3]. Graphs of significant wave height vs. GM showed a distinct separation into “bands” of data by residual freeboard, which suggested GM as a good indicator of capsize survivability

Figures 9 and 10 show a similar “banded” behaviour of the data for the Phase II model.

GM (obviously) reflects upon the ability of a vessel to remain stable while at the same time displaying a sensitivity to residual freeboard variation. These results have been borne out in Phase II, as the results thus far indicate that GM is, if not always an ideal predictor, at least never a poor one.

The indicative nature of GM with respect to capsize safety is discussed in more detail later, using the method of Spouge.

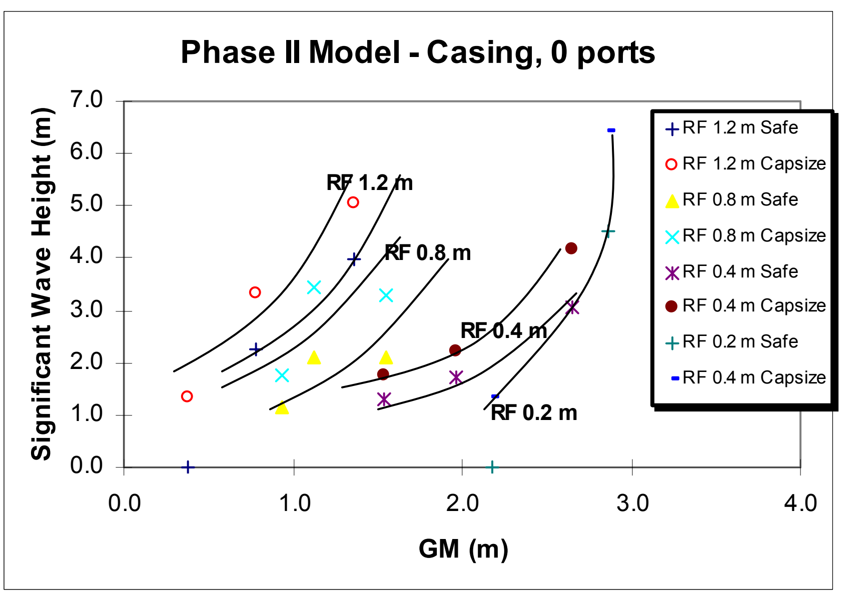

Figure 9 Significant wave height “bands” – Casing, 0 ports

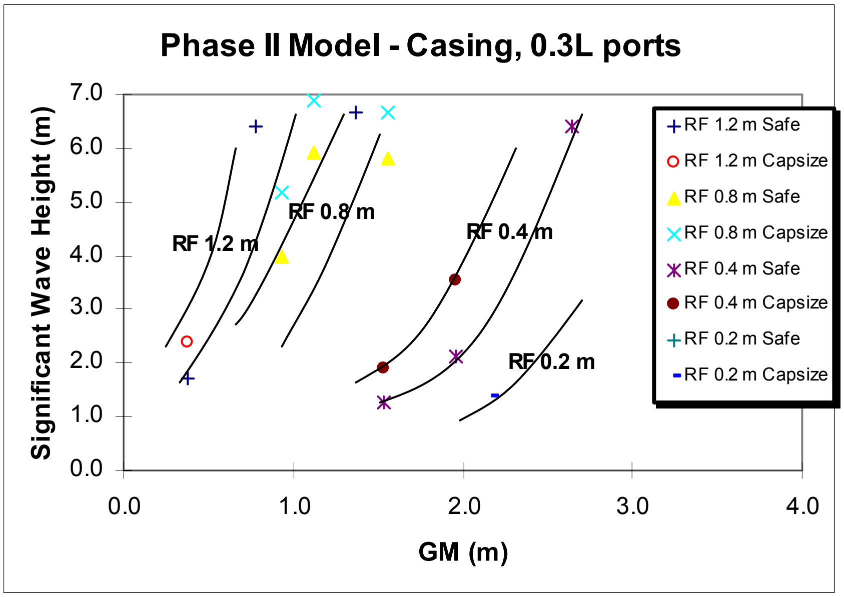

Figure 10 Significant wave height "bands" – Casing, 0.3L ports

8.5 Water on Deck vs. GM

One of the most significant results from the first phase was the conclusion that capsize itself occurs from hydrostatic considerations once a certain destabilizing volume accumulates on the RO-RO deck. This was illustrated as in Figure 11, where there is a clear delineation between the upright and capsize data sets for the model tests. This implied the static nature of the process, and introduced the concept of GM as a valuable variable in the evaluation of safety.

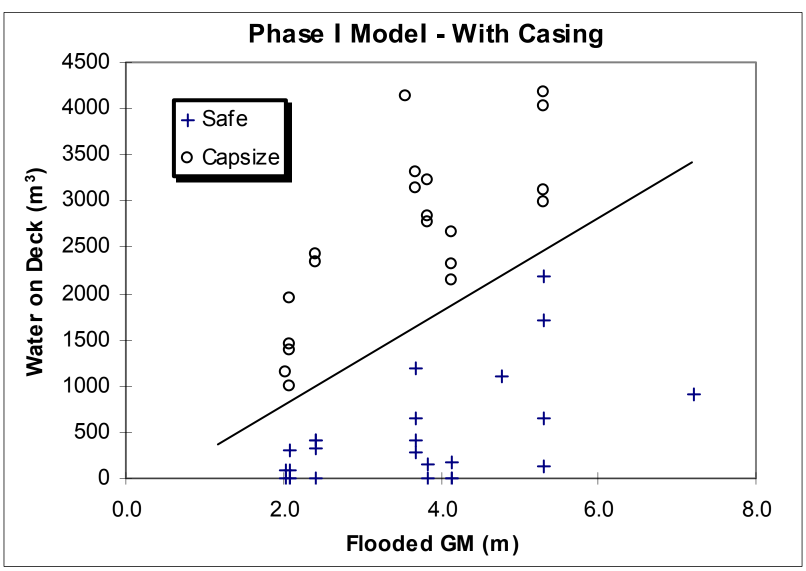

Figure 11 Volume of water on deck vs. GM -- Phase I

Figure 12 is the equivalent presentation for the Phase II data, and reveals the same information regarding separation of data. The two data sets are combined in Figure 13, with non-dimensionalization of GM from equation (1) and volume from equation (2).

$$Vn = \frac{1025 \times (Volume)}{\Delta} \qquad (2)$$

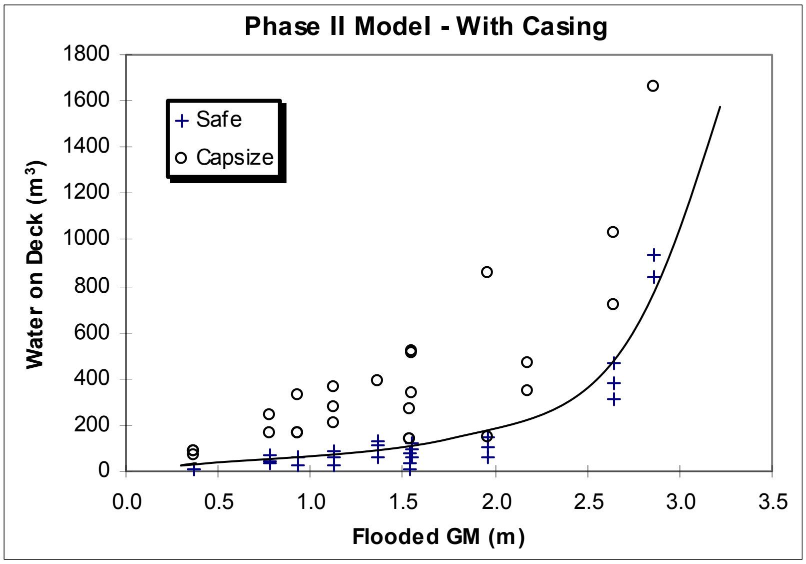

Figure 12 Volume of water on deck vs. GM -- Phase II

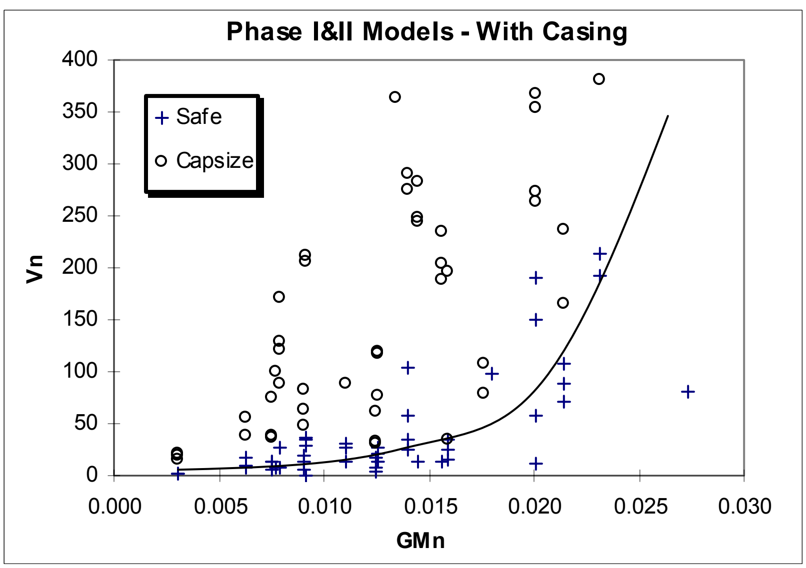

Figure 13 Water on deck (Vn) vs. GMn -- Phase I & II

While there may be a couple of safe data points within the capsize region, the converse is not true. Any transition line from these data would therefore be slightly conservative, encompassing these safe points within the capsize region.

In Phase II, there is slightly less “spread” between the two data sets (i.e., less blank space between the capsize points and the safe points), which may be a reflection of the smaller size of the ferry, the relatively low variation in stability parameters in comparison with Phase I and the comprehensive nature of the test program.

Figure 14 shows the results for tests performed without the casing. As mentioned elsewhere, the removal of the casing tends to enhance the safety of the vessel, and hence there is a predominance of “safe” data points in the graph.

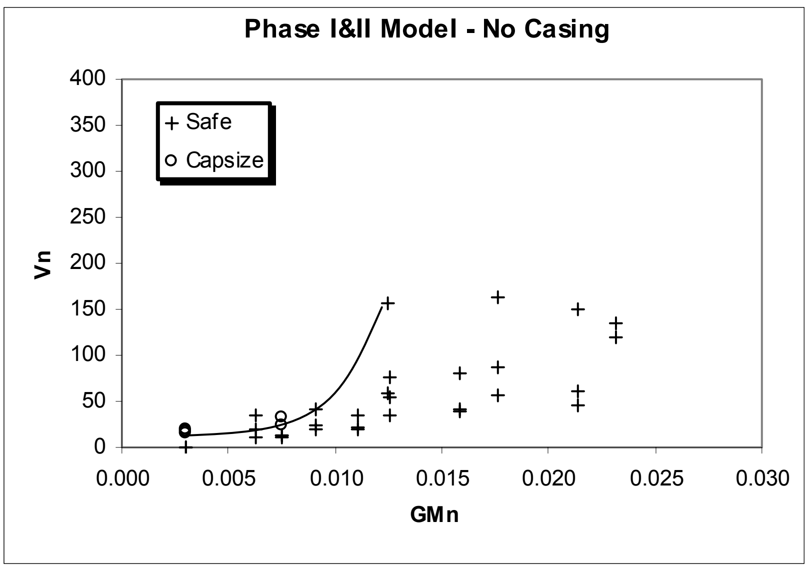

Figure 14 Water on deck (Vn) vs. GMn -- Phase I & II, no casing

8.6 GZ Area

As noted in Phase I, the GZ area parameter is not a good indicator of survivability. This is supported by Phase II data wherein the results show no distinct relationships with GZ area whereby the trends are indicative of the importance of residual freeboard or any other parameter identified thus far.

This situation is illustrated in Figure 15, where the tightly clustered data do not show any sensitivity to residual freeboard.

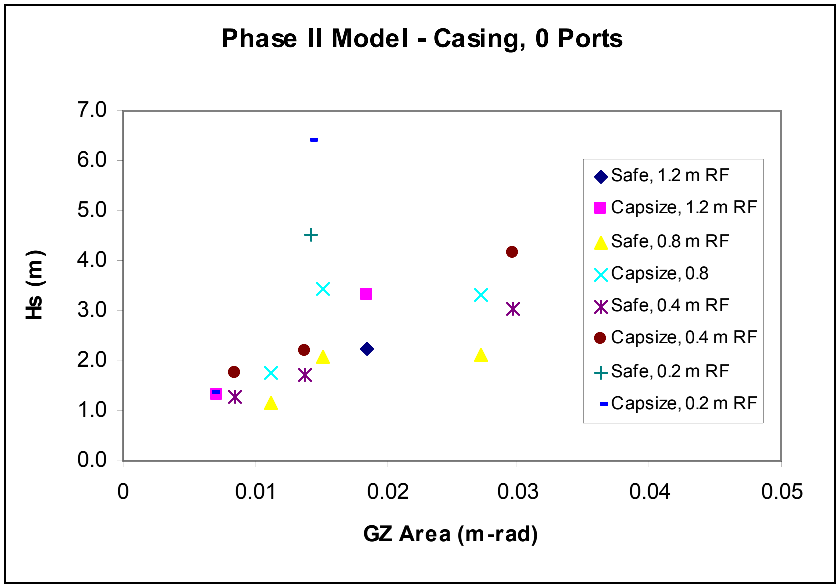

Figure 15 Phase II wave height (Hs) vs. GZ Area – Casing, no freeing ports

8.7 Wave Spectra

Based on preliminary observations, the Phase II model showed better survivability in the ITTC (ocean) spectrum than in Jonswap (coastal) seas. This is an area for further study, possibly to investigate any relationship between the spectral characteristics and the dynamics of the vessel.

8.8 Spouge Formulation

The methodology put forward by Spouge [11] for comparing different vessels was applied to the Phase II data, involving graphs of non-dimensional wave height vs. non-dimensional GM. The latter is calculated as per equation (1); the former is defined as follows:

$$Hn = \frac{\omega^2 \times Hs \times B \times C}{4g \times (RF)} \qquad (3)$$

In ref.[11], Spouge derives an empirical expression for limiting GMn as a function of Hn, although he notes that it is not necessarily applicable across all ships due to the small sample upon which it is based: the curve fit is based on a small sample of data which were available at the time. The expression is:

$$1000GMn = -0.904Hn^2 + 11.4Hn - 0.885 \qquad (4)$$

The data from Phase II were plotted according to Spouge's method, and these are shown in Figures 16-18 below, with the curve in equation (4) superimposed. The equation shows a good match at 0 freeing port area, and with the casing. As freeing port area increases, the equation fit becomes less accurate.

For the model without the casing, the Spouge line is not as close to the data since the model proved to be more survivable in this configuration. This is shown in Figure 18.

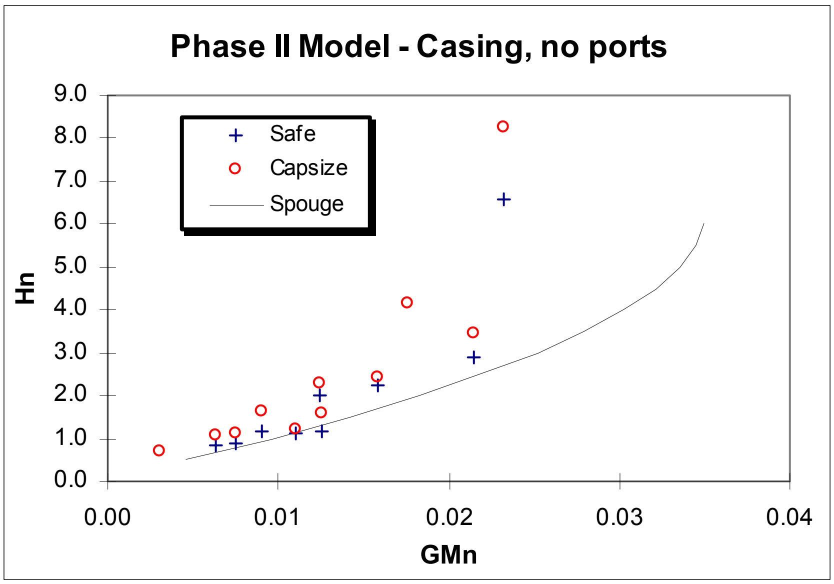

Figure 16 Spouge-type graph, Phase II -- Casing, no freeing ports

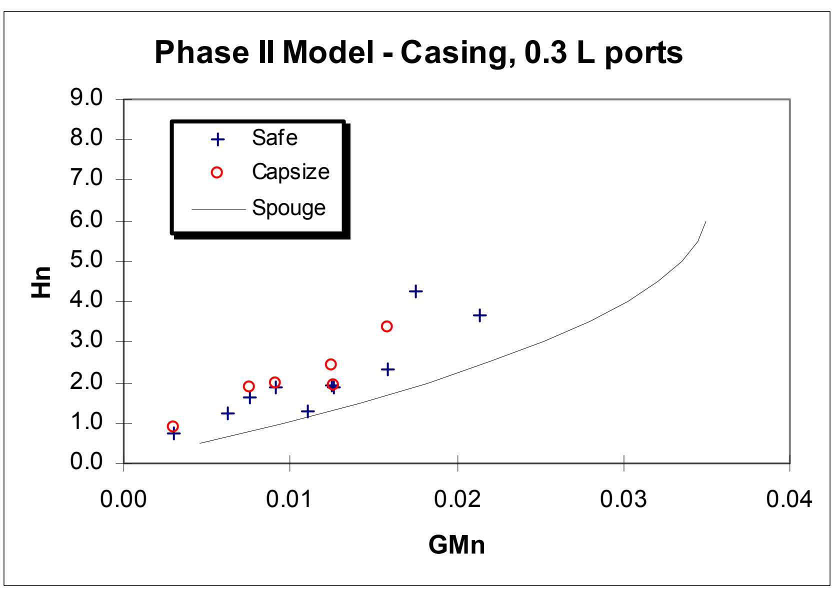

Figure 17 Spouge-type graph, Phase II -- Casing, 0.3L freeing ports

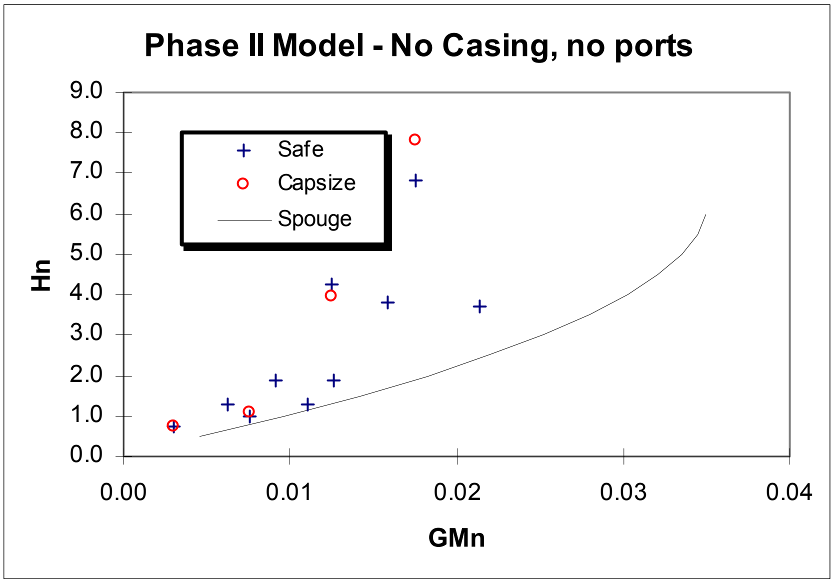

Figure 18 Spouge-type graph, Phase II – No casing, no freeing ports

Figures 16-18 may be compared with the Phase I results presented below in Figure 19. It is evident that equation 4 is still a good fit through these data, despite representing a hull form which is peculiar to the Canadian west coast (with high freeboard and stability in comparison to existing ferries).

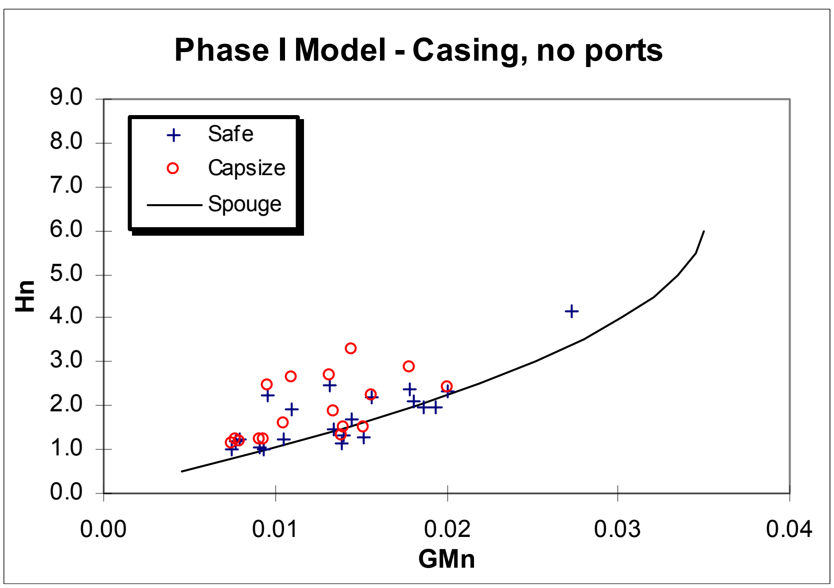

Figure 19 Spouge-type graph, Phase I – Casing, no freeing ports

Based on the above findings, and on the preceding discussion of the nature of the capsize phenomenon, it appears that the Spouge approach is an important part of the investigations leading toward an understanding of the capsize safety of RO-RO vessels.

Despite GM being a simplistic predictor, it is quite possible that it could be a useful one given a sufficiently large database from which to derive its numerical coefficients. It is expected that factors could be determined which are applicable to vessels with and without side or centreline casings, and with and without freeing ports or other drainage devices. The alternative is the development of a method which uses GM in combination with some other variables which implicitly take account of such factors in order to set a uniformly applicable standard. This possibility is discussed in the sections which follow.

8.9 SNAME/Hutchison Stationary Model

As part of the efforts of the SNAME *ad hoc* RO-RO Safety Panel, research into the numerical modelling of the water inflow/outflow balance was performed as summarized by Hutchison *et al.* [20].

The research centred on investigating the relationship between a time domain simulation model and a simple Gaussian model for computing RO-RO deck flooding, so that the asymptotic average water depth could be computed and compared to data from model tests.

The main simplification made in the approach is the assumption of a "stationary" ship, i.e., there is no vessel motion in response to waves, nor is there sinkage, trim or heel. The freeboard at the damage is thus assumed constant.

While this may be viewed as a severe limitation on the applicability of the method, it may be observed that such numerical models, in conjunction with similar work such as that of Vassalos and Pawlowski, which will eventually have a great influence on the drafting and approval of safety regulations.

Under the Gaussian approach to the problem, the asymptotic average water depth on the RO-RO deck was reduced to the following expression (5):

$$\overline{D} = \left[\frac{\overline{Q}_{IN}}{W \times C_W \times \frac{2}{3} \times \sqrt{2g}} \right]^{\frac{2}{3}} \tag{5}$$

with $\overline{Q}_{IN}$ being the average inflow rate based on a combination of the basic weir flow equation and the normal probability density function from equation (6). Note that the term "f" is equivalent to residual freeboard (RF).

$$\overline{Q}_{IN} = W \int_f^\infty C_W \left(\tfrac{2}{3}\right) \sqrt{2g} \left(\eta - f\right)^{3/2} \frac{e^{-\left\{\eta^2 / 2\left(\frac{H_S}{4}\right)^2\right\}}}{\left(\frac{H_S}{4}\right)\sqrt{2\pi}} \, d\eta \tag{6}$$

Figures 20 through 27 show the Phase II and Phase I data expressed as in [20], in the form of D/Hs vs. RF/Hs and with the Hutchison curve (computed by IMD) superimposed. The depth (D) value was calculated simply as the volume of water on deck divided by the deck area.

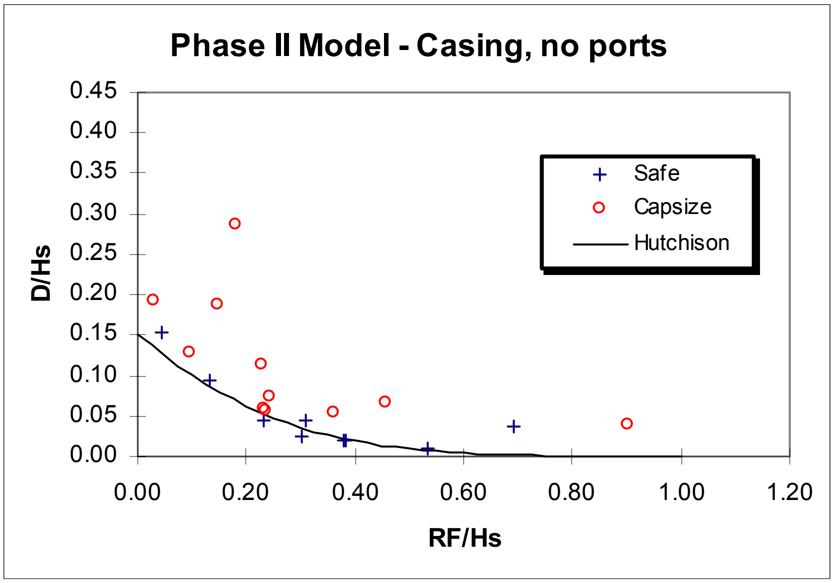

Figure 20 Phase II depth vs. residual freeboard – Casing, 0 freeing ports

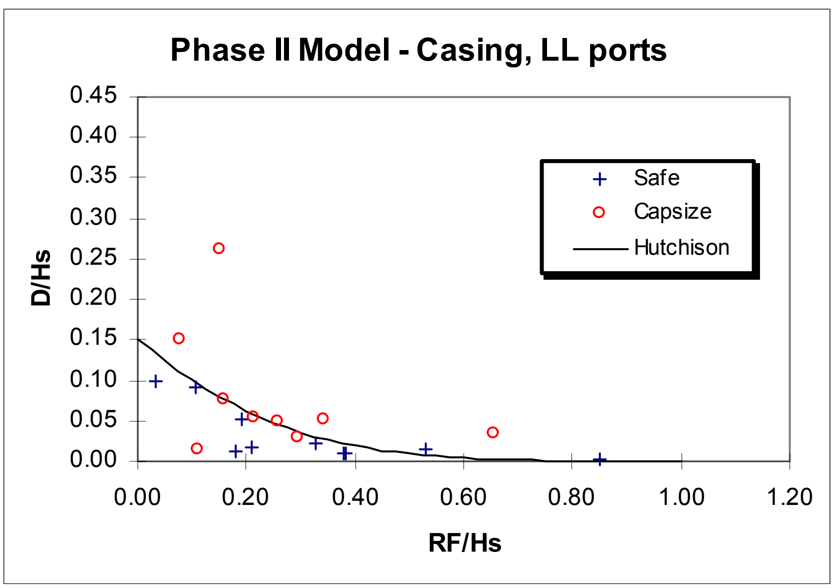

Figure 21 Phase II depth vs. freeboard – Casing, Load Line freeing ports

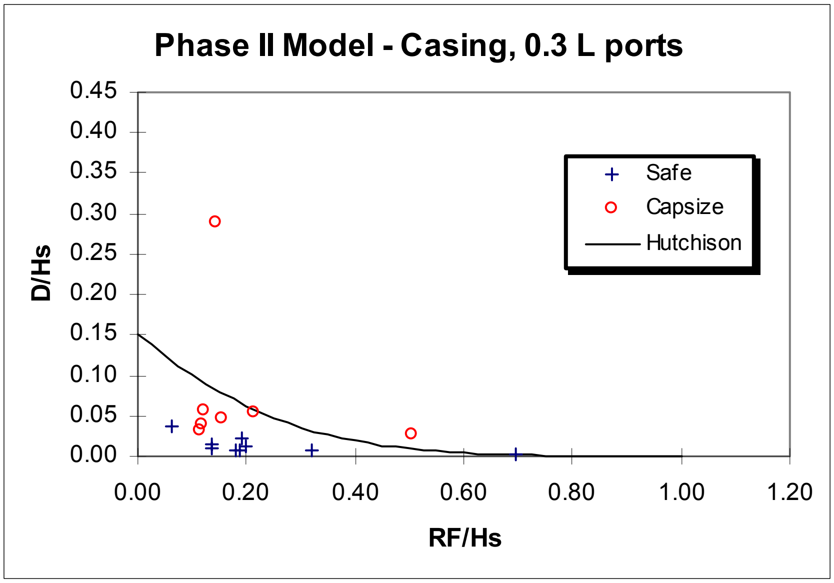

Figure 22 Phase II depth vs. freeboard – Casing, 0.3L freeing ports

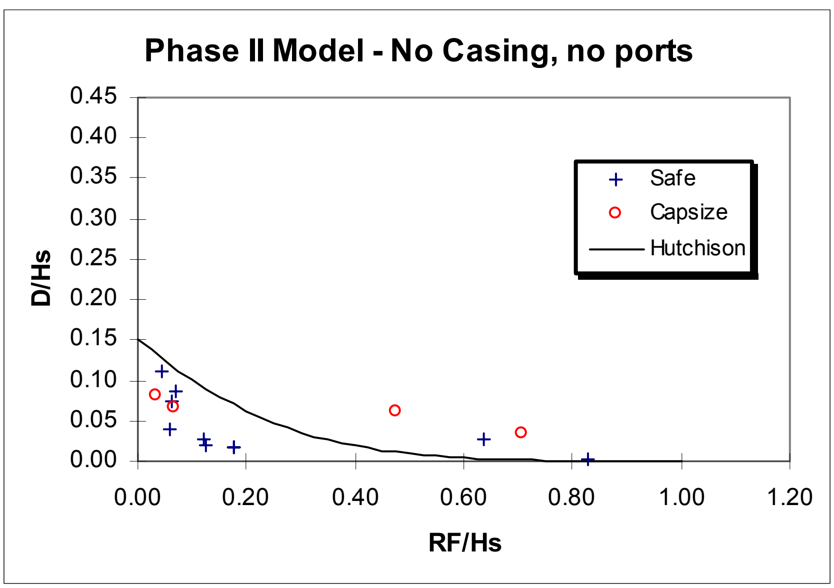

Figure 23 Phase II depth vs. freeboard – No casing, 0 freeing ports

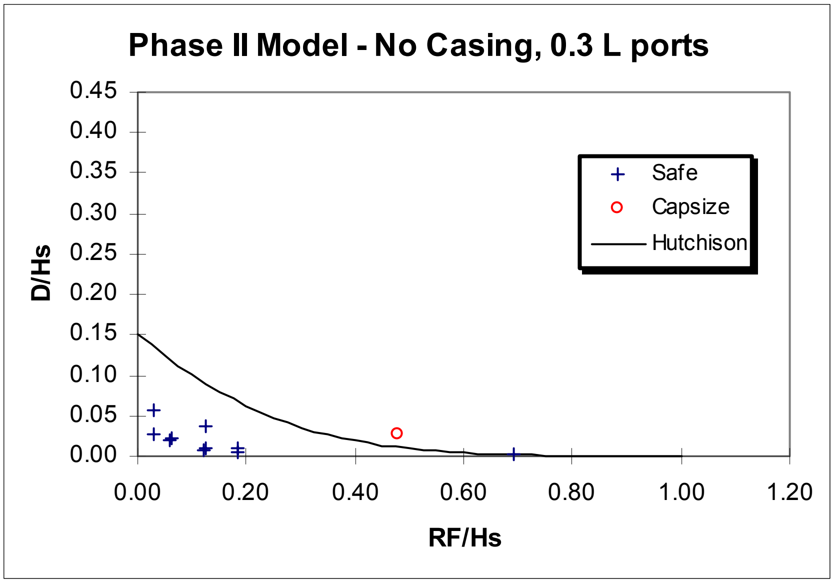

Figure 24 Phase II depth vs. freeboard – No casing, 0.3L freeing ports

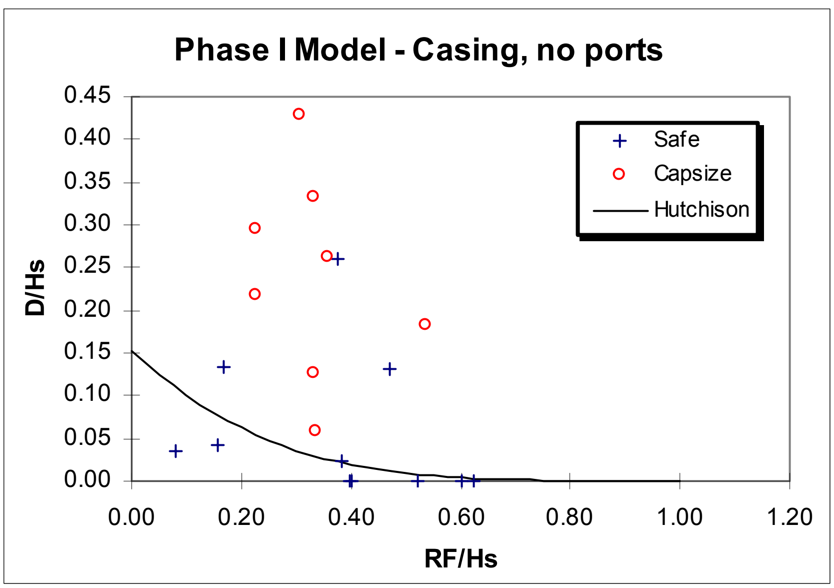

Figure 25 Phase I depth vs. freeboard – Casing, 0 freeing ports

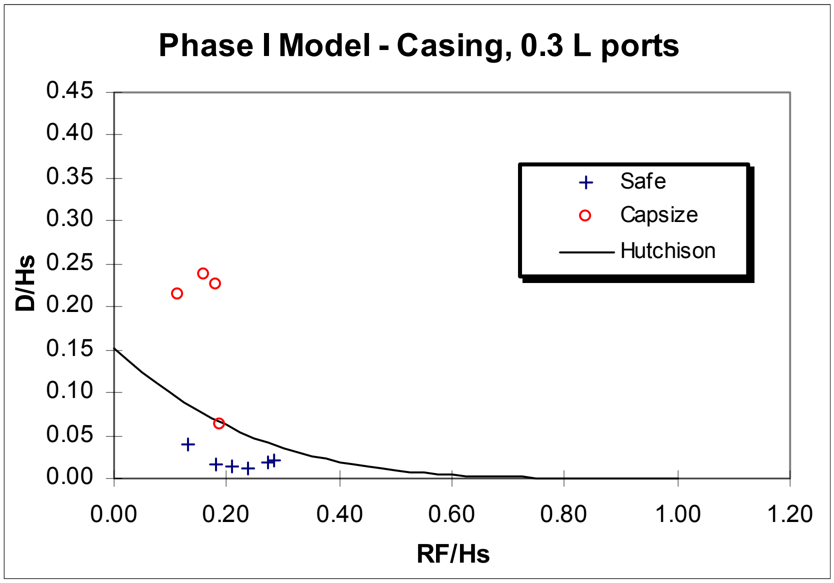

Figure 26 Phase I depth vs. residual freeboard – Casing, 0.3L freeing ports

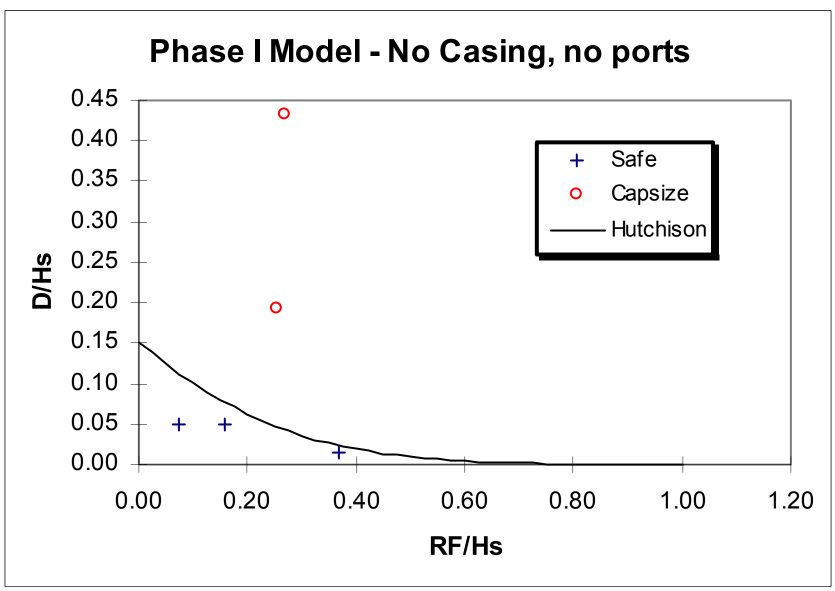

Figure 27 Phase I depth vs. residual freeboard – No casing, 0 freeing ports

It is worth noting that the Hutchison method relies on the prediction of a mean phenomenon (asymptotic water depth), whereas the rolling ship may experience much more severe hazards from the transient effects of water motion.

8.10 Vassalos Method

The data published by Vassalos [23] in 1994 expressed the survivability of RO-RO ferries in terms of the ratio of significant wave height to residual freeboard after damage (Hs/RF). The results from this particular presentation form the basis of the probabilistic method discussed in the next section.

Some results are shown below for this particular variable vs. non-dimensional GMn, for both Phases I and II.

As can be seen in Figures 28 to 33, the data are rather well behaved for both models, with a definite flattened shape in accordance with the form of the Vassalos data. It is notable that the work by Vassalos involved a parent hull form which was "stretched" in various directions to produce the different models used for the research, as opposed to the two very different ships used here. Nonetheless, the approach appears to offer some developments in eventually predicting a transition, as discussed in the next section.

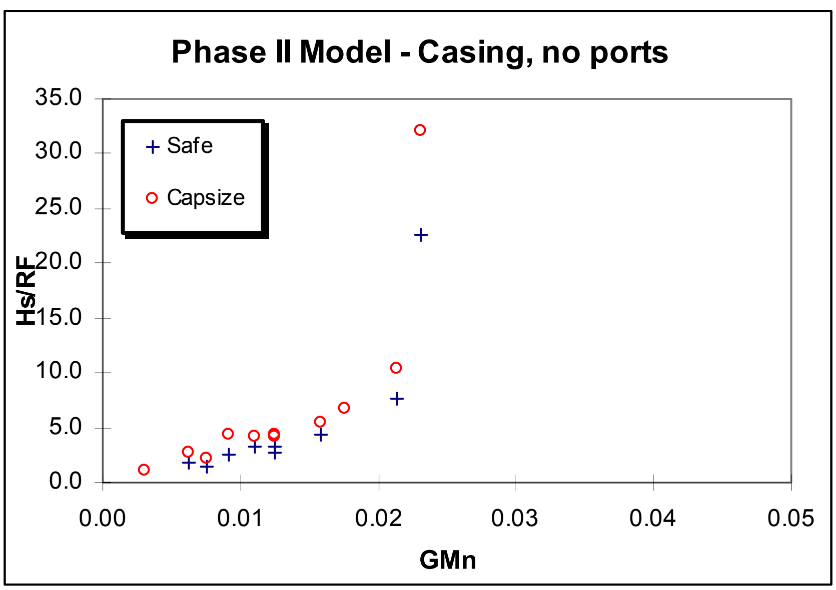

Figure 28 Vassalos graph for Phase II -- Casing, no ports

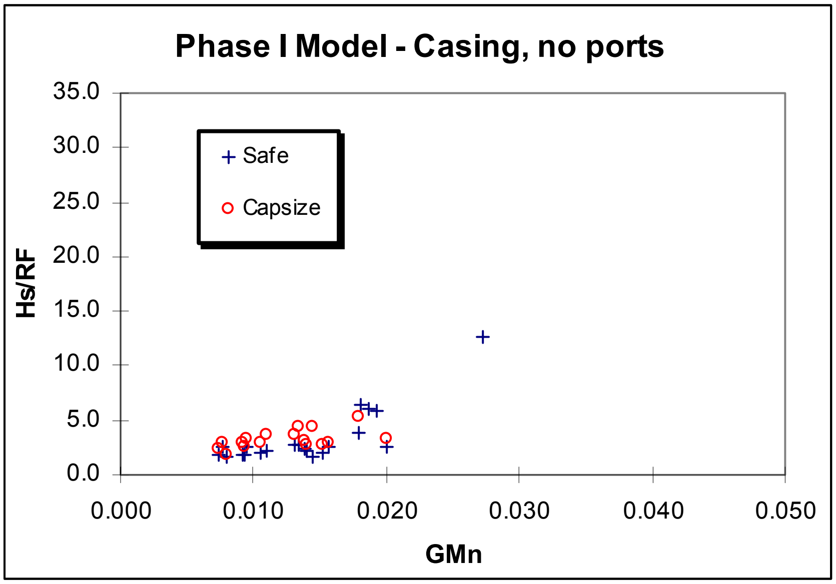

Figure 29 Vassalos graph for Phase I -- Casing, no ports

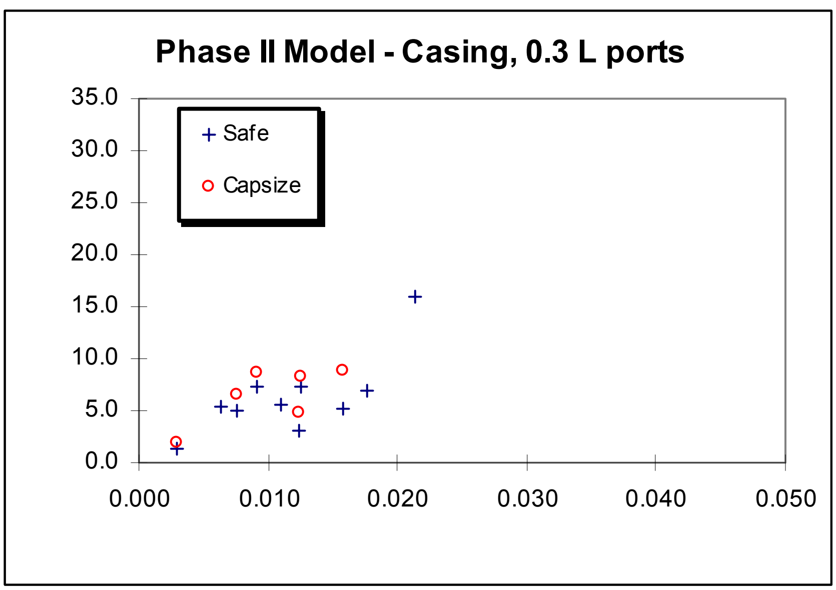

Figure 30 Vassalos graph for Phase II -- Casing, 0.3L freeing ports

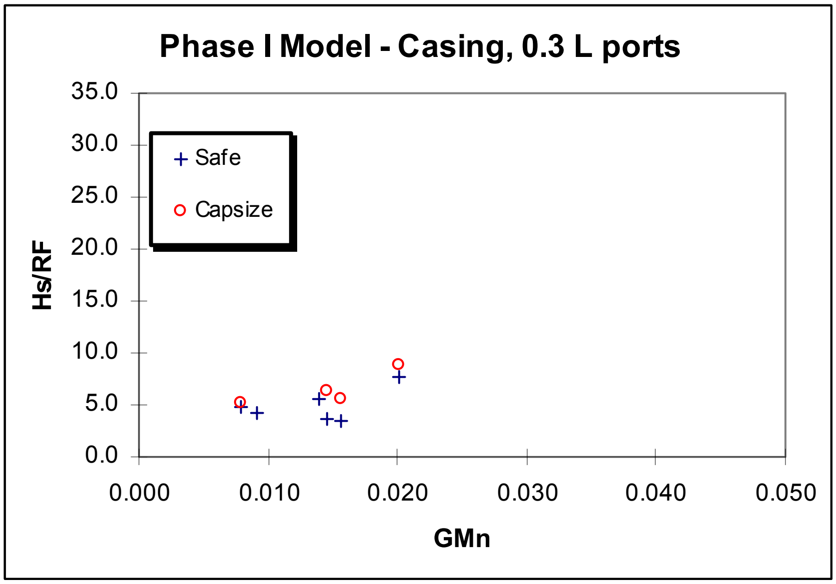

Figure 31 Vassalos graph for Phase I -- Casing, 0.3L freeing ports

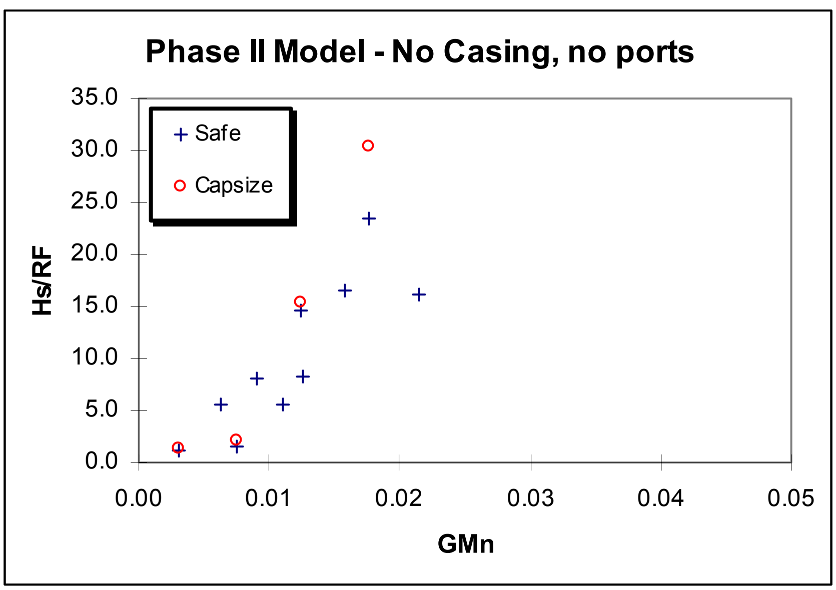

Figure 32 Vassalos graph for Phase II – No casing, no ports

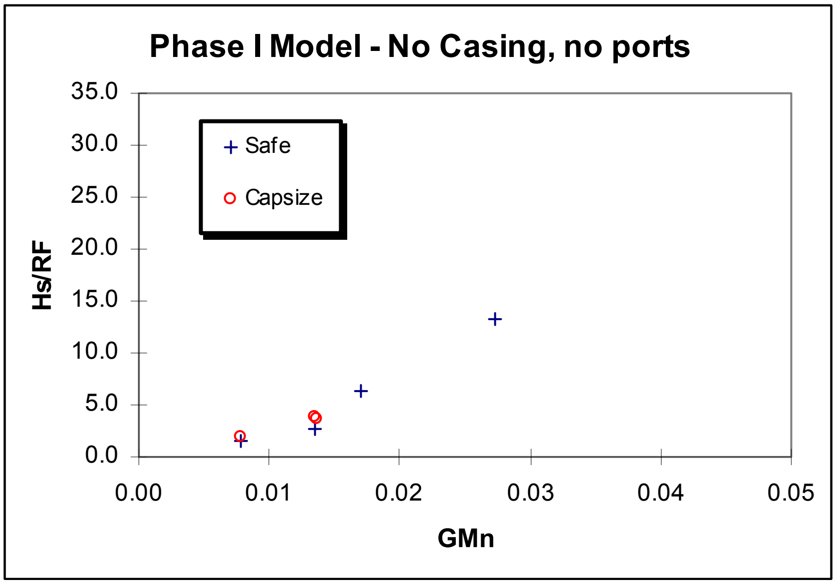

Figure 33 Vassalos graph for Phase I – No casing, no ports

8.11 Probabilistic Methods

Papers by Pawlowski [19] and Vassalos [24] have moved on to the realm of probabilistic analysis, as put forward by the Joint North West European research project [22]. The most significant, and perhaps controversial, part of this research is the determination of the factor "s_i", which expresses the probability that a damaged ship will survive.

Such research follows on from the approaches of the preceding sections, in that it involves the concept of a net volume of water on deck due to a net inflow (as in Hutchison), and sets up a relationship between significant wave height and the head of water on deck (as in Vassalos) based on static stability (as in the GM analyses of Spouge).

The research into "s_i" is centred on the use of the "critical volume" concept. In this method, the first calculation is the volume of water on deck required to loll the ship to its angle of maximum GZ, denoted σ_{MAX}. For this calculation only, the vertical damage extent is modified to assume that the space above the RO-RO deck is intact. The head of water above the static waterline in this condition is then plotted against the significant wave height.

The critical volume concept of Vassalos/Pawlowski is quite dependent on residual freeboard, showing distinct relationships between the freeboard and the progression of "critical volumes" with GM. This is illustrated in Figures 34 and 35. This is significant, since the amount of water on deck, the metacentric height, and freeboard were identified as key parameters in Phase I.

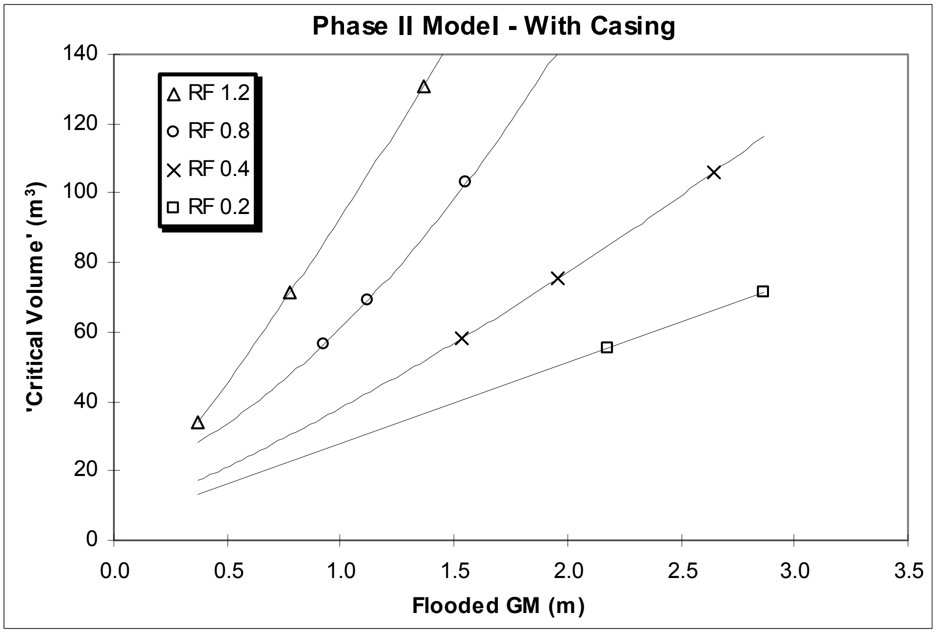

Figure 34 Phase II Critical volume sorted by residual freeboard

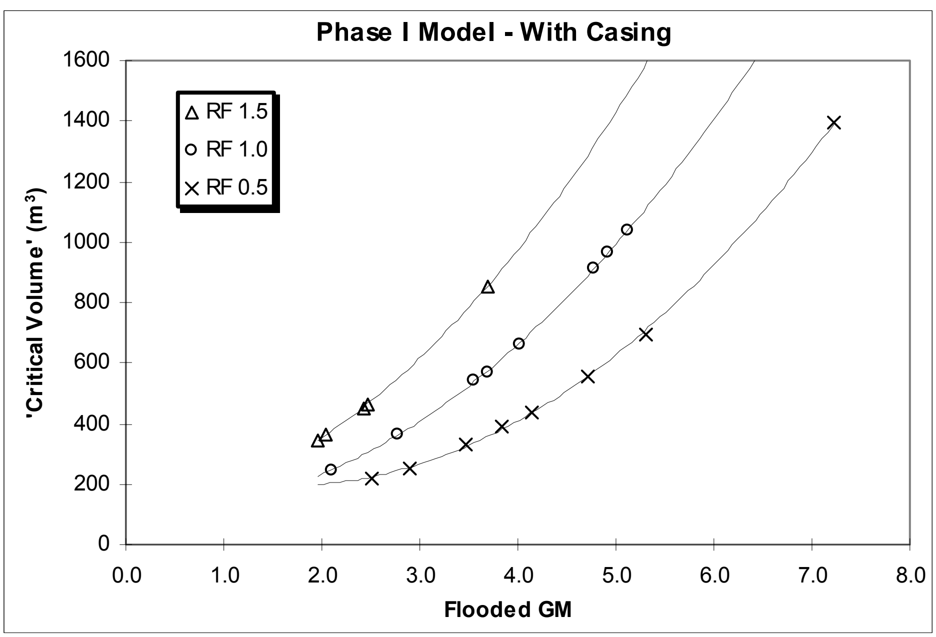

Figure 35 Phase I Critical volume sorted by residual freeboard

Vassalos derived the following equation (7) relating the head and the survivable significant wave height:

$$h = 0.085 \times Hs^{1.3} \qquad (7)$$

It is notable that when calculating the critical volume to reach σ_{MAX}, the *method assumes damage below the vehicle deck only*. The portion of the hull above the RO-RO deck is allowed to make a positive contribution to stability.

As shown in Figure 36, the equation line slightly underpredicts the safe boundary for the tests undertaken in this project. In other words, there is a greater build-up of water on the vehicle deck in both the safe and capsize conditions, and hence an added margin of safety. As freeing port area increases to 0.3L in Figures 36 and 37, the underprediction disappears and the approach is less conservative. The same progression is evident in the Phase I data, illustrated in Figures 38 and 39.

Overall, the approach fits the data rather well, considering the difference in parameters involved in the Phase I and II models and those tested by Vassalos *et al*. There is an inherent uncertainty involved in any case, since Vassalos notes the non-precise nature of ship behaviour in a random sea and the probability of non-repeatability lowering the precision of any results.

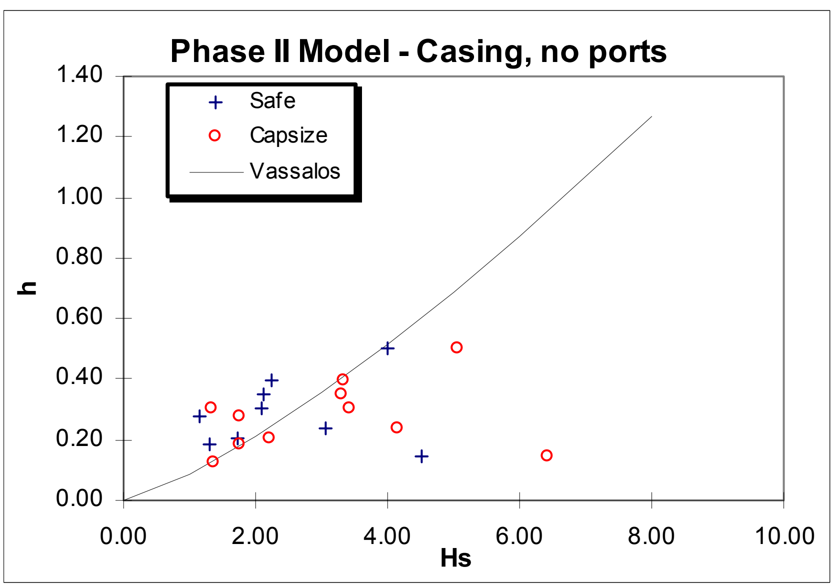

Figure 36 Phase II head vs. wave height -- Casing, 0 freeing ports

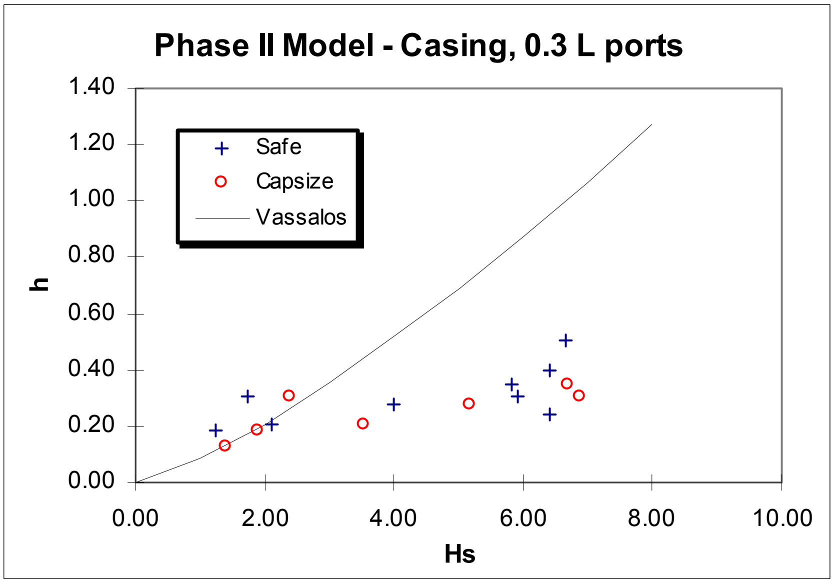

Figure 37 Phase II head vs. wave height -- Casing, 0.3L freeing ports

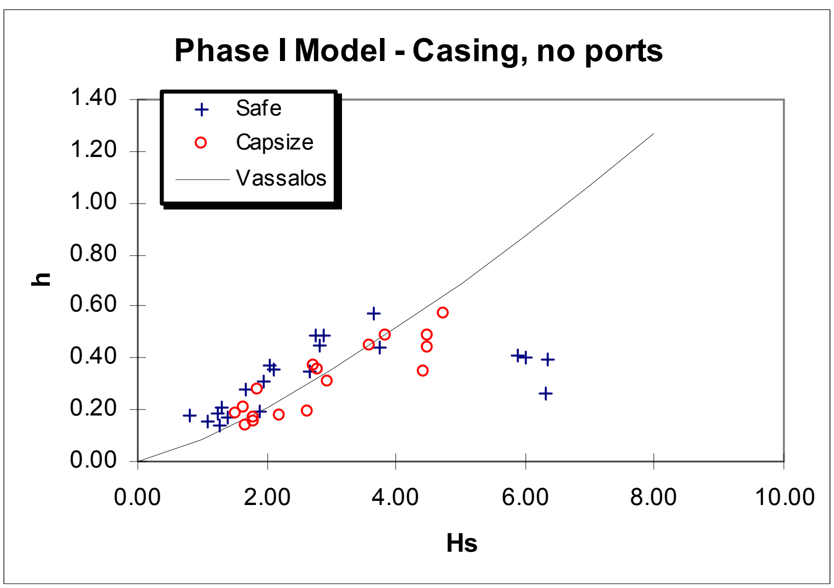

Figure 38 Phase I head vs. wave height -- Casing, 0 freeing ports

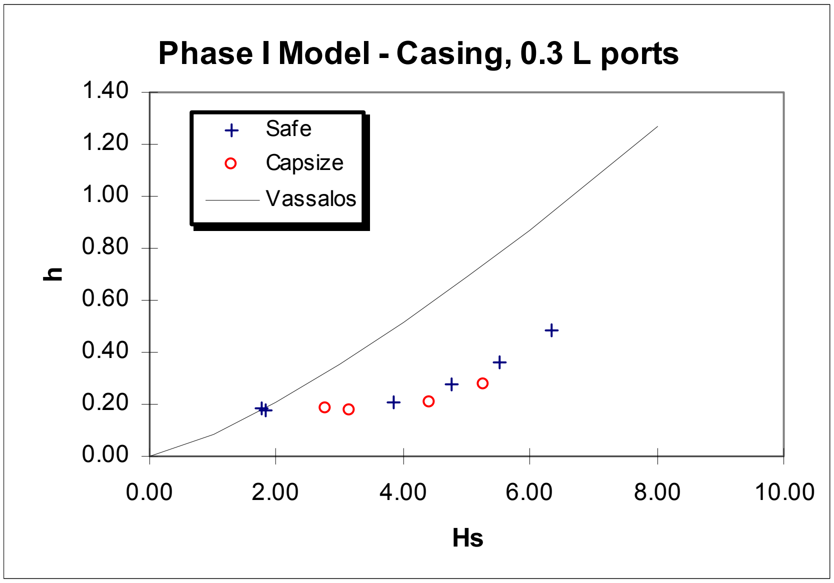

Figure 39 Phase I head vs. wave height -- Casing, 0.3L freeing ports

The results show better correlation to the data with a casing than without, and to the data without freeing ports, as a result of the data from which they have been derived. However, no concrete conclusions have been drawn from the non-casing graphs, as the data are rather sparse for Phase I, and consist mainly of "safe" points for Phase II (i.e., there is no capsize reference from which to differentiate between the two cases).

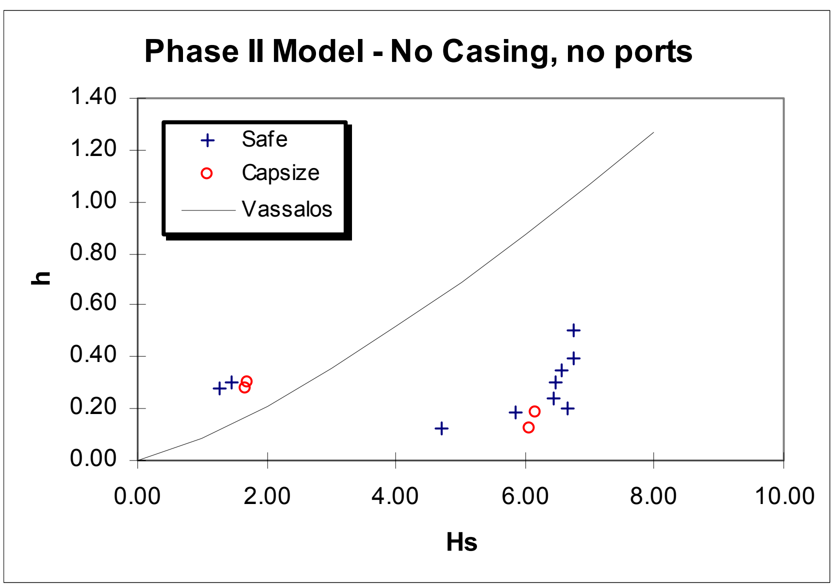

Figure 40 Phase II head vs. wave height – No casing, 0 freeing ports

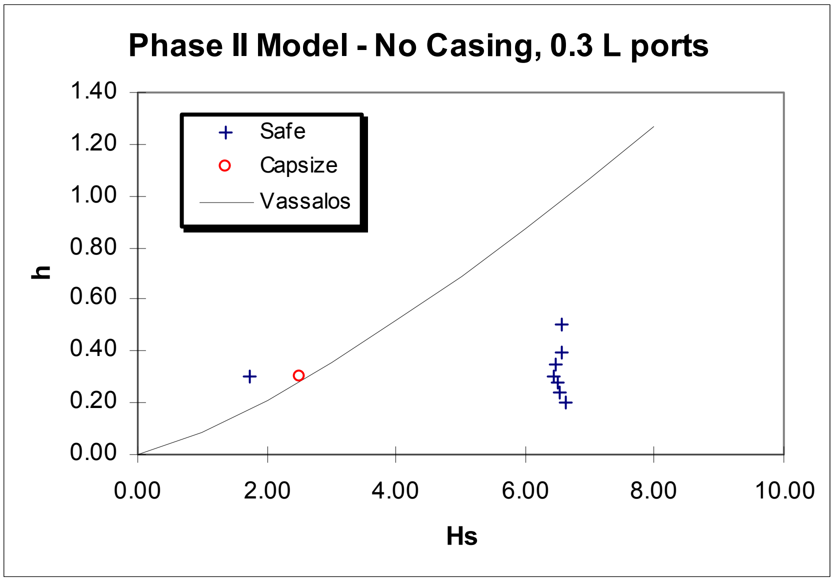

Figure 41 Phase II head vs. wave height – No casing, 0.3L freeing ports

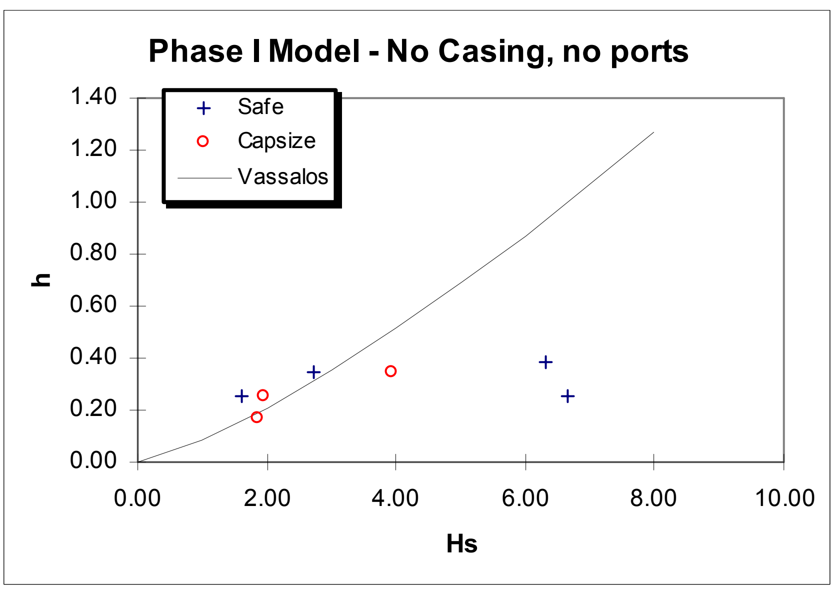

Figure 42 Phase I head vs. wave height – No casing, 0 freeing ports

9. CONCLUSIONS

The results of the Phase II model test program have provided some useful information and have confirmed results from Phase I. It is hope that findings from Phases I and II will provide researchers with meaningful physical data for some time. Both are based on existing Canadian RO-RO vessels, and hence are available to make valuable representation to Canadian and foreign researchers of the particular configuration and operating environment of the domestic flag fleet. The design of the models and data collection has also been aimed at ensuring that the Phase I and II data are useful in numerical simulations as well as physical correlations with other model test programmes. Numerical simulation efforts are an important next step for follow-on research.

Freeing ports have once again demonstrated an ability to enhance the safety of the RO-RO vessel when fitted with biased flow devices (in this case, flaps).

A centreline casing seems to have a slight detrimental effect. Most likely this stems from the effect it seems to have upon the ability of water to flow within the RO-RO space, which despite the free surface effect can have benefits in terms of heeling away from the damage or allowing the opposite side freeing ports to help in deck drainage.

The research of individuals such as Spouge, Hutchison, Pawlowski, and Vassalos has led to a probabilistic formulation which incorporates static stability, deck flooding, and sea state in leading to a calculation for "s_i" which may be used in a process similar to that of the IMO Resolution A.265(VIII). The resulting trends seem to apply to the vessels tested in this project despite the wide range in geometry and configuration.

Neither freeing ports nor casing are explicitly or implicitly included in the combined probabilistic approach. Further research may be advisable in this area to determine whether or not the perceived shifts in the survivability boundaries are indeed taking place, especially at higher sea states with freeing ports.

These limitations notwithstanding, the critical volume approach may be concluded to offer a valid solution to the survivability question at the present time. From the standpoint of the designer, the process begins with calculation of the angle of maximum GZ for a given damage condition in the standard manner. This is followed by determination of the critical volume of flood water on the vehicle deck which leads to a heel approximately equal to the angle of maximum GZ. This second computation is performed with the RO-RO deck considered as an intact displacer.

The relationship between head of water on the vehicle deck in this condition (with reference to the outside mean waterline) as proposed by Vassalos (equation 8) may then be applied, yielding an approximate safe significant wave height which may be compared with wave statistics (e.g., from a "wave atlas") for the area of operation. The survivable wave height should be in excess of the prevailing sea conditions. This exceedence should be applied in a probabilistic manner throughout the vessel, taking account of all damage conditions at representative loading conditions. The probabilistic formulation permits the inclusion of other factors such as the likelihood of collision, in the normal manner of these calculations. The alternative, of course, is to design for the worst case scenario, and ensure that the vessel survives in all conditions (i.e., the safe significant wave height always generously exceeds the prevailing significant wave height).

Based on the above methodology, an estimated "s_i" factor to be used in probabilistic calculations has been derived by Vassalos *et al.* [24] and is given in equation 8:

$$s_i = [h/0.6 + h(0.6 - h)(1.7h^2 - 16.9h + 8.40)]^{1/4} \tag{8}$$

This project has determined that some adjustments may be made to the survivable wave height for certain vessels, although firm values should be the subject of further study. For example, the contribution of bilge keels may offer additional safety of up to 1 m in significant wave height. Flapped freeing ports also contribute to enhanced survivability if the vessel has sufficient freeboard after damage. The presence of a centreline casing will diminish survivability to a certain extent. The precise amount of survivability increase/decrease as a function of ship parameters is not identifiable at this stage since it would be based on a rather small two ship sample.

The results of the research to date have reinforced the critical volume method as a valuable means to indicate safety of RO-RO passengers and crew in the future. The data would suggest that the present SOLAS regulations contain parameters which are more indicative of capsize avoidance than others. The identified critical items include GM and GZ range as direct components of the safety issue. Dynamic stability as expressed by GZ area is important in terms of the ability to withstand vehicle deck flood water, but was not found to be very useful in the prediction of overall capsize safety. These variables are all contained in the current SOLAS criteria, although in a more deterministic form which does not explicitly address the RO-RO flooding problem. The SOLAS-mandated GM is quite low and is hence met perhaps too easily; the maximum GZ criterion is usually met simply by complying with the other criteria.

The issue of RO-RO safety will continue to be the subject of much study and eventual regulation in the near future as rational scientific methods to ensuring survivability are proposed, researched, and refined. This will include quantifying the effects of various design parameters such as those mentioned herein (e.g., freeing ports, casings, bilge keels, etc.). There are considerable data available from model tests already, and these may be applied in the near future to the development of numerical simulation models which can define the precise physics involved in the various dynamic components of the damaged RO-RO in waves, and thereby validate and enhance the work to date.

In the long term, ships meeting the criteria adopted by international convention as a result of international research efforts will provide an acceptable level of safety to the travelling public and the working crews, by ensuring that the risk of maritime disasters is reduced through rational design and in concert with human factors measures for safer operations.

10. RECOMMENDATIONS

Based on the research presented herein, the following recommendations are made for further research:

- Numerical simulation studies of the dynamic flooding problem, including the effects of inflow/outflow, sea-induced motions and internal sloshing on the buoyancy and stability of the ship.
- Additional tests and analysis to quantify the survivability impact of bilge keels, casings, and freeing ports in a form compatible with survivability formulations by expanding the database available.
- Investigations into the effect of asymmetric flooding of spaces below the vehicle deck, and asymmetry in weight distribution due to load shifting.
- Tests involving flow restriction on the RO-RO deck (i.e., as a result of vehicles).

REFERENCES

1. Stubbs, J.T., van Diepen, P., Carreras, J., and Rousseau, J.H. "Flooding Protection of RO-RO Ferries, Phase I," Transport Canada Report TP 12310E Volume I, prepared by Polar Design Associates Ltd., March 1995
2. Molyneux, D. *et al.* "RO-RO Ferry Passenger Vessel Capsize Safety Investigation: Physical Model Experiments, Phase 1," Transport Canada Report TP 12310E Volume II, March 1995, prepared by National Research Council of Canada Institute for Marine Dynamics, St. John's, Newfoundland [IMD report TR-1994-04]
3. Rousseau, J.H. "Flooding Protection of RO-RO Ferries, Phase I - Extension," Transport Canada Report TP 12581E Volume I, prepared by Polar Design Associates Ltd., October 1995
4. Molyneux, W.D. and Sullivan, M. "RO-RO Ferry Passenger Vessel Capsize Safety Investigation: Additional Model Tests with a Simplified Ferry Model," Transport Canada Report TP 12581E Volume II, September 1995, prepared by National Research Council of Canada Institute for Marine Dynamics, St. John's, Newfoundland [IMD report TR-1995-47]
5. Rousseau, J.H. "Flooding Protection of RO-RO Ferries, Phase II - Interim Report No.1: Model Design & Test Plan," Transport Canada Interim Report, prepared by Polar Design Associates Ltd., July 1995
6. Bird, H. and Browne, R.P. "Damage stability model experiments," Vol. 116, Transactions of The Royal Institution of Naval Architects, London, England, 1973
7. Dand, I.W. "Hydrodynamic Aspects of the Sinking of the Ferry 'Herald of Free Enterprise'," Transactions of The Royal Institution of Naval Architects, Vol. 141, London England, 1988
8. Pucill, F. and Velschou, S. "RO-RO Passenger Ferry Safety Studies -- Model Test of a Typical Ferry," Danish Maritime Institute, 1990
9. Graham, A. "The Assessment of Damage Stability Criteria Using Model Tests," U.K. Department of Transport, 1990
10. Spouge, J.R., "The Technical Investigation of the Sinking of the RO-RO Ferry EUROPEAN GATEWAY," Transactions of RINA, 1985
11. Spouge, J., "Technique to Predict the Capsize of a Damaged RO-RO Ferry," RINA Symposium on RO-RO Ships' Survivability, London, 1994
12. Blume, P., "Survivability Tests for a Damaged RO-RO Passenger Vessel," The Hamburg Ship Model Basin, Report S 323 / 95
13. IMO paper submitted by Denmark, Finland, Norway and Sweden, "Required Height of Transverse Bulkheads on the RO-RO Deck, Based upon Model Tests Performed under the Project 'Safety of Passenger/RO-RO Vessels,'" RO-RO/ISWG 1/3/20, October 1995

14. IMO paper submitted by Denmark, Finland, Norway, Sweden and the United Kingdom, “Results of Model Tests Carried out by Marine Safety Agency (U.K.) and Joint North West European R&D Project,” SOLAS/CONF.3/.INF.3, November 1995

15. IMO paper submitted by Japan, “Some Results of Model Test,” RORO/ISWG 1/3/15, October 1995

16. IMO paper submitted by Spain, “Seakeeping Tests of a Damaged Ferry Vessel,” SOLAS/CONF.3/INF.5, November 1995

17. Vassalos, D., “Damage Survivability of Passenger Ships,” a paper presented at the Annual Meeting of SNAME in New Orleans, Louisiana, U.S. in November 1994

18. Vassalos, D., “Capsizal Resistance of Damaged RO-RO Ferries: Modelling and Applications”, WEGEMT Workshop - Damage Stability of Ships, Copenhagen, October 1995

19. Pawlowski, M., “A Closed-Form Assessment of the Capsizal Probability - the s_i Factor”, WEGEMT Workshop - Damage Stability of Ships, Copenhagen, October 1995

20. Hutchison, B., Molyneux, D., and Little, P., “Time Domain Simulation and Probability Domain Integrals for Water on Deck Accumulation”, SNAME California Joint Sections Meeting, Long Beach, California, April 1995

21. Molyneux, D. and Cumming, D., “RO-RO Ferry Passenger Vessel Capsize Safety Investigation: Physical Model Experiments, Phase 2”, TR-1997-01, January 1997

22. “Harmonization of Damage Stability Provisions in IMO Instruments”, IMO SLF 40/4/5, submitted to the Subcommittee on Stability & Load Lines and on Fishing Vessels, by Denmark, Finland, Norway, Sweden, and the United Kingdom, 7 June 1996

23. Vassalos, D., “Capsizal Resistance Prediction of a Damaged Ship in a Random Sea”, RINA Symposium on RO-RO Ship’s Survivability, 25 November 1994

24. Vassalos, D., Pawlowski, M., Turan, O., “Criteria for Survival in Damaged Condition”, 1996

25. “Regulation on Subdivision and Stability of Passenger Ships (as an equivalent to Part B of Chapter II of the 1974 SOLAS Convention)”, International Maritime Organization, London, 1974

APPENDIX A

HULL GEOMETRY & HYDROSTATICS

(*Not available in electronic format /
Non disponible en format électronique*)

APPENDIX B

STABILITY CALCULATION OUTPUT

```
GHS 6.50                   Phase II Model
                     Model flooded to 1.2m of freeboard
                      Initial draft = 16'3" (4.95 m)
                           Double bottom intact
                KG nominal = 7.00m, KG actual = 6.976m [A1]


                      WEIGHT and DISPLACEMENT STATUS
                     Baseline draft: 5.506,  Heel: zero

Part------------------------------Weight(MT)----LCG-----TCG-----VCG
WEIGHT                              4,465.77   0.000   0.000   6.976

                         SpGr------Displ(MT)----LCB-----TCB-----VCB------RefHt
HULL                     1.025      5,147.70   0.000   0.000   3.112     -5.506
B12.C           Flooded  1.025       -681.93   0.000   0.000   3.307     -5.506
  Total Displacement--> 1.025      4,465.77   0.000   0.000   3.083
------------------------------------------------------------------------------
               Righting Arms:                  0.000   0.000
Distances in METERS.----------------------------------------------------------


                     HYDROSTATIC PROPERTIES WITH DAMAGE
                        No Trim, No Heel, VCG = 6.976

   LCF   Displacement   Buoyancy-Ctr.  Weight/         Moment/
  Draft----Weight(MT)----LCB-----VCB-------CM-----LCF---CM trim----GML-----GMT
  5.506     4,465.77   0.000   3.083    10.98   0.000    61.63  117.86   1.366
 Distances in METERS.-----Specific Gravity = 1.025.-----------Moment in M.-MT.
                             Trim is per 85.40M.
 Draft is from Baseline.
```

Phase II Model
Model flooded to 1.2m of freeboard
Initial draft = 16'3" (4.95 m)
Double bottom intact
KG nominal = 7.00m, KG actual = 6.976m [A1]

RIGHTING ARMS vs HEEL ANGLE with DAMAGE

LCG = 0.000 TCG = 0.000 VCG = 6.976

Origin Depth	Degrees of Trim	Heel	Displacement Weight(MT)	Righting Arms in Trim	in Heel	--> Area	Flood Pt Height
5.506	0.00	0.00	4,465.77	0.000	0.000	0.0000	1.200(1)
5.501	0.00	2.00s	4,465.76	0.000	0.048s	0.0008	0.879(1)
5.484	0.00	4.00s	4,465.71	0.000	0.096s	0.0033	0.562(1)
5.457	0.00	6.00s	4,465.65	0.000	0.146s	0.0076	0.248(1)
5.428	0.00	7.60s	4,465.85	0.000	0.187s	0.0122	-0.000(1)
5.419	0.00	8.00s	4,465.86	0.000	0.198s	0.0136	-0.062(1)
5.384	0.00	10.00s	4,465.79	0.000	0.225s	0.0209	-0.381(1)
5.378	0.00	10.44s	4,465.77	0.000	0.226s	0.0227	-0.453(1)
5.361	0.00	12.00s	4,465.79	0.000	0.217s	0.0287	-0.719(1)
5.348	0.00	14.00s	4,465.79	0.000	0.183s	0.0357	-1.072(1)
5.342	0.00	16.00s	4,466.09	0.000	0.132s	0.0413	-1.438(1)
5.341	0.00	18.00s	4,465.84	0.000	0.068s	0.0448	-1.812(1)
5.343	0.00	19.85s	4,465.87	0.000	0.000s	0.0459	-2.166(1)
5.343	0.00	20.00s	4,465.69	0.000	-0.006s	0.0459	-2.195(1)
5.347	0.00	22.00s	4,465.63	0.000	-0.087s	0.0443	-2.583(1)
5.352	0.00	24.00s	4,465.61	0.000	-0.173s	0.0398	-2.976(1)
5.357	0.00	26.00s	4,465.62	0.000	-0.265s	0.0322	-3.372(1)
5.360	0.00	27.00s	4,465.73	0.000	-0.312s	0.0271	-3.570(1)
5.362	0.00	28.00s	4,465.74	0.000	-0.360s	0.0213	-3.769(1)
5.365	0.00	30.00s	4,465.69	0.000	-0.458s	0.0070	-4.168(1)

Distances in METERS.----Specific Gravity = 1.025.---------Area in M.-Rad.

	Critical Point		LCP	TCP	VCP
(1)	Deck edge	FLOOD	0.000	9.220s	6.706

LIM	"solas 90 criteria" CRITERION		Min/Max		Attained	
(1)	GM at Equilibrium	>	0.050	M.	1.366	P
(2)	Area from Equilibrium to RAzero or 27 deg	>	0.0150	M.-Rad	0.0459	P
(3)	Righting Arm at MaxRA	>	0.100	M.	0.226	P
(4)	Absolute Angle at MaxRA	>	1.00	deg	10.44	P
(5)	Angle from Equilibrium to RAzero	>	15.00	deg	19.85	P

--------------------Relative angles measured from 0.000 ---------------------

GHS 6.50

Phase II Model
Model flooded to 1.2m of freeboard
Initial draft = 16'3" (4.95 m)
Double bottom intact
KG nominal = 7.59m, KG actual = 7.566m [A2]

WEIGHT and DISPLACEMENT STATUS
Baseline draft: 5.506, Heel: zero

Part		Weight(MT)	LCG	TCG	VCG	
WEIGHT		4,465.77	0.000	0.000	7.566	
	SpGr	Displ(MT)	LCB	TCB	VCB	RefHt
HULL	1.025	5,147.70	0.000	0.000	3.112	-5.506
B12.C Flooded	1.025	-681.93	0.000	0.000	3.307	-5.506
Total Displacement-->	1.025	4,465.77	0.000	0.000	3.083	
Righting Arms:			0.000	0.000		

Distances in METERS.

HYDROSTATIC PROPERTIES WITH DAMAGE
No Trim, No Heel, VCG = 7.566

LCF Draft	Displacement Weight(MT)	Buoyancy-Ctr. LCB	VCB	Weight/ CM	LCF	Moment/ CM trim	GML	GMT
5.506	4,465.77	0.000	3.083	10.98	0.000	61.32	117.27	0.776

Distances in METERS.-----Specific Gravity = 1.025.-----------Moment in M.-MT.
Trim is per 85.40M.
Draft is from Baseline.

Phase II Model
Model flooded to 1.2m of freeboard
Initial draft = 16'3" (4.95 m)
Double bottom intact
KG nominal = 7.59m, KG actual = 7.566m [A2]

RIGHTING ARMS vs HEEL ANGLE with DAMAGE

LCG = 0.000 TCG = 0.000 VCG = 7.566

Origin Depth	Degrees of Trim	Heel	Displacement Weight(MT)	Righting Arms in Trim	in Heel	--> Area	Flood Pt Height
5.506	0.00	0.00	4,465.77	0.000	0.000	0.0000	1.200(1)
5.501	0.00	2.00s	4,465.76	0.000	0.027s	0.0005	0.879(1)
5.484	0.00	4.00s	4,465.71	0.000	0.055s	0.0019	0.562(1)
5.457	0.00	6.00s	4,465.65	0.000	0.084s	0.0043	0.248(1)
5.428	0.00	7.60s	4,465.85	0.000	0.109s	0.0070	-0.000(1)
5.419	0.00	8.00s	4,465.86	0.000	0.116s	0.0078	-0.062(1)
5.394	0.00	9.36s	4,465.78	0.000	0.125s	0.0107	-0.276(1)
5.384	0.00	10.00s	4,466.05	0.000	0.123s	0.0121	-0.381(1)
5.361	0.00	12.00s	4,465.86	0.000	0.094s	0.0158	-0.719(1)
5.348	0.00	14.00s	4,465.81	0.000	0.040s	0.0182	-1.072(1)
5.344	0.00	15.18s	4,465.92	0.000	0.000s	0.0186	-1.287(1)
5.342	0.00	16.00s	4,465.81	0.000	-0.031s	0.0184	-1.437(1)
5.341	0.00	18.00s	4,465.82	0.000	-0.114s	0.0159	-1.812(1)
5.343	0.00	20.00s	4,465.69	0.000	-0.207s	0.0103	-2.195(1)
5.347	0.00	22.00s	4,465.63	0.000	-0.308s	0.0013	-2.583(1)
5.352	0.00	24.00s	4,465.61	0.000	-0.413s	-0.0112	-2.976(1)
5.357	0.00	26.00s	4,465.62	0.000	-0.523s	-0.0276	-3.372(1)
5.360	0.00	27.00s	4,465.73	0.000	-0.580s	-0.0372	-3.570(1)
5.362	0.00	28.00s	4,465.74	0.000	-0.637s	-0.0478	-3.769(1)
5.365	0.00	30.00s	4,465.69	0.000	-0.753s	-0.0721	-4.168(1)

Distances in METERS.----Specific Gravity = 1.025.---------Area in M.-Rad.

Critical Point		LCP	TCP	VCP
(1) Deck edge	FLOOD	0.000	9.220s	6.706

LIM---"solas 90 criteria" CRITERION		Min/Max		Attained
(1) GM at Equilibrium	>	0.050	M.	0.776 P
(2) Area from Equilibrium to RAzero or 27 deg	>	0.0150	M.-Rad	0.0186 P
(3) Righting Arm at MaxRA	>	0.100	M.	0.125 P
(4) Absolute Angle at MaxRA	>	1.00	deg	9.36 P
(5) Angle from Equilibrium to RAzero	>	15.00	deg	15.18 P

--------------------Relative angles measured from 0.000 ---------------------

GHS 6.50

Phase II Model
Model flooded to 1.2m of freeboard
Initial draft = 16'3" (4.95 m)
Double bottom intact
KG nominal = 8.00m, KG actual = 7.969m [A3]

WEIGHT and DISPLACEMENT STATUS
Baseline draft: 5.506, Heel: zero

Part			Weight(MT)	LCG	TCG	VCG	
WEIGHT			4,465.77	0.000	0.000	7.969	
		SpGr	**Displ(MT)**	**LCB**	**TCB**	**VCB**	**RefHt**
HULL		1.025	5,147.70	0.000	0.000	3.112	-5.506
B12.C	Flooded	1.025	-681.93	0.000	0.000	3.307	-5.506
Total Displacement-->		1.025	4,465.77	0.000	0.000	3.083	
Righting Arms:				0.000	0.000		

Distances in METERS.

HYDROSTATIC PROPERTIES WITH DAMAGE
No Trim, No Heel, VCG = 7.969

LCF Draft	Displacement Weight(MT)	Buoyancy-Ctr. LCB	Buoyancy-Ctr. VCB	Weight/ CM	LCF	Moment/ CM trim	GML	GMT
5.506	4,465.77	0.000	3.083	10.98	0.000	61.11	116.86	0.373

Distances in METERS.-----Specific Gravity = 1.025.-----------Moment in M.-MT.
Trim is per 85.40M.
Draft is from Baseline.

Phase II Model
Model flooded to 1.2m of freeboard
Initial draft = 16'3" (4.95 m)
Double bottom intact
KG nominal = 8.00m, KG actual = 7.969m [A3]

RIGHTING ARMS vs HEEL ANGLE with DAMAGE

LCG = 0.000 TCG = 0.000 VCG = 7.969

Origin Depth	Degrees of Trim	Heel	Displacement Weight(MT)	Righting Arms in Trim	in Heel	--> Area	Flood Pt Height
5.506	0.00	0.00	4,465.77	0.000	0.000	0.0000	1.200(1)
5.501	0.00	2.00s	4,465.76	0.000	0.013s	0.0002	0.879(1)
5.484	0.00	4.00s	4,465.71	0.000	0.027s	0.0009	0.562(1)
5.457	0.00	6.00s	4,465.65	0.000	0.042s	0.0021	0.248(1)
5.428	0.00	7.60s	4,465.85	0.000	0.056s	0.0035	-0.000(1)
5.419	0.00	8.00s	4,465.86	0.000	0.059s	0.0039	-0.062(1)
5.406	0.00	8.68s	4,465.77	0.000	0.062s	0.0046	-0.168(1)
5.384	0.00	10.00s	4,465.78	0.000	0.053s	0.0059	-0.381(1)
5.361	0.00	12.00s	4,465.86	0.000	0.010s	0.0070	-0.719(1)
5.358	0.00	12.34s	4,465.77	0.000	0.000s	0.0071	-0.778(1)
5.348	0.00	14.00s	4,465.79	0.000	-0.057s	0.0062	-1.072(1)
5.342	0.00	16.00s	4,466.09	0.000	-0.142s	0.0028	-1.438(1)
5.341	0.00	18.00s	4,465.84	0.000	-0.239s	-0.0038	-1.812(1)
5.343	0.00	20.00s	4,465.69	0.000	-0.345s	-0.0139	-2.195(1)
5.347	0.00	22.00s	4,465.63	0.000	-0.459s	-0.0280	-2.583(1)
5.352	0.00	24.00s	4,465.61	0.000	-0.577s	-0.0461	-2.976(1)
5.357	0.00	26.00s	4,465.62	0.000	-0.700s	-0.0683	-3.372(1)
5.360	0.00	27.00s	4,465.73	0.000	-0.763s	-0.0811	-3.570(1)
5.362	0.00	28.00s	4,465.74	0.000	-0.826s	-0.0950	-3.769(1)
5.365	0.00	30.00s	4,465.69	0.000	-0.955s	-0.1260	-4.168(1)

Distances in METERS.----Specific Gravity = 1.025.---------Area in M.-Rad.

	Critical Point		LCP	TCP	VCP
(1)	Deck edge	FLOOD	0.000	9.220s	6.706

LIM	"solas 90 criteria" CRITERION		Min/Max		Attained	
(1)	GM at Equilibrium	>	0.050	M.	0.373	P
(2)	Area from Equilibrium to RAzero or 27 deg	>	0.0150	M.-Rad	0.0071	F
(3)	Righting Arm at MaxRA	>	0.100	M.	0.062	F
(4)	Absolute Angle at MaxRA	>	1.00	deg	8.68	P
(5)	Angle from Equilibrium to RAzero	>	15.00	deg	12.34	F

--------------------Relative angles measured from 0.000 ---------------------

GHS 6.50

Phase II Model
Model flooded to 0.8m of freeboard
Initial draft = 16'3" (4.95 m)
Double bottom intact
KG nominal = 6.77m, KG actual = 6.779m [B1]

WEIGHT and DISPLACEMENT STATUS
Baseline draft: 5.906, Heel: zero

Part		Weight(MT)	LCG	TCG	VCG
WEIGHT		4,465.77	0.000	0.000	6.779

		SpGr	Displ(MT)	LCB	TCB	VCB	RefHt
HULL		1.025	5,659.18	0.000	0.000	3.347	-5.906
B08.C	Flooded	1.025	-1,193.41	0.000	0.000	3.511	-5.906
Total Displacement-->		1.025	4,465.76	0.000	0.000	3.303	
Righting Arms:				0.000	0.000		

Distances in METERS.

HYDROSTATIC PROPERTIES WITH DAMAGE
No Trim, No Heel, VCG = 6.779

LCF Draft	Displacement Weight(MT)	Buoyancy-Ctr. LCB	VCB	Weight/ CM	LCF	Moment/ CM trim	GML	GMT
5.906	4,465.76	0.000	3.303	10.46	0.000	66.86	127.85	1.554

Distances in METERS.-----Specific Gravity = 1.025.-----------Moment in M.-MT.
Trim is per 85.40M.
Draft is from Baseline.

Phase II Model
Model flooded to 0.8m of freeboard
Initial draft = 16'3" (4.95 m)
Double bottom intact
KG nominal = 6.77m, KG actual = 6.779m [B1]

RIGHTING ARMS vs HEEL ANGLE with DAMAGE

LCG = 0.000 TCG = 0.000 VCG = 6.779

Origin Depth	Degrees of Trim	Heel	Displacement Weight(MT)	Righting Arms in Trim	in Heel	--> Area	Flood Pt Height
5.906	0.00	0.00	4,465.76	0.000	0.000	0.0000	0.800(1)
5.900	0.00	2.00s	4,465.76	0.000	0.054s	0.0009	0.480(1)
5.883	0.00	4.00s	4,465.73	0.000	0.109s	0.0038	0.163(1)
5.868	0.00	5.05s	4,465.75	0.000	0.140s	0.0061	0.000(1)
5.854	0.00	6.00s	4,465.78	0.000	0.165s	0.0086	-0.148(1)
5.841	0.00	7.45s	4,465.60	0.000	0.177s	0.0130	-0.387(1)
5.839	0.00	8.00s	4,465.82	0.000	0.176s	0.0146	-0.482(1)
5.842	0.00	10.00s	4,465.72	0.000	0.148s	0.0203	-0.839(1)
5.857	0.00	12.00s	4,465.70	0.000	0.099s	0.0246	-1.215(1)
5.880	0.00	14.00s	4,465.69	0.000	0.034s	0.0269	-1.603(1)
5.891	0.00	14.96s	4,465.13	0.000	0.000s	0.0272	-1.793(1)
5.907	0.00	16.00s	4,465.43	0.000	-0.040s	0.0269	-2.002(1)
5.938	0.00	18.00s	4,465.75	0.000	-0.121s	0.0241	-2.409(1)
5.970	0.00	20.00s	4,465.75	0.000	-0.208s	0.0184	-2.822(1)
6.003	0.00	22.00s	4,465.76	0.000	-0.298s	0.0095	-3.239(1)
6.036	0.00	24.00s	4,465.76	0.000	-0.391s	-0.0025	-3.660(1)
6.066	0.00	26.00s	4,465.17	0.000	-0.486s	-0.0178	-4.081(1)
6.082	0.00	27.00s	4,465.62	0.000	-0.535s	-0.0267	-4.293(1)
6.097	0.00	28.00s	4,465.64	0.000	-0.583s	-0.0365	-4.504(1)
6.123	0.00	30.00s	4,465.36	0.000	-0.681s	-0.0585	-4.926(1)

Distances in METERS.----Specific Gravity = 1.025.---------Area in M.-Rad.

	Critical Point		LCP	TCP	VCP
(1)	Deck edge	FLOOD	0.000	9.220s	6.706

LIM	"solas 90 criteria" CRITERION		Min/Max		Attained	
(1)	GM at Equilibrium	>	0.050	M.	1.554	P
(2)	Area from Equilibrium to RAzero or 27 deg	>	0.0150	M.-Rad	0.0272	P
(3)	Righting Arm at MaxRA	>	0.100	M.	0.177	P
(4)	Absolute Angle at MaxRA	>	1.00	deg	7.45	P
(5)	Angle from Equilibrium to RAzero	>	15.00	deg	14.96	P

--------------------Relative angles measured from 0.000 ---------------------

GHS 6.50

Phase II Model
Model flooded to 0.8m of freeboard
Initial draft = 16'3" (4.95 m)
Double bottom intact
KG nominal = 7.22m, KG actual = 7.210m [B2]

WEIGHT and DISPLACEMENT STATUS
Baseline draft: 5.906, Heel: zero

Part			Weight(MT)	LCG	TCG	VCG	
WEIGHT			4,465.77	0.000	0.000	7.210	
		SpGr	Displ(MT)	LCB	TCB	VCB	RefHt
HULL		1.025	5,659.18	0.000	0.000	3.347	-5.906
B08.C	Flooded	1.025	-1,193.41	0.000	0.000	3.511	-5.906
Total Displacement-->		1.025	4,465.76	0.000	0.000	3.303	
Righting Arms:				0.000	0.000		

Distances in METERS.

HYDROSTATIC PROPERTIES WITH DAMAGE
No Trim, No Heel, VCG = 7.210

LCF Draft	Displacement Weight(MT)	Buoyancy-Ctr. LCB	VCB	Weight/ CM	LCF	Moment/ CM trim	GML	GMT
5.906	4,465.76	0.000	3.303	10.46	0.000	66.63	127.42	1.123

Distances in METERS.-----Specific Gravity = 1.025.-----------Moment in M.-MT.
Trim is per 85.40M.
Draft is from Baseline.

Phase II Model
Model flooded to 0.8m of freeboard
Initial draft = 16'3" (4.95 m)
Double bottom intact
KG nominal = 7.22m, KG actual = 7.210m [B2]

RIGHTING ARMS vs HEEL ANGLE with DAMAGE

LCG = 0.000 TCG = 0.000 VCG = 7.210

Origin Depth	Degrees of Trim	Degrees of Heel	Displacement Weight(MT)	Righting Arms in Trim	Righting Arms in Heel	--> Area	Flood Pt Height
5.906	0.00	0.00	4,465.76	0.000	0.000	0.0000	0.800(1)
5.900	0.00	2.00s	4,465.76	0.000	0.039s	0.0007	0.480(1)
5.883	0.00	4.00s	4,465.73	0.000	0.079s	0.0027	0.163(1)
5.868	0.00	5.05s	4,465.75	0.000	0.102s	0.0044	0.000(1)
5.854	0.00	6.00s	4,465.78	0.000	0.120s	0.0063	-0.148(1)
5.845	0.00	6.81s	4,465.95	0.000	0.124s	0.0080	-0.280(1)
5.840	0.00	8.00s	4,466.16	0.000	0.116s	0.0105	-0.482(1)
5.842	0.00	10.00s	4,465.72	0.000	0.074s	0.0138	-0.839(1)
5.857	0.00	12.00s	4,465.70	0.000	0.009s	0.0152	-1.215(1)
5.860	0.00	12.23s	4,465.79	0.000	0.001s	0.0152	-1.259(1)
5.880	0.00	14.00s	4,465.70	0.000	-0.070s	0.0142	-1.603(1)
5.907	0.00	16.00s	4,465.75	0.000	-0.159s	0.0102	-2.002(1)
5.938	0.00	18.00s	4,465.75	0.000	-0.254s	0.0030	-2.409(1)
5.970	0.00	20.00s	4,465.75	0.000	-0.355s	-0.0076	-2.822(1)
6.003	0.00	22.00s	4,465.76	0.000	-0.459s	-0.0218	-3.239(1)
6.036	0.00	24.00s	4,465.76	0.000	-0.566s	-0.0397	-3.660(1)
6.066	0.00	26.00s	4,465.17	0.000	-0.675s	-0.0614	-4.081(1)
6.082	0.00	27.00s	4,465.62	0.000	-0.730s	-0.0736	-4.293(1)
6.097	0.00	28.00s	4,465.64	0.000	-0.786s	-0.0869	-4.504(1)
6.123	0.00	30.00s	4,465.36	0.000	-0.897s	-0.1162	-4.926(1)

Distances in METERS.----Specific Gravity = 1.025.---------Area in M.-Rad.

	Critical Point		LCP	TCP	VCP
(1)	Deck edge	FLOOD	0.000	9.220s	6.706

LIM	"solas 90 criteria" CRITERION		Min/Max		Attained	
(1)	GM at Equilibrium	>	0.050	M.	1.123	P
(2)	Area from Equilibrium to RAzero or 27 deg	>	0.0150	M.-Rad	0.0152	P
(3)	Righting Arm at MaxRA	>	0.100	M.	0.124	P
(4)	Absolute Angle at MaxRA	>	1.00	deg	6.81	P
(5)	Angle from Equilibrium to RAzero	>	15.00	deg	12.23	F

--------------------Relative angles measured from 0.000 ---------------------

```
GHS 6.50                    Phase II Model
                     Model flooded to 0.8m of freeboard
                      Initial draft = 16'3" (4.95 m)
                           Double bottom intact
                KG nominal = 7.42m, KG actual = 7.404m [B3]


                      WEIGHT and DISPLACEMENT STATUS
                     Baseline draft: 5.906,  Heel: zero

Part------------------------------Weight(MT)----LCG-----TCG-----VCG
WEIGHT                              4,465.77   0.000   0.000   7.404

                         SpGr------Displ(MT)----LCB-----TCB-----VCB------RefHt
HULL                     1.025      5,659.18   0.000   0.000   3.347     -5.906
B08.C           Flooded  1.025     -1,193.41   0.000   0.000   3.511     -5.906
  Total Displacement--> 1.025      4,465.76   0.000   0.000   3.303
------------------------------------------------------------------------------
               Righting Arms:                  0.000   0.000
Distances in METERS.----------------------------------------------------------


                     HYDROSTATIC PROPERTIES WITH DAMAGE
                        No Trim, No Heel, VCG = 7.404

   LCF   Displacement   Buoyancy-Ctr.  Weight/         Moment/
  Draft----Weight(MT)----LCB-----VCB-------CM-----LCF---CM trim----GML-----GMT
  5.906     4,465.76   0.000   3.303    10.46   0.000    66.53  127.23   0.929
 Distances in METERS.-----Specific Gravity = 1.025.-----------Moment in M.-MT.
                              Trim is per 85.40M.
 Draft is from Baseline.
```

Phase II Model
Model flooded to 0.8m of freeboard
Initial draft = 16'3" (4.95 m)
Double bottom intact
KG nominal = 7.42m, KG actual = 7.404m [B3]

RIGHTING ARMS vs HEEL ANGLE with DAMAGE

LCG = 0.000 TCG = 0.000 VCG = 7.404

Origin Depth	Degrees of Trim	Heel	Displacement Weight(MT)	Righting Arms in Trim	in Heel	--> Area	Flood Pt Height
5.906	0.00	0.00	4,465.76	0.000	0.000	0.0000	0.800(1)
5.900	0.00	2.00s	4,465.76	0.000	0.033s	0.0006	0.480(1)
5.883	0.00	4.00s	4,465.73	0.000	0.065s	0.0023	0.163(1)
5.868	0.00	5.05s	4,465.75	0.000	0.085s	0.0037	0.000(1)
5.854	0.00	6.00s	4,465.78	0.000	0.100s	0.0052	-0.148(1)
5.848	0.00	6.56s	4,465.77	0.000	0.102s	0.0062	-0.239(1)
5.840	0.00	8.00s	4,466.40	0.000	0.088s	0.0086	-0.482(1)
5.842	0.00	10.00s	4,465.72	0.000	0.040s	0.0108	-0.839(1)
5.849	0.00	11.18s	4,465.20	0.000	0.000s	0.0112	-1.058(1)
5.857	0.00	12.00s	4,465.75	0.000	-0.031s	0.0110	-1.215(1)
5.880	0.00	14.00s	4,465.74	0.000	-0.117s	0.0084	-1.603(1)
5.907	0.00	16.00s	4,465.75	0.000	-0.212s	0.0027	-2.002(1)
5.938	0.00	18.00s	4,465.75	0.000	-0.314s	-0.0064	-2.409(1)
5.970	0.00	20.00s	4,465.75	0.000	-0.421s	-0.0193	-2.822(1)
6.003	0.00	22.00s	4,465.76	0.000	-0.532s	-0.0359	-3.239(1)
6.036	0.00	24.00s	4,465.76	0.000	-0.645s	-0.0565	-3.660(1)
6.066	0.00	26.00s	4,465.17	0.000	-0.760s	-0.0810	-4.081(1)
6.082	0.00	27.00s	4,465.62	0.000	-0.818s	-0.0948	-4.293(1)
6.097	0.00	28.00s	4,465.64	0.000	-0.877s	-0.1095	-4.504(1)
6.123	0.00	30.00s	4,465.36	0.000	-0.994s	-0.1422	-4.926(1)

Distances in METERS.----Specific Gravity = 1.025.---------Area in M.-Rad.

	Critical Point		LCP	TCP	VCP
(1)	Deck edge	FLOOD	0.000	9.220s	6.706

LIM	"solas 90 criteria" CRITERION		Min/Max		Attained	
(1)	GM at Equilibrium	>	0.050	M.	0.929	P
(2)	Area from Equilibrium to RAzero or 27 deg	>	0.0150	M.-Rad	0.0112	F
(3)	Righting Arm at MaxRA	>	0.100	M.	0.102	P
(4)	Absolute Angle at MaxRA	>	1.00	deg	6.56	P
(5)	Angle from Equilibrium to RAzero	>	15.00	deg	11.18	F

--------------------Relative angles measured from 0.000 ----------------------

GHS 6.50

Phase II Model
Model flooded to 0.4m of freeboard
Initial draft = 16'3" (4.95 m)
Double bottom intact
KG nominal = 5.70m, KG actual = 5.694m [C1]

WEIGHT and DISPLACEMENT STATUS
Baseline draft: 6.306, Heel: zero

Part		Weight (MT)	LCG	TCG	VCG
WEIGHT		4,465.77	0.000	0.000	5.740

		SpGr	Displ (MT)	LCB	TCB	VCB	RefHt
HULL		1.025	6,188.11	0.000	0.000	3.583	-6.306
B04.C	Flooded	1.025	-1,722.33	0.000	0.000	3.716	-6.306
Total Displacement-->		1.025	4,465.77	0.000	0.000	3.532	
Righting Arms:				0.000	0.000		

Distances in METERS.

HYDROSTATIC PROPERTIES WITH DAMAGE
No Trim, No Heel, VCG = 5.740

LCF Draft	Displacement Weight (MT)	Buoyancy-Ctr. LCB	Buoyancy-Ctr. VCB	Weight/ CM	LCF	Moment/ CM trim	GML	GMT
6.306	4,465.77	0.000	3.532	10.03	0.000	72.25	138.17	2.647

Distances in METERS.-----Specific Gravity = 1.025.-----------Moment in M.-MT.
Trim is per 85.40M.
Draft is from Baseline.

Phase II Model
Model flooded to 0.4m of freeboard
Initial draft = 16'3" (4.95 m)
Double bottom intact
KG nominal = 5.70m, KG actual = 5.694m [C1]

RIGHTING ARMS vs HEEL ANGLE with DAMAGE

LCG = 0.000 TCG = 0.000 VCG = 5.740

Origin Depth	Degrees of Trim	Heel	Displacement Weight(MT)	Righting Arms in Trim	in Heel	Area	Flood Pt Height
6.306	0.00	0.00	4,465.77	0.000	0.000	0.0000	0.400(1)
6.299	0.00	2.00s	4,465.58	0.000	0.094s	0.0016	0.081(1)
6.292	0.00	2.51s	4,465.67	0.000	0.123s	0.0026	0.003(1)
6.284	0.00	4.00s	4,465.84	0.000	0.178s	0.0066	-0.238(1)
6.301	0.00	5.50s	4,465.76	0.000	0.189s	0.0114	-0.509(1)
6.310	0.00	6.00s	4,465.49	0.000	0.187s	0.0131	-0.604(1)
6.359	0.00	8.00s	4,465.49	0.000	0.164s	0.0193	-1.002(1)
6.422	0.00	10.00s	4,465.54	0.000	0.124s	0.0243	-1.419(1)
6.494	0.00	12.00s	4,465.59	0.000	0.075s	0.0278	-1.851(1)
6.569	0.00	14.00s	4,465.63	0.000	0.020s	0.0295	-2.293(1)
6.595	0.00	14.67s	4,465.78	0.000	0.000s	0.0296	-2.444(1)
6.647	0.00	16.00s	4,465.76	0.000	-0.039s	0.0291	-2.742(1)
6.724	0.00	18.00s	4,465.74	0.000	-0.101s	0.0267	-3.196(1)
6.801	0.00	20.00s	4,465.75	0.000	-0.165s	0.0220	-3.653(1)
6.876	0.00	22.00s	4,465.75	0.000	-0.230s	0.0151	-4.112(1)
6.948	0.00	24.00s	4,465.76	0.000	-0.297s	0.0060	-4.571(1)
7.016	0.00	26.00s	4,465.76	0.000	-0.364s	-0.0056	-5.031(1)
7.048	0.00	27.00s	4,465.62	0.000	-0.397s	-0.0122	-5.259(1)
7.080	0.00	28.00s	4,465.63	0.000	-0.431s	-0.0194	-5.488(1)
7.139	0.00	30.00s	4,465.31	0.000	-0.498s	-0.0356	-5.942(1)

Distances in METERS.----Specific Gravity = 1.025.---------Area in M.-Rad.

	Critical Point		LCP	TCP	VCP
(1)	Deck edge	FLOOD	0.000	9.220s	6.706

LIM	"solas 90 criteria" CRITERION		Min/Max		Attained	
(1)	GM at Equilibrium	>	0.050	M.	2.647	P
(2)	Area from Equilibrium to RAzero or 27 deg	>	0.0150	M.-Rad	0.0296	P
(3)	Righting Arm at MaxRA	>	0.100	M.	0.189	P
(4)	Absolute Angle at MaxRA	>	1.00	deg	5.50	P
(5)	Angle from Equilibrium to RAzero	>	15.00	deg	14.67	F

--------------------Relative angles measured from 0.000 ---------------------

GHS 6.50

Phase II Model
Model flooded to 0.4m of freeboard
Initial draft = 16'3" (4.95 m)
Double bottom intact
KG nominal = 6.36m, KG actual = 6.426m [C2]

WEIGHT and DISPLACEMENT STATUS
Baseline draft: 6.306, Heel: zero

Part		Weight (MT)	LCG	TCG	VCG
WEIGHT		4,465.77	0.000	0.000	6.426

	SpGr	Displ (MT)	LCB	TCB	VCB	RefHt
HULL	1.025	6,188.11	0.000	0.000	3.583	-6.306
B04.C Flooded	1.025	-1,722.33	0.000	0.000	3.716	-6.306
Total Displacement-->	1.025	4,465.77	0.000	0.000	3.532	
Righting Arms:			0.000	0.000		

Distances in METERS.

HYDROSTATIC PROPERTIES WITH DAMAGE
No Trim, No Heel, VCG = 6.426

LCF Draft	Displacement Weight (MT)	Buoyancy-Ctr. LCB	VCB	Weight/ CM	LCF	Moment/ CM trim	GML	GMT
6.306	4,465.77	0.000	3.532	10.03	0.000	71.90	137.49	1.961

Distances in METERS.-----Specific Gravity = 1.025.-----------Moment in M.-MT.
Trim is per 85.40M.
Draft is from Baseline.

Phase II Model
Model flooded to 0.4m of freeboard
Initial draft = 16'3" (4.95 m)
Double bottom intact
KG nominal = 6.36m, KG actual = 6.426m [C2]

RIGHTING ARMS vs HEEL ANGLE with DAMAGE

LCG = 0.000 TCG = 0.000 VCG = 6.426

Origin Depth	Degrees of Trim	Heel	Displacement Weight(MT)	Righting Arms in Trim	in Heel	--> Area	Flood Pt Height
6.306	0.00	0.00	4,465.77	0.000	0.000	0.0000	0.400(1)
6.299	0.00	2.00s	4,465.58	0.000	0.070s	0.0012	0.081(1)
6.292	0.00	2.51s	4,465.67	0.000	0.093s	0.0020	0.003(1)
6.284	0.00	4.00s	4,465.84	0.000	0.130s	0.0049	-0.238(1)
6.287	0.00	4.43s	4,465.85	0.000	0.131s	0.0059	-0.313(1)
6.310	0.00	6.00s	4,465.66	0.000	0.115s	0.0093	-0.604(1)
6.359	0.00	8.00s	4,465.49	0.000	0.068s	0.0126	-1.002(1)
6.422	0.00	10.00s	4,465.54	0.000	0.005s	0.0139	-1.419(1)
6.427	0.00	10.13s	4,465.82	0.000	0.000s	0.0139	-1.448(1)
6.494	0.00	12.00s	4,465.61	0.000	-0.068s	0.0128	-1.851(1)
6.569	0.00	14.00s	4,465.72	0.000	-0.146s	0.0091	-2.293(1)
6.647	0.00	16.00s	4,465.73	0.000	-0.228s	0.0026	-2.742(1)
6.724	0.00	18.00s	4,465.74	0.000	-0.313s	-0.0069	-3.196(1)
6.801	0.00	20.00s	4,465.75	0.000	-0.400s	-0.0193	-3.653(1)
6.876	0.00	22.00s	4,465.75	0.000	-0.487s	-0.0348	-4.112(1)
6.948	0.00	24.00s	4,465.76	0.000	-0.576s	-0.0533	-4.571(1)
7.016	0.00	26.00s	4,465.76	0.000	-0.664s	-0.0750	-5.031(1)
7.048	0.00	27.00s	4,465.62	0.000	-0.708s	-0.0869	-5.259(1)
7.080	0.00	28.00s	4,465.63	0.000	-0.753s	-0.0997	-5.488(1)
7.139	0.00	30.00s	4,465.31	0.000	-0.841s	-0.1275	-5.942(1)

Distances in METERS.----Specific Gravity = 1.025.---------Area in M.-Rad.

Critical Point		LCP	TCP	VCP
(1) Deck edge	FLOOD	0.000	9.220s	6.706

LIM	"solas 90 criteria" CRITERION		Min/Max		Attained	
(1)	GM at Equilibrium	>	0.050	M.	1.961	P
(2)	Area from Equilibrium to RAzero or 27 deg	>	0.0150	M.-Rad	0.0139	F
(3)	Righting Arm at MaxRA	>	0.100	M.	0.131	P
(4)	Absolute Angle at MaxRA	>	1.00	deg	4.43	P
(5)	Angle from Equilibrium to RAzero	>	15.00	deg	10.13	F

--------------------Relative angles measured from 0.000 ---------------------

GHS 6.50

Phase II Model
Model flooded to 0.4m of freeboard
Initial draft = 16'3" (4.95 m)
Double bottom intact
KG nominal = 6.86m, KG actual = 6.850m [C3]

WEIGHT and DISPLACEMENT STATUS
Baseline draft: 6.306, Heel: zero

Part			Weight (MT)	LCG	TCG	VCG	
WEIGHT			4,465.77	0.000	0.000	6.850	
		SpGr	**Displ (MT)**	**LCB**	**TCB**	**VCB**	**RefHt**
HULL		1.025	6,188.11	0.000	0.000	3.583	-6.306
B04.C	Flooded	1.025	-1,722.33	0.000	0.000	3.716	-6.306
Total Displacement-->		1.025	4,465.77	0.000	0.000	3.532	
Righting Arms:				0.000	0.000		

Distances in METERS.

HYDROSTATIC PROPERTIES WITH DAMAGE
No Trim, No Heel, VCG = 6.850

LCF Draft	Displacement Weight (MT)	Buoyancy-Ctr. LCB	Buoyancy-Ctr. VCB	Weight/ CM	LCF	Moment/ CM trim	GML	GMT
6.306	4,465.77	0.000	3.532	10.03	0.000	71.67	137.06	1.537

Distances in METERS.-----Specific Gravity = 1.025.-----------Moment in M.-MT.
Trim is per 85.40M.
Draft is from Baseline.

Phase II Model
Model flooded to 0.4m of freeboard
Initial draft = 16'3" (4.95 m)
Double bottom intact
KG nominal = 6.86m, KG actual = 6.850m [C3]

RIGHTING ARMS vs HEEL ANGLE with DAMAGE

LCG = 0.000 TCG = 0.000 VCG = 6.850

Origin Depth	Degrees of Trim	Heel	Displacement Weight(MT)	Righting Arms in Trim	in Heel	--> Area	Flood Pt Height
6.306	0.00	0.00	4,465.77	0.000	0.000	0.0000	0.400(1)
6.299	0.00	2.00s	4,465.58	0.000	0.055s	0.0010	0.081(1)
6.292	0.00	2.51s	4,465.67	0.000	0.074s	0.0015	0.003(1)
6.284	0.00	4.00s	4,465.84	0.000	0.101s	0.0039	-0.238(1)
6.310	0.00	6.00s	4,465.48	0.000	0.071s	0.0070	-0.604(1)
6.359	0.00	8.00s	4,465.49	0.000	0.009s	0.0085	-1.002(1)
6.367	0.00	8.23s	4,465.83	0.000	0.000s	0.0085	-1.050(1)
6.422	0.00	10.00s	4,465.59	0.000	-0.069s	0.0075	-1.419(1)
6.494	0.00	12.00s	4,465.59	0.000	-0.156s	0.0036	-1.851(1)
6.569	0.00	14.00s	4,465.63	0.000	-0.249s	-0.0035	-2.293(1)
6.647	0.00	16.00s	4,465.73	0.000	-0.345s	-0.0138	-2.742(1)
6.724	0.00	18.00s	4,465.74	0.000	-0.444s	-0.0276	-3.196(1)
6.801	0.00	20.00s	4,465.75	0.000	-0.545s	-0.0449	-3.653(1)
6.876	0.00	22.00s	4,465.75	0.000	-0.646s	-0.0656	-4.112(1)
6.948	0.00	24.00s	4,465.76	0.000	-0.748s	-0.0900	-4.571(1)
7.016	0.00	26.00s	4,465.76	0.000	-0.850s	-0.1179	-5.031(1)
7.048	0.00	27.00s	4,465.62	0.000	-0.901s	-0.1332	-5.259(1)
7.080	0.00	28.00s	4,465.63	0.000	-0.952s	-0.1493	-5.488(1)
7.139	0.00	30.00s	4,465.31	0.000	-1.053s	-0.1843	-5.942(1)

Distances in METERS.----Specific Gravity = 1.025.---------Area in M.-Rad.

Critical Point		LCP	TCP	VCP
(1) Deck edge	FLOOD	0.000	9.220s	6.706

LIM	"solas 90 criteria" CRITERION		Min/Max		Attained	
(1)	GM at Equilibrium	>	0.050	M.	1.537	P
(2)	Area from Equilibrium to RAzero or 27 deg	>	0.0150	M.-Rad	0.0085	F
(3)	Righting Arm at MaxRA	>	0.100	M.	0.101	P
(4)	Absolute Angle at MaxRA	>	1.00	deg	4.00	P
(5)	Angle from Equilibrium to RAzero	>	15.00	deg	8.23	F

---------------------Relative angles measured from 0.000 ----------------------

CONDITION D1 (KG=5.02m) WAS NOT TESTED

KG WAS TOO LOW TO BE ATTAINED

Phase II Model
Model flooded to 0.2m of freeboard
Initial draft = 16'3" (4.95 m)
Double bottom intact
KG nominal = 5.51m, KG actual = 5.550m [D2]

WEIGHT and DISPLACEMENT STATUS
Baseline draft: 6.506, Heel: zero

Part			Weight (MT)	LCG	TCG	VCG	
WEIGHT			4,465.77	0.000	0.000	5.550	
		SpGr	Displ (MT)	LCB	TCB	VCB	RefHt
HULL		1.025	6,458.99	0.000	0.000	3.702	-6.506
B02.C	Flooded	1.025	-1,993.17	0.000	0.000	3.820	-6.506
Total Displacement-->		1.025	4,465.82	0.000	0.000	3.649	
Righting Arms:				0.000	0.000		

Distances in METERS.

HYDROSTATIC PROPERTIES WITH DAMAGE
No Trim, No Heel, VCG = 5.550

LCF Draft	Displacement Weight (MT)	Buoyancy-Ctr. LCB	VCB	Weight/ CM	LCF	Moment/ CM trim	GML	GMT
6.506	4,465.82	0.000	3.649	9.83	0.000	74.58	142.61	2.865

Distances in METERS.-----Specific Gravity = 1.025.-----------Moment in M.-MT.
Trim is per 85.40M.
Draft is from Baseline.

Phase II Model
Model flooded to 0.2m of freeboard
Initial draft = 16'3" (4.95 m)
Double bottom intact
KG nominal = 5.51m, KG actual = 5.550m [D2]

RIGHTING ARMS vs HEEL ANGLE with DAMAGE

LCG = 0.000 TCG = 0.000 VCG = 5.550

Origin Depth	Degrees of Trim	Heel	Displacement Weight(MT)	Righting Arms in Trim	in Heel	--> Area	Flood Pt Height
6.506	0.00	0.00	4,465.82	0.000	0.000	0.0000	0.200(1)
6.494	0.00	1.29s	4,465.81	0.000	0.080s	0.0009	0.002(1)
6.490	0.00	2.00s	4,466.42	0.000	0.113s	0.0021	-0.110(1)
6.516	0.00	3.50s	4,465.73	0.000	0.128s	0.0054	-0.385(1)
6.530	0.00	4.00s	4,465.15	0.000	0.125s	0.0065	-0.484(1)
6.612	0.00	6.00s	4,465.32	0.000	0.097s	0.0105	-0.907(1)
6.712	0.00	8.00s	4,465.47	0.000	0.054s	0.0133	-1.355(1)
6.822	0.00	10.00s	4,465.56	0.000	0.003s	0.0143	-1.818(1)
6.829	0.00	10.13s	4,465.88	0.000	-0.000s	0.0143	-1.849(1)
6.935	0.00	12.00s	4,465.64	0.000	-0.051s	0.0134	-2.293(1)
7.050	0.00	14.00s	4,465.69	0.000	-0.107s	0.0107	-2.774(1)
7.165	0.00	16.00s	4,465.72	0.000	-0.166s	0.0059	-3.260(1)
7.277	0.00	18.00s	4,465.73	0.000	-0.225s	-0.0009	-3.749(1)
7.387	0.00	20.00s	4,465.74	0.000	-0.285s	-0.0098	-4.239(1)
7.492	0.00	22.00s	4,465.75	0.000	-0.345s	-0.0208	-4.728(1)
7.591	0.00	24.00s	4,465.24	0.000	-0.405s	-0.0339	-5.214(1)
7.686	0.00	26.00s	4,465.32	0.000	-0.466s	-0.0491	-5.701(1)
7.733	0.00	27.00s	4,465.67	0.000	-0.496s	-0.0575	-5.944(1)
7.778	0.00	28.00s	4,465.68	0.000	-0.526s	-0.0665	-6.185(1)
7.860	0.00	30.00s	4,465.48	0.000	-0.586s	-0.0859	-6.663(1)

Distances in METERS.----Specific Gravity = 1.025.---------Area in M.-Rad.

Critical Point		LCP	TCP	VCP
(1) Deck edge	FLOOD	0.000	9.220s	6.706

LIM	"solas 90 criteria" CRITERION		Min/Max		Attained	
(1)	GM at Equilibrium	>	0.050	M.	2.865	P
(2)	Area from Equilibrium to RAzero or 27 deg	>	0.0150	M.-Rad	0.0143	F
(3)	Righting Arm at MaxRA	>	0.100	M.	0.128	P
(4)	Absolute Angle at MaxRA	>	1.00	deg	3.50	P
(5)	Angle from Equilibrium to RAzero	>	15.00	deg	10.13	F

--------------------Relative angles measured from 0.000 ---------------------

GHS 6.50

Phase II Model
Model flooded to 0.2m of freeboard
Initial draft = 16'3" (4.95 m)
Double bottom intact
KG nominal = 6.1m, KG actual = 6.241m [D3]

WEIGHT and DISPLACEMENT STATUS
Baseline draft: 6.506, Heel: zero

Part		Weight(MT)	LCG	TCG	VCG
WEIGHT		4,465.77	0.000	0.000	6.241

		SpGr	Displ(MT)	LCB	TCB	VCB	RefHt
HULL		1.025	6,458.99	0.000	0.000	3.702	-6.506
B02.C	Flooded	1.025	-1,993.17	0.000	0.000	3.820	-6.506
Total Displacement-->		1.025	4,465.82	0.000	0.000	3.649	
Righting Arms:				0.000	0.000		

Distances in METERS.

HYDROSTATIC PROPERTIES WITH DAMAGE
No Trim, No Heel, VCG = 6.241

LCF Draft	Displacement Weight(MT)	Buoyancy-Ctr. LCB	VCB	Weight/ CM	LCF	Moment/ CM trim	GML	GMT
6.506	4,465.82	0.000	3.649	9.83	0.000	74.21	141.92	2.174

Distances in METERS.-----Specific Gravity = 1.025.-----------Moment in M.-MT.
Trim is per 85.40M.
Draft is from Baseline.

Phase II Model
Model flooded to 0.2m of freeboard
Initial draft = 16'3" (4.95 m)
Double bottom intact
KG nominal = 6.1m, KG actual = 6.241m [D3]

RIGHTING ARMS vs HEEL ANGLE with DAMAGE

LCG = 0.000 TCG = 0.000 VCG = 6.241

Origin Depth	Degrees of Trim	Heel	Displacement Weight(MT)	Righting Arms in Trim	in Heel	--> Area	Flood Pt Height
6.506	0.00	0.00	4,465.82	0.000	0.000	0.0000	0.200(1)
6.494	0.00	1.29s	4,465.81	0.000	0.064s	0.0007	0.002(1)
6.490	0.00	2.00s	4,466.42	0.000	0.089s	0.0017	-0.110(1)
6.496	0.00	2.62s	4,465.76	0.000	0.093s	0.0027	-0.219(1)
6.531	0.00	4.00s	4,465.52	0.000	0.077s	0.0048	-0.484(1)
6.612	0.00	6.00s	4,465.31	0.000	0.024s	0.0067	-0.907(1)
6.648	0.00	6.73s	4,465.84	0.000	0.001s	0.0069	-1.068(1)
6.713	0.00	8.00s	4,465.65	0.000	-0.043s	0.0064	-1.355(1)
6.822	0.00	10.00s	4,465.56	0.000	-0.117s	0.0037	-1.818(1)
6.935	0.00	12.00s	4,465.63	0.000	-0.194s	-0.0018	-2.293(1)
7.050	0.00	14.00s	4,465.66	0.000	-0.275s	-0.0100	-2.774(1)
7.165	0.00	16.00s	4,465.71	0.000	-0.356s	-0.0210	-3.260(1)
7.277	0.00	18.00s	4,465.73	0.000	-0.439s	-0.0348	-3.749(1)
7.387	0.00	20.00s	4,465.74	0.000	-0.521s	-0.0516	-4.239(1)
7.492	0.00	22.00s	4,465.75	0.000	-0.604s	-0.0712	-4.728(1)
7.591	0.00	24.00s	4,465.24	0.000	-0.686s	-0.0938	-5.214(1)
7.686	0.00	26.00s	4,465.32	0.000	-0.769s	-0.1192	-5.701(1)
7.733	0.00	27.00s	4,465.67	0.000	-0.810s	-0.1329	-5.944(1)
7.778	0.00	28.00s	4,465.68	0.000	-0.851s	-0.1474	-6.185(1)
7.860	0.00	30.00s	4,465.48	0.000	-0.932s	-0.1786	-6.663(1)

Distances in METERS.----Specific Gravity = 1.025.---------Area in M.-Rad.

	Critical Point		LCP	TCP	VCP
(1)	Deck edge	FLOOD	0.000	9.220s	6.706

LIM	"solas 90 criteria" CRITERION		Min/Max		Attained	
(1)	GM at Equilibrium	>	0.050	M.	2.174	P
(2)	Area from Equilibrium to RAzero or 27 deg	>	0.0150	M.-Rad	0.0069	F
(3)	Righting Arm at MaxRA	>	0.100	M.	0.093	F
(4)	Absolute Angle at MaxRA	>	1.00	deg	2.62	P
(5)	Angle from Equilibrium to RAzero	>	15.00	deg	6.73	F

--------------------Relative angles measured from 0.000 ---------------------

```
97-04-10 15:17:08                                                    Page 1
GHS 6.50                    PHASE II MODEL WITH SS
                                 condition A1

                        WEIGHT and DISPLACEMENT STATUS
 Baseline draft: 5.616 @ Origin,  Trim: 0.000/85.400,  Heel: Stbd 10.40 deg.

Part------------------------------Weight(MT)----LCG-----TCG-----VCG
FIXED WEIGHT                        4,465.77   0.000   0.000   6.976
                Load-----SpGr                                            RefHt
DK_C.C         0.030    1.025         192.98   0.000   6.855s  7.046     -6.026
  Total Weight-------->             4,658.75   0.000   0.284s  6.979

                                    Displ(MT)----LCB-----TCB-----VCB
HULL                    1.025       5,298.49   0.000   0.899s  3.260     -5.524
CARDK                   1.025          50.05   0.000   7.932s  6.889     -5.524
B12.C          Flooded  1.025        -689.73   0.000   0.973s  3.412     -5.524
  Total Displacement--> 1.025       4,658.81   0.000   0.963s  3.276
------------------------------------------------------------------------------
               Righting Arms:                  0.000   -0.000s
Distances in METERS.----------------------------------------------------------


                                  TANK STATUS
                  Trim: 0.000/85.400,  Heel: Stbd 10.40 deg.

Part------------Load-----SpGr-----Weight(MT)----LCG-----TCG-----VCG-------FSM
DK_C.C         0.030    1.025         192.98   0.000   6.855s  7.046   1129.77
Distances in METERS.----------------------------------------Moments in M.-MT.


                        WEIGHT and DISPLACEMENT STATUS
 Baseline draft: 5.616 @ Origin,  Trim: 0.000/85.400,  Heel: Stbd 10.41 deg.

Part------------------------------Weight(MT)----LCG-----TCG-----VCG
FIXED WEIGHT                        4,465.77   0.000   0.000   6.976
                Load-----SpGr                                            RefHt
DK_NC.C        0.028    1.025         193.29   0.000   6.853s  7.046     -6.026
  Total Weight-------->             4,659.05   0.000   0.284s  6.979

                                    Displ(MT)----LCB-----TCB-----VCB
HULL                    1.025       5,298.78   0.000   0.899s  3.260     -5.524
CARDK                   1.025          50.18   0.000   7.930s  6.889     -5.524
B12.C          Flooded  1.025        -689.76   0.000   0.973s  3.412     -5.524
  Total Displacement--> 1.025       4,659.19   0.000   0.964s  3.276
------------------------------------------------------------------------------
               Righting Arms:                  0.000   -0.001s
Distances in METERS.----------------------------------------------------------
```

```
                          TANK STATUS
             Trim: 0.000/85.400,  Heel: Stbd 10.41 deg.

Part-----------Cu.M.-----SpGr-----Weight(MT)----LCG-----TCG-----VCG-------FSM
DK_NC.C         188.6   1.025        193.29   0.000   6.853s  7.046   1131.89
Distances in METERS.----------------------------------------Moments in M.-MT.

                         condition A2

                  WEIGHT and DISPLACEMENT STATUS
 Baseline draft: 5.540 @ Origin,  Trim: 0.000/85.400,  Heel: Stbd 9.39 deg.

Part------------------------------Weight(MT)----LCG-----TCG-----VCG
FIXED WEIGHT                        4,465.77   0.000   0.000   7.566
               Load-----SpGr                                           RefHt
DK_C.C          0.015    1.025         92.63   0.000   7.418s  6.937     -5.862
  Total Weight-------->             4,558.40   0.000   0.151s  7.553

                                    Displ(MT)----LCB-----TCB-----VCB
HULL                     1.025      5,224.56   0.000   0.854s  3.217     -5.466
CARDK                    1.025         17.39   0.000   8.374s  6.815     -5.466
B12.C          Flooded  1.025       -683.67   0.000   0.937s  3.385     -5.466
  Total Displacement--> 1.025      4,558.27   0.000   0.870s  3.205
-------------------------------------------------------------------------------
               Righting Arms:                  0.000    0.000s
Distances in METERS.-----------------------------------------------------------


                          TANK STATUS
              Trim: 0.000/85.400,  Heel: Stbd 9.39 deg.

Part------------Load-----SpGr-----Weight(MT)----LCG-----TCG-----VCG-------FSM
DK_C.C          0.015    1.025         92.63   0.000   7.418s  6.937    455.05
Distances in METERS.----------------------------------------Moments in M.-MT.


                  WEIGHT and DISPLACEMENT STATUS
 Baseline draft: 5.540 @ Origin,  Trim: 0.000/85.400,  Heel: Stbd 9.38 deg.

Part------------------------------Weight(MT)----LCG-----TCG-----VCG
FIXED WEIGHT                        4,465.77   0.000   0.000   7.566
               Load-----SpGr                                           RefHt
DK_NC.C         0.014    1.025         92.48   0.000   7.419s  6.937     -5.862
  Total Weight-------->             4,558.24   0.000   0.151s  7.553

                                    Displ(MT)----LCB-----TCB-----VCB
HULL                     1.025      5,224.47   0.000   0.854s  3.217     -5.466
CARDK                    1.025         17.30   0.000   8.375s  6.815     -5.466
B12.C          Flooded  1.025       -683.68   0.000   0.937s  3.385     -5.466
  Total Displacement--> 1.025      4,558.10   0.000   0.870s  3.205
-------------------------------------------------------------------------------
               Righting Arms:                  0.000    0.001s
Distances in METERS.-----------------------------------------------------------
```

```
                            TANK STATUS
               Trim: 0.000/85.400,  Heel: Stbd 9.38 deg.

Part-----------Cu.M.-----SpGr-----Weight(MT)----LCG-----TCG-----VCG-------FSM
DK_NC.C          90.2   1.025         92.48   0.000   7.419s  6.937    454.30
Distances in METERS.-----------------------------------------Moments in M.-MT.

                          condition A3

                     WEIGHT and DISPLACEMENT STATUS
 Baseline draft: 5.502 @ Origin,  Trim: 0.000/85.400,  Heel: Stbd 8.66 deg.

Part-------------------------------Weight(MT)----LCG-----TCG-----VCG
FIXED WEIGHT                        4,465.77   0.000   0.000   7.969
               Load-----SpGr                                          RefHt
DK_C.C         0.006    1.025          40.92   0.000   7.911s  6.860     -5.744
  Total Weight-------->             4,506.68   0.000   0.072s  7.959

                                    Displ(MT)----LCB-----TCB-----VCB
HULL                    1.025       5,181.73   0.000   0.806s  3.189     -5.439
CARDK                   1.025           5.08   0.000   8.717s  6.768     -5.439
B12.C          Flooded  1.025        -680.49   0.000   0.896s  3.368     -5.439
  Total Displacement--> 1.025       4,506.32   0.000   0.802s  3.166
-------------------------------------------------------------------------------
               Righting Arms:                  0.000    0.000s
Distances in METERS.-----------------------------------------------------------


                            TANK STATUS
               Trim: 0.000/85.400,  Heel: Stbd 8.66 deg.

Part------------Load-----SpGr-----Weight(MT)----LCG-----TCG-----VCG-------FSM
DK_C.C         0.006    1.025         40.92   0.000   7.911s  6.860    158.91
Distances in METERS.-----------------------------------------Moments in M.-MT.


                     WEIGHT and DISPLACEMENT STATUS
 Baseline draft: 5.502 @ Origin,  Trim: 0.000/85.400,  Heel: Stbd 8.69 deg.

Part-------------------------------Weight(MT)----LCG-----TCG-----VCG
FIXED WEIGHT                        4,465.77   0.000   0.000   7.969
               Load-----SpGr                                          RefHt
DK_NC.C        0.006    1.025          41.17   0.000   7.909s  6.861     -5.740
  Total Weight-------->             4,506.94   0.000   0.072s  7.959

                                    Displ(MT)----LCB-----TCB-----VCB
HULL                    1.025       5,181.62   0.000   0.809s  3.189     -5.439
CARDK                   1.025           5.36   0.000   8.706s  6.769     -5.439
B12.C          Flooded  1.025        -680.40   0.000   0.899s  3.368     -5.439
  Total Displacement--> 1.025       4,506.57   0.000   0.805s  3.167
-------------------------------------------------------------------------------
               Righting Arms:                  0.000    0.000s
Distances in METERS.-----------------------------------------------------------
```

```
                              TANK STATUS
               Trim: 0.000/85.400,  Heel: Stbd 8.69 deg.

Part-----------Cu.M.-----SpGr-----Weight(MT)----LCG-----TCG-----VCG-------FSM
DK_NC.C           40.2   1.025         41.17   0.000   7.909s  6.861    159.52
Distances in METERS.----------------------------------------Moments in M.-MT.

                            condition B1

                       WEIGHT and DISPLACEMENT STATUS
 Baseline draft: 6.017 @ Origin,  Trim: 0.000/85.400,  Heel: Stbd 7.45 deg.

Part------------------------------Weight(MT)----LCG-----TCG-----VCG
FIXED WEIGHT                        4,465.77   0.000   0.000   6.779
               Load-----SpGr                                              RefHt
DK_C.C         0.027    1.025         168.76   0.000   6.636s  6.971     -6.314
  Total Weight-------->             4,634.53   0.000   0.242s  6.786

                                    Displ(MT)----LCB-----TCB-----VCB
HULL                    1.025       5,780.77   0.000   0.597s  3.438     -5.966
CARDK                   1.025          54.56   0.000   7.670s  6.863     -5.966
B08.C          Flooded  1.025      -1,201.47   0.000   0.603s  3.561     -5.966
  Total Displacement--> 1.025       4,633.87   0.000   0.679s  3.446
-------------------------------------------------------------------------------
               Righting Arms:                  0.000    0.000s
Distances in METERS.-----------------------------------------------------------


                              TANK STATUS
               Trim: 0.000/85.400,  Heel: Stbd 7.45 deg.

Part------------Load-----SpGr-----Weight(MT)----LCG-----TCG-----VCG-------FSM
DK_C.C         0.027    1.025         168.76   0.000   6.636s  6.971   1479.30
Distances in METERS.----------------------------------------Moments in M.-MT.


                       WEIGHT and DISPLACEMENT STATUS
 Baseline draft: 6.017 @ Origin,  Trim: 0.000/85.400,  Heel: Stbd 7.44 deg.

Part------------------------------Weight(MT)----LCG-----TCG-----VCG
FIXED WEIGHT                        4,465.77   0.000   0.000   6.779
               Load-----SpGr                                              RefHt
DK_NC.C        0.025    1.025         168.66   0.000   6.634s  6.971     -6.316
  Total Weight-------->             4,634.43   0.000   0.241s  6.786

                                    Displ(MT)----LCB-----TCB-----VCB
HULL                    1.025       5,781.57   0.000   0.596s  3.438     -5.967
CARDK                   1.025          54.29   0.000   7.672s  6.863     -5.967
B08.C          Flooded  1.025      -1,201.66   0.000   0.602s  3.561     -5.967
  Total Displacement--> 1.025       4,634.20   0.000   0.677s  3.446
-------------------------------------------------------------------------------
               Righting Arms:                  0.000   -0.000s
Distances in METERS.-----------------------------------------------------------
```

```
                              TANK STATUS
               Trim: 0.000/85.400,  Heel: Stbd 7.44 deg.

Part-----------Cu.M.-----SpGr-----Weight(MT)----LCG-----TCG-----VCG-------FSM
DK_NC.C         164.5   1.025       168.66   0.000   6.634s  6.971   1481.64
Distances in METERS.----------------------------------------Moments in M.-MT.

                            condition B2

                    WEIGHT and DISPLACEMENT STATUS
 Baseline draft: 5.969 @ Origin,  Trim: 0.000/85.400,  Heel: Stbd 6.82 deg.

Part------------------------------Weight(MT)----LCG-----TCG-----VCG
FIXED WEIGHT                        4,465.77   0.000   0.000   7.210
                Load-----SpGr                                             RefHt
DK_C.C         0.017    1.025       105.55   0.000   7.027s  6.911      -6.230
  Total Weight-------->             4,571.32   0.000   0.162s  7.203

                                   Displ(MT)----LCB-----TCB-----VCB
HULL                    1.025       5,740.57   0.000   0.575s  3.416      -5.927
CARDK                   1.025          27.74   0.000   8.020s  6.817      -5.927
B08.C          Flooded  1.025      -1,196.99   0.000   0.587s  3.549      -5.927
  Total Displacement--> 1.025       4,571.32   0.000   0.617s  3.402
-------------------------------------------------------------------------------
               Righting Arms:                  0.000    0.000s
Distances in METERS.-----------------------------------------------------------


                              TANK STATUS
               Trim: 0.000/85.400,  Heel: Stbd 6.82 deg.

Part------------Load-----SpGr-----Weight(MT)----LCG-----TCG-----VCG-------FSM
DK_C.C         0.017    1.025       105.55   0.000   7.027s  6.911    854.39
Distances in METERS.----------------------------------------Moments in M.-MT.


                    WEIGHT and DISPLACEMENT STATUS
 Baseline draft: 5.969 @ Origin,  Trim: 0.000/85.400,  Heel: Stbd 6.80 deg.

Part------------------------------Weight(MT)----LCG-----TCG-----VCG
FIXED WEIGHT                        4,465.77   0.000   0.000   7.210
                Load-----SpGr                                             RefHt
DK_NC.C        0.015    1.025       105.04   0.000   7.029s  6.910      -6.231
  Total Weight-------->             4,570.81   0.000   0.162s  7.203

                                   Displ(MT)----LCB-----TCB-----VCB
HULL                    1.025       5,740.72   0.000   0.574s  3.416      -5.927
CARDK                   1.025          27.19   0.000   8.028s  6.816      -5.927
B08.C          Flooded  1.025      -1,197.11   0.000   0.586s  3.549      -5.927
  Total Displacement--> 1.025       4,570.81   0.000   0.615s  3.402
-------------------------------------------------------------------------------
               Righting Arms:                  0.000    0.000s
Distances in METERS.-----------------------------------------------------------
```

```
                            TANK STATUS
               Trim: 0.000/85.400,  Heel: Stbd 6.80 deg.

Part-----------Cu.M.-----SpGr-----Weight(MT)----LCG-----TCG-----VCG-------FSM
DK_NC.C         102.5   1.025        105.04   0.000   7.029s  6.910    852.40
Distances in METERS.-----------------------------------------Moments in M.-MT.

                          condition B3

                     WEIGHT and DISPLACEMENT STATUS
 Baseline draft: 5.951 @ Origin,  Trim: 0.000/85.400,  Heel: Stbd 6.58 deg.

Part------------------------------Weight(MT)----LCG-----TCG-----VCG
FIXED WEIGHT                        4,465.77   0.000   0.000   7.404
               Load-----SpGr                                             RefHt
DK_C.C         0.013    1.025          82.31   0.000   7.219s  6.886     -6.192
  Total Weight-------->             4,548.08   0.000   0.131s  7.395

                                    Displ(MT)----LCB-----TCB-----VCB
HULL                    1.025       5,723.58   0.000   0.564s  3.407     -5.912
CARDK                   1.025          19.56   0.000   8.174s  6.800     -5.912
B08.C          Flooded  1.025      -1,195.05   0.000   0.580s  3.544     -5.912
  Total Displacement--> 1.025       4,548.08   0.000   0.593s  3.386
-------------------------------------------------------------------------------
               Righting Arms:                  0.000    0.000s
Distances in METERS.-----------------------------------------------------------


                            TANK STATUS
               Trim: 0.000/85.400,  Heel: Stbd 6.58 deg.

Part------------Load-----SpGr-----Weight(MT)----LCG-----TCG-----VCG-------FSM
DK_C.C         0.013    1.025          82.31   0.000   7.219s  6.886    630.43
Distances in METERS.-----------------------------------------Moments in M.-MT.


                     WEIGHT and DISPLACEMENT STATUS
 Baseline draft: 5.951 @ Origin,  Trim: 0.000/85.400,  Heel: Stbd 6.57 deg.

Part------------------------------Weight(MT)----LCG-----TCG-----VCG
FIXED WEIGHT                        4,465.77   0.000   0.000   7.404
               Load-----SpGr                                             RefHt
DK_NC.C        0.012    1.025          82.20   0.000   7.219s  6.885     -6.192
  Total Weight-------->             4,547.96   0.000   0.130s  7.395

                                    Displ(MT)----LCB-----TCB-----VCB
HULL                    1.025       5,723.91   0.000   0.564s  3.407     -5.912
CARDK                   1.025          19.49   0.000   8.175s  6.800     -5.912
B08.C          Flooded  1.025      -1,195.13   0.000   0.579s  3.545     -5.912
  Total Displacement--> 1.025       4,548.27   0.000   0.592s  3.386
-------------------------------------------------------------------------------
               Righting Arms:                  0.000    0.000s
Distances in METERS.-----------------------------------------------------------
```

```
                              TANK STATUS
                 Trim: 0.000/85.400,  Heel: Stbd 6.57 deg.

Part-----------Cu.M.-----SpGr-----Weight(MT)----LCG-----TCG-----VCG-------FSM
DK_NC.C          80.2   1.025         82.20   0.000   7.219s  6.885    629.82
Distances in METERS.-----------------------------------------Moments in M.-MT.

                            condition C1

                    WEIGHT and DISPLACEMENT STATUS
 Baseline draft: 6.514 @ Origin,  Trim: 0.000/85.400,  Heel: Stbd 5.50 deg.

Part------------------------------Weight(MT)----LCG-----TCG-----VCG
FIXED WEIGHT                        4,465.77   0.000   0.000   5.694
                Load-----SpGr                                           RefHt
DK_C.C         0.046    1.025         289.35   0.000   5.550s  6.998     -6.725
  Total Weight-------->             4,755.11   0.000   0.338s  5.773

                                    Displ(MT)----LCB-----TCB-----VCB
HULL                    1.025       6,323.23   0.000   0.315s  3.654     -6.484
CARDK                   1.025         158.24   0.000   6.414s  6.919     -6.484
B04.C          Flooded  1.025      -1,726.56   0.000   0.274s  3.731     -6.484
  Total Displacement--> 1.025       4,754.91   0.000   0.533s  3.734
-------------------------------------------------------------------------------
               Righting Arms:                  0.000   -0.001s
Distances in METERS.-----------------------------------------------------------


                              TANK STATUS
                 Trim: 0.000/85.400,  Heel: Stbd 5.50 deg.

Part------------Load-----SpGr-----Weight(MT)----LCG-----TCG-----VCG-------FSM
DK_C.C         0.046    1.025        289.35   0.000   5.550s  6.998   3968.90
Distances in METERS.-----------------------------------------Moments in M.-MT.


                    WEIGHT and DISPLACEMENT STATUS
 Baseline draft: 6.518 @ Origin,  Trim: 0.000/85.400,  Heel: Stbd 5.50 deg.

Part------------------------------Weight(MT)----LCG-----TCG-----VCG
FIXED WEIGHT                        4,465.77   0.000   0.000   5.694
                Load-----SpGr                                           RefHt
DK_NC.C        0.043    1.025         293.09   0.000   5.472s  6.994     -6.724
  Total Weight-------->             4,758.85   0.000   0.337s  5.774

                                    Displ(MT)----LCB-----TCB-----VCB
HULL                    1.025       6,327.22   0.000   0.313s  3.655     -6.488
CARDK                   1.025         160.35   0.000   6.396s  6.920     -6.488
B04.C          Flooded  1.025      -1,727.43   0.000   0.271s  3.732     -6.488
  Total Displacement--> 1.025       4,760.13   0.000   0.533s  3.737
-------------------------------------------------------------------------------
               Righting Arms:                  0.000    0.000s
Distances in METERS.-----------------------------------------------------------
```

```
                            TANK STATUS
                 Trim: 0.000/85.400,  Heel: Stbd 5.50 deg.

Part-----------Cu.M.-----SpGr-----Weight(MT)----LCG-----TCG-----VCG-------FSM
DK_NC.C         285.9   1.025       293.09   0.000   5.472s  6.994   4998.98
Distances in METERS.----------------------------------------Moments in M.-MT.

                          condition C2

                     WEIGHT and DISPLACEMENT STATUS
 Baseline draft: 6.413 @ Origin,  Trim: 0.000/85.400,  Heel: Stbd 4.43 deg.

Part----------------------------------Weight(MT)----LCG-----TCG-----VCG
FIXED WEIGHT                            4,465.77   0.000   0.000   6.426
               Load-----SpGr                                                RefHt
DK_C.C         0.024    1.025            155.03   0.000   6.095s  6.898     -6.597
  Total Weight-------->                 4,620.79   0.000   0.204s  6.442

                                         Displ(MT)----LCB-----TCB-----VCB
HULL                    1.025           6,275.34   0.000   0.308s  3.632     -6.394
CARDK                   1.025              67.03   0.000   7.093s  6.835     -6.394
B04.C          Flooded  1.025          -1,721.55   0.000   0.268s  3.723     -6.394
  Total Displacement--> 1.025           4,620.82   0.000   0.421s  3.644
-------------------------------------------------------------------------------
               Righting Arms:                       0.000    0.000s
Distances in METERS.-----------------------------------------------------------


                            TANK STATUS
                 Trim: 0.000/85.400,  Heel: Stbd 4.43 deg.

Part------------Load-----SpGr-----Weight(MT)----LCG-----TCG-----VCG-------FSM
DK_C.C         0.024    1.025       155.03   0.000   6.095s  6.898   2732.65
Distances in METERS.----------------------------------------Moments in M.-MT.


                     WEIGHT and DISPLACEMENT STATUS
 Baseline draft: 6.414 @ Origin,  Trim: 0.000/85.400,  Heel: Stbd 4.43 deg.

Part----------------------------------Weight(MT)----LCG-----TCG-----VCG
FIXED WEIGHT                            4,465.77   0.000   0.000   6.426
               Load-----SpGr                                                RefHt
DK_NC.C        0.023    1.025            155.64   0.000   6.090s  6.898     -6.598
  Total Weight-------->                 4,621.41   0.000   0.205s  6.442

                                         Displ(MT)----LCB-----TCB-----VCB
HULL                    1.025           6,276.17   0.000   0.308s  3.632     -6.395
CARDK                   1.025              67.40   0.000   7.089s  6.835     -6.395
B04.C          Flooded  1.025          -1,721.72   0.000   0.268s  3.723     -6.395
  Total Displacement--> 1.025           4,621.86   0.000   0.421s  3.645
-------------------------------------------------------------------------------
               Righting Arms:                       0.000   -0.000s
Distances in METERS.-----------------------------------------------------------
```

```
                              TANK STATUS
               Trim: 0.000/85.400,  Heel: Stbd 4.43 deg.

Part-----------Cu.M.-----SpGr-----Weight(MT)----LCG-----TCG-----VCG-------FSM
DK_NC.C         151.8   1.025        155.64   0.000   6.090s  6.898   2747.16
Distances in METERS.----------------------------------------Moments in M.-MT.

                            condition C3

                     WEIGHT and DISPLACEMENT STATUS
 Baseline draft: 6.376 @ Origin,  Trim: 0.000/85.400,  Heel: Stbd 4.01 deg.

Part----------------------------------Weight(MT)----LCG-----TCG-----VCG
FIXED WEIGHT                            4,465.77   0.000   0.000   6.850
                Load-----SpGr                                             RefHt
DK_C.C         0.017    1.025            105.94   0.000   6.453s  6.859     -6.543
  Total Weight-------->                 4,571.71   0.000   0.150s  6.850

                                         Displ(MT)----LCB-----TCB-----VCB
HULL                    1.025           6,250.95   0.000   0.301s  3.620     -6.360
CARDK                   1.025              39.68   0.000   7.451s  6.802     -6.360
B04.C          Flooded  1.025          -1,718.90   0.000   0.265s  3.718     -6.360
  Total Displacement--> 1.025           4,571.72   0.000   0.376s  3.611
-------------------------------------------------------------------------------
               Righting Arms:                      0.000   -0.000s
Distances in METERS.-----------------------------------------------------------


                              TANK STATUS
               Trim: 0.000/85.400,  Heel: Stbd 4.01 deg.

Part------------Load-----SpGr-----Weight(MT)----LCG-----TCG-----VCG-------FSM
DK_C.C         0.017    1.025        105.94   0.000   6.453s  6.859   1821.95
Distances in METERS.----------------------------------------Moments in M.-MT.


                     WEIGHT and DISPLACEMENT STATUS
 Baseline draft: 6.376 @ Origin,  Trim: 0.000/85.400,  Heel: Stbd 3.99 deg.

Part----------------------------------Weight(MT)----LCG-----TCG-----VCG
FIXED WEIGHT                            4,465.77   0.000   0.000   6.850
                Load-----SpGr                                             RefHt
DK_NC.C        0.016    1.025            105.38   0.000   6.454s  6.858     -6.543
  Total Weight-------->                 4,571.15   0.000   0.149s  6.850

                                         Displ(MT)----LCB-----TCB-----VCB
HULL                    1.025           6,251.33   0.000   0.300s  3.620     -6.360
CARDK                   1.025              38.94   0.000   7.461s  6.801     -6.360
B04.C          Flooded  1.025          -1,719.11   0.000   0.264s  3.719     -6.360
  Total Displacement--> 1.025           4,571.16   0.000   0.374s  3.610
-------------------------------------------------------------------------------
               Righting Arms:                      0.000   -0.001s
Distances in METERS.-----------------------------------------------------------
```

TANK STATUS
Trim: 0.000/85.400, Heel: Stbd 3.99 deg.

Part	Cu.M.	SpGr	Weight(MT)	LCG	TCG	VCG	FSM
DK_NC.C	102.8	1.025	105.38	0.000	6.454s	6.858	1821.33

Distances in METERS.--Moments in M.-MT.

condition D2

WEIGHT and DISPLACEMENT STATUS
Baseline draft: 6.657 @ Origin, Trim: 0.000/85.400, Heel: Stbd 3.50 deg.

Part	Load	SpGr	Weight(MT)	LCG	TCG	VCG	RefHt
FIXED WEIGHT			4,465.77	0.000	0.000	5.550	
DK_C.C	0.036	1.025	226.47	0.000	5.260s	6.915	-6.790
Total Weight-------->			4,692.24	0.000	0.254s	5.616	
			Displ(MT)	LCB	TCB	VCB	
HULL		1.025	6,527.34	0.000	0.168s	3.735	-6.645
CARDK		1.025	141.77	0.000	5.962s	6.864	-6.645
B02.C	Flooded	1.025	-1,976.85	0.000	0.116s	3.800	-6.645
Total Displacement-->		1.025	4,692.26	0.000	0.366s	3.802	
Righting Arms:				0.000	0.001s		

Distances in METERS.---

TANK STATUS
Trim: 0.000/85.400, Heel: Stbd 3.50 deg.

Part	Load	SpGr	Weight(MT)	LCG	TCG	VCG	FSM
DK_C.C	0.036	1.025	226.47	0.000	5.260s	6.915	5788.17

Distances in METERS.--Moments in M.-MT.

WEIGHT and DISPLACEMENT STATUS
Baseline draft: 6.666 @ Origin, Trim: 0.000/85.400, Heel: Stbd 3.50 deg.

Part	Load	SpGr	Weight(MT)	LCG	TCG	VCG	RefHt
FIXED WEIGHT			4,465.77	0.000	0.000	5.550	
DK_NC.C	0.035	1.025	237.22	0.000	5.057s	6.910	-6.793
Total Weight-------->			4,702.99	0.000	0.255s	5.619	
			Displ(MT)	LCB	TCB	VCB	
HULL		1.025	6,534.13	0.000	0.164s	3.737	-6.653
CARDK		1.025	147.15	0.000	5.907s	6.866	-6.653
B02.C	Flooded	1.025	-1,978.28	0.000	0.112s	3.801	-6.653
Total Displacement-->		1.025	4,703.01	0.000	0.366s	3.809	
Righting Arms:				0.000	0.000s		

Distances in METERS.---

TANK STATUS
Trim: 0.000/85.400, Heel: Stbd 3.50 deg.

Part	Cu.M.	SpGr	Weight(MT)	LCG	TCG	VCG	FSM
DK_NC.C	231.4	1.025	237.22	0.000	5.057s	6.910	6996.01

Distances in METERS.--Moments in M.-MT.

condition D3

WEIGHT and DISPLACEMENT STATUS
Baseline draft: 6.586 @ Origin, Trim: 0.000/85.400, Heel: Stbd 2.63 deg.

Part	Load	SpGr	Weight(MT)	LCG	TCG	VCG	RefHt
FIXED WEIGHT			4,465.77	0.000	0.000	6.241	
DK_C.C	0.020	1.025	126.92	0.000	5.658s	6.839	-6.705
Total Weight-------->			4,592.69	0.000	0.156s	6.258	
			Displ(MT)	LCB	TCB	VCB	
HULL		1.025	6,509.10	0.000	0.161s	3.726	-6.579
CARDK		1.025	61.64	0.000	6.649s	6.799	-6.579
B02.C	Flooded	1.025	-1,977.95	0.000	0.106s	3.801	-6.579
Total Displacement-->		1.025	4,592.79	0.000	0.272s	3.735	
Righting Arms:				0.000	-0.001s		

Distances in METERS.--

TANK STATUS
Trim: 0.000/85.400, Heel: Stbd 2.63 deg.

Part	Load	SpGr	Weight(MT)	LCG	TCG	VCG	FSM
DK_C.C	0.020	1.025	126.92	0.000	5.658s	6.839	3630.02

Distances in METERS.--Moments in M.-MT.

WEIGHT and DISPLACEMENT STATUS
Baseline draft: 6.586 @ Origin, Trim: 0.000/85.400, Heel: Stbd 2.62 deg.

Part	Load	SpGr	Weight(MT)	LCG	TCG	VCG	RefHt
FIXED WEIGHT			4,465.77	0.000	0.000	6.241	
DK_NC.C	0.019	1.025	127.22	0.000	5.615s	6.837	-6.705
Total Weight-------->			4,592.99	0.000	0.156s	6.258	
			Displ(MT)	LCB	TCB	VCB	
HULL		1.025	6,509.92	0.000	0.160s	3.727	-6.579
CARDK		1.025	61.30	0.000	6.650s	6.798	-6.579
B02.C	Flooded	1.025	-1,978.19	0.000	0.106s	3.801	-6.579
Total Displacement-->		1.025	4,593.04	0.000	0.271s	3.735	
Righting Arms:				0.000	-0.000s		

Distances in METERS.--

TANK STATUS
Trim: 0.000/85.400, Heel: Stbd 2.62 deg.

Part	Cu.M.	SpGr	Weight(MT)	LCG	TCG	VCG	FSM
DK_NC.C	124.1	1.025	127.22	0.000	5.615s	6.837	4349.67

Distances in METERS.--Moments in M.-MT.

APPENDIX C

MODEL TEST RESULTS

(*Not available in electronic format / Non disponible en format électronique*)

APPENDIX D

MODEL PHOTOGRAPHS

(*Not available in electronic format /
Non disponible en format électronique*)