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The Sinking Sequence of *MV* Estonia

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The Sinking Sequence of MV Estonia

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Abstract

This thesis reconstructs the sinking of the RoPax Ferry MV Estonia on September 28th 1994, with a strong focus on describing the chain of events that caused the eventual sinking, and how the ship sank. Once the sinking is understood, this thesis explores possible safety improvements that should be implemented in the design of new vessels of this type. The investigation is based on a combination of testimonies of survivors as well as numerical calculations based on the framework of the testimonies.

Sea loads on the bow visor broke its locks and hinges. Consequently, the bow visor separated from the vessel and with it the bow ramp was ripped open because of box-like-housing of the visor at top of the bow ramp. The loss of watertight integrity was followed by massive water ingress on the Main Car Deck and MV Estonia partially capsized to a quasi-static equilibrium floating condition. This persisted for a few minutes, whilst several side ventilation openings became immersed. From that time on, a progressive flooding started, leading to consecutively submerged windows in the superstructure failing and allowing further water ingress. Finally, at a list of about 130°, the ferry hit the sea floor stern first and the bow subsided soon after.

Abstract in German

Die vorliegende Arbeit rekonstruiert den Untergang der RoPax Fähre MV Estiona am 28. September 1994 vor allem hinsichtlich des zeitlichen Ablaufes, sowie der zugehörigen Kausalketten mit dem Ziel, die Sicherheit dieses Schiffstyps zu verbessern. Ausgangspunkt der Untersuchung waren die Zeugenaussagen der Überlebenden und numerische Berechnungen, die folgenden Hergang ergaben:

Seegangslasten auf das Bugvisier führten zum Bruch der Verriegelung und der Scharniere, so dass das Bugvisier beim Herunterfallen, bedingt durch eine Einhausung am oberen Ende der Bugrampe, diese mit aufriss. Dieser Verlust der Wasserdichtigkeit des Schiffes führte zu erheblichem Wassereinbruch auf dem Fahrzeugdeck. Dadurch kenterte die MV Estonia bis zu einer quasi stabilen Gleichgewichtslage und verharrte in dieser, bis einige seitliche Lüfter zu Wasser kamen. Ab diesem Zeitpunkt setzte eine kontinuierliche Flutung der Fähre ein, die die Fenster des Aufbaudecks zerbarsten ließ. Bei einem Krängungswinkel von etwa 130° schlug das Heck des Schiffes schließlich auf dem Meeresgrund auf und danach senkte sich auch der Bug auf diesen ab.

Acknowledgement

This thesis is based on research I carried out at the Institute of Ship Design and Ship Safety of the Hamburg University of Technology. Firstly I would like to express my thanks and appreciation of Prof. Dr.-Ing. Stefan Krüger, who offered me the opportunity to research at his institute and encouraged me to investigate this topic.

Additional thanks go to Prof. Dr.-Ing. Dr. E.h. Dr. h.c. Eike Lehmann for his first advisory of this thesis and the second advisors Prof. Dr.-Ing. Moustafa Abdel-Maksoud and Prof. Dr.-Ing. Wolfgang Fricke.

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Special thanks are directed to my colleagues of institutes M-6 and M-8 for helpful hints and ideas during the development of this thesis. Namely I dedicate thanks to Dipl.-Ing. Florian Kluwe, for sharing the office with me for more than three and a half years and our numerous, sustained and fruitful discussions on the topic of the sinking of the MV Estonia.

Finally I am deeply thankful to my family and Sabine for their tremendous and continuous support, great patience and their unwavering encouragement.

This thesis is dedicated to Director Senior Engineer Walter Haissig and his wife Erika.

Contents

1 Introduction

On the evening of September 27th 1994, the RoPax ferry MV Estonia departed Tallin's harbour headed for Stockholm. The weather was stormy, but not unusual for that time of year. Wind speed and wave height increased during the course of the night. Between 01:21 and 01:29[1] a radio distress traffic was heard and recorded by several nearby ships and land based stations. MV Estonia was calling "MAYDAY". The ship then reported a heavy list to the Starboard side. Radio contact was lost and the ferry disappeared from radar screens between 01:48 and 01:52. This was before surrounding ships or the first rescue helicopters were able to reach the site of the foundering vessel. As they arrived, they found survivors in rafts and life boats. Of the 989 passengers and crew members that were on board the MV Estonia, only 137 survived the catastrophe.

An official investigation commission by Sweden, Finland and Estonia, namely the "Joint Accident Investigation Commission" (JAIC), began their investigations shortly after the sinking. In 1997, the JAIC presented their final report.

However, the Swedish government decided in 2005 to start another investigation, conducted by the governmental agency VINNOVA entitled "Research Study on the Sinking Sequence on the MV Estonia", with the focus not only on the sinking sequence but also on the consequences for maritime Safety in both Swedish and wider waters. The international tender for this research project was won by two consortia, in one of them the Institute of Ship Design and Ship Safety of Hamburg University of Technology (TUHH) is a member. In summer 2008 both consortia presented their results.

Two reasons for this new investigation may be exposed here. Shortly after the sinking of MV Estonia, a new safety regulation was introduced in 1995 called the "Stockholm Agreement" and became compulsory for the countries Sweden, Finland, Norway, Denmark and Germany. The new regulation increased the safety standard for RoPax

[1] This, and all subsequent times are local, Estonian time.

vessels, because they had to comply with both the SOLAS '74 Amendments '88 and the 'Stockholm Agreement' referring to a specified amount of water on the vehicle deck including free surfaces. The regulation was introduced rapidly after the loss of MV Estonia, due to the fact that this foundering was part of a series of serious accidents of at least MV Jan Heweliusz in 1993 and MV Herald of Free Enterprise in 1987 in northern European waterways.

Safety standards of RoRo and RoPax vessels have remained part of the discourse since the sinking of MV Estionia. The question of measurable safety standards of these ship types is raised once again with the expected introduction of the harmonized damage stability regulations in 2009. As the name 'harmonized' indicates, passenger and merchant ships will have a common, but extended probabilistic damage calculation procedure. This probabilistic concept is based on damage statistics of all major classification societies. But it does not consider the complex problems caused by water-on-deck. The problem is: does the harmonized damage calculation cover at least the same safety level without considering water on the vehicle deck than the hitherto existing deterministic damage calculation for passenger ships in addition with the 'Stockholm Agreement'? Will the 'Stockholm Agreement' become obsolete in future? Is it possible to have the 'Stockholm Agreement' in force at the same time with the harmonized probabilistic damage calculations or are there contradictions in those two regulations? Today, it is not finally decided whether the 'Stockholm Agreement' will remain in force or not.

And further on, there are uncertainties concerning bow- and stern openings in terms of the interpretation of what is meant to be with 'watertight' due to the rules of the classification societies. Still today, no common methodology is in use to proof the quality of the seal for bow doors, compared e.g. to the procedure of pressure tests of tanks.

All these problems are closely linked with the 'Stockholm Agreement' and this is closely linked with the foundering of MV Estonia. The above exposed reasons are the main wherefores why MV Estonia is in a strong focus of ship safety again. So it is worth to have a detailed look on the foundering of MV Estonia – although, as mentioned, an official investigation were carried out by the JAIC and their final report on this investigation has been published.

One question shall be investigated with particular consideration, the crucial question of this thesis. Numerous witnesses stated that the first list came all of a sudden and had a large final heeling angle before the vessel up righted again. In terms of naval architecture, this is only possible with the loss of positive initial metacentric height. One likely possibility that would eliminate the positive initial metacentric height is an accumulation of the necessary amount of water on the Main Car Deck. But this question is a superficial problem. The main question is, if it is possible to eliminate the positive initial metacentric height within a very short period of time. When there is an approach to this question which seems to be likely, it should be validated using a sinking simulation of which the whole foundering is in line with the observations of the witnesses on board of MV Estonia. This leads directly to the structure of this thesis.

First of all a survey of the available facts like is carried out. They are, within reason, the point to start all subsequent calculations and include results of other investigations and publications where a description of MV Estonia was given. To reconstruct the incidents of the last night of MV Estonia and to set up the most possible realistic simulation it was necessary to review the surrounding conditions of vessel on the night of the sinking due to weather etc. and the situation of the wreck on the sea floor. A special attention is given to the testimonies of the survivors. They were investigated – the first time in the context of the sinking of MV Estonia – in a synoptic way to gain the time sequence of the foundering which give a significant insight into the sequence of the sinking, which in turn leads into the condition of the wreck on the sea floor. The synoptic time schedule finally results in a link between the time sequence and the list of the vessel.

To carry out any simulations, a calculation model of the vessel itself had to be set up and to be validated with the stability booklet of MV Estonia after it was checked for inconsistencies. This calculation model was combined with the data of the load case of the final voyage. This marked the end of the preparations and the starting point of the actual calculations and simulations.

Different hydrostatic scenarios considering the subdivision of the ferry were investigated to figure out that scenario which causes the largest list with the smallest amount of water. This so to say 'worst' scenario is joined with the state of knowledge that the bow visor was not attached to the vessel anymore in the relevant and detailed presented step of the sinking sequence. With this combination, dynamic motion calculations were preformed to evaluate the average amount of water that can enter the vessel in certain period of time. To complete the modelling of the first phase of the foundering, drawing from the metallic noise numerous passengers observed and crew members recognizing the quasi static equilibrium floating condition, the influence of the heeling force due to the ship's manoeuvres is calculated in separate motion simulations. A likely over-all scenario of the first phase, the capsizing phase, was developed.

The second phase, the actual sinking sequence, is not a capsizing but a progressive flooding procedure. To simulate this phase and to find the right parameters of the sinking and what influenced the sinking sequence, openings have to be investigated. Two major openings were pointed out: The windows with their different sizes and collapse loads as well as the ventilation system. Especially of note is the fact that the ventilation system connects the outside of the vessel with compartments below the Freeboard Deck and by this tremendously speeds the course of the progressive flooding. The influence of trapped air inside the vessel – again especially below the Freeboard Deck – is also taken into account.

Finally, a comparison of the calculation and simulation results with key points of the witnesses is carried out and concluding remarks were made. Most of the work presented in this doctoral thesis was developed during the VINNOVA research study. Finally, the general approach on sinking scenarios is discussed and ideas are examined to improve future maritime safety, especially that of RoRo- and RoPax-Vessels.

2 MV Estonia – A Description of the vessel

The ship was built according to the contract between Jos L Meyer Werft GmbH of Papenburg, Germany and the ship's original owners, AB Sally of Marienehamn, Finnland, signed in 1979. The RoPax vessel with hull number S590 was delivered in Summer 1980 and started service on the Stockholm - Mariehamn - Åbo and Kapellskär - Mariehamn – Nådendal routes under the name MV Viking Sally. The ducktail and the stabilizer fins were not fitted during the original construction, but during later conversions.

In 1990/ 91 there was a conversion, covering the upper decks mainly, and a new inclining test was carried out leading to a new 'Trim and Stability Booklet'. In 1993 the ferry was sold to Nordström & Thulin of Stockholm, Sweden, and she received her final name: MV Estonia.

Figure 2.1: MV Estonia entering the Stockholm Archipelago in July 1994

Table 2.1: Main Data of MV Estonia

Building Number	S590
Length over all	157.02m
Length between perpendiculars	137.40m
Breadth	24.20m
Draft, design	5.567m
Depth to Freeboard Deck	7.65m
Displacement, design	12708t
Dead Weight	2975t
C_B	0.681
GT	15667
Main Engine	4 x MAN 8L 40/45
P_B	17600kW
Service Speed	21.2kn[2]
Number of Propellers	2
Type of Propellers	CPP
Passenger Capacity	2000
Berth in Cabins	1190
Car Capacity	460
Class Sign	BV I 3/3 + Deep Sea Ice Class IA Car/ Passenger Ferry
IMO-Number	7921033

[2] At 90% MCR, 188rpm of both propellers, dw = 1460t, without stabiliser fins

2.1 The Machinery of MV Estonia

Main Engines

4 x 8 cylinder main engines type MAN 8L 40/45

4 stroke single acting non-reversible, with supercharging straight engine

Engine output 4400 kW at 600 rpm.

Auxiliary Engines

4 x 6 cylinder Burmeister & Wain engines type 6S 28 LH 4

4 stroke single acting pressure charged

Engine output 1104 kW ar 750 rpm

4 generators A. van Kaick Type DIDB 140 G/8

Emergency Aggregate

1 x 12 Cylinder MAN engine type D 2542 MLE

4 stroke single acting

Engine output 312 kW at 1500 rpm

Generator Unelec type 315 LB 81 365 kVA 440/213 V 50 Hz

Propulsion

Each set of two main engines acted through a gear box on one shaft line, ending with a controllable pitch propeller of 4.0m in diameter. The port-side (PS) propeller rotated clockwise and the starboard-side (STB) propeller anticlockwise. With increasing power, up to 70%, the electro-hydraulic combinator increased both propellers pitch and rpm. Beyond 70%, only the pitch of the propellers is increased.

2.2 General Arrangement Plan

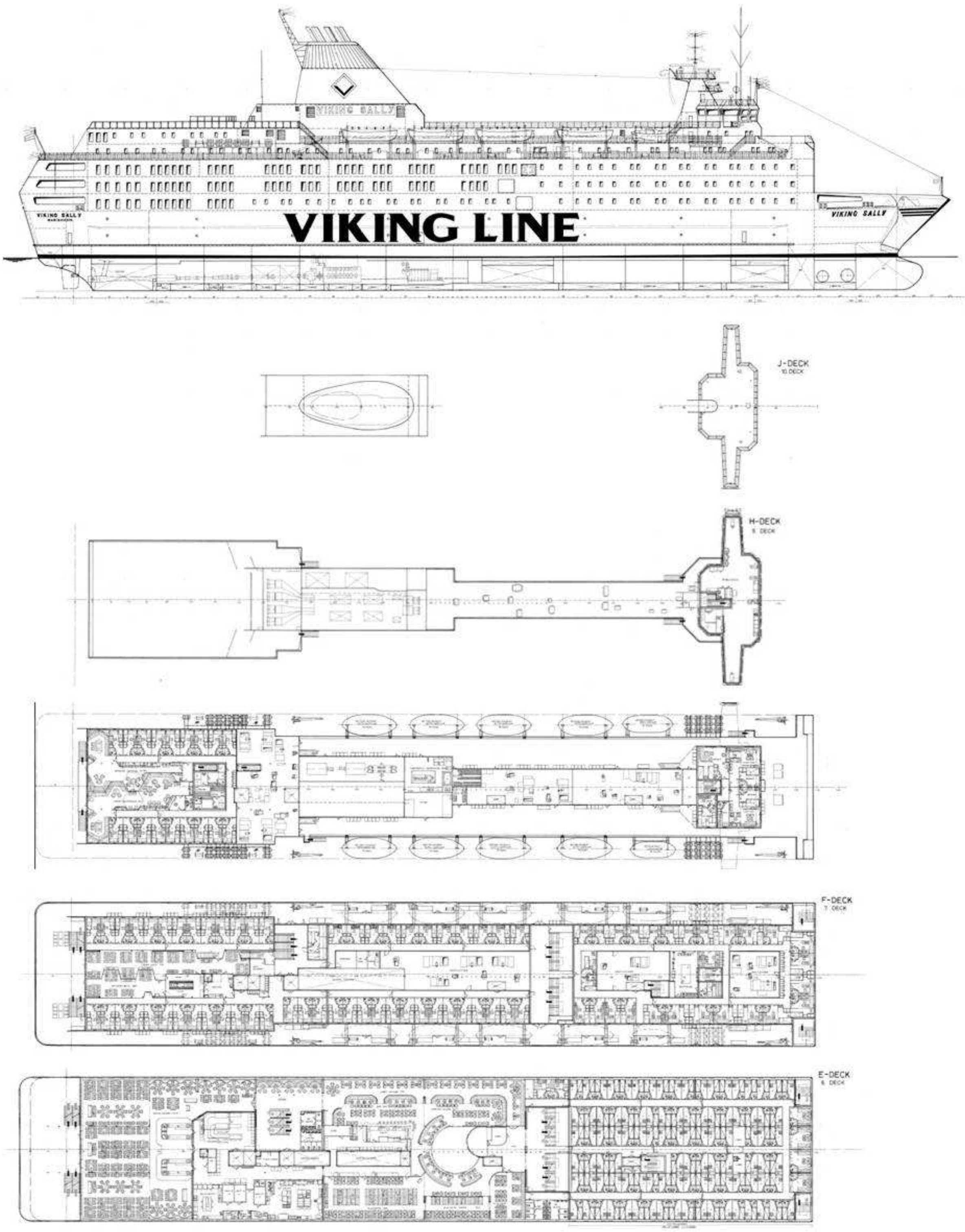


Figure 2.2: General Arrangement Plan of MV Estonia, Deck 6 – 10, Side View

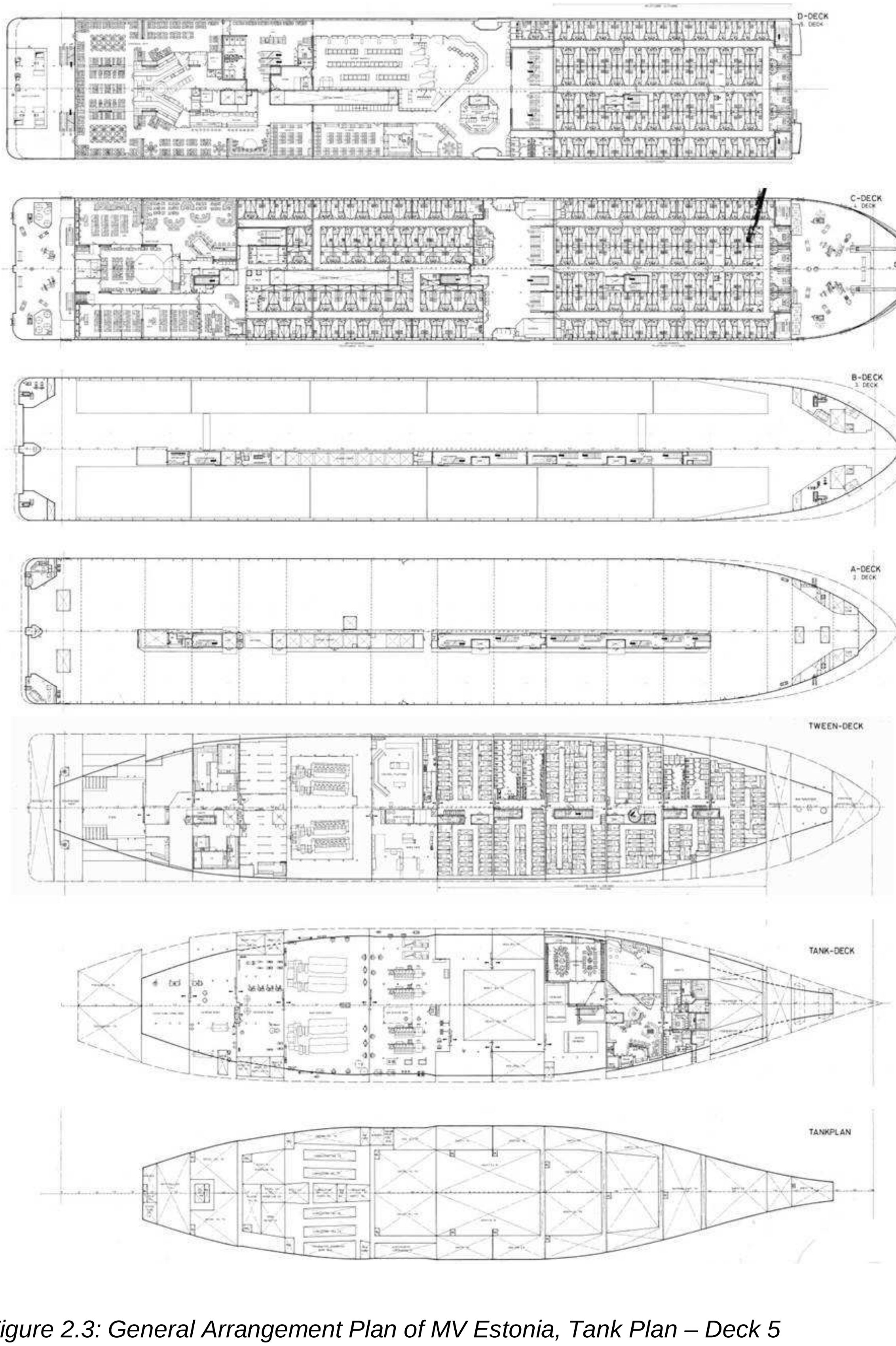


Figure 2.3: General Arrangement Plan of MV Estonia, Tank Plan – Deck 5

3 State of the Scientific and Technical Knowledge

Three different and independent main consortia investigated the sinking of MV Estonia scientifically. Firstly, the Joint Accident Investigation Commission (JAIC) during the years 1994 to 1997 and later, the SSPA- and the HSVA-consortia running concurrently during the years 2005 to 2008.

Beside several organisations representing the victims, two groups with a technical background shall be mentioned - the so called "Independent Fact Group" [IFG] formed in 1999 and the "German Group of Experts" [GGE] acting on behalf of the Meyer Werft GmbH since 1995.

3.1 Heading, Dropped Material and Bow Visor of MV Estonia

MV Estonia was travelling westbound, but the bow points eastward on the seabed. [ROCK]. MV Estonia must have therefore changed heading just before or during her sinking sequence.

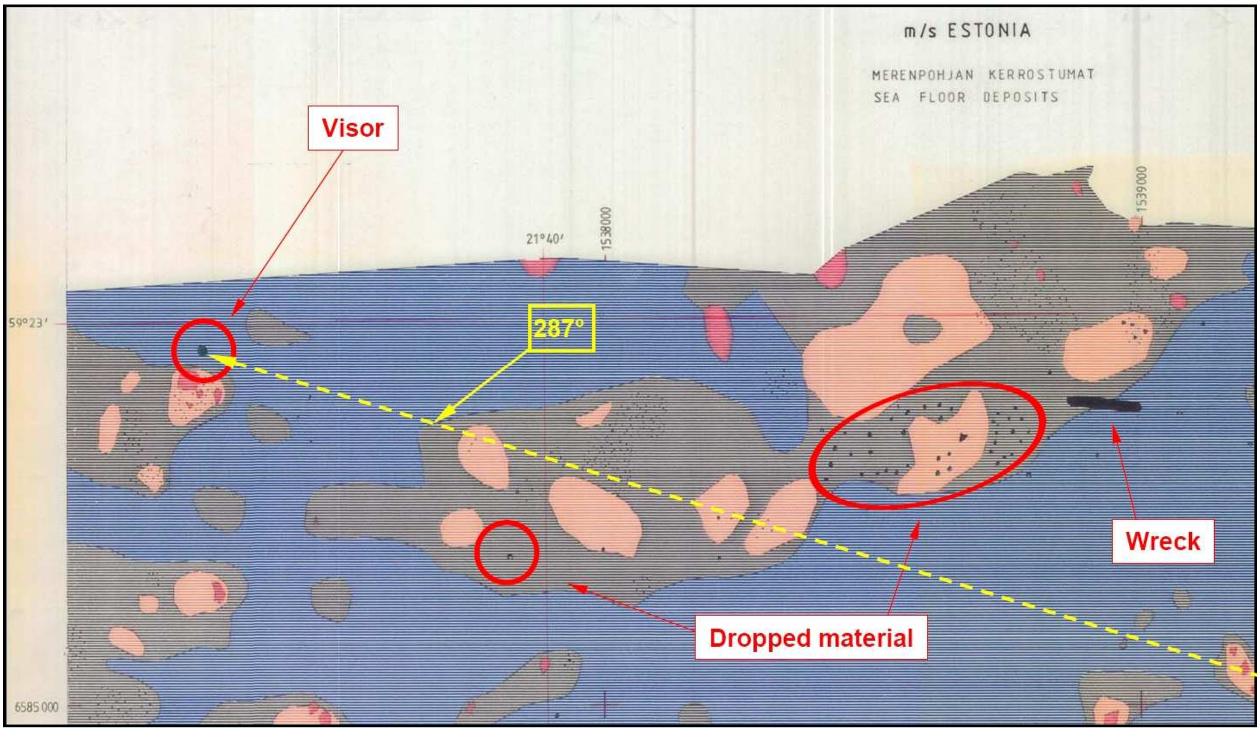


Figure 3.1: Map of the sea floor deposits based on sonar measurements in October 1994

A sonar scan and evaluation of Dr. Nuorteva of October 1994 shows the most probable sailing direction of MV Estonia was 287°, from the direction of (?) the visor about one nautical mile westerly of the wreck. See *Figure 3.1* with explanations of Dr. Valanto [HSVA02]. In between these two points, but significantly away of the most probable course, several remnants of the vessel were detected. The JAIC concluded a turn to starboard side after the loss of the visor, a reduction of velocity till finally the ferry was drifting due to wind and wave action [JAIC05].

The HSVA-consortium [HSVA02] and the SSPA-consortium [SSPA05] reconstructed the last turn of MV Estonia and both outcomes are very similar, but differs with the JAIC with a different time sequence. The basis of this reconstruction was the map of dropped material, *Figure 3.1*.

Neither the JAIC, the HSVA- nor SSPA-consortium contests that, in connection with the foundering of MV Estonia, the bow visor separated from the vessel.

3.2 Bow Visor Arrangement of MV Estonia and compliance with SOLAS

The Main Car Deck of MV Estonia, same as the Freeboard Deck, was sealed at bow with an unfoldable bow ramp attached to the vessel with four hinges and moved via two hydraulic actuators, one starboard side and one on portside. In the in-sea condition, the ramp was fixed by four locking lugs pressing the ramp on to a rubber seal. At top of the ramp, flaps were attached to level out the height of the ramp and the quay during loading and unloading operations. The whole ramp arrangement was covered by the bow visor faired in the lines of the bow. The bow ramp in the upright position exceeded the height of the forecastle, for which reason a box-like housing around the top of the bow ramp was built. The bow visor itself was attached to the vessel by two beams connected to two hinges on the forecastle and moved by two hydraulic actuators. The visor was locked with a bottom lock and two side locks and two side hooks. The bottom lock often called “atlantic lock” is a bolt that could slide through three lugs. The arrangement of bow ramp and bow visor can be seen in *Figure 3.2*.

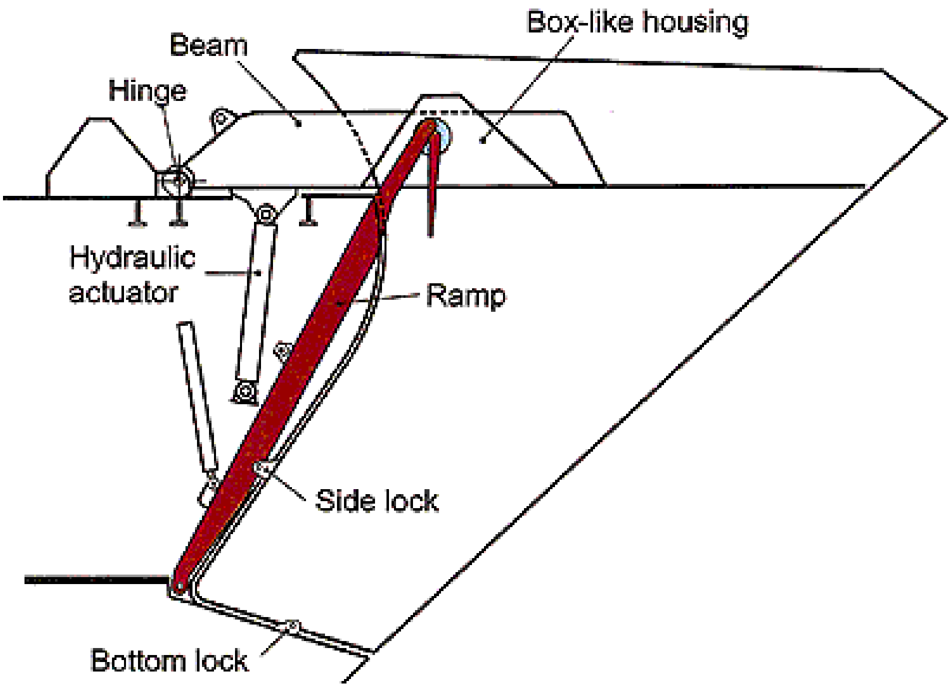


Figure 3.2: Arrangement of bow visor and bow ramp [JAIC03]

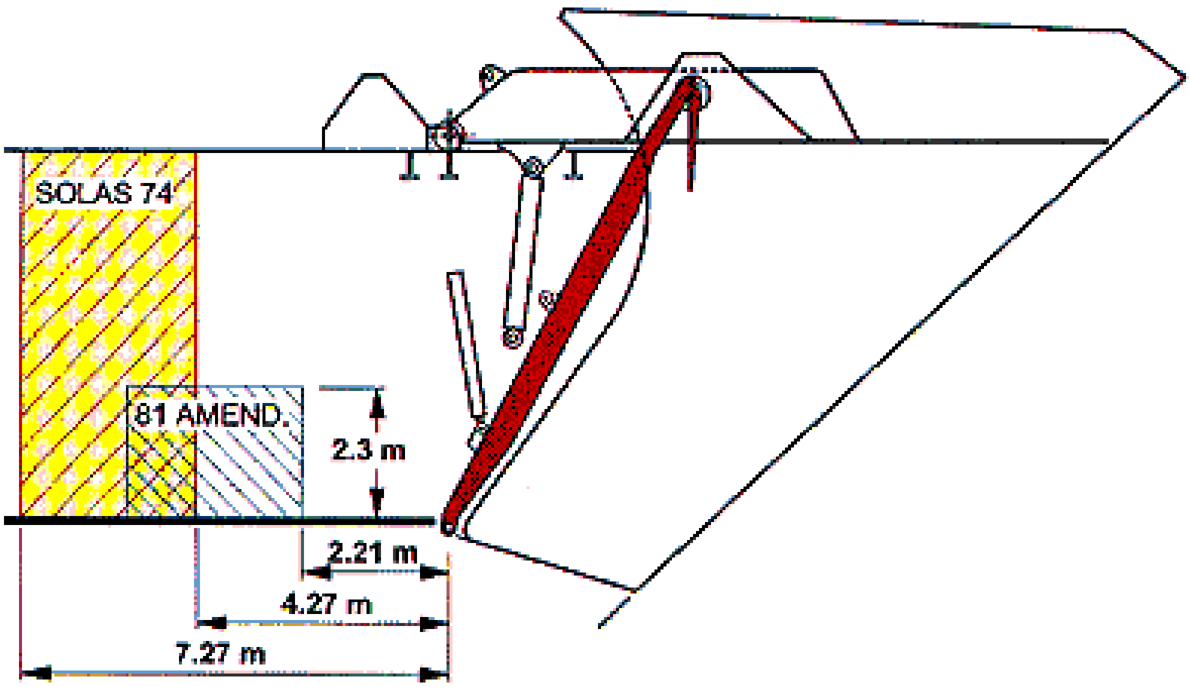


Figure 3.3: Positions of the upper extension of the collision bulkhead complying with SOLAS 1974 and the 1981 Amendment [JAIC04]

The bow visor and bow ramp arrangement of MV Estonia was not in compliance with the SOLAS 1974, which was in force during the design, building and delivery of the vessel. The upper extension of the collision bulkhead had not been installed, but the vessel was nonetheless accepted by the authorities [JAIC06].

3.3 Sequence of Bow Ramp Opening

The sequence of events surrounding the detachment of the bow visor and the consequent opening is plausibly reconstructed by [CARLS01] and [CARLS02], authored by a member of the IPE, and lays out the following possible chain of events:

- “Bow visor locking devices and hinges break due to forces exerted from severe sea-loads. Visor detaches from vessel prior to substantial vessel heel developing.
- The ramp remains closed and secured during the night of the accident until forced open by the visor, prior to the complete visor detachment from the vessel.
- The ramp remained partially open with broken lockings and actuating cylinders until the visor detached from the hull. During this period, a significant amount of water may have entered and flooded the car deck to such an extent as to cause a permanent heel. […]
- The visor hydraulic actuator eyeplates continues to cut through the deck beam, forecastle deck and bulkhead until finally complete visor detachment occurs from the vessel.
- The shell plating at the lower part of the visor deformed due to heavy contact between visor and bulbous bow/ stem post. Paint scratch marks indicate contact between visor and bulbous bow/ stem post. […]

- Deep, sharp indentations in 20mm thick visor shell plating tracks from visor bottom upwards approximately 3.0m parallel to the visor centreline girder. Most likely cause is that damage occurred when the visor contacts the straight part of the stem post following detachment from the vessel. […]
- In this position the gap between upper part of the ramp and forecastle deck is approximately 0.6 – 0.8 meters. This was the ramp´s final position on the wreck in 1994.
- The ramp fully opens crashing down onto the tank top as the visor completely detaches from the vessel. Massive flooding of the car deck ensues and within a few minutes could increase the heel of the vessel rapidly from 10-15 degrees to more than 30 degrees.
- The ramp main structure and secondary stiffeners are heavily deformed, buckled and bent due to sea-loads to such an extent that the for-ward part of the ramp is touching and resting on the bulbous bow. This may explain why the ramp did not detach from the vessel following the detachment of the visor when the fully open ramp became exposed to heavy sea-loads. […]
- During the later stage of the sinking sequence, when the vessel´s heel is approximately 90 degrees, and the stern starts to point towards the seabed, the bow ramp begins to close under its own gravity. Broken hinges on port side makes the ramp lean to starboard and the ramp upper starboard console makes contact with the front bulkhead preventing the ramp from closing fully. In this position the gap between upper and part of ramp and forecastle deck is approximately 0.6 – 0.8 meters. This was the ramp final position on the wreck in 1994."

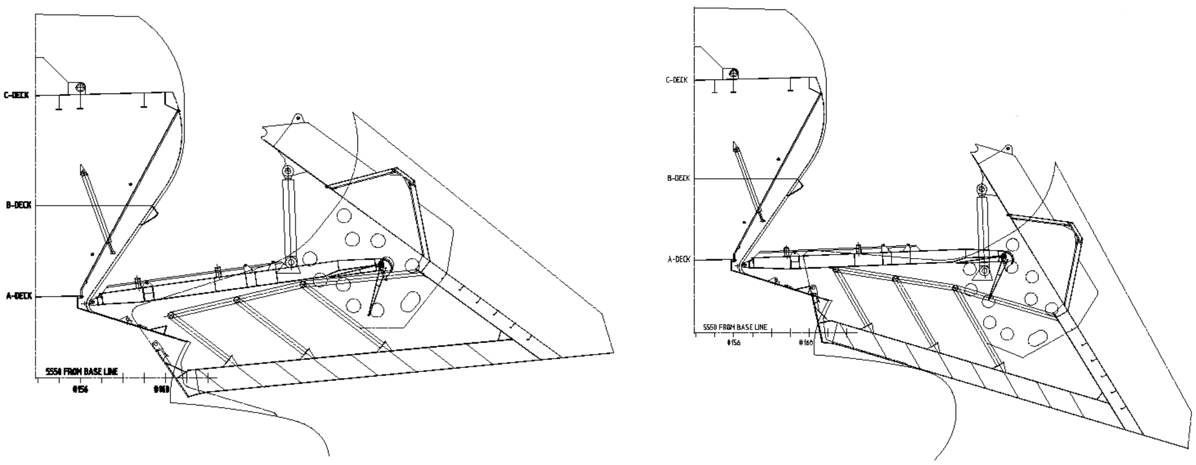


Figure 3.4 and Figure 3.5: The bow visor forcing the bow ramp open and falling on the bulbous bow [CARLS01]

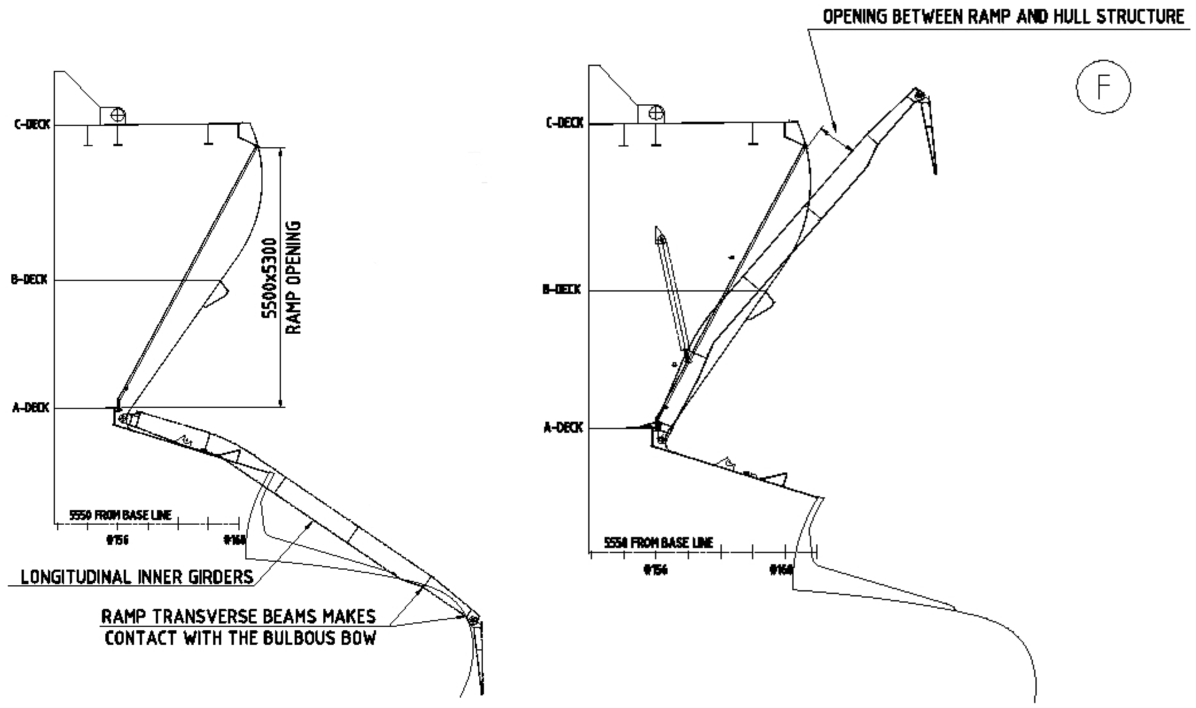


Figure 3.6 and Figure 3.7: The bow ramp fully pulled open and the condition as found on the seabed [CARLS01]

3.4 Opening Moment of Bow Visor

[LEH] distinguishes between two failure modes. The causa prima is a fatigue failure of the visor hinges, but all consequential failure of the bow ramp opening sequence had a causa secunda of an overload of the visor hinges. [LEH] calculates a bow visor opening moment of 225kN conservatively, disregarding the water most likely in the bow visor as assumed by [CARLS01]. Furthermore [LEH] calculates a ramp opening force of about 200kN with the following conditions: Only the two starboard hinges of the ramp are intact and the hooks were not engaged as can be seen on the video material of [ROCK]. Only one of the four locking bolts are closed. The statement of [LEH] on this calculation is: "This force 'P' is less than 225kN, therefore this load explains very clear, that the ramp has been opened by reason of the bad condition of the ramp securing system."

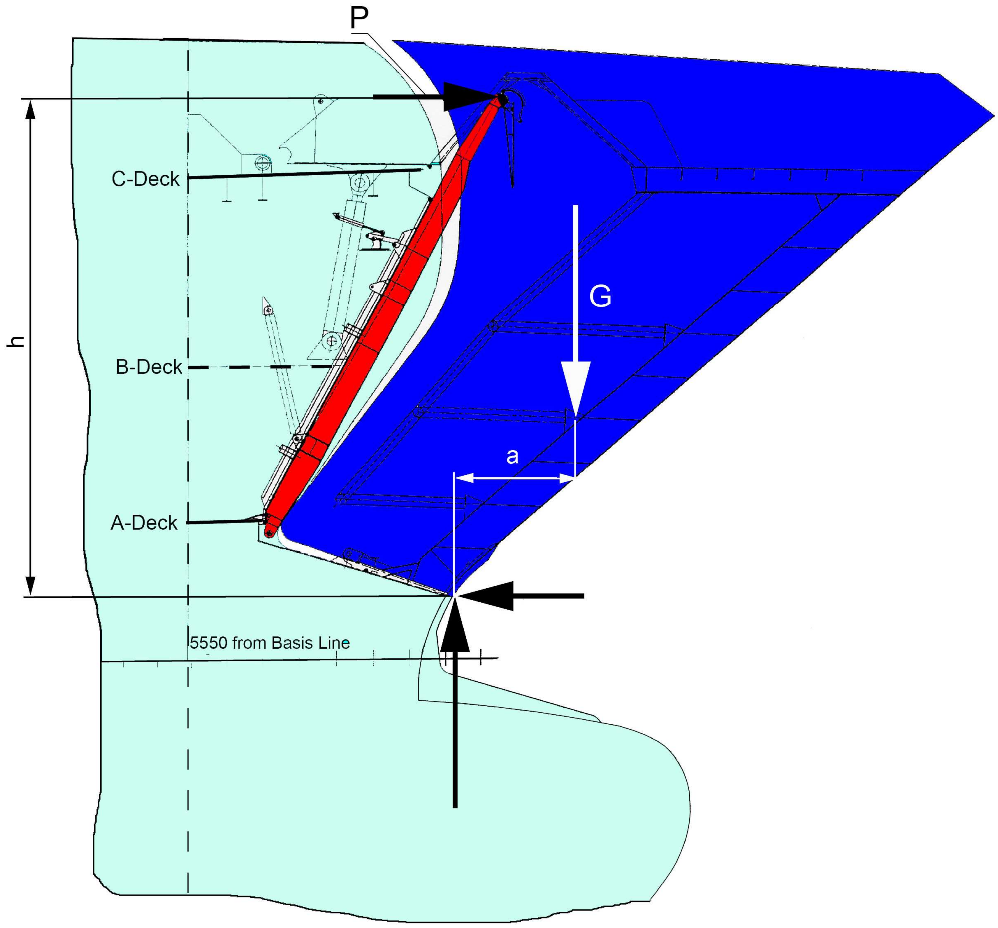


Figure 3.8: Direction of the forces pulling the bow ramp open [LEH]

3.5 Wave-Loads on Bow Visors

Ongoing research work, as carried out by [STOYE] of Flensburger, indicates that the wave-loads on bow visors may have been underestimated by authorities and classification societies by a factor of 2, or even more. The force caused by waves slamming on the bow can be characterised as strong but short-lived. But the direction and magnitude of the longer-lasting force due to the displacement of the seawater have not been quantitatively studied. This is, however, a topic for further research.

3.6 A Comparable RoPax-Ferry to MV Estonia

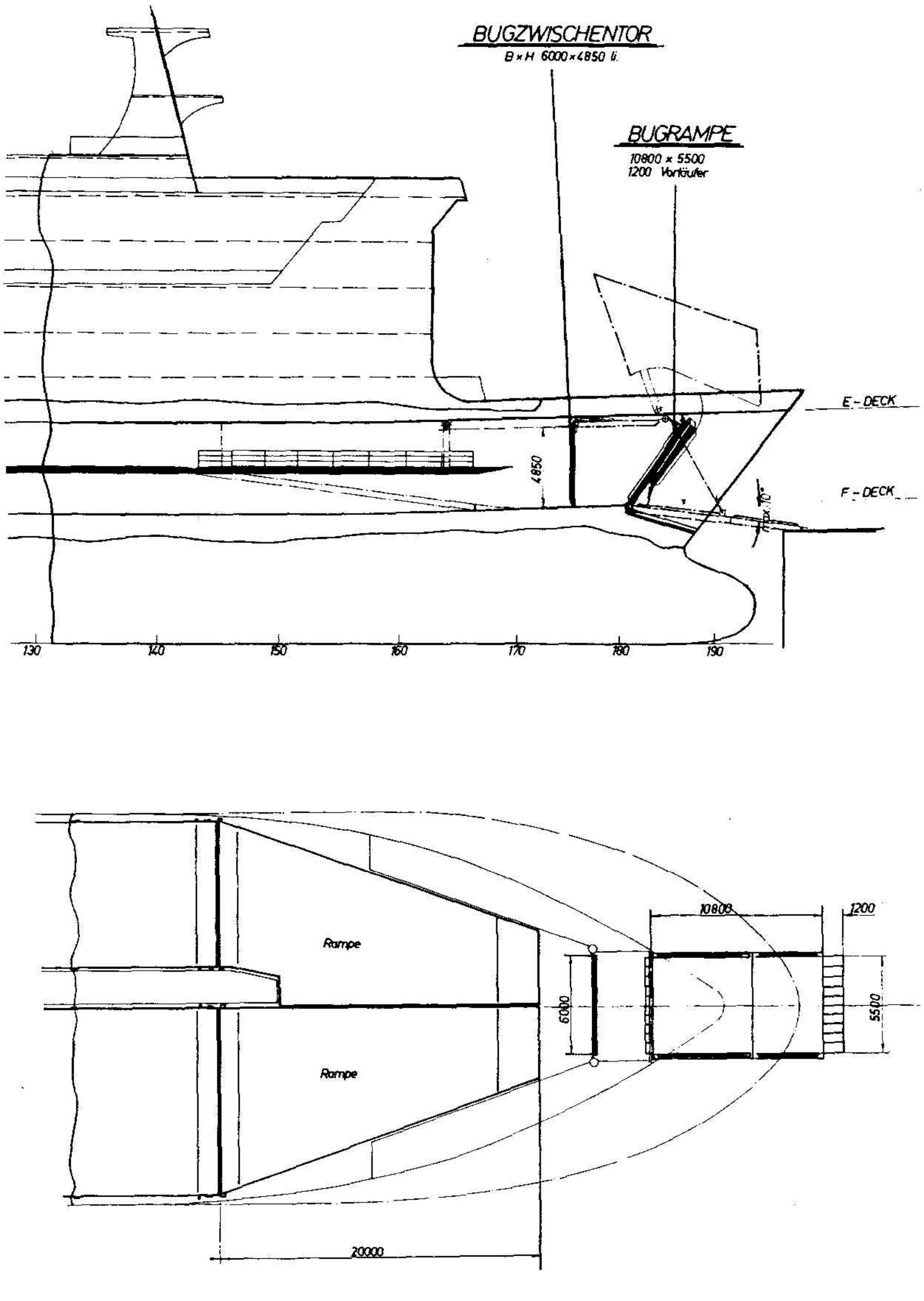
To compare the state of the technical knowledge a comparable RoPax ferry is presented here. Around one year after the delivery of MV Viking Sally - the later MV Estonia - by Meyer Werft GmbH, another German shipyard, Seebeckwerft of Bremerhaven, delivered the RoPax Ferry MV Olau Hollandia to Olau-Line in March 1981. MV Olau Hollandia was very similar to MV Estonia, so similar that owner of Meyer Werft GmbH said in 1981: "…könnte man annehmen, daß die 'Viking Sally' als Vorbild für die 'Olau Hollandia' gedient hat…" [HANSA02]

MV Olau Hollandia had a different bow visor and bow ramp arrangement: Her bow ramp was foldable and because of this, the 12m long bow ramp - including flaps - did not need a box-like housing [Hansa01]. This arrangement is shown in *Figure 3.9*. This means in case of a loss of the bow visor, it would be much less likely that the bow visor pulls open the bow ramp with it, as [CARLS01] explained for MV Estonia.

The collision bulkhead of MV Olau Hollandia has an upper extension from her Main Car Deck to the lowest deck of the superstructure. This can also be seen in *Figure 3.9.*[3]

It may be added here that further differences between MV Estonia and MV Olau Hollandia were investigated in [VOSSEN].

[3] The upper extension of the collision bulkhead is indicated by the German word "Bugzwischentor".



Bugrampe

Figure 3.9: Arrangement of bow visor and bow ramp on MV Olau Hollandia [HANSA01]

4 Surrounding Conditions on the Night of the Sinking

4.1 Position of the Wreck

The position of the wreck is 59°22,9' N 21°41,0' E [BSH]. This location is outside the territorial waters of, but within the "Exclusive Economic Zone" (EEZ) of Finland.

This information is provided by the „Bundesamt für Schifffahrt und Hydrographie", the German Federal Maritime and Hydrographic Agency, which is under the jurisdiction of the Federal Ministry of Transport, Building and Urban Development.

4.2 Density of Sea Water

All calculations in the stability booklet of the MV Estonia were carried out with the density of seawater equalling 1.025t/m³. In order to provide a like-for-like comparison, the CAD-Model calculations also use a water density of 1.025t/m³.

The JAIC carried out their calculations with a sea water density of 1.010t/m³ [JAIC01].

In this thesis, hydrostatic calculations follow [KHBOCK], in which the area of study is indicated by a sea water density of 1.004 t/m³.

4.3 Weather Conditions

4.3.1 General

The weather data is taken from [EMHI], [FMI], [SMHI] and [FIMR]. These documents were also used in the final report of the JAIC.

4.3.2 Observations of Vessels in the area around MV Estonia

At the beginning of the evening of September 27th 1994, all vessels in the area of study reported a southerly wind of about 10-15m/s, increasing later to about 15-20m/s. Then 2-3 hours before midnight the wind shifted to a south-westerly 15-20m/s. By the time the MV Estonia sank, the wind was westerly 20-25m/s with gusts of up to 26-30m/s. Before the sinking of the MV Estonia, the wave height was estimated to 4-5m with some waves reaching 6-7m. After the sinking, the waves were estimated to be 5-6m in height with some waves up to 7-8m.

4.3.3 Helicopter Observations

The helicopters of the Swedish Air Force and Navy arrived at the site of the sinking between 02.50 and 05.00 and made the following estimates:

Westerly wind of 25m/s, gusts up to 30m/s. One helicopter reported gusts of up to 40m/s.

Their reported wave heights varied more than for the wind. The majority reported 5-6m or 6-8m.

4.3.4 Wind

Before the sinking, reports from ferries and merchant ships suggested with close agreement the wind was a south-westerly 15-20m/s, which is also supported by meteorological observations and computer models. After the sinking of MV Estonia, an increase of wind speed was noted.

4.3.5 Significant Wave Height, Wave Length and Wave Period

There is close agreement between observations and calculations of the significant wave height of 3.5 to 4.5m before the sinking. After the sinking, there is a increase in the significant wave height. The maximum wave height, both observed and theoretical, is also in close agreement here, before the sinking it is estimated to be about 7m, although statistically, an 8m wave is likely to have occurred every second hour. It is important to note that, during the rescue operation later in the night, a southwesterly swell with a longer period was observed to be superimposed on a westerly sea wind with a shorter period, leading to a confused sea state. Note that the mean wave height is calculated from direct observations whilst the maximum wave height is based on theory, statistics and eyewitness estimates. If we have, for example, a set of conditions in the northern Baltic with wind speeds of 17m/s and wave heights of around 4.0m, measurements and theoretical modelling gives a significant wave period of about 8s and a corresponding significant wave length of about 100m.

4.3.6 Weather Conditions on the last Voyage of MV Estonia

The following table gives an overview of the weather conditions along the probable route on the night of the final voyage of the MV Estonia.

Table 4.1: Table of Weather Conditions on the last Voyage of MV Estonia

L.T.	Position from >>> to	Wind direction	wind strength	gusts up to	sign. wave height	max wave height
			m/s	m/s	m	m
18:00 - 19:00	Tallinn roadstead >>> point just west of Naissar	S -SW	8-10	13	1.0 – 1.5	2.0
19:00 - 20:00	Point just west of Naissar >>> line Pakri / Jussarö	S	10 -13	16	1.5 -2.0	3.0
20:00 - 21:00	line Pakri / Jussarö >>> abeam of Osmussar	S	11 - 15	18	2.0 - 3.0	4.0
21:00 - 22:00	abeam of Osmussar >>> line Tahkuna / Russarö	S -SW	13 - 17	24	2.5 - 3.5	5.0
22:00 - 23:00	line Tahkuna / Russarö >>> abeam of Bengtskär	SW	13 - 17	21	3.0 - 4.0	6.0
23:00 - 24:00	abeam of Bengtskär >>> abeam of Ristna	S -SW	14 - 18	21	3.5 - 4.5	7.0
00:00 - 00:30	abeam of Ristna >>> point just east of the sinking	SW	16 - 20	23	3.5 - 4.5	7.0
00:30 - 02:00	at the sight of the sinking	SW	16 - 20	24	4.0 - 5.0	7.5

5 Testimonies

The testimonies are of particular importance to the reconstruction of the sinking sequence of MV Estonia. The persons, who luckily survived the catastrophe can give valuable hints and details to shed light on the course of events during the last night of ferry. Thus the testimonies were investigated very carefully at the beginning of this research work.

5.1 Synoptic

The following tables are based on the testimonies provided by the Styrelsen för Psykologiskt Försvar (SPF), the Swedish National Board of Psychological Defence, a Central Swedish Authority. It was commissioned by the government to provide information on the sinking of the MV Estonia. The SPF also provided the official passenger list, including the number and type of vehicles on the Main Car Deck, which is also included in this thesis.

The names of the survivors and external witnesses are confidential and not revealed in this thesis due to their right to privacy. A cryptic name is used for each person and can be decrypted via the confidential list 'WitnessKey.xls' possessed by the HSVA- and the SSPA- Consortium of the Research Study of the Sinking Sequence of MV Estonia. The code is structured thusly:

P# Passenger#

C# Crew#

E# External#

Marine Claims Partner (Germany) GmbH[4] provided both a second source of testimonies and also testimony from external witnesses.

[4] The company 'Marine Claims Partner (Germany) GmbH' provides documents related to MV Estonia such as testimonies or drawings on behalf of Meyerwerft GmbH.

5.2 Why a Synoptic Time Schedule

For passengers and crew on the MV Estonia, the heavy listing of the ship came all of a sudden – in the middle of the night. Many people on board had gone to bed to be awoken by the listing or a loud bang. Most people realised very quickly that the situation was dangerous or even life-threatening, some even left relatives in order to save their own life. Under such strenuous circumstances, people lose their sense of time. The people on board are victims in this catastrophe.

In order to reconstruct the sinking sequence of the MV Estonia it is necessary to extract each incident to gain the most objective view. As every question can not be answered in sufficient detail, this synopsis provides an opportunity to approach a kind of objectivity. The concept of the synopsis is that one or two witnesses can often be mistaken, but it becomes increasingly improbable that they are wrong with more people saying the same thing at the same time. By the method of this synopsis it is possible to add a web of evident facts and feed back this information into a comparison with the testimonies.

All testimonies were studied carefully and parts concerning the list or other relevant incidents are selected and compiled on a timeline. After listing all selected testimonies, a particular incident is looked at in all testimonies and connected to a certain time on the time line. This is especially the case for incidents which could be recognized by a large number of persons on board, for example flickering of the on board illumination or a loudspeaker announcement. In the next step a careful selection is carried out to determine which testimonies can be considered the most significant. A range of possible times are narrowed to a single time. This process is repeated and fact by fact one is able to develop an outline of the time sequence of the sinking of MV Estonia, and express the compiled testimony in pictorial form, with an emphasis on the listing.

Unfortunately there are gaps - even in major incidents. A complete and detailed reconstruction of the entire sinking is impossible, so the aim is to the best job possible in reconstructing the sinking sequence of the MV Estonia. We must remember, however, that all events must conform with the laws of physics - and we can use this to fill in some gaps in the testimony. In the end, it was possible to reconstruct a framework for the incidents surrounding the sinking of MV Estonia on September 28th 1994.

5.3 Synoptic Time Schedule

The cells in the synoptic time schedule are connected to a timeline. One standard cell represents one minute. If a range of time is under consideration, some standard cells are amalgamated into a larger cell. For example, if a witness testifies "It was about 11:45 pm." then a few standard cells before and after the exact time are merged to reflect the statement "about". If a witness testifies: "I looked on my watch and it was 01:31am." one standard cell represents this exact point in time.

To lay out the synoptic time schedule clearly, colours are used to identify the different phases in the sinking sequence.

The key is shown in the following table.

Table 5.1: Table of Key: Colours in Synoptic Time Schedule

Colour	Key
	Beginning of disaster, bangs
	List of about 15°
	List of about 20°...35°
	List of about 40°...50°
	List of about 60°...80°
	List of about nearly 90°...90°
	List >90° / information about final sinking

The colours are used in two different ways. First, if the background of the cell - standard or merged - is filled with the relevant colour, this means that the whole extent of the cell is relevant to a certain event. Secondly, if the words are coloured, then only part of the testimony is relevant to an event. This is less meaningful for the evaluation.

The following listed testimonies are the relevant extracts of the selected witness testimony and are not the complete testimonies. This is done for reasons of conciseness.

All times mentioned in the statements either are or have been converted to Estonian time. The following table shows an example of the methodology of the colour key and the size of the cells of the matrix.

Table 5.2: Example for the Methodology of the Synoptic Time Schedule

Witness	9	10	12
Name	P59	P12	P48
Source	SPF	SPF	SPF
Date	03. Oct 1994		05. Oct 1994
PAX / Crew	P	P	P, but employed
Cabin	??? Deck 4	622	4329 / 4331 /
00:57			
00:58			
00:59	hard bang, too hard to come from the storm dull, from bow		
01:00		01:00h: woke up due to a bang and seesaw	
01:01			
01:02			
01:03			
01:04			
01:05	2nd met. bang		
01:06	left cabin, list 25°		list increasing stepwise
01:07			
01:08			
01:09			
01:10	reach outside		
01:11	list 45°, life vest on		
01:12			
01:13			
01:14			
01:15			
01:16	loosed a Ladder, lights flickering		
01:17			
01:18			at a list of 45° the light went out for two times came back and
01:19			
01:20			

The synoptic time schedule can be found in the Supplementum.

5.4 Summary of the Testimonies

From the synoptic time schedule and these external sources we can construct a basic sequence of events running up to the sinking. Throughout the night of September 27th, MV Estonia was continuously pitching and rolling. At about 00:30 the two stabiliser fins were deployed, dampening but not eliminating the rolling. Half an hour later at about 01:00, there were two or perhaps three heavy bangs described as sounding 'metallic' within the space of a minute. After these bangs, the ship heeled to starboard at an angle of about 30°. The vessel then quickly righted itself, only to heel, again to starboard approximately 30° to 40°. MV Estonia started to right up again, but never reached a fully upright position. In the following 6 to 8 minutes, the starboard list increased stepwise – an increase with each roll of the ship - and, by around 01:08 to 01:09, an average heeling angle of about 30° was reached. At this angle, a kind of quasi static equilibrium appears to have been established. At 01:17, starting from an angle of 35°, the heeling angle increased at a faster rate.

Two witnesses state that the ship was 90° from the upright condition at between 01:31 and 01:32. At this point the ship's horn was blown.

The list had increased further to perhaps 120° or 130°.

The vessel disappeared beneath the surface most probably close after 01:50, although no eyewitnesses of the MV Estonia report a time in their testimony. This time of 01:50 for the final sinking was determined from the radar contact log of the crew of the MV Mariella.

The announcements "Häire, häire, leaval on häire" and "Mr. Skylight no.1 and no.2" – "Mr. Skylight" being a cryptic code for emergency procedures – cannot be connected to an exact time with any certainty. Nor could the stopping of the main engines - at a heeling angle of 40° - or the auxiliary engines, at 55°, which led to the loss of lighting. It is most likely that the engines stopped automatically due to lack of lubrication oil. The lubrication oil is pumped from a tank below the engines, and the list meant that the oil pumps were sucking in air, causing the automatic shut down of the four main and the four auxiliary engines.

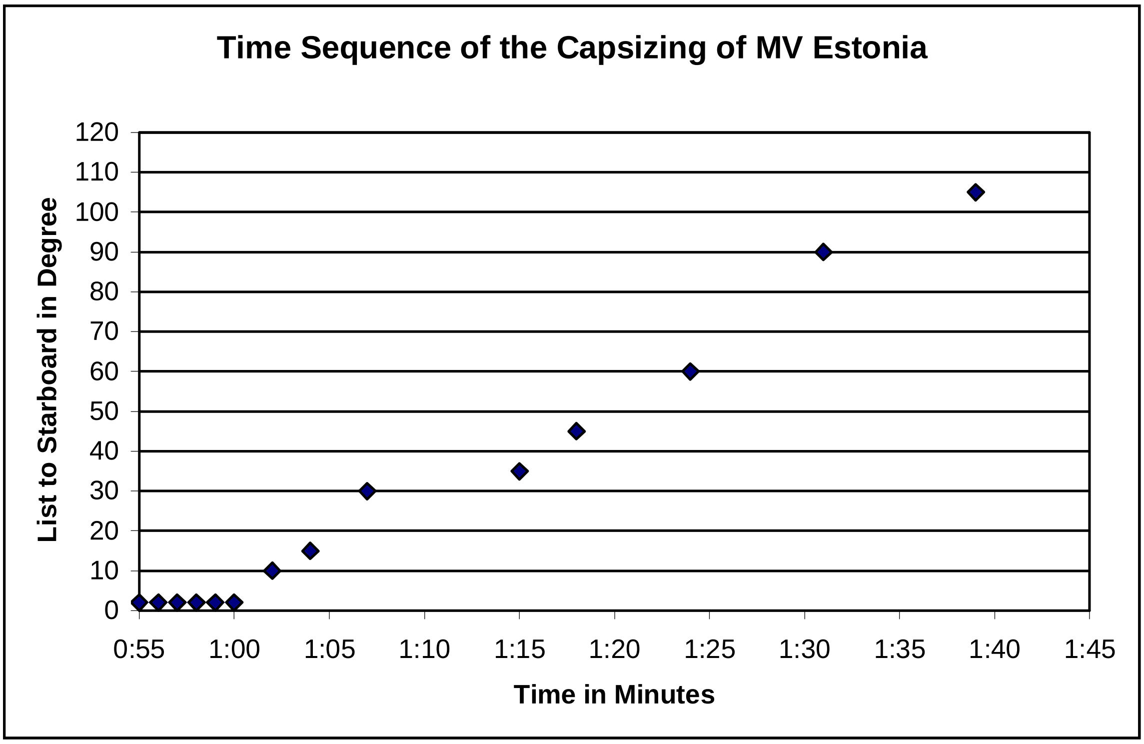


Figure 5.1: Graphical representation of the reconstructed time sequence of the capsizing of MV Estonia. Note: The points are not linked. This is to indicate that is not possible to reconstruct every detail in this sinking sequence, and it would be unwise to interpolate the data between points.

5.5 Other Significant Observations

5.5.1 Effect of Water on the forecastle

The Chief Mate on the RoRo-Ferry MV Amber recognized MV Estonia on the radar screen shortly before 23.00 on the Automatic Radar Plotting Aid (ARPA). The closest point of approach (CPA) was calculated by the ARPA to be 1.5nm. The course of MV Estonia was about 260° to 265° and its speed around 18 to 19kn. At the CPA, which was reached at about 23:15 or 23:20, the Chief Mate observed MV Estonia via binoculars. MV Estonia was observed to be sailing full speed, pitched heavily and green water on her forecastle was observed. The Chief Mate commented that he had never before seen a ferry in the Baltic pitching that heavily.

He observed that the forecastle of MV Estonia was being continuously refilled with seawater by – at the very least - spray. It is possible that the water could have also poured into the bow visor, filling it that way.

From the visor, the water may have entered the Main Car Deck through gaps in the bow ramp, which was not properly sealed. Water ingress through gaps on both sides of the ramp was reported by crew member C33, having observed this on a monitor in the Engine Control Room (ECR) from a camera which was located under the ceiling and directed at the bow ramp. See also Figure 6.1, p. 66 in the Final Report of the JAIC [JAIC02].

It seems reasonable to assume that a certain amount of water had already accumulated on the Main Car Deck before the visor was lost.

5.5.2 Effect of Possible Stern Ramp Operation

Possible as well, is a scenario where the crew opened the stern ramp a little to run off water some of the water that had accumulated. To keep the stern ramp in this slightly opened position, continuous operation of the hydraulic pump would have been necessary. A high frequency noise, which was most likely caused by a hydraulic pump, forced a conference being held on Deck 4 towards the stern, to end prematurely. It is noted in the testimonies that a member of this conference asked a crew member whether it was possible to stop the noise, to which the answer was no. As the MV Estonia left Tallinn harbour with a slight list to starboard, it is logical to assume that the crew may have opened the stern starboard side ramp. However, as will be discussed in Chapter 5 - "Condition of MV Estonia on the Seabed", this ramp is totally submerged under the seabed – so it will never be known if this assumption is true.

6 Condition of MV Estonia on Sea Floor

Beside the testimonies, the condition of MV Estonia on the sea floor is an important source of information. Inferences can be compromised from the position and orientation of the vessel on the sea floor. Possible damages at the vessel may give hints to how the ferry touched the sea ground and what possible scenario of the very last part of the sinking could be eliminated. These problems are investigated in this chapter and complement the results of the evaluation of the testimonies.

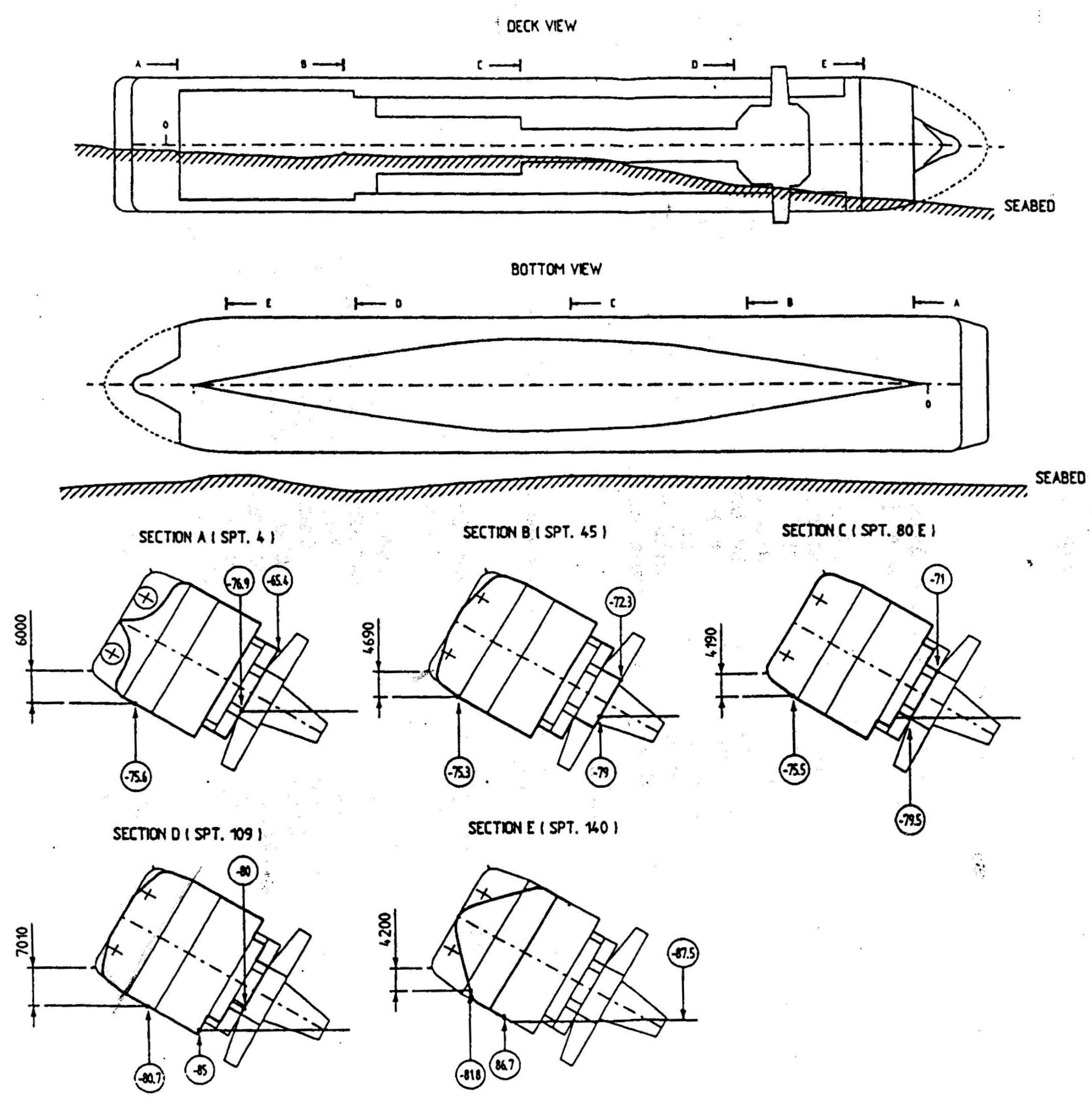


Figure 6.1: The position of MV Estonia on the seabed by [ROCK]

Due to a treaty between Estonia, Finland and Sweden it is not permitted to perform diving or ROV-surveying[5] of the wreck to due to its status as a sea grave. Because of this, this thesis only has access to the diving reports and the video-tapes that were published along with the investigation carried out by the JAIC in order to investigate the condition of the MV Estonia on the seabed. According to the 1994 report of the Diving Company [ROCK], MV Estonia laid on the seabed on her starboard side at a heel angle of about 120°. The bow of the vessel points towards the east - 95°/ 97° true. Due to the clay in the seabed and the position of the vessel it is not possible to see the starboard side, so there is no possibility to check the condition of the windows or the overall damage to the vessel there.

Figure 6.1 shows the position of MV Estonia on the seabed. It is noteworthy that the stern of MV Estonia is dug in the seabed nearly to centre line, but the bow is not. The bow area seems to be laid down on the seabed. The numbers in circles are the water depth in meters.

The available video tapes were analysed with attention paid to the damage condition of windows and damage at the stern of the ship - e.g. railing, shell damage etc. This investigation may reveal manifestations of air trapped in the ships' hull and may hence reveal the way MV Estonia hit the sea bed. By this it may shed light on the sinking sequence of MV Estonia.

6.1 Position of Stabilizer Fins

MV Estonia had two stabiliser fins, one on each side of the ship in the area between frames e and r, see *Figure 6.2*. According to the testimonies of crew members, the stabiliser fins were deployed at about 00:30, half an hour before the first heavy heel occurred. On the video-tape of the ROV-inspection of October 10th 1994, at time code 02:03, the port side stabiliser fin can be seen. The stabiliser is in its drawn-in position – into the ship's hull, see *Figure 6.3*. There is no obvious damage observed.

[5] Remotely Operated Vehicle

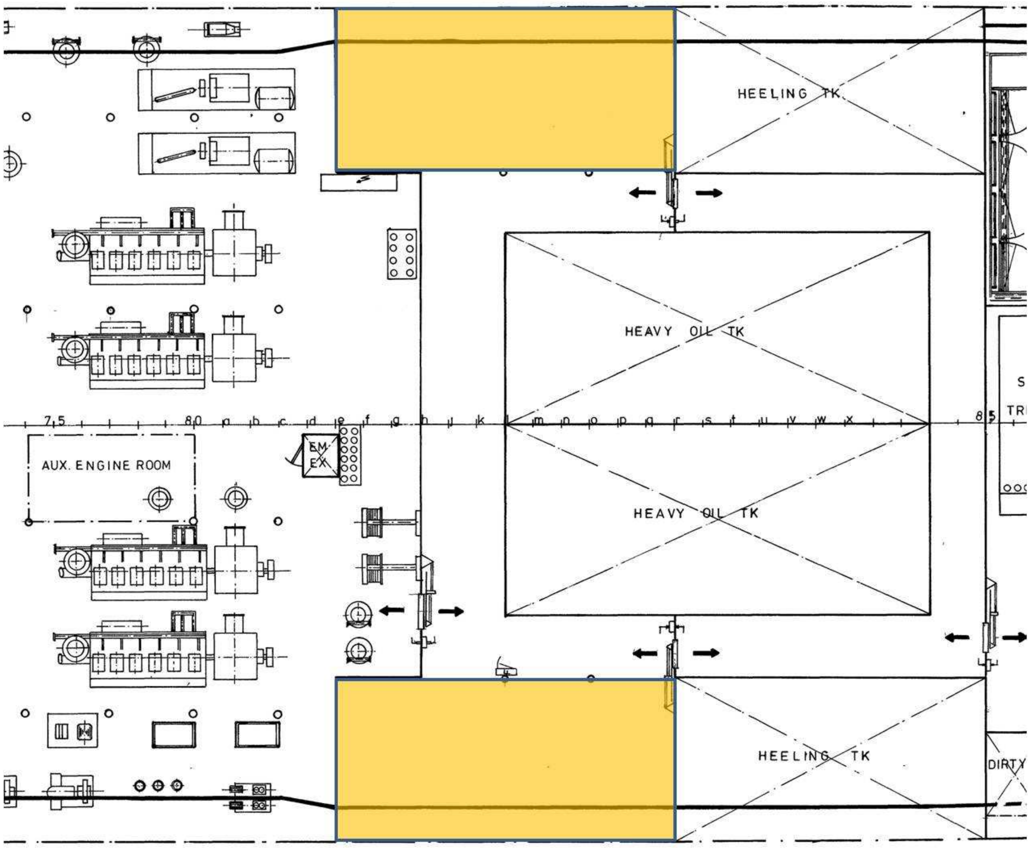


Figure 6.2: The position stabiliser fins of MV Estonia, frame e to r

Figure 6.3: The drawn in-position of stabiliser fins of MV Estonia [ROCK]

What is unclear is whether the stabiliser fin was drawn-in by the crew or as MV Estonia lay on the seabed after having lost hydraulic system pressure. In the latter case, the stabiliser fin would have swung back into its drawn-in position due to the action of gravity, as the bow of the vessel lies deeper in the seabed than the stern and the hinge is installed sternwards.

6.2 Position of Rudders

[ROCK] reported "Both rudders are clear and do have an angle of 35 degrees to starboard".

Each rudder angle is kept the same by a connecting bar in the steering gear room. On the videotape the rudders have no obvious damage and the angle of about 35° can be confirmed on the videotape of ROV-inspection - October 2nd 1994 at a time of 17:37 on the tape, see *Figure 6.4*. This is position the rudders would be in due to the action of gravity in the case of a loss of system pressure, so it cannot definitely deduced what position of the rudder is as last controlled by the bridge.

Figure 6.4: The position of rudder

6.3 Propeller Pitch

MV Estonia had two controllable pitch propellers. On the ROV-inspection videotape on October 2nd 1994 at the time-codes 17:37 to 17:47 and 18:27, a propeller can be seen, but it is not possible to identify its pitch. This means it is not possible to deduce the final propulsion commands from the bridge. In addition, the tape shows the propellers to be clearly undamaged.

6.4 Situation on the Main Car Deck

According to [ROCK], says "A ROV survey was conducted in the car deck covering until a distance of 20 meters inside the wreck. It was observed that cargo had fallen to the lower side and although trucks have not been seen it can be assumed that they have also fallen to the lower side of the car deck.". Clearly, a cargo shift has taken place.

6.5 Video Material – Situation of the Windows

The windows of the starboard side of MV Estonia were observed to be nearly completely intact, very few windows are broken. Only two broken windows are observed on the port side, and they are shown in *Figure 6.5* and *Figure 6.6*.

Figure 6.5 shows a broken window on Deck 4, the curtains can be seen clearly. Also on Deck 4, *Figure 6.6* shows a broken window with a mattress hanging out.

According to the window drawings no S 590 - 26/11 and S590 - 26/12, several of the windows - sized 400mm x 800mm - on Deck 7 and 8 were of openable type. *Figure 6.7* shows one of these windows opened.

Finally, *Figure 6.8* shows several cans touching the glass of the window. Due to this, it is clear that there is no trapped air, no air bubbles nor any lower water surface within this compartment.

It is reasonable to conclude from this that there is no trapped air in areas of the vessel which are not water tight in terms of the IMO regulations. At least it is to conclude that the effect of trapped air between Deck 4 to Deck 8 on the sinking sequence is minor.

Figure 6.5: Broken window on Deck 4

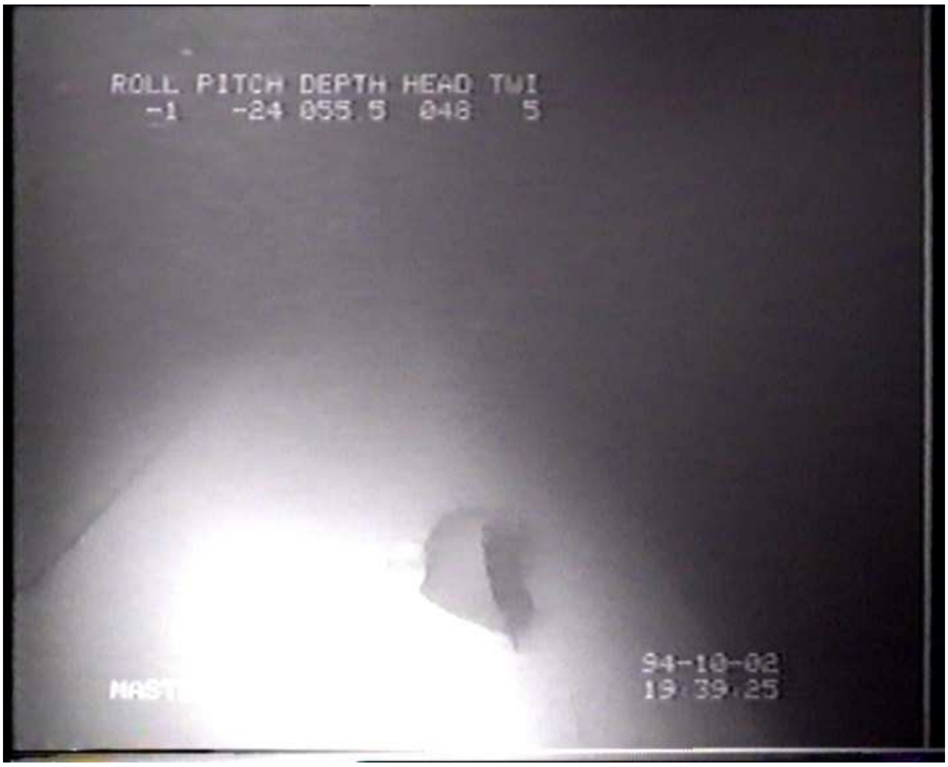


Figure 6.6: Broken window on Deck 4

Figure 6.7*: One of the* *openable type windows of Deck 7/ 8 in an opened state*

Figure 6.8: No trapped air in this cabin

6.6 Video Material – Situation of Damages at Stern of MV Estonia

To answer the question of how MV Estonia hit the sea floor, different scenarios were developed. By the information provided by *Figure 6.1*, it is most likely that MV Estonia sank stern first and that the ferry hit the sea bottom with her starboard side. To exclude scenarios in which MV Estonia hits the sea bed portside or upside down, the available video tapes were analysed, looking for damage to the stern area of the vessel.

The following figures *Figure 6.9* to *Figure 6.19* show the stern area first on the port side, Deck 5 upwards to Deck 7 and on Deck 7 along the railing to the Centre Line and the stern lights. No obvious damage, no contorted stiffeners, no buckling in the shell plating nor even scratches in the coating are noted. Due to these observations, it is very unlikely that MV Estonia hit the sea floor with the stern part of her port side or in an upside-down position.

Figure 6.9: Stern view of MV Estonia, see Figure 6.10

Figure 6.10: Deck 5, stern from portside, for comparison, see Figure 6.9

Figure 6.11: Stern view of MV Estonia, see Figure 6.12

Figure 6.12: Deck 6, Stern, Portside, compare Figure 6.11

Figure 6.13: Stern View of MV Estonia, see Figure 6.14

Figure 6.14: Railing Deck 7 stern on portside, for comparison, see Figure 6.13

Figure 6.15: Stern view of MV Estonia, see Figure 6.16

Figure 6.16: Railing Deck 7, stern, compare with Figure 6.15

Figure 6.17: Stern view of MV Estonia, see Figure 6.18

Figure 6.18: Stern Light, Deck 7, compare with Figure 6.17

There is unfortunately no video available that shows the stern railing on Deck 9, see *Figure 6.19*, but [ROCK] records that there are "some minor buckles in the superstructure at the stern near deck 8". This indicates MV Estonia hit the seabed stern-first with a list of significantly more than 90°, but not in an upside-down condition. A list of 120°-140° at time of collision seems to be likely, looking at the damage to the vessel's stern.

Figure 6.19: Stern view of MV Estonia, unfortunately no underwater video material available

7 Stability Booklet and Validation of the Calculation-Model

To carry out any simulations a calculation model of the vessel itself had to be set up and to be validated with the stability booklet of MV Estonia. It was also checked, whether the stability booklet contains inconsistencies and if, how they may influence the actual behavior of the vessel. This chapter deals also with the additional buoyancy provided by the superstructure.

The assembly plans of hull No. S590, built by Jos. L. Meyer GmbH, today's Meyer Werft GmbH, were digitised with the ship design system software E4. Hydrostatic particulars and cross curves of stability were calculated. These results were compared to MV Estonia's stability booklet. This is the base of the validation of the calculation-model.

Originally the vessel was built without a ducktail, and in order to compare the results of the of the hydrostatic calculations with the original stability booklet of MV Estonia - when it was still called MV Viking Sally - the ducktail was removed from the Calculation-model. The specific gravity of seawater was assigned to be 1.025t/m^3, the coefficient of displacement of the shell-plating was set to 1.007 due to her ice-class, and the keel-thickness was equal to zero. The stability booklet states that the calculations were carried out on an even keel, in other words with a trim equal to zero, as in the documents produced by Meyer Werft GmbH.

The hydrostatic particulars were calculated by Maierform GmbH engineering company of Bremen on June 26th 1980. The software "KUBLENG" was used to perform a numerical integration approximating the whole ship to just 46 frames. The results of those calculations can be seen in the Supplementum and the corresponding lines of the vessel in *Figure 7.1* and *Figure 7.2*.

The stability cross curves were calculated by Maierform GmbH on September 20th 1979. The "PANTOBO" software was used to perform a numerical integration approximating the ship to just 49 frames. The stability cross curves can be found as well in the Supplementum.

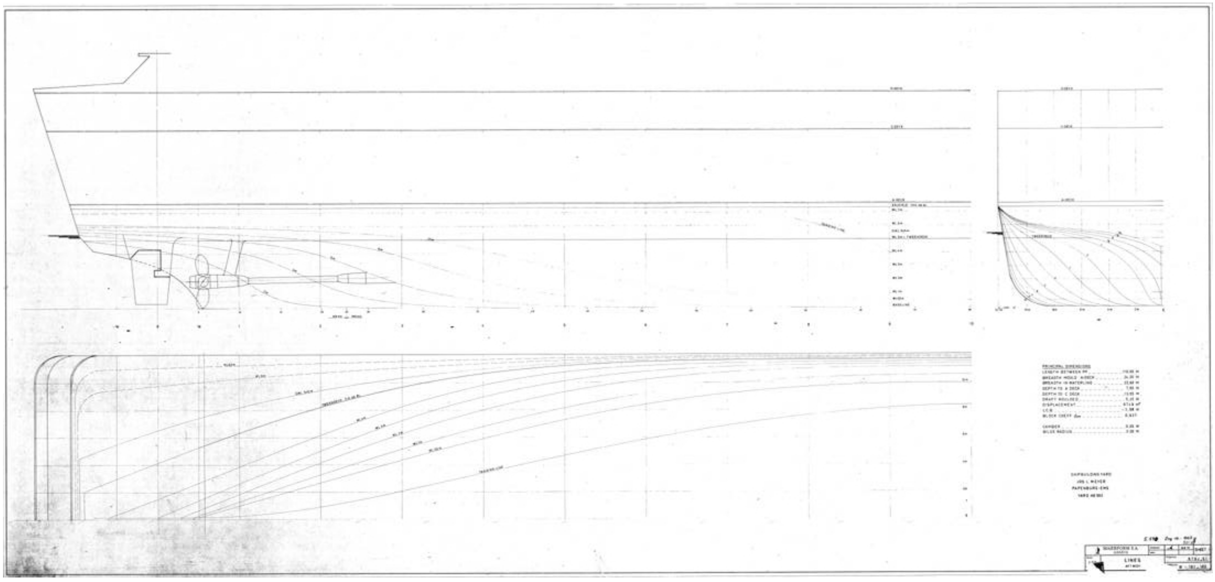


Figure 7.1: Lines of aftbody of MV Estonia

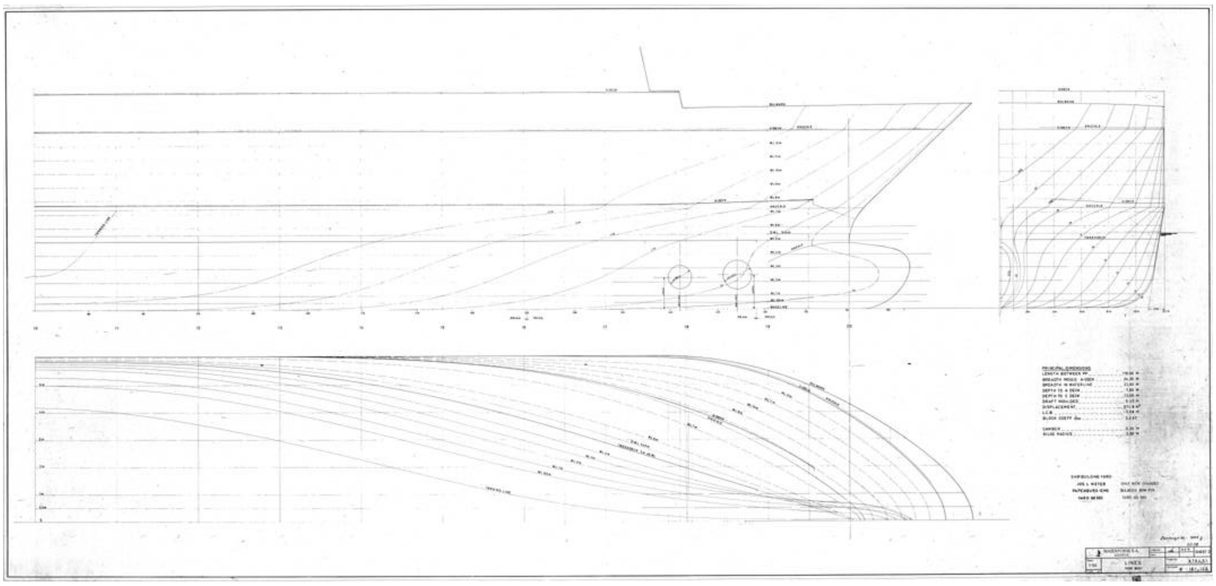


Figure 7.2: Lines of forbody of MV Estonia

7.1 Validation

The differences between the hydrostatic calculations of Maierform GmbH and the hydrostatic calculation-model are negligible. The difference is mostly of the order of one-tenth of a percent, and never more than one percent. This accuracy is sufficient and the calculation-model can be considered to be usable.

Figure 7.3 shows a screenshot of the calculation-model of the MV Estonia in a light ship weight floating condition.

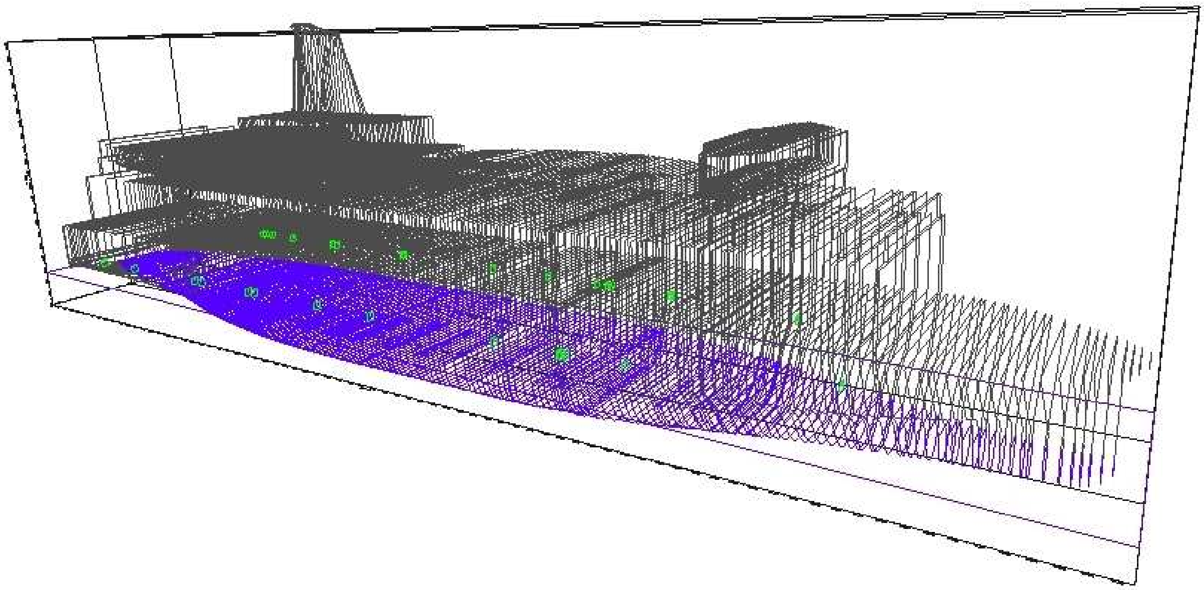


Figure 7.3: Screen Shot of Light Ship Condition of MV Estonia, via the calculation-model

Note that the superstructure of MV Estonia is assumed to be watertight, window collapse loads come under consideration in a later chapter. This has the consequence of the superstructure providing a supporting or additional buoyancy. All calculations carried out in each of the scenarios include this buoyancy and consequently express the lowest possible heeling angle – in other words the scenarios are calculated in a conservative way. The lever arm in *Figure 7.4* clearly shows this.

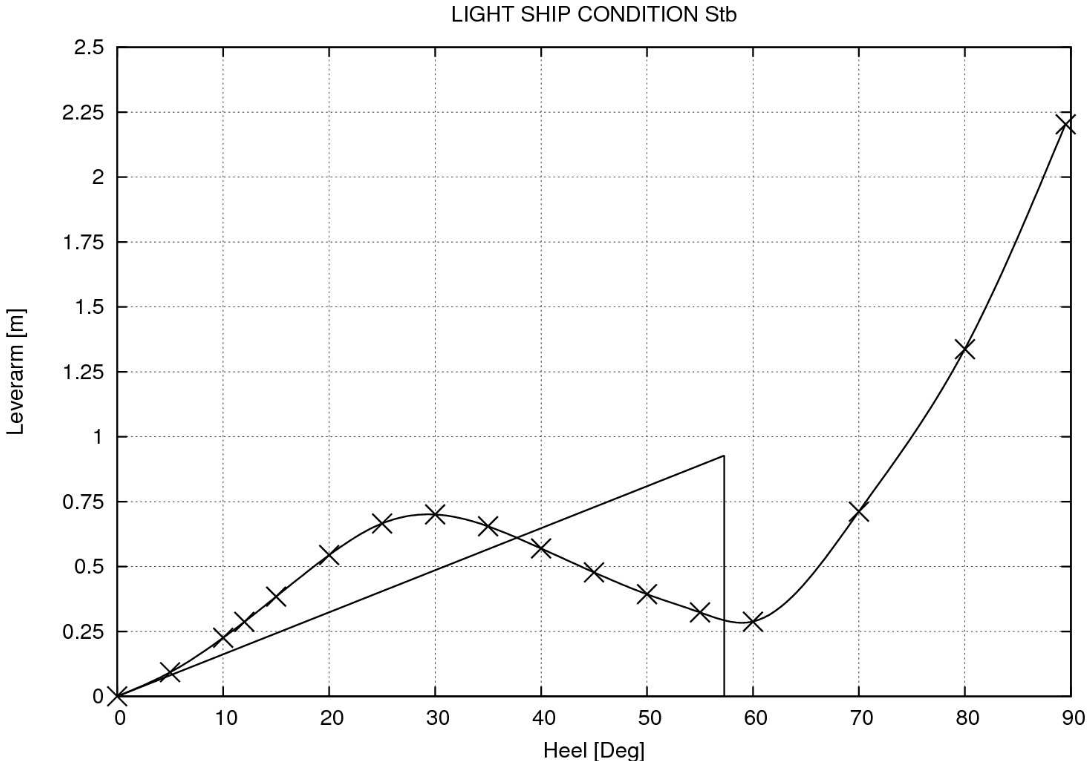


Figure 7.4: Lever arm in the light ship weight condition of MV Estonia, up to 90°

On January 11th 1991 the MV Estonia - which at that time was called MV Wasa King – had an inclining experiment performed by the engineering company 'Ship Consulting Ltd. OY' Turku, Finland. On January 21st 1991, they delivered the last official stability booklet, which was still valid for the final voyage of the MV Estonia. The light ship weight condition is designated in the stability booklet as 'Load Case 1' and the corresponding the values are given in *Table 7.1.*

In the course of this thesis 'Load Case 1' was recalculated – in light ship condition with a displacement of 9733t. The results are given in *Table 7.2*.

Table 7.1: Load Case 1 - light ship condition of MV Estonia from the Stability Booklet

Displacement	9733t
Mean draught	4.47m
Trim	2.28m
Draught aft	5.41m
Draught for-ward	3.13m
KM	12.00m
KG	11.56m
GM	0.44m
MM'	0.00m
GM'	0.44m

Table 7.2: Load Case 1 - Light Ship Condition of MV Estonia, recalculation 1

Yard number:	Ship name:	Date:
590	Estonia	

Trim	: -2.280 m	(positive forward)
Heel	: 0.000 Deg.	(positive starboard)
Density sea water	: 1.025 t/m3	
Light ship weight	: 9733.000 t	

HYDROSTATIC TABLES

T AP Metre	Dis.SW Ton	Dis.FW Ton	LCB m.f.AP	TCB m.f.CL	VCB m.a.BL	LCF m.f.AP	KM.T m.a.BL	T FP Metre
5.380	9424.2	9194.3	60.262	-4.E-14	2.375	59.469	12.593	3.100
5.385	9437.6	9207.5	60.261	-4.E-14	2.378	59.445	12.591	3.105
5.390	9451.1	9220.6	60.260	-4.E-14	2.381	59.421	12.590	3.110
5.395	9464.6	9233.8	60.259	-4.E-14	2.384	59.397	12.588	3.115
5.400	9478.1	9246.9	60.258	-4.E-14	2.386	59.373	12.586	3.120
5.405	9491.6	9260.1	60.257	-4.E-14	2.389	59.348	12.585	3.125
5.410	9505.1	9273.3	60.256	-4.E-14	2.392	59.324	12.583	3.130
5.415	9518.6	9286.5	60.254	-4.E-14	2.395	59.300	12.582	3.135
5.420	9532.2	9299.7	60.253	-4.E-14	2.398	59.275	12.581	3.140
5.425	9545.7	9312.9	60.252	-4.E-14	2.401	59.251	12.579	3.145
5.430	9559.2	9326.1	60.251	-3.E-14	2.404	59.226	12.578	3.150
5.435	9572.8	9339.3	60.249	-3.E-14	2.407	59.202	12.577	3.155
5.440	9586.4	9352.5	60.248	-3.E-14	2.410	59.177	12.576	3.160

Obviously the values do not fit: There is a difference in displacement of 200t, the KM value is too large by almost 0.6m. The recalculation 1 regards the same trim like the last stability booklet with an aftward trim of 2.28m. Another calculation was carried out, recalculation 2, but this time on even keel. By the results of recalculation 2 presented in *Table 7.3*, the difference of due to the values of displacement and KM are rather small. however, it becomes clear, that the calculations in the stability booklet were based on values on even keel. Consequently, MV Estonia has more stability than the stability booklet would indicate. This is taken into account in all further calculations in this thesis.

Table 7.3: Load Case 1 - light ship condition of MV Estonia, TUHH recalculation 2

Yard number:	Ship name:	Date:
590	Estonia	

Trim	:	0.000 m	(positive forward)
Heel	:	0.000 Deg.	(positive starboard)
Density sea water	:	1.025 t/m3	
Keel thickness	:	0.000 m	
Shell plating factor	:	1.007 m	
Light ship weight	:	9733.000 t	

HYDROSTATIC TABLES

T AP Metre	Dis.SW Ton	Deadw.SW Ton	LCB m.f.AP	TCB m.f.CL	VCB m.a.BL	LCF m.f.AP	KM.T m.a.BL	T FP Metre
4.450	9677.2	-55.8	65.474	8.2E-13	2.384	63.743	11.999	4.450
4.460	9702.9	-30.1	65.469	8.9E-13	2.390	63.723	11.992	4.460
4.470	9728.6	-4.4	65.465	9.6E-13	2.395	63.703	11.984	4.470
4.480	9754.3	21.3	65.460	9.7E-13	2.401	63.684	11.976	4.480
4.490	9780.1	47.1	65.455	1.0E-12	2.406	63.664	11.968	4.490
4.500	9805.9	72.9	65.451	1.1E-12	2.412	63.644	11.960	4.500

8 Load case of the Final Voyage

After the calculation-model is validated and with it is ready to use for calculations and simulations. The next step is to reconstruct the load case of the final voyage of MV Estonia. It is very difficult to carry out this, because some components can be reconstructed accurately, like the contribution of vehicles on the Main Car Deck, but information on the fuel oil tank levels, lubricants, fresh or ballast water is only sparsely available. The central data concerning tank levels is based on an estimation by the shipping company. It can be found in the Supplementum, entitled 'Tank Filling'.

8.1 Light Ship Weight

The light ship weight of MV Estonia was newly determined in an inclining experiment, performed on January 11th 1991. Compared to the first inclining experiment on delivery to its owner, AB Sally, there is a difference in mass of 313t. This difference can be explained by the additional ducktail and conversion of cabins in the upper decks - by the company "Ship Consulting Ltd. OY", Finland, which also carried out the inclining experiment. The light ship weight of MV Estonia was determined to be 9733t.

8.2 Ballast

The Chief Engineer of MV Viking Sally was involved in the building process between 1979/ 1980 and worked until 1991 aboard the vessel. He stated that Tank 14, the port-side heeling ballast water tank, had to be filled with about 50t of water to bring the vessel to a completely upright position. The hydrostatic calculations showed that the vessel in the light ship condition trims down to the stern. Summarising, one can say it seems to be very reasonable that Tank 14 and Tank 1, the fore peak ballast water tank, were both completely filled. This is in line with the estimations of the shipping company mentioned above, and the testimonies of several crew members. This assumption is used in the calculations of this thesis.

8.3 Bunker and Stores

The bunker fillings were handled in the same way as the ballast tank fillings. A detailed list of the contents of the bunker is given in *Table 8.2*. Store contents were estimated to have a mass of 100t and is labelled 'Miscellaneous' in *Table 8.2*. Store components consists of dishes, goods from the shops, and other items necessary to run the hotel on board, and so on.

8.4 Payload

Various payload components were being transported on MV Estonia on the night of her sinking. First of all, passengers and crew members – about 1000 people – travelled with the ship on the night in question. It is not possible to work out the exact total weight of these people, so an estimation is necessary. Including their luggage, one person is estimated to have an average mass of about 0.1t. This results in about 100t total mass of both people and their luggage. The largest payload component were the vehicles transported with the ship. The Main Car Deck on Deck 2 provides, according to the General Arrangement Plan, 850 metres of lanes of the appropriate width for trucks and trailers. The Hoistable Deck, Deck 3, was – according to the testimonies of the witnesses – not in use on the last voyage, so all vehicles were placed on the Main Car Deck. The vehicles on the Main Car Deck were identified by license plate number. The official passenger list, provided by SPF, the "Cargo Manifest" and the "Freight Manifest" together list 76 vehicles on the Main Car Deck. The masses and required lanemetres of the trailer and trucks were exactly summed up, see *Table 8.1*. The masses and required lanemetres of minibuses of mass 3t are estimated to be 6 lanemetres, of busses with a mass of 15t is 12 lanemetres, and 1.5t cars are estimated to have taken 6 lanemetres. In total, 841 lanemetres were occupied with a total mass of about 1113t, which is rounded to 1100t in the calculations. The vehicle list is shown below. Counted in the payload as well is the water in the swimming pool on Deck 0 with a mass of 25t. All other payload components are summarised under the title of "Miscellaneous", to about 100t. The total payload sums to 1325t.

Table 8.1: Vehicles on Main Car Deck

Ser. No.	Type	Maker	Reg. No	mass	LM	Type of Cargo
1	Car	VOLVO	125 SAF	1.5	5	~
2	Minibus	Mazda	KSX 647	3	6	~
3	Car	Porsche	OER 309	1.5	5	~
4	Truck + Trailer	DAF	BB-JJ-55	18	16	Blankets
5	Truck + Trailer	VOLVO	VH-43-FG	34	16	Peatm.+ Fish
6	Truck + Trailer	VOLVO	NXF 876	14	18	Empty
7	Car	Subaru	XT-60711	1.5	5	~
8	Car	Opal	CSF 709	1.5	5	~
9	Car	Saab	NWD 465	1.5	5	~
10	Lorry	Scania	AG 565	25	18	~
11	Car	Ford Sierra	LHY 240	1.5	5	~
12	Car	Pontiac	CKA 102	1.5	5	~
13	Car	VOLVO	DZL 988	1.5	5	~
14	Truck + Trailer	VOLVO	HFT 939	23	19	Furniture
15	Car	Mercedes	Waf-BJ 748	1.5	5	~
16	Car	Mitsubishi	703 AFU	1.5	5	~
17	Car	Lada	493 AFU	1.5	5	~
18	Lorry	Scania	AL 65	27	20	Textiles
19	Minibus	Mercedes	PD 3499	3	6	~
20	Bus	VOLVO	912 ABO	15	12	~
21	Truck + Trailer	Scania	DDG 182	16	16	Generals
22	Minibus	Mercedes	LDC 100	3	6	~
23	Car	Moskvitch	743 HEV	1.5	5	~
24	Bus	VOLVO	XJB 943	15	12	~
25	Lorry	VOLVO	GVD 695	25	18	~
26	Minibus	Ford	MRP 794	3	6	~
27	Car	VOLVO	NHC 180	1.5	5	~
28	Truck + Trailer	Scania	EPG 355	50	24	Timber
29	Car	VOLVO	TPH 846 ?	1.5	5	~
30	Truck + Trailer	VOLVO	OER 669	47	24	Flooring
31	Lorry	VOLVO	250 AUN	7	9	Empty
32	Minibus	VW	ASR 263	3	6	~
33	Truck + Trailer	VOLVO	MOV 996	55	24	Lumber
34	Truck + Trailer	Scania	801 ABV	21	16	Generals
35	Lorry	VOLVO	125 TAU	12	10	Generals
36	Truck + Trailer	VOLVO	GJO 121	32	18	Generals
37	Car	VOLVO	PUH 662	1.5	5	~
38	Car	VW	PVY 215 ?	1.5	5	~

Ser. No.	Type	Maker	Reg. No	mass	LM	Type of Cargo
39	Truck + Trailer	VOLVO	CSJ 052	28	21	Textiles
40	Car	Dodge	289 AFR	1.5	5	~
41	Truck + Trailer	Scania	NRY 806	22	18	???
42	Truck + Trailer	Scania	AKC 153	54	24	Boards
43	Car	VOLVO	CWD 853	1.5	5	~
44	Car	Ford Sierra	ERS 519	1.5	5	~
45	Car	VOLVO	EXE 276	1.5	5	~
46	Car	Mercedes	SLS 151	1.5	5	~
47	Minibus	Iveco	CVK 445	3	6	~
48	Minibus	VW	679 AAG	3	6	~
49	Lorry	VOLVO	020 GAD	9	9	Loaded
50	Truck + Trailer	DAF	688 GAD	36	18	Timber
51	Truck + Trailer	VOLVO	533 EEV	28	15	Generals
52	Lorry	Scania	183 RAJ	10	10	Textiles
53	Lorry	VOLVO	417 EEE	11	10	Generals
54	Minibus	Toyota	ODT 471	3	6	~
55	Truck + Trailer	VOLVO	NLT 251	29	15	Fish Frozen
56	Truck + Trailer	Scania	AA 65	27	20	Textiles
57	Car	VOLVO	110 AET	1.5	5	~
58	Car	Saab	FAU 388	1.5	5	~
59	Minibus	VW	979 AFN	3	6	~
60	Car	Mercedes	NTX 278	1.5	5	~
61	Trailer	~	CXW 384	29	14	Polyethylene
62	Trailer	~	GXW 803	16	13	Generals
63	Trailer	~	GCU 777	30	14	Furniture
64	Trailer	~	PUE 652	19	14	Wooden Mat.
65	Truck + Trailer	~	GWD 695	50	24	Wood
66	Trailer	~	PGU 212	35	13	Chipboards
67	Trailer	~	398 BB	10	13	Generals
68	Trailer	~	PZS 089	31	13	Wood
69	Trailer	~	PMG 172	28	13	Furniture
70	Lorry	~	015 SAA	9	8	Textiles
71	Trailer	~	LFB 202	34	13	Star Redboard
72	Trailer	~	EOB 968	17	13	Generals
73	Truck + Trailer	~	AS 7312	18	16	Generals
74	Lorry	~	AEC 769	6	10	Empty
75	Lorry	~	890 SAC	9	10	Textiles
76	Truck + Trailer	~	116 AFT	19	16	Generals

8.5 Summary – Load Case Compilation

The following table gives an overview of the load case compilation used for the calculations in this thesis in the right column, and compares this to the compilation in the JAIC Final Report, middle column.

Table 8.2: Load case compilation and comparison to JAIC

Type	***JAIC***	***This Thesis***
Tank 10 – HFO (IFO 180)	250t	105t
Tank 11 – HFO (IFO 180)		105t
Daytank 36 – HFO (IFO 180)		25t
Settling Tank 38 – HFO (IFO 180)		20t
Tank 18 - MDO	35t	26t
Tank 41 - MDO		8t
Tank 20 - Gas oil	10t	10t
Tank 1 – Ballast Water	360t	173t
Tank 14 – Ballast Water		186t
Fresh Water	300t	***
Tank 4A – Fresh Water	***	55t
Tank 4B – Fresh Water		74t
Tank 5 – Fresh Water		144t
Tank 56 – Fresh Water		***
Tank 29 – Fresh Cool Water		***
Tank 17 – Fresh Water Circulation		***
Mass of Vehicle on Car Deck	1100t	1100t
Crew and Passenger, incl. Luggage	100t	100t
Miscellaneous liquids	50t	50t (TK19)
Pool	***	25t
Miscellaneous	95t	100t
Sum Deadweight	**2300t**	**2306t**
Light Ship Weight	**9750t**	**9733t**
Total Sum	***12050t***	***12039t***

9 Hydrostatic Investigation of Scenarios

The hydrostatic calculations carried out in this thesis shall give an overview of the influence of the ingress of water in different compartments on the list. This chapter, however, does not seek to answer the question of what caused the water ingress, but investigates what would be its consequences.

This chapter tries to find an answer how MV Estonia heeled that suddenly to about 30° like the witnesses stated in their testimonies. The slot of time for the development of that list is rather short – maybe one, two minutes or less. From the physics point of view it is only possible to eliminate the positive initial metacentric height via free surfaces. The principal lever arm curve of a progressive flooding can be seen in *Figure 9.1* (left). To get from the first to the second to the third equilibrium condition it will take some time and it will last too long for the sequence of heeling the witnesses stated. A typical chance of the lever arm curve from a stable floating condition to an elimination of the initial metacentric height is presented in *Figure 9.1* (right). By a certain amount of water on the Main Car Deck the change of the lever arm curve can be very quickly – via free surface. So in this chapter a scenario is looked for involving the elimination of the initial metacentric height, like the sketch on the right hand side indicated. – But other hydrostatic scenarios will be also investigated to ensure none is left out.

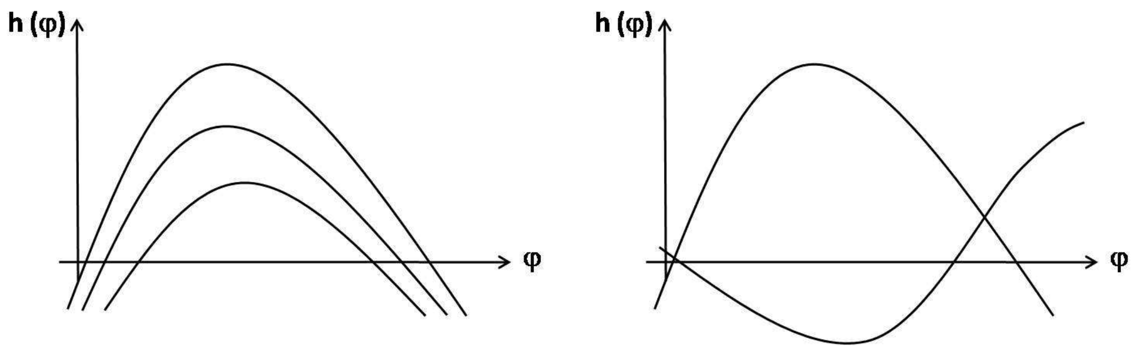


Figure 9.1: Principal change in lever arm curve of a progressive flooding (left) and the principal change in lever arm curve with the elimination of the initial metacentric height of a capsizing (right)

9.1 Overview and Approach

The way this thesis approaches the hydrostatic calculations is by selecting a probable sinking scenario or scenarios of MV Estonia via close examination of the testimonies. Several witnesses stated that they saw water on the Main Car Deck after the vessel had heeled heavily to starboard.

For each calculation step the momentary equilibrium floating condition is calculated by the added mass method. According to the determined inflow rates of a flooded compartment or group of compartments, the filling level of these compartments is determined, which results in an additional mass. During the calculation procedure, the fluid in the compartments is allowed to move freely, until a final equilibrium with respect to draft, trim and heel is reached. The calculation procedure is based on the algorithm ARCHIMEDES II originally developed by Soeding at the former "Institut für Schiffbau", Universität Hamburg, where additional algorithms have been programmed to handle large scale flooded compartments. The advantage of using this software package instead of commercially available code lies in the fact that the author has full access to the FORTRAN source code. This enables programming of additional features if required, and, if necessary, to directly check whether the computed equilibrium conditions have fully converged and are therefore realistic.

The fluid shifting moments related to these partially filled tanks are included in the determination of a hydrostatic stiffness matrix. Before the iteration of the equilibrium floating condition starts, the initial masses of all partially flooded or filled compartments are determined and the initial condition is treated like a fixed mass item in the load case weight data. During one step of the iteration, the filling levels of all partially filled compartments are computed, based on the momentary values of trim and heel. For these momentary filling levels, which do lead to exactly the same masses in each compartment as the initial filling, the fluid shifting moments with respect to all three coordinates x, y and z are determined and these fluid shifting moments are then summed up for all elements of the hydrostatic stiffness matrix. A three dimensional Newton-Iteration which starts with guessed initial values for draft, trim and heel is then used to find the equilibrium floating condition, which is defined by the difference between solid masses and moments and hydrostatic masses and moments being close to zero (0.001m for draft, 1E-5rad for trim and 2E-5rad for heel). Once the equilibrium floating condition has been determined, the hydrostatic stiffness matrix is calculated for this floating condition - which is done by computing the derivatives of masses and moments to with respect to small alterations in draft, trim and heel in all relevant combinations. Whenever these derivatives are computed, all fluid shifting moments in all compartments are accurately accounted for. In a second step after the determination of the equilibrium floating condition, the righting levers are computed for a given heel - but on a free trimming basis where the fluid is also allowed to move freely in all partially filled tanks or compartments.

The first step is to consider the Main Car Deck in scenario No.1. For the hydrostatic calculation the Main Car Deck and all its inner doors are assumed to be watertight, i.e. water is not able to flow to the lower decks. In the calculation, the Main Car Deck is flooded and water is added in increasing steps. The calculations, which allow us to model the floating condition, include a consideration of the geometry of the Main Car Deck, developing free surfaces and all fluid shifting moments and coupling terms.

The scenarios No. 2 to No. 5 model a selected mass of water on the Main Car Deck including the above mentioned parameters with an additional consideration of cargo-shift - of the vehicles - on the Main Car Deck. For the hydrostatic calculations, the movement of the vehicles is carried out in 0.2 metre steps with a maximum shift of 4 metres to starboard. The maximum shift selected was 4m because it is considered unlikely that there could have been a larger shift, because the Main Car Deck was completely filled with vehicles and due to this the possible sliding ways short. These scenarios then look at the cargo-shift's effect on the list.

The scenarios No. 6 to No. 15 consider more than just the Main Car Deck as well. In these cases, water is modelled to be on both the Main Car Deck and in lower compartments, although the models are separate – i.e. they do not influence each other. Again, water is added stepwise, starting with smaller amount - 5t - with the amount added gradually increasing. Depending on the dimensions of the compartments, the calculated maximum mass of water is chosen to be appropriate to their sizes. For example, 250t of water was calculated to be in the Main & Auxiliary Engine Rooms.

Scenario 16 is a combination of the previous scenarios, with of water on Main Car Deck and on each of the previously considered six lower compartments.

Once again, the water is not allowed to flow between compartments. The total free surface area is comparably large and this has a detrimental effect on the stability of the vessel. The main intention is use this to show the range of steady list for various flooding levels.

Scenario 17 follows on from scenario 16, except now a cargo-shift of the vehicles on the Main Car Deck is also considered, with the maximum total centre of gravity (TCG) shift set to 4m. This is carried out to show the influence of both large free surfaces on several decks and a cargo shift of the vehicles on the Main Car Deck. These TCG shift calculations are carried out in the same way as in scenarios 2 to 5.

Once again: the maximum TCG shift value of 4m is most likely too large and it was calculated here to show a most extreme case.

Finally scenario 18 represents – from the hydrostatic point of view – the most likely scenario: a certain amount of water on the Main Car Deck with various amounts of water on Deck 0 and Deck 1, both generating large free surfaces, along with a consideration of the sliding vehicles on the Main Car Deck.

Table 9.1: The initial equilibrium floating condition of each scenario

```
+---------------------------+---------------------------+------------+
|Yard number:               |Ship name:                 |Date:       |
|590                        |Estonia                    |            |
+---------------------------+---------------------------+------------+
|Equilibrium Floating Condition of Case:                             |
|Shell Plating Factor:   1.007   |Density of Sea Water:   1.004 t/m3 |
|--------------------------------------------------------------------|
|For the determination of the floating condition, the VCG is         |
|corrected for all partly filled tanks according to the initial      |
|free surface moment as stated in the loadcase item tables below.    |
|--------------------------------------------------------------------|
|Equilibrium Floating Condition :                                    |
|Ships Weight                              :  12038.974 t            |
|Longit. Centre of Gravity                 :     63.551 m.b.AP       |
|Transv. Centre of Gravity                 :     -0.026 m.f.CL       |
|Vertic. Centre of Gravity (Solid)         :     10.584 m.a.BL       |
|Free Surface Correction of V.C.G.         :      0.098 m            |
|Vertic. Centre of Gravity (Corrected)     :     10.683 m.a.BL       |
|Draft at A.P    (moulded)                 :      5.662 m            |
|Draft at LBP/2  (moulded)                 :      5.339 m            |
|Draft at F.P    (moulded)                 :      5.016 m            |
|Trim (pos. fwd)                           :     -0.647 m            |
|Heel (pos. stbd)                          :      1.218 Deg.         |
|Volume (incl. Shell Plating)              :  11955.286 m3           |
|Longit. Centre of Buoyancy                :     63.515 m.b.AP       |
|Transv. Centre of Buoyancy                :     -0.192 m.f.CL       |
|Vertic. Centre of Buoyancy                :      2.897 m.a.BL       |
|Area of Waterline                         :   2812.723 m2           |
|Longit. Centre of Waterline               :     58.977 m.b.AP       |
|Transv. Centre of Waterline               :     -0.304 m.f.CL       |
|Metacentric Height                        :      1.229 m            |
|--------------------------------------------------------------------|
|Righting Arm Calculation :                                          |
|                                                                    |
|Trim chosen from Equilibrium condition.                             |
| Draft   |  Trim   |  Heel   | Lever   |                            |
| m.a.BL  |   m     | Degree  |   m     |                            |
|    5.342|  -0.654|    0.001|  -0.026|                             |
|    5.296|  -0.549|    5.000|   0.086|                             |
|    5.167|  -0.335|   10.000|   0.226|                             |
|    5.093|  -0.256|   12.000|   0.291|                             |
|    4.963|  -0.148|   15.000|   0.392|                             |
|    4.693|   0.021|   20.000|   0.569|                             |
|    4.354|   0.179|   25.000|   0.745|                             |
|    3.931|   0.322|   30.000|   0.890|                             |
|    3.406|   0.447|   35.000|   0.974|                             |
|    2.782|   0.551|   40.000|   1.021|                             |
|    2.070|   0.649|   45.000|   1.047|                             |
|    1.278|   0.749|   50.000|   1.074|                             |
|    0.405|   0.855|   55.000|   1.134|                             |
|   -0.557|   0.962|   60.000|   1.261|                             |
|   -2.772|   1.232|   70.000|   1.838|                             |
|   -5.094|   1.398|   80.000|   2.335|                             |
|   -7.383|   1.534|   89.500|   3.008|                             |
+--------------------------------------------------------------------+
```

9.2 Conclusions from the Hydrostatic Calculations

In scenario 1, where the Main Car Deck is filled with water, but the rest of the compartments are entirely watertight, the list of MV Estonia increases nearly linearly to a list of 50° - corresponding to 3000t of water being taken on, and then to about 55° at an amount of 7000t. After that, the list starts to decrease.

The scenarios 2 to 5 deal with a cargo shift on the Main Car Deck. There is confusion in the testimonies on whether any vehicles were strapped down, or whether this treatment was reserved only for trucks. Of course these calculated magnitudes of displacement are likely much larger than what actually took place, but these calculations show that cargo shift leads to a significant effect on the list. Even though the amount of water on the Main Car Deck varies, the value of the gradient is nearly constant, as in the following figure:

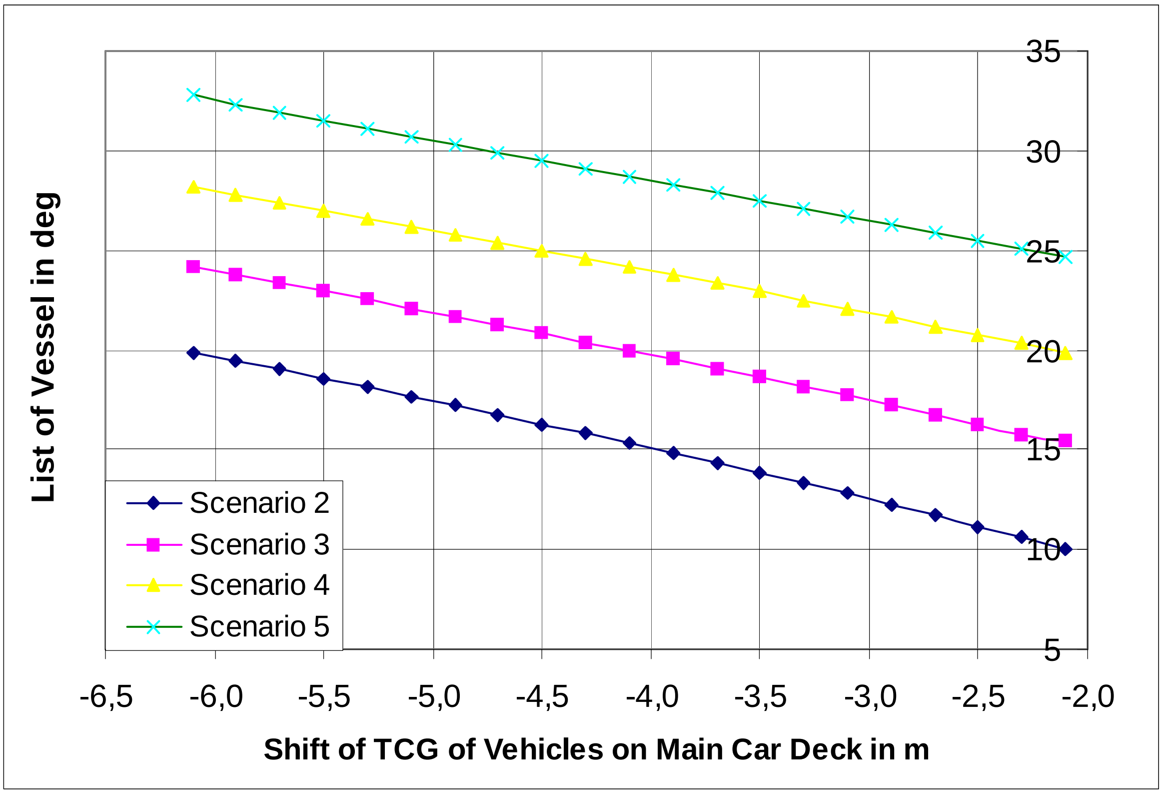


Figure 9.2: Comparison of scenarios 2 to 5 concerning the list and cargo shift.

Because of this, the cargo shift due to list can be estimated quite accurately, which eases the selection of dynamic scenarios involving this parameter. The comparison of the scenarios 6 to 15 also indicates a well-behaved relationship.

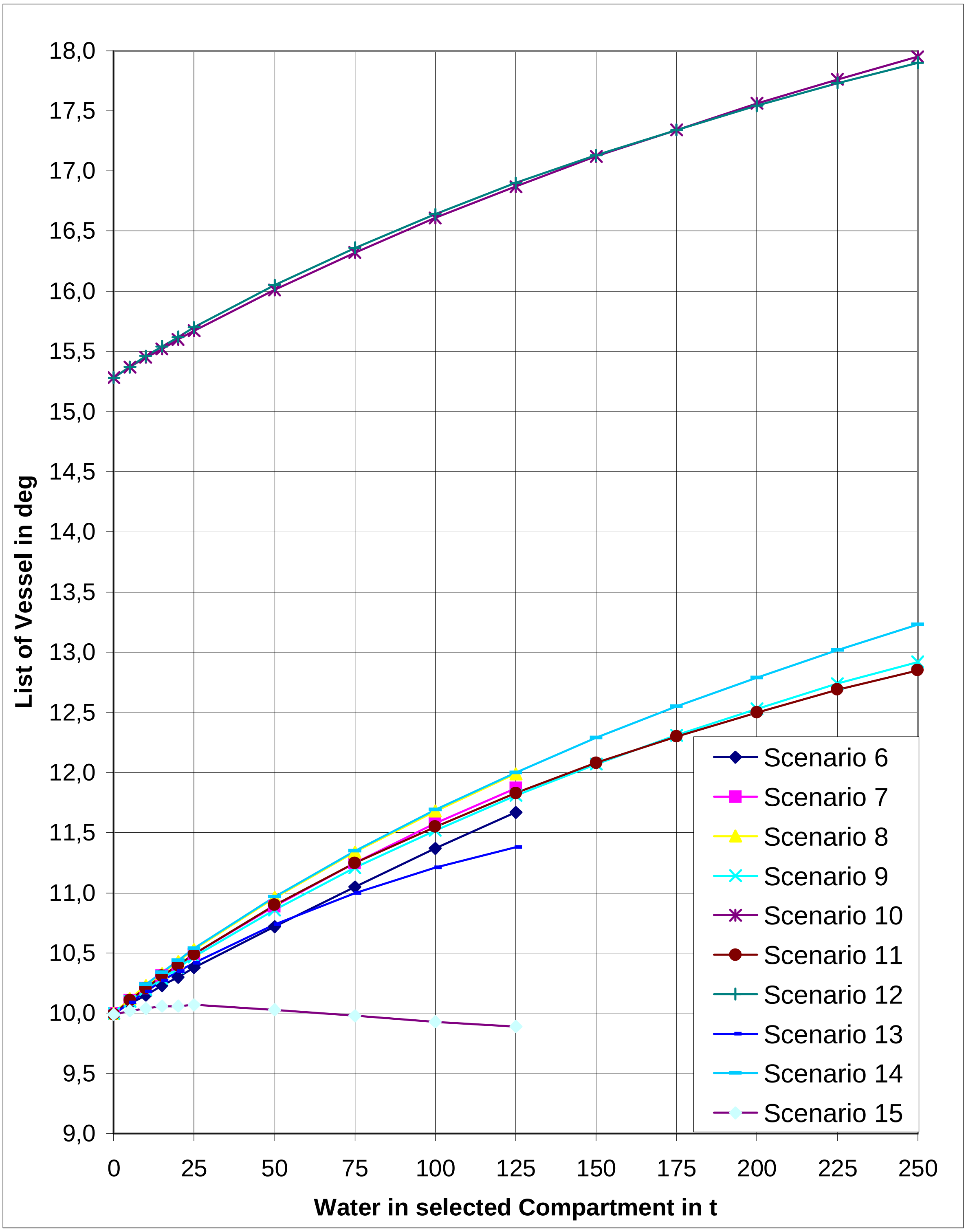


Figure 9.3: Comparison of scenarios 6 to 15 concerning list and the mass of water in selected compartments.

The gradient at small heeling angles is as expected to be larger than at large angles. The only exception to this behaviour is when considering the Sauna Room on the Tank Deck, Frame 110 to 120 – scenario 15. This room is less than 4m wide about the Centre Line and due to this the lever arm of the fluid shifting moments is short, which is compounded by a small free surface. These both mean that this compartment only influences the ship's stability in a minor way. The main contributor to the stability of the vessel is the amount of water on the Main Car Deck, see *Figure 9.3*:

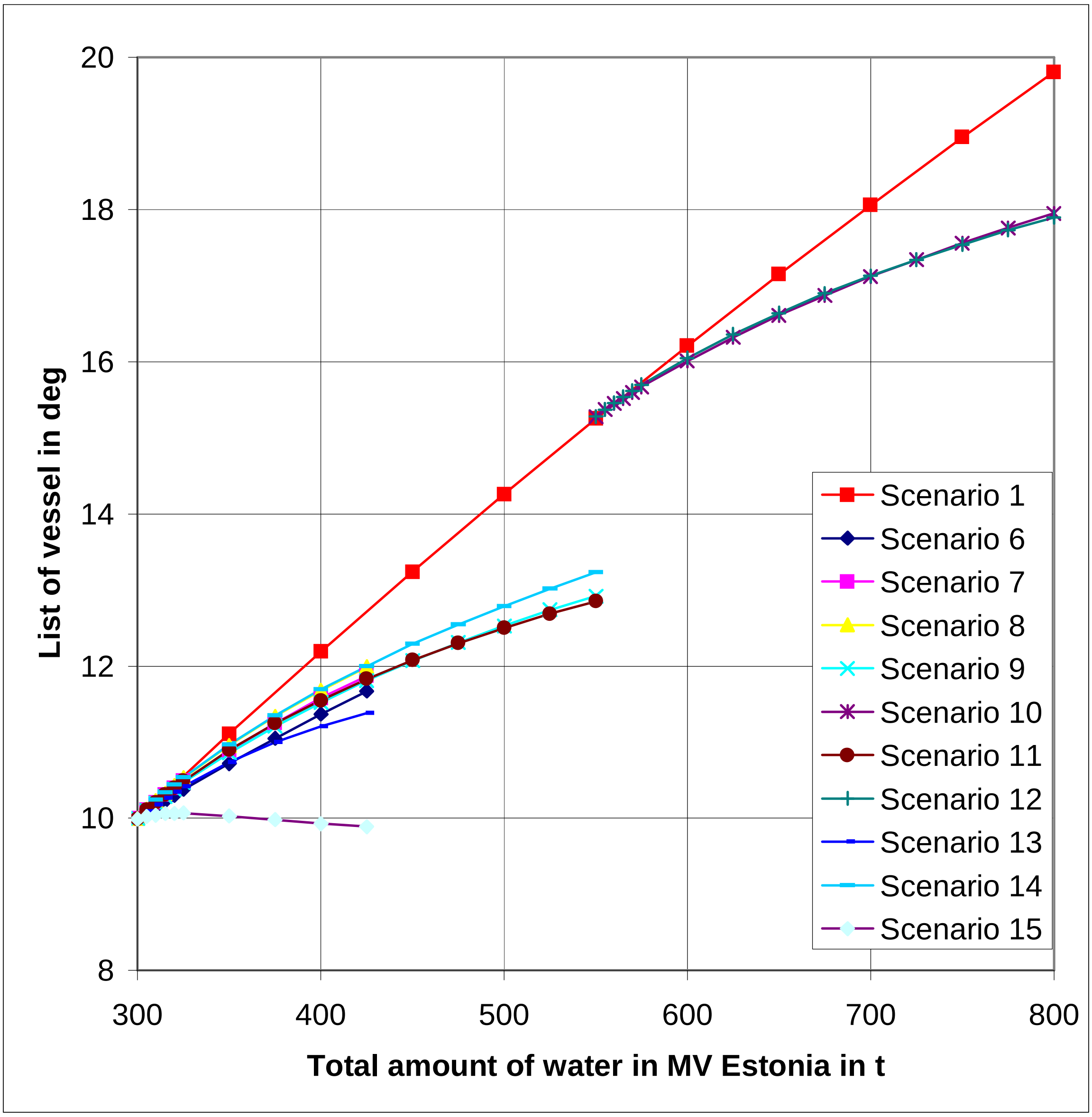


Figure 9.4: Overview of different amounts of water in various compartments leading to hydrostatic list

Some compartments below the Main Car Deck are not considered. Two examples are given, along with why. The first is the Stern Tube / Store Room on the Tank Deck at the stern of the ship. This room was only infrequently accessed by the crew only, and the largest opening to that room is one watertight door leading to the KaMeWa-Room. As this door would in all probability have been closed it is very unlikely that a significant amount of water entered.

A similar situation is found on the Tank Deck at the Heeling Tanks, Frame r to 85. Once again the crew were the only ones with access, but rarely needed it. It is hence likely that the door was securely closed.

In modelling the disaster after the event, we can only say with certainty that the Main Car Deck received significant water ingress during the first half of the sinking sequence. Conversely, we can say that the Engine Control Room was unaffected during the first half of the sinking – as the doors were probably closed.

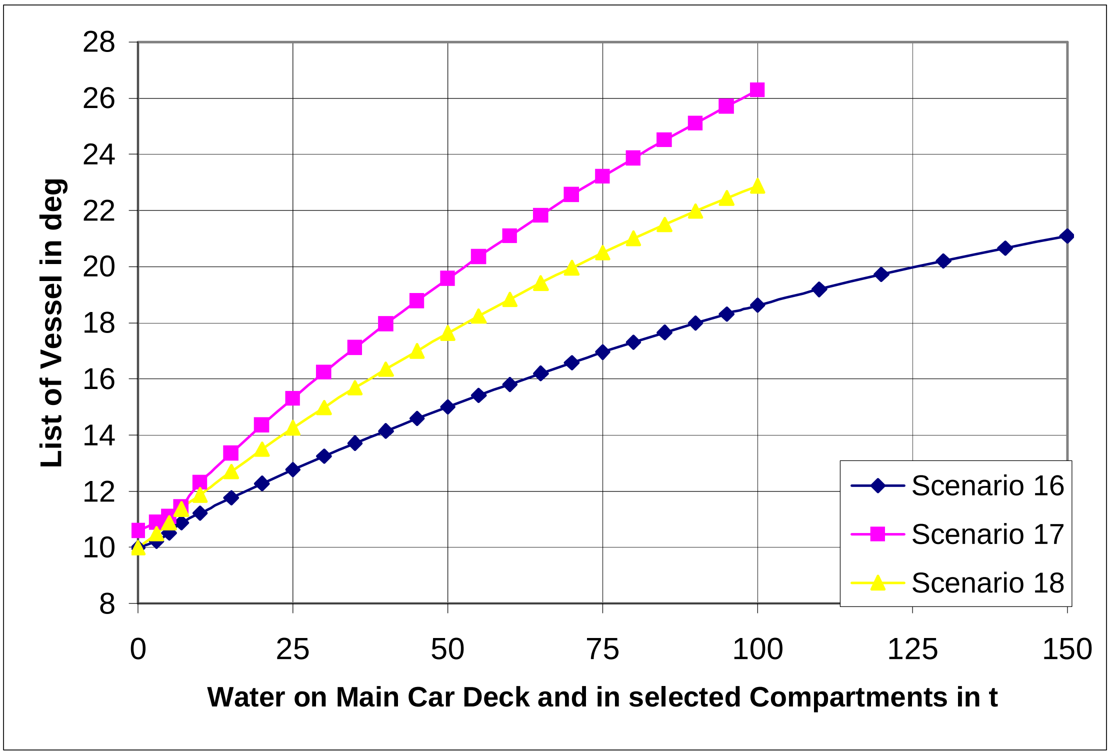


Figure 9.5: Comparison of list in scenarios 16 to 18.

Figure 9.4 shows the trim of the vessel against the amount of water in the scenarios 16, 17 and 18. By this graph it can be shown that MV Estonia sank stern first in this model, as is stated by most witnesses.

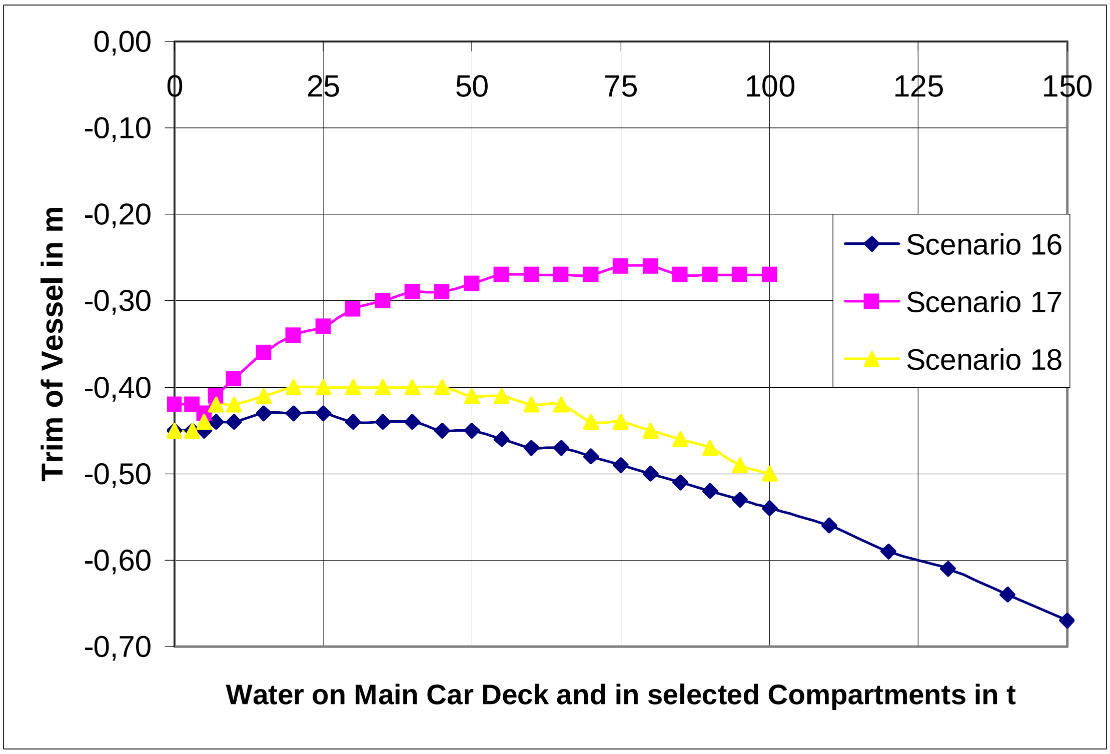


Figure 9.6: Comparison of the trim of the vessel in scenarios 16 to 18

More detailed results of these calculations of the equilibrium floating conditions can be found in [KEH01].

The largest heeling angle with the smallest amount of water is the scenario water on Main Car Deck only. Caused by the Centre Casing the first inflow of water is divided in an amount of water on the starboard side an on the port side, as presented in *Figure 9.6*. Although there are free surfaces, it will take a moment till the water flows to one side of the vessel and with it the list develops. For example: 800t[6] water would flow on the Main Car Deck and the water and will be divided by the Centre Casing to 400t of

[6] In Chapter 10 it will be presented that max. inflow of about 800t per minute on the Main Car Deck was simulated.

water on each side of the Centre Casing. Is this situation kept in hydrostatics, it will lead to the lever arm curve given in *Figure 9.7.* with a comparable low heeling angle. But this situation will last very shortly.

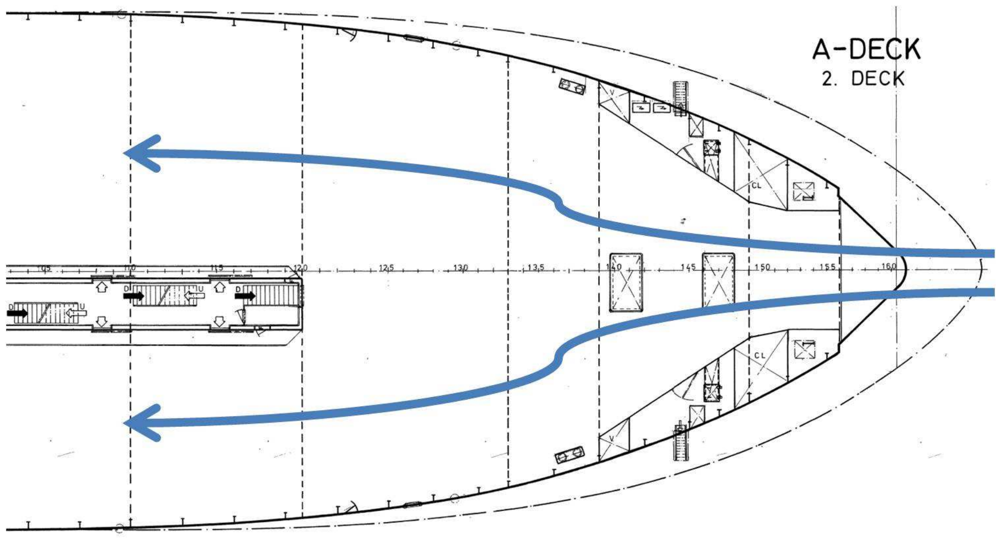


Figure 9.7: First inflow of water on the Main Car Deck divided by the Centre Casing

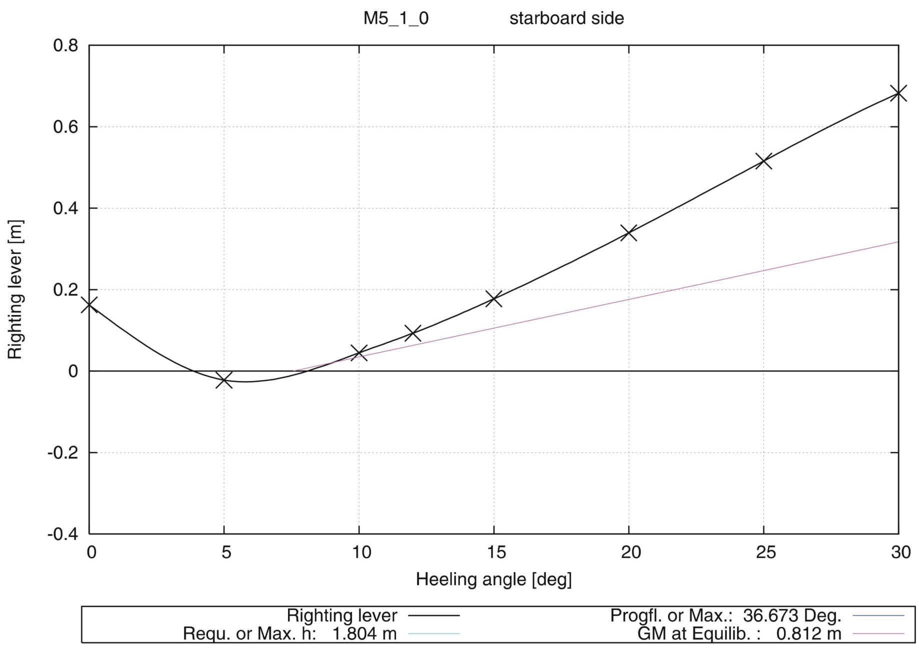


Figure 9.8: Lever arm curve of 800t water on Main Car Deck: 400t water on each side of the Centre Casing

The very short period of time later, the water will accumulate on one side of the vessel and the lever arm curve will be completely different, as shown in *Figure 9.8*.

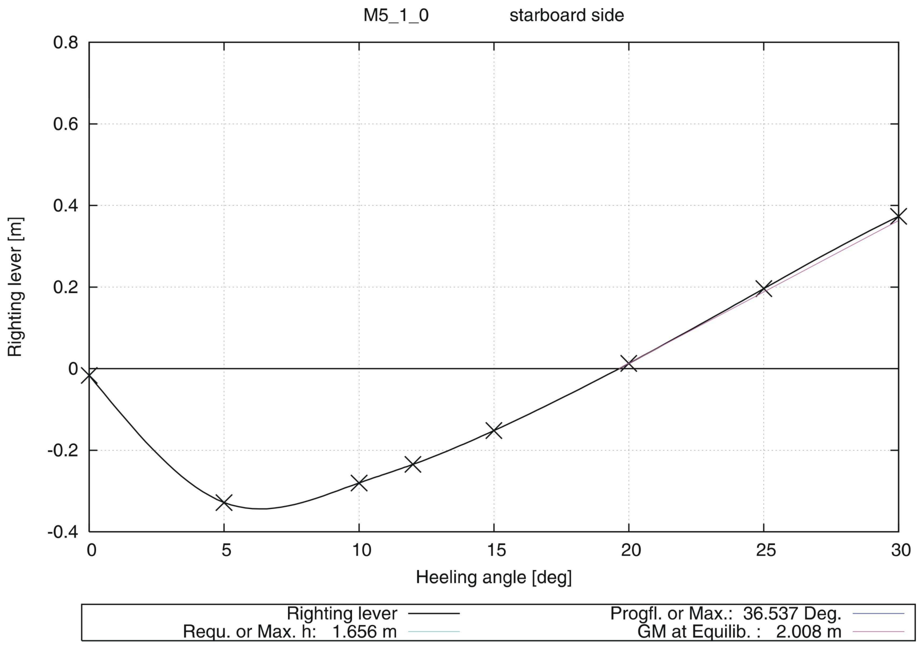


Figure 9.9: 800t of water on the Main Car Deck, but accumulated on the starboard side only

This explains the sudden development of the list of MV Estonia, as the witnesses stated in their testimonies congruently. And they stated also that the sudden and large heel connected to time to the two or three metallic bangs. It seems to be very reasonable that a large amount of water on the Main Car Deck caused the sudden heeling. Water on the Main Car Deck is in focus of the following investigations: How could have had the water entered the Main Car Deck? What were possible amounts of water to enter Main Car Deck? How did the waves influence the water flushing on the Main Car Deck?

The 18 investigated scenarios are exposed on the following pages of this chapter and the retain of water behind Centre Casing is explained in more detail in Chapter 10.

9.3 Scenarios in Detail

Scenario 1

In scenario No.1, the investigation is focused on the heeling behaviour with water on Main Car Deck - Deck 4. An initial heel is assumed at 1.22° to starboard, as a heel of 1° to 3° is mentioned in several testimonies. The calculation is carried out with the amount of water on the Main Car Deck going up in 50t steps from 0t up to 2000t, in 100t steps to 3000t. Further calculations can be found in the Supplementum. In these calculations the Main Car Deck is assumed to be closed and watertight.

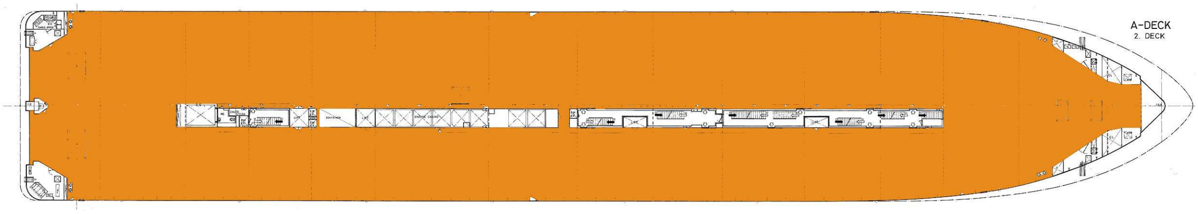


Figure 9.10: Scenario 1 – compartment under consideration

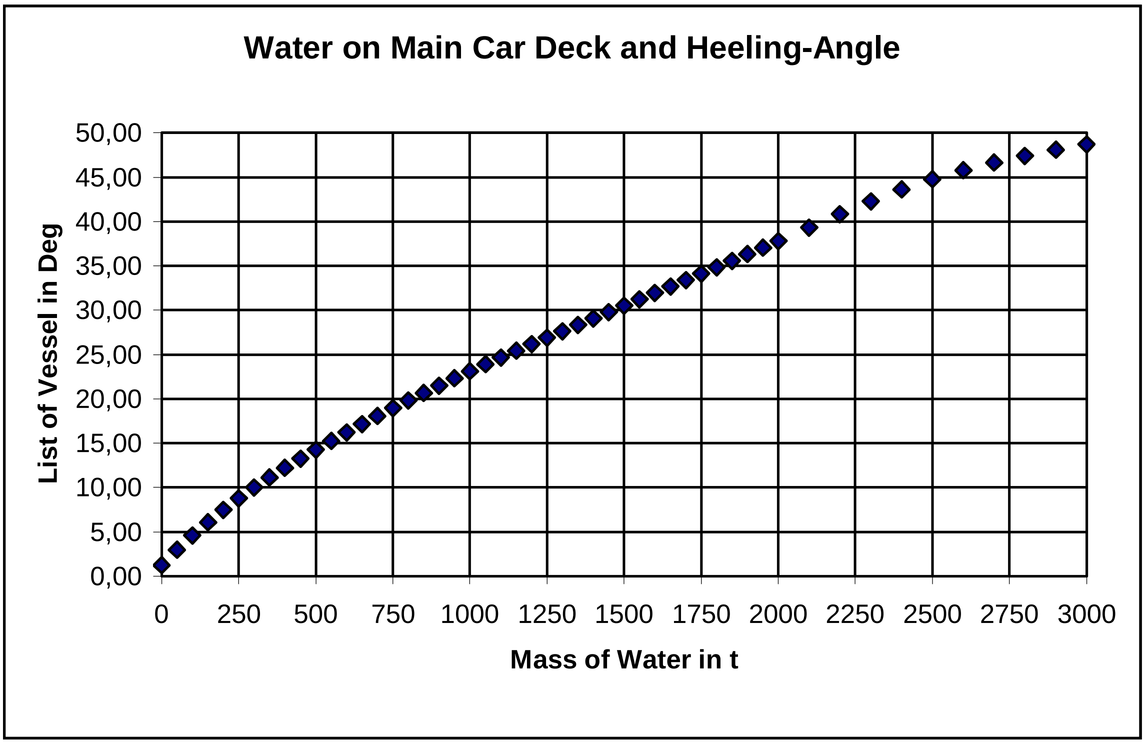


Figure 9.11: Water on Main Car Deck, Range up to 3000t, Mass over List. A stable equilibrium floating condition is reached in every calculation step.

Scenario 2

In scenario No.2, the amount of water on the Main Car Deck is set to 300t and kept constant during the whole calculation. The amount of 300t is chosen because 300t corresponds to a list of about 10°. At a list of 10°, a layman might feel uncomfortable or even concerned - with some objects with a low friction coefficient, like glasses on an smooth surface, starting to slide, as reported.

The transversal centre of gravity of the vehicles on Main Car Deck is moved in 0.2m steps from -2.1m from the centre line to starboard, up to -6.1m.

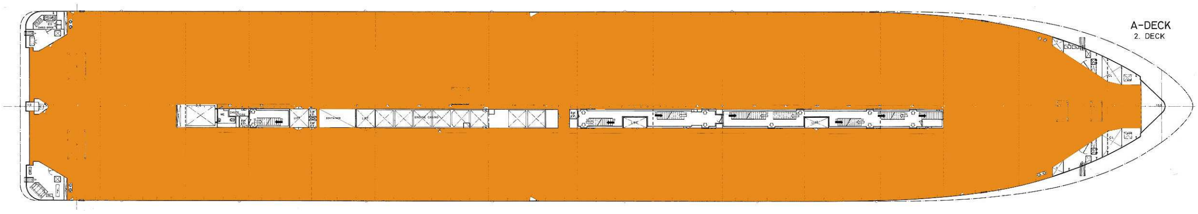


Figure 9.12: Scenario 2 – compartment under consideration

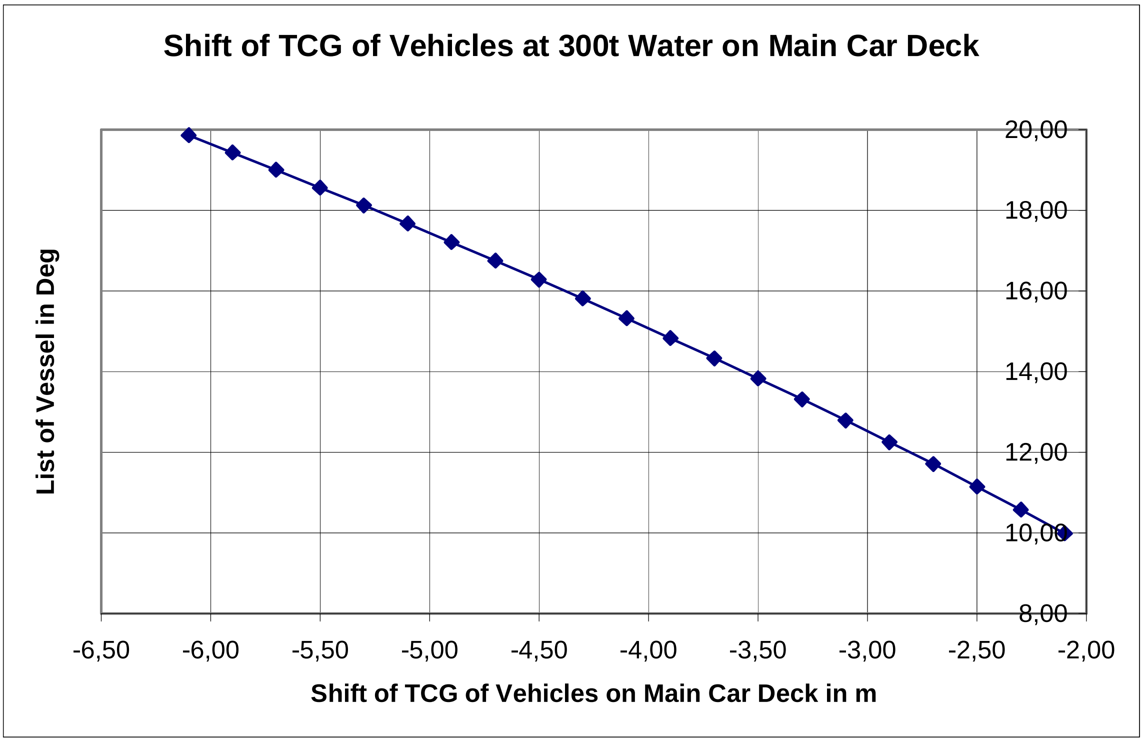


Figure 9.13: Shift of the TCG of vehicles, 300t water on Main Car Deck, shift over list

Scenario 3

Scenario 3 is identical to 2 except for the fact that 550t of water are modelled to be on the Main Car Deck, which are also kept constant throughout this calculation. The amount of 550t on the Main Car Deck corresponds to a list of about 15°.

The transversal centre of gravity of the vehicles on Main Car Deck is moved in 0.2m steps from -2.1m from the centre line to starboard, up to -6.1m.

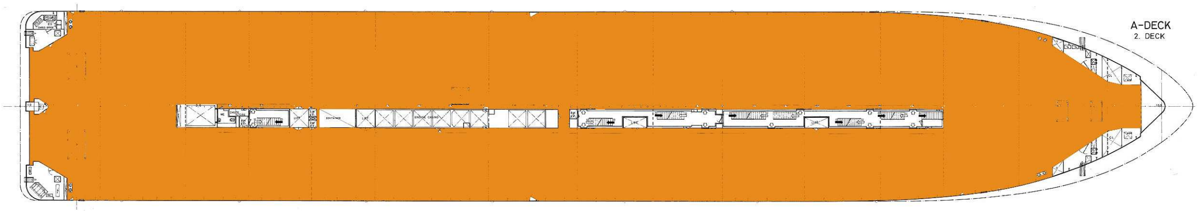


Figure 9.14: Scenario 3 – compartment under consideration

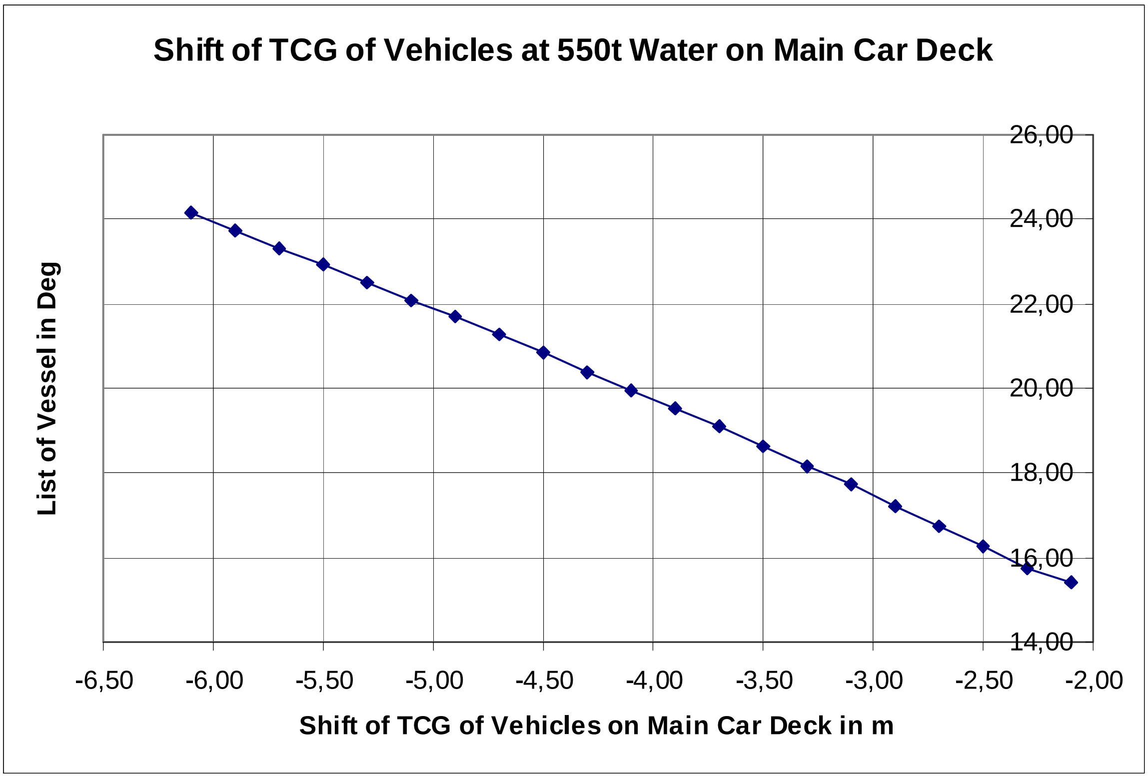


Figure 9.15: Shift of the TCG of vehicles, 550t water on Main Car Deck, shift over list

Scenario 4

Scenario 4 is again identical to 2 except for the fact that 800t of water are modelled to be on the Main Car Deck, kept constant throughout this calculation. The amount of 800t water on the Main Car Deck corresponds to a list of about 20°.

The transversal centre of gravity of the vehicles on Main Car Deck is moved in 0.2m steps from -2.1m from the centre line to starboard, up to -6.1m.

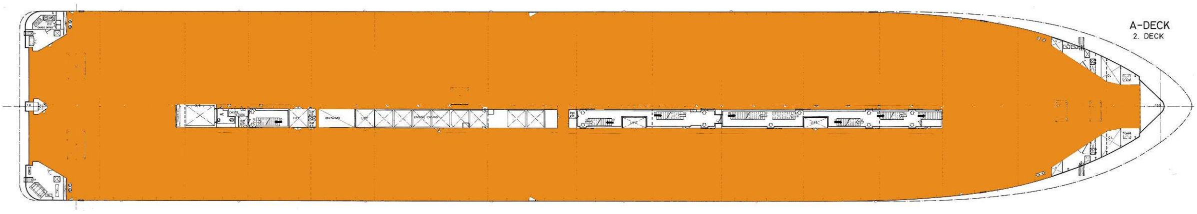


Figure 9.16: Scenario 4 – compartment under consideration

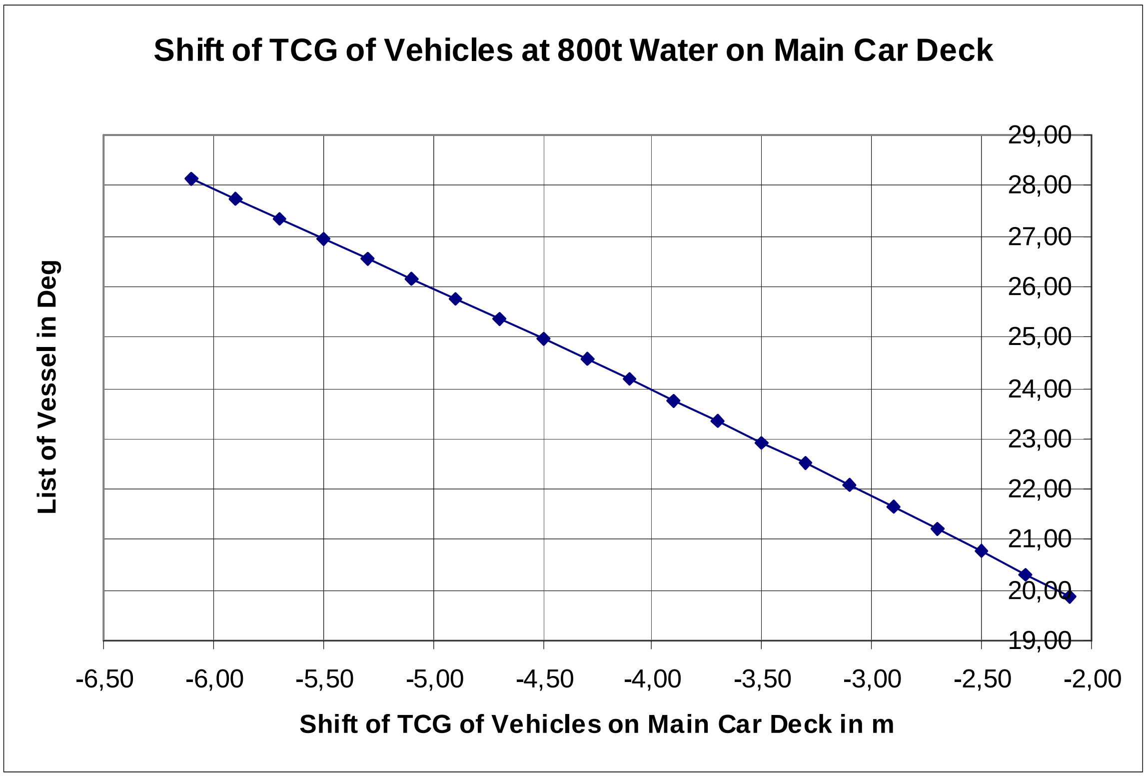


Figure 9.17: Shift of the TCG of Vehicles, 800t water on Main Car Deck, shift over list

Scenario 5

Scenario 5 is identical to 2 except for the fact that 1100t of water is modelled to be on the Main Car Deck, which are kept constant throughout this calculation. The amount of 1100t water on the Main Car Deck corresponds to a list of about 25°.

The transversal centre of gravity of the vehicles on Main Car Deck is moved in 0.2m steps from -2.1m from the centre line to starboard, up to -6.1m.

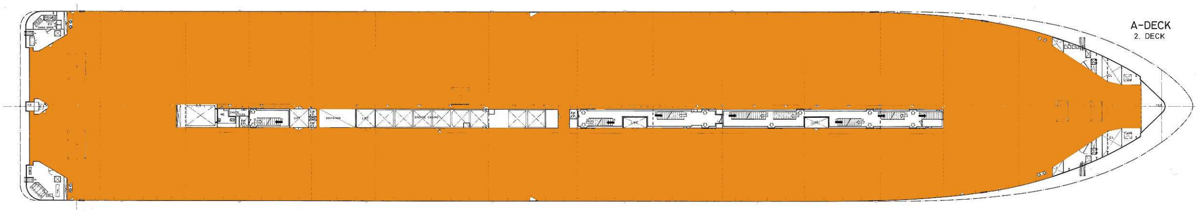


Figure 9.18: Scenario 5 – compartment under consideration

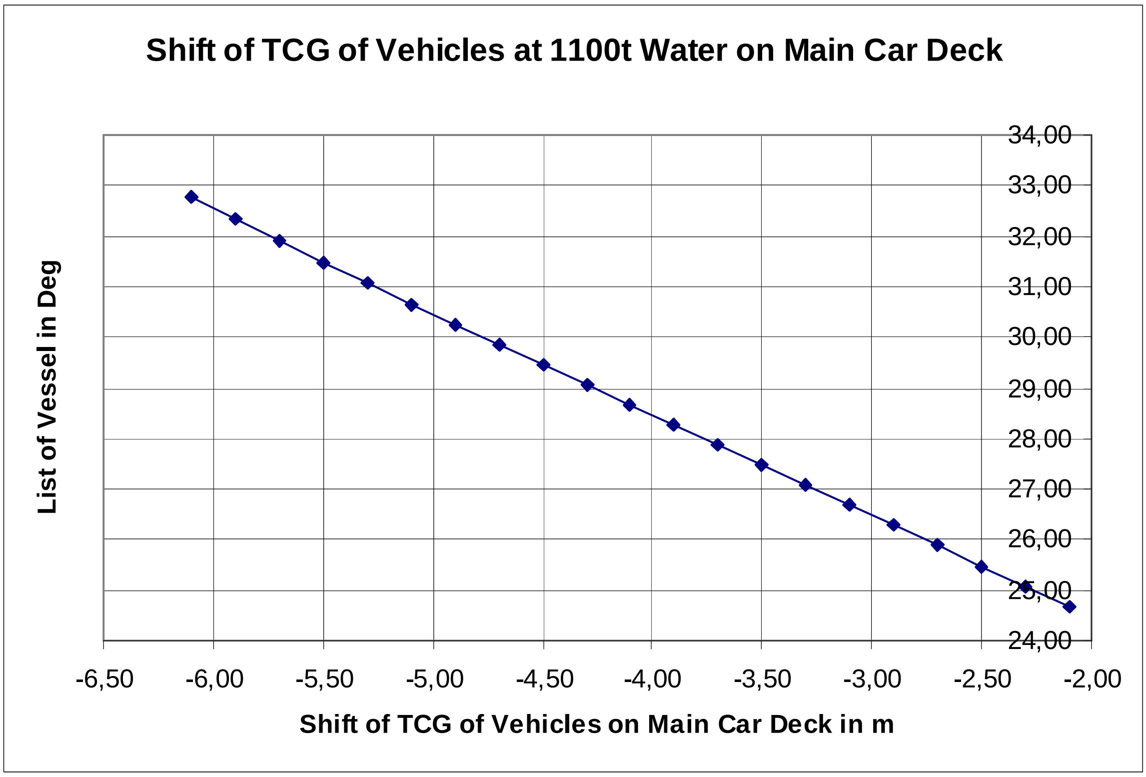


Figure 9.19: Shift of the TCG of Vehicles, 1100t water on Main Car Deck, shift over list

Scenario 6

In Scenario 6 a mass of 300t of water on the Main Car Deck is modelled and this mass is kept constant. In addition to the water on the Main Car Deck water is modelled also to be in a lower compartment, the Steering Gear Room, which starts in frame –3, and the store of Tween Deck, beginning at frame 5. The calculation is carried out with the mass of water in these compartments increasing in 5t steps up to 25t and then in 25t steps to 125t.

In order for this scenario to take place, the water may enter the considered compartment by the cargo lift, beginning at frame 23. The TCG of vehicles on Main Car Deck is kept fixed at –2.1m.

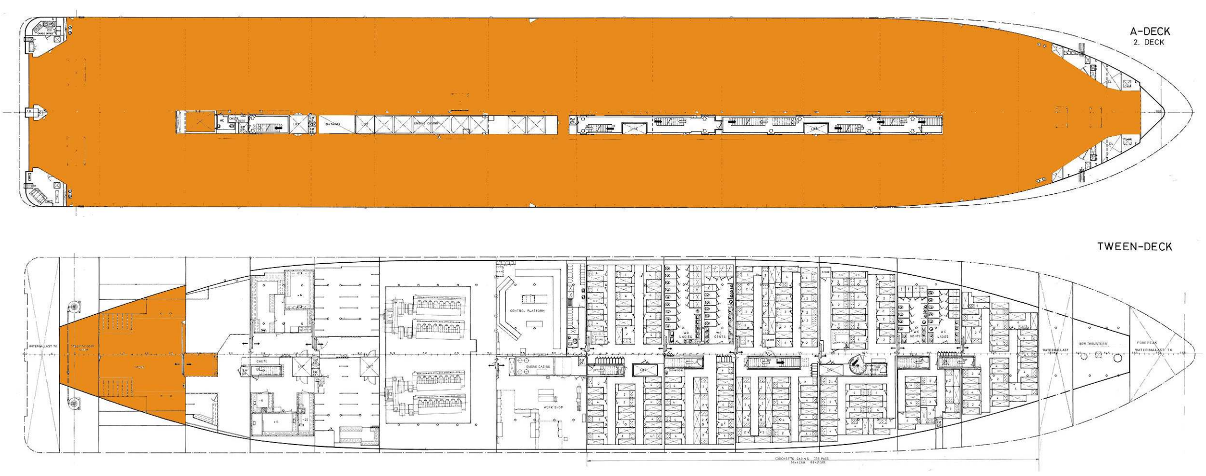


Figure 9.20: Scenario 6 – compartments under consideration

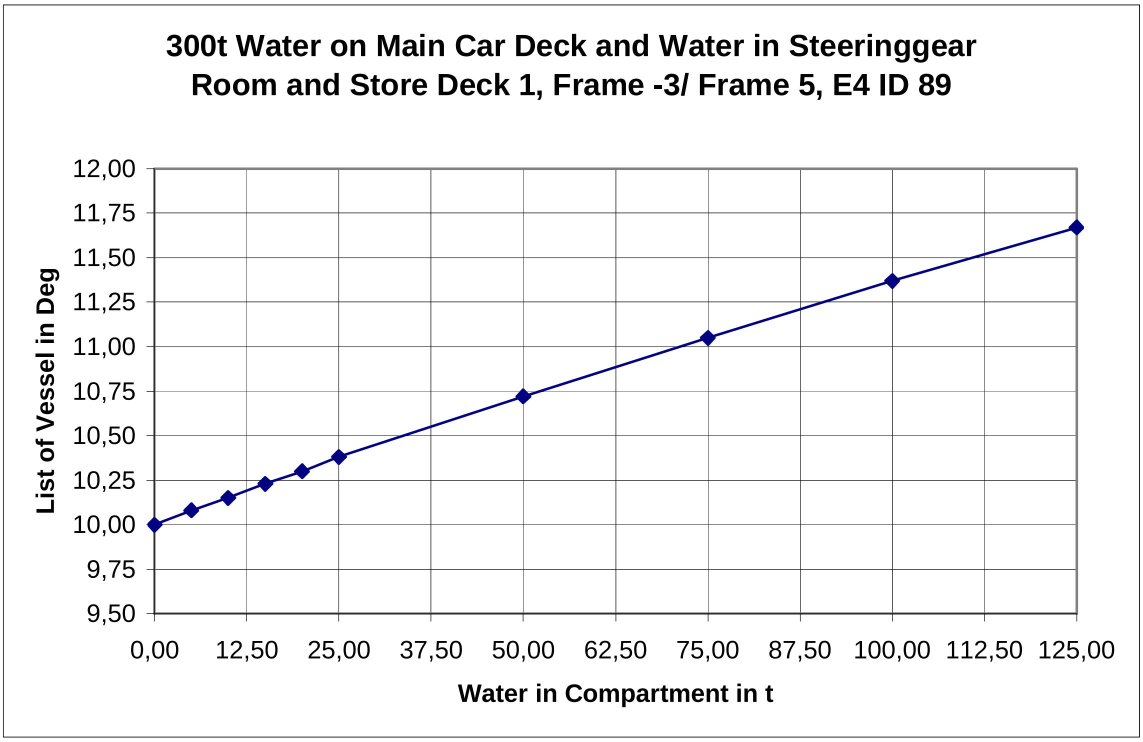


Figure 9.21: Water in compartment 89 and 300t water on Main Car Deck, mass over list

Scenario 7

Scenario 7 is quite similar to scenario 6, with the compartment under consideration now being the store, beginning at frame 33, ending at frame 43. Again, a mass of 300t of water on Main Car Deck is modelled and this mass is kept constant. The calculation is carried out with the amount of water in the store increasing in 5t steps up to 25t and then in 25t steps to 125t of water, as in scenario 6.

In order for this scenario to take place, water may enter the compartment by the lift beginning at frame 39.5. The TCG of vehicles on Main Car Deck is kept fixed at –2.1m.

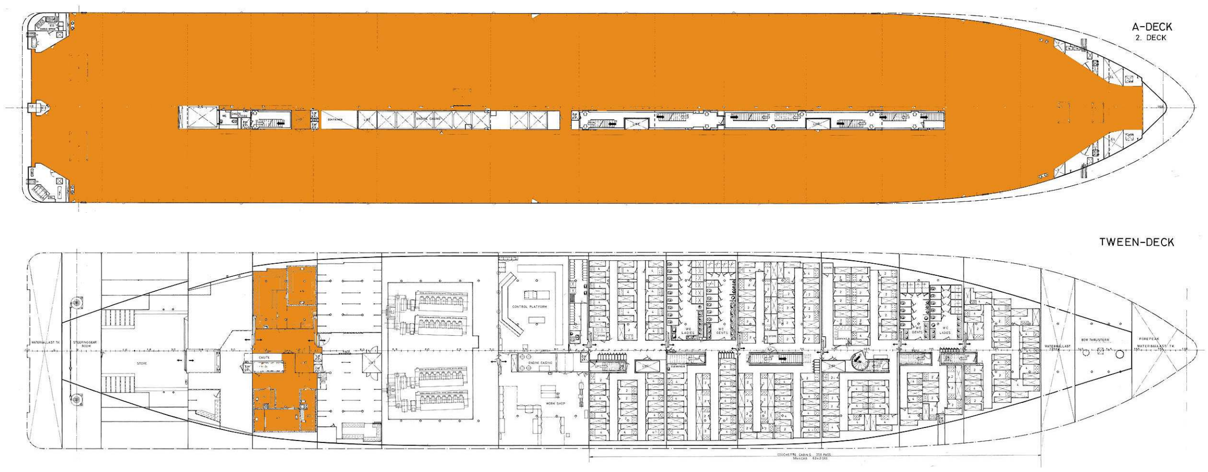


Figure 9.22: Scenario 7 – compartments under consideration

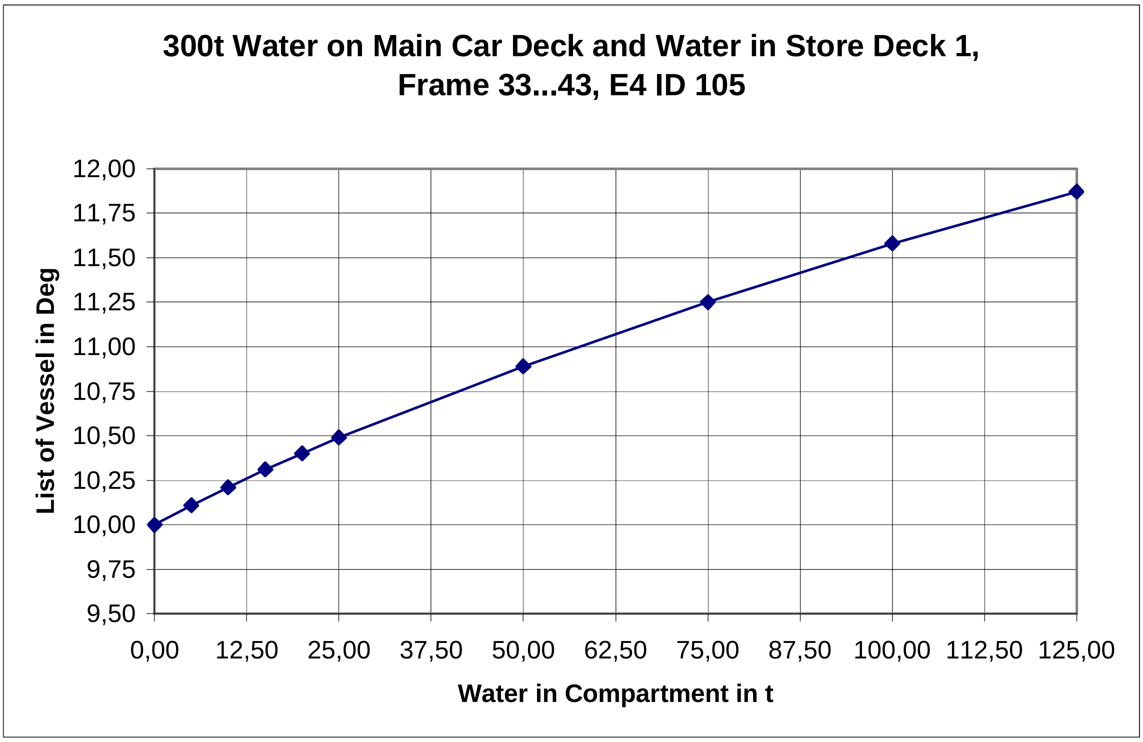


Figure 9.23: Water in compartment 105 and 300t water on Main Car Deck, mass over list

Scenario 8

Scenario 8 is again similar to scenario 6 – a mass of 300t of water on Main Car Deck is assumed and this mass is kept constant.. The compartment under consideration is the store, beginning in frame 43, ending at frame 53 with the amount of water in the store increasing in 5t steps up to 25t and then in 25t steps to 125t of water, as in scenario 6. In order for this scenario to take place, water may enter the compartment by the lift beginning at frame 50. The TCG of vehicles on Main Car Deck is kept fixed at –2.1m.

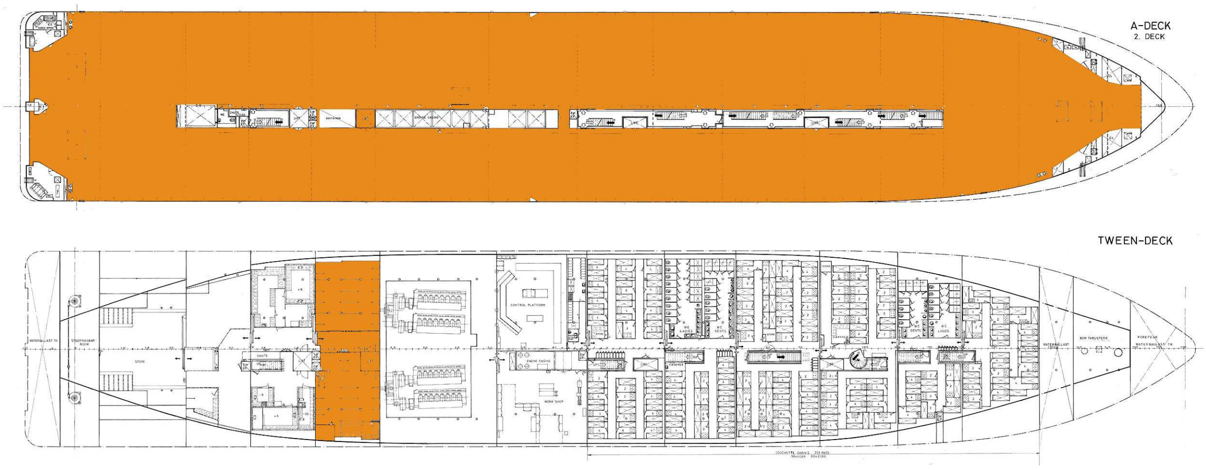


Figure 9.24: Scenario 8 – compartments under consideration

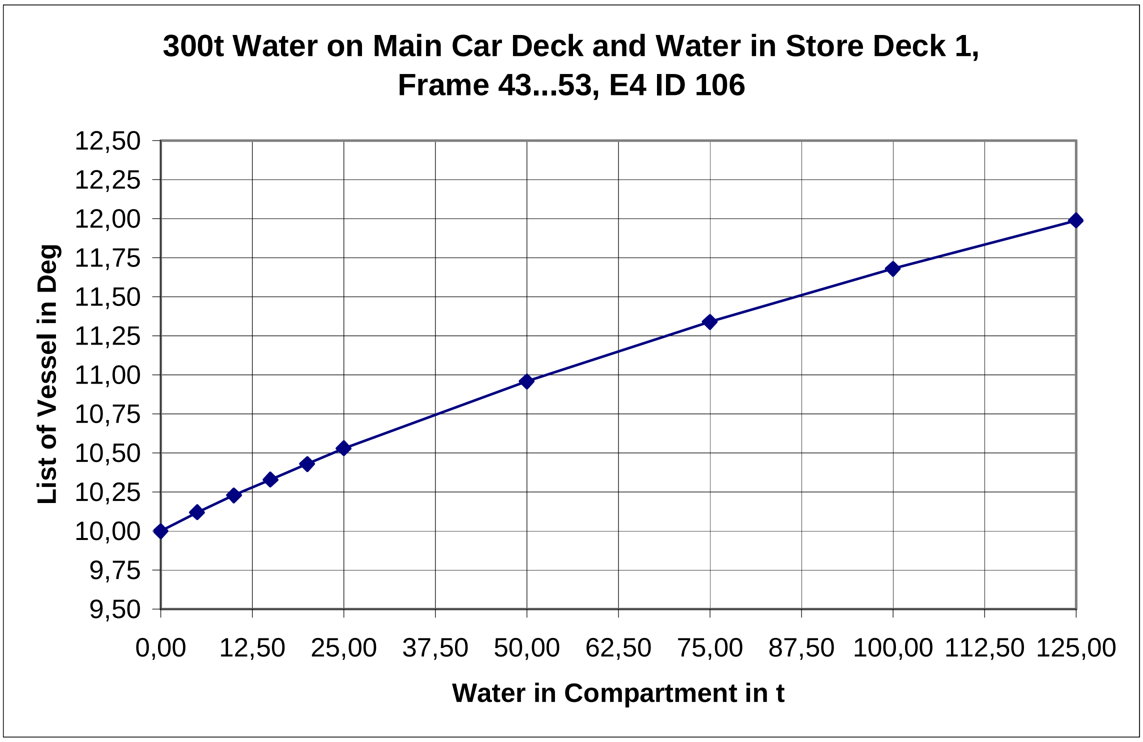


Figure 9.25: Water in compartment 106 and 300t water on Main Car Deck, mass over list

Scenario 9

In Scenario 9, a mass of 300t of water on Main Car Deck is assumed and this mass is kept constant. In addition to the water on Main Car Deck, the flooding of the Main Engine Room is considered. The calculation is carried out with the water in the Main Engine Room increasing in 5t steps up to 25t and then in 25t steps to 250t of water.

In this scenario, water enters the Main Engine Room through the air ducts. The TCG of vehicles on Main Car Deck is kept fixed at –2.1m.

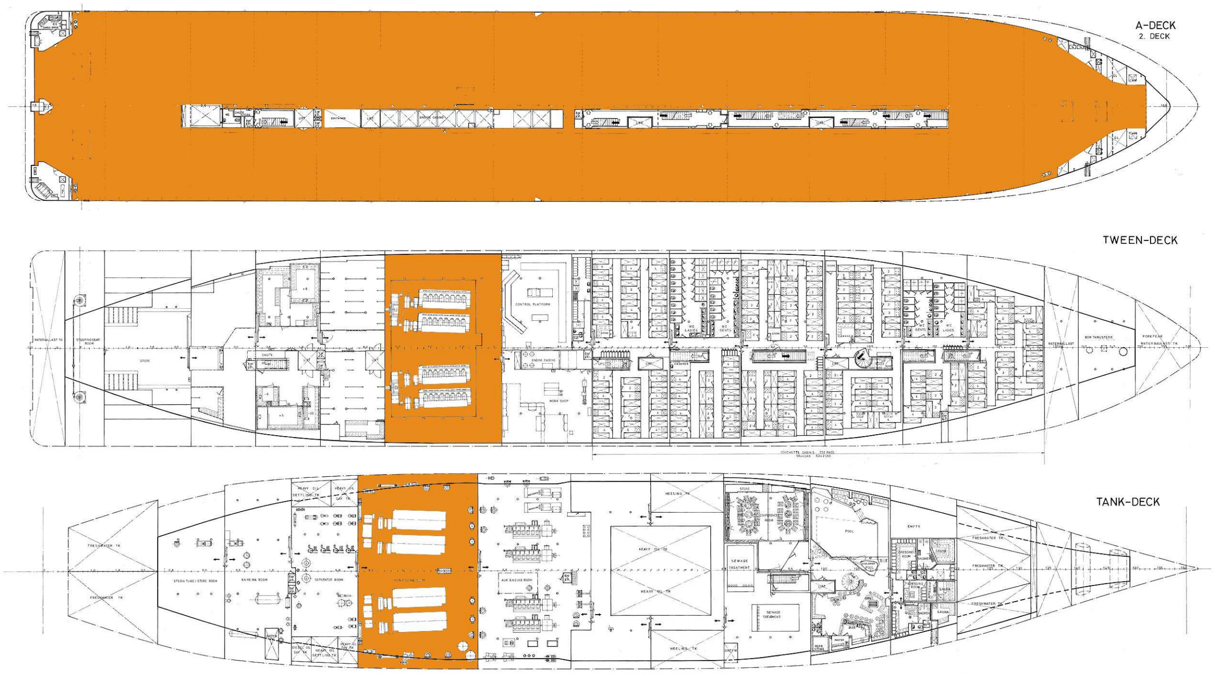


Figure 9.26: Scenario 9 – compartments under consideration

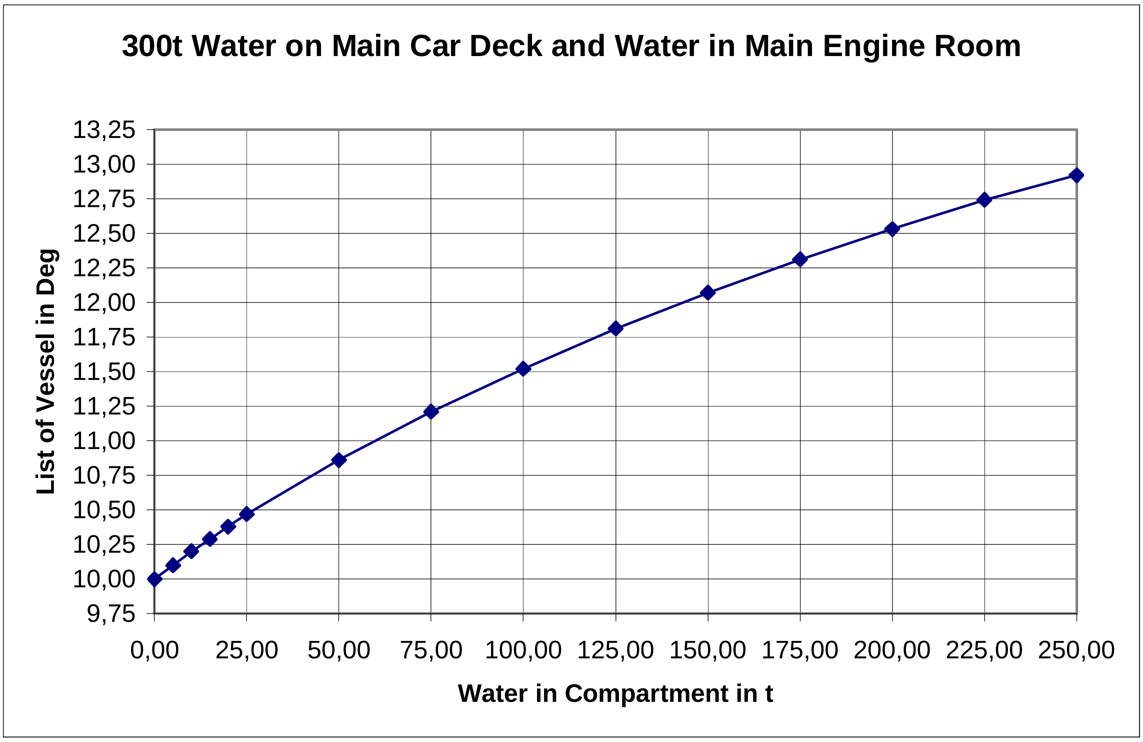


Figure 9.27: Water in Main Engine Room, 300t water on Main Car Deck, mass over list

Scenario 10

Scenario 10 is completely identical to scenario 9, except the amount of water on the Main Car Deck is 550t, and this mass is kept constant. In addition to the water on Main Car Deck, the flooding of the Main Engine Room is considered. The calculation is carried out with the water in the Main Engine Room increasing in 5t steps up to 25t and then in 25t steps to 250t of water.

In this scenario, water enters the Main Engine Room through the air ducts. The TCG of vehicles on Main Car Deck is kept fixed at –2.1m

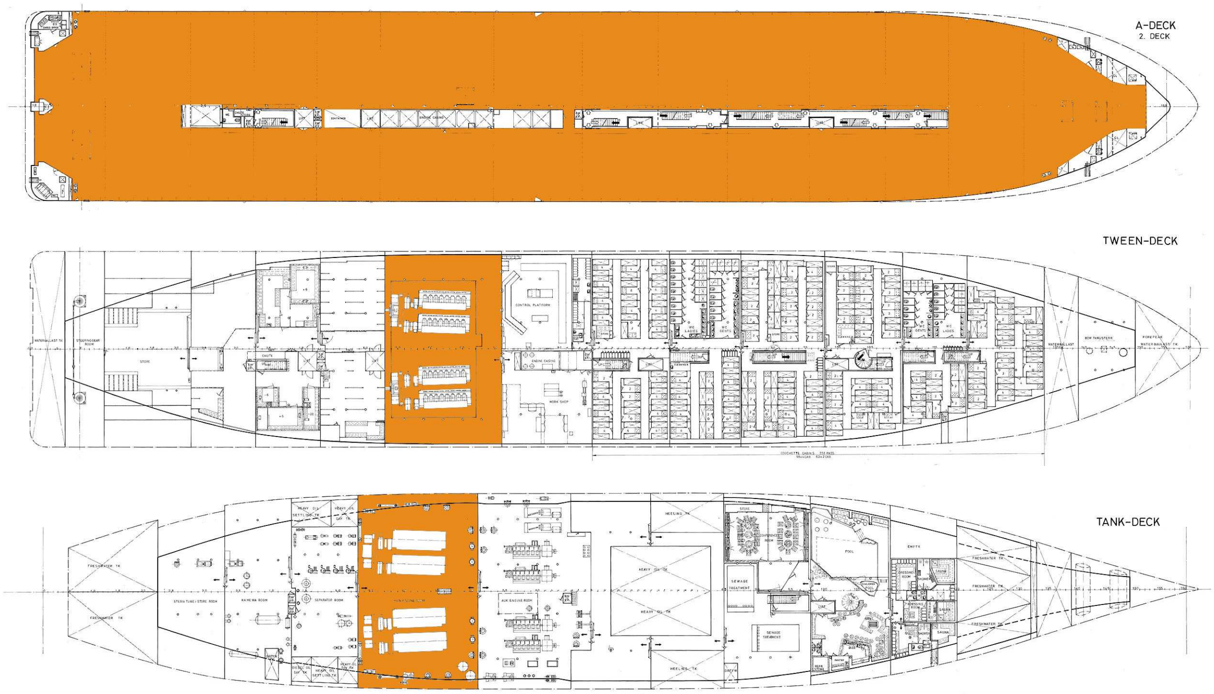


Figure 9.28: Scenario 10 – Compartments under consideration

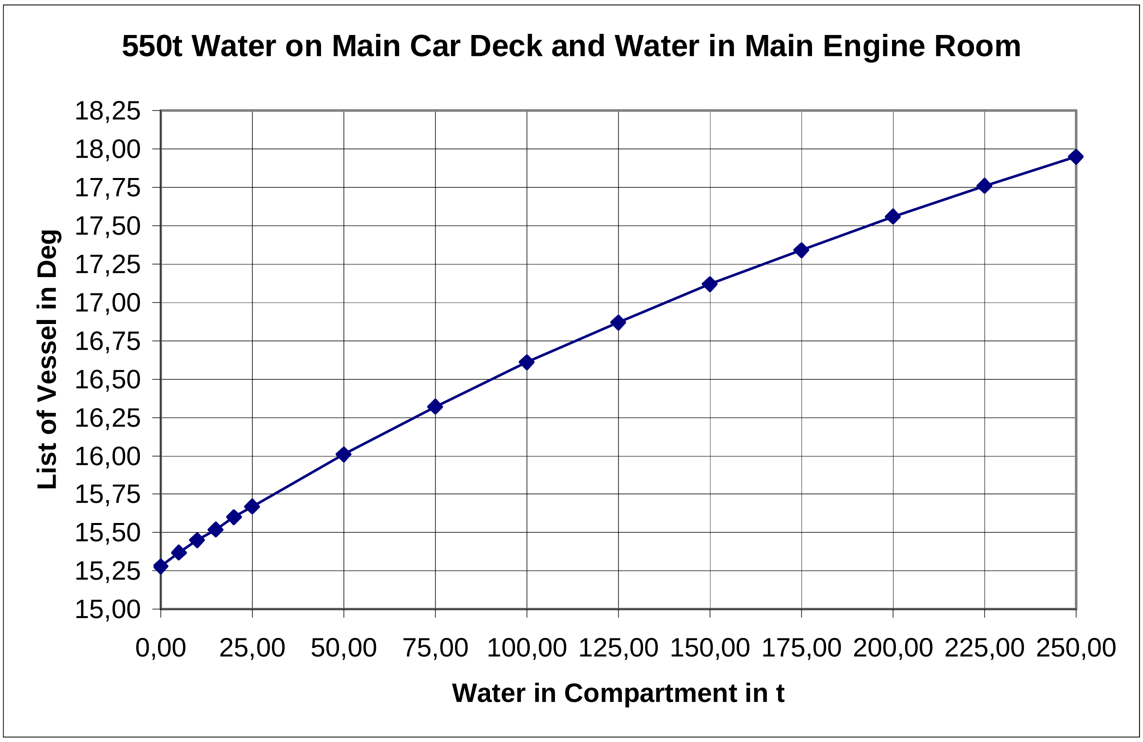


Figure 9.29: Water in Main Engine Room, 550t water on Main Car Deck, mass over list

Scenario 11

In scenario 11, a mass of 300t of water on Main Car Deck is assumed and this mass is kept constant.. In addition to the water on Main Car Deck, the flooding of the Auxiliary Engine Room is considered. The calculation is carried with the water in the Auxiliary Engine Room increasing in 5t steps up to 25t and then in 25t steps to 250t of water.

In this scenario, the water enters the Auxiliary Engine Room through the air ducts. The TCG of vehicles on Main Car Deck is kept fixed at –2.1m.

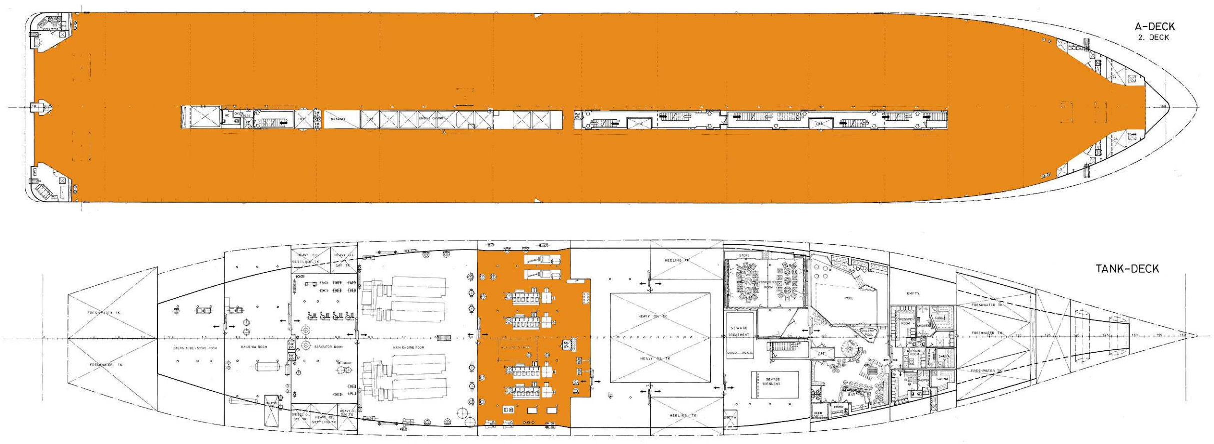


Figure 9.30: Scenario 11 – Compartments under consideration

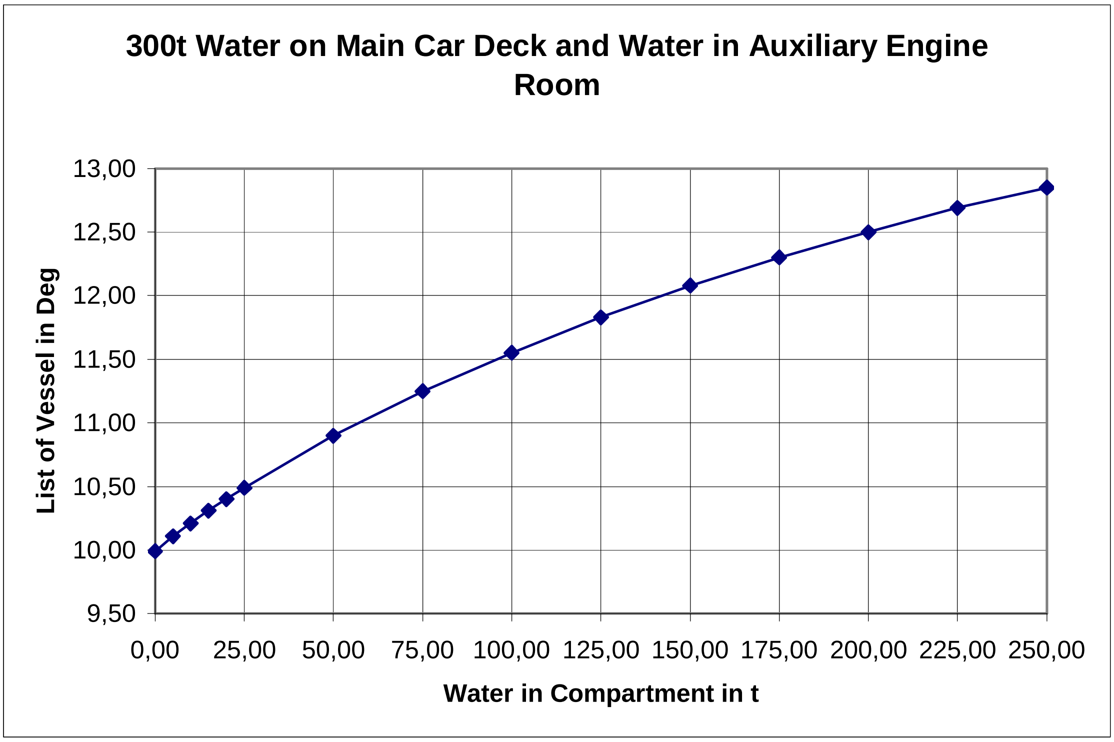


Figure 9.31: Water in Auxiliary Engine Room, 300t water on Main Car Deck, mass over list

Scenario 12

Scenario 12 is exactly the same a scenario 11, except the mass of water on the Main Car Deck is now 550t and this mass is kept constant.. In addition to the water on Main Car Deck, the flooding of the Auxiliary Engine Room is considered. The calculation is carried with the water in the Auxiliary Engine Room increasing in 5t steps up to 25t and then in 25t steps to 250t of water.

In this scenario, the water enters the Auxiliary Engine Room through the air ducts. The TCG of vehicles on Main Car Deck is kept fixed at –2.1m.

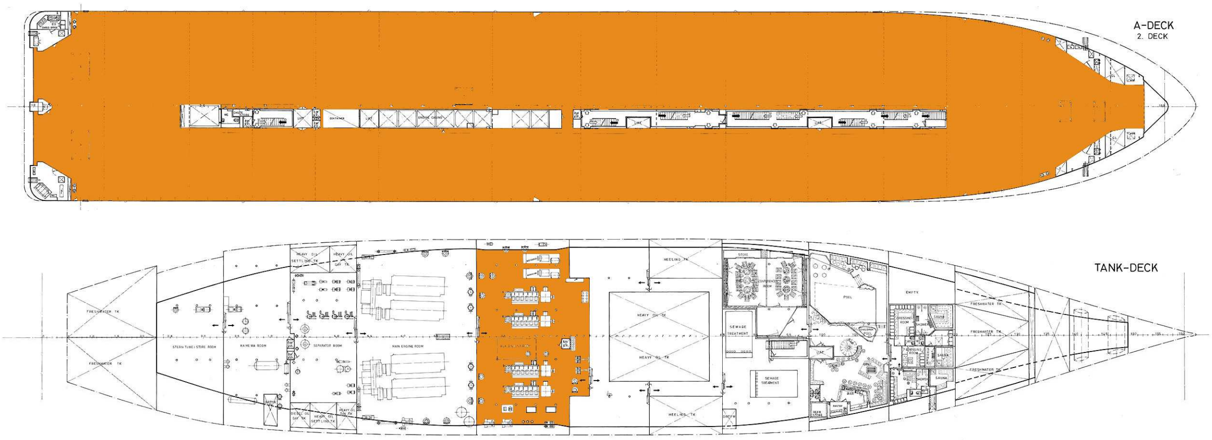


Figure 9.32: Scenario 12 – Compartments under consideration

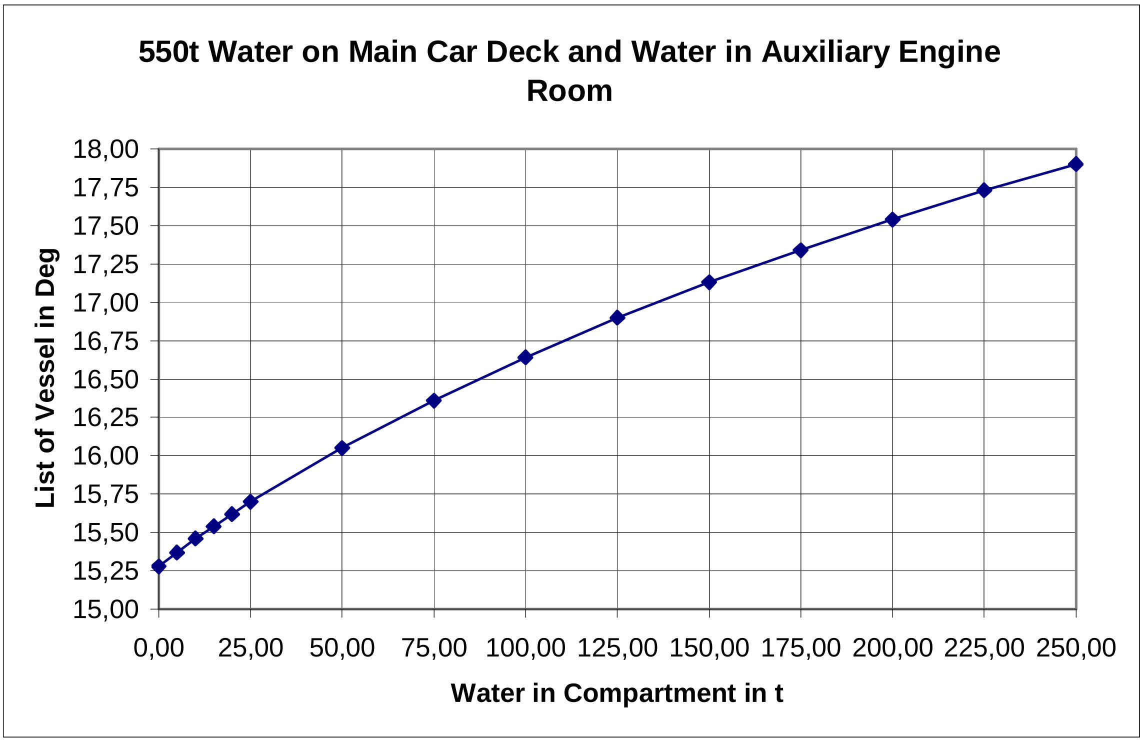


Figure 9.33: Water in Auxiliary Engine Room, 550t water on Main Car Deck, mass over list

Scenario 13

In Scenario 13, a mass of 300t of water on Main Car Deck is assumed and this mass is kept constant. In addition to the water on Main Car Deck, the flooding of the Pool Room is considered. The calculation is carried out with the amount of water in the Pool Room increasing in 5t steps up to 25t and then in 25t steps to 250t . Note that this water in the Pool Room is in addition to the pool water, which is dealt with by the final load case. The TCG of vehicles on Main Car Deck is kept fixed at –2.1m.

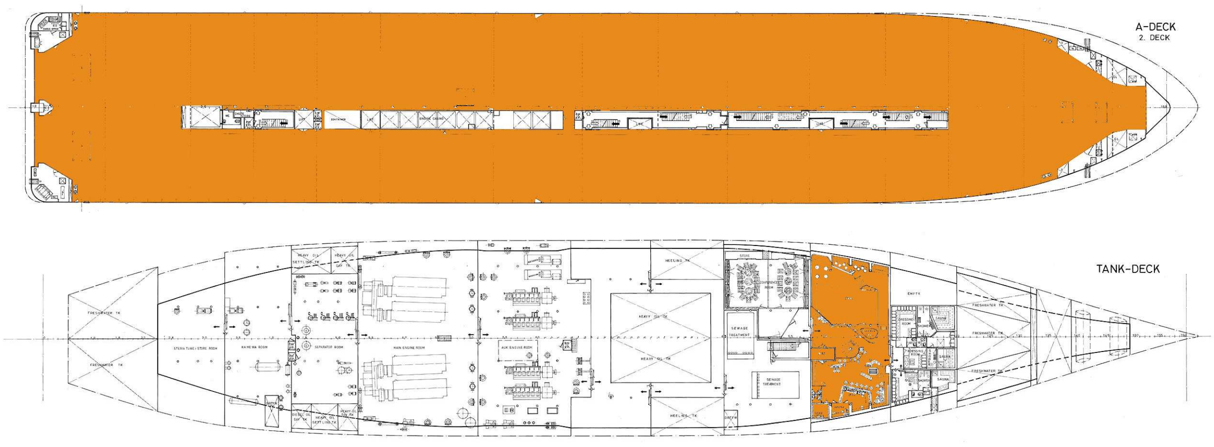


Figure 9.34: Scenario 13 – Compartments under consideration

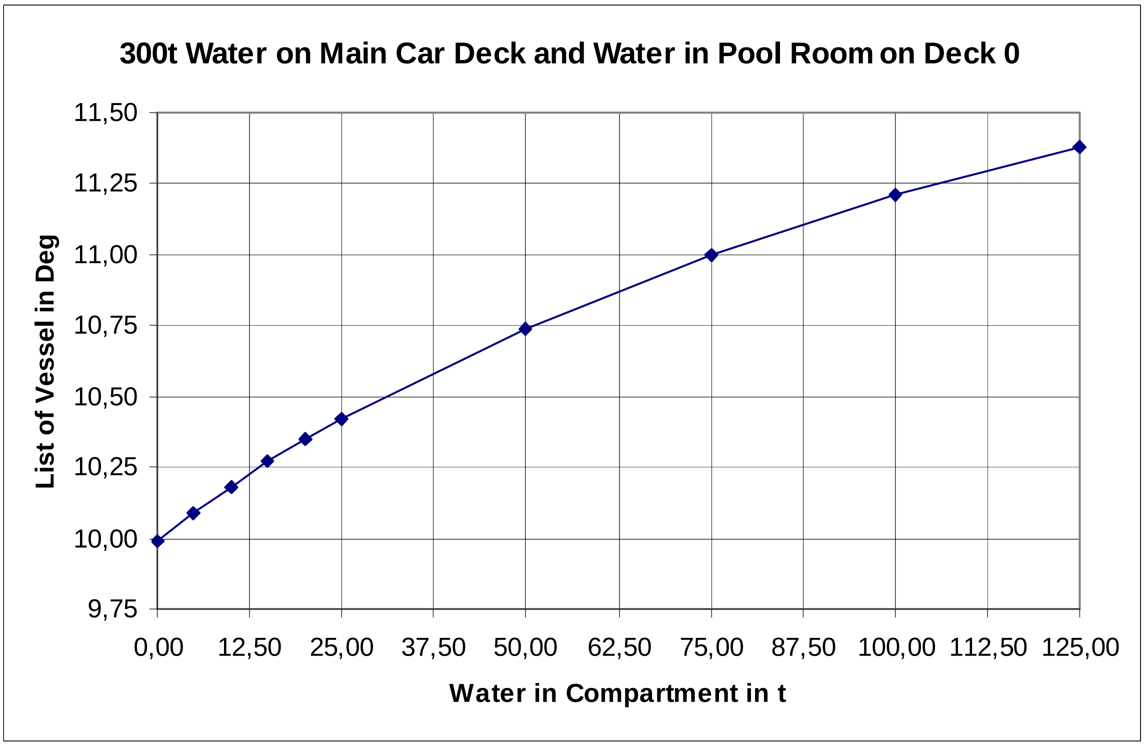


Figure 9.35: Water in Pool Room, 300t water on Main Car Deck, mass over list

Scenario 14

In Scenario 14, a mass of 300t of water on Main Car Deck is assumed and this mass is kept constant.. In addition to the water on Main Car Deck, flooding of the Pool Room is considered, along with additional compartments connected by a non-watertight staircase. The calculation is carried out with the amount of water in the Pool Room increasing in 5t steps up to 25t and then in 25t steps to 250t. Note that this water in the Pool Room is in addition to the pool water, which is dealt with by the final load case.

Water enters in this area by the door at frame 105 on Main Car Deck; the first door of the Centre Casing on the port side. From there it enters the stairs at frame 90, 95 and 105, as well as the lift at frame 100 and flowed in the compartments under consideration. The TCG of vehicles on Main Car Deck is kept fixed at –2.1m.

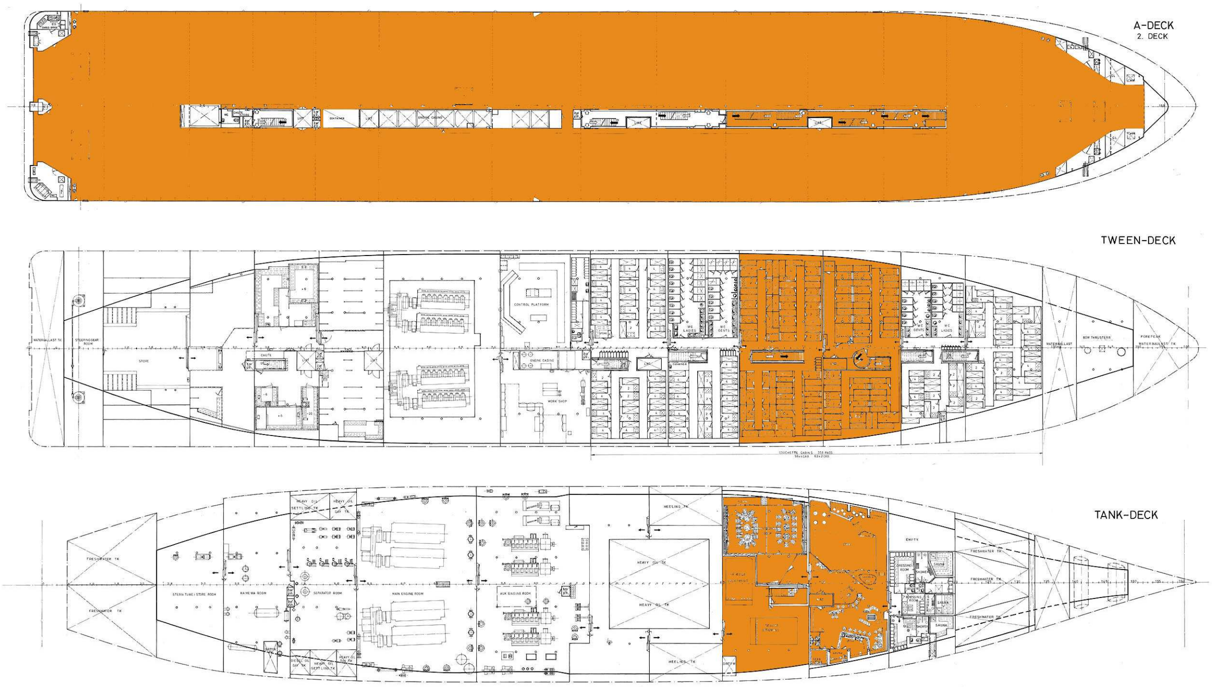


Figure 9.36: Scenario 14 Compartments under consideration

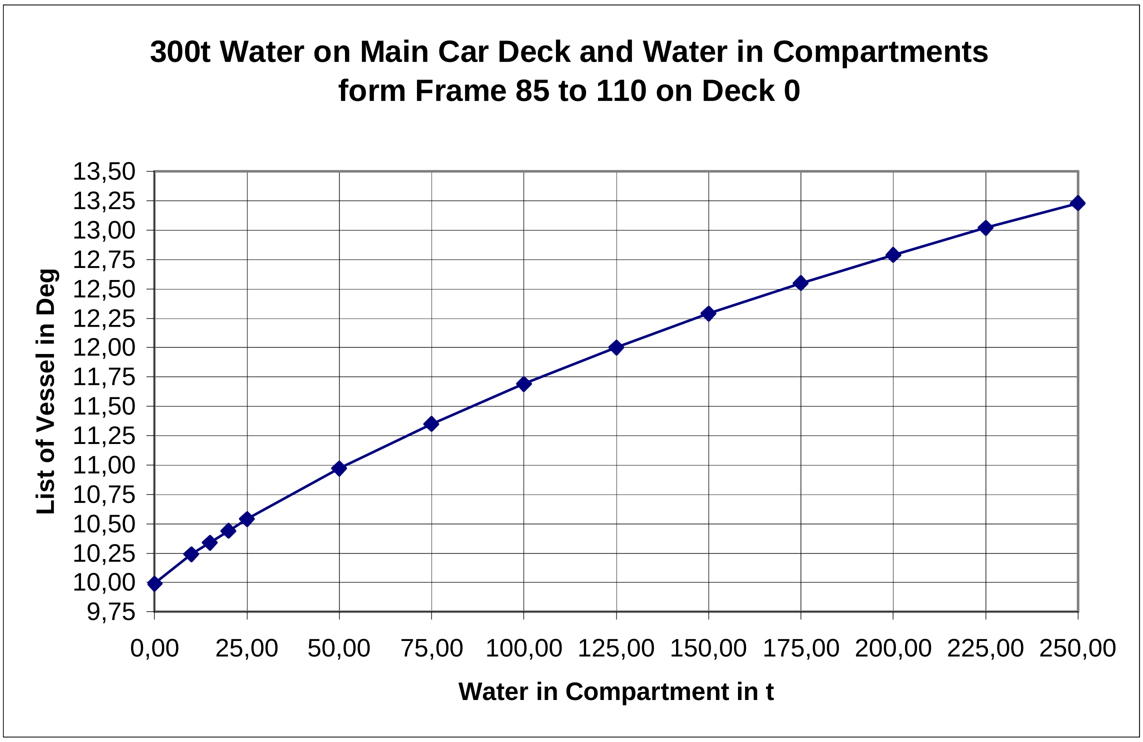


Figure 9.37: Water in compartments Fr. 85 to 110, 300t water on Main Car Deck, mass over list

Scenario 15

In Scenario 15, a mass of 300t of water on Main Car Deck is assumed and this mass is kept constant. In addition to the water on Main Car Deck, flooding of the Sauna Room at the Centre Line is considered between frames 110 and 120. The calculation is carried out with the amount of water in the Sauna Room increasing in 5t steps up to 25t and then in 25t steps to 125t. The TCG of vehicles on Main Car Deck is kept fixed at –2.1m.

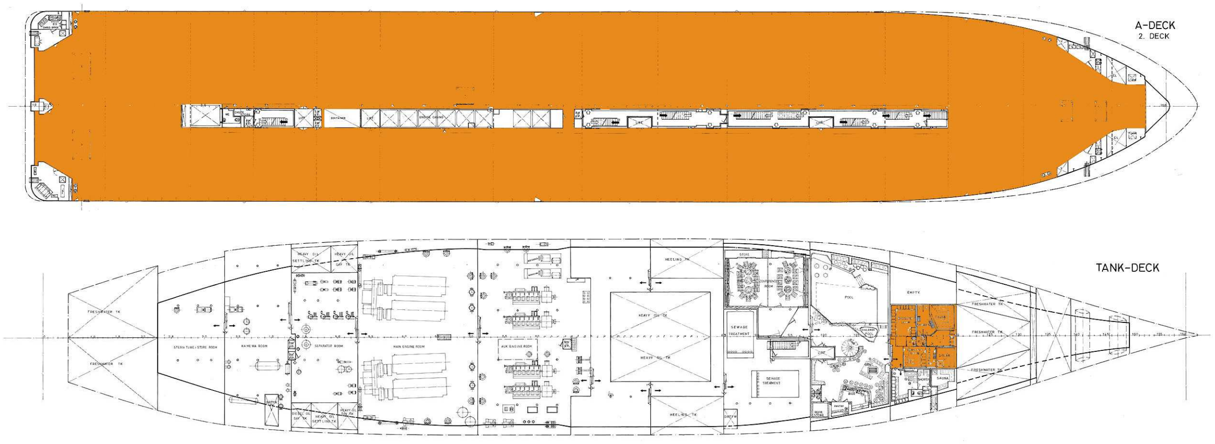


Figure 9.38: Scenario 15 Compartments under consideration

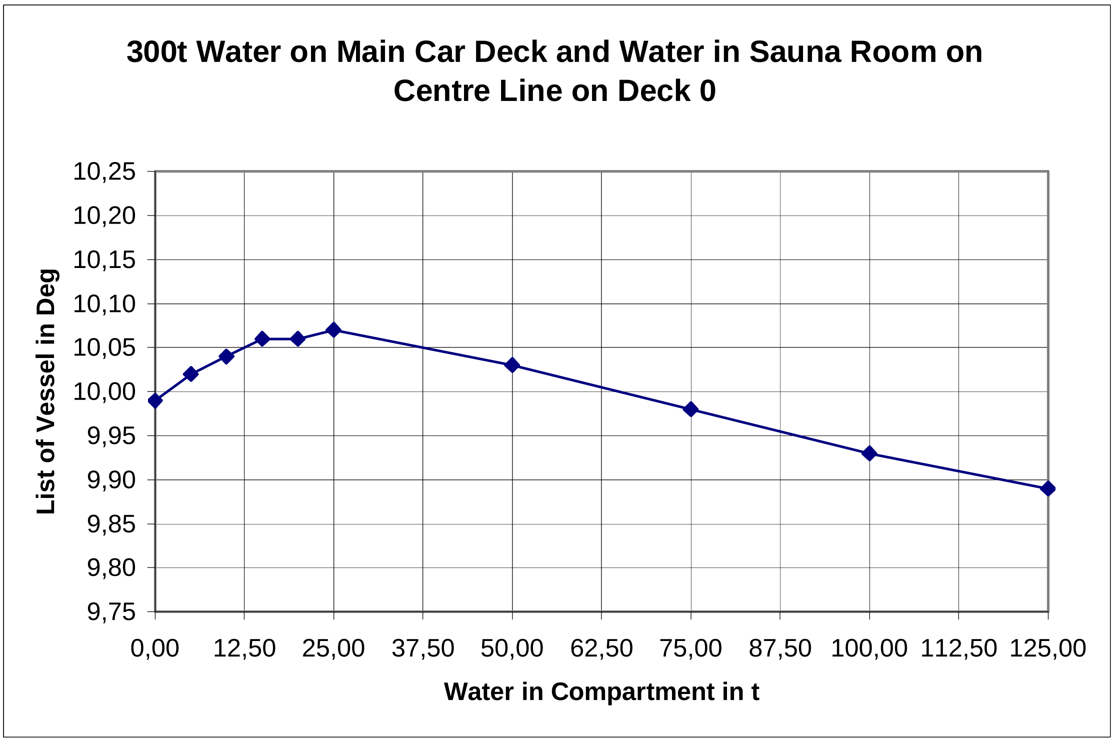


Figure 9.39: Water in Sauna Room with 300t Water on Main Car Deck, mass over list

Scenario 16

In Scenario 16, a mass of 300t of water on Main Car Deck is assumed and this mass is kept constant. In addition to the water on Main Car Deck, selected compartments were equally loaded to levels of 3t, 5t, 7t, 10t, and then on from 10t to 100t in steps of 5t and then up to 150t in steps of 10t.

The compartments filled are:

- Steering Gear Room and Store, frame –3 to 23
- Store, frame 33 to 43
- Store, frame 43 to 53
- Main Engine Room
- Auxiliary Engine Room

Starting with the 7t level, these compartments were filled, once again equally with the others:

- Sewage Treatment/ Conference on Deck 0 and Pool Room, frame 85 to 110

The water is assumed to enter the compartments via the Main Car Deck and pouring through open doors in the Centre Casing.

The two cabin compartments on Deck 1, from frame 110 to 120 and 120 to 132 are connected by the central stair case. The TCG of vehicles on Main Car Deck is kept fixed at –2.1m.

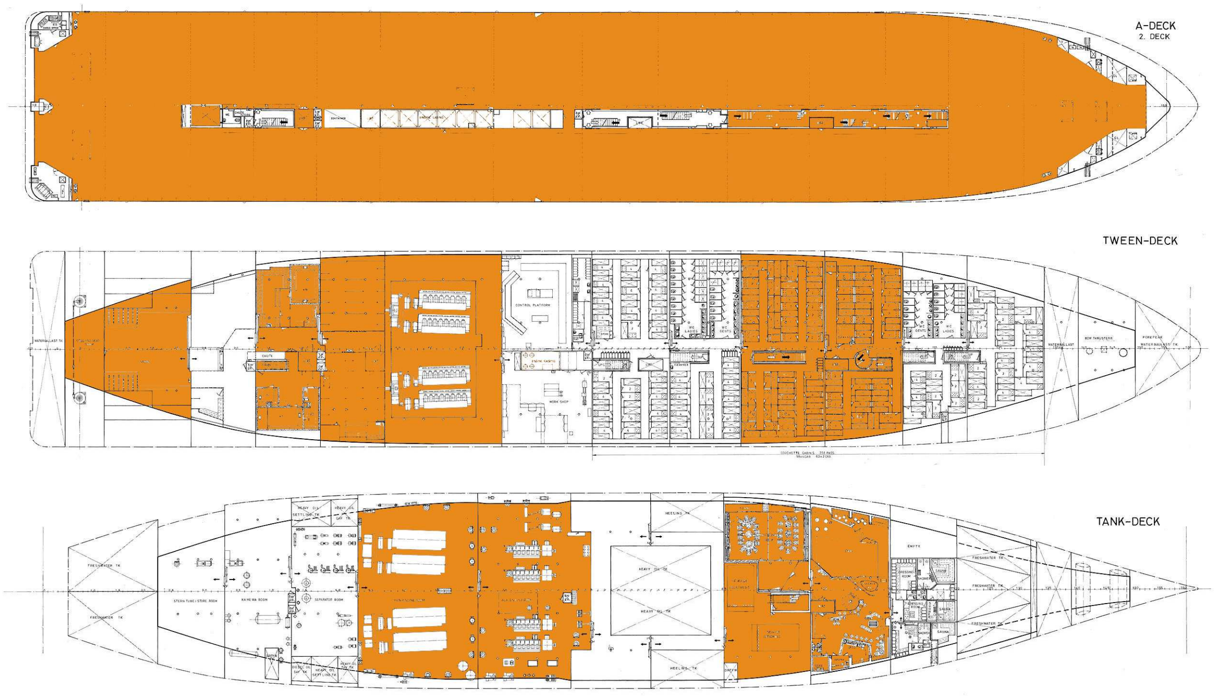


Figure 9.40: Scenario 16 – Compartments under consideration

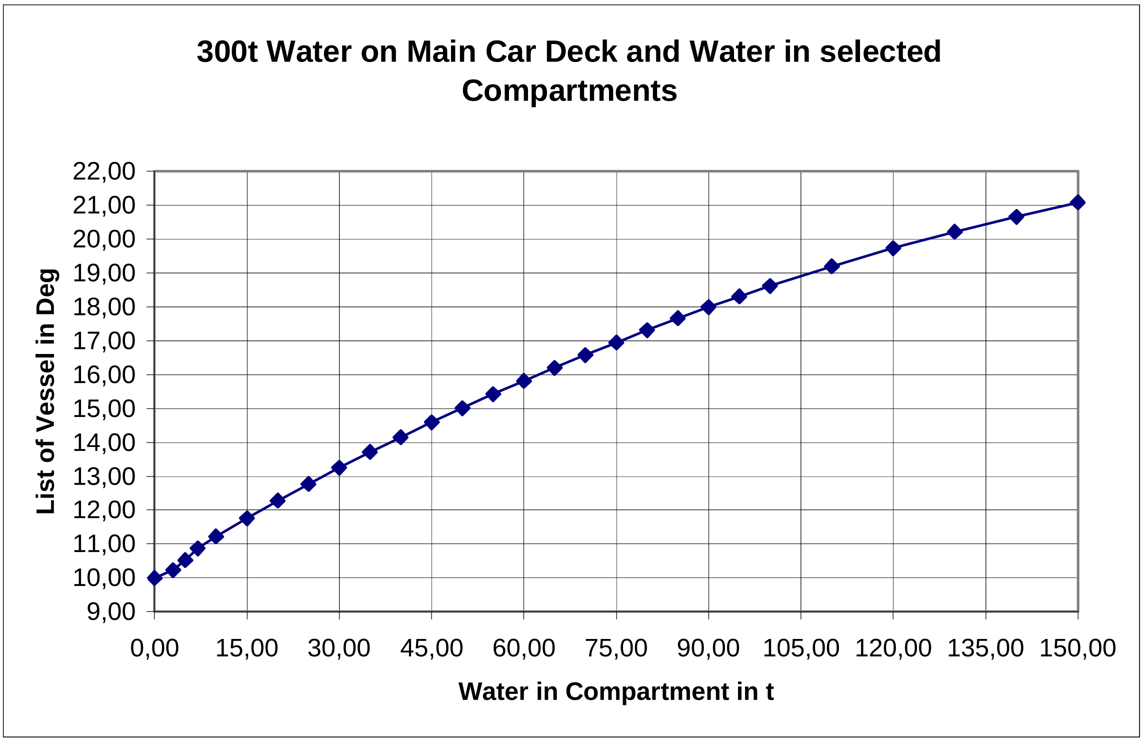


Figure 9.41: Water in selected Compartments with 300t water on Main Car Deck, mass over list

Scenario 17

Scenario 17 is identical to Scenario 16, apart from a combination of water ingress with cargo shift. A mass of 300t of water on Main Car Deck is assumed and this mass is kept constant. The selected compartments were equally loaded to levels of 3t, 5t, 7t, 10t, and then on from 10t to 100t in steps of 5t and then up to 150t in steps of 10t.
The compartments filled are:

- Steering Gear Room and Store, frame –3 to 23
- Store, frame 33 to 43
- Store, frame 43 to 53
- Main Engine Room
- Auxiliary Engine Room

Starting with the 7t level, these compartments were filled, once again equally with the others:

- Sewage Treatment/ Conference on Deck 0 and Pool Room, frame 85 to 110

The water is assumed to enter the compartments via the Main Car Deck and pouring through open doors in the Centre Casing.
The two cabin compartments on Deck 1, from frame 110 to 120 and 120 to 132 are connected by the central stair case.
The cargo shifts of the vehicles on the Main Car Deck are linked to amounts of water added to the compartments. The reasoning behind this is that an increase in water in the compartments leads to an increase in list, which in turn causes a cargo shift increasing the list still further. The allocation of the cargo shift to mass of water in compartments, shown in the following table, is arbitrary, but is the only way to refine the model without the calculations becoming too overwhelming.

Table 9.2: Allocation of water on the Main Car Deck and water in the compartments to cargo shift of the vehicles on the Main Car Deck in scenario 17.

Water on Main Car Deck	**Cargo Shift of TCG of vehicles**	**Water in Compartment**
t	*m off Centre Line*	*t*
300	-2.30	0.00
300	-2.30	3.00
300	-2.30	5.00
300	-2.30	7.00
300	-2.50	10.00
300	-2.70	15.00
300	-2.90	20.00
300	-3.10	25.00
300	-3.30	30.00
300	-3.50	35.00
300	-3.70	40.00
300	-3.90	45.00
300	-4.10	50.00
300	-4.30	55.00
300	-4.50	60.00
300	-4.70	65.00
300	-4.90	70.00
300	-5.10	75.00
300	-5.30	80.00
300	-5.50	85.00
300	-5.70	90.00
300	-5.90	95.00
300	-6.10	100.00

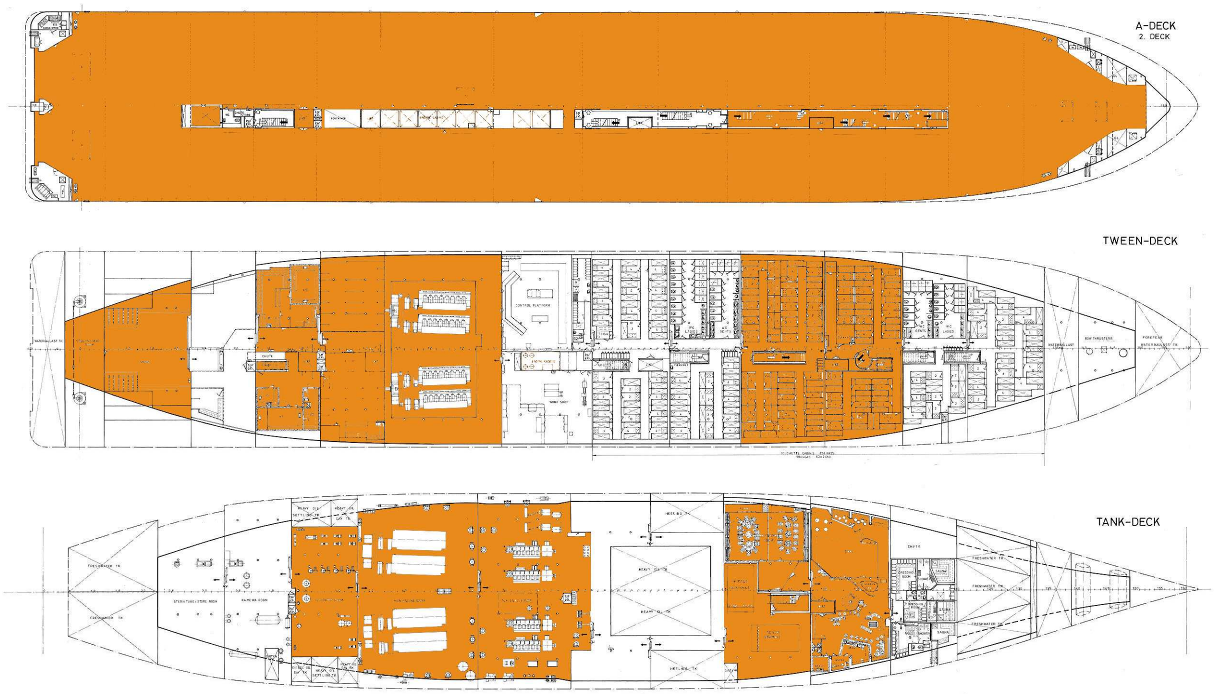


Figure 9.42: Scenario 17 – compartments under consideration

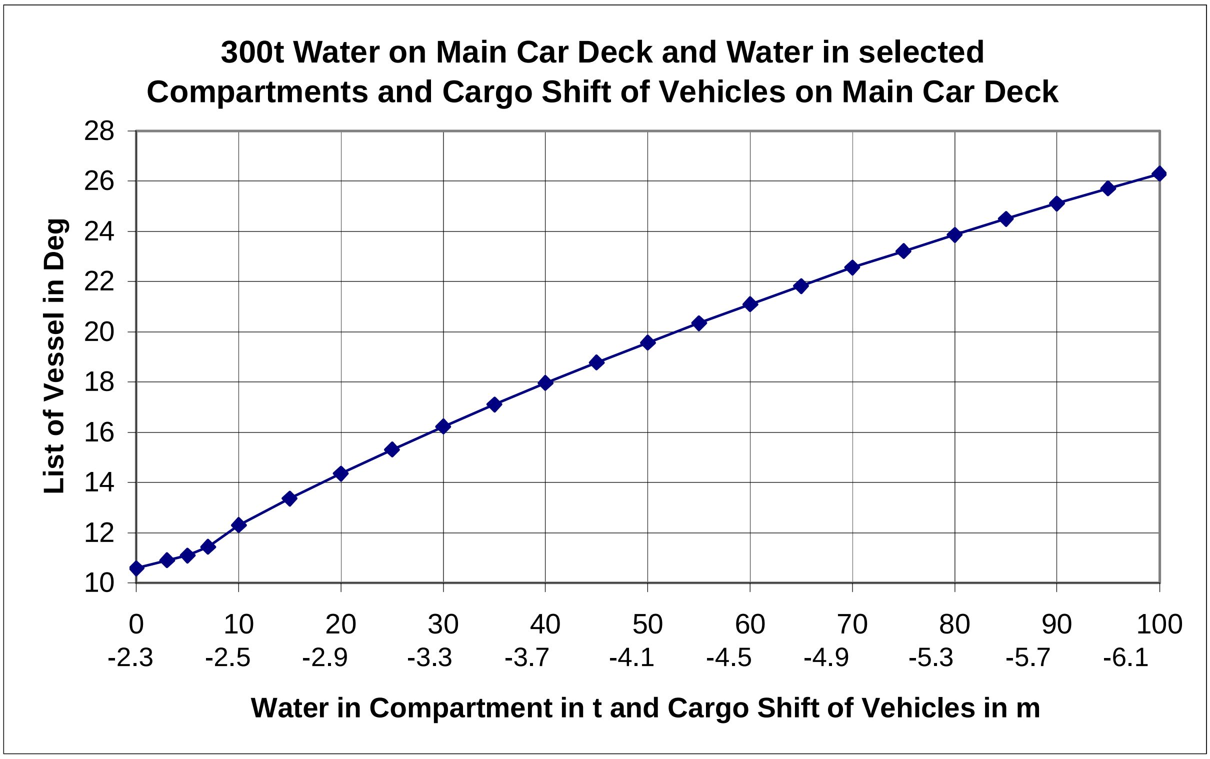


Figure 9.43: 300t water on Main Car Deck with additional water in selected compartments, mass and cargo shift over list

Scenario 18

Scenario 18 to the same as Scenario 17, except for the addition of a new compartment added to the number filled and the cargo shift being set to be less strongly related to the amount of water added to the selected compartments – see *Table 8.3*.

A mass of 300t of water on Main Car Deck is assumed and this mass is kept constant. The selected compartments were equally loaded to levels of 3t, 5t, 7t, 10t, and then on from 10t to 100t in steps of 5t and then up to 150t in steps of 10t.
The compartments filled are:

- Steering Gear Room and Store, frame –3 to 23
- Store, frame 33 to 43
- Store, frame 43 to 53
- Main Engine Room
- Auxiliary Engine Room

The additional compartment (filled from the very beginning) is:

- Separator Room

Starting with the 7t level, these compartments were filled, once again equally with the others:

- Sewage Treatment/ Conference on Deck 0 and Pool Room, frame 85 to 110

The water is assumed to enter the compartments via the Main Car Deck and pouring through open doors in the Centre Casing.
The two cabin compartments on Deck 1, from frame 110 to 120 and 120 to 132 are connected by the central stair case.

Table 9.3: Allocation of water on the Main Car Deck and water in the compartments to cargo shift of the vehicles on the Main Car Deck in scenario 18

Water on Main Car Deck	**Cargo Shift of TCG of Vehicles**	**Water in Compartment**
t	*m off Centre Line*	*t*
300	-2.10	0.00
300	-2.15	3.00
300	-2.20	5.00
300	-2.25	7.00
300	-2.30	10.00
300	-2.40	15.00
300	-2.50	20.00
300	-2.60	25.00
300	-2.70	30.00
300	-2.80	35.00
300	-2.90	40.00
300	-3.00	45.00
300	-3.10	50.00
300	-3.20	55.00
300	-3.30	60.00
300	-3.40	65.00
300	-3.50	70.00
300	-3.60	75.00
300	-3.70	80.00
300	-3.80	85.00
300	-3.90	90.00
300	-4.00	95.00
300	-4.10	100.00

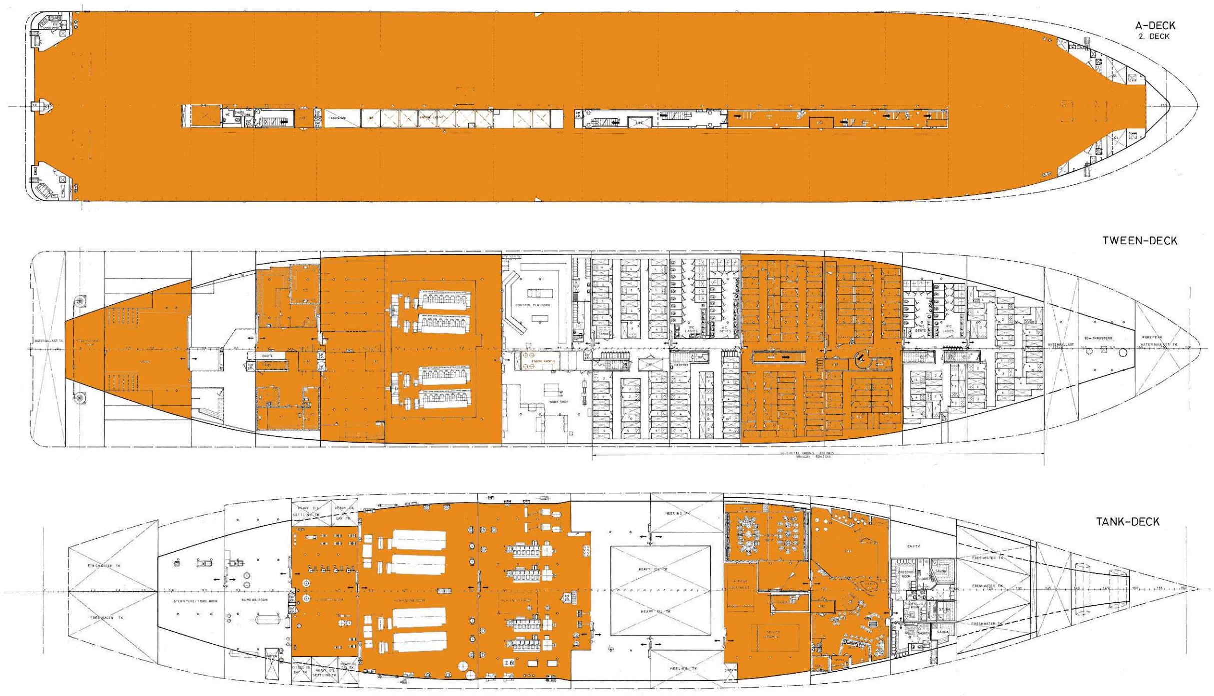


Figure 9.44: Scenario 18 – compartments under consideration

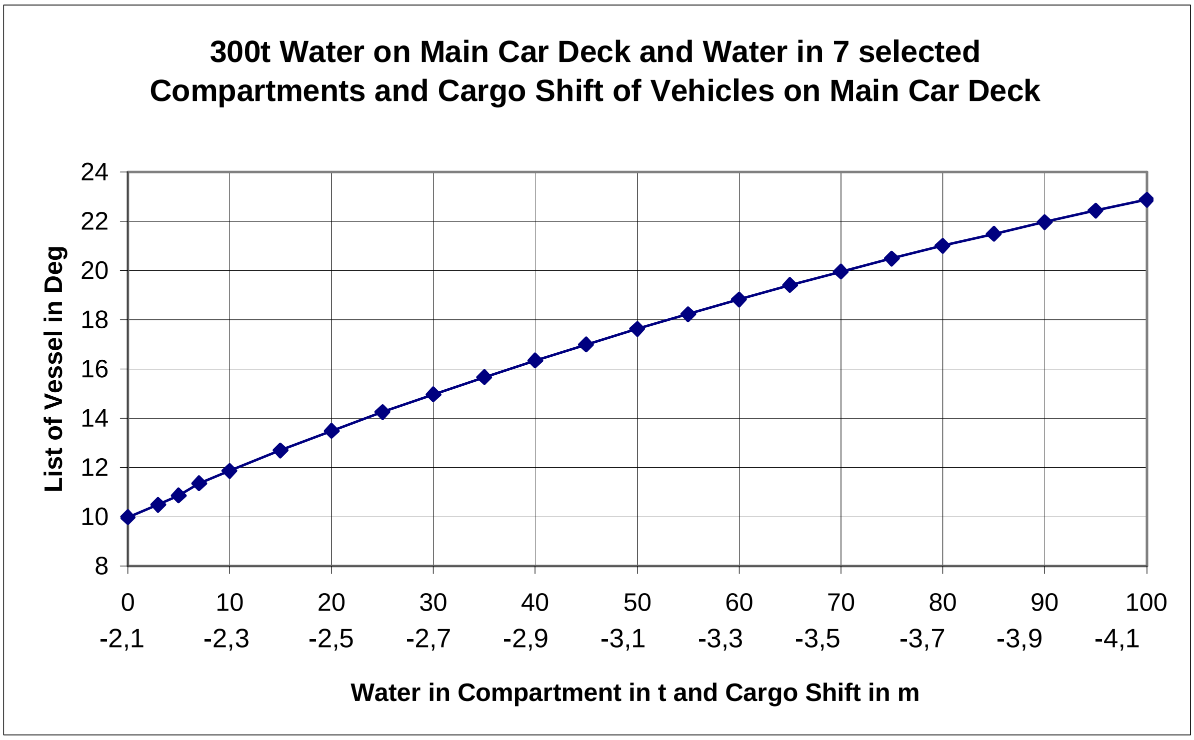


Figure 9.45: 300t water on Main Car Deck with additional water in selected compartments, mass and cargo shift over list

10 Motion Simulation and Inflow Rate Calculation

The results of the different hydrostatic evaluations have shown that for any assumed scenario, a significant amount of water intake is required to generate a steady list of about 30 degrees.

This list requires an amount of water of at least 1500t, which must have entered the Main Car Deck within about 10 to 15 minutes. To decide which scenario may be the most probable one, one must determine how quickly the water could have entered the Main Car Deck or other compartments, within the time period suggested by the synoptic time schedule.

Consequently, it is most important to determine possible flow rates through the open bow under various conditions, because if it is not possible to accumulate the amount of water required on the Main Car Deck in the given time, the assumptions behind the scenarios, and hence the scenarios themselves, cannot be valid.

The preliminary hydrostatic investigations showed that the stability of the vessel is most effected when all the accumulated seawater collects on the Main Car Deck.

Therefore, the investigation now aims to create a large matrix of possible inflow rates on the Main Car Deck which can be used to judge whether each of the scenarios are plausible or not. Later in this thesis, flow rates between the Main Car Deck and other compartments will be considered. As indicated above, even if a cargo shift and other (external) moments are included, they do not affect the list anywhere near as much as the accumulated water. It is hence safe, at least initially, to deal with these variables as a lower priority.

The flow rates into the Main Car Deck are dependent on:

- speed of encounter between ship and waves
- the level to which the opening is submerged relative to the current wave height.

This momentary submergence of the open bow depends on

- the relative motion between ship and waves
- the mean value of trim, heel and sinkage
- the wave height at the position of the opening
- the height of the ship's own bow wave, dynamic sinkage and trim
- spray

The mean values of trim, heel and sinkage do depend on the amount of water that has already entered the car deck, where two possibilities have to be taken into account: There may have been some initial water on the car deck **before** the visor has fallen off, and of course water enters **after** the visor has fallen off. It was considered that water could also flow back outside the vessel.

Hence, the next step was to generate a very simple dynamic model of the ship and the vehicle compartment that allows calculation of a number of cases regarding possible inflow rates into the Main Car Deck. This model was kept as simple as possible to use as little computational time as feasible. Therefore the model consists only of one cuboid with the dimensions of the Main Car Deck, and the leak was assumed to be the full size of the open visor and bow ramp. Consequently, the Toricelli-Number of the leak was assumed to be 1.0. These flow rates are only intended to further distinguish between different scenarios and should cover a sufficient range of input parameters. As we converge on a final scenario, the model will of course be refined to a more computationally intense one.

10.1 Environmental Data for the Dynamic Investigations

MV Estonia departed from Tallinn harbour between 19:00 and 19:30 on the September 27th, 1994. Witness C11, practising for second mate on MV Estonia, stated that at around 20:00: "When we reached the open sea, a strong wind started to blow from the left side". This indicates a westerly course, as the wind direction at that time

was southerly and pointed to the route being south of Naissaar island. But it is not definitely excluded that MV Estonia took the route north around this island.
At about 21:00, a passenger who visited the bridge stated that the heading was exactly 262° and the wind speed was about 20m/s.
The Chief Mate on the MV Amber observed MV Estonia on the radar screen on the ARPA. The ARPA plotted a course for MV Estonia of about 260° to 265° in the time between 23:00 to about 23:20 corresponding to the position of 59° 20' N to 59° 26' N and around 22° 30' E.
This indicates the course of about 262° after passing the southern tip of Island Naissaar until the change of heading at about 00:00 - as stated by C11 along with the order to deploy the stabiliser fins.
In all probability, MV Estonia was heading to Söderarm after the course change at midnight, the direction of course would then be about 290°.
The wave direction was west to southwest, around 250°, so after the change of course the encounter angle of the waves and MV Estonia increased, which would explain the deployment of the stabilizer fins because the larger encounter angle may have led to an increase in roll amplitude. These findings lead to an estimate of encounter angle between ship and waves of about 130 to 140 degrees: with 0 degrees denoting following seas and 180 degrees denoting head seas.
During the time of the accident, the wind was strong at about 17m/s, which resulted in a significant wave height - of 3.5 to 4.5m - with significant wave periods of about 8s. The speed of the vessel can be taken to be 15-18 knots.

In previous chapters, hydrostatic scenarios were investigated and found that an amount of water on the Main Car Deck can lead to the largest heeling angles. But one should note that water ingress on the Main Car Deck via the open bow ramp will flow to both sides of the centre casing, whereas the distribution of the amount of water to the port and starboard sides depends on the heeling angle of the vessel. A gedankenexperiment: the mass of water on the Main Car Deck is set to be constant at 1500t. The distribution of this 1500t is varied, e.g. 250t of water retained behind the centre casing leading consequently to 1250t on the starboard side. The following *Figure 10.1* visualises this idea of retained water behind the centre casing:

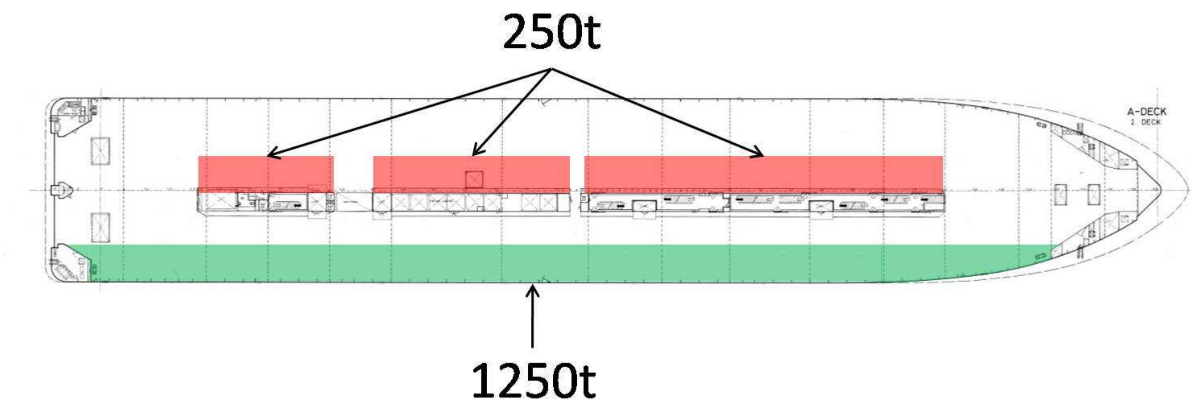


Figure 10.1: Example of the visualisation of retained water behind the centre casing at starboard heel – here: 250t retained behind the centre casing

Generally, this retained water behind the centre casing is an intermediate stage and not a fully converged equilibrium floating condition, but this leads to decrease in heeling angle depending on how much water is retained on portside of the vessel. This shows clearly the necessity of dynamic calculations such as the following.

A few results of this experiment are shown in *Figure 10.2*.

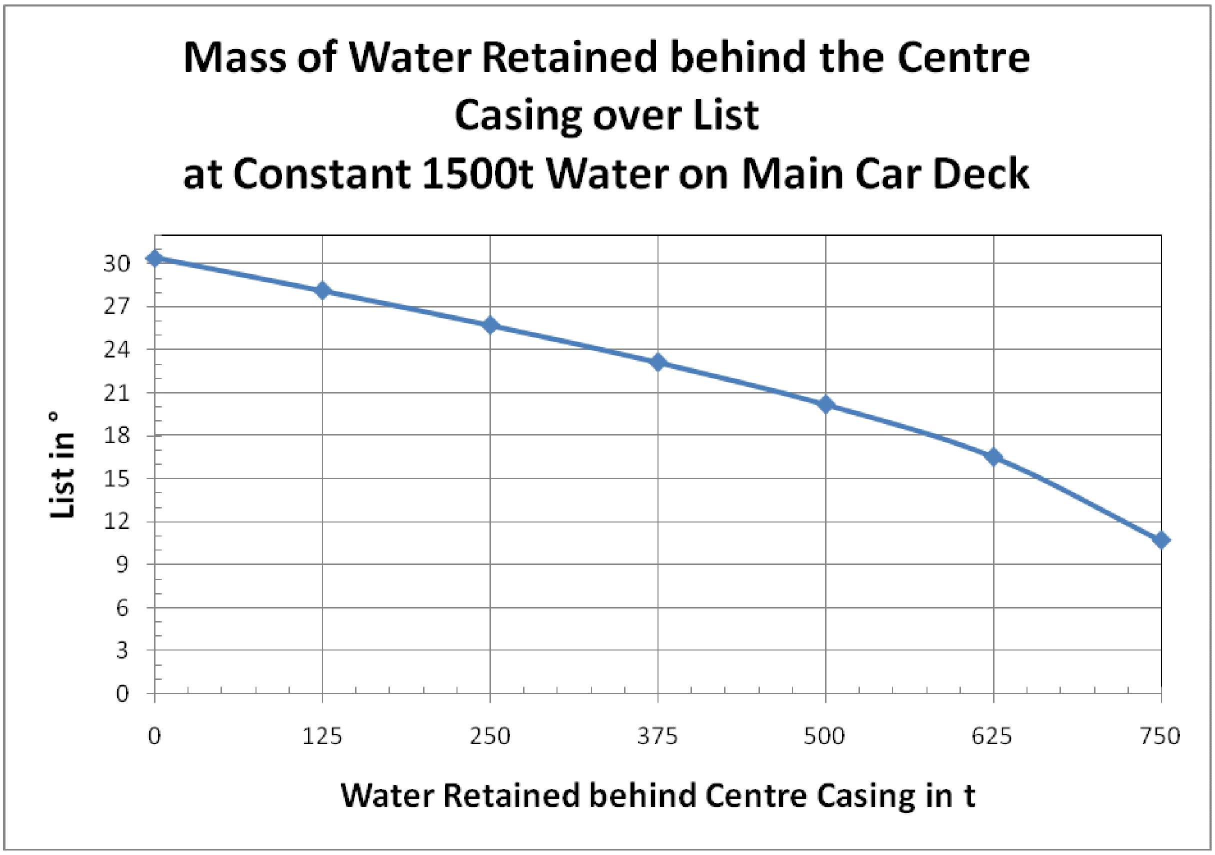


Figure 10.2: Mass of water retained behind the Centre Casing over list at a constant 1500t of water on the Main Car Deck

10.2 Simulation Model

For the investigation, a computer model for use in the seakeeping code ROLLS, was developed. Using six degrees of freedom, but four of them linear - namely pitch, heave, sway and yaw - ROLLS uses linear Response Amplitude Operators (RAO) which have been computed beforehand by the linear strip theory code STRIP.

The mass moments of inertia are automatically generated from the detailed input data - the masses and their location - for each situation. The roll radius of gyration was determined to be 0.44B including the section added hydro-mass, the “dry” roll radius of gyration amounts to 0.41B. The resulting natural roll period was 18.6s, which is only relevant for small roll angles.

The HSVA carried out roll decay tests with a physical model of MV Estonia [HSVA01]. Their results differ a little from the E4 results, which were used in the simulations of this chapter, apart from the non linear damping values, which were taken from the HSVA report.

For the non-linear roll damping, the results of the model tests at HSVA were used. The tests were conducted with and without stabiliser fins. The roll damping as such seems to be somewhat on the high side for this kind of ship, even without stabiliser fins, which may be a result of the large bilge keels.

RAOs were calculated for 0 – 18 knots in intervals of 2 knots as well as 15 knots, as that was the last known speed. The following graphs show, as an example, all the linear RAOs for a speeds of 15 knots and zero speed.

Here follows the linear Response Amplitude Operators for a speed of15 knots, which roughly corresponds to the speed MV Estonia travelled, *Figure 10.3 - 10.6*:

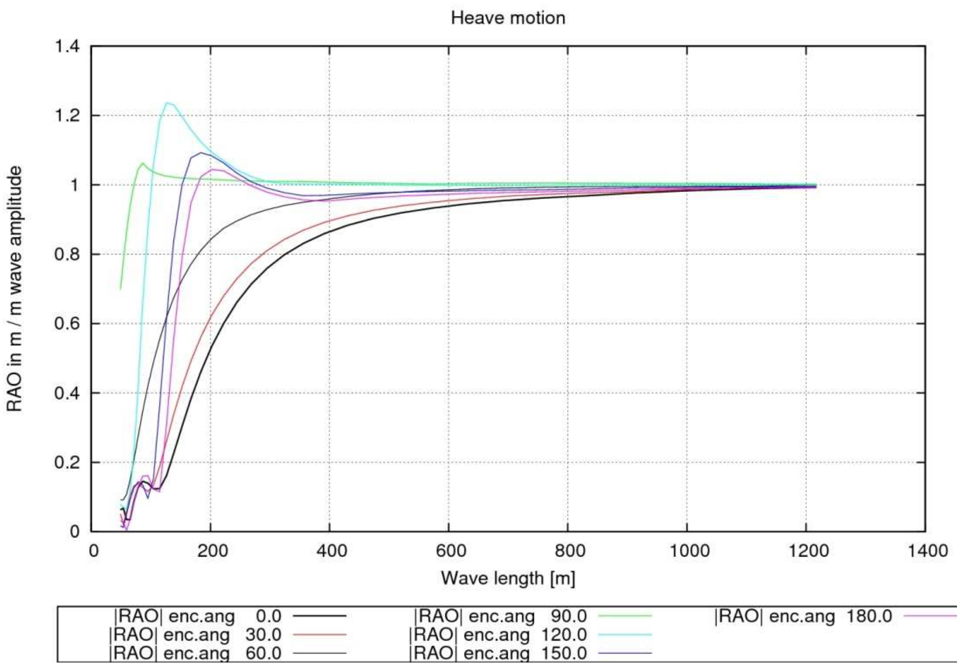


Figure 10.3: Heave motion, speed of 15 knots

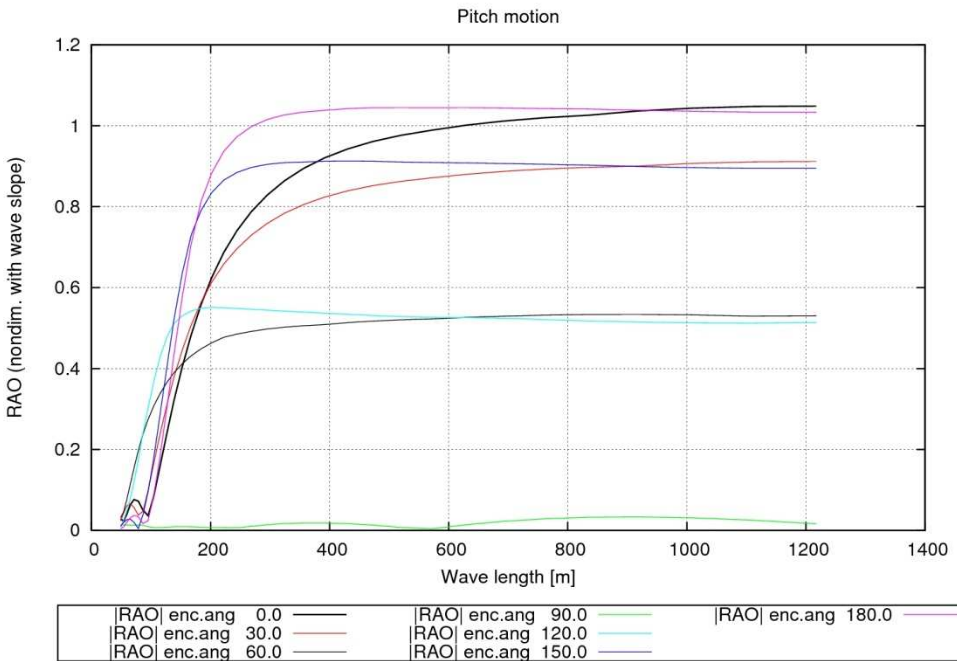


Figure 10.4: Pitch motion, speed of 15 knots

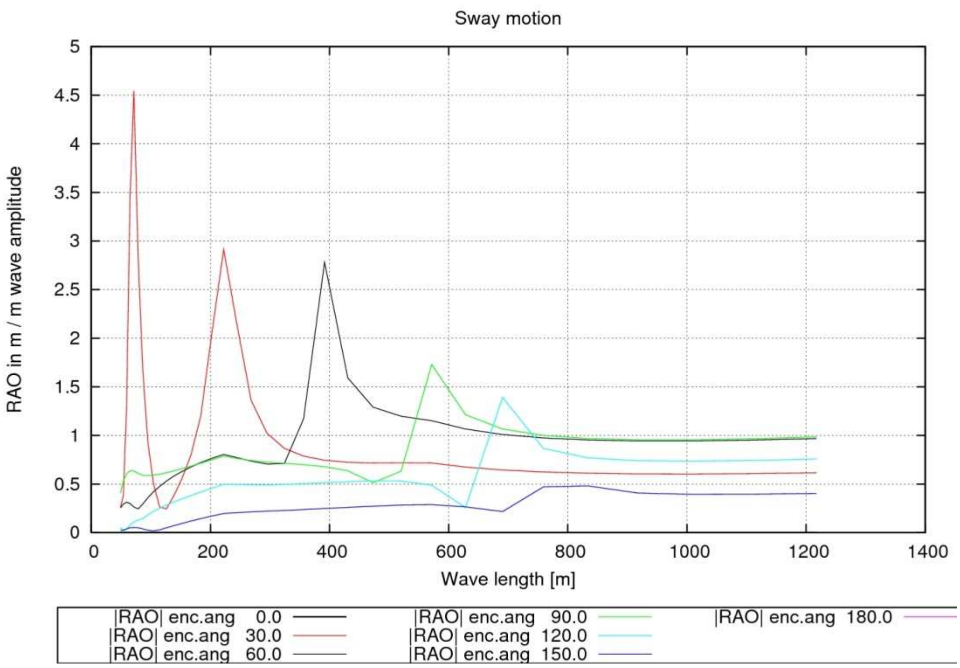


Figure 10.5: Sway motion, speed of 15 knots

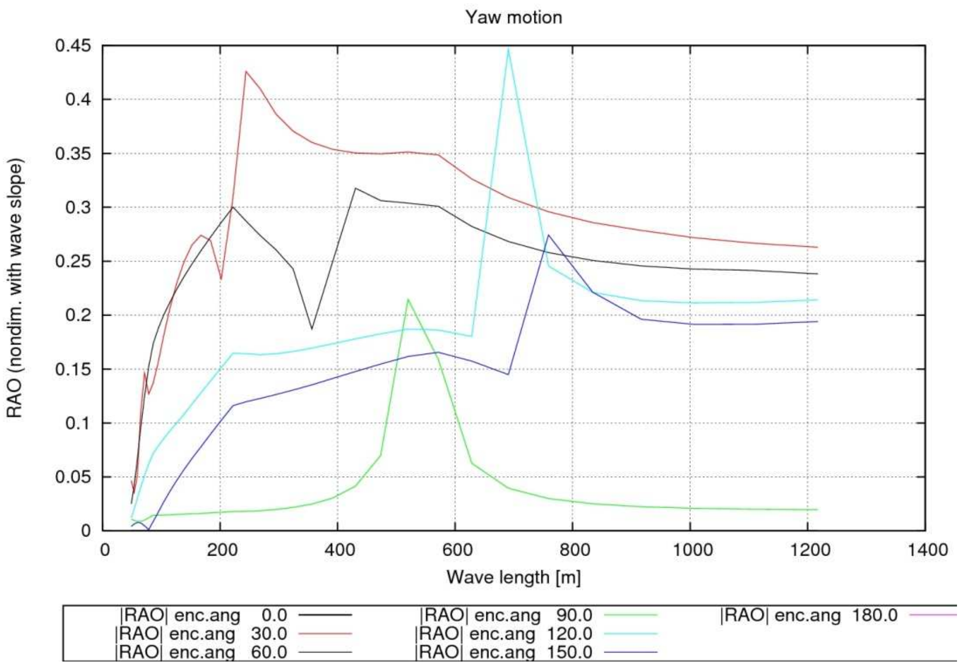


Figure 10.6: Yaw motion, speed of 15 knots

10.3 Simulation of MV Estonia in a Sea State

As an exemplification, a motion simulation of MV Estonia was carried out to show the motion of the vessel in general but especially the pitching motion. The chapter 4, 'Surrounding Conditions on the Night of the Sinking' describes the sea state to a wave height of around 4.0m and measurements and theoretical modelling gives a wave period of about 8s and a wave length of about 100m. The speed of MV Estonia was set to 14.0 knots, the encounter angle of the waves to 135°[7] on portside.

To simulate the ship's motions the program code ROLLS was used which is implemented in the ship design software E4. The simulate the sea state, a JONSWAP-Spectrum was used.

In *Figure 10.7* a series of snapshots of the ROLLS-simulation is presented and please note that the pitch motion is distinctive because mostly head seas encountering the vessel. *Figure 10.8* shows in comparison to *Figure 10.7* a series of snapshots of the SSPA model tests in a significant wave height of 4.5m.

[7] 0° encountering angle means following seas.

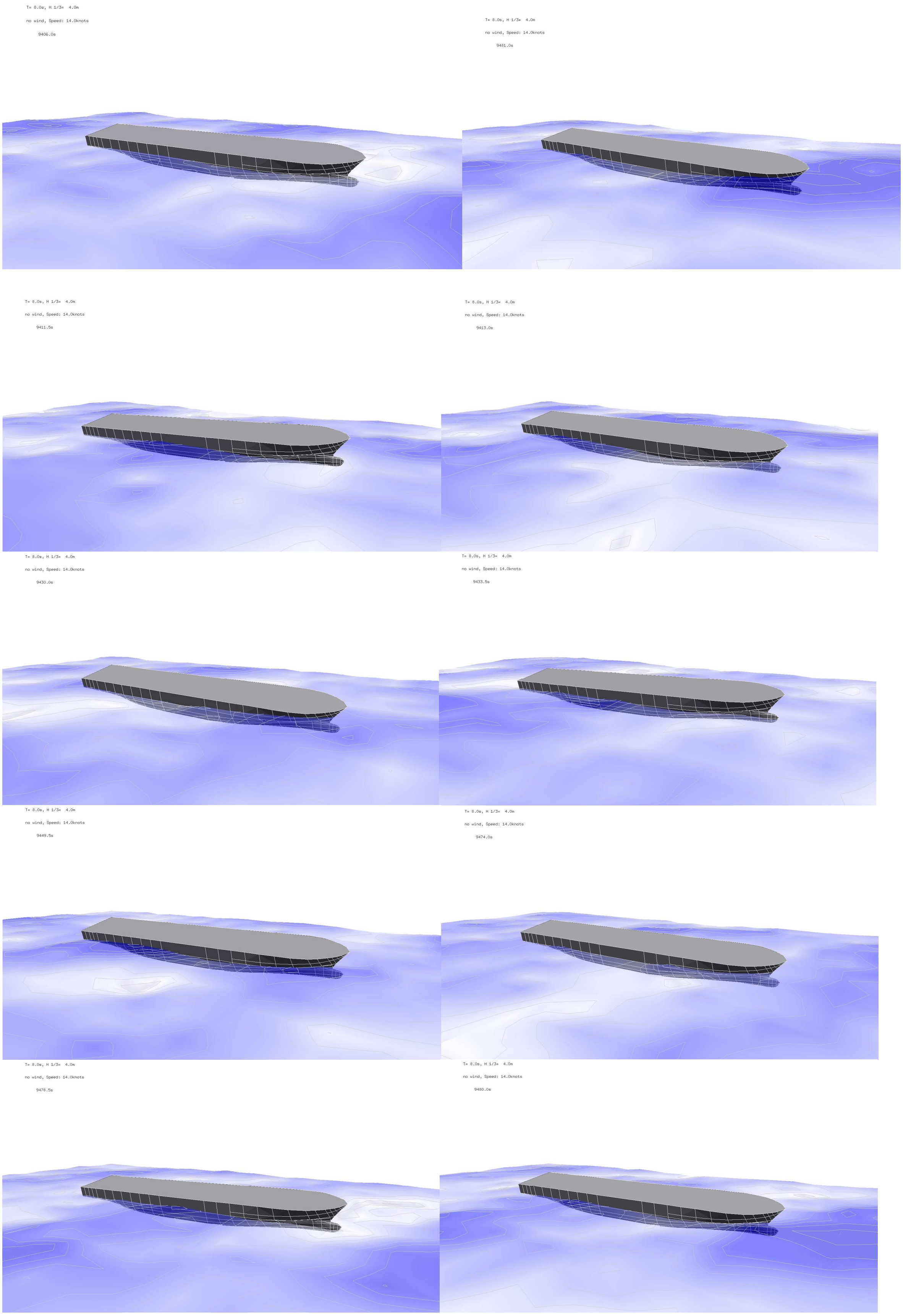


Figure 10.7: Snapshots of the ROLLS-simulation with distinctive pitch motion

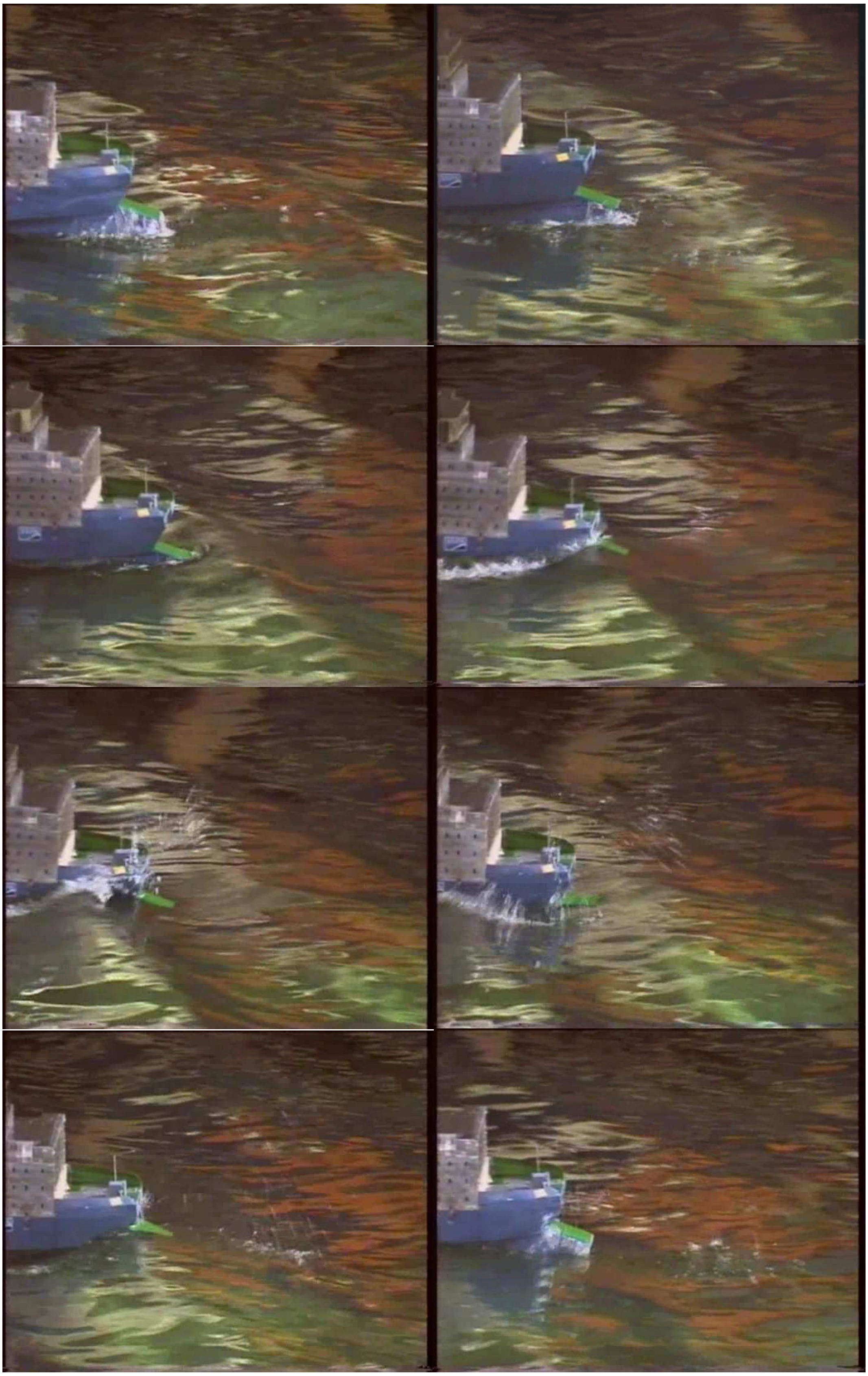


Figure 10.8: Snapshots of the SSPA model tests at 4.5m significant wave height

10.4 Effect of the Ship's own Wave System and of Sinkage and Trim

During the initial phase of the flooding of the Main Car Deck, which is assumed to be immediately after the bow visor had fallen off, the speed of the vessel was about 15 - 18 knots. In this first phase, the vessel must have collected a significant amount of water on the deck. The first phase of flooding of the Main Car Deck is especially important, as it would take a long time for the water to enter the Main Car Deck if it is hardly submerged. At a later stage, when there is already a substantial amount of water in the Main Car Deck, the flow rates into the Main Car Deck are substantially larger, when the ship's speed was kept constant, because the vessel immerses more and the moment of inertia is larger and by this the vessel reacts more lethargically to wave induced movement impulses. From the previous investigations it can be demonstrated that the amount of water required for the assumed scenarios is of the order of about 1500t leading to a list of about 30° - disregarding the intermediate stage of retained water behind the centre casing. This amount of 1500t must have entered the Main Car Deck within the space of about 10min. The theoretical still water freeboard of the open bow in the loading condition amounts to 7.95m-5.03m = 2.92m – 7.95m being the distance between the baseline and the opening at the bow ramp and 5.03m being the draft, which is still large with respect to the significant wave height of about 3.5m to 4.5m.

From the "Herald of Free Enterprise" accident it is known that water can be taken on even keel without rough seas simply through the interaction of the ship's own wave system and the open bow. Therefore, it was decided to determine the ship's own wave system, see *Figure 10.9 to 10.11* and to calculate how large amounts of water could have entered the Main Car Deck.

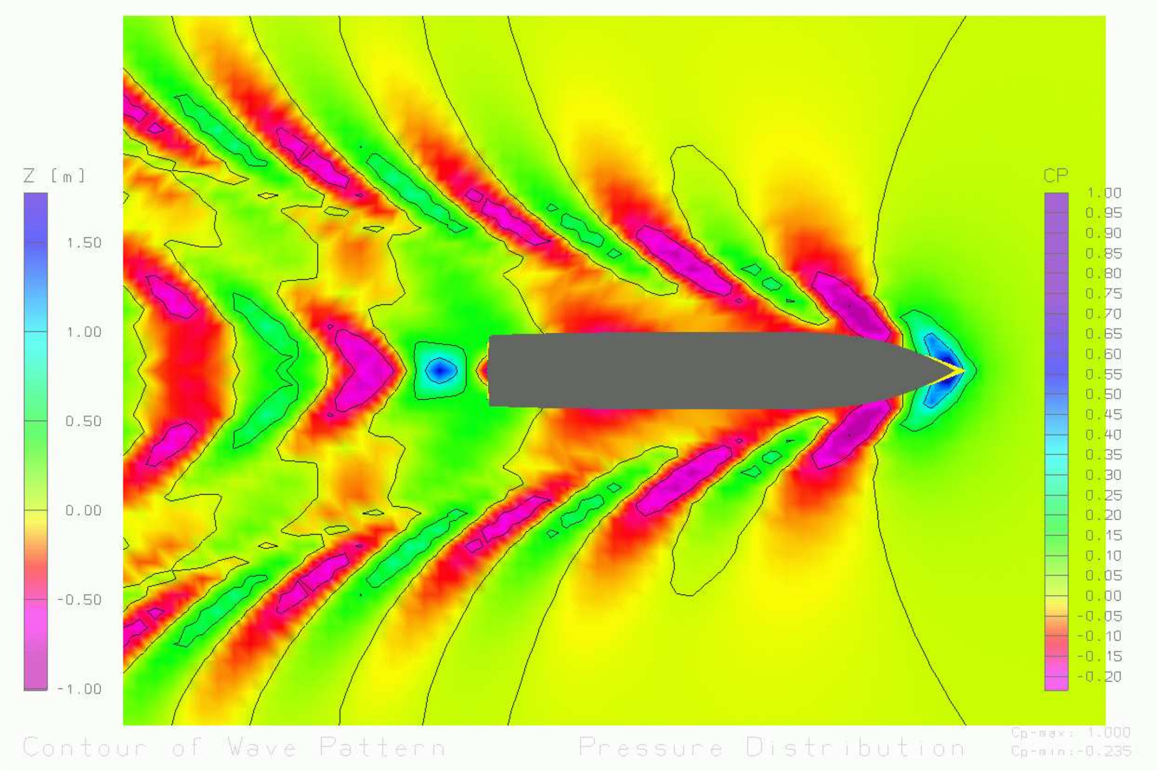


Figure 10.9: MV Estonia's own wave system at a ship speed of 18kn, complete wave pattern

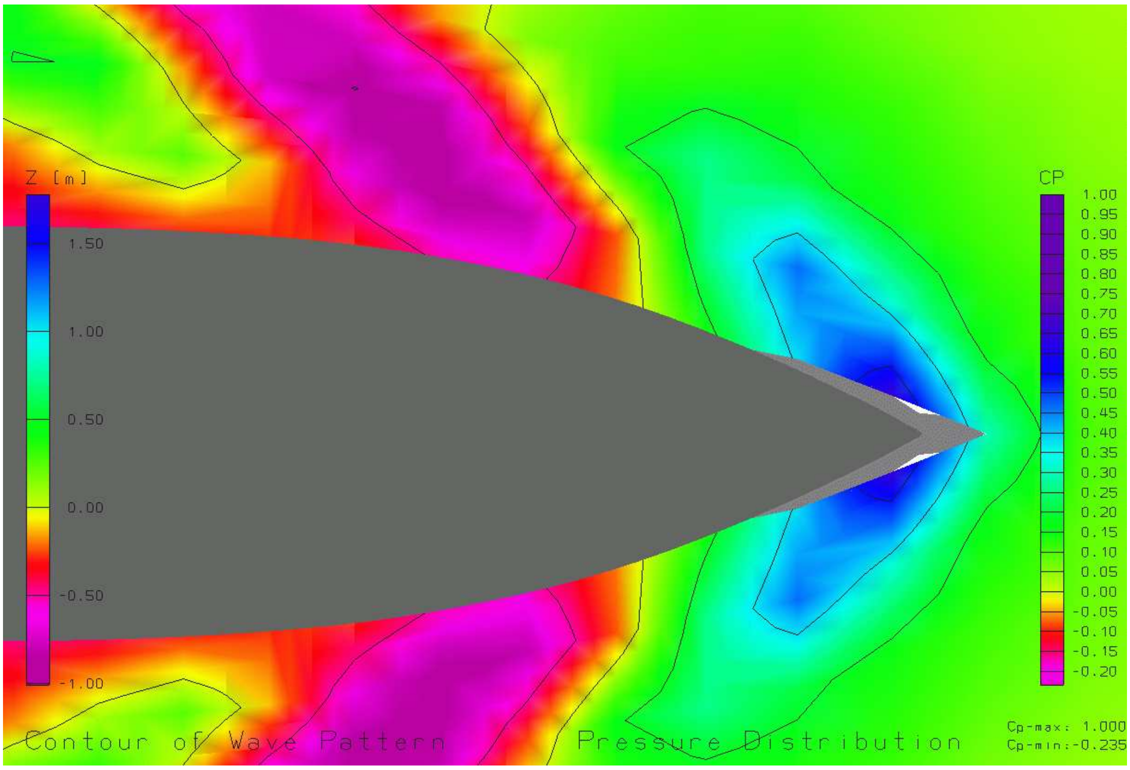


Figure 10.10: MV Estonia's own wave System at a ship speed of 18kn, detailed bow view

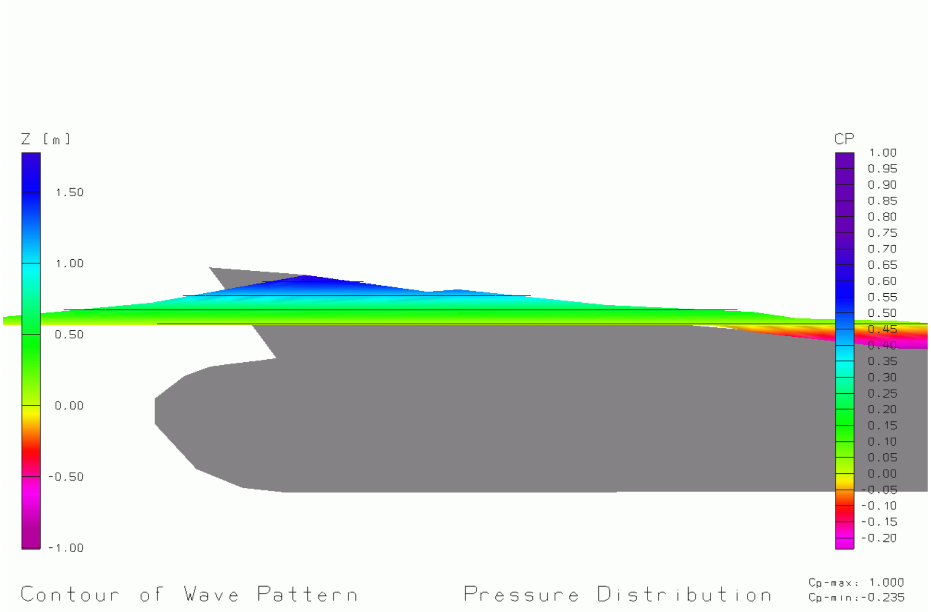


Figure 10.11: MV Estonia's own wave System at a ship speed of 18kn, side view of bow

The determination of the ships' own wave system for a ship speed of 18 knots resulted in a bow wave of more than 1m in height, whereas the largest elevation close to the hull was determined to be 1.50m. Further to this, the vessel shows a clear tendency to dynamically trim down by the bow, the sinkage at the F.P. was determined to be 0.24m, where the sinkage at the A.P. was determined to be –0.04m. Therefore, it can clearly be concluded that both effects cannot be disregarded when determining inflow rates to the Main Car Deck. Immediately after the flooding of the Main Car Deck started, the theoretical freeboard of the Main Car Deck must be reduced by a minimum of 1.25m -1m bow wave height plus sinkage - to a maximum of 1.75m - 1.50m bow wave height plus sinkage. These values will be taken into account when determining flow rates onto the Main Car Deck.

10.5 Determination of Flow Rates onto the Main Car Deck

The basic simulation model used for the intact condition was now used to determine water ingress onto the Main Car Deck for when the vessel first loses its watertight integrity. The Main Car Deck was modelled as a simple cuboid of the correct dimensions. The size of the opening was assumed to be that of the opening sealed by the bow ramp. This simplifies the geometry significantly and this simplification is justified, because it reduces the computational effort significantly and thus allows one to compute more situations. The results of this phase are scenarios that shall be investigated further. To model the effect of non-zero for-ward speed, the $\frac{1}{2}mv^2$ term has been added into the Bernoulli Equation of the simulation code [SOEDING]. To account for the reduced (dynamic) freeboard of the Main Car Deck due to its own wave system and sinkage the position of the ramp-opening, called 'leak' in the code, was modified accordingly. With respect to the other orders of magnitude considered, this simplification is acceptable. The computations were carried out for several speeds and for the encounter angles of both 150 degrees and 135 degrees, which correspond to the situation when the loss of watertight integrity occurred. Each simulation was carried out over a time interval of 10,000s in 0.5s time steps. In case when the simulated vessel experienced heavy rolling due to the water accumulated on deck, she was righted again and the simulation continued. The simulations were carried out both with and without a 1.50m reduced freeboard to investigate the effect of the bow wave system. *Figures 10.13* and *10.14* show the time plots of the roll angle and the volume accumulated on the Main Car Deck for one representative simulation without considering the bow wave. *Figures 10.15* and *10.16* show the roll angle and the volume of water accumulated on the Main Car Deck at a speed of 14kn, with an encounter angle of 150 degrees, significant wave height is 4.5m and the significant period is 8s. Freeboard is 1.50m reduced due to the bow wave and sinkage at F.P. From the results, an average flow rate of 472m^3/min into the Main Car Deck is determined. This value is reasonable, but maybe even a little too conservative with regards to the results of the experiments of the Swedish ship model basin SSPA [SSPA01] and [SSPA02]. All in all, these results from SSPA cement the justification of the simplifications to the Main Car Deck model for the simulation in ROLLS. These results reflect the general trend that the simulated flow rate increases significantly with speed, and less significantly with the encounter angle. Most important is the fact that the flow rate for the static freeboard is very low. Although the vessel took on sufficient water to the Main Car Deck to finally reach significant heeling angles, the flow rates without the

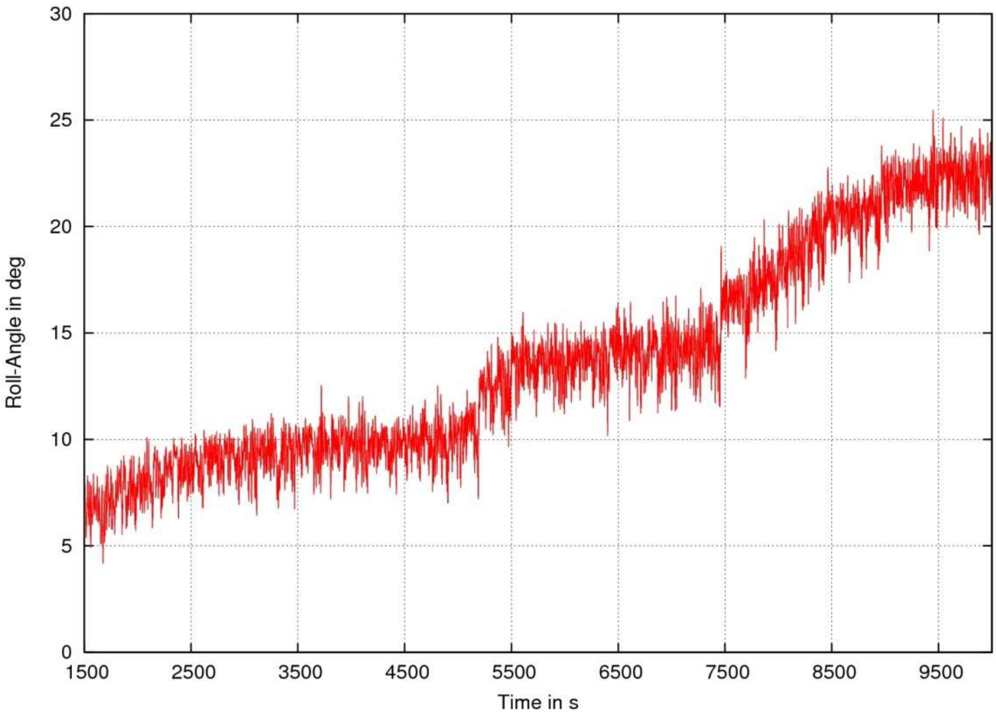


Figure 10.12: Roll-Angle over time at a speed of 12 knots, with a significant wave height of4.5 m, significant wave period of 8s and an encounter angle of150°- without considering the bow wave

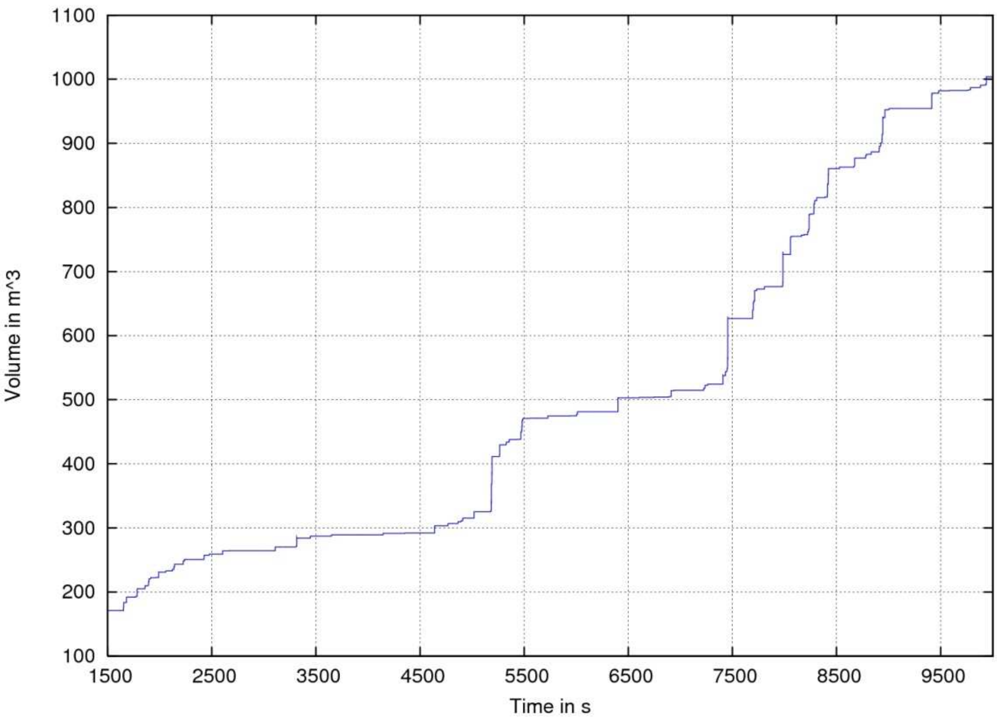


Figure 10.13: Accumulated volume over time at a speed of 12 knots, with a significant wave height of 4.5 m, significant wave period of 8s and an encounter angle of 150°- without considering the bow wave

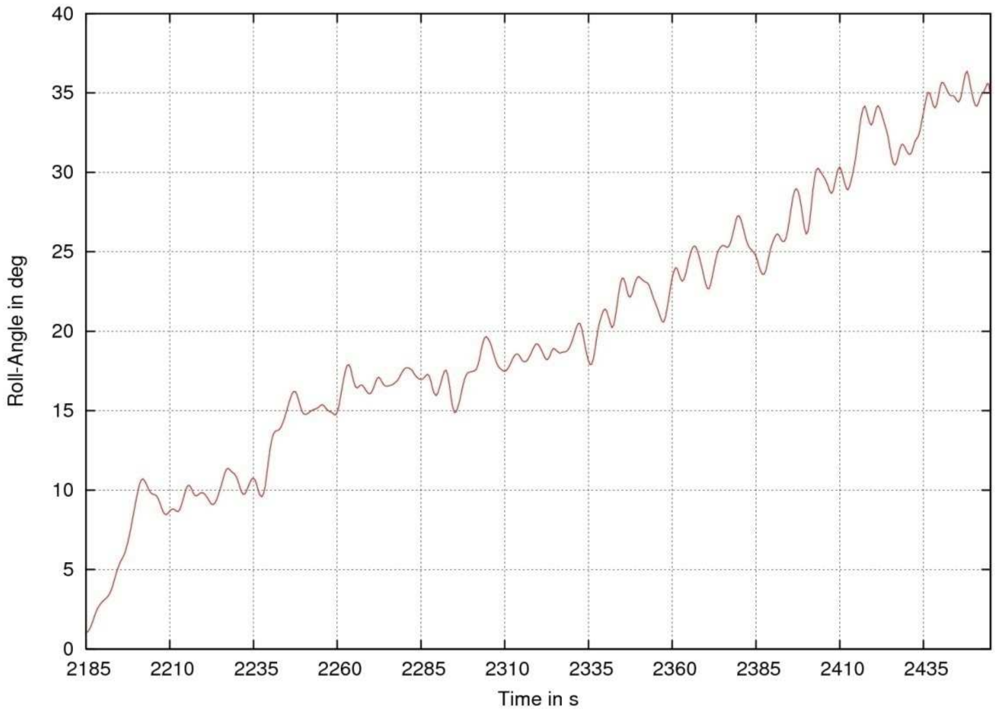


Figure 10.14: Roll angle over time at a speed of 14 knots, with a significant wave height of 4.5 m, significant wave period of 8s and an encounter angle of 150°- considering the bow wave

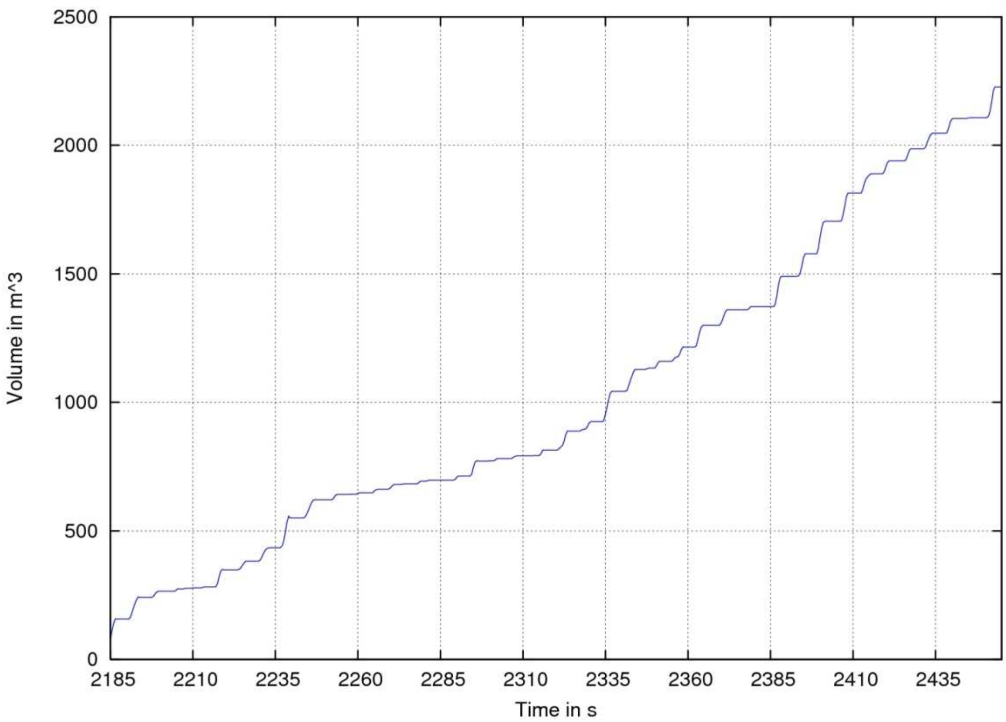


Figure 10.15: Accumulated volume over time at a speed of 14 knots, with a significant wave height of 4.5 m, significant wave period of 8s and an encounter angle of 150°- considering the bow wave

inclusion of the effect of the bow wave determined by our procedure are by far too low to accumulate 1500t in a time span of about 10min. On the other hand, the results including the simplified bow wave influence show that the flow rate increases drastically to values that do clearly lead to amounts of water on deck of the required order of magnitude. This was the intention -to demonstrate with the simplified simulations that it is possible to collect the required amount of water on the Main Car Deck in the time interval of interest, making the proposed scenarios generally plausible. The simplified calculations also show that the flow rates into the Main Car Deck do – as expected– strongly depend on the assumptions with respect to the inflow and freeboard. *Figure 10.17* shows a comparison of inflow rates with two different encounter angles and the 'normal' freeboard and the reduced freeboard.

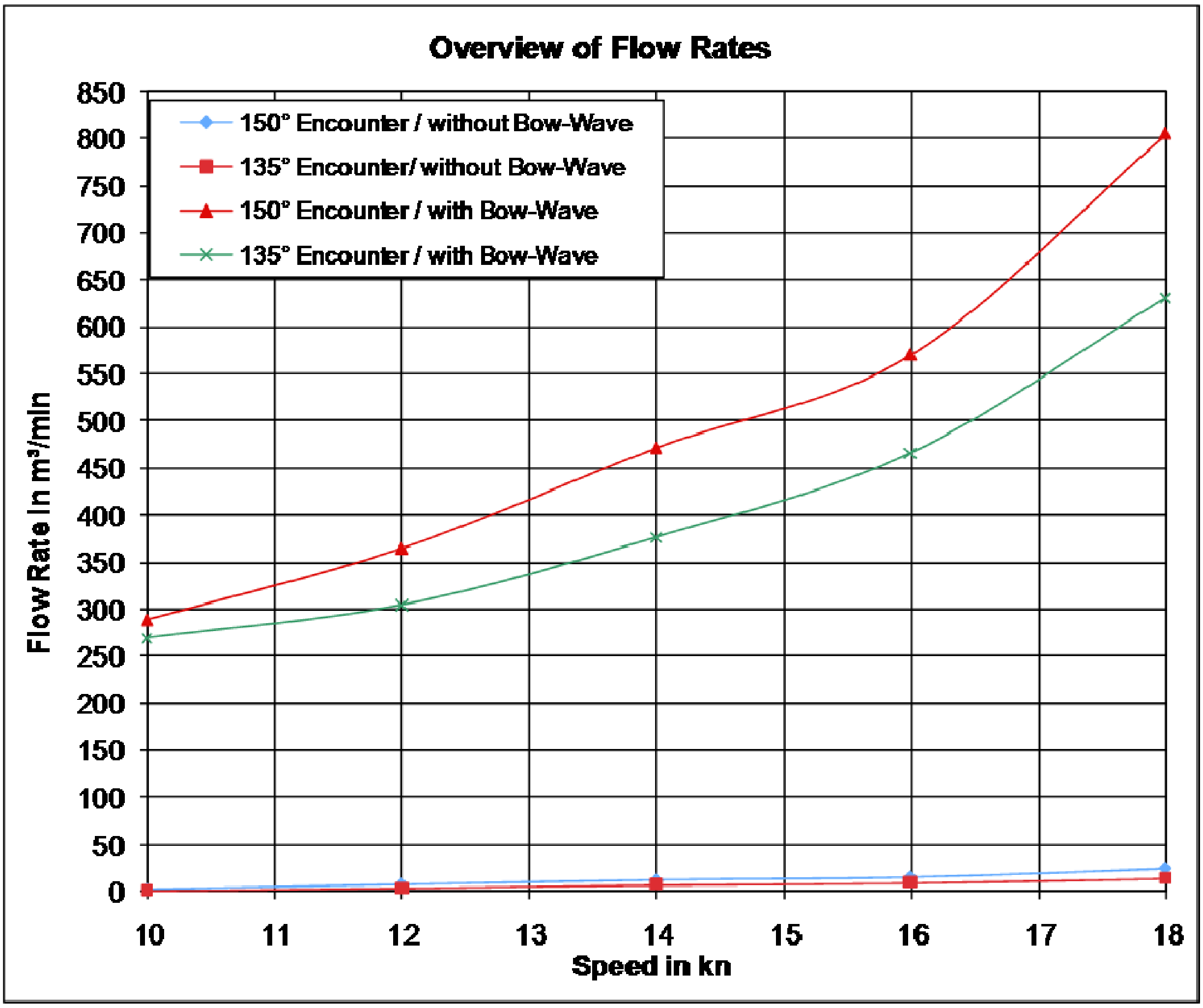


Figure 10.16: Flow rates with and without the ship's own wave system

11 Influence of Manoeuvring on Heeling

As exposed previous in a chapter, MV Estonia turned to the direction where she had come from. Therefore is probably sharp turn contributes the heeling of the ferry, which is investigated in this chapter. The initial speed is assumed in both to be about 14.4kn to 15.0kn and the tactical turning diameter was measured in model experiments by the SSPA-consortium to $3.01L_{PP}$ or 413.6m. [VTT] compared five different car and passenger ferries with regards to their turning diameters which resulted in an average of $3.1L_{OA}$, and worked out a tactical diameter of 480m for MV Estonia. The calculations of the author using the E4 software result in a tactical diameter of 441m or $3.21L_{PP}$ at an initial speed of 14.5kn, shown in *Figure 11.1*.

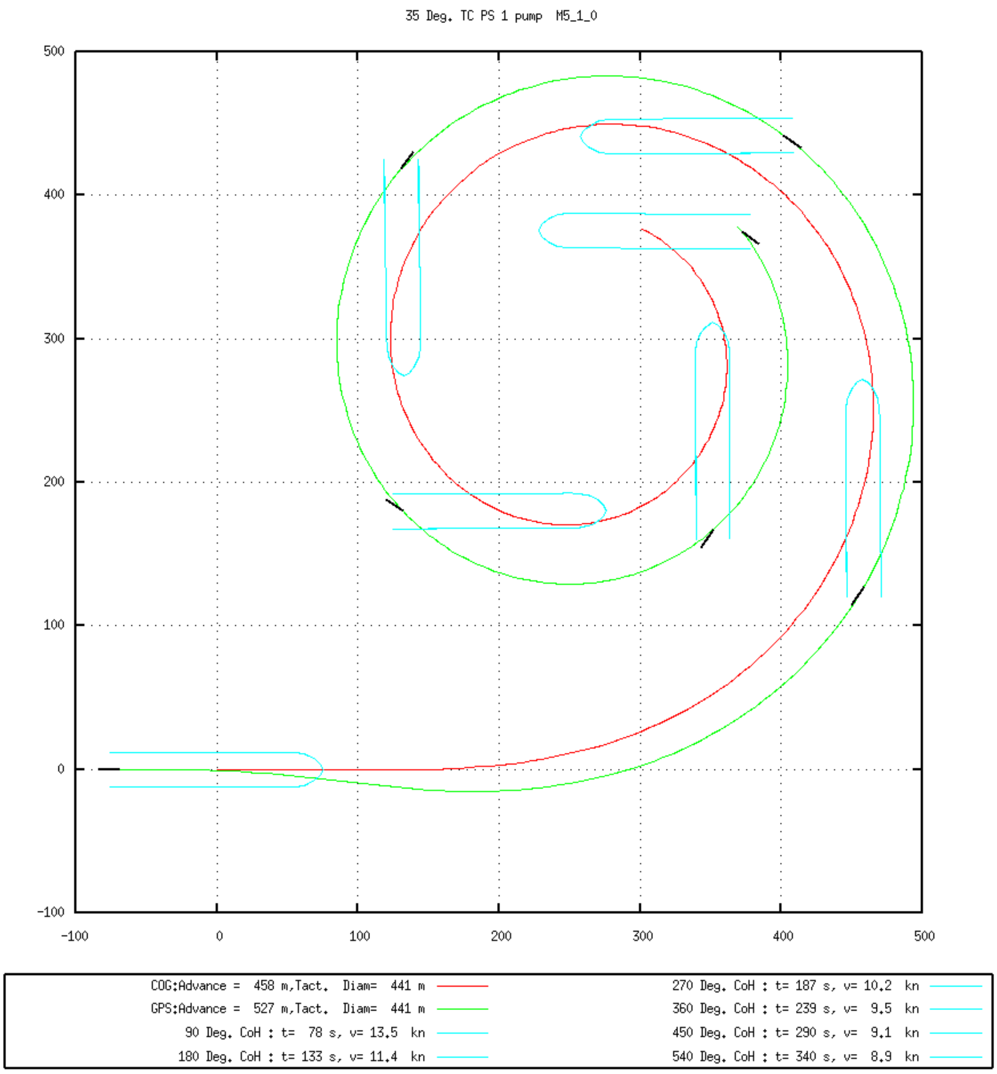


Figure 11.1: Graph of turning circle of MV Estonia with loss of speed

This diameter is in the range of all the model tests and calculations carried out concerning MV Estonia directly. The maximum heeling angle is calculated to be 5.8° at a maximum of 35° rudder angle, see *Table 11.1*. The rudder angle of 35° is reached in less than 20 seconds.

During the turning phase this heeling angle contributes to the water inflow on the Main Car Deck of MV Estonia. The magnitude of the inflow depends strongly on the actual wave train, but considering the heeling due to the turn, the inflow rates presented in previous chapters can be assumed to be conservative calculations.

Table 11.1*: Results of manoeuvring simulation, 3 minutes in 10 sec steps*

Yard number:	Ship name:	Date:
590	Estonia	

T s	x m	-y m	Head. m	Heel Deg.	Rud.A Deg.	Eff.A Deg.	vx kn	vcros kn	FxRud kN	FyRud kN
1	7.E-4	0.	0.0	1.1	0.0	0.0	14.5	0.0	24.	-69.
10	67.	0.	-0.4	2.2	-20.0	-18.5	14.5	0.4	3.	-217.
20	142.	0.	-5.3	3.1	-34.9	-28.5	14.4	2.0	-49.	-321.
30	216.	-5.	-16.0	3.9	-34.9	-26.7	14.2	2.6	-37.	-303.
40	287.	-21.	-29.9	4.8	-34.9	-26.5	13.8	2.6	-36.	-300.
50	351.	-52.	-45.2	5.4	-34.9	-26.4	13.2	2.7	-36.	-298.
60	403.	-96.	-61.2	5.6	-34.9	-26.2	12.6	2.8	-39.	-304.
70	440.	-149.	-77.3	5.8	-34.9	-26.2	12.0	2.8	-46.	-316.
80	461.	-208.	-93.6	5.8	-34.9	-26.2	11.5	2.8	-52.	-325.
90	465.	-267.	-109.	5.8	-34.9	-26.3	11.0	2.8	-56.	-334.
100	453.	-323.	-126.	5.8	-34.9	-26.4	10.5	2.8	-62.	-345.
110	427.	-372.	-142.	5.8	-34.9	-26.5	10.0	2.8	-67.	-355.
120	391.	-410.	-158.	5.8	-34.9	-26.6	9.6	2.8	-71.	-364.
130	347.	-436.	-175.	5.8	-34.9	-26.7	9.3	2.8	-76.	-374.
140	300.	-448.	-191.	5.8	-34.9	-26.8	8.9	2.8	-80.	-384.
150	252.	-447.	-208.	5.8	-34.9	-26.8	8.6	2.8	-85.	-394.
160	209.	-433.	-225.	5.8	-34.9	-26.9	8.3	2.8	-89.	-404.
170	172.	-408.	-241.	5.8	-34.9	-26.9	8.0	2.8	-92.	-410.
180	145.	-376.	-258.	5.8	-34.9	-27.0	7.7	2.8	-94.	-415.

12 Sinking Simulation

The sinking simulation, as dealt with in this thesis, has a focus on the time sequence from the intermediate equilibrium at a list of about 30° to the final sinking of the vessel. After staying in the intermediate floating condition for a few minutes, MV Estonia started to increase list to starboard and started to increase aft ward trim. In this chapter different factors are investigated due to the further sinking of the vessel to integrate their effects to the sinking process into the sinking simulation. A central question to answer is through which openings water entered the ferry. Therefore window collapse loads were investigated, as well as the ventilation system of the vessel and the effect of the cargo shift. The calculations again have to be in line with the testimonies of the survivors. Mapping of events to a certain time from testimonies becomes increasingly more unreliable the further along the sinking sequence you go. The people on board MV Estonia were struggling for their lives; some may have been in a state of shock. Further to this, there is no evidence from the testimonies of the witnesses with regards to the trim of MV Estonia, as it sank. The main reason for this is that the trim of the vessel is significantly smaller and less noticeable, compared to the list, especially as it would have provided less of an impediment to those trying to escape the vessel.

The trim, however, plays a major part in the final sinking sequence. Selected statements state that MV Estonia sank stern first, and it is possible to indicate from this that MV Estonia's stern was just about submerged at a list of around 90°. Further backed up by the testimony that some of the life rafts on Deck 7/ 8 were self-inflated on water contact.

P28: At hearing typhoon, saw life rafts inflating at stern

P20: At hearing typhoon, saw life rafts inflating at stern

P79: As the Funnel touched the water surface:

- capsized quickly
- saw life rafts inflating at stern

– min later stern under water, 50...60m of the vessel above the surface

P49: At hearing typhoon, the ship is sunk to one half

P59: at capsizing upside down, MV Estonia had a trim, not much, perhaps 15°, bow up

P48: As lying on her side, most of MV Estonia [superstructure] was above the surface

P93: stern was lower than bow after the list of 90°

P35: – life rafts were wheeled from stern to bow

– stern sank deeper and deeper as the lights went out

P1: ferry sank stern first

P8: at a list of 90°, water raised quickly in the vessel

P25: at MV Estonia disappearing from the surface, life rafts entered the surface form below

P33: final sinking, bow steep in the air

P7: sitting on the side of the ship, seeing lots of life rafts at the stern of the ship

12.1 Window Collapse Loads

The dimensions of the rectangular windows installed on the MV Estonia followed the DIN ISO 3903 “Shipbuilding and marine structures - Ships' ordinary rectangular windows” [DIN3903] and the DIN ISO 3254 “Shipbuilding and marine structures - Toughened safety glass panes for rectangular windows and side scuttles - Punch method of non-destructive strength testing” [DIN3254]. Two sizes of non-openable windows were installed on MV Estonia. The smaller one being 400mm wide and 800mm high, the larger being 600mm wide and 1500mm high. Both have a thickness of 10mm and belong to window group “N”. Annex B to DIN ISO 3903 indicates maximum allowable pressures for rectangular ship windows. The German manufacturer of the windows installed on MV Estonia did not add a safety load factor, on top of the DIN ISOs. This was certified by the classification society Bureau Veritas.

The glass type in the window was toughened safety glass. A property of toughened safety glass is that in case of an impact the hydrostatic collapse load is reduced considerably. This is of concern with regards to the sudden list and the numerous testimonies of witnesses reporting of sliding and falling items on the vessel.

12.1.1 The 400mm x 800mm Windows

According to the DIN ISO 3903 and DIN ISO 3254, some values and a factor are to be determined to calculate the collapse loads.

t: thickness of the window panes

β: an enlargement factor reflecting the width-to-height ratio, here width-to-height ratio of the small window is 2.0 leading to the β factor being 0.61

b: breadth of the window

The maximum resistible pressure of the windows is calculated to be:

$$p = \frac{40000 \cdot t^2}{\beta \cdot b^2} kPa \qquad (1)$$

$$p_{400x800} = \frac{40000 \cdot 10^2}{0.61 \cdot 400^2} kPa = 41 kPa \qquad (2)$$

The resulting hydrostatic pressure corresponds to a static water column of height:

$$p = \rho \cdot g \cdot h \Leftrightarrow h = \frac{p}{\rho \cdot g} \qquad (3)$$

$$h_{400x800} = \frac{41000\frac{N}{m^2}}{9.81\frac{m}{s^2}\cdot 1004\frac{kg}{m^3}} = 4.16m \tag{4}$$

p: pressure

ρ: density of sea water, here 1.004tm^{-3}

g: acceleration due to gravity

h: height of the corresponding static water column

The resulting hydrostatic pressure corresponds to a static water column of 4.16m.

12.1.2 The 600mm x 1500mm Windows

Analogue to the small window types, the collapse load of the large window types is calculated to the maximum resistible pressure of the windows:

$$p = \frac{40000\cdot t^2}{\beta\cdot b^2}kPa \tag{5}$$

$$p_{600x1500} = \frac{40000\cdot 10^2}{0.685\cdot 600^2}kPa = 16.2kPa \tag{6}$$

The resulting hydrostatic pressure corresponds to a static water column of height:

$$p = \rho\cdot g\cdot h \Leftrightarrow h = \frac{p}{\rho\cdot g} \tag{7}$$

$$h_{600x1500} = \frac{16200\frac{N}{m^2}}{9.81\frac{m}{s^2}\cdot 1004\frac{kg}{m^3}} = 1.64m \tag{8}$$

The resulting hydrostatic pressure corresponds to a static water column of 1.64m – but according to paragraph 7.2.1 of DIN ISO 3903, the whole window assembly – of type series „F“ – must resist a minimum pressure of 0.35bar. This is equal to a water column of 3.55m.

12.1.3 Resulting Window Collapse Loads

The 400mm x 800mm window resists a hydrostatic water column of 4.16m and the 600mm x 1500mm window resists a hydrostatic water column of 3.55m. These hydrostatical water columns are the minimum resisting values; a conservative approach. But the ferry rolled in a sea state and a additional hydrostatical water column should be added. It is assumed in the following simulation that these two effect compensate each other. The values of 4.16m and 3.55m were implemented in the sinking simulation.

The outside doors on decks 4 to deck 8, also containing windows, were assumed to resist a hydrostatic water column of 2.50m, the double-door on deck 7 at frame "x" leading to the life boats from the centre staircase is assumed to resist a hydrostatic water column of 2.00m. After a window or a door has collapsed, the opening is assumed to be completely free. In other words after the window of the size of 400mm x 800mm has collapsed, the cross-sectional area of the inlet is $0.32m^2$.

12.2 Ventilation

The ventilation-system of MV Estonia has a major influence on her sinking-sequence. Three main parts of the ventilation-system are highlighted in the following chapters: the ventilation of the main car deck, the ventilation with air intake on the vessels sides - just below Deck 4 - and the ventilation through the centre casing.

12.2.1 Ventilation of the Main Car Deck

The main ventilation to and from the Main Car Deck was carried out by four sets of four large pipes. In the front wing house, *Figure 12.1* and *Figure 12.2,* there were four on the starboard side and four on the portside sucking air on the Main Car Deck and similarly in the aft ward wing house, *Figure 12.3* and *Figure 12.4*, had two set of four ventilation pipes each to blow out the exhaust air. Each of these pipes of the aft ward and the front wing house has a diameter of 1131mm. Between frames 55 to 56, 80 to a, a to b and 89 to 90 an additional side air intakes are installed on both the starboard and portside, each with intake cross section of 0.16m². They are presented in chapter "Ventilation with Side Air Intake".

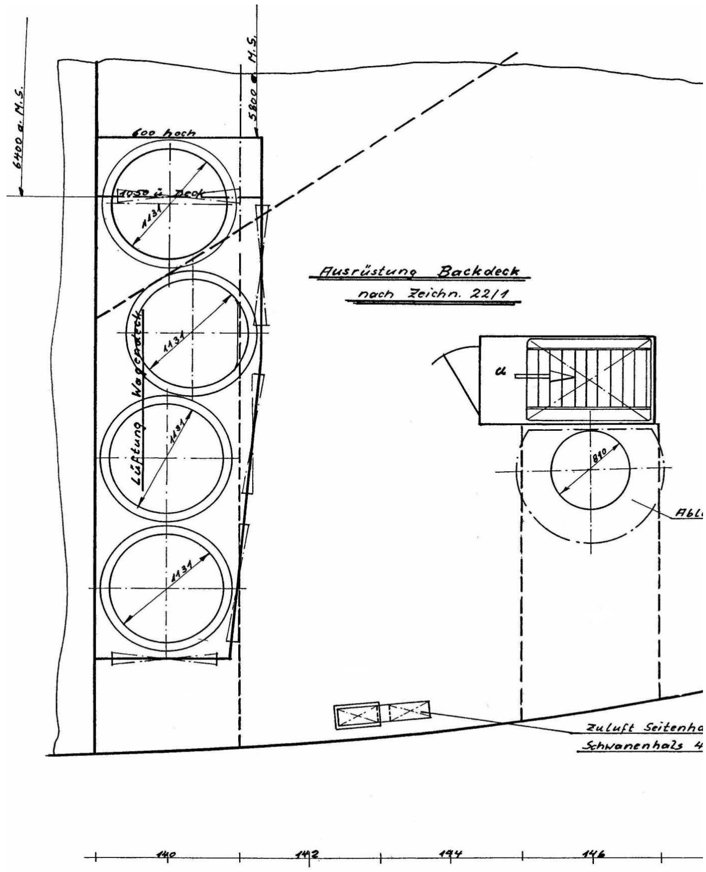


Figure 12.1: For-ward Wing House, starboard side, top view, Drawing S590 – 24/3

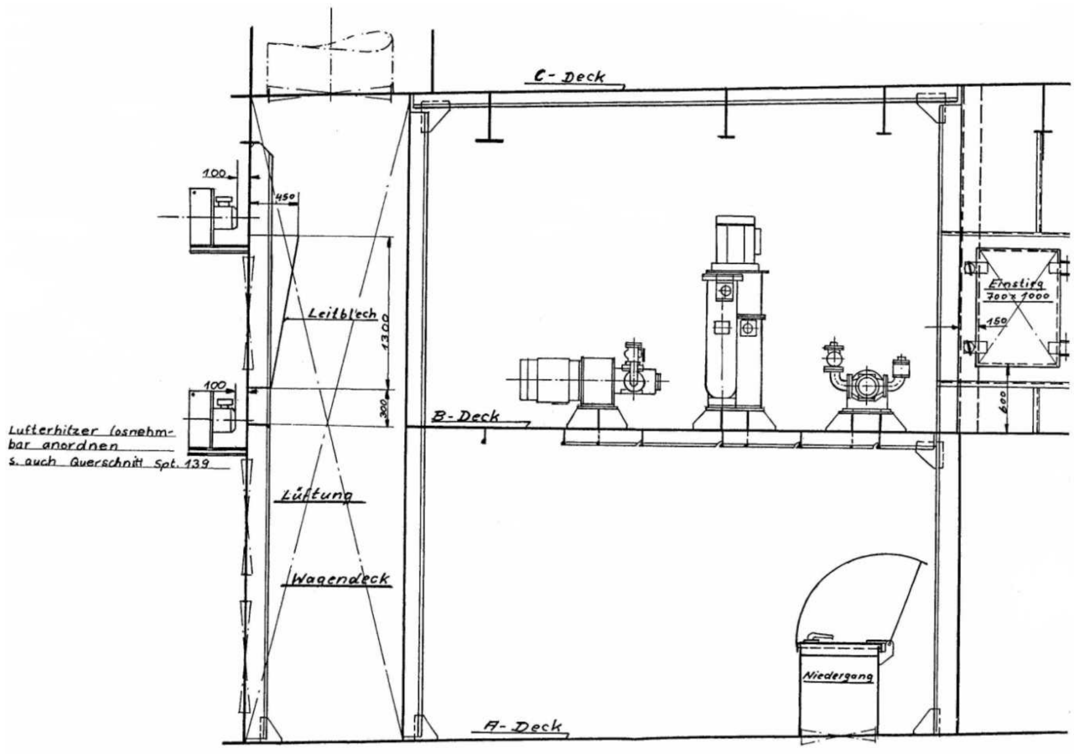


Figure 12.2: Front Wing House, starboard side, lateral view, Drawing S590 – 24/3

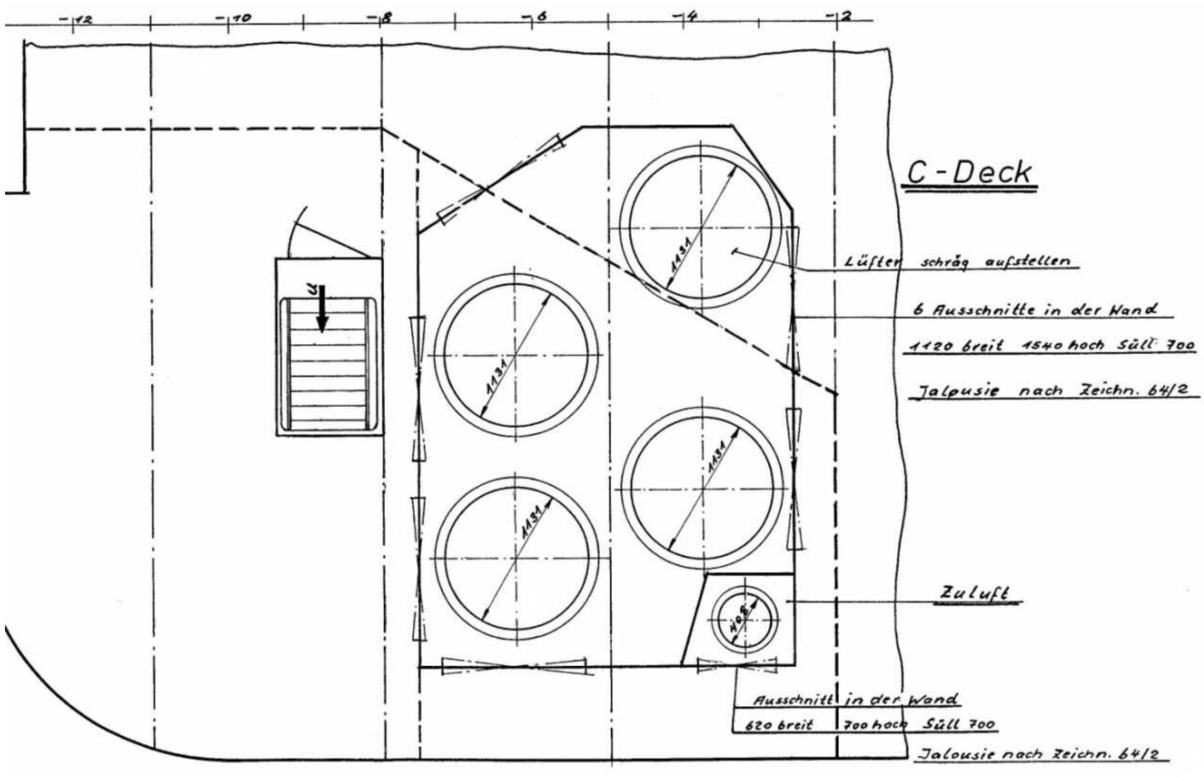


Figure 12.3: Aft Wing House, starboard side, top view, Drawing S590 – 24/2

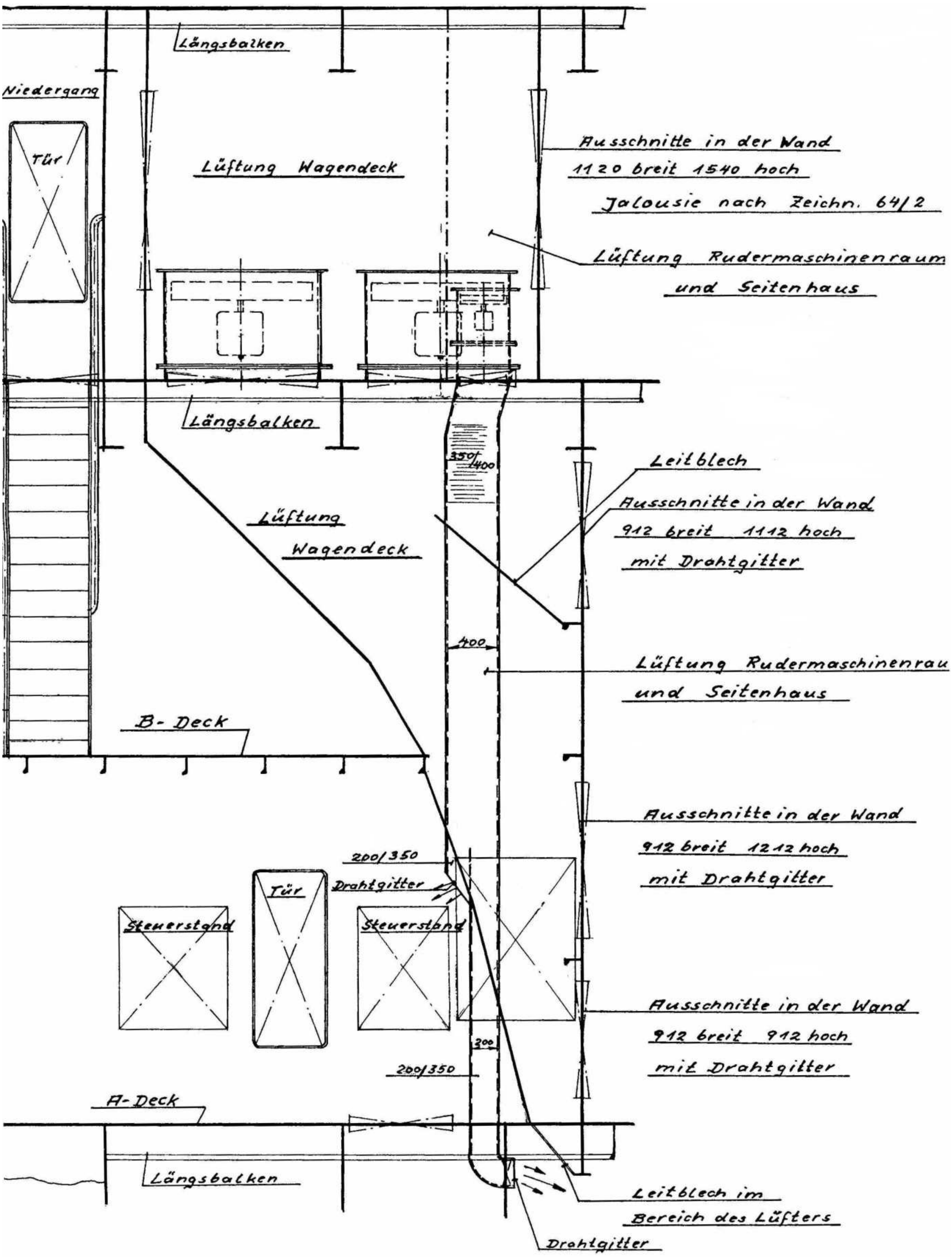


Figure 12.4: Aft Wing House, starboard side, lateral view, Drawing S590 – 24/2

12.2.2 Ventilation through Centre Casing

The following compartments contain the ventilation ducts - through the centre casing - that perform the ventilation for some of the compartments below the Main Car Deck: the engine control room, the workshop, all compartments with cabins, both compartments of the Spa-Area on Deck 0 and the auxiliary engine room. The centre casing is not symmetrically amidships, but between the distances 300mm and 2700mm from the Centre Line on the starboard side of the vessel. Further to this, these compartments below the Margin Line were designed to be watertight, each compartment arranged in longitudinal direction with watertight doors to the adjacent compartment. Consequently, in the case of a capsize to the starboard on an even keel, these compartments can flood to just about half their volume because of trapped air inside excluding the effect of compression from outside pressure and the effect of holes in the shell below Margin Line. In the case of outside pressure, for example from surrounding water of a sinking ship, the compartments can fill to more than half, depending on the pressure level.

12.2.3 Ventilation with Side Air Intake

As mentioned in chapter "Ventilation of the Main Car Deck" there are eight side ventilation ducts in the aft and middle part of the ship. An outside view can be seen in *Figure 12.5* and the corresponding drawing in *Figure 12.6*.

These side ventilation ducts, all of a similar design, lead to different compartments below the Main Car Deck.

Figure 12.5: Outside view of the side ventilation openings

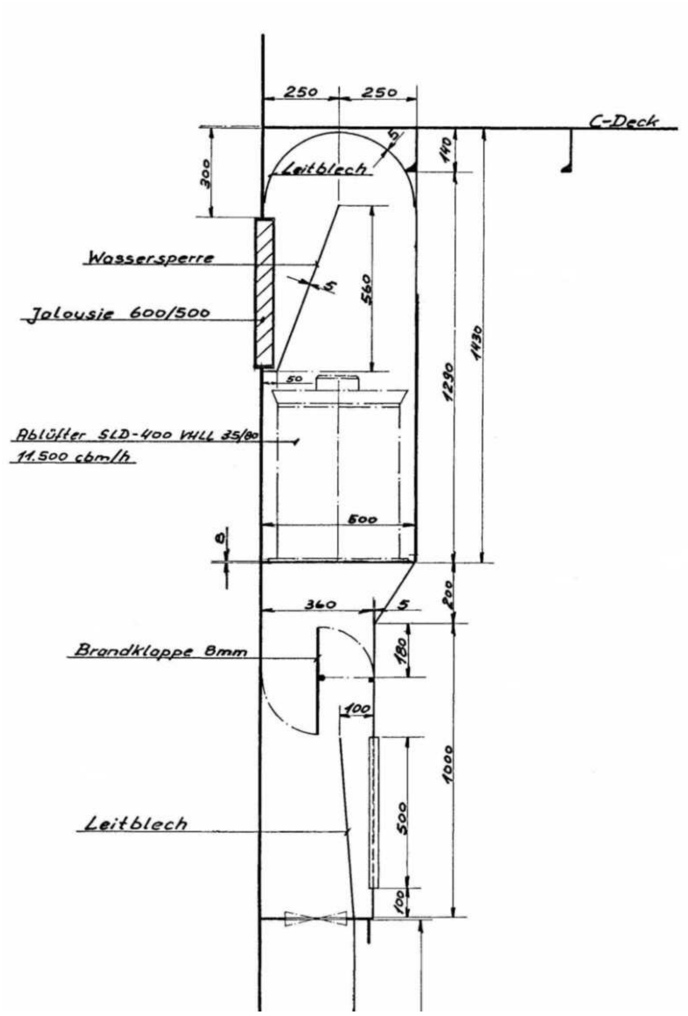


Figure 12.6: Drawing of the side ventilation ducts, Drawing S 590 – 64/11

The following table gives an overview of all side ventilation ducts:

Table 12.1: Overview of the side ventilation openings

Connected Compartment	Ships´ Side	Area of inlet in m²	Frame
Stern Tube/ Store Room	PS and STB	0.28	26...27
KaMeWa	PS and STB	0.28	37...38
Separator Room	PS only	0.28	40...41
Store (Provision)	PS and STB	0.08	43...44
Store (Provision)	PS and STB	0.08	44...45
Separator Room	PS and STB	0.28	46...47
Separator Room	PS only	0.28	47...48
Separator Room	PS and STB	0.28	49...50
Car Deck	PS and STB	0.16	55...56
Main Engine Room	PS and STB	0.28	64...65
Main Engine Room	PS and STB	0.28	65...66
Car Deck	PS and STB	0.16	80...a
Car Deck	PS and STB	0.16	a...b
Car Deck	PS and STB	0.16	89...90
Sewage Treatment	PS only	0.32	90...91
Sewage Treatment	PS only	0.32	93...94

All hydrostatic calculations are carried out for the 'Later Phase' of the sinking of MV Estonia of course consider the so-called "Wassersperre" or water barrier, the metal sheet designed to prevent spray entering the ducts.

12.2.4 Details of Aft Wing House

The aft wing house of MV Estonia has access from the Main Car Deck via a mesh wire door, which is clearly not watertight, so water could easily flow into the aft wing house. See *Figure 12.7*[8]. The ventilation duct, supplying the aft wing house and the steering gear room with fresh air, separates 2.1m above Main Car Deck level into a duct for the wing house, and a duct for the steering gear room, see *Figure 12.8*. The cross section of the duct ending in the steering gear compartment is 0.07m². The result of a large amount of water on the Main Car Deck is that it can flow from Main Car

[8] The German word for mesh wire door is "Drahttür".

Deck into the aft wing house and then into the ventilation duct and finally to the steering gear compartment, following the red arrows of *Figure 12.8*. The effect on MV Estonia is an increase of aft-ward trim with a comparably small mass of water, caused by the extreme aft position of the of the steering gear room.

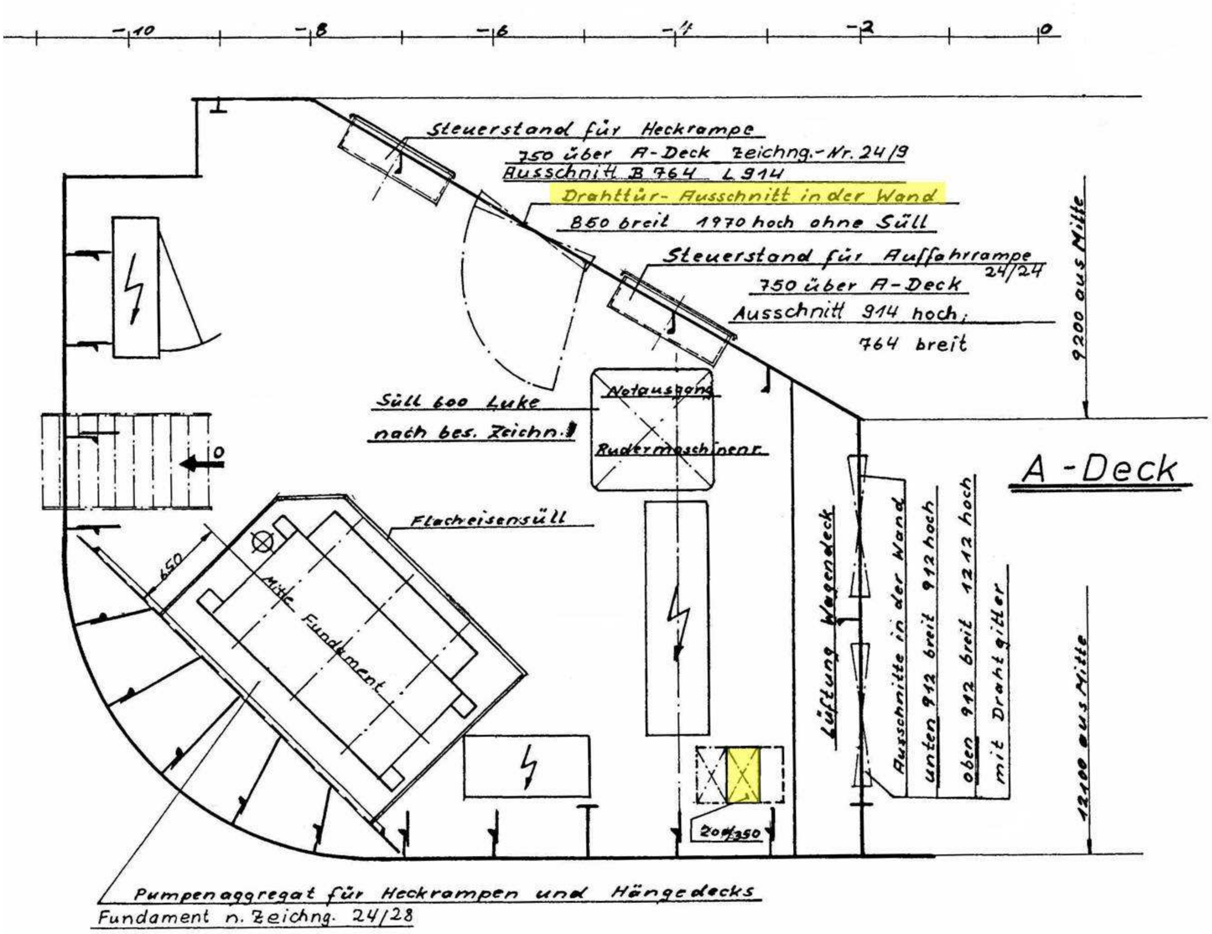


Figure 12.7: Aft Wing House on Main Car Deck level, starboard side, top view, Drawing S 590 – 24/2

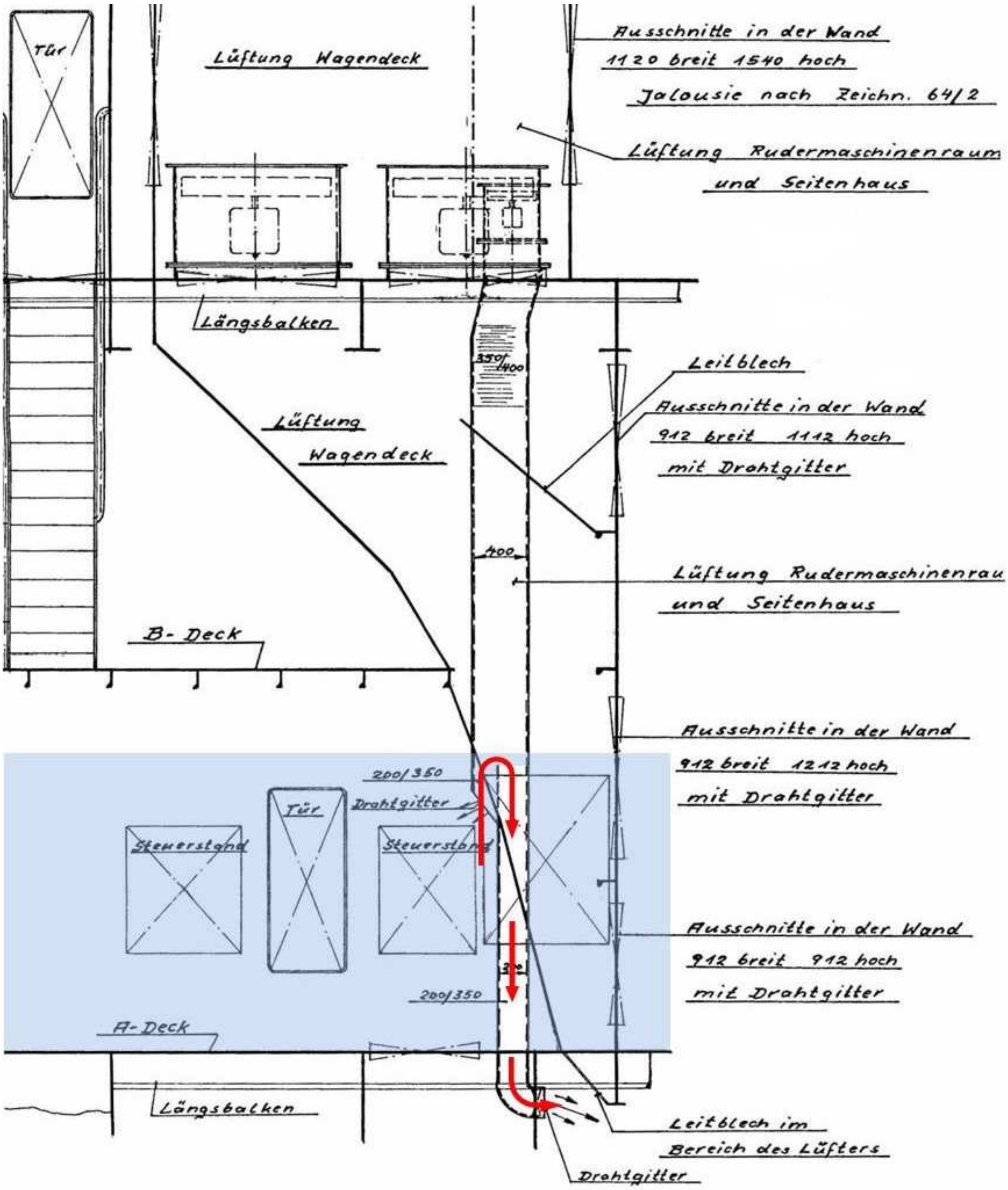


Figure 12.8: Aft Wing House from Deck 2 to Deck 4, starboard side, lateral view, Drawing S 590 – 24/2

12.3 Cargo Shift

On the last voyage of MV Estonia on September 27th/ 28th 1994, the Hoistable Car Deck was not in use and all vehicles were stored on the Main Car Deck, Deck 2, which was almost completely filled. As mentioned in chapter "Condition of MV Estonia on Sea Floor" a cargo shift took place during the sinking. There are, however, no testimonies reporting at what time or to what extent the cargo shift took place. Assumptions on this are very difficult because of the large scope of uncertainty due to, for example, the coordinates of the centre of gravity of each vehicle or the coefficient of adhesion of each vehicle on dry, partially wet or completely wet deck.

Because of this situation, the cargo shift of the vehicles on Main Car Deck is idealised in two steps. The first is upon passing the steady list of 30°, the cargo shift is set to 1m. The second step is at 60° steady list, where the cargo shift now increases by a further 0.5m.

Of course, there is a cargo shift of other items on MV Estonia, like the interior, items of the hotel business, luggage and others. However, the total mass of these items and their possible direction of shift - in other words the inclining moment – is, compared to other effects, of minor importance and will not be taken into account.

12.4 Calculation Procedure

The evaluation of the hydrostatic scenarios have clearly shown that water on the Main Car Deck is a key-factor in the sinking sequence of MV Estonia. The time that water started entering the Main Car Deck was between 01:00 and 01:02. The beginning of the calculations of the sinking sequence is set to 01:00. Should the beginning in reality have been one or two minutes later, the whole sinking sequence would be shifted later according to the time offset.

A result of Scenario 1 is that, most likely, a mass more than 1500t of water on the Main Car Deck caused a hydrostatic list of 30°. Up to this stage, it was the main focus of this thesis – now the focus is on the later phase of the sinking sequence, namely on the quasi static equilibrium floating condition when the list is of more than 30°. Each calculation step corresponds to a time step, mostly with an increment of 30 seconds. Based on the equilibrium floating condition, the actual freeboard of all relevant openings, both external and internal with respect to the relevant fluid level and either outside ship or actual compartment filling, is determined which permits computation of the actual pressure level at that opening and the filling stage for the next step. The lost buoyancy method, which is also typically preferred for damage stability calculations where intermediate stages of flooding have to be determined, is not applicable for this type of problem. This is because care should be taken for all righting or trimming levers, metacentric heights etc. to actually refer to the momentary values of the ship's mass. Therefore the added mass method is used throughout the whole calculation procedure. This method is based on algorithms where similar calculations of intact and damage stability problems have already been approved by several statutory authorities during the approval process of recent RoRo- Ferries designed and built by Flensburger Schiffbau- Gesellschaft (FSG).

The calculation procedure adopted for the sinking process of MV Estonia is as follows:

- Calculate the freeboard of all relevant openings that lead to a further flooding, either with respect to the outside of the ship or to an internal fluid level for a momentary floating condition given by draft, trim and heel.
- Calculate the pressure height and the inflow rate into the flooded compartment or group of compartments
- Calculate the momentary filling for all momentarily flooded compartments and the actual amount of water in these compartments for the next time step. It may be possible that a compartment is now 100% filled or a new compartment may additionally be flooded.

- For the assumed filling condition of all compartments involved in the momentary time step, calculate the momentary equilibrium floating condition, the hydrostatic stiffness matrix and -
- Additionally, the righting levers. The momentary equilibrium in trim is determined allowing all fluids to move freely.

For this floating condition, the freeboards of the relevant openings are determined again and the next iteration step is performed. The procedure starts from the submergence of the first opening until a final sinking of MV Estonia can be assumed.

The inflow-rates of water into the ventilation ducts, the collapsed windows and doors and, in the final stage, through the bow-opening as well is calculated with the *Torricelli Theorem* as follows

$$\dot{m} = \rho \cdot \mu \cdot A \cdot \sqrt{2 \cdot g \cdot h \cdot \cos(\varphi)} \qquad (9)$$

ρ: density of sea water, here 1.004tm^{-3}

$\mu = \varphi_{dvo} \cdot \psi = 0.59$

$\varphi_{dvo} = 0.9656$ - decrease of velocity at outflow [MHAN]

$\psi = \frac{A_S}{A} \quad with \quad A_S \rightarrow \infty \Rightarrow \psi = \frac{\pi}{\pi + 2}$

A_S: cross section of the surrounding surface

A: cross section of inflow

g: acceleration due to gravity

h: vertical difference of water level from outside to inside, at first inflow into ventilation ducts and then vertical distance from inflow to outlet

φ: heeling angle; only used at first inflow of ventilation ducts, otherwise left out

In the following hydrostatic calculations, the hydrostatic model is modified, compared to the model used in the first chapters of this thesis, in a way such that the bow visor is removed from the model and subtracted from the mass distribution of the light ship weight. The longitudinal centre of gravity of the visor is assumed to be 140.2m from A.P., and the mass of the bow visor is assumed 60.0t, according to [JAIC01].

Other factors that influence the sinking sequence, like the window and door collapse loads, the arrangement of the ventilation ducts and the cargo shift were discussed in pervious chapters.

In the later phase of the sinking, especially in the compartments below the Main Car Deck, the situation of entrapped air must be considered. The water ingress in such compartments with entrapped air will not stop completely, but will compress the air the compartment in accordance with the hydrostatic pressure at the inflow opening. To calculate the possible amount of water that ingresses into a compartment with trapped air, a calculation is performed according to the Boyle-Mariotte gas law. With an assumption that the entire area of study is isothermal, the volume decreases proportionally to the increasing pressure, according to:

$$V_2 = V_1 \cdot \frac{p_1}{p_2} \qquad (10)$$

V_1: volume of trapped air at the moment of the air lock

V_2: final volume of trapped air at considered time step

p_1: pressure of trapped air at the moment of the air lock

p_2: final pressure of trapped air at the considered time step

With these calculation procedures, a quasi-static approach was used to calculate the so called 'later phase' of the sinking. 64 calculation steps were carried out with an increment of 30 seconds in this later phase.

The detailed data sheet to each floating condition is given in [KEH02].

12.5 Time Steps of Sinking Simulation

The following *Table 12.2* connects the calculation steps to a time in the sinking sequence and to the order of flooding. Each compartment is mentioned in the table when the first water enters the compartment.

All watertight doors are assumed to be closed.

Table 12.2: Sequence of flooding of the compartments

Step	Time	Flooded Compartment	Flooded by
0	01:00:00	Deck 2: Main Car Deck	Bow Opening
2	01:04:00	Deck 1: Steering Gear Compartment and adjacent store	Ventilation Duct
6	01:09:00	Deck 2: Cargo Shift on Main Car Deck – all vehicles 1m to STB	---
15	01:18:00	Deck 0: Stern Tube/ Store Room	Ventilation Duct
16	01:18:30	Deck 0: „KaMeWa"-Room	Ventilation Duct
		Deck 1: Store Frame 43...53	Ventilation Duct
		Deck 0: Separator Room	Ventilation Duct
17	01:19:00	Deck 0/ Deck 1: Main Engine Room	Ventilation Duct
23	01:22:00	Deck 4: Main Fire Zone 3 (aft), incl. of Deck 1, 2, 3	Window
26	01:23:30	Deck 5: Main Fire Zone 3 (aft)	Window
27	01:24:00	Deck 4: Main Fire Zone 2 (middle)	Window
29	01:25:00	Deck 5: Main Fire Zone 2 (middle)	Window
30	01:25:30	Deck 4: Main Fire Zone1 (front)	Window
		Deck 6: Restaurant (Main Fire Zone 3, aft)	Window
31	01:26:00	Deck 6: Galley (Main Fire Zone 3, aft)	Window
32	01:26:30	Deck 1: Bowthruster Room	Ventilation Duct
		Deck 6: Main Fire Zone 2 (middle)	Window
34	01:27:30	Deck 1: Store Frame 33...43	Stair Case
35	01:28:00	Deck 2: Cargo Shift on Main Car Deck – all Vehicles 0,5m to STB	---
		Deck 5: Main Fire Zone 1 (front)	Window
37	01:29:00	Deck 7/ Deck 8 Main Fire Zone 3 (aft)	Window/ Door
38	01:29:30	Deck 0 to Deck 7: Centre Stair Case, connection from Deck 0 to Deck 7	Door
39	01:30:00	Deck 6: Main Fire Zone 1 (front)	Window
41	01:31:00	Deck 8: Engine/ Machinery Room Frame 40...53	Door
42	01:31:30	Deck 7: Main Fire Zone 2 (middle), Starboard Side	Window
		Deck 9: Funnel, Frame 45...79	Jalousie
		Deck 8/ Deck 9: Main Fire Zone 1 (front) and Bridge	Window (Wing)
43	01:32:00	Deck 7: Main Fire Zone 1 (front)	Window
44	01:32:30	Deck 2 to Deck 8: Engine Casing Main Engine	Door/ Jalousie
		Deck 1 to Deck 8: Engine Casing Auxiliary Engine	Door/ Jalousie
46	01:33:30	Deck 10: Funnel	Opening
48	01:34:30	Deck 0: Auxiliary Engine Room	Ventilation Duct
		Deck 1: Engine Control Room and Work Shop	Ventilation Duct
50	01:35:30	Deck 2 to Deck 8: Ventilation	Door/ Jalousie
52	01:36:30	Deck 7: Main Fire Zone 2 (middle), Portside	Stair Case

Step 0, 01:00:00

The loss of watertight integrity of the Main Car Deck is most likely related to the two or three metalic bangs numerous witness heard at different positions on MV Estonia. The water easily enters the wing houses from the Main Car Deck, because they were closed by mesh grid doors. The aft-ward trim of the ferry starts to decrease due to the water ingress, although during the whole calculations some aft-ward trim remains.

By the time some several hundred tonnes of water was taken on to the Main Car Deck, its free shifting fluid moments led to a quick increase of a previously steady list.

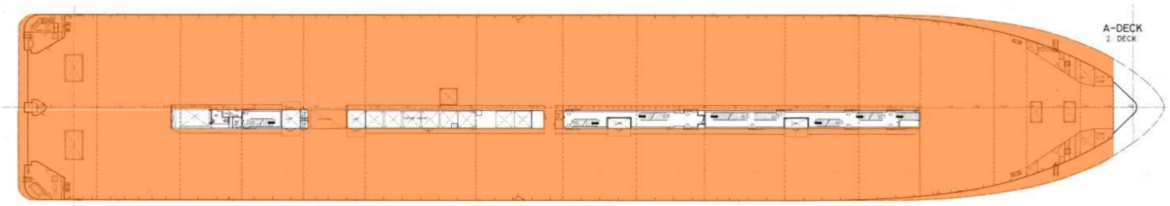


Figure 12.9 : Graphic of flooded areas in step 0, 01:00:00

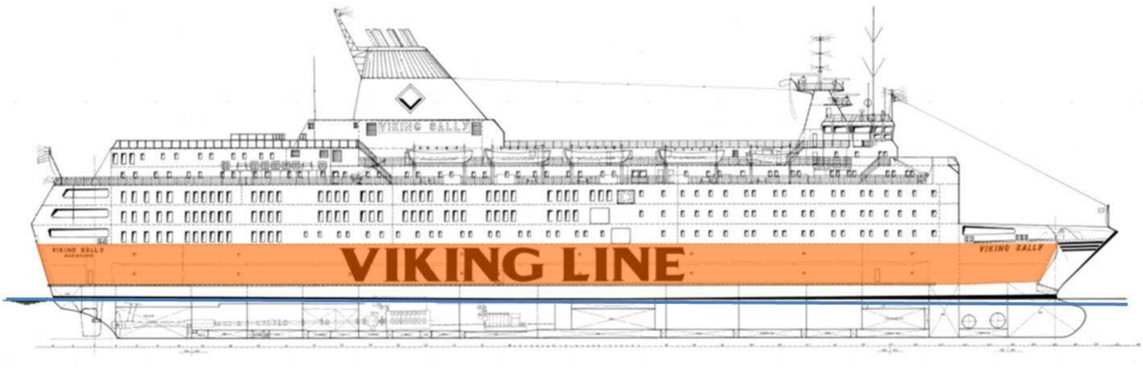


Figure 12.10: Side view of step 0 with highlighted compartments beginning to flood and the waterline

Step 2, 01:04:00

Water enters Deck 1 through the ventilation duct connecting the aft Starboard Side wing house on Deck 2 and the Steering Gear Room with the adjacent, non-watertight Store Room,. Note the technical drawings of this arrangement in the chapter "Detail of Aft Wing House".

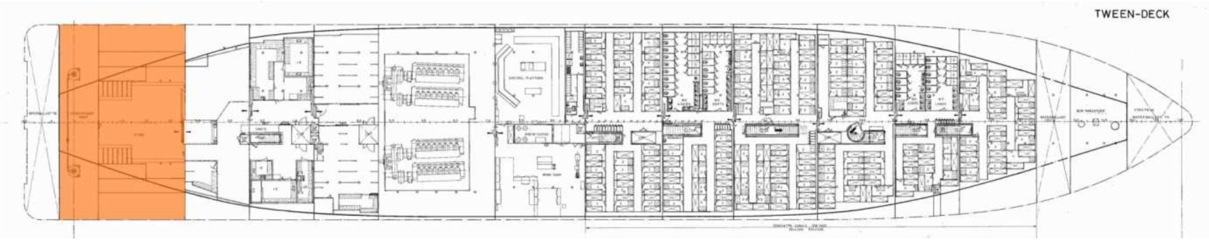


Figure 12.11: Graphic of flooded compartment in Step 2, 01:04:00

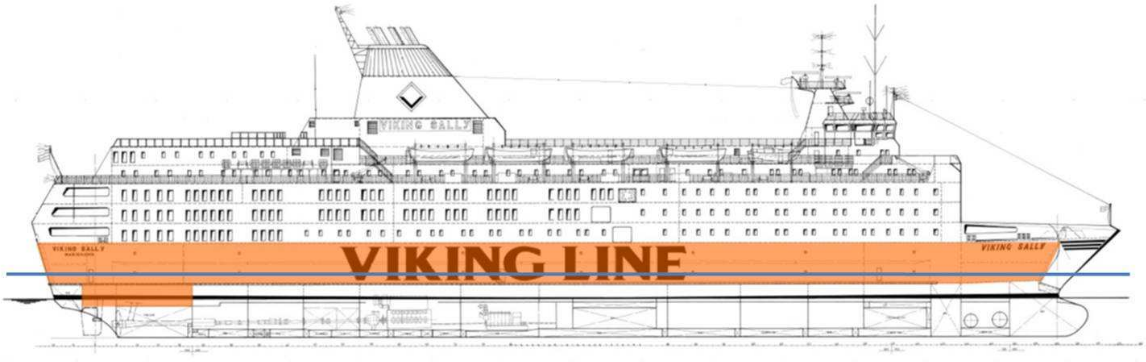


Figure 12.12: Side view of step 2 with highlighted compartments beginning to flood and the waterline

Step 6, 01:09:00

As the heel increases to more than 30°, a first cargo shift of all vehicles on the Main Car Deck is assumed: 1.00m to the starboard side.

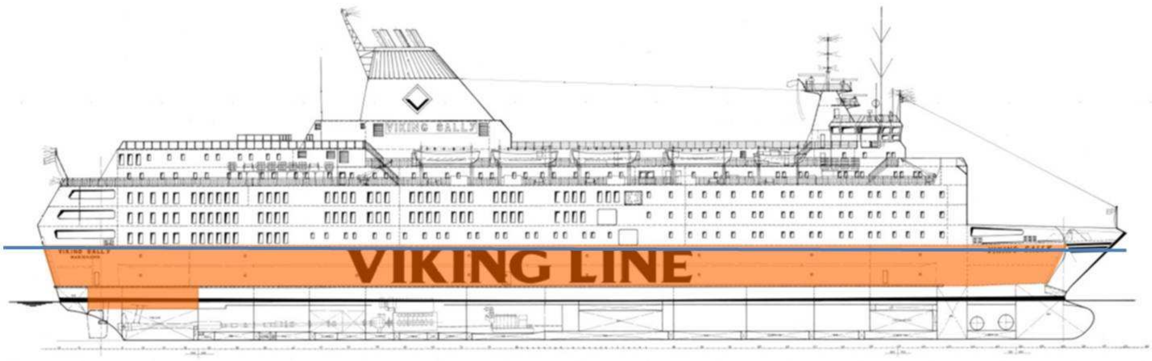


Figure 12.13: Side view of step 6 with highlighted compartments beginning to flood and the waterline

Step 15, 01:18:00

During the relatively long period of time from Step 6 to Step 15 the water ingress on the Main Car Deck is compareably low. This is in line with the testimonies of the witnesses: it is stated that there is, at this time, a quasi static euqilirium floating condition. By successive water ingresses to the Steering Gear Compartment and the adjacent connected Store Room the aft-ward trim increases. In Step 15 the first side ventilation opening is immersed. This is the ventilation duct of the "Stern Tube/ Store Room" compartment on Deck 0. This second compartment below the Main Car Deck is also located in the aft part of MV Estonia and due to top this it contributes also the aft-ward trim.

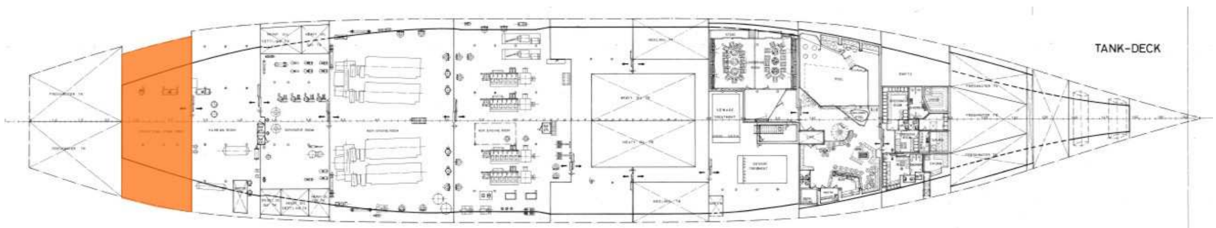


Figure 12.14: Graphic of flooded compartments in step 15, 01:18:30

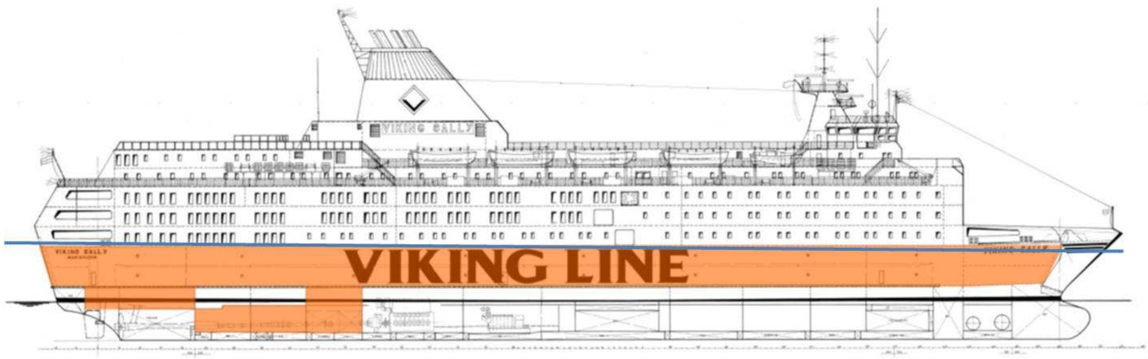


Figure 12.15: Side view of step 15 with highlighted compartments beginning to flood and the waterline

Step 16, 01:18:30

In Step 16, the next three side ventilation openings are immersed - in the Store Room on Deck 1 between frames 43 and 53, the Separator Room on Deck 0 and in the so-called “KaMeWa-Room”, also on Deck 0. Contained within the “KaMeWa-Room” is the hydraulic equipment necessary for the controllable pitch propellers (CPP).

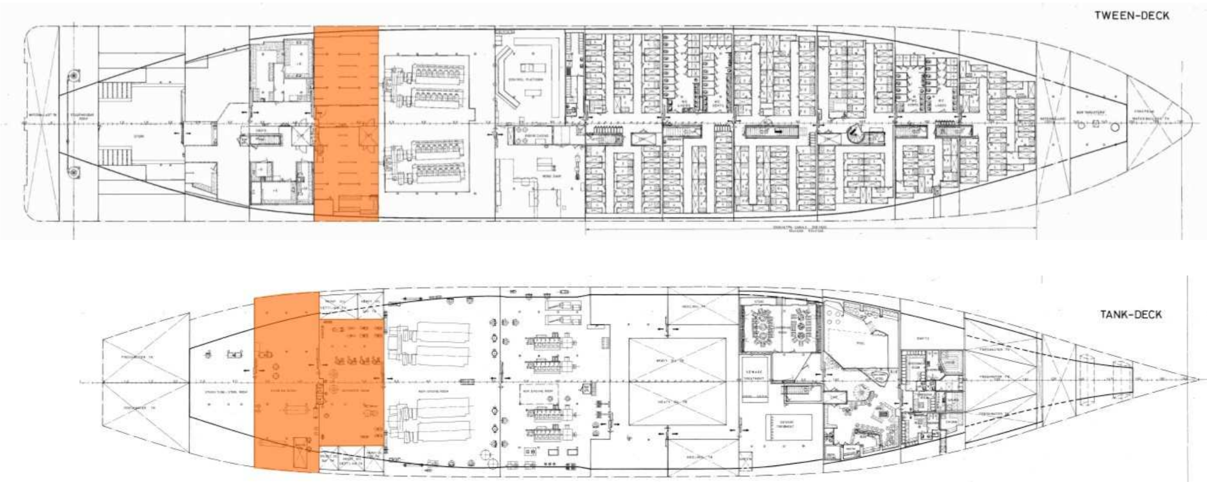


Figure 12.16: Graphic of flooded compartments in step 16, 01:18:30

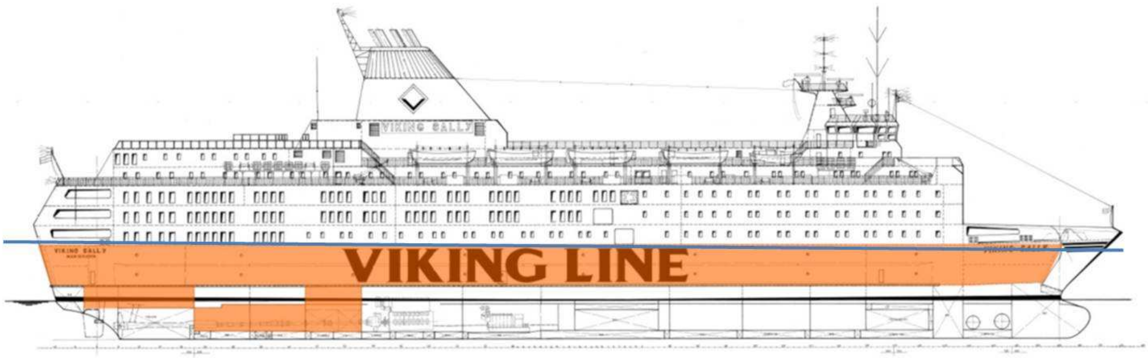


Figure 12.17: Side view of step 16 with highlighted compartments beginning to flood and the waterline

Step 17, 01:19:00

In calculation Step 17, the two starboard side ventilation openings of the main Engine Room are immersed. As in the cases before, the air escapes through the opposite side, because all ventilation openings on the Starboard Side are symmetricly arranged and there is an identical ventilation duct on the portside.

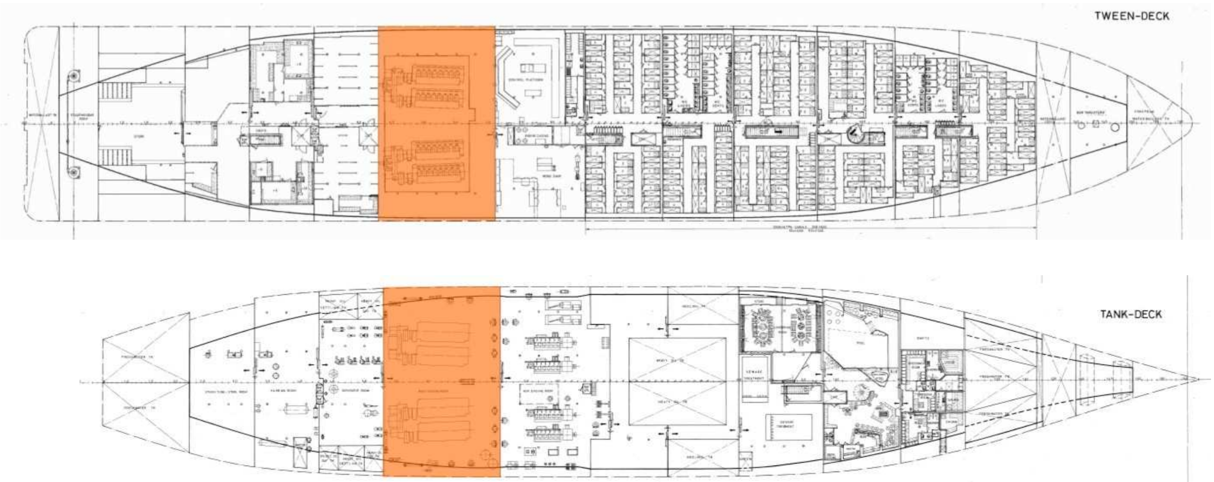


Figure 12.18: Graphic of flooded compartments in step 17, 01:19:00

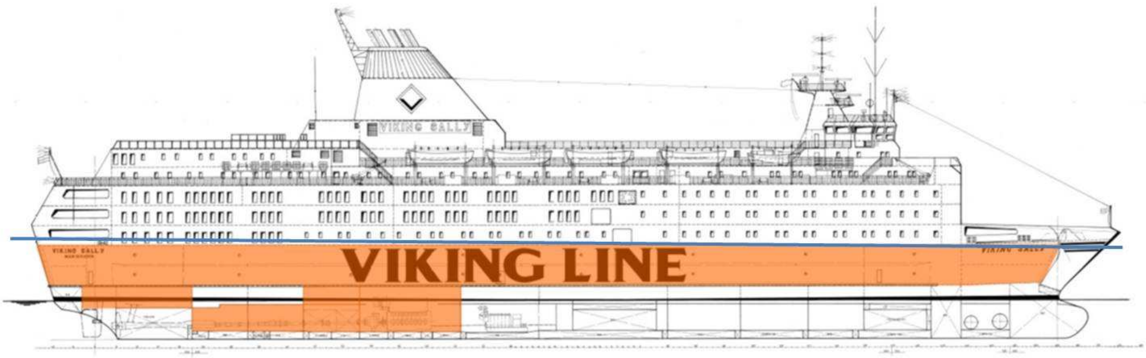


Figure 12.19: Side view of step 17 with highlighted compartments beginning to flood and the waterline

Step 23, 01:22:00

In Step 23, the first window collapses - due to a hydrostatic load of a column of over 3.55m. It is the last window on Deck 4 on the starboard side and the compartment behind the window is Main Fire Zone 3 (MFZ). Over subsequent steps, as the water level in this compartment rises, the water pours down to Deck 3, Deck 2 and finally in the Store Room between frames 33 and 43 on Deck 1. This last compartment floods in calculation Step 34.

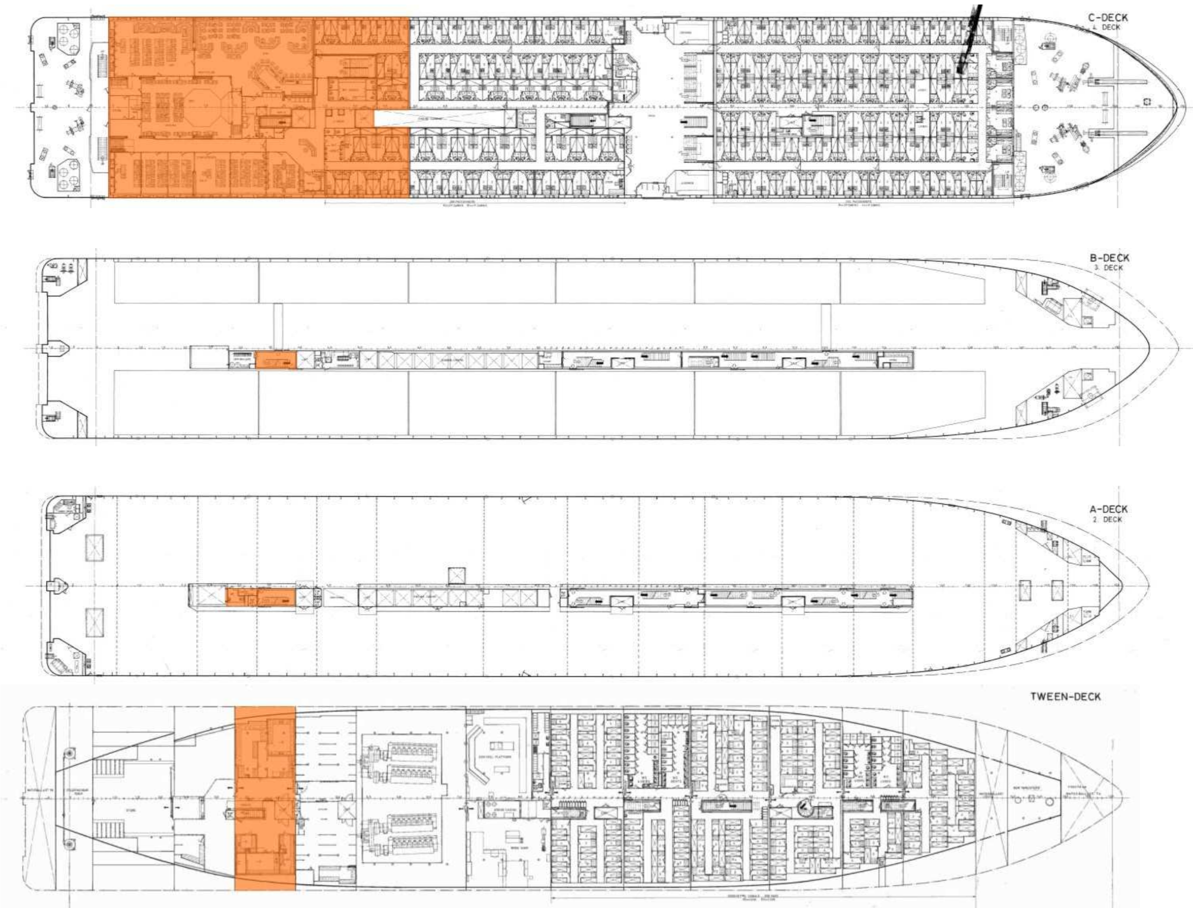


Figure 12.20: Graphic MFZ 3, deck 4 with later flooding of the Aft Stair Case on Deck 2 and 3 along with the Store Room between frame 33 and 43 of Deck 1, see step 34

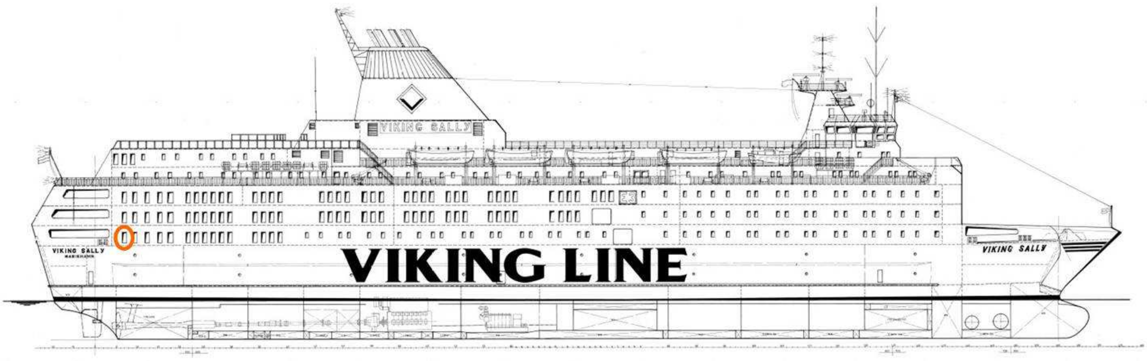


Figure 12.21: Graphic of collapsed window on Deck 4 which fails in step 23, 01:22:00

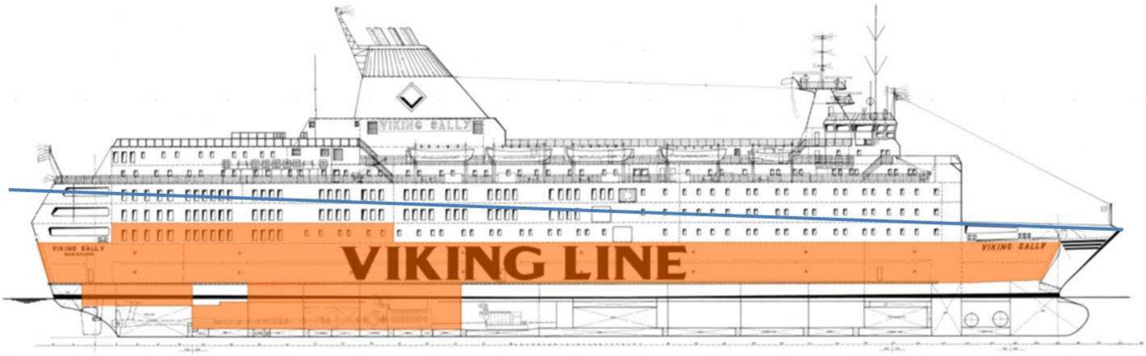


Figure 12.22: Side view of step 23 with highlighted compartments beginning to flood and the waterline

Step 26, 01:23:30

In this calculation step, the second window collapses. The last window on the starboard side on Deck 5, connected to Main Fire Zone 3 with a size of 600mm x 1500mm.

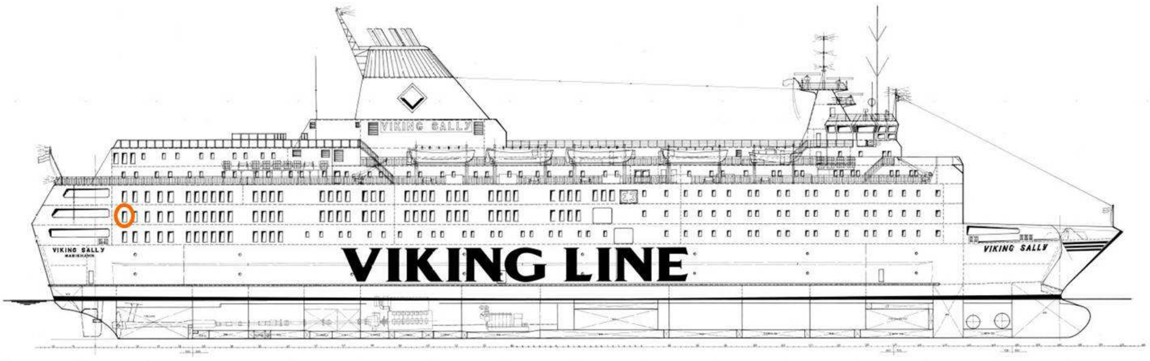


Figure 12.23: Graphic of collapsed window in MFZ 3 on Deck 5 which fails in step 26, 01:23:30

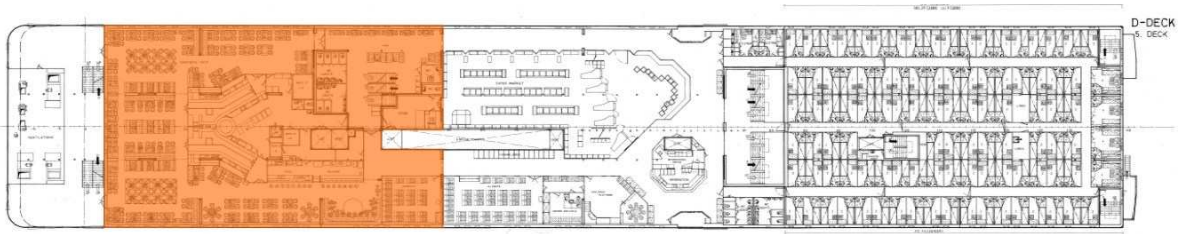


Figure 12.24: Graphic of flooded compartment on Deck 5 in step 26, 01:23:30

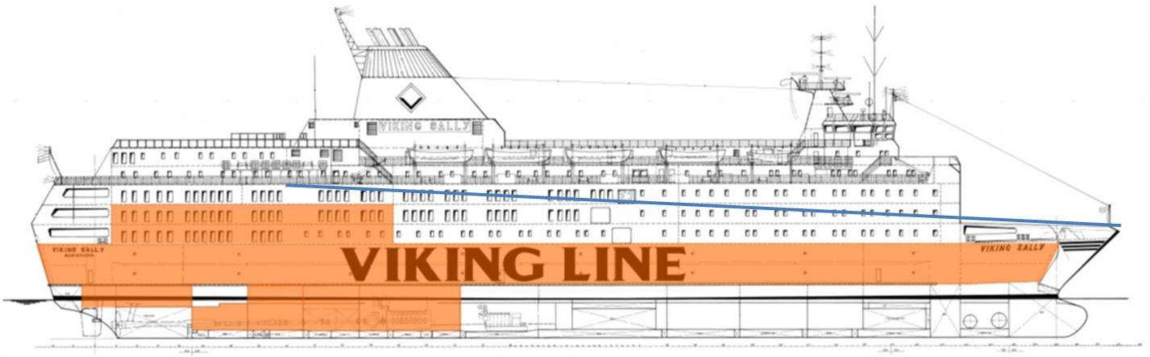


Figure 12.25: Side view of step 26 with highlighted compartments beginning to flood and the waterline

Step 27, 01:24:00

A third window, the first small window with a size of 400mm x 800mm, collapses due to a hydrostatic pressure equivalent to a water column of more than 4.15m. This window is part of the Main Fire Zone 2 on Deck 4.

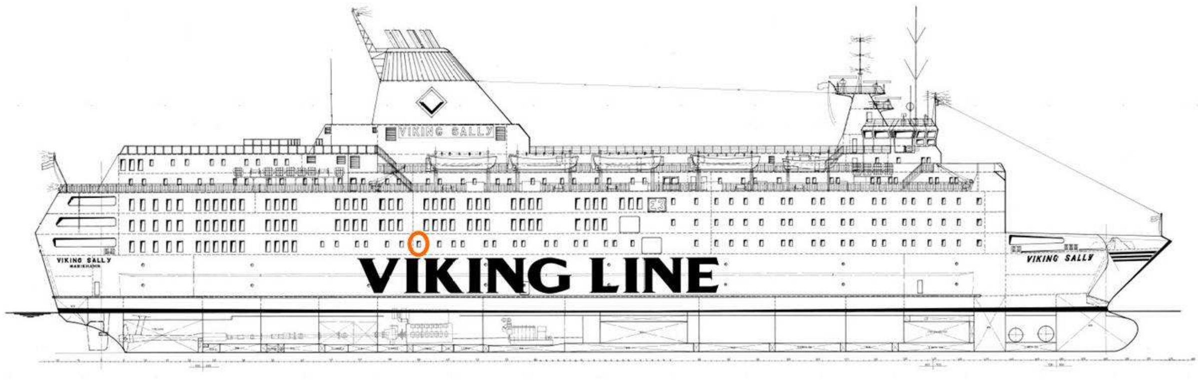


Figure 12.26: Graphic of collapsed window on Deck 4, Main Fire Zone 2 which failed in Step 27, 01:24:00

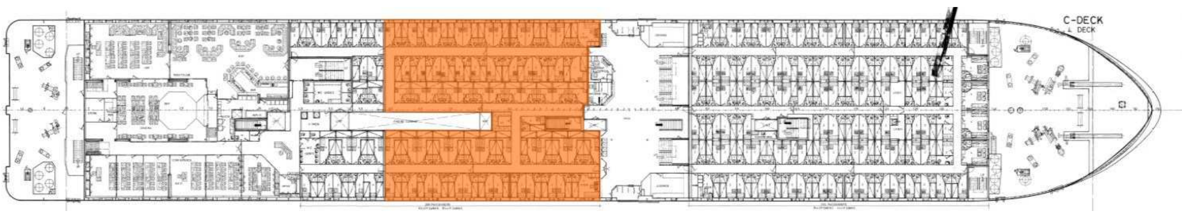


Figure 12.27: Graphic of flooded area on Deck 4, MFZ 2 in step 27, 01:24:00

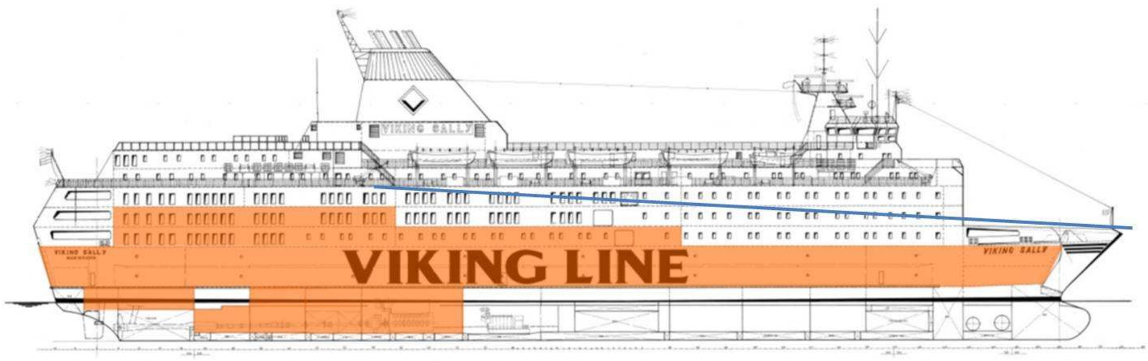


Figure 12.28: Side view of step 27 with highlighted compartments beginning to flood and the waterline

Step 29, 01:25:00

Nearly the same situation as in Step 27, but in this calculation step the large sized window on Deck 5 of Main Fire Zone 2 collapses.

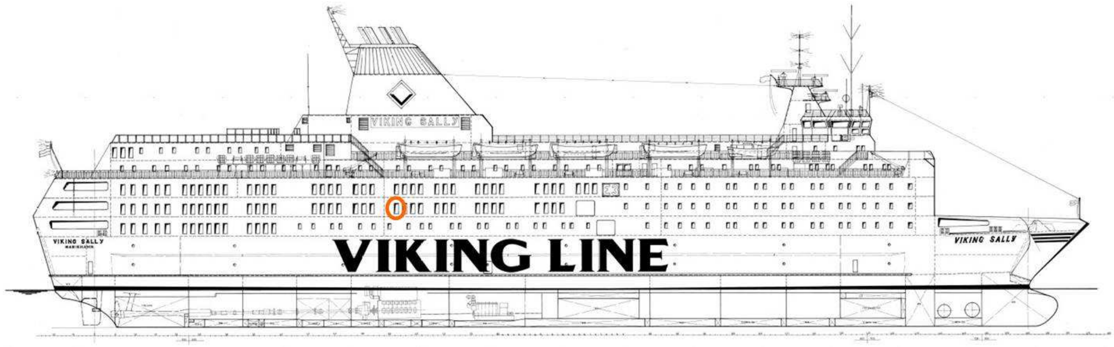


Figure 12.29: Graphic of collapsed window on Deck 5 which failed inStep 29, 01:25:00

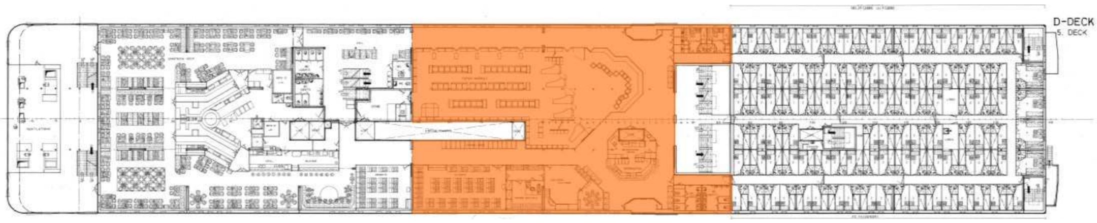


Figure 12.30: Graphic of flooded area on Deck 5, MFZ 2 in step 29, 01:25:00

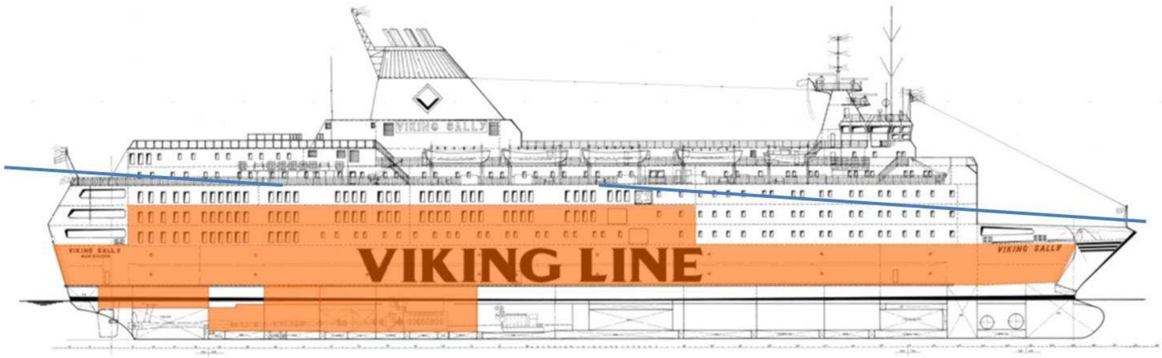


Figure 12.31: Side view of step 29 with highlighted compartments beginning to flood and the waterline

Step 30, 01:25:30

At 01:25:30, the large sized window on Deck 6 of the Restaurant, MFZ 3, as well as the small sized window on Deck 4 MFZ 1 collapsed. Just a glance at the side view of the general arrangement plan suggests the aft-ward trim increased to more than 6.00m, which is more than the height of two decks in the superstructure.

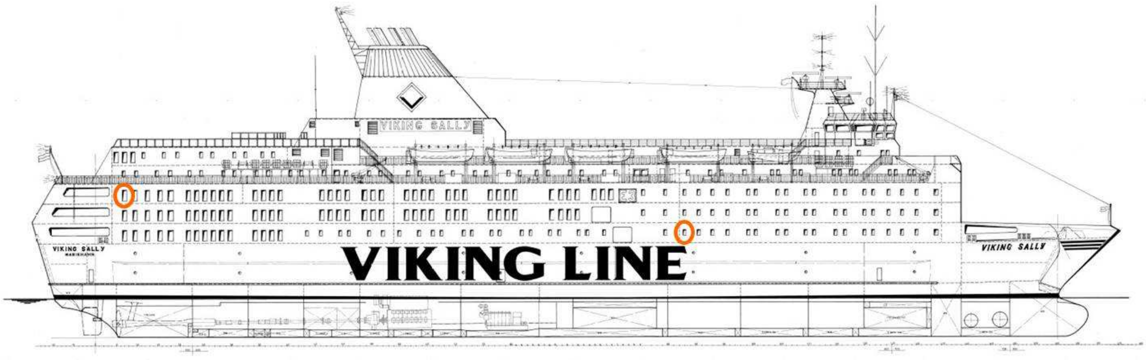


Figure 12.32: Graphic of collapsed windows on Deck 4 and Deck 6, which falied in step 30, 01:25:30

Figure 12.33: Graphic of flooded compartments on Deck 6, Restaurant, MFZ 3 and MFZ 1 on Deck 4 – in step 30

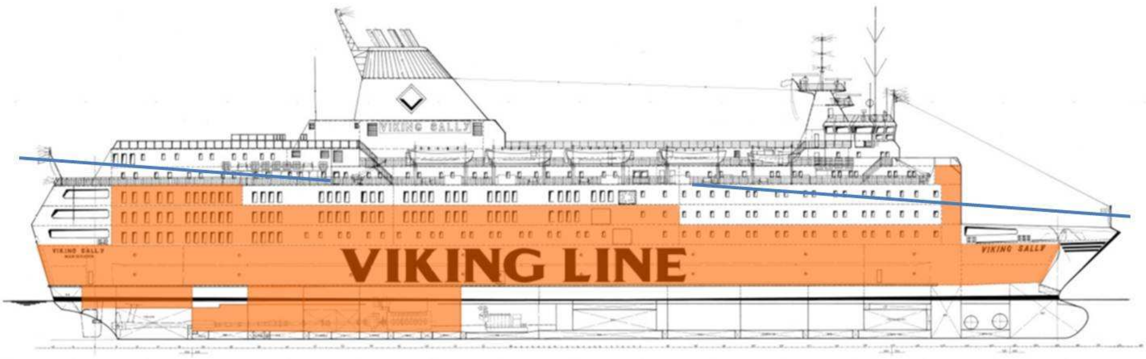


Figure 12.34: Side View of step 30 with highlighted compartments beginning to flood and the waterline

Step 31, 01:26:00

Another window fails, again in Main Fire Zone 3 on Deck 6 - along with the restaurant – this time in the Galley. The Galley is structurally separated from the Restaurant and its very aft ward window collapses in this time step. The following graphic indicates the collapsed window and the adjacent 'bulkhead', which divides the Restaurant from the Galley on the starboard side.

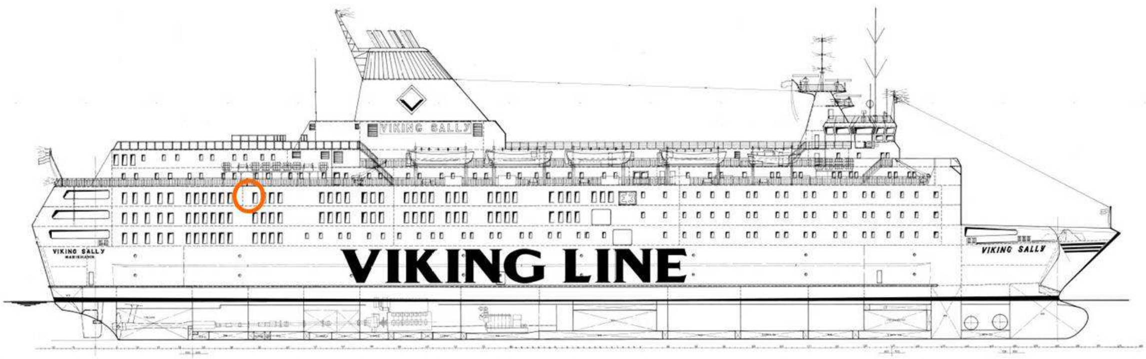


Figure 12.35: Graphic of collapsed window on Deck 6 inthe Galley along with the 'Bulkhead', which devides the restaurant from the Galley

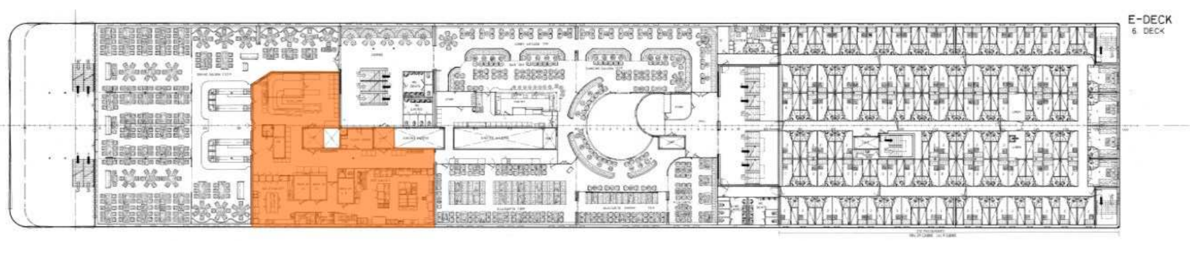


Figure 12.36: Graphic of the flooding of the Galley on Deck 6, MFZ 3, Step 31, 01:26:00

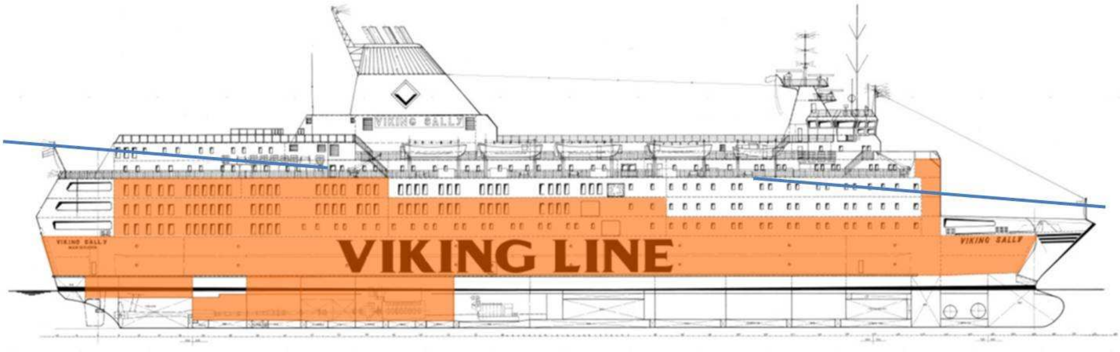


Figure 12.37: Side view of step 31 with highlighted compartments beginning to flood and the waterline

Step 32, 01:26:30

At 01:26:30, the most aft-ward window of Main Fire Zone 2 on Deck 6 on the starboard side collapses. Moreover, the gooseneck ventilator on the forecastle deck on the starboard side is immersed and connects, amongst other things to the Bowthruster Room and the outside of MV Estonia. Again, the gooseneck ventilator is symmetrically arranged, so that as well in this case the air can escape the gooseneck ventilator on Portside of MV Estonia.

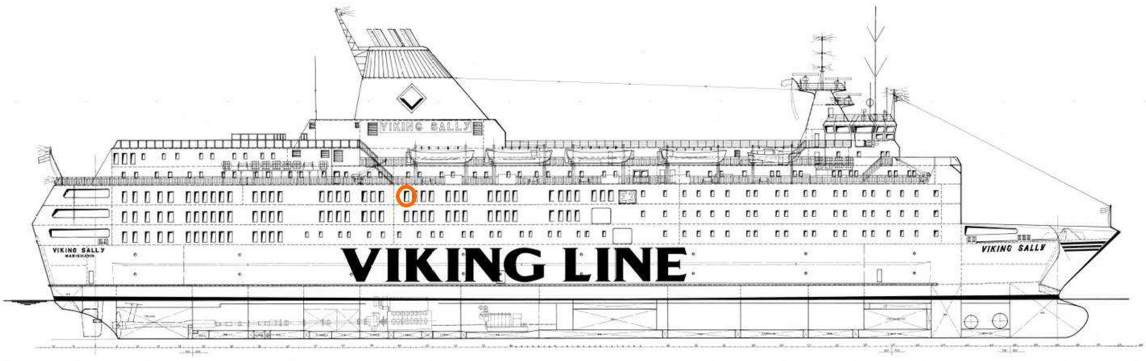


Figure 12.38: Graphic of collapsed window on Deck 6, MFZ 2, Step 32, 01:26:30

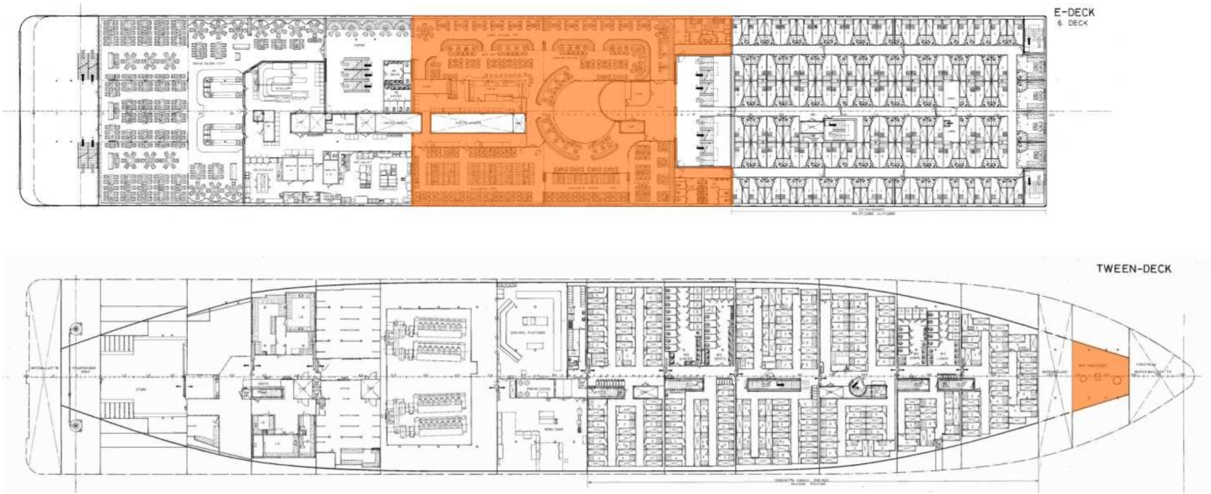


Figure 12.39: Graphic of flooding of MFZ2, Deck 6 and Bowthruster Room on Deck 1 during Step 32

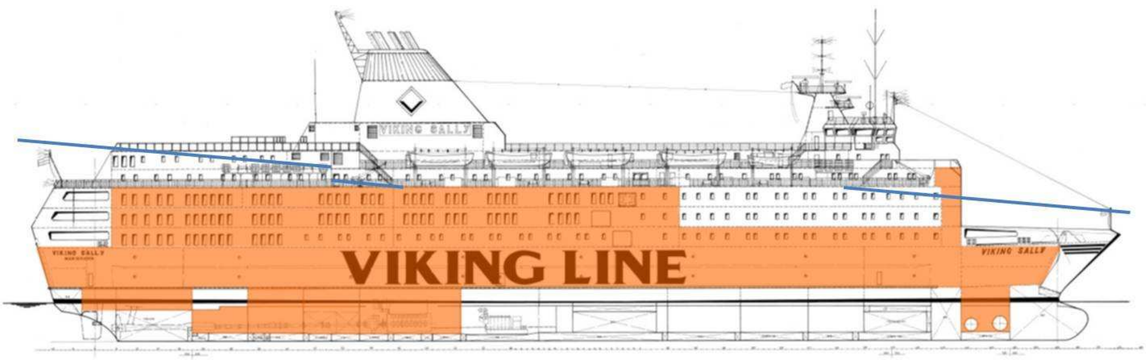


Figure 12.40: Side view of step 32 with highlighted compartments beginning to flood and the waterline

Step 34, 01:27:30

This calculation step follows on from Step 23: The water level of Main Fire Zone 3 on Deck 4 has reached the staircase and now starts flooding the store Room on Deck 1 between frame 33 and 43 via Deck 3 and Deck 2.

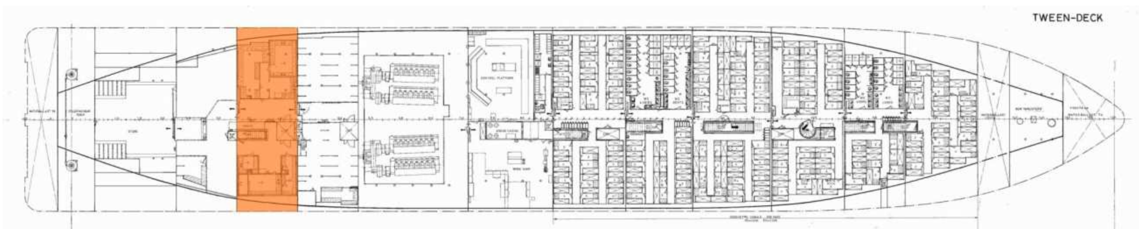


Figure 12.41: Graphic showing flooding of the Store Room between Frame 33 and 43 of Deck 1, see step 23

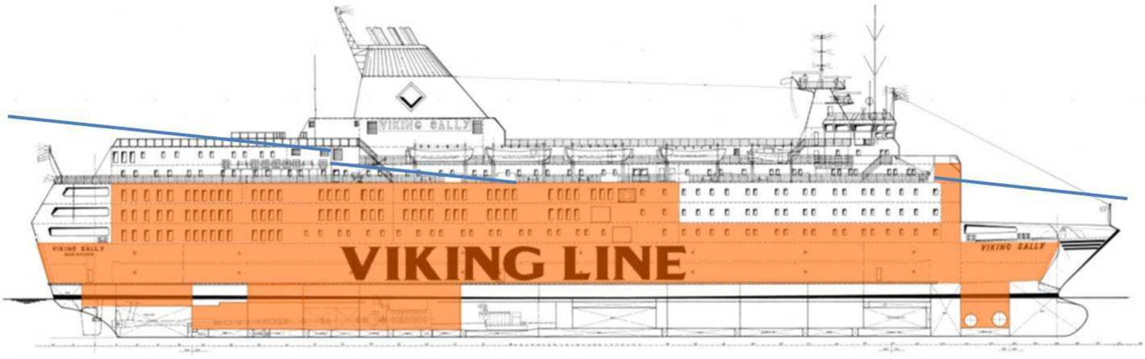


Figure 12.42: Side view of step 34 with highlighted compartments beginning to flood and the waterline

Step 35, 01:28:00

With calculation Step 35 at 01:28:00, a steady list of more than 60° has been reached. As described before, the second cargo shift takes place with an amplitude of 0.50m – leading to a total shift of 1.5m – of all vehicles on the Main Car Deck. At the same time, the aft-ward window of Main Fire Zone 1 on Deck 5 on the starboard side, collapses.

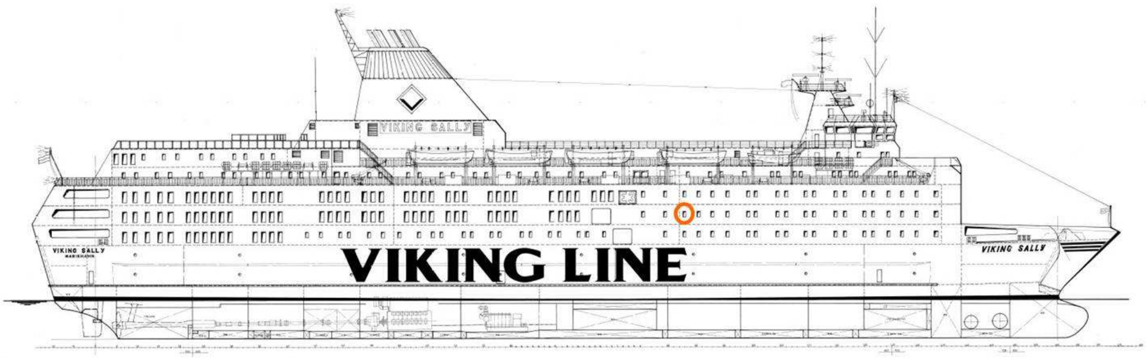


Figure 12.43: Graphic of collapsed window on Deck 5, MFZ 1, step 35, 01:28:00

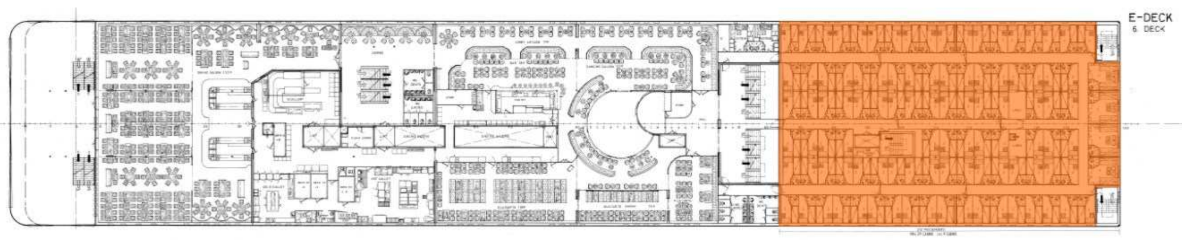


Figure 12.44: Graphic of flooded compartments on Deck 5, MFZ 1 in step 35, 01:28:00

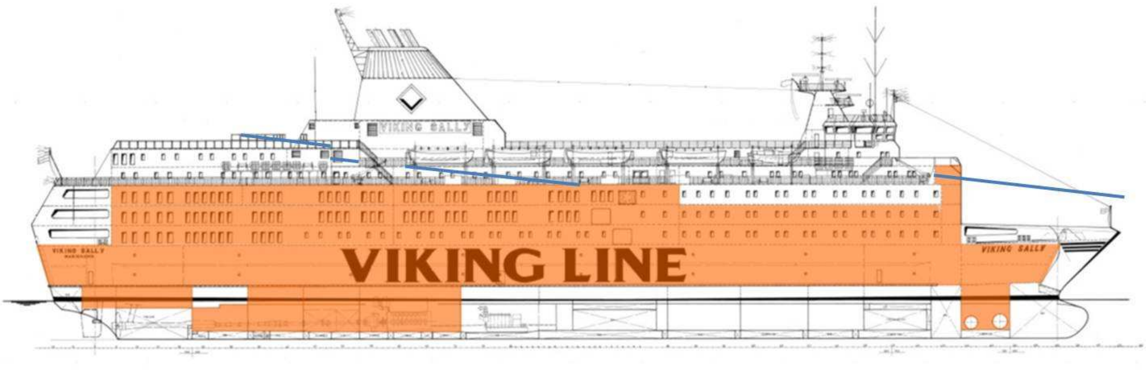


Figure 12.45: Side view of step 35 with highlighted compartments beginning to flood and the waterline

Step 37, 01:29:00

At 01:29:00, the most aft ward window of Deck 7 collapses. This is a large sized window in Main Fire Zone 3, which is non-water-tightly connected by an internal staircase to Deck 8. For these simulations, these two Main Fire Zones were calculated together. In later time steps the following occurs: in step 38, the door on Deck 7 at frame 48 collapses and in step 39 the aft most window on Deck 8, Main Fire Zone 3 collapses.

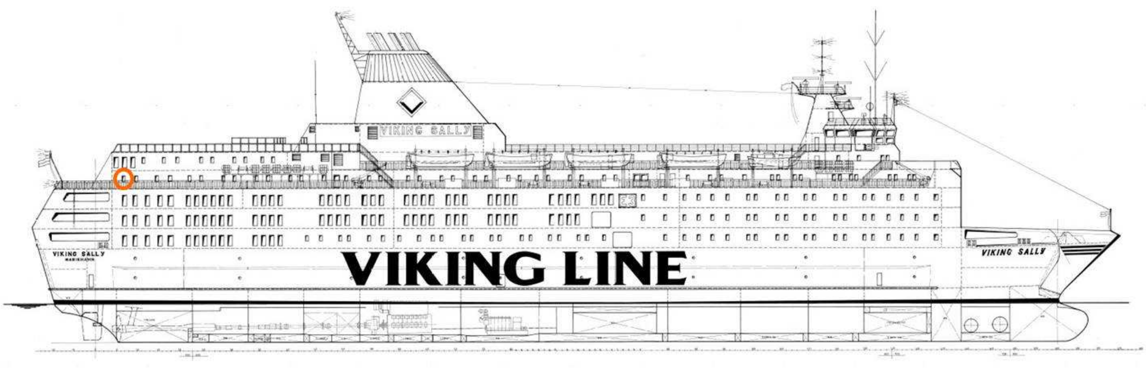


Figure 12.46: Graphic of collapsed window on Deck 7, MFZ 3, step 37, 01:29:00

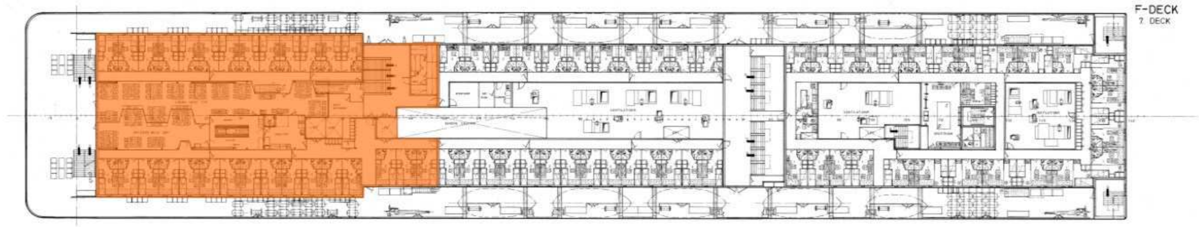


Figure 12.47: Graphic of flooded compartments on Deck 7, MFZ 3, step 37, 01:29:00

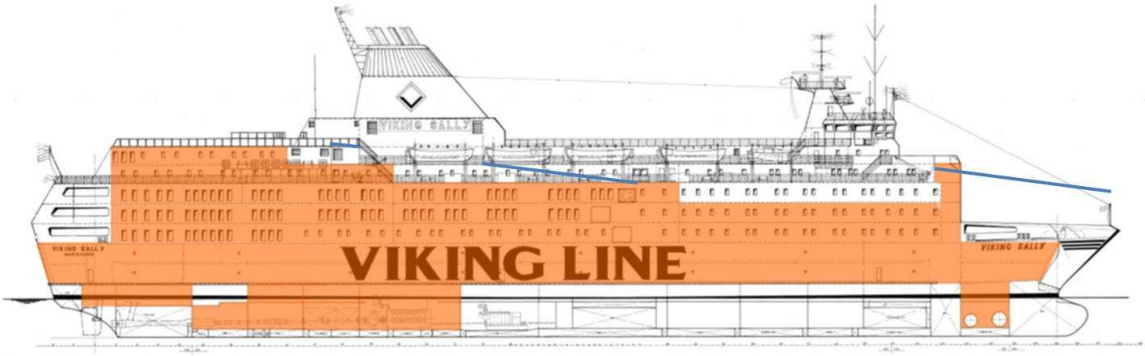


Figure 12.48: Side view of step 37 with highlighted compartments beginning to flood and the waterline

Step 38, 01:29:30

As mentioned in Step 37 the door on Deck 7, frame 48 collapses. Although the hydrostatic pressure is less on the door on Deck 7 at frame v leading to the Centre Stair Case than on the door at frame 48 on the same Deck they collapse in the same time step. This is due to the fact that the door at frame v is two-wing door, which can only resist a lower hydrostatic pressure.

The Centre Stair Case connects all decks beginning from Deck 0 at the spa-area and up to the conference rooms on Deck 7.

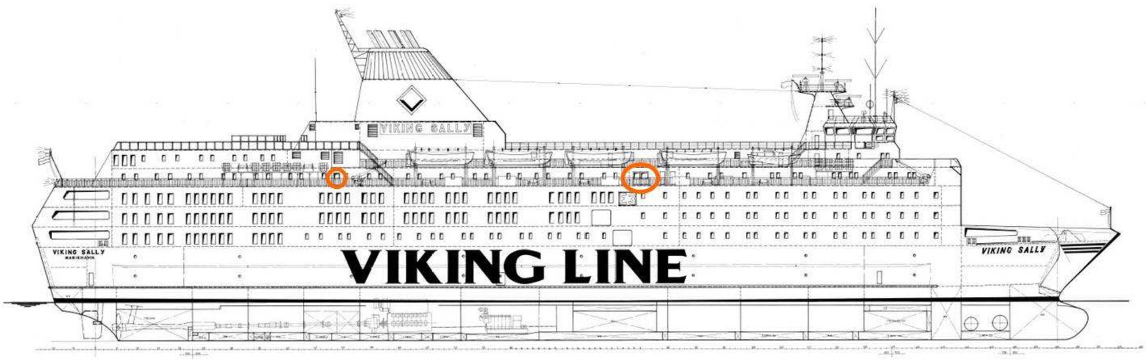


Figure 12.49: Graphic of the two collapsing doors on Deck 7, MFZ 3 and the Centre Stair Case

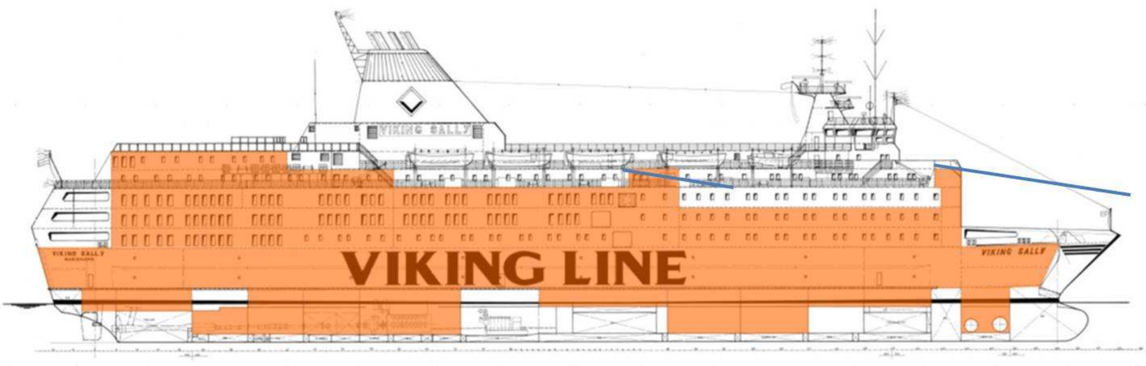


Figure 12.50: Side view of step 38 with highlighted compartments beginning to flood and the waterline

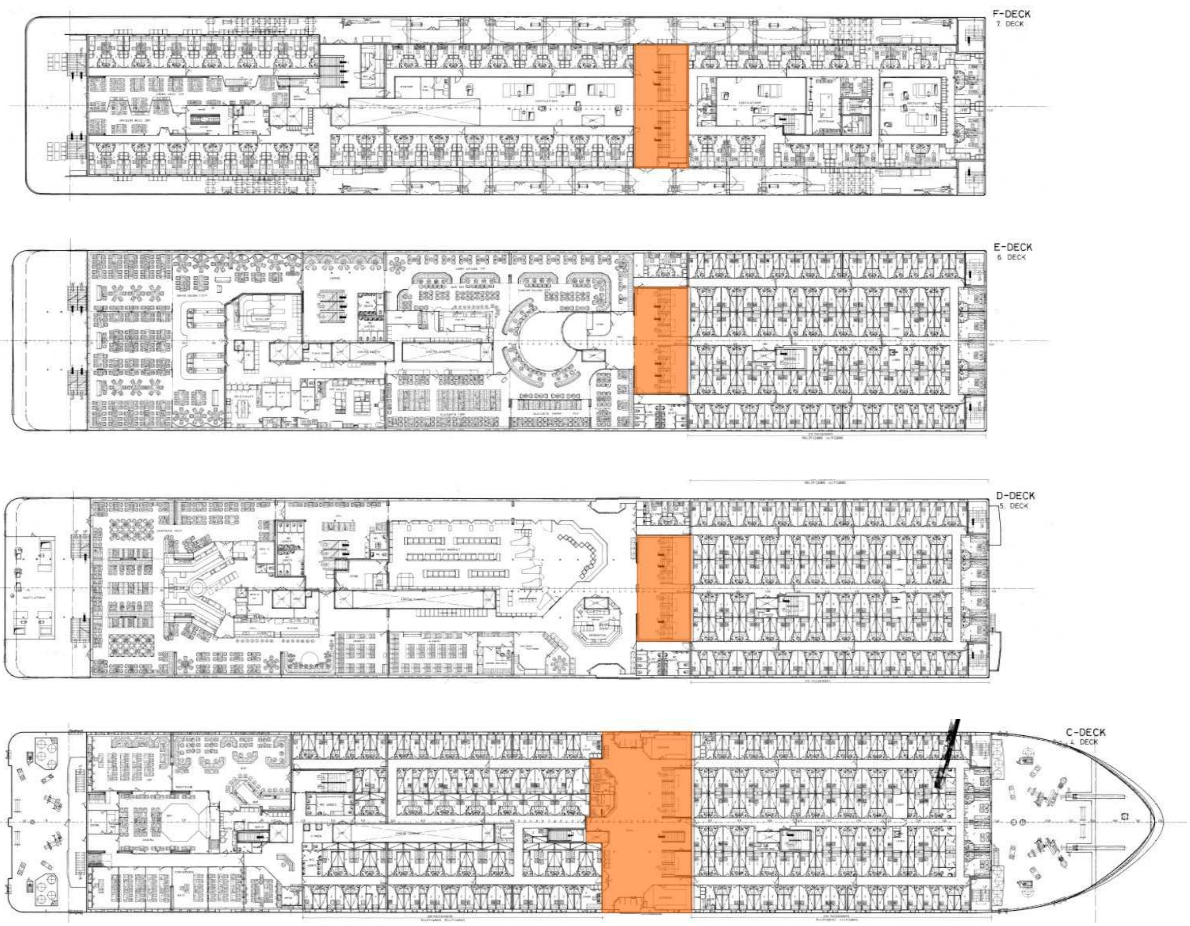


Figure 12.51: Graphic of Centre Stair Case part one, Deck 4 to Deck 7

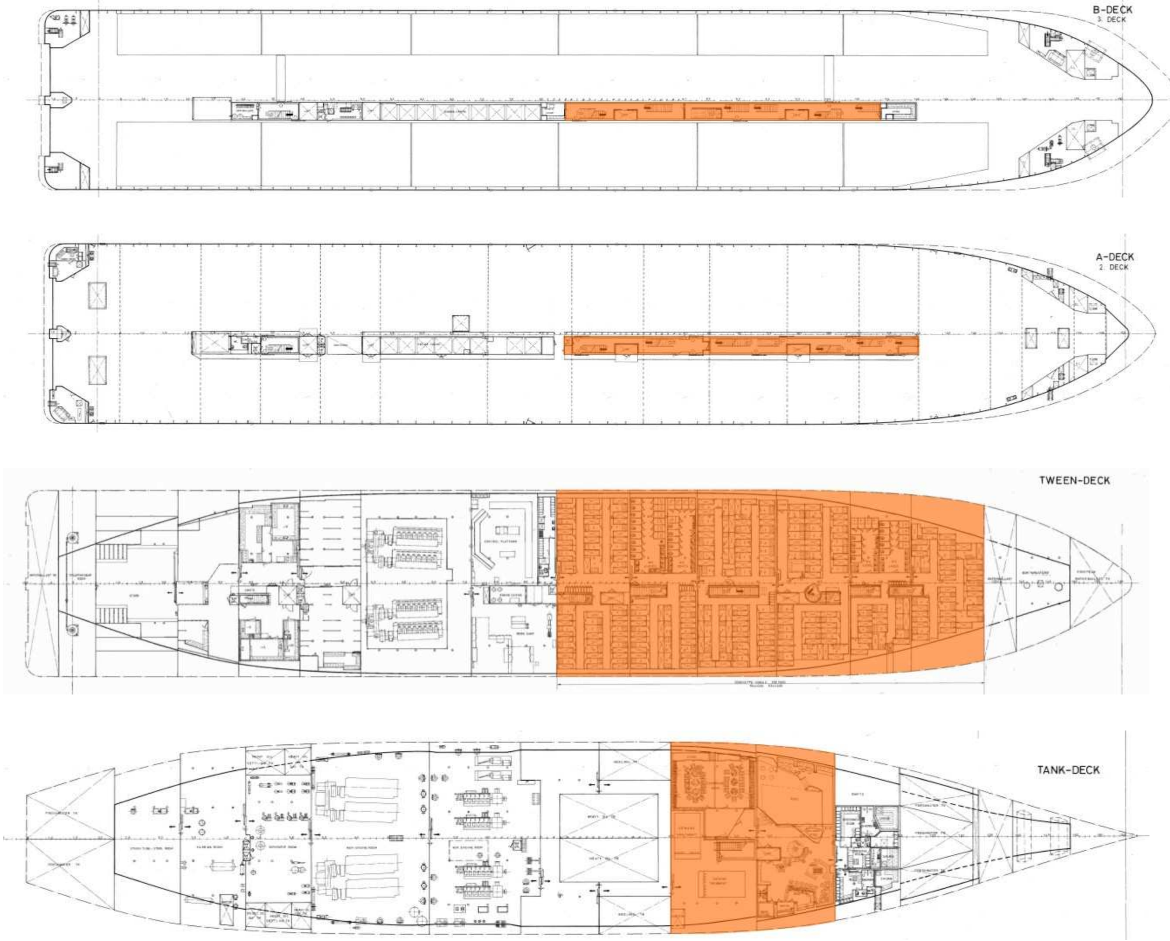


Figure 12.52: Graphic of Centre Stair Case part two, Deck 0 to Deck 3

Step 39, 01:30:00

At half past one, the aft most window of Main Fire Zone 1 on Deck 6 collapses.

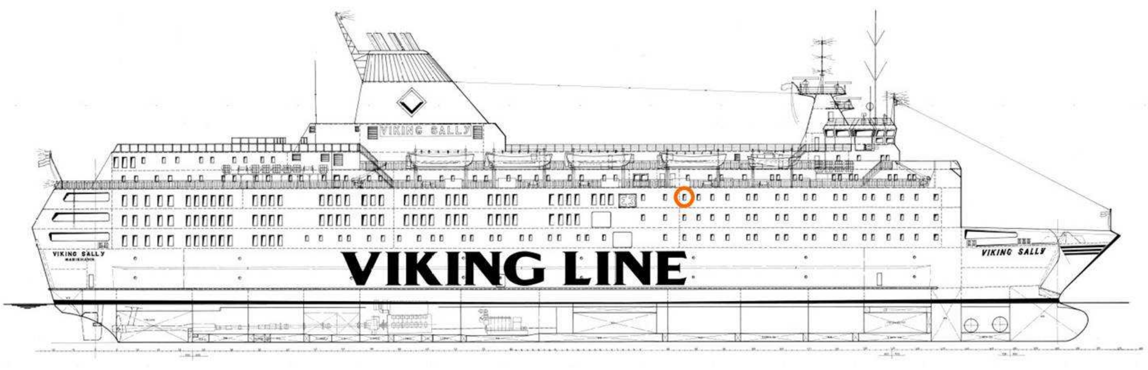


Figure 12.53: Graphic of collapsed window on Deck 6, MFZ 1, step 39, 01:30:00

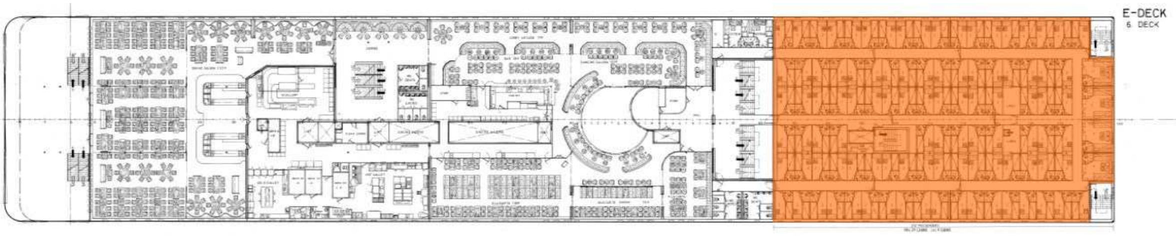


Figure 12.54: Graphic of flooded compartments on Deck 6, MFZ 1,in step 39, 01:30:00

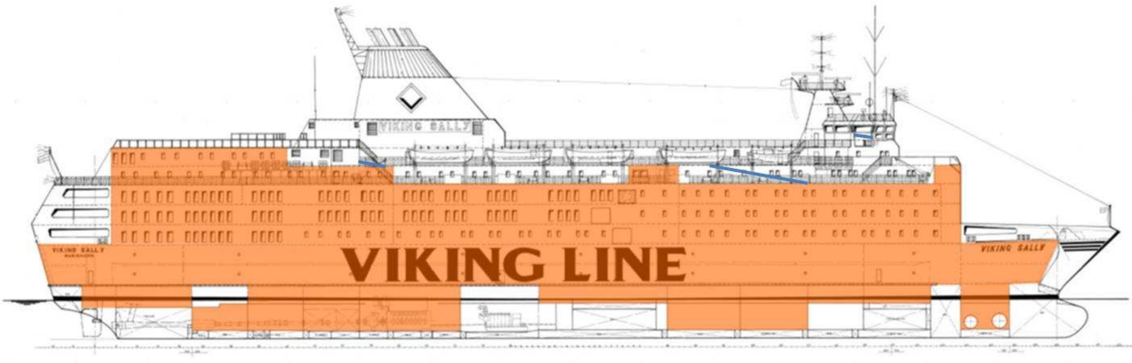


Figure 12.55: Side view of step 39 with highlighted compartments beginning to flood and the waterline

Step 41, 01:31:00

The Engine/Machinery Room on Deck 8 in Main Fire Zone 3 is calculated separately from crew-cabin area of this Main Fire Zone. The water ingress to this compartment takes place by the indicated door.

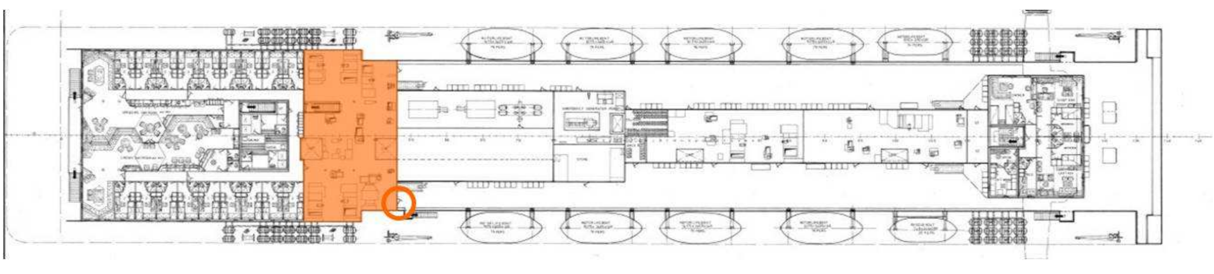


Figure 12.56: Graphic of floodedcompartments, along with the door through which the water flows on Deck 8, MFZ 3, step 41, 01:31:00

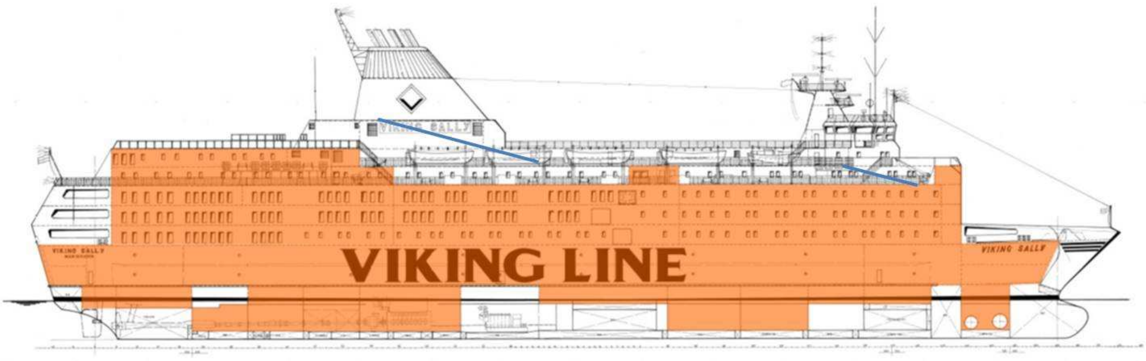


Figure 12.57: Side View of step 41 with highlighted compartments beginning to flood and the waterline

Step 42, 01:31:30

In this calculation step, the last window of Main Fire Zone 2 on the starboard side collapses, as does the window of the wing bridge on Deck 9. Additionally, the compartment on Deck 9 below the funnel is flooded, but note, that the jalousie is not the same as drawn on the side view. Nevertheless, the influence on the calculation is neglect able.

The crew cabin area of Main Fire Zone 3 on Deck 8 and the Wheel House on Deck 9 were calculated as one compartment.

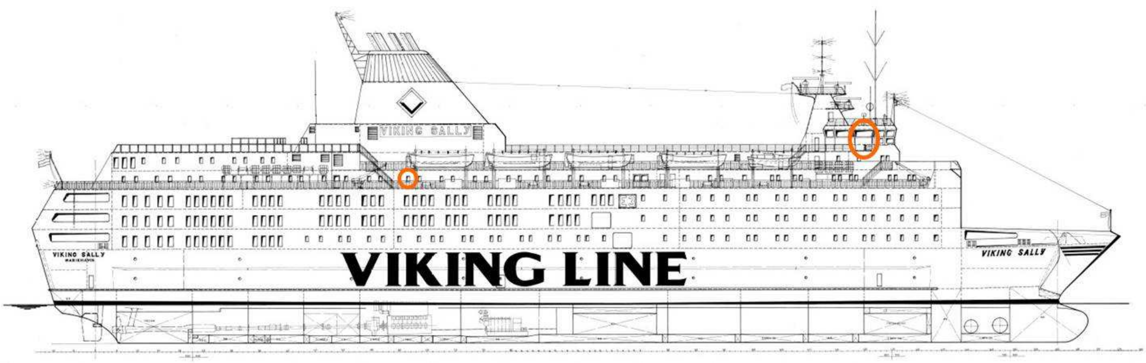


Figure 12.58: Graphic of Collapesed Windows on Deck 7, MFZ 2 and the wing of bridge, Deck 9

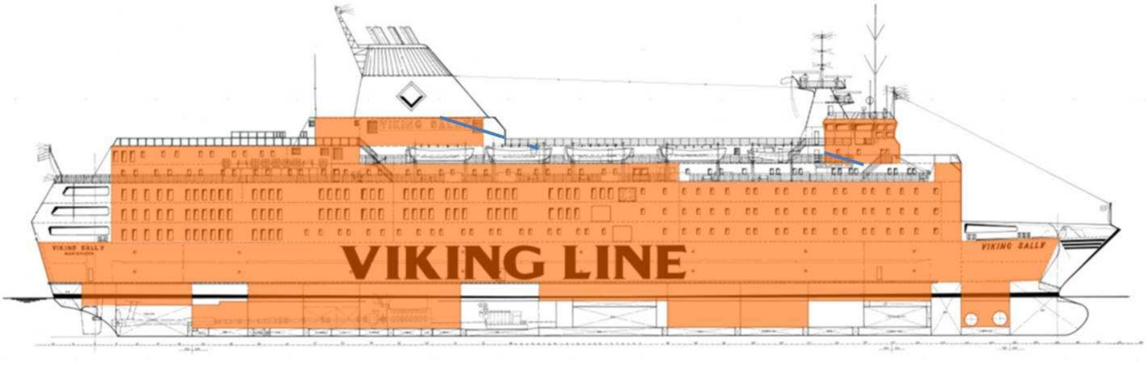


Figure 12.59: Side View of step 42 with highlighted compartments beginning to flood and the waterline

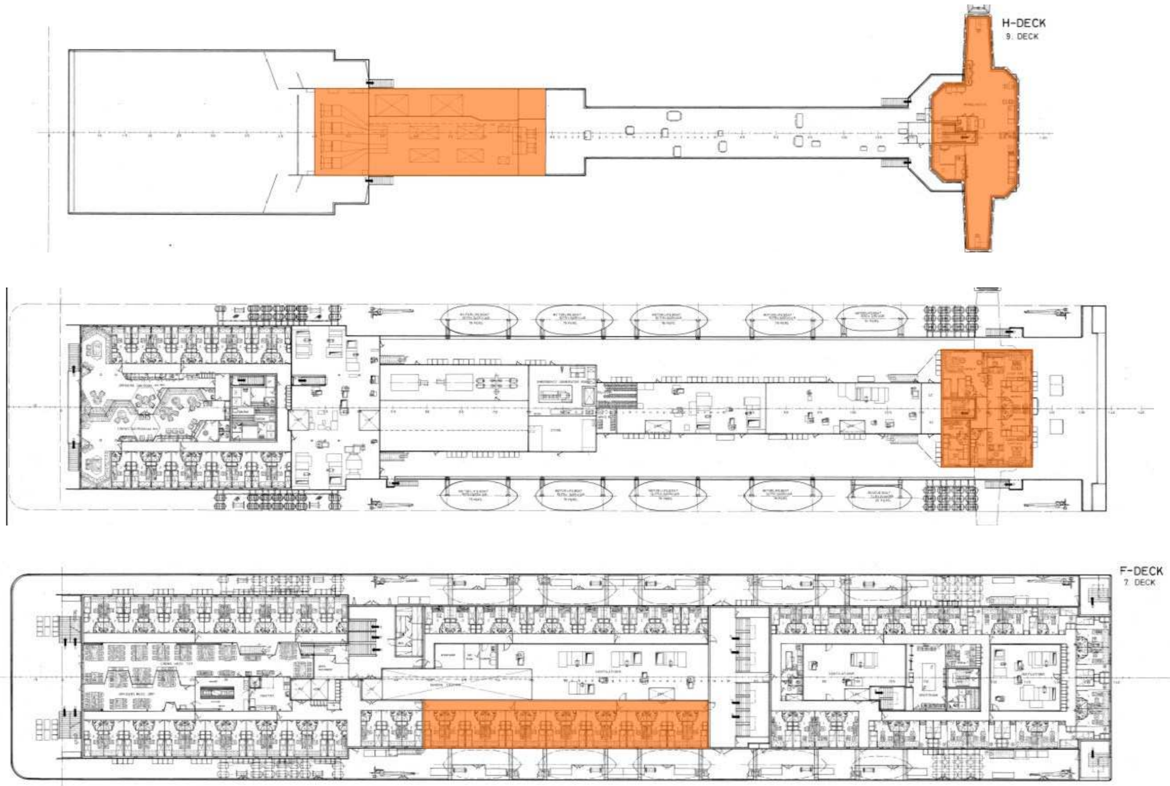


Figure 12.60: Graphic of the flooded compartments on Deck 7, Main Fire Zone 2, starboard side, the compartment below the funnel and the combined compartment of the Crew-Cabin Area of Deck 8, Main Fire Zone 1, and the Wheel House

Step 43, 01:32:00

In Step 43, the aft most window of Main Fire Zone 1 of Deck 7 collapses.

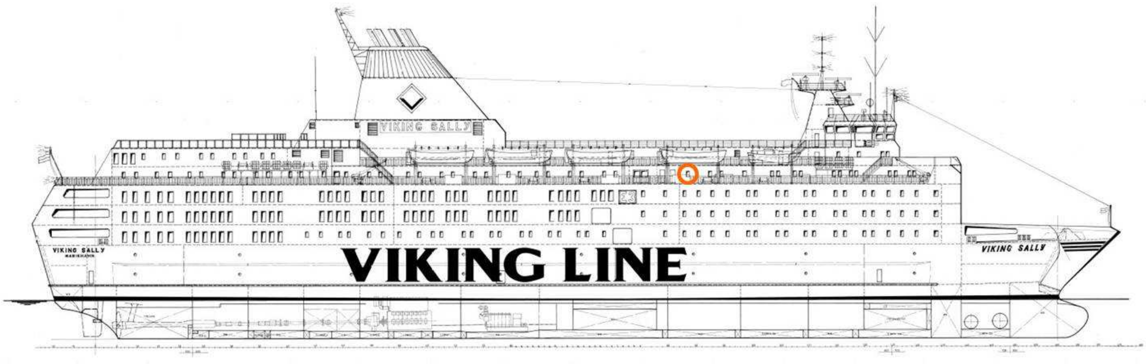


Figure 12.61: Graphic of collapsed window on Deck 7, MFZ 1, step 43, 01:32:00

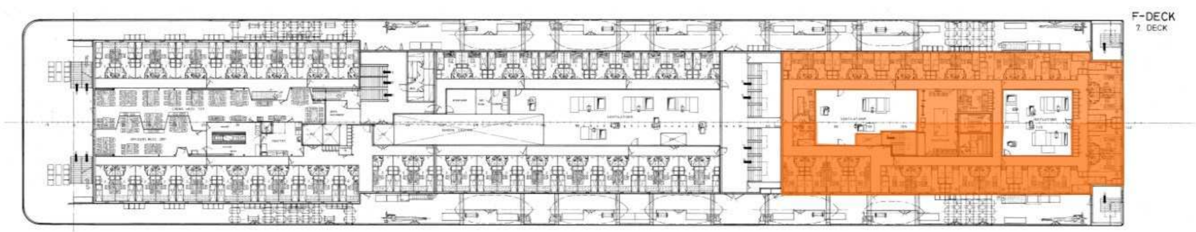


Figure 12.62: Graphic of flooded compartments on Deck 7, MFZ 1, step 43, 01:32:00

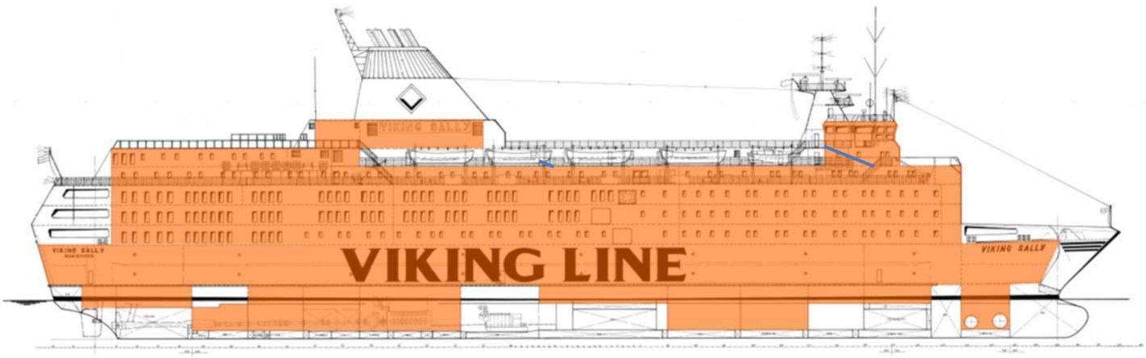


Figure 12.63: Side View of Step 43 with highlighted compartments beginning to flood and the waterline

Step 44, 01:32:30

At 01:32:30, the Engine Casing of the Main Engine Room and the Auxiliary Engine Room are immersed. The water ingress into the two casing systems are via the large jalousies of the compartment below the funnel, which is immersed in step 42.

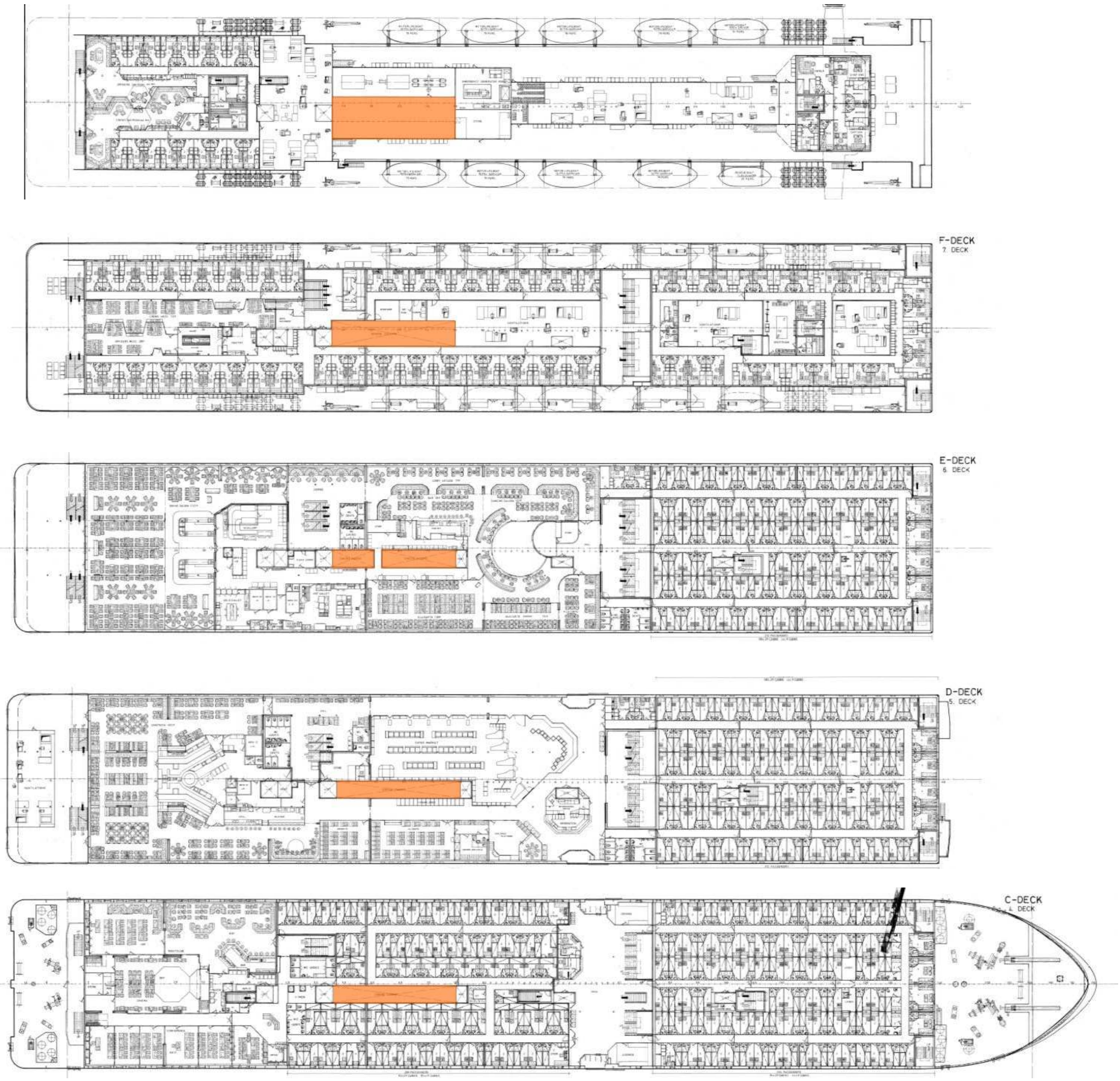


Figure 12.64: Graphic of the flooded engine casings for the Main and the Auxiliary Engine Room, part one

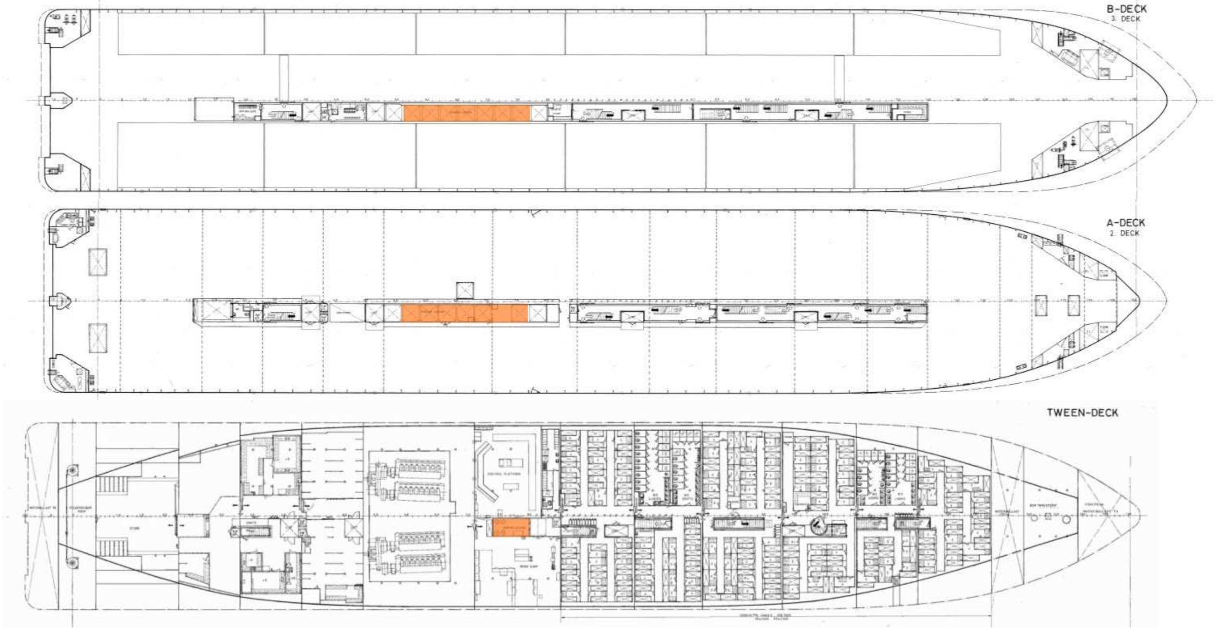


Figure 12.65: Graphic of the flooded engine casings for the Main and the Auxiliary Engine Room, part two

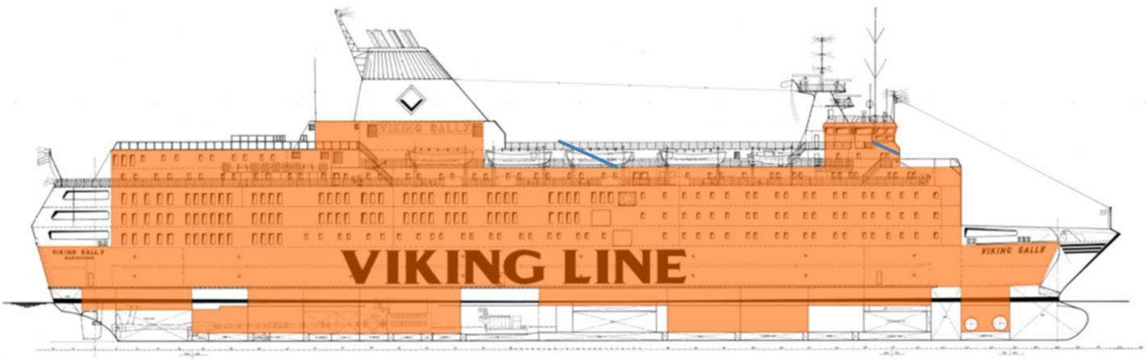


Figure 12.66: Side view of step 44 with highlighted compartments beginning to flood and waterline

Step 46, 01:33:30

In this calculation step, the top of the funnel is immersed.

Figure 12.67: Graphic of the immersed area of the funnel in Step 46, 01:33:30

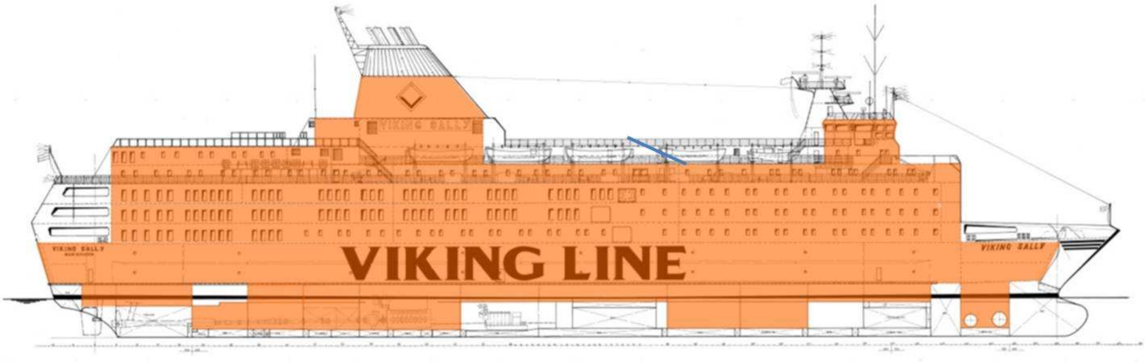


Figure 12.68: Side view of step 46 with highlighted compartments beginning to flood and the waterline

Step 48, 01:34:30

Via the Auxiliary Engine Case, the Engine Control Room and the Work Shop on Deck 1 are flooded.

Figure 12.69: Graphic of flooded compartmentson Deck 1, Engine Control Room and Workshop

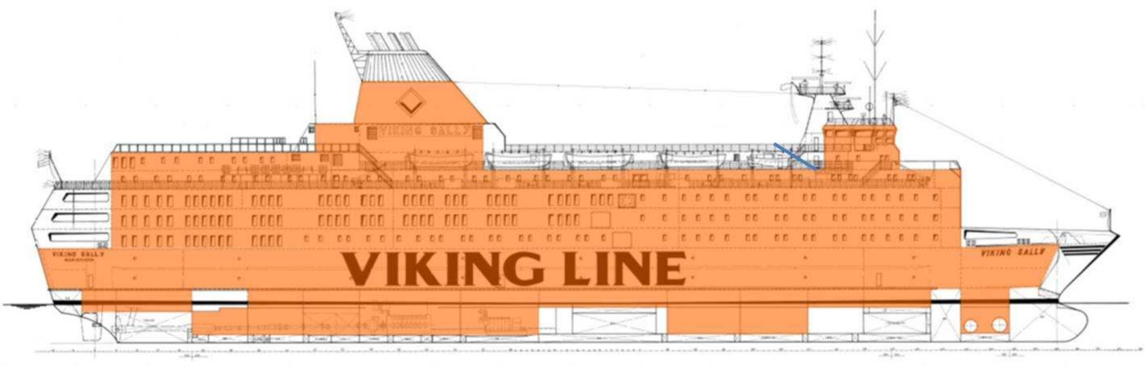


Figure 12.70: Side view of step 48 with highlighted compartments beginning to flood and waterline

Step 50, 01:35:30

This step is very similar to step 44 in that the ventilation system cutting through nearly all decks becomes waterlogged via water ingress through the doors of the Ventilation Compartments on Deck 8.

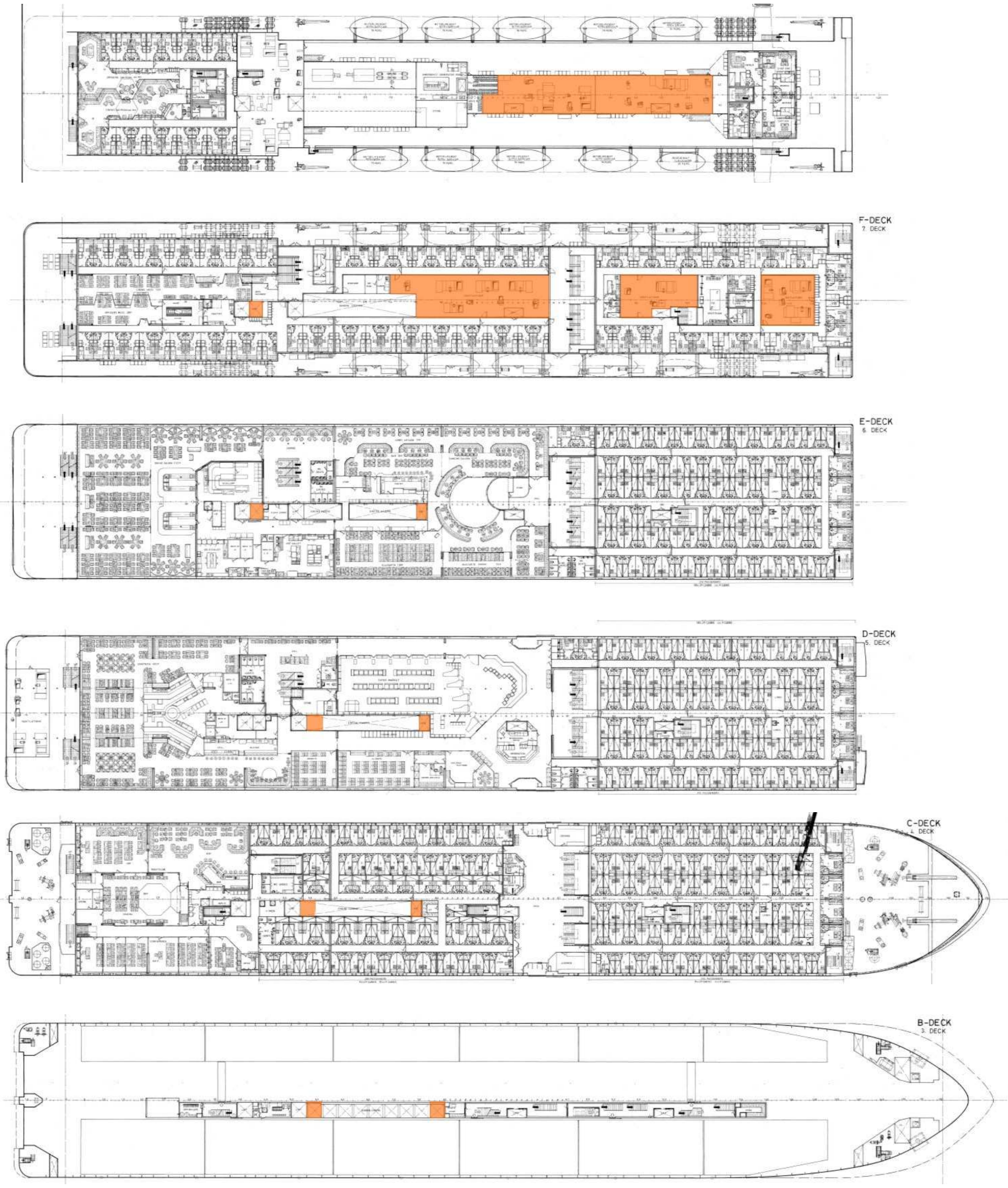


Figure 12.71: Graphic of the flooded ventilation ducts and compartments, part one

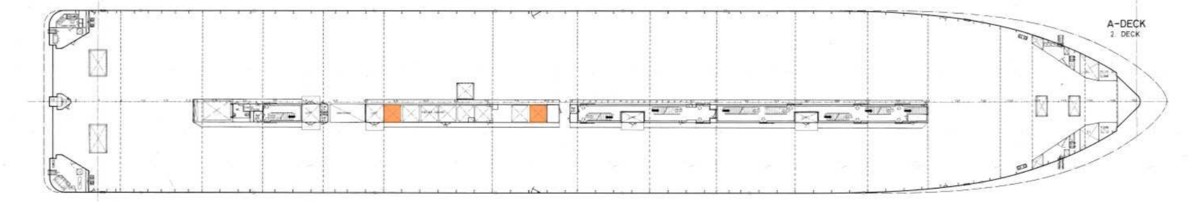


Figure 12.72: Graphic of the flooded ventilation ducts and compartments, part two

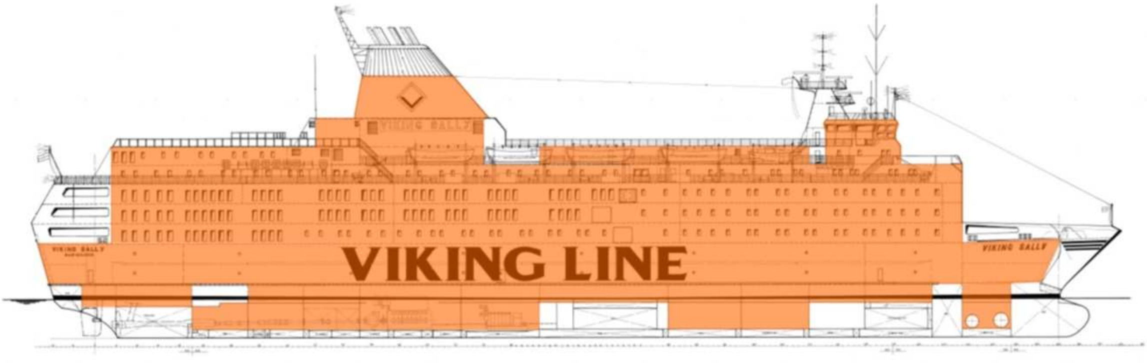


Figure 12.73: Side view of step 50 with highlighted compartments beginning to flood and the waterline

Step 52, 01:36:30

The last compartment to begin to flood is the Main Fire Zone 2, Portside on Deck 7.

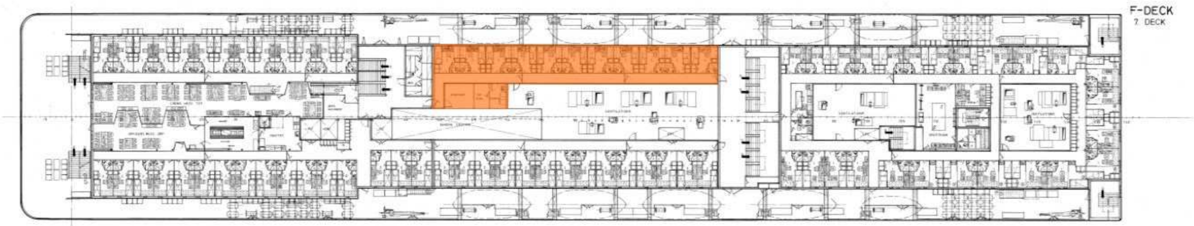


Figure 12.74: Graphic of flooded area on Deck 7, MFZ 2, Portside, Step 52, 01:36:30

12.6 Results of the Sinking Simulation

The main finding of the quaisi-static approach, with its the hydrostatic calculation steps, is that the loss of watertight integrety started a chain reaction. The vast amount of water entering the Main Car Deck at 01:00 or very shortly after causes, due to the large free surface and the corresponding fluid shifting moments, a steady list of a little more than 30° to starboard in a period of less than 9 minutes.

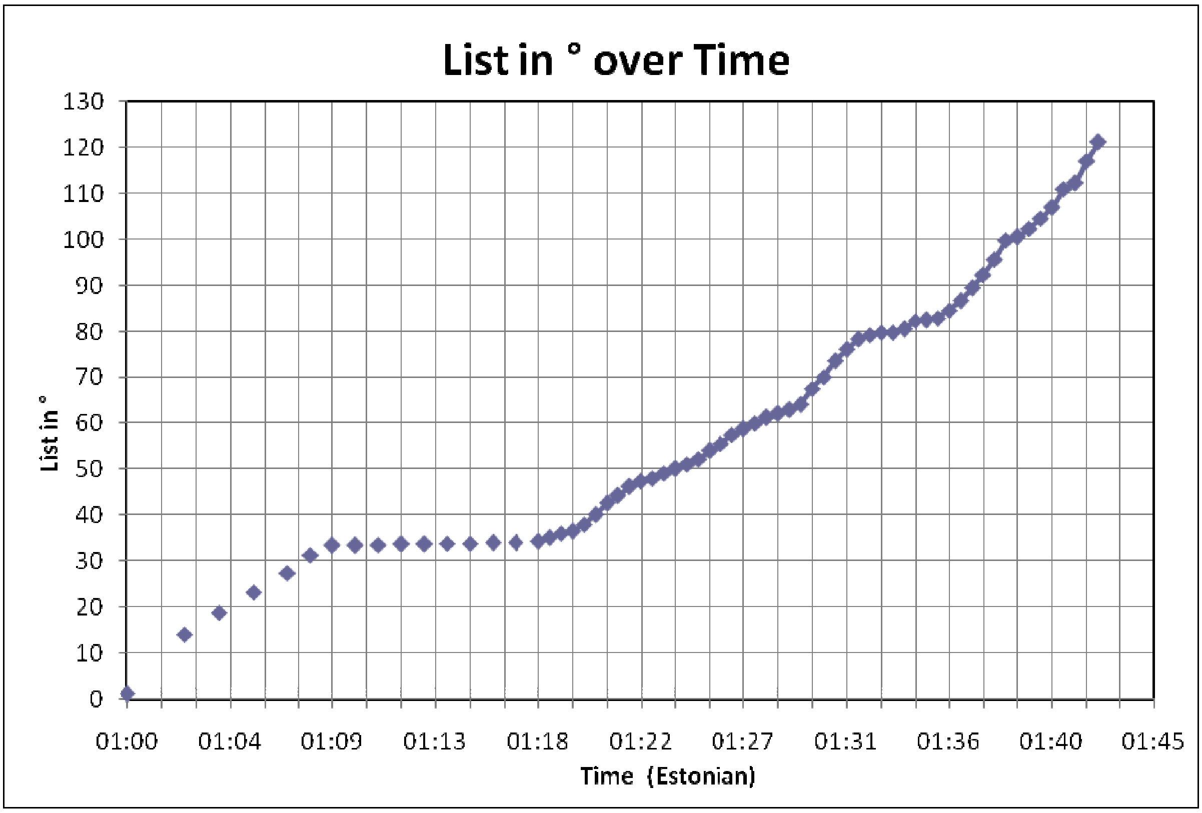


Figure 12.75: Graph of list in °over local Estonian ti me

The initial aft-ward trim was reduced by the ingressing water, but – from the static point of view – at no time was MV Estonia on even keel or had a forward trim. The phase of between 01:09 to 01:18 is a quasi-steady list. The average water ingress onto the Main Car Deck was 20t to 40t per minute during this period of time. Water then flowed into the Steering Gear Compartment on Deck 1 through the ventilation duct in the starboard aft wing house. Due to its aft postion, a compareably small amount of water causes a significant aft-ward trim. Due to the increasing aft-ward trim, the row of ventilation ducts of the Engine and Machinery Compartments of Deck 0 and Deck 1 and the Store Rooms of Deck 1 are submerged and in turn accelerate the increase of the aft-ward trim and the steady list.

At about 01:22, the first window collapses on the first deck above the vehicle decks, Deck 4, at the aft part of the ferry. This again increases the starboard list and the aft-ward trim. The rate of increase of the trim however decreases as more and more of the forward compartments begin to flood. From 01:39 onwards, the trim increases rapidly until 01:43 when the the stern of the vessel hit the sea bed. At this time the heeling angle is a little more than 120° and thus about the angle of the vessel on the seabed, as described in the Rockwater Report [Rock].

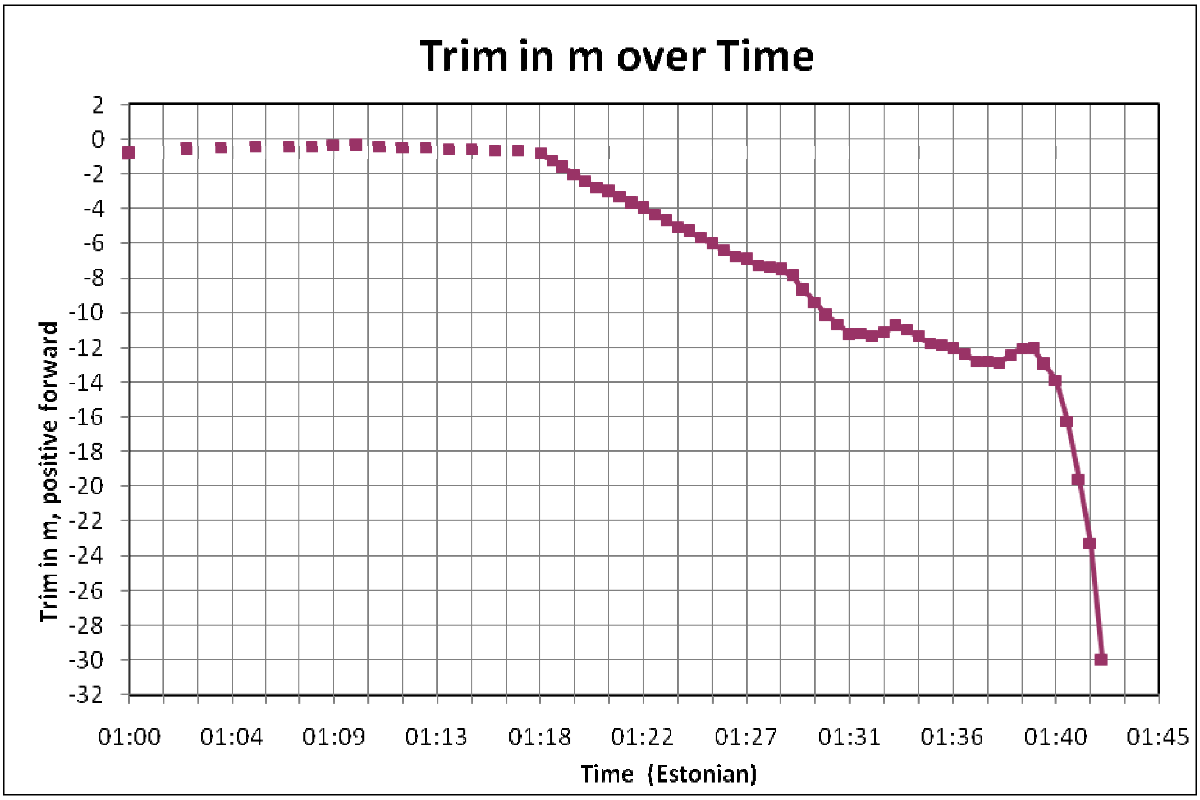


Figure 12.76: Graph list in °over local time

This is an explaination for both the completely intact port-side stern part of the vessel and the circumstances of the wreck, dug in the sea bed nearly to the centre line (CL).

At the time of collision with the seabed, 9 minutes before the last radar contact with MV Estonia at 01:52, she had a residual buoyancy of about 5700t. Extraplolating the water ingress, according to the calculations and simlulations presented here, MV Estonia would disappear from the surface at about 01:50 or 01:51. This is in line with the time of the last radar contact with the near-by MV Mariella.

The match of the calculations with the testimonies of survivors of the catastrophe is welcome due to the fact that, especially in the later phase of the sinking, useful testimonies become sparse. It is obvious that people struggling to save their lives perceive their surroundings in a non-objective way.

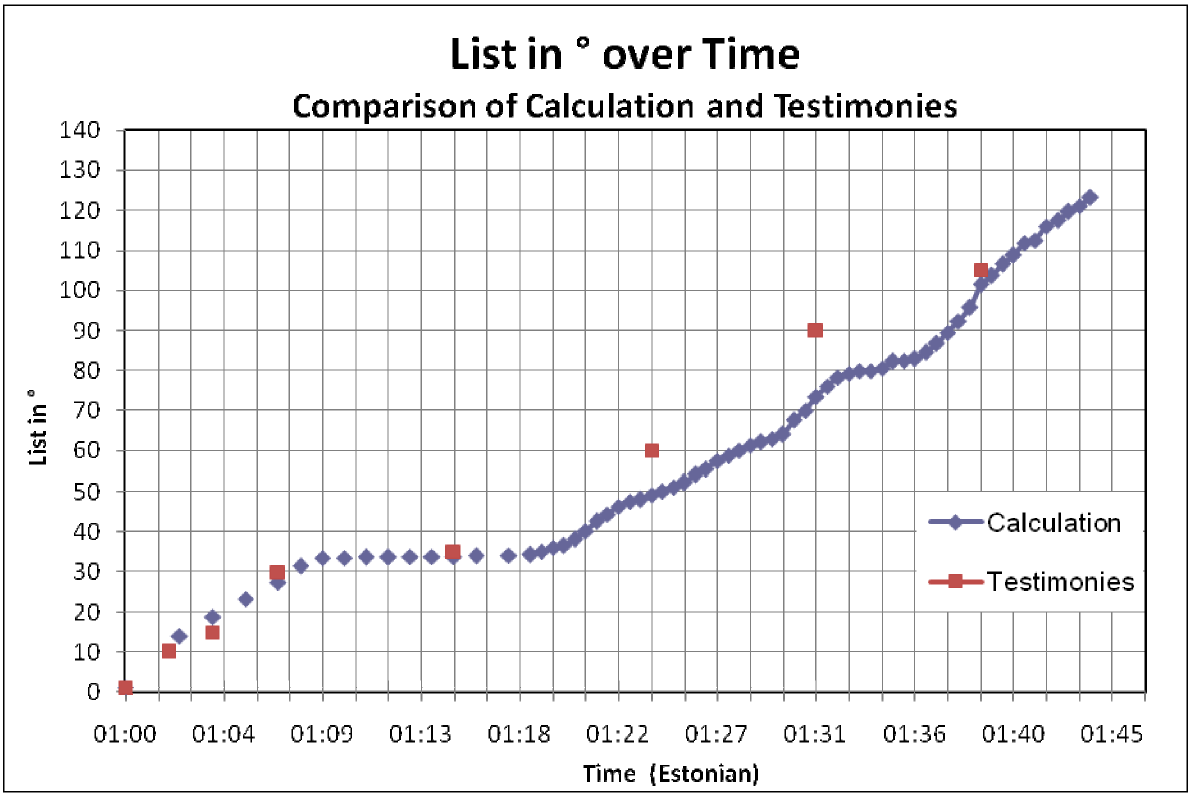


Figure 12.77: Graph showing a comparison of calculation with testimony, list in °over local time

Note: many survivors report of walking on the shell of the Portside of MV Estonia. The time for which the heeling angle is from about 80° to 100°, when walking on the vessel's side is possible, lasts for about 6 or 7 minutes – which is long in comparison to the overall sinking time– and is most likely an explanation for this.

To sum it up, the results of the calculations are in line with the testimonies of the witnesses, see also *Figure 12.77*.

The diagram "Graph of metacentric height in equilibrium floating condition over local time", *Figure 12.78*, shows very clearly a high level for the metacentric hight over a large period of the sinking sequence. As the metacentric height is an indicator of the engergy needed to move a vessel out of its equilibrium floating condition, it is very unlikely, that MV Estonia completely overturned. In other words: it is very unlikely that MV Estonia capsized upside down within a very short period of time, as explained in [JASIO01].

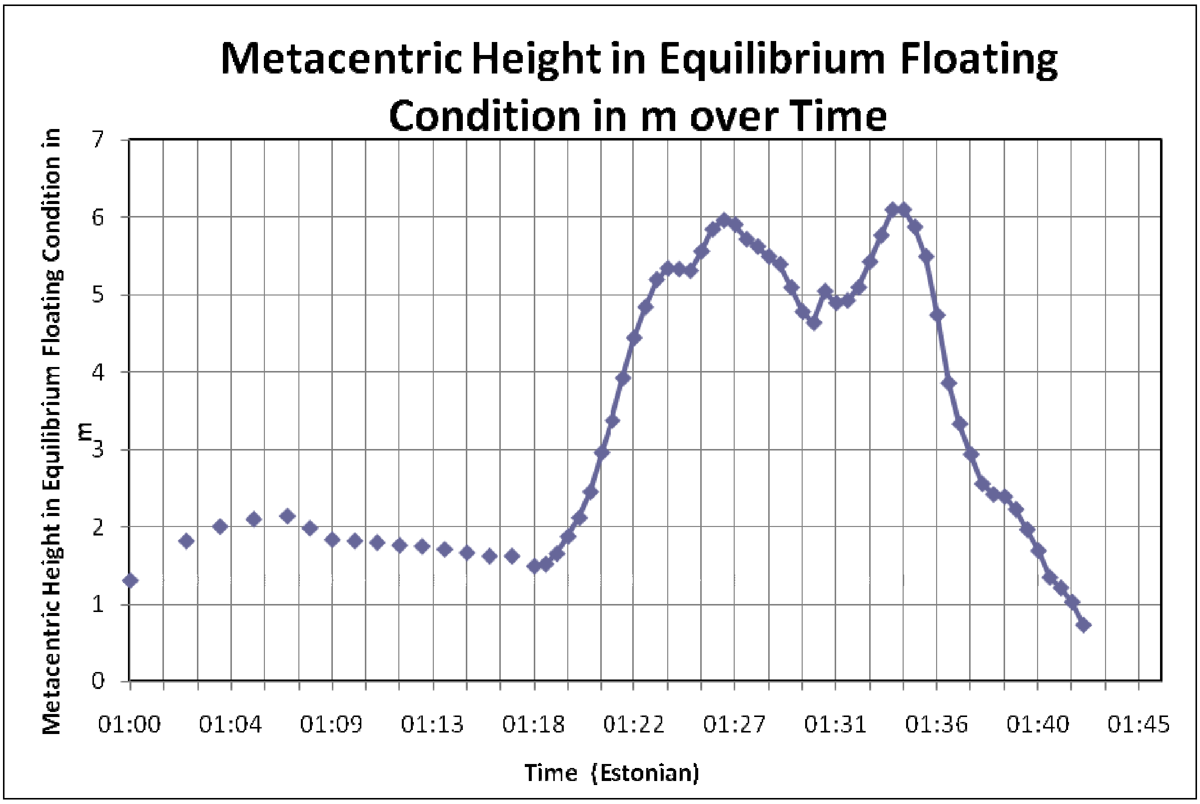


Figure 12.78: Graph of metacentric height in equilibrium floating condition over local time

The figure "Graph of total mass of MV Estonia over time", *Figure 12.79*, indicates a smooth and steady increase of the mass of the vessel with an acceleration of the sinking sequence beginning at about half past one. This again goes in line with the testimonies of the survivors. At that time, the double door on Deck 7 connecting the Centre Stair Case with the boarding area of the lifeboats bursts and a large amount of water flushes in to the Centre Stair Case.

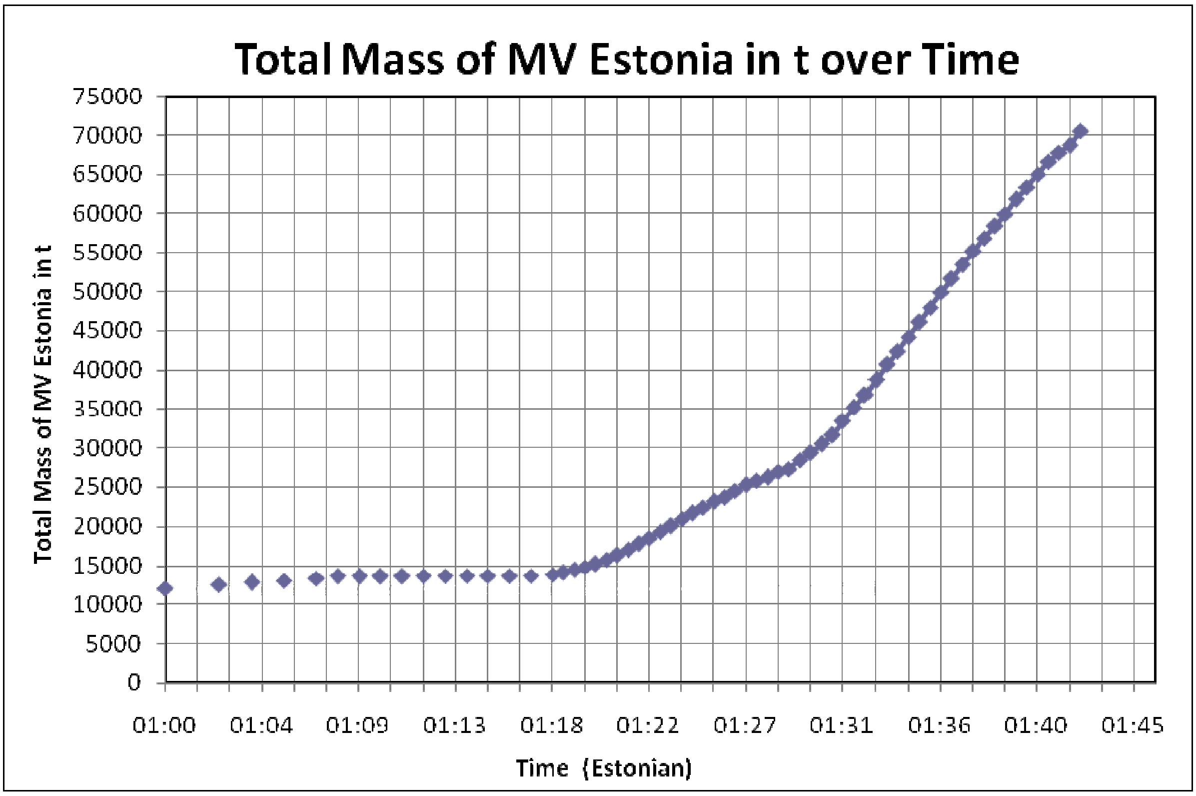


Figure 12.79: Graph of total mass of MV Estonia over time

13 Comparison to the SSPA-Results due to Aft Ward Trim

Governmental Agency VINNOVA initiated the Research project "Research Study on the Sinking Sequence of MV Estonia", by contracting two independent consortia. The result is intended to provide a greater insight into this incident, gaining more objectivity though different approaches. In this study the results of the two consortia are in some cases identical and in most similar. However, the final sinking sequence of each consortium differs. The SSPA-consortium has noticeably smaller aft-ward trim than the HSVA-consortium in the second half of the sinking, compare *Figure 13.1, Figure 13.10* and *Figure 12.76*. Another difference is the heeling angle of MV Estonia as she hit the seafloor. These two aspects are closely linked together.

Looking at the list and trim development of the foundering experiments carried out in the model basin of SSPA in Goteborg, it is noticeable, that at least until 01:30 no trim is recorded in several readings, see *Figure 13.5* and *Figure 13.9*. The same behaviour concerning trim is observed in other simulations of the SSPA-consortium.

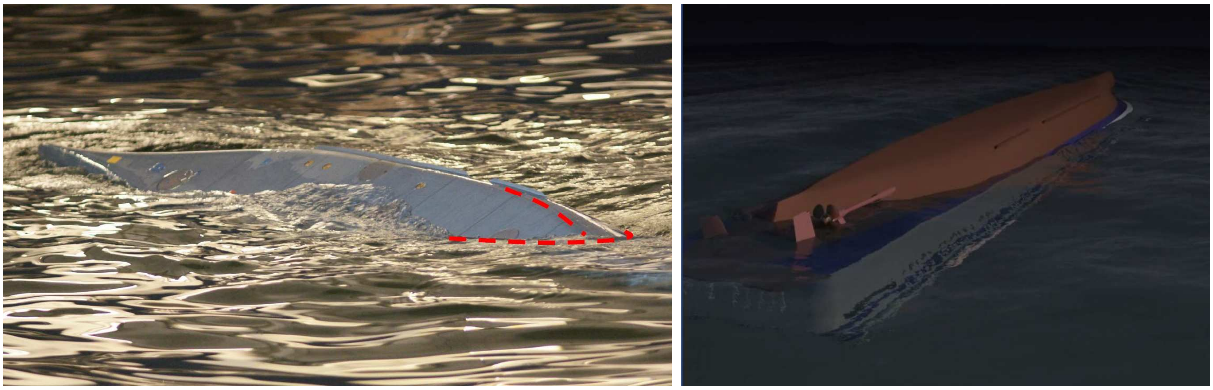


Figure 13.1: Model of MV Estonia at a heeling angle of 150° to 160° with very rarely trim during the foundering experiment in the model basin of the SSPA-consortium [SSPA05] (left) and the corresponding simulation of [SSPA05] (right) at a list of about 170°

A survivor of the catastrophe, P92, who took the picture *Figure 13.2/ Figure 13.3* sitting on the bilge keel a few minutes before MV Estonia disappeared from the surface, noted after the presentation of the results of both consortia in May 2008 in

Stockholm, that the trim presented by the SSPA-Consortium was too low compared to his experience.

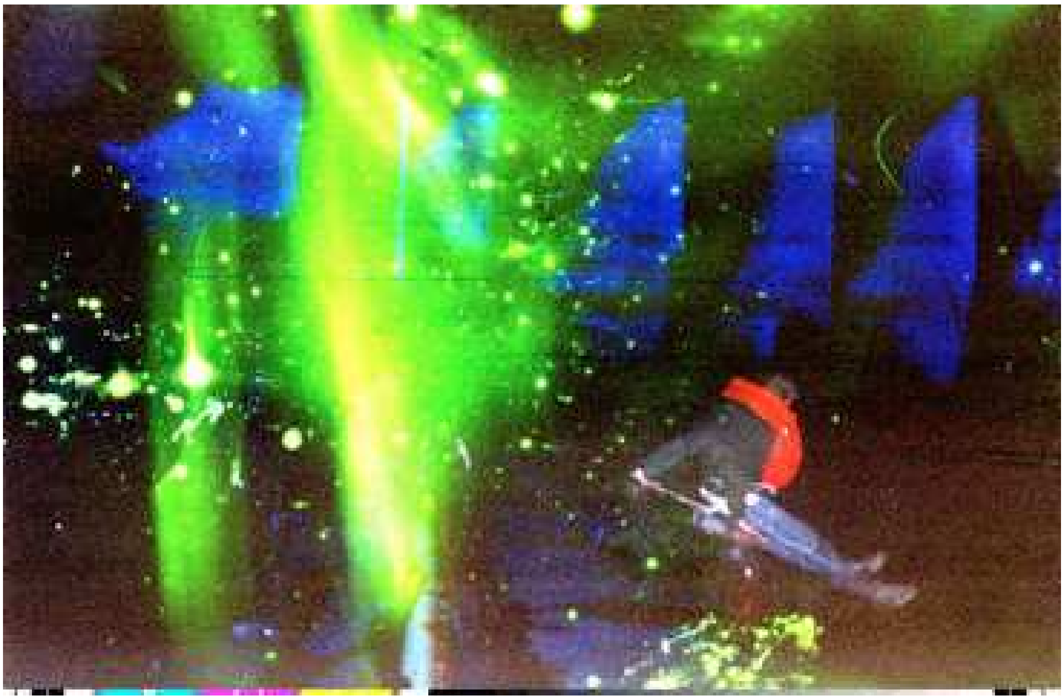


Figure 13.2: Picture taken by a survivor a few minutes before MV Estonia disappeared from the surface whilst sitting on the Bilge Keel [P92]

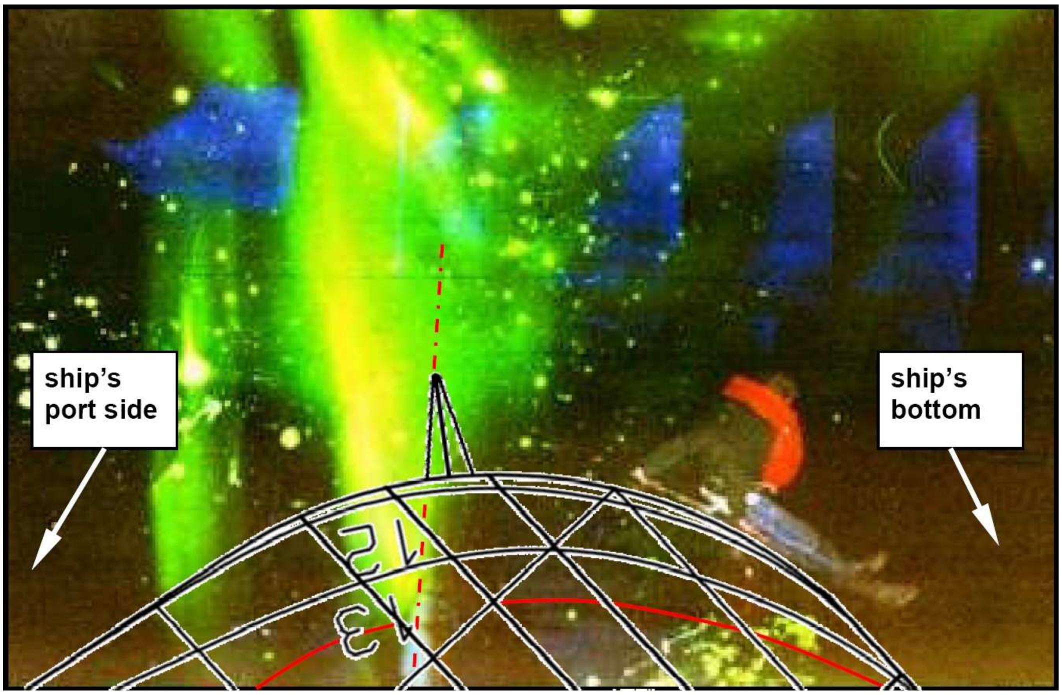


Figure 13.3: The same picture like Figure 13.7, but the body plan of MV Estonia also plotted in this picture, [HSVA02]. [HSVA02] calculated a list of 133°

Beside the observations of passenger P92, another fact is to supplement in this context. The SSPA-consortium calculated and found out by experiment that MV Estonia turtle turned completely in a upside-down condition to a list of 180° before she hit the sea floor. A picture of the experiment can be seen in see *Figure 13.4* as well as a snapshot of the simulation. In Chapter 6 was exposed that the stern had no or only on Deck 8/ Deck 9 minor damages. The observation of P92 and the none existing damage situation of the stern of MV Estonia does not fit to the last step of the sinking sequence of the SSPA-consortium.

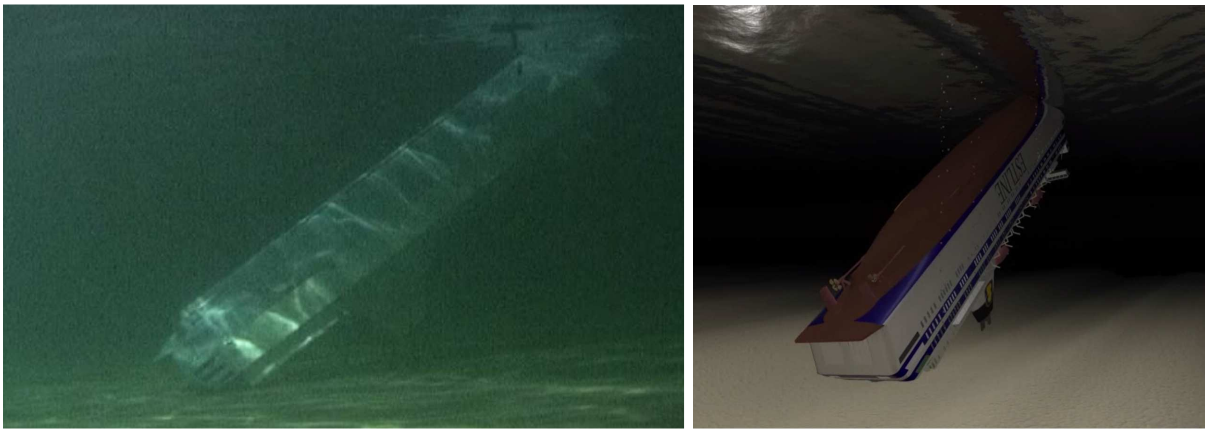


Figure 13.4: Hitting the sea floor in complete up-side-down condition, a list of 180°in model test and simulation of [SSPA05]

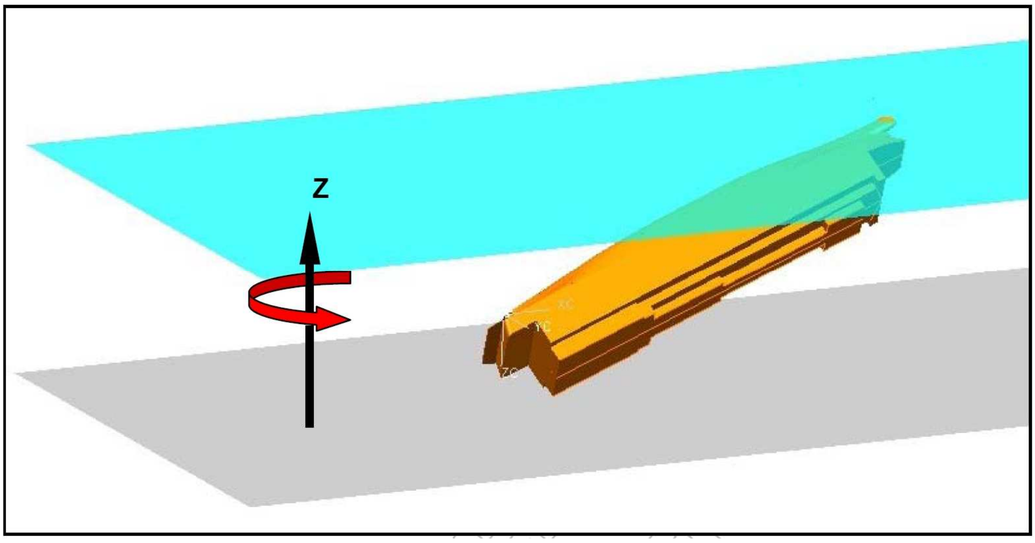


*Figure 13.5: Hitting the sea floor **not** completely turtle turned, at a list of about 130°like the author calculated [HSVA02]*

It seems to be more likely that MV Estonia developed more trim than the SSPA-consortium calculated. And it also seems to be more likely that MV Estonia hit the sea floor about in that list how she was found by the salvage company Rockwater. *Figure 13.5* shows the heeling angle in which MV Estonia probably hit the sea floor, about 130°.

In this thesis, water ingresses into the Steering Gear Compartment in a very early stage of the sinking, namely at about 01:05 or when 1000t water had flooded on to the Main Car Deck – see *Figure 12.8*. Due to the ingress to the Main Car Deck, the aft-ward trim decreases, however as the water ingress proceeds to the Steering Gear Compartment, this stops and the aft-ward trim increases again.

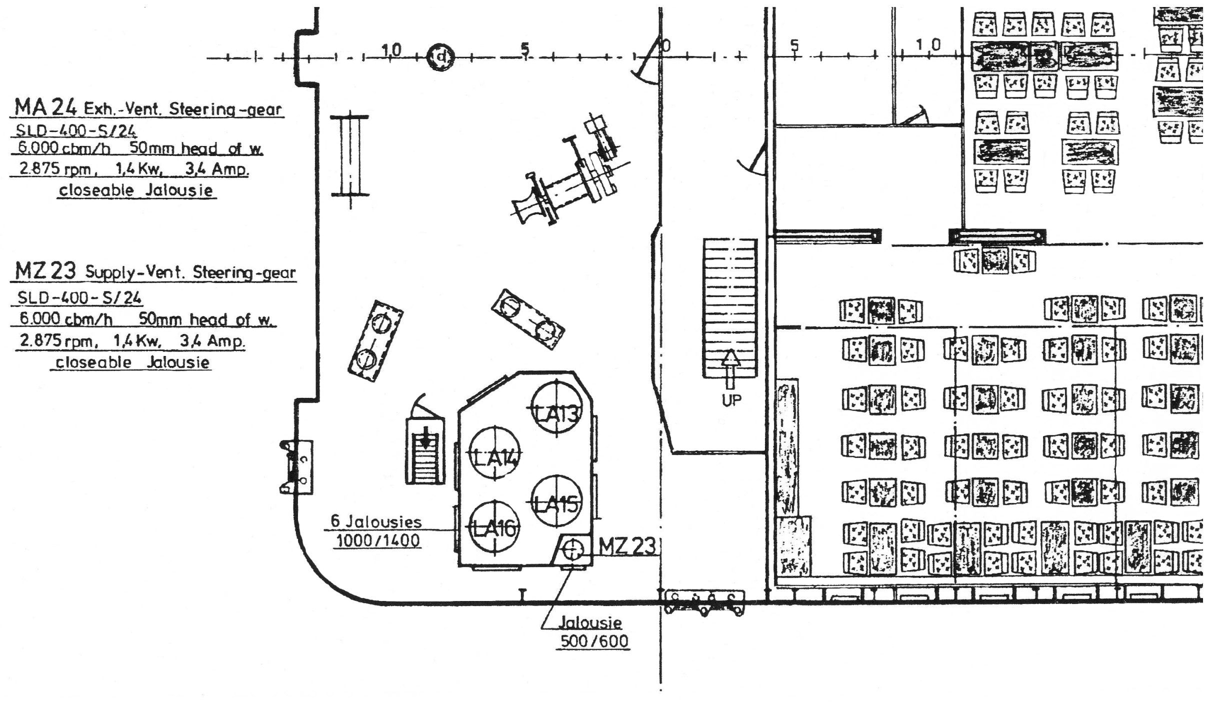


Figure 13.6: Aft Wing House, Starboard Side, Deck 4, top view, Drawing S590 – 64/1

The upper opening of this ventilation duct, called 'MZ23' see *Figure 13.6*, is immersed between 01:19:00 and 01:19:30 whilst the trim is registered to be 1.65m to 2.0m.

The lower opening of the ventilation duct - as shown in *Figure 12.8* - is not documented in any report of the SSPA-consortium. Even the corresponding upper ventilation opening is not modelled in the digital model showing spaces and is not listed in the opening codes of the SSPA-consortium, as shown in the detail *Figure 13.7*. Only the four ventilation ducts, cylindrical in shape, which pump out the exhaust air off the Main Car Deck were modelled to be two rectangular ducts. Consequently, the Steering Gear Compartment and the horizontally non-watertight linked compartment stays dry.

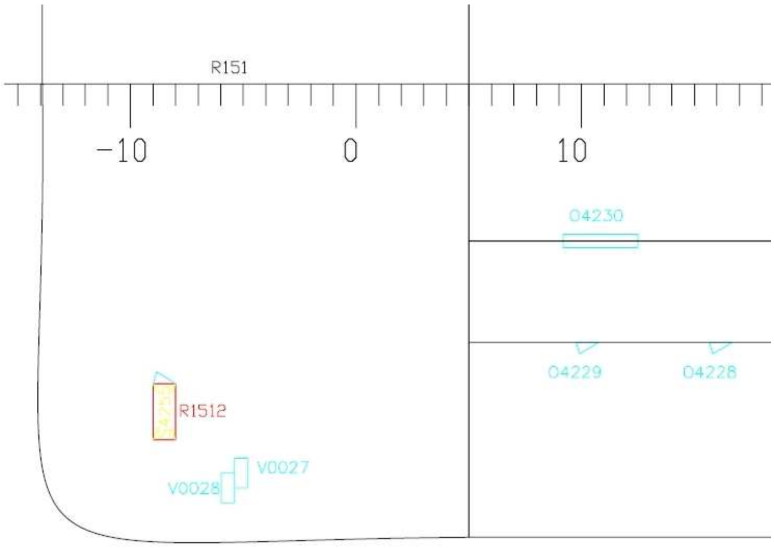


Figure 13.7: Aft of MV Estonia, Deck 4, digital-model, spaces and opening codes [JASIO02]

The calculations of this thesis were carried out with all doors, as well as the all emergency exits, below the Main Car Deck assumed to be closed in a watertight fashion. The same arrangement was used in the calculations of [JASIO01]. He argues, that quote "…then the ship would not trim and ultimately sink for a long time, possibly at all […] This is because there is no connection to auxiliary rooms through any other opening and its volume would be sufficient to keep the vessel afloat, see Figure 6." The Figure 6 of [JASIO01] is given in *Figure 13.8* of this thesis. [JASIO01] says that the red coloured areas of *Figure 13.8* sum up to 2050m³ states this "…would be nearly sufficient for the ship to remain afloat even with every other space flooded completely." However, the buoyancy is far too small to keep the vessels mass of about 12000t afloat. Furthermore [JASIO01] neglects to note that the stabiliser fins occupy a certain amount space in the vessels hull, in the compartment in front of the Auxiliary

Engine Room. Looking at *Figure 13.8*, where in this particular compartment the stabiliser fins were fitted, [JASIO01] states that this compartment was not flooded, however, the digital model of [SSPA03] indicates that this compartment will flood - by its white colour in this figure , *Figure 13.9*.

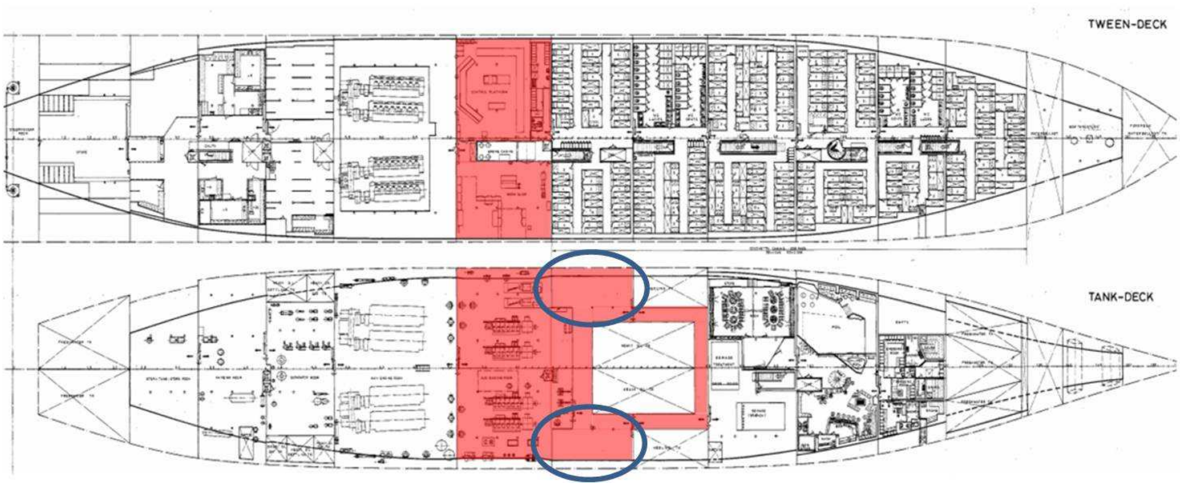


Figure 13.8: The blue circles mark the areas of the Stabiliser Fins which are not considered in [JASIO01]

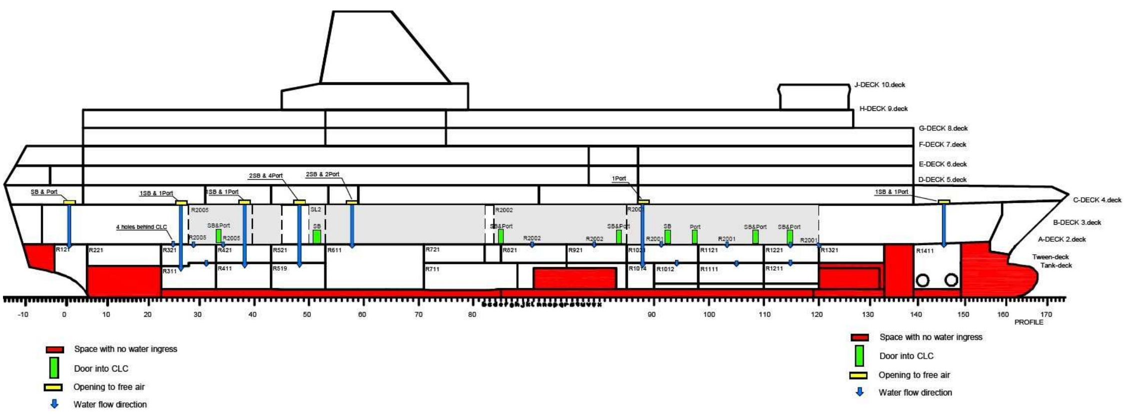


Figure 13.9: Ventilation Duct 'MZ23' connecting the Steering Gear Compartment and the adjacent and not watertight compartment is modeled [SSPA03]

Drawings of *Figure 13.8* and *Figure 13.9* do not fit together, because *Figure 13.8* shows the Steering Gear Compartment and the linked, non-watertight, compartment to be flooded, but again without modelling the appropriate ventilation duct.

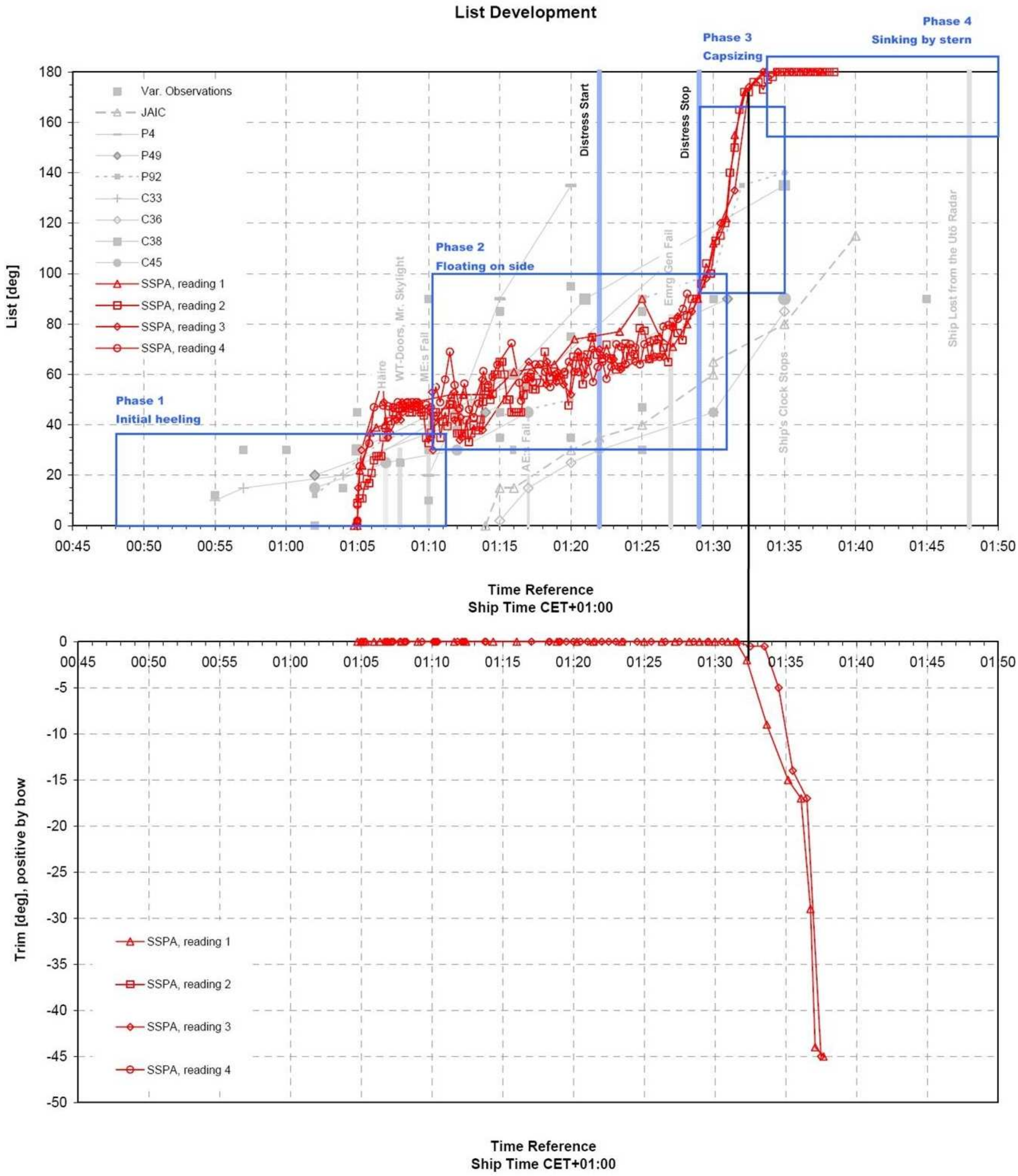


Figure 13.10: List and trim development from the foundering experiment in the model basin of the SSPA-consortium [SSPA04]

Beside the above explained differences it remains unclear how well the difference between the calculations of this thesis and the calculations of the SSPA-consortium can be explained.

14 Concluding Remarks and Recommendations for Future Work

The research project "Research Study of Sinking Sequence of MV Estonia" founded by the Swedish Governmental Agency for Innovation Systems VINNOVA was carried out by two research consortia. One consortium was led by the Hamburg Ship Model Basin (HSVA) in which the Institute of Ship Design and Ship Safety of Hamburg University of Technology is a member. This thesis was conducted based on this work.

Between 01:00 and 01:02 local Estonian time, two or three metallic bangs were heard by several passengers and crew members at different locations on MV Estonia. This investigation has connected these metallic bangs with the loss of watertight integrity of the Main Car Deck. In the following minutes, an amount of at least 1500t of sea water accumulated on Main Car Deck and led to a quasi-static equilibrium floating condition of about 30° list to starboard. This list was in line with the reports of the surviving witnesses. The water entered via the bow opening, but is assumed that a certain, but unknown, quantity of water was already on the Main Car Deck. The vessel decelerated and consequently both bow wave and dynamic sinkage decreased, leading to the water inflow rate into the Main Car Deck to decrease as well. However, MV Estonia had reached an equilibrium floating condition with a steady list of about 30°. The last manoeuvre of MV Estonia, a sharp turn to port, contributes to the heeling shortly after the metallic bangs.

The bow visor was separated from MV Estonia and this is associated with the above mentioned metallic bangs. Several factors contributed to the loss of the bow visor, e.g. improper maintenance or an assumption by classification societies and authorities that loads induced on bow visors by wave impacts would be far lower than experienced that night.

The loss of the bow visor results in an increased trim to the stern which impeded water outflow from the Main Car Deck. This, and the initial trim to the stern, has a strong influence on the final sinking scenario.

The first amount of water on Main Car Deck reduced this trim slightly, but during the subsequent sinking sequence of the vessel, an aft-ward trim remained. Via a ventilation duct connecting the aft starboard side wing house with the Steering Gear Compartment and Store Compartment below, on Tween Deck and Deck 1, water entered both compartments and increased the aft-ward trim again. Water that continues to enter the Main Car Deck increases the list further. The increasing list, as well as the increasing aft-ward trim, lead then to the submerging of the starboard side ventilation openings, which were located just below Deck 4. Several compartments were ventilated by these ducts such as the Main Car Deck, the Main Engine Room, the Separator Room and others. This was the beginning of a domino effect, where more and more water entered MV Estonia through these openings and was distributed throughout the ship. This again caused an increase of list and trim, as the side ventilation openings were located in the aft part of the vessel. Additionally, in the aft part of the vessel the windows had a larger size and lower collapse loads than those in the forward part. After reaching a critical hydrostatic water pressure – the collapse load – on such a window or a door, it fails and allows for further water ingress. Due to this, the compartments above the Car Deck were flooded consecutively.

After reaching a heeling angle of nearly 80 degrees, the ventilation ducts through the centre casing were flooded, as well as the engine casing.

MV Estonia sank stern first with a list of a little more than 120° to starboard and consequently hit the seabed, with the top of Deck 9 making first contact. This corresponds to the observation of the diving company Rockwater, which surveyed the vessel a few days after its sinking. The computed list over time graph is roughly in line with the testimonies of the survivors as investigated and evaluated at the beginning of this thesis. The "Graph of comparison of calculation and testimonies, list in ° over local Estionian Time", *Figure 14.1* documents this result. This physically plausible sinking scenario suggests that the sinking sequence has taken place more or less or like these calculations.

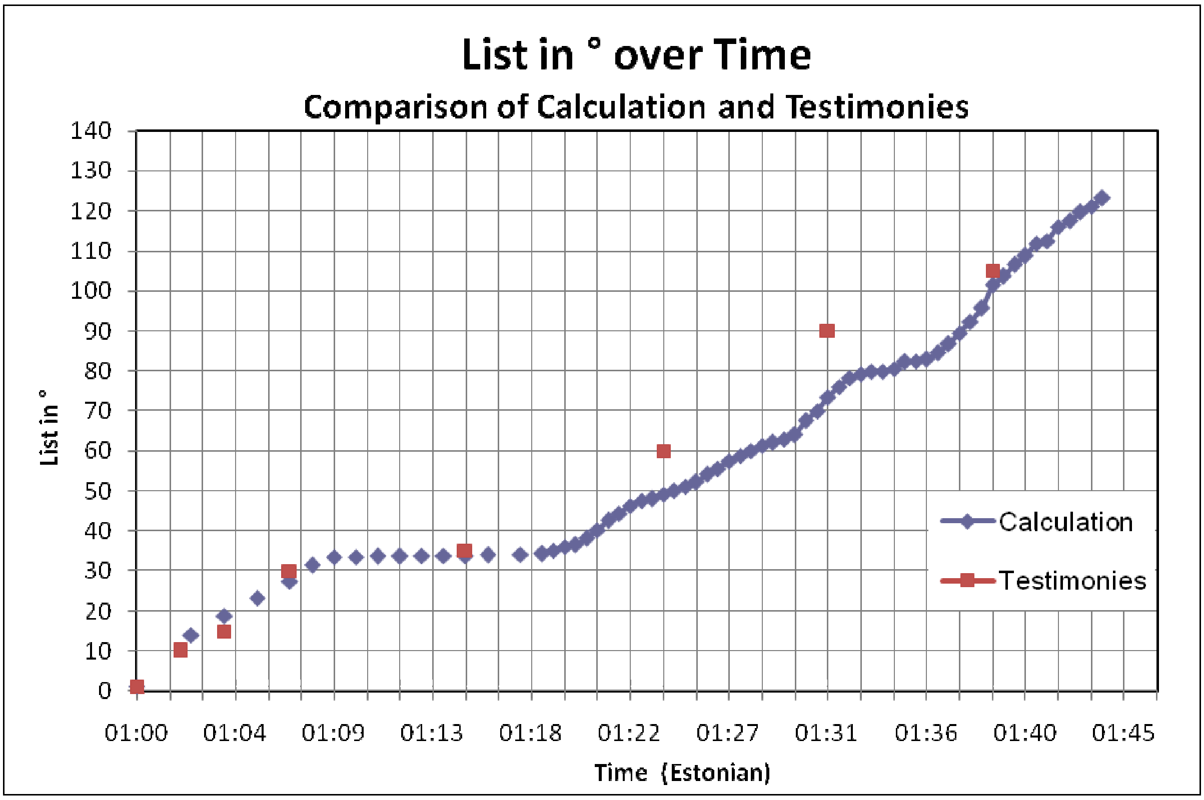


Figure 14.1: Graph of comparison of calculation and testimonies, list in °over local Estionian time

It was further found that during all calculation steps that the individual equlibrium floating conditions were all determined to be stable, which means that the vessel would have remained for a long time in this floating condition should the water ingress have been stopped. As a consequence of these findings, it can be stated that the vessel would not have capsized raipdly or turned upside down, a fact which is also fully inline with the position of the vessel on the ground. In fact, MV Estonia capsized only in the first phase up to the intermediate equlibrium floating condition. But from the intermediate equlibrium floating condition on MV Estonia did not capsize at all – capsizing would mean a loss of stability. The sinking sequence of MV Estonia is instead a case of progressive flooding.

From all these investigations and calculations it is possible to come to the following conclusions: The loss of MV Estonia can be described as a chain of events which, in this combination, led consequently and irreversibly to the sinking of the ferry:

- Once the watertight integrity of the bow was lost, large volumes of water were able to enter the Main Car Deck. The fact that these large volumes of water actually entered the Main Car Deck, when the vessel pitched against the waves, supported due to the reduced freeboard of the Main Car Deck which itself was a consequence of the forward speed and the related dynamic effects.
- When a critical amount of water had entered the Main Car Deck, this led to a drastic reduction in the initial stability of the ship which resulted in a rapidly increasing heel - until an intermediate equilibrium floating condition of about 30° was reached. The last manoeuvre of MV Estonia contributes to the heel. Due to this rapidly increasing heel, it was hardly possible for people to escape to the outside and to abandon ship.
- During this intermediate equilibrium, additional flooding took place. Here, the side ventilation system played the dominant role. Once the side ventilation openings were submerged, a domino effect ensued where more and more water could enter the ship. Due to this water ingress, heel and aftward trim increased until the vessel then finally sank:

A number of conclusions for the general safety of RoRo- Passenger Ships can be drawn from the MV Estonia accident, which must focus on ensuring thatthe above chain of events can never happen again.

- Firstly, the watertight integrity of all design elements of the Main Car Deck of RoRo-Passenger Ferries must be ensured under all possible design conditions. This especially holds for all design elements which are exposed to sea keeping loads. For future designs, especially for such where it may be expected that high loads might occur, it is the recommendation to first carry out principle based investigations of the actual loading scenarios, as well as of the structural response of the design element. This will ensure that, under all relevant operational conditions, the watertight integrity of the Main Car Deck is assured, because it became obvious that the design of the bow visor could not resist the actual loads.

- Secondly, it was found by these investigations that a core safety element of a RoRo-Passenger Ferry - in case of a loss of its watertight integrity – is, in that equilibrium floating condition, a sufficient freeboard is maintained from the waterline to the vehicle deck. This design element prevents massive water ingress into the ship and, consequently, a rapidly increasing heel due to reduced or even negative initial stability. Preventing a rapidly increasing heel is also a core element in enabling passengers and crew to escape from the ship, if necessary. **Whenever modifications of the existing damage stability requirements for RoRo Passenger Ferries are discussed, these findings need to be accounted for.**
- Thirdly, it was found that from that moment on when the side ventilation ducts were submerged, the vessel's sinking was unstoppable. With this in mind, it may be recommended to better take into account these kinds of situations during the design of such systems, or to ensure that during the damage stability assessment of RoRo- Passenger Ferries there is always sufficient freeboard to openings through which a massive progressive flooding can take place.
- Fourthly, as a matter of course every merchant vessel must be in compliance with the SOLAS regulation in force.

15 List of Tables

16 Table of Figures

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17 Picture Credits

Figure 2.1, courtesy of Marko Stampehl

Figure 3.1, courtesy of Dr. Nuorteva/ Dr. Valanto

Figure 3.2, courtesy of JAIC, see [JAIC03]

Figure 3.3, courtesy of JAIC, see [JAIC04]

Figure 3.4 – Figure 3.7, courtesy of Jan-Öve Carlsson, see [CARLS01]

Figure 3.8, courtesy of Prof. Dr.-Ing. Dr.-Ing. E.h. Dr. h.c. E. Lehmann, see [LEH]

Figure 3.9, courtesy of HANSA, see [HANSA01]

Figure 6.1, 6.3, 6.4, 6.5, 6.6, 6.7, 6.8, 6.10, 6.12, 6.14, 6.16, 6.18 are snap shots from the video tapes by the ROV inspection of [ROCK] in October 1994

Figure 6.9, 6.11, 6.13, 6.15, 6.17, 6.19, 12.5 courtesy of Marine Claims Partner (Germany) GmbH

Figure 13.2 courtesy of the SSPA-Consortium, see[JASIO02]

Figure 13.3 courtesy of the SSPA-Consortium, see[JASIO01]

Figure 13.4 courtesy of the SSPA-Consortium, see[SSPA03]

Figure 13.5 courtesy of the SSPA-Consortium, see[SSPA04]

Figure 13.5 courtesy of the SSPA-Consortium, see[SSPA05]

Figure 13.7 courtesy of the survivor P92 (Witness Key shared by the SSPA- and HSVA-Consortium of the “Research Study on the Sinking Sequence of MV Estonia”)

Figure 13.8 courtesy of Dr. Valanto, HSVA [HSVA02]

Figure 13.9 courtesy of the SSPA-Consortium, see[SSPA05]

Figure 13.10 courtesy of Dr. Valanto, HSVA [HSVA02]

18 List of Abbreviations

ARPA	Automatic Radar Plotting Aid
Aux.	Auxiliary
ch.	Chapter
CL	Centre Line
Comp.	Compartment
CPA	Closest Point of Approach
ECR	Engine Control Room
HSVA	Hamburgische Schiffbau Versuchsanstalt GmbH, The Hamburg Ship Model Basin
IPE	International Panel of Experts, assembled by VINNOVA to provide specialized support to the two consortia of the "Research Study of the Sinking Sequence of MV Estonia" by VINNOVA
JAIC	The Joint Accident Investigation Commission of Estonia, Finland and Sweden
L.T.	Local Time
N.f.S.	"Nachrichten für Seefahrer", professional journal
p.	Page
PS	Port-side
ROV	Remote Operated Vehicle
rpm	rotations per minute
SPF	Styrelsen för Psykologiskt Försvar, The Swedish National Board of Psychological Defence
SSPA	Statens Skepsprovnings Anstalt, SSPA Sweden AB, The Swedish Ship Model Basin

STB	Starboard side
TUHH	Hamburg University of Technology
Vol.	Volume

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20 Supplementum

20.1 Synoptic Time Schedule

Witness	recorded	1	2	3	3	4
Name		P28	P20	P79	P79	P56
Source		SPF	SPF	SPF	GGE	SPF
Date		13 Oct. 1994	17 Oct. 1994	03 Oct. 1994	14 Oct. 1994	04 Oct. 1994
PAX / Crew		P	P	P	P	P
Cabin	7.3.3	1027	1026	deck 4	deck 4	deck 4
Time						
19:00					late departure	
to						
20:00						
to						
21:00					swung more than usual (4 or 5 times travelled with Estonia)	
to						
22:00						
to						
23:00						
to						
23:30						
to						
00:00						went to bed
00:01						
00:02						
00:03						
00:04						
00:05						
00:06						
00:07						
00:08						
00:09						
00:10						
00:11						
00:12						
00:13						
00:14						
00:15						
00:16						
00:17						
00:18						
00:19						
00:20				was in Karaoke-Bar on deck 4, while hearing the bangs, although noise and music were playing, sure that bangs not wave induced bangs at 00:45am, half a minute in between		
00:21						
00:22						
00:23						
00:24						
00:25						
00:26						
00:27						
00:28						
00:29						
00:30					entered Karaoke bar	
00:31						
00:32						
00:33						

Witness	recorded	1	2	3	3	4
Name		P28	P20	P79	P79	P56
Source		SPF	SPF	SPF	GGE	SPF
Date		13 Oct. 1994	17 Oct. 1994	03 Oct. 1994	14 Oct. 1994	04 Oct. 1994
PAX / Crew		P	P	P	P	P
Cabin	7.3.3	1027	1026	deck 4	deck 4	deck 4
00:34						
00:35						
00:36						
00:37						
00:38						
00:39						
00:40						
00:41						
00:42						
00:43						
00:44		was out side on deck 6 at stern -- watched two ships abeam and astern				
00:45				a dull bang		
00:46				2nd dull bang		
00:47				ship started pitching for about 10 min, list to STB increased		
00:48						
00:49						
00:50						
00:51						
00:52					01:02 am: strong bang, metallic noise, 20...30 sec later same noise, started to swing longitudinal, not only rolling anymore	
00:53						
00:54						
00:55			was at the shop on STB-side, Ship starts to list, all of the sudden the ship starts to shake, list increased, matters starts to slide, in this order: Estonian message by loudspeaker, then "Mayday, Mayday", Ships horn honking, light of went out, while standing on ships hull --- Ship sank bow-wards			
00:56				list 10°...15°		
00:57						start to howl, to crunch, to scour, recognized a list and less vibration
00:58						
00:59				list 30°		
01:00						
01:01						
01:02						
01:03					list began, did not go back over 0°,loose things fell off	weird noise
01:04				list 35°		went stairs to deck 2, water on floor and wall
01:05		look on watch				
01:06		suddenly, without warning ship listed to STB -- Tables side away -- Ship were changing course to PS -- for some time list were constant -- heard two Massages by loudspeaker: one in Estonian and one "Mayday, Mayday"				
01:07						
01:08					became stabilized at 30°...35° oscillated 5° in each direction for maybe 7...8 min.	no water between Deck 2 and 3
01:09						
01:10						
01:11				45° list, stays about 5 minutes at this list, lights jitter		enormous list
01:12						
01:13						
01:14						reach deck7
01:15						
01:16					list increasing, lights blinked at 45° several times	
01:17						
01:18						
01:19						
01:20				list 70° lights went finally of, when funnel hits the water a dull signal, a horn was heard, after funnel hitting the water, a list of 90° was very		
01:21	1st Mayday					
01:22					list 60°, stays 3...5 min	
01:23						
01:24	2nd Mayday					got life vest
01:25	blackout					
01:26	blackout					
01:27						list about 80°

Witness	recorded	1	2	3	3	4
Name		P28	P20	P79	P79	P56
Source		SPF	SPF	SPF	GGE	SPF
Date		13 Oct. 1994	17 Oct. 1994	03 Oct. 1994	14 Oct. 1994	04 Oct. 1994
PAX / Crew		P	P	P	P	P
Cabin	7.3.3	1027	1026	deck 4	deck 4	deck 4
01:28	Estonia tells			fast reached, stabilizer-fins moved	stayed at about 90°...100°, bell	
01:29	last radio					when funnel hits water the lights jitter, then went out
01:30						
01:31						
01:32					quick increasing from 100° onwards	
01:33						list increased, ship
01:34						
01:35						
01:36						
01:37						
01:38					funnel disappeared at 105°...110°	
01:39						
01:40						
01:41						
01:42						Estonia upside down
01:43						
01:44						
01:45						
01:46						
01:47						
01:48						
01:49						
01:50						
01:51						
01:52						
01:53						
01:54						
01:55						
01:56						
01:57						
01:58						
01:59						
02:00						
02:01						
02:02						
02:03						
02:04						
Comments				broker and consultant of boats, Estonia sank stern first, estimated time from 1st list 90° 20min, Bow-Visor maybe missing, ferry looks strangely	drunk the whole evening one Irish Coffee, 4 cl. alcohol, went down by aft, visor missing	

Witness	5	5	5	6	7	8
Name	P76	P76	P76	P49	C37	P15
Source	SPF	GGE	GGE	SPF	SPF	SPF
Date	04 Oct. 1994	??	??	02 Oct. 1994	04 Oct. 1994	04. Oct 1994
PAX / Crew	P	P	P	P	member of band	P
Cabin	6217	??	6217	deck 6 -6223?	771 ?	5205
Time						
19:00			conference on deck 4, had to give a speech, showed overheads, while a high whining noise started, had to speak up, end of speech, break, hostess asked to if the noise could turned off, could nothing do about it, noise changed to turn on/ off, even more disturbing, conference closed 15...20min earlier than planed, 20:40 or 20:45 Swedish time!!			
to	20:45 h was in conference room on deck 4, heard just before closing the conference an engine staring and running with constant high rpm - remembered this afterwards, no special regards during the conference	20:45 h was in conference room on deck 4, disturbing noise so loud that conference was closed down, noise like hydraulic pump				
20:00						
to						
21:00						
to						
22:00						
to						
23:00						
to						
23:30						
to						
00:00				went to bed in cabin on deck 6		
00:01						
00:02						
00:03						
00:04						
00:05						
00:06						
00:07						
00:08						
00:09						
00:10						
00:11						
00:12						
00:13						
00:14						
00:15						
00:16						
00:17						
00:18						
00:19						
00:20						
00:21						
00:22						
00:23						
00:24						
00:25						
00:26						
00:27						
00:28				band stopped playing due to sea state, a dancer tumbled due to sea state		
00:29						
00:30						
00:31						
00:32						
00:33						
00:34						

Witness	5	5	5	6	7	8
Name	P76	P76	P76	P49	C37	P15
Source	SPF	GGE	GGE	SPF	SPF	SPF
Date	04 Oct. 1994	??	??	02 Oct. 1994	04 Oct. 1994	04. Oct 1994
PAX / Crew	P	P	P	P	member of band	P
Cabin	6217	??	6217	deck 6 -6223?	771 ?	5205
00:35						
00:36						
00:37						
00:38						
00:39						
00:40						
00:41						
00:42						
00:43						
00:44						
00:45			felt change in ship motion			
00:46						
00:47						
00:48						
00:49			suddenly felt 2 or 3 shocks			
00:50						went to bed
00:51						
00:52						
00:53						
00:54						
00:55			vessel heeled over slowly, came up, heeled deeper, tables sliding, no engine noises			
00:56						
00:57						
00:58				was awoken at 1:00am by Gutelind due to heavy list to PS		
00:59						
01:00						
01:01						
01:02			further list stepwise			
01:03				increasing list, luggage slipping and blocking cabin door		
01:04						
01:05	list to PS	first list				
01:06	back to 0°list					
01:07				on corridor		
01:08	list PS, more then before, glasses fell of the bar		lights were flickering, but came back, list 70°.. .90°, two persons coming out of a door near funnel, smaller one: "water coming up from the car deck			
01:09						
01:10						
01:11						
01:12	on way out bar counter slipped away			at staircase		
01:13					heavy list, back to upright position	
01:14				list increasing		
01:15						
01:16				outside deck 7, list 45°		
01:17	short horn, list 90°, steam when funnel hit water - two persons escaping emergency exit near funnel, one yelling: "Water is coming up form car deck"					
01:18				water flushing in door deck 7		
01:19						woke up
01:20						
01:21				heard 3 times horn (sound like lorry) lights out	heard met. noise connected to 3-4 bangs, seemed to come from below the ship	
01:22						
01:23						entered 7, light working
01:24						
01:25						
01:26						list to 45°, stepwise
01:27				walked on hull, broke through		
01:28					soon after the	

Witness	5	5	5	6	7	8
Name	P76	P76	P76	P49	C37	P15
Source	SPF	GGE	GGE	SPF	SPF	SPF
Date	04 Oct. 1994	??	??	02 Oct. 1994	04 Oct. 1994	04. Oct 1994
PAX / Crew	P	P	P	P	member of band	P
Cabin	6217	??	6217	deck 6 -6223?	771 ?	5205
01:29				window, injured, watch damaged at **01:31** am	bangs ship started to list, casino table slipped	
01:30						
01:31						90°, fog horn blowing, lights off
01:32	lights went out					
01:33						
01:34					increasing list	
01:35	distress rocket lighting the scene					
01:36						
01:37					something by loudspeaker	
01:38				Estonia upside down		
01:39	ship sunk					
01:40						
01:41						
01:42						
01:43						
01:44				bow under water stern out of water		
01:45						
01:46						
01:47						
01:48						
01:49						
01:50				ship sunk		
01:51						
01:52						
01:53						
01:54						
01:55						
01:56						final sinking
01:57						
01:58						
01:59						
02:00						
02:01						
02:02						
02:03						
02:04						
Comments	has seen keel of Estonia up side down, stern under water, at front a "buckle"	saw "Mariella" on STB side	was on conference trip onboard Estonia	his lifeboat was astern the Estonia	list to STB, time from 1st list to sinking ca. 5min., stern sank first	was on conference trip by his company Statoil, Dept. Gas market

Witness	9	9	10	11	12	13
Name	P59	P59	P12	P16	P48	P83
Source	GGE	SPF	SPF	SPF	SPF	SPF
Date		03. Oct 1994		04. Oct 1994	05. Oct 1994	05. Oct 1994
PAX / Crew		P	P	P	P, but employed	P
Cabin		??? Deck 4	622	4131	4329 / 4331 /	
Time						drove on Estonia at 18:40h to STB, few cars / mostly trucks on board, after leaving Tallinn, went on car deck to fetch a pillow from his car
19:00						
to						
20:00				21:00h: visited bridge, remembered exactly vessel was heading 262°, wind speed about 20km/h		
to						
21:00						
to			went to bed			
22:00						
to						
23:00						
to						
23:30		went to bed				was in the fore part of the vessel on deck 5
	ship motion increasing	couldn't sleep, because ship was "bouncing"				
to						
						heard and felt a metallic bang against the hull, never heard such a bang on a ferry before, shortly after first list, stayed at this list, could see water nearby the STB windows
00:00	went to bed					
00:01						
00:02						
00:03						
00:04						
00:05						
00:06						
00:07						
00:08						
00:09						
00:10						
00:11						list about 45°
00:12						
00:13						
00:14						
00:15						list increased
00:16						
00:17						
00:18						
00:19						announcement "Mayday +something. about the list"
00:20						
00:21						
00:22						
00:23						
00:24						
00:25						
00:26						
00:27	15 min before list heard one heavy metallic banging noises and then another two					
00:28						
00:29						
00:30						
00:31						
00:32						

Witness	9	9	10	11	12	13
Name	P59	P59	P12	P16	P48	P83
Source	GGE	SPF	SPF	SPF	SPF	SPF
Date		03. Oct 1994		04. Oct 1994	05. Oct 1994	05. Oct 1994
PAX / Crew		P	P	P	P, but employed	P
Cabin		??? Deck 4	622	4131	4329 / 4331 /	
00:33						
00:34						
00:35						
00:36						
00:37						
00:38						
00:39						
00:40						
00:41						
00:42						
00:43						
00:44						
00:45						
00:46						
00:47						
00:48						
00:49						
00:50				was in cabin, tried to sleep		
00:51						
00:52						
00:53						
00:54						
00:55					heard a noise, like pitching in a big wave, slight list, but something was abnormal, left the pub, nearly upright walking, 1min later heavy list	
00:56						
00:57						
00:58						
00:59		hard bang, too hard to come from the storm dull, from bow				
01:00			01:00h: woke up due to a bang and seesaw	2 heavy bangs		
01:01				dressed, left his cabin		
01:02						
01:03				first heel, was in staircase		
01:04						
01:05		2nd met. bang		decrease of heel, but list		
01:06		left cabin, list 25°			list increasing stepwise	
01:07				list increasing, 30°, ship stayed in this position for about 15 min., --- heeling a bit more?? --- heard a bell ringing, while distributing the life vests		
01:08						
01:09						
01:10		reach outside				
01:11		list 45°, life vest on				
01:12						
01:13						
01:14						
01:15						
01:16		loosed a Ladder, lights flickering				
01:17						
01:18					at a list of 45° the light went out for two times came back and shortly after there was a blackout	
01:19						
01:20						
01:21		climbing ladder, light off				
01:22				capsizing started		
01:23		swimming				
01:24						
01:25						
01:26				heard a loud		

Witness	9	9	10	11	12	13
Name	P59	P59	P12	P16	P48	P83
Source	GGE	SPF	SPF	SPF	SPF	SPF
Date		03. Oct 1994		04. Oct 1994	05. Oct 1994	05. Oct 1994
PAX / Crew		P	P	P	P, but employed	P
Cabin		??? Deck 4	622	4131	4329 / 4331 /	
01:27				signal, when list 90° just before heeling more		
01:28						
01:29						
01:30						
01:31						
01:32		sinking of vessel				
01:33						
01:34					90°: heard a signal, interpreted this to leave the ship and jumped into the water	
01:35						
01:36						
01:37						
01:38						
01:39						
01:40						
01:41						
01:42						
01:43						
01:44						
01:45						
01:46						
01:47						
01:48						
01:49						
01:50						
01:51						
01:52						
01:53						
01:54						
01:55						
01:56						
01:57						
01:58						
01:59						
02:00						
02:01						
02:02						
02:03						
02:04						
Comments		vessel turned upside down, sank stern first, bow up in an angle of 15°			didn't smell anything unusual, didn't recognize any water ingress, didn't hear any announcements, time estimated from pub to jumping in the water 20...30 min.	left vessel (washed away) without wearing a lifejacket

Witness	14	16	18	19	20	22
Name	P60	P18	P17	P71	P69	P93
Source	SPF	SPF	SPF	SPF	SPF	SPF
Date	05. Oct 1994	05. Oct 1994	06. Oct 1994	07. Oct 1994	05. Oct 1994	10.10.94
PAX / Crew	P	P	P	P	P	P
Cabin	4222/4223??	1002	5229	1015	63??	1049
Time						
19:00	trucks weren't lashed					
to						
20:00						
To						
21:00						
To						
22:00						
To				went to bed		
23:00			went to bed			
To						
23:30						
To						
00:00						went to bed
00:01						
00:02						
00:03						
00:04						
00:05						
00:06						
00:07						
00:08						
00:09						
00:10						
00:11						
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00:26						
00:27						
00:28						
00:29						
00:30						
00:31						
00:32						

Witness	14	16	18	19	20	22
Name	P60	P18	P17	P71	P69	P93
Source	SPF	SPF	SPF	SPF	SPF	SPF
Date	05. Oct 1994	05. Oct 1994	06. Oct 1994	07. Oct 1994	05. Oct 1994	10.10.94
PAX / Crew	P	P	P	P	P	P
Cabin	4222/4223??	1002	5229	1015	63??	1049
00:33						
00:34						
00:35						
00:36						
00:37						
00:38						
00:39						
00:40						
00:41						
00:42						
00:43						
00:44						
00:45						
00:46						
00:47						
00:48						
00:49						
00:50						
00:51	was in cabin, when ship starts bucking unusually he left his cabin, went 3 decks upward, stepped outside, went to a lifeboat, he recognized that he was nor able to lower the lifeboat without tools, no information by loudspeaker were given, heeling was quickly, he saw water on STB-corridors on his way up, lights went off just before reaching 90°, the vessel stayed at 90° for a shot time, at 90° he heard a loud ship's whistle, the ferry was nearly upside down when she sank, there was a loud noise when the tackled air was blown out of the ferry					
00:52						
00:53						
00:54						
00:55						
00:56						
00:57			woke up by one metallic bang, the bang sounds like steel-plates crushing against each other, immediately after the bang the first heel started, just after the first heel she left her cabin, on the way to the next higher deck the list increased, she had to crawl, reaching the outside deck the ferry laid on her side, list increased further			heard familiar noise, maybe hydraulic, thought about visor
00:58						
00:59						
01:00						
01:01						heard metallic bang
01:02						
01:03		was thrown out of his bed, needed plenty of time to reach outside, when reaching outside the ferry laid on her side				
01:04					Ferry heeled all of a sudden ending with a list of 15°, 10 sec later another heel, and just close to it another heel ending at 40°	another met. bang
01:05						
01:06						
01:07						
01:08						
01:09						
01:10						
01:11						
01:12						
01:13						
01:14						
01:15						left his cabin, ferry trimmed to the aft, and then heeled to STB
01:16						
01:17						
01:18						
01:19						
01:20						
01:21						on stairs to Car Deck saw water downstairs
01:22						
01:23						
01:24					at 90° he heard a fog horn blasting, the only alarm	
01:25				woke up due to heavy list to STB,		
01:26						due to list it was

Witness	14	16	18	19	20	22
Name	P60	P18	P17	P71	P69	P93
Source	SPF	SPF	SPF	SPF	SPF	SPF
Date	05. Oct 1994	05. Oct 1994	06. Oct 1994	07. Oct 1994	05. Oct 1994	10.10.94
PAX / Crew	P	P	P	P	P	P
Cabin	4222/4223??	1002	5229	1015	63??	1049
01:27				heard bang, heard indefinable noises and muted alarm, saw water on corridor on deck 2 (car deck), lights off at nearly 90°, ship sank bow first	signal he heard the whole time	difficult to reach deck 6, got outside, got life vest, lights still on, climbed over board to rescue boat, didn't manage to get them into water, lights off, white light at bridge, aft lower than bow, managed to inflate 3 life rafts pushed them on ship's side finally into the water, smelled oil, heard fog horn, ferry sank aft first at about. 90°
01:28						
01:29						
01:30						
01:31						
01:32						
01:33						
01:34						
01:35						
01:36						
01:37						
01:38						
01:39						
01:40						
01:41						
01:42						
01:43						
01:44					ship upside down, bow ahead sinking	
01:45						
01:46						
01:47						
01:48						
01:49						
01:50						
01:51						
01:52						
01:53						
01:54						
01:55						
01:56						
01:57						
01:58						
01:59						
02:00					Propeller disappeared	
02:01						
Comments	truck driver, sailed at least 50 times with MV Estonia, heard no explosion, the whole sinking sequence lasted about an hour		she estimated the time need from leaving the cabin to reaching the life raft to a few minutes, saw no signs on the ferry what to do in case of an emergency, saw during the whole sequence no crew member, first list was heavy then the list increased by and by, smelt "Diesel" when ferry was lying on her side, her cabin was very in the front and she supposes that the metallic bang came from the bow visor			

Witness	23	25	25	26	28	28
Name	P35	P1	P1	P5	P9	P9
Source	SPF	SPF	SPF	SPF	SPF	SPF
Date	11. Oct. 1994	28.09.1994	03.10.1994	29.09.1994	01.10.1994	01.10.1994
PAX / Crew	P	P	P	P	P	P
Cabin	1007	4319	4319	6129	5128	5128
Time						
19:00						
to						
20:00						
to						
21:00						
to						
22:00						
to				went to bed		
23:00						
to						
23:30						
to						
00:00						
00:01			went to outside decks far in he front, carpets between deck 5 and 6 were wet, there was a trickle of water, to deck 6 it became dryer			
00:02						
00:03						
00:04						
00:05						
00:06						
00:07						
00:08						
00:09						
00:10						
00:11						
00:12						
00:13				did not really sleep due to ship motions		
00:14						
00:15						
00:16						
00:17						
00:18						
00:19						
00:20						
00:21						
00:22						
00:23						
00:24						
00:25						
00:26						
00:27						
00:28						
00:29						
00:30						went to bed
00:31						
00:32						

Witness	23	25	25	26	28	28
Name	P35	P1	P1	P5	P9	P9
Source	SPF	SPF	SPF	SPF	SPF	SPF
Date	11. Oct. 1994	28.09.1994	03.10.1994	29.09.1994	01.10.1994	01.10.1994
PAX / Crew	P	P	P	P	P	P
Cabin	1007	4319	4319	6129	5128	5128
00:33						
00:34						
00:35						
00:36						hard wave impacts, unusual sound, engines stopped
00:37						
00:38						
00:39						
00:40						
00:41						
00:42						
00:43						
00:44						
00:45						
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00:55						
00:56						
00:57						
00:58		was going to sleep, heard a forcibly crack, the ferry started to heel				
00:59						
01:00	he was in Karaoke-Bar, storm was heavy, glasses fell,				first sound was like a car, 30 to 60 sec later there was a small metallic bang, 40 to 50 sec later a strong metallic bang was heard, 1-2 min later the engine stopped 1-2 later a list to STB started, about 20°, list increased stepwise, outside deck 7 he tried to loosening a life raft, inflated it, climbed in and slid on the ship's side into the water, light were on to a list of about 90°, flickered and went out	
01:01						
01:02						
01:03						
01:04				two heavy roll motions, then a list to STB started, things fell off the table, chair, table, things slid in front of the cabin door an blocked it internally, she throw the thing in the toilet and stepped out the cabin, on the way to deck 7 she heard an announcement by a woman "Mayday", reached deck 7, got a life vest, afoul in a rope of a life raft, climbed in it		
01:05			knows the time of met. not exactly, supposes 5 or 10 min past one o'clock			
01:06						
01:07						
01:08						
01:09						
01:10						
01:11						
01:12		he went to the deck with the life rafts, , he jumped in a life boat an them in a life raft, short aft the list the lights went out, emergency light went out, he thought that it took 35 min form the crack to his jump into the water				
01:13						
01:14						
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01:17						
01:18						
01:19						
01:20						outside he heard "alarm you can't not hear"
01:21						
01:22						
01:23						
01:24						
01:25						
01:26						

Witness	23	25	25	26	28	28
Name	P35	P1	P1	P5	P9	P9
Source	SPF	SPF	SPF	SPF	SPF	SPF
Date	11. Oct. 1994	28.09.1994	03.10.1994	29.09.1994	01.10.1994	01.10.1994
PAX / Crew	P	P	P	P	P	P
Cabin	1007	4319	4319	6129	5128	5128
01:27						
01:28						
01:29						
01:30						
01:31						
01:32						
01:33						
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01:56						
01:57						
01:58						
01:59						
02:00						
02:01						
02:02						
02:03						
02:04						
Comments			did not hear any announcement		he heard one announcement of maybe a woman, it was not possible to identify the language, the list at the time of the announcement was about 45°, ship sank in about 90° condition , he didn't smell anything strange, his car is a Mazda	

Witness	28a	29	30	32	33	34
Name	P10		P8	C3	P19	P24
Source	SPF	SPF	SPF	SPF	SPF	SPF
Date	29.09.1994	typed 03.10.1994	01.10.1994	01.10.1994	02.10.1994	02.10.1994
PAX / Crew	P	P	P	Crew, Musician	P	P
Cabin	4602	???	6119	770 on Deck 7	6107	Deck 5, 5503???
Time						
19:00				Member of "Henrik Gojs Orkester"	travelled together with a group of Stockholm police	
to						
20:00						
to						
21:00						
to						
22:00						
to						
23:00				played in bar on Deck 7, should play till 01:00h but due to ship's movement ended at 23:40h		
to						
23:30						
to						
00:00				went to cabin and stayed there		
00:01						
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00:33						

Witness	28a	29	30	32	33	34
Name	P10		P8	C3	P19	P24
Source	SPF	SPF	SPF	SPF	SPF	SPF
Date	29.09.1994	typed 03.10.1994	01.10.1994	01.10.1994	02.10.1994	02.10.1994
PAX / Crew	P	P	P	Crew, Musician	P	P
Cabin	4602	???	6119	770 on Deck 7	6107	Deck 5, 5503???
00:34						
00:35						
00:36						
00:37						
00:38						
00:39						
00:40						
00:41						
00:42						
00:43						
00:44						
00:45	went to but couldn't fell asleep due to seastate, suddenly the ferry heeled to Portside about 45°, connected to the heeling he heard a tough noise a strong slump like a truck tipping over, he crawled out of his cabin, recognized panic on the floor, went back to his cabin, dressed, left cabin crawling and climbing up to Deck 7, while on the way to Deck 7 lights went to					
00:46						
00:47						
00:48					was in Karaoke Bar, ship moving heavily, glasses hanging above the bar fell, everything in the bar suddenly collapsed, a chain of human being were build and she managed to reach the outside deck, life vests were distributed, she put one on, lights flickered and connected to this a long signal were heard,	
00:49			was in pub on Deck 5			
00:50				he recognized a small list, but short afterwards the list increased still not very strong, a third increase of list so strong, that things fell, he thought this movement are not due to seastate and left his cabin, 2 short bell signals were heard, to reach the outer deck he has to climb, outside was panic, list about 20°, 2 crew tried to lower a lifeboat, but missed due to the list, life vests were distributed, crew: "we got to bring life raft into the water", vessel at 90° he climbed over the reeling and the side of the ship was now the bottom, he was washed into the sea, injured his arm, managed to enter a life raft		
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00:58						
00:59						
01:00						
01:01						
01:02			heavy hits, one bang heel to PS increased			
01:03						
01:04						
01:05						
01:06			one of crew ordered to build a chain to help people out of the pub, he moved to Deck 6, heel was now 45° and it went on quick to 90°, he climbed to Deck 7, some people managed to loosen life rafts, at 90° lights went out, there was an announcement he couldn't understand because it was Estonian			
01:07						
01:08						
01:09						
01:10						
01:11						
01:12						
01:13						bang, coming from bow
01:14						
01:15						
01:16						
01:17						vessel heeled
01:18						2nd bang
01:19						immediately after 2nd bang vessel heeled to Portside, chairs and tables fell, injured at head
01:20						
01:21						
01:22						
01:23						
01:24						
01:25						
01:26						
01:27						managed to get

Witness	28a	29	30	32	33	34
Name	P10		P8	C3	P19	P24
Source	SPF	SPF	SPF	SPF	SPF	SPF
Date	29.09.1994	typed 03.10.1994	01.10.1994	01.10.1994	02.10.1994	02.10.1994
PAX / Crew	P	P	P	Crew, Musician	P	P
Cabin	4602	???	6119	770 on Deck 7	6107	Deck 5, 5503???
01:28						outside Deck 6 and to get a life vest, waked to the aft and climbed over the reeling
01:29						
01:30						
01:31						
01:32						
01:33						
01:34						
01:35						
01:36						heard a bang and lights went off, it came back and went finally out, stand on the ship's side, beside him a life raft and grabbed a rope and slid with the raft into the water, two men heaved him inside
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01:58						
01:59						
02:00						
02:01						
02:02						
02:03						
02:04						
Comments	ferry sank bow first, didn't hear any alarm, but something like a doorbell	works on a shipyard and owned a boat. He heard 3 bangs within 2 min. He described the sound of the bangs like strokes with a hammer, he means to locate the noise from the bow on Portside, he said the ferry roll not much, but pitched in head seas	he didn't see how the Estonia sank	2 short bell signals were heard, announcement by loudspeaker were heard but on Estonian, ship sank by aft, a officer named Vasil acted in a very professional way brought may lift rafts into the water	she is not able to give any particulars about the time sequence, was some time unconscious, she woke up on a life raft, she did not see how the ship sank, saw not lifeboats or life rafts before	heard no announcements, smelled nothing unusual, saw no water entering the ship, he didn't see how the ship sank

Witness	35	36	37	38	38	39
Name	P20	P21	P27	P26	P26	P25
Source	SPF	SPF	SPF	SPF	GGE	SPF
Date	29.09.1994	30.09.1994	02.10.1994	02.10.1994	???	01 Oct 1994
PAX / Crew	P	P	P	P	P	P
Cabin		Deck 6	6126	no cabin		1047
Time	nonofficial translating	interview by telephone			watch broken, woke up from 2 heavy bangs, went upwards to aft, heard Typhoon (whistle) twice, condition of ship changed very fast, went downwards to aft now, smelled oil, smelled a bit burnt, some smoke in the air, saw no other ferries, in Huddinge Hospital P79 was not allowed to give a full statement	
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Witness	35	36	37	38	38	39
Name	P20	P21	P27	P26	P26	P25
Source	SPF	SPF	SPF	SPF	GGE	SPF
Date	29.09.1994	30.09.1994	02.10.1994	02.10.1994	???	01 Oct 1994
PAX / Crew	P	P	P	P	P	P
Cabin		Deck 6	6126	no cabin		1047
00:34						
00:35						
00:36						
00:37						
00:38						
00:39				was in cafe on Deck 5 sleeping on a sofa		
00:40						
00:41						
00:42						
00:43						
00:44						
00:45						
00:46			was in Karaoke Bar			
00:47						
00:48						
00:49						
00:50						
00:51						
00:52	was in Discothèque on Deck 6 or 7, when the vessel started to heel, the list increased and things fell, when he recognized the Situation, he ran to the lifeboats and managed to reach a life raft					
00:53						
00:54						
00:55				woke up by falling china, heard a hard bang, fall asleep again and woke up by falling from the sofa, climbed to the exit on fixed tables, saw a crew member helping persons on the way up, climbed outside herself, got a life vest, tried to loosening a life raft but didn't manage it, vessel started turning completely so she walked towards the water, slipped and slid into it, just in front of her was a life raft, she was pulled into it.		
00:56		was in Karaoke Bar				
00:57						
00:58						
00:59		recognized a heavy list, short after list increased	bang came from Car deck, list started, glasses and bottles fell, after first heeling the ferry had a list of about 20°,			
01:00					finished dinner	
01:01						
01:02						
01:03		took stairs to next higher Deck				
01:04					went to karaoke bar	
01:05						
01:06						
01:07		reached outside Deck list about 30°, put life vest on				
01:08						
01:09						
01:10						
01:11		list about. 80...85°				
01:12						
01:13						
01:14						
01:15		slipped, fell into the water, saw a life raft, swam to it and climbed in				
01:16						
01:17						
01:18						
01:19						
01:20						
01:21			lights went three times out and on, 20 min after first list completely dark, list 90°			
01:22						
01:23						
01:24					moderator: last song, bar closing at 01:30, list 45°	
01:25						
01:26						
01:27						

Witness	35	36	37	38	38	39
Name	P20	P21	P27	P26	P26	P25
Source	SPF	SPF	SPF	SPF	GGE	SPF
Date	29.09.1994	30.09.1994	02.10.1994	02.10.1994	???	01 Oct 1994
PAX / Crew	P	P	P	P	P	P
Cabin		Deck 6	6126	no cabin		1047
01:28					bar falling, chaos	
01:29						
01:30					managed to reach Deck 7, "relatively easy to walk upstairs", looking down he could see the car deck and saw water coming from car deck entering the inner part of the ship, he saw nobody on the corridor, he put a life vest on, ferry capsized, there was a short time between turning upside down and final sinking, keel area was red painted and he saw a marine propeller and a second smaller one in a hole	
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02:04						
Comments	saw nobody from the crew	heard no announcements, saw no water entering the ship, he did not see how the ship sank	saw no water entering the ship, he did not see how the ship sank, was alone in life raft, travelled without car	heard no announcement, she had no watch	heard NO bang, heard no announcements by loudspeaker, saw nobody of the crew, about 5 minutes after heeling lights off, ship laying on her side two horn blasts were heard, after the sinking life rafts entered the surface, he saw no damages at the ferry	

Witness	39	39	40	40	41	41
Name	P25	P25	P31	P31	C6	C6
Source	SPF	GGE	SPF	SPF	GGE	GGE
Date	07 Oct 1994	01 Oct 1994	01 Oct 1994	06 Oct 1994	09. Aug 96	09. Aug 96
PAX / Crew	P	P	P	P	C (Croupier)	C (Croupier)
Cabin	1047	1047	Deck 6?	Deck 6?		8843, aft, STB
Time						
19:00						
to						
20:00						
to						
21:00						
to						
22:00						
to						
23:00						
to						
23:30						
to						
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00:19						
00:20						Was at work in the casino on Deck 6 next to dancing restaurant "Baltic Bar", chips (jetton) were falling into the play card table, seconds later the vessel was shaking, afterwards the ferry reduced velocity and heeled a little but didn't upright again, the situation was
00:21						
00:22						
00:23					before 1st permanent list heard by walkie-talkie that C16 told bridge of water on car deck	
00:24						
00:25						
00:26						
00:27						
00:28						
00:29			went sleeping and fell asleep			
00:30						
00:31						
00:32						
00:33						

Witness	39	39	40	40	41	41
Name	P25	P25	P31	P31	C6	C6
Source	SPF	GGE	SPF	SPF	GGE	GGE
Date	07 Oct 1994	01 Oct 1994	01 Oct 1994	06 Oct 1994	09. Aug 96	09. Aug 96
PAX / Crew	P	P	P	P	C (Croupier)	C (Croupier)
Cabin	1047	1047	Deck 6?	Deck 6?		8843, aft, STB
00:34						strange to him, then another step of increasing list appeared, a college of him slid down the floor, went upstairs to get his jacket, waited about one minute in crew-dayroom, by loudspeaker he heard twice a female voice "Heiri" the Estonian word for "Alarm", just after he heard by loudspeaker "Mr. Skylight" the signal for fire on the ship, he walked to Deck 7, the list is so heavy he had to walk on the wall with one feet, at the outside door to Deck 7 there was a chain of people to help the people to reach the outside, most form the helpers were from crew, he managed to put on a children life vest, lit up a cigarette, he didn't thought the ferry would sink, but recognized that the ferry sank, then he is washed into the sea and managed to climb into a life raft
00:35						
00:36					was in casino when Estonia got the first permanent list, engine sound disappeared like the ship stopped, proper smell was heard first list and some glasses fell down 10...15sec. but max. 30sec. The ship got a list of about 20°..30°, only one metallic sound was heard, first permanent list at 01:10am ...01:15am. seastate nothing special, but special was spray on crew's dayroom, ship listed again 1min after the first big list, could not see Viking and Silja Line, before 45° list announcement "Häire, Häire" by a woman and something in addition by a man shouted somebody blows the foghorn at nearly 90°	
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00:55			woke up by an weird noise like the propellers were coming out of the water with every rolling, he got up, ferry heeled, things fell from the table, he left his cabin and saw people, some hardly dressed, lights on, people were helping each other to get outside, list of the vessel increased at first jerkily and quickly then it increased more slowly, lights flickered and lighted then with less intensity probable the emergency lights, someone distributed life vests he put one on, he tried to enter a life raft, but it was full he detained to a rope of the life raft and slid with it into the water, got tangled up with the rope, came free and swam to another life raft and were			
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01:21						
01:22		was in karaoke bar on deck 4				
01:23						
01:24						
01:25		list 45°				
01:26		bar desk fell on top of the				
01:27						

Witness	39	39	40	40	41	41
Name	P25	P25	P31	P31	C6	C6
Source	SPF	GGE	SPF	SPF	GGE	GGE
Date	07 Oct 1994	01 Oct 1994	01 Oct 1994	06 Oct 1994	09. Aug 96	09. Aug 96
PAX / Crew	P	P	P	P	C (Croupier)	C (Croupier)
Cabin	1047	1047	Deck 6?	Deck 6?		8843, aft, STB
01:28		personnel	pulled in			
01:29		saw down to corridor deck 4 water coming from car deck				
01:30						
01:31						
01:32						
01:33		2 blasts by fog horn				
01:34						
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02:03						
02:04						
Comments	During the whole evening he was on Deck 4, 5 and 6 in shops, restaurants and other facilities. He saw no officers/ mates, but just one engine crew member and female crew members of the service, literally: "nobody with ribbons on his arms" - this was different to former voyages.	did not hear any bangs, when ship heeled, ship turned completely upside down before sinking, finial sinking very fast, light off 5 min after keel developed talked to crew member, was told of 50cm water on car deck	Cabin: he entered ship, went two stairs upwards and turned to the aft for about. 40...50m - his cabin had no window, heard no explosions and smelled nothing unusual, didn't see how the ferry sank, fog horn blasting for about a minute, travelled often with ferries and was seaman in his youth, maybe something was said by loudspeaker, later Mayday came by loudspeaker	added something to his testimony: he thought that the crew of this vessel were amateurs, he had slept when heard the weird noise, he said, it was not possible to drive such a large vessel with a high velocity in such kind of weather		heard no explosion, bangs

Witness	42	43	43	44	46	51
Name	P33	P44	P44	P7	C15	P66
Source	SPF	SPF	GGE	SPF	GGE	SPF
Date	01. Oct 94	01. Oct 94	08. Aug 96	03. Oct 94	09. Aug 96	30. Sep 94
PAX / Crew	P	P, lorry driver			C	P
Cabin	4405	4214				1094
Time						
19:00						
to						
20:00						
to						
21:00						
to						
22:00						
to						
23:00						
to						
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00:26						
00:27						
00:28						
00:29						
00:30						
00:31					was in cabin, was not able to eat due of the wave induced motions	
00:32						
00:33						

Witness	42	43	43	44	46	51
Name	P33	P44	P44	P7	C15	P66
Source	SPF	SPF	GGE	SPF	GGE	SPF
Date	01. Oct 94	01. Oct 94	08. Aug 96	03. Oct 94	09. Aug 96	30. Sep 94
PAX / Crew	P	P, lorry driver			C	P
Cabin	4405	4214				1094
00:34					of the ship,	
00:35						
00:36						
00:37						
00:38						
00:39						
00:40						
00:41						
00:42						
00:43						all of a sudden heard two strong unusual sounds like scratching, coming from below, he left his cabin and saw on the corridor a "small vattensträng" a small rill, ferry had a small list, he was not sure whether a list or motion due to sea state, went upstairs told two crew members about the rill went outside, distributed life vests and tried later to loosen a life boat but didn't manage, went to a life raft but this was not inflated and he saw other inflated rafts so he jumped into the water
00:44						
00:45		at the beginning of the sinking he was in his cabin, an inside cabin without window, he heard several bangs and one loud bang like cutting in strong steel, he recognized that something is unusual and he wanted to leave the cabin on his way from the bed to the cabin door the ferry heeled when opening the cabin door nearly every door on the corridor opens, engine sound were heard, lights on, he pulled himself at the balustrade up to deck 7, he put a life vest on	23:45pm he went to bed, Immediately he heard a metallic knocking sound, finally he powerful metallic blow, he left immediately his cabin in underwear and being on the corridor the list began			
00:46					went to casino	
00:47					talked to Peter Järvinen about the weather, chips were jumping out of their places, she left the casino 5 min after together with C6, just after the the ship became silent and stopped fully	
00:48						
00:49						
00:50	was in his cabin preparing for bed, leaving the bathroom he recognized an abnormal list, the vessel didn't upright again, he could see the sea out of his cabin window, he left his cabin, the list was so heavy that one has to lean against the wall for walking, saw persons sliding down the lobby, he followed the green exit/ emergency exit signs, climbed stairs up, finally he reached deck 7 outside, on his way up he saw no water in the ship, he was not in panic, but scared by the list of the vessel so heavy that the wall is now the floor, put a life vest on, there was a bang probable from a wave, loosing his balance by the bang and fell into the water			was in Karaoke bar		
00:51						
00:52						
00:53						
00:54						
00:55						
00:56				went back to her cabin		
00:57						
00:58						
00:59				list to STB		
01:00						
01:01						
01:02						
01:03				people had to try hard to come to the upper deck, she had to hold herself tight to the balustrade, list increased again and the increasing of the list accelerated		
01:04						
01:05						
01:06						
01:07						
01:08						
01:09						
01:10						
01:11						
01:12						
01:13						
01:14						
01:15						
01:16						
01:17						
01:18						
01:19						
01:20						
01:21						
01:22						
01:23						
01:24						
01:25						
01:26						
01:27						

Witness	42	43	43	44	46	51
Name	P33	P44	P44	P7	C15	P66
Source	SPF	SPF	GGE	SPF	GGE	SPF
Date	01. Oct 94	01. Oct 94	08. Aug 96	03. Oct 94	09. Aug 96	30. Sep 94
PAX / Crew	P	P, lorry driver			C	P
Cabin	4405	4214				1094
01:28						
01:29						
01:30						
01:31						
01:32						
01:33						
01:34						
01:35						
01:36						
01:37						
01:38						
01:39						
01:40						
01:41						
01:42						
01:43						
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01:50						
01:51						
01:52						
01:53						
01:54						
01:55						
01:56						
01:57						
01:58						
01:59						
02:00						
02:01						
02:02						
02:03						
02:04						
Comments	on his way up he saw no water in the ship, it was not possible to bring the lifeboats down into the water, only the life rafts, he heard an short announcement in Estonia by loudspeaker when he entered Deck 7, maybe he heard an alarm signal, vessel sinking by stern, he was not on the car deck	heard no alarm signal or bell, has travelled with the "Estonia" before once a week since 1,5 years, has not seen water entering the ferry, didn't see how the ship sank, his lorry wasn't lashed - it was never lashed on trips on MV "Estonia" before	travels with Estonia every week, crew often great problems to open the ramp, the crew often used a heavy hammer and a crowbar to open the locking. The opening could take up to 20 min. he has never seen clothing in the sides of the ramp to seal it, he heard from his friends in the crew that there were a celebration for those crew members who will change to MV Vironia		she did not see water in the ship	he heard an alarm when he told the crew-member about the rill, lights went out, when he was outside

Witness	57	77	80	80	80	82
Name	P85	C10	C11	C11	C11	C16
Source	GGE	GGE	GGE	GGE	GGE	GGE
Date	29. Sep 94	29. Sep 94	29. Sep 94	07. Oct 1994	07. Feb 95	29. Sep 94
PAX / Crew	P	C	C (practising for	C (practising for	C (practising for	C (Mate)
Cabin	1618 (4618?)	deck 7	4103	4103	4103	
Time				boarding at 16:20pm	boarding at 16:20pm	
19:00						
to					left car deck at 18:40h	
20:00						
to		20:30pm small list				
21:00					on bridge, wind 20...25m/sec from port side, initial speed 15...16kn, Capt Anderson was on bridge at 23:30 to 24:00h. gave order to extend stabilizers, 2nd officer explained that would drop speed, stabilizers were deployed at waypoint an changing course at 24:00h, all waves from ahead, initially normal course near Estonian coast were used, full load on car deck with cars and trucks, but upper car decks were not in use. ship had list 2°...4°from jetty on which couldn't be corrected, because ballast tanks are full	
to						
22:00						started tour
to						22:35 on car deck, water came in by ventilation duct happens more than one
23:00						
to						
23:30						
to						
00:00						
00:01						
00:02						
00:03						
00:04						
00:05						
00:06						
00:07						
00:08						
00:09						
00:10						
00:11						
00:12						
00:13						
00:14						
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00:16						
00:17						
00:18						
00:19						
00:20						
00:21						
00:22						
00:23						
00:24						
00:25						
00:26						
00:27						
00:28						
00:29						
00:30	went to cabin			C16: everything OK		
00:31					went to his cabin, left notes, went to	
00:32						on car deck storm increased, ship
00:33						

Witness	57	77	80	80	80	82
Name	P85	C10	C11	C11	C11	C16
Source	GGE	GGE	GGE	GGE	GGE	GGE
Date	29. Sep 94	29. Sep 94	29. Sep 94	07. Oct 1994	07. Feb 95	29. Sep 94
PAX / Crew	P	C	C (practising for	C (practising for	C (practising for	C (Mate)
Cabin	1618 (4618?)	deck 7	4103	4103	4103	
00:34					Admirals Pub	motions so heavy that walking difficult a wave hit the bow a completely different noise a hard cracking noise like two pieces of metal banging, duration: half a second, vibration he nearly fell, told the bridge, order to stay, visor ok, green lights
00:35				left bridge		
00:36				went to his cabin, put the notebook in, went to the "Admirals Pub", saw nobody he knows an went to his cabin again		
00:37						
00:38					saw C16 at Admirals Pub 00:30...00:40	
00:39						
00:40						
00:41					went to his cabin, washed, go to bed, but didn't fell asleep	
00:42						
00:43						
00:44						
00:45						
00:46					heard strange noise, might have a blow, not a sound you hear at sae, then the ship heeled, he dressed, table slid against door, ran out of cabin, few people on deck 4, at info on deck 5 20...30 people, got to deck 6 very difficult due to the heel heard bang in staircase between deck 6 and 7 (thought moving trucks and hitting each other) on deck 7 heel so great only crawling was possible, out on deck 7 started to distribute life vests together with V. Ruben, list 45°...50° rope ladders were lowered, list 80°, stern already sinks	
00:47				tried to sleep, but never fell asleep, , did not know what it was		
00:48						
00:49						
00:50						
00:51						
00:52						
00:53						
00:54						
00:55						
00:56						
00:57				heard a hard strange noise for him as seaman unfamiliar, became curious about the noise and dressed, before putting on shoes, ship heeled and table slid towards the door, went up, while between 6th and 7th floor heard rather felt a vibration: believes that cars slid against each other, thereafter list increased remarkably, reached deck 7 distributed life jackets with Vello Ruben		
00:58						on bridge
00:59	loud "crash", ship heeled to STB					order to check again
01:00						
01:01						
01:02		one weird noise				at info, list things sliding,
01:03	situation calm					
01:04						back to deck7
01:05	01:05am was on outside deck at bridge put life vest on	list about 5°, quiet noise				told bridge by radio men in panic
01:06						
01:07		dressing and waiting for instruction				
01:08						
01:09						
01:10		list about 30°				
01:11		out of cabin				
01:12		lights short off				
01:13						
01:14		suddenly list to 60°...70° lights off fore reaching 90°, emergency lights off short after 90°				
01:15	lights flickering and went out, heard a loud fog horn					
01:16						
01:17						
01:18						
01:19						
01:20		list 90°				
01:21						
01:22						
01:23						
01:24						
01:25		ship vertical				
01:26		aft sunk first				
01:27						

Witness	57	77	80	80	80	82
Name	P85	C10	C11	C11	C11	C16
Source	GGE	GGE	GGE	GGE	GGE	GGE
Date	29. Sep 94	29. Sep 94	29. Sep 94	07. Oct 1994	07. Feb 95	29. Sep 94
PAX / Crew	P	C	C (practising for	C (practising for	C (practising for	C (Mate)
Cabin	1618 (4618?)	deck 7	4103	4103	4103	
01:28						
01:29				90° list	run to aft	
01:30				look on watch	look on watch	
01:31				ran to stern slid into water	stern already under water up to stabilizer-fin-level, slid in water under a raft	
01:32						
01:33						
01:34						
01:35						
01:36						
01:37						
01:38						
01:39						
01:40						
01:41						
01:42						
01:43						
01:44						
01:45						
01:46						
01:47						
01:48						
01:49						
01:50						
01:51						
01:52						
01:53						
01:54						
01:55						
01:56						
01:57						
01:58						
01:59						
02:00						
02:01						
02:02						
02:03						
02:04						
Comments	heard no announcements by loudspeaker, no instructions by the crew		was in cabin before the disaster started	some alarm message via radio, did not understand, lights went out for a few seconds, engines not running anymore	had been assigned on M/S Vironia	missing bow visor, sinking by stern, ship finally upside down, from first list to final sinking 15...20min.

Witness	82	82	82	94	94	94
Name	C16	C16	C16	C36	C36	C36
Source	GGE	GGE	GGE	GGE	GGE	GGE
Date	03. Oct.1994	17. Oct.1994	Mar 1995	28. Sep 94	28. Sep 94	29. Sep 94
PAX / Crew	C (Mate)	C (Mate)	C (Mate)	C, 3rd engineer	C, 3rd engineer	C, 3rd engineer
Cabin						
Time						
19:00						
to					1°..2° list STB at departure although he tried to compensate by heeling tanks	1° list STB, heeling tanks full, heard by walkie-talkie the order to lash the cargo due to the expected seastate
20:00						
to						
21:00						
to						
22:00						
to						
23:00						
to						
23:30						
to						
00:00				start working		on duty in ECR
00:01						
00:02						speed 15kn
00:03						
00:04						
00:05						
00:06						
00:07						
00:08						
00:09						
00:10						
00:11						
00:12						
00:13						
00:14						
00:15						
00:16						
00:17						
00:18						
00:19						
00:20						
00:21						
00:22						
00:23						
00:24						
00:25						
00:26						
00:27						
00:28						
00:29						
00:30		tour started	round started			
00:31		(on bridge)				
00:32						
00:33						

Witness	82	82	82	94	94	94
Name	C16	C16	C16	C36	C36	C36
Source	GGE	GGE	GGE	GGE	GGE	GGE
Date	03. Oct.1994	17. Oct.1994	Mar 1995	28. Sep 94	28. Sep 94	29. Sep 94
PAX / Crew	C (Mate)	C (Mate)	C (Mate)	C, 3rd engineer	C, 3rd engineer	C, 3rd engineer
Cabin						
00:34						
00:35		on car deck	15 min spent on car deck			
00:36		(start at stern)				
00:37						
00:38		loud noises heard, doors locked, waited for 5min order from bridge				
00:39						
00:40						
00:41						
00:42						
00:43		light green door closed				
00:44	on car deck					
00:45	heard crash	left car deck				
00:46	(behind ramp)					
00:47						
00:48						
00:49						
00:50	bottom deck					
00:51						
00:52						
00:53						
00:54						
00:55						
00:56						
00:57						
00:58						
00:59						
01:00	on bridge	on bridge		01:00h two double hard strokes against bow	3...4 bangs, turned camera towards the bow, saw very much water coming in and immediately a list 10°...15°	
01:01	bow still there	2nd and 4th officer there				
01:02	list of 10°		list 30°			
01:03	went down to deck 4 (want to car deck) turned around to deck 7	captain came				
01:04		heeling at 01:01h can't get down due to heeling, from bridge visor, antenna and lamp in place, left bridge, went down, people: water on 1st deck				
01:05			vessel was shaking			
01:06						
01:07						
01:08	distributed life vests on deck 7				water only on car deck not in engine room	
01:09						
01:10						
01:11						
01:12						
01:13						
01:14						
01:15				01:15h saw on camera water gushed in on car deck		2 heavy waves
01:16						water ingress
01:17						
01:18						quick increase to 10°...15°, 4 ME run, 2 aux run, tried to trim, failed
01:19						
01:20				01:20h bridge: is possible to list to PS?, list 30...35°: PS engines stop, 5...6kn, 4th eng stop, 3rd stop, aux run		
01:21					first main engines on PS stopped, then the two of STB, started aux eng, power was there, started pumping water out	
01:22						
01:23						
01:24						ME 1, 2 stop
01:25						
01:26						ME 4 stop
01:27						ME 3 stop

Witness	82	82	82	94	94	94
Name	C16	C16	C16	C36	C36	C36
Source	GGE	GGE	GGE	GGE	GGE	GGE
Date	03. Oct.1994	17. Oct.1994	Mar 1995	28. Sep 94	28. Sep 94	29. Sep 94
PAX / Crew	C (Mate)	C (Mate)	C (Mate)	C, 3rd engineer	C, 3rd engineer	C, 3rd engineer
Cabin						
01:28					of ship	
01:29				list about 45° aux stop, emergency Start		
01:30						40°...45° list
01:31						aux eng stop
01:32				left ECR to control emergency diesel when reached deck 8th nearly 90° list, emergency generator functioned for a while, went out ran to sternwards a life raft		bridge: fresh water STB out
01:33						
01:34						no, no power
01:35						left ECR to deck, because nothing to do
01:36						
01:37						
01:38						no water in ER doors closed
01:39						
01:40						
01:41						
01:42						
01:43						
01:44						
01:45						
01:46						
01:47						
01:48						
01:49						
01:50						
01:51						
01:52						
01:53						
01:54						
01:55						
01:56						
01:57						
01:58						
01:59						
02:00						
Comments	only control lamps show, whether the visor is looked or not, car deck was fully loaded, after the crash he did not see any water penetrate, after the crash within 5min. no noise was heard, after the list he heard "Mr. Skylight" the code for a fire alarm, he heard two spells	He thinks the waves came from the funnel side, ship speed 15kn, 4 engines running, it was said alarm in Estonian and English, then the fog horn was sounded		left ballast tank full and right empty - creation of a PS list not possible, tried to fill the PS tank at stern, failed only air sucked, list 30°...35° PS engines automatically disconnected start again in vain, before leaving ECR Captain wants to know, if possible to pump fresh water over board - but not enough electricity		two years employed on Estonia, bunkered fuel on 26.09.1994 in Stockholm, the two waves were quick after each other, never experienced so heavy bangs on a ship ever before, the picture of the camera was quite unclear, because the camera was washed over, pump sucking air only, ME stop by automatic-shut-down, at list 90° emergency diesel out, heard cargo shift while climbing up, ship sinking by stern, bow short upright to 45°, bow visor missing

Witness	94	94	94	94	94	94
Name	C36	C36	C36	C36	C36	C36
Source	GGE	GGE	GGE	GGE	GGE	GGE
Date	03. Oct 1994	11. Oct 1994	16. Oct 1994	17. Oct 1994	Mar 1995	???
PAX / Crew	C, 3rd engineer	C, 3rd engineer	C, 3rd engineer	C, 3rd engineer	C, 3rd engineer	C, 3rd engineer
Cabin						
Time						
19:00						
to						
20:00						
to						
21:00						
to						
22:00						
to						
23:00						
to						
23:30						
to						
00:00	duty		watch	speed 14.7...15kn, 560 rpm		
00:01						
00:02						
00:03						
00:04						
00:05						
00:06						
00:07						
00:08						
00:09						
00:10						
00:11						
00:12						
00:13						
00:14						
00:15						
00:16						
00:17						
00:18						
00:19						
00:20						
00:21						
00:22						
00:23						
00:24						
00:25						
00:26						
00:27						
00:28						
00:29						
00:30			stabilizers deployed	stabilizers deployed		arrived ECR
00:31						
00:32						
00:33						

Witness	94	94	94	94	94	94
Name	C36	C36	C36	C36	C36	C36
Source	GGE	GGE	GGE	GGE	GGE	GGE
Date	03. Oct 1994	11. Oct 1994	16. Oct 1994	17. Oct 1994	Mar 1995	???
PAX / Crew	C, 3rd engineer	C, 3rd engineer	C, 3rd engineer	C, 3rd engineer	C, 3rd engineer	C, 3rd engineer
Cabin						
00:34						
00:35						
00:36						
00:37						
00:38						
00:39						
00:40						
00:41						
00:42						
00:43						
00:44						
00:45						
00:46						
00:47						
00:48						
00:49						
00:50						
00:51						
00:52						
00:53						
00:54						
00:55						
00:56	about 14,5kn, C16 on car deck		14,7kn			
00:57						
00:58						
00:59						saw C16 on camera
01:00	2 bangs, not ordinary wave impacts, lots of water pressing trough sides of ramp			C16 on cam	C16 on cam	
01:01				speed 10... 11kn, 500rpm		
01:02						
01:03					heard some strong bangs 2...3, looked on monitor of car deck, saw water ingress	
01:04						
01:05						
01:06						
01:07						
01:08				water coming in around the ramp edges		
01:09						
01:10						
01:11						
01:12						
01:13						water pressing in heard C16 by walkie-talkie water on car deck
01:14						
01:15			C16 report to bridge		no speed reduction	
01:16						
01:17						
01:18						PS eng stop
01:19						list 25°...30°
01:20			Mr. Skylight were sounded	Mr. Skylight		STB eng stop
01:21						
01:22			all engines 500rpm	engines stop	Mr. Skylight	aux eng stop
01:23						
01:24			engines stop			re-pump fresh water possible?
01:25						
01:26					order from bridge ballast water	
01:27						

Witness	94	94	94	94	94	94
Name	C36	C36	C36	C36	C36	C36
Source	GGE	GGE	GGE	GGE	GGE	GGE
Date	03. Oct 1994	11. Oct 1994	16. Oct 1994	17. Oct 1994	Mar 1995	???
PAX / Crew	C, 3rd engineer	C, 3rd engineer	C, 3rd engineer	C, 3rd engineer	C, 3rd engineer	C, 3rd engineer
Cabin						
01:28					pumping	left ER at list 65°...70°
01:29						
01:30		left ER		aux stop / lights out	left ER 70-80°	
01:31		list about 90°	70°...75°list			
01:32			left ECR			
01:33						
01:34						
01:35	left ECR by funnel, went to emergency generator and went out on deck					
01:36						
01:37						
01:38						
01:39						
01:40						
01:41						
01:42						
01:43						
01:44						
01:45			ship sank	ship sank		
01:46						
01:47						
01:48						
01:49						
01:50						
01:51						
01:52						
01:53						
01:54						
01:55						
01:56						
01:57						
01:58						
01:59						
02:00						
02:01						
02:02						
02:03						
02:04						
Comments	during the casualty none of the engines were running full power or full speed, pumps did not manage to pump seawater due to list, heeling tank STB 150t PS 180t capacity, left the engine room by the funnel the engine room was dry, watertight doors were closed, no pumps to pump out water on car deck, bulb was intact when vessel sank,	4 engines at about 70%...74% power, speed almost 15kn, ship sank stern first, ship sank 15min after water on car deck seen, camera mounted in the roof of the car deck on the central casing bulkhead	500rpm means at normal pitch 10...11kn (during casualty)	normal rpm 580...600, no change in pitch observed, lube oil level higher than normal in engines	water ingress water was smashing against the camera, recognized the voice in walkie-talkie as C16 telling bridge that water is on car deck but could not see him on monitors, 4th mate asked for Ballast water pumping	

Witness	97	109	110	113	120	120
Name	P90	C32	C28	C25	C19	C19
Source	GGE	GGE	GGE	GGE	GGE	GGE
Date	03.Oct 1994	08. Mar 1995	02. Sep 96	29. Sep 94	03. Oct 95	29. Sep 94
PAX / Crew	P	C (motorman)	C (Clerk)	C (kitchen)	C	C
Cabin	6320		7013	7026		
Time						
19:00						
to						
20:00						
to						
21:00						
to						
22:00						
to						
23:00						went to bed
to						
23:30						
to						
00:00						
00:01						
00:02						
00:03						
00:04						
00:05						
00:06						
00:07						
00:08						
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00:16						
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00:18						
00:19						
00:20						
00:21						
00:22						
00:23						
00:24						
00:25						
00:26						
00:27						
00:28						
00:29						
00:30	heavy bang	went to bed				
00:31	list to STB					
00:32						
00:33	in drive more list					

Witness	97	109	110	113	120	120
Name	P90	C32	C28	C25	C19	C19
Source	GGE	GGE	GGE	GGE	GGE	GGE
Date	03.Oct 1994	08. Mar 1995	02. Sep 96	29. Sep 94	03. Oct 95	29. Sep 94
PAX / Crew	P	C (motorman)	C (Clerk)	C (kitchen)	C	C
Cabin	6320		7013	7026		
00:34						
00:35	another bang					
00:36	announcement in Estonian					
00:37						
00:38	3rd bang, his son broke arm					
00:39						
00:40						
00:41						
00:42						
00:43						
00:44						
00:45						
00:46						
00:47						
00:48						
00:49						
00:50						
00:51						
00:52						
00:53						
00:54						
00:55						
00:56						
00:57						
00:58						
00:59						
01:00		woke up from curtain sliding, and band, list began				
01:01						
01:02						
01:03						
01:04						
01:05						
01:06						
01:07						
01:08						
01:09						
01:10			while waking due lurch up, the ship was vibrating, sliding in bed due to list, switched on walkie-talkie mo traffic, by loudspeaker some announcements e.g. "Alarm", saw C16 on deck at a list of 45° distributing life vests, C28 made life rafts ready	woke up due to a mirror falling from wall, recognized list, looked in corridor, heard "Skylight 1" and "Skylight 2", got dressed, water to level of deck 7, engines were not running anymore, before leaving the ship: long foghorn blast, when funnel already under water		
01:11						
01:12						
01:13						
01:14						
01:15						woke up, list
01:16						vibrations => main engine running, couldn't dress himself standing, due to heavy list, woman's voice: "Alarm, alarm",
01:17						
01:18						
01:19						
01:20						
01:21						
01:22						
01:23						
01:24						
01:25						
01:26						
01:27						

Witness	97	109	110	113	120	120
Name	P90	C32	C28	C25	C19	C19
Source	GGE	GGE	GGE	GGE	GGE	GGE
Date	03.Oct 1994	08. Mar 1995	02. Sep 96	29. Sep 94	03. Oct 95	29. Sep 94
PAX / Crew	P	C (motorman)	C (Clerk)	C (kitchen)	C	C
Cabin	6320		7013	7026		
01:28						
01:29						sinking of ship
01:30						
01:31						
01:32						
01:33						
01:34						
01:35						
01:36						
01:37						
01:38						
01:39						
01:40						
01:41						
01:42						
01:43						
01:44						
01:45						
01:46						
01:47						
01:48						
01:49						
01:50						
01:51						
01:52						
01:53						
01:54						
01:55						
01:56						
01:57						
01:58						
01:59						
02:00						
02:01						
02:02						
02:03						
02:04						
Comments	2...3 min horn while going down	left his cabin by climbing out of the window, did not hear "Mr Skylight 1", black out at a list of 60°...70°in connection when engines stopped, 3 times warnings in Estonian were given, warning shortly before sinking ship practically on side	ship sank by stern		everything OK during his watch, last steering engine check at beginning of week, ship left on time at 19:00, watch 04:00-08:00 and 16:00-20:00	

Witness	124	124	124	124	126	127
Name	C33	C33	C33	C33	P13	P42
Source	GGE	GGE	GGE	GGE	GGE	GGE
Date	28. Sep 94	28. Sep 94	29. Sep 94	10. Mar 1995	28. Sep 94	29. Sep 94
PAX / Crew	C, engineer	C, engineer	C, engineer	C, engineer	P	P
Cabin		deck 7	deck 7	deck 7	6304 (5304?)	deck pass.
Time						
19:00		departure without heel				
to						
20:00						
to						
21:00						
to						
22:00						
to						
23:00						
to						
23:30						heavy rolling
to						
00:00						searchlight on
00:01						
00:02						
00:03						
00:04						
00:05						
00:06						waves became heavier and more water seemed to come in on the foredeck
00:07						
00:08						
00:09						
00:10						
00:11						
00:12						
00:13						
00:14						
00:15						
00:16						
00:17						00:26am: considerable part of the stem bouncing up, that part rose an sank. There was a straight through opening in the stem water sprouted in, search lighter off, no engine sound anymore, bow seemed to sink under water
00:18						
00:19						
00:20						
00:21						
00:22						
00:23						
00:24						
00:25						
00:26						
00:27						
00:28						
00:29						
00:30		woke up by crew to repair a toilet	ordered to ECR, deck 0			
00:31						
00:32						
00:33		walked due to the				

Witness	124	124	124	124	126	127
Name	C33	C33	C33	C33	P13	P42
Source	GGE	GGE	GGE	GGE	GGE	GGE
Date	28. Sep 94	28. Sep 94	29. Sep 94	10. Mar 1995	28. Sep 94	29. Sep 94
PAX / Crew	C, engineer	C, engineer	C, engineer	C, engineer	P	P
Cabin		deck 7	deck 7	deck 7	6304 (5304?)	deck pass.
00:34		repair on deck 0, bow part looking for the vacuum-problem				
00:35			on site			
00:36						
00:37						
00:38					woke up by indefinable shocking differing from normal noises of the ferry, shocking repeated regularly 4 to 5 times "tong tong,..." noise break and repeating, the noise coming from below and front, the noise was not suddenly, no explosion and not induced due seastate, stood up dressed the ship heeled and the furniture slid into the door, first list was 25°...30° this list stayed for a quiet long time, no instruction by staff, being on outside area there was a short announcement in Estonian list increased to 45°, ship stay about half an hour (rough estimation) from 30° to 45°, but without trim, navigational light on till 50°...60° black, but came again, at the horizon two ships but didn't approach, list over 90° lights completely off, when the ship was nearly upside down the stern started to sink, bulbous bow upright, looking normal, bow flap looking normal, the final sinking was very quick, stabilizer fin looking normal	
00:39						00:28am thought the ship would sink, began to remove a tarpaulin from a lifeboat for 10...20 min., six Estline-men began to remove lifeboats (capsules'), light were flickering
00:40						
00:41						
00:42						
00:43						
00:44		found problem				
00:45						
00:46						
00:47						
00:48						
00:49						
00:50						
00:51						
00:52						
00:53						
00:54						
00:55						
00:56						
00:57						
00:58				two impacts		
00:59			two, three hard wave impacts, thereafter ship heeled, he back to ECR			
01:00		heavy list STB, walked to ECR, saw on monitor of car deck water ingress, maybe on more on STB, visor not visible by camera, always water ingress although there was no wave impact, due to lack of fuel because of list firstly two then the 3rd and the 4th main engine stopped, didn't know if two or 4 aux eng running, at list of 40°...45°, bridge asked if trim by heeling tanks possible, everybody, except C36 left ECR, at that time electric power was delivered, at being at deck 6 blackout 2...3 sec emergency eng started, light came back until a list of				
01:01						
01:02						
01:03						
01:04						
01:05			water entering car deck seen			
01:06						
01:07			watertight doors closed			
01:08						
01:09			list 30°...35°			
01:10			trucks not moving			
01:11						
01:12			at list of 40° ME stopped, aux running			
01:13						
01:14						
01:15						
01:16						
01:17						
01:18			bridge: possible to stabilize?, left ECR			
01:19						
01:20						
01:21						
01:22						
01:23			aux off			
01:24						
01:25						
01:26			80°...85° fog horn			
01:27						

Witness	124	124	124	124	126	127
Name	C33	C33	C33	C33	P13	P42
Source	GGE	GGE	GGE	GGE	GGE	GGE
Date	28. Sep 94	28. Sep 94	29. Sep 94	10. Mar 1995	28. Sep 94	29. Sep 94
PAX / Crew	C, engineer	C, engineer	C, engineer	C, engineer	P	P
Cabin		deck 7	deck 7	deck 7	6304 (5304?)	deck pass.
01:28		minimum 90°, at list 90° captain blow fog horn for final leaving of the ship				
01:29						
01:30						
01:31						
01:32						
01:33						
01:34						
01:35						
01:36						
01:37						
01:38						
01:39						
01:40						
01:41						
01:42						
01:43						
01:44						
01:45						
01:46						
01:47						
01:48						
01:49						
01:50						
01:51						
01:52						
01:53						
01:54						
01:55						
01:56						
01:57						
01:58						
01:59						
02:00						
02:01						
02:02						
02:03						
02:04						
Comments	ship turned on side in 20min., sank bow first, was in ECR, towards the end saw cars move, got out at a list of 75°...80°	time on board was Estonian time, as well as his watch, ship sank by stern first, bow upright, visor missing, time from seeing water ingress on monitor to final sinking 15...20min,	vessel sank stern first, visor was gone	visor was gone, "Mr. Skylight"-Signal were given when main engines already shut off, had to do lifeboat no 9 but due to the list didn't get there	Travelled without car, sales manager from "United Distillers" sold alcohol to the ship, over all about 100 sea days on this ship inclusive that time at former owners, knows some of the staff, some are friends	car deck fully loaded with cars, heavy cars, trucks etc on both sides, had no cabin

20.2 Table of Hydrostatic Particulars from the Stability Booklet of Hull No. S590

JOS. L. MEYER PAPENBURG EMS	HYDROSTATIC PARTICULARS	MAIERFORM GMBH, BREMEN 6891.06 – 171.120	PAGE 5 / 6 / 7

SPEC. GRAVITY OF SEA-W. = 1,025 T / CBM

COEFF. FOR DISPL. OF SHELL PL. = 1,007

TRIM = 0,000 m ON EVEN KEEL

KEEL - THICKNESS = 0.000 mm

DRAUGHTS INDICATED FOR Lpp / 2

DRAFT BK	MOUL-DED VOLUME	DISPL. FR–W.	DISPL. SEA-W.	LCB	VCB	KM (T)	KM (L)	WL - AREA	LCF	TMI	LMI	MCT BP	D / MCT	TPCI	ALPHA (BP)	DELTA (BP)
Metres	m^3	Metric-t.	Metric-t.	m	m	m	m	m^2	m	m^4	m^4	MT / M	-	T/CM	-	-
4.30	8999.63	9062.63	9289.19	-3.19	2.30	12.10	298.81	2461.35	-4.73	88197.7	2668554.	19421.8	0.478	25.41	0.772	0.656
4.35	9122.99	9186.85	9416.52	-3.21	2.32	12.05	297.31	2470.60	-4.84	88730.2	2691188.	19586.5	0.481	25.50	0.774	0.657
4.40	9246.85	9311.58	9544.37	-3.23	2.35	12.01	295.90	2480.08	-4.96	89274.8	2714409.	19755.5	0.483	25.60	0.777	0.658
4.45	9371.16	9436.76	9672.68	-3.25	2.38	11.96	294.60	2489.81	-5.08	89832.4	2738436.	19930.4	0.485	25.70	0.779	0.659
4.50	9495.92	9562.39	9801.45	-3.28	2.41	11.93	293.41	2499.79	-5.20	90403.3	2763347.	20111.7	0.487	25.80	0.782	0.660
4.55	9621.15	9688.50	9930.71	-3.30	2.43	11.89	292.34	2510.06	-5.32	90988.6	2789265.	20300.3	0.489	25.91	0.785	0.661
4.60	9746.88	9815.11	10060.49	-3.33	2.46	11.86	291.41	2520.65	-5.45	91589.1	2816362.	20497.5	0.491	26.02	0.787	0.662
4.65	9873.12	9942.23	10190.79	-3.36	2.49	11.83	290.63	2531.58	-5.59	92205.9	2844811.	20704.6	0.492	26.13	0.790	0.663
4.70	9999.91	10069.91	10321.65	-3.39	2.52	11.80	290.00	2542.90	-5.72	92840.2	2874778.	20922.7	0.493	26.25	0.793	0.664
4.75	10127.27	10198.16	10453.11	-3.42	2.55	11.78	289.53	2554.62	-5.86	93493.3	2906415.	21152.9	0.494	26.37	0.796	0.665
4.80	10255.24	10327.02	10585.20	-3.45	2.57	11.76	289.24	2566.79	-6.00	94166.8	2939851.	21396.3	0.495	26.49	0.799	0.665
4.85	10383.85	10456.54	10717.95	-3.48	2.60	11.74	289.12	2579.41	-6.14	94862.4	2975179.	21653.4	0.495	26.62	0.803	0.666
4.90	10513.14	10586.73	10851.40	-3.52	2.63	11.72	289.18	2592.53	-6.29	95582.8	3012559.	21925.5	0.495	26.76	0.806	0.667
4.95	10643.15	10717.73	10985.59	-3.55	2.66	11.71	289.39	2606.09	-6.44	96327.0	3051757.	22210.7	0.495	26.90	0.810	0.668
5.00	10773.88	10849.29	11120.53	-3.59	2.69	11.70	289.71	2620.00	-6.58	97095.9	3092329.	22506.0	0.494	27.04	0.814	0.669
5.05	10905.32	10981.66	11256.20	-3.63	2.71	11.69	290.11	2634.29	-6.73	97896.8	3134192.	22810.7	0.493	27.19	0.818	0.670
5.10	11037.49	11114.75	11392.62	-3.66	2.74	11.69	290.64	2649.05	-6.89	98739.8	3177634.	23126.9	0.493	27.34	0.822	0.671
5.15	11170.43	11248.62	11529.83	-3.70	2.77	11.69	291.30	2664.35	-7.05	99629.3	3223043.	23457.4	0.492	27.50	0.826	0.672
5.20	11304.15	11383.28	11667.87	-3.75	2.80	11.69	292.10	2680.17	-7.22	100566.2	3270288.	23801.2	0.490	27.66	0.830	0.673
5.25	11438.69	11518.76	11806.73	-3.79	2.83	11.70	292.98	2696.38	-7.40	101548.4	3318932.	24155.3	0.489	27.83	0.835	0.674
5.30	11574.04	11655.06	11946.43	-3.83	2.86	11.72	293.91	2712.90	-7.57	102573.9	3368652.	24517.1	0.487	28.00	0.839	0.675
5.35	11710.21	11792.18	12086.99	-3.88	2.88	11.73	294.86	2729.63	-7.75	103639.6	3419080.	24884.1	0.486	28.17	0.844	0.677

JOS. L. MEYER PAPENBURG EMS	HYDROSTATIC PARTICULARS	MAIERFORM GMBH, BREMEN 6891.06 – 171.120	PAGE 5 / 6 / 7

SPEC. GRAVITY OF SEA-W. = 1,025 T / CBM

COEFF. FOR DISPL. OF SHELL PL. = 1,007

TRIM = 0,000 m ON EVEN KEEL

KEEL - THICKNESS = 0.000 mm

DRAUGHTS INDICATED FOR Lpp / 2

DRAFT BK	MOUL-DED VOLUME	DISPL. FR–W.	DISPL. SEA-W.	LCB	VCB	KM (T)	KM (L)	WL - AREA	LCF	TMI	LMI	MCT BP	D / MCT	TPCI	ALPHA (BP)	DELTA (BP)
Metres	m^3	Metric-t.	Metric-t.	m	m	m	m	m^2	m	m^4	m^4	MT / M	-	T/C M	-	-
5.40	11847.21	11930.14	12228.40	-3.92	2.91	11.75	295.79	2746.45	-7.92	104741.6	3469822.	25253.4	0.484	28.35	0.848	0.678
5.45	11985.04	12068.94	12370.66	-3.97	2.94	11.78	296.68	2763.24	-8.09	105874.7	3520473.	25622.1	0.48	28.52	0.853	0.679
5.50	12123.70	12208.56	12523.78	-4.02	2.97	11.80	297.49	2779.87	-8.25	107033.4	3570630.	25987.1	0.482	28.69	0.857	0.680
5.55	12263.17	12349.01	12657.73	-4.07	3.00	11.82	298.19	2796.24	-8.40	108211.6	3570630.	26345.8	0.480	28.86	0.862	0.681
5.60	12403.44	12490.27	12802.52	-4.12	3.03	11.85	298.77	2812.27	-8.53	109404.2	3619913.	26696.9	0.480	29.03	0.866	0.682
5.65	12544.52	12632.33	12948.14	-4.17	3.06	11.88	299.19	2827.82	-8.65	110604.3	3714850.	27036.8	0.479	29.19	0.870	0.683
5.70	12686.37	12775.17	13094.55	-4.22	3.09	11.90	299.42	2842.72	-8.75	111801.4	3759327.	27360.5	0.479	29.34	0.874	0.685
5.75	12828.95	12918.76	13241.73	-4.27	3.12	11.92	299.44	2856.98	-8.83	112986.1	3801461.	27667.1	0.479	29.49	0.878	0.686
5.80	12972.23	13063.04	13389.61	-4.32	3.15	11.95	299.29	2870.71	-8.90	114154.5	3841657.	27949.7	0.479	29.63	0.882	0.687
5.85	13116.18	13208.00	13538.20	-4.37	3.18	11.97	299.03	2884.05	-8.96	115308.3	3880521.	28242.5	0.479	29.77	0.885	0.688
5.90	13260.80	13353.62	13687.46	-4.42	3.21	11.99	298.69	2897.06	-9.00	116449.3	3918322.	28517.6	0.480	29.90	0.889	0.689
5.95	13406.06	13499.90	13837.40	-4.47	3.23	12.00	298.26	2909.74	-9.04	117576.7	3955110.	28785.4	0.481	30.03	0.892	0.691
6.00	13551.95	13646.81	13987.98	-4.52	3.26	12.02	297.76	2922.15	-9.06	118691.9	3991054.	29047.0	0.482	30.16	0.895	0.692
6.05	13698.46	13794.35	14139.21	-4.57	3.29	12.04	297.22	2934.34	-9.08	119796.9	4026322.	29303.7	0.483	30.29	0.898	0.693
6.10	13845.59	13942.51	14291.07	-4.62	3.32	12.05	296.64	2946.34	-9.09	120893.8	4061078.	29556.6	0.484	30.41	0.901	0.694
6.15	13993.31	14091.27	14443.55	-4.67	3.35	12.07	296.03	2958.19	-9.09	121985.5	4095480.	29807.0	0.485	30.53	0.904	0.696
6.20	14141.63	14240.63	14596.64	-4.72	3.38	12.09	295.40	2969.94	-9.09	123074.5	4129674.	30055.9	0.486	30.65	0.907	0.697
6.25	14290.55	14390.58	14750.34	-4.76	3.41	12.10	294.78	2981.62	-9.08	124163.4	4163798.	30304.2	0.487	30.78	0.910	0.698
6.30	14440.04	14541.12	14904.65	-4.81	3.44	12.12	294.15	2993.21	-9.07	125250.7	4197841.	30552.0	0.488	30.90	0.913	0.699
6.35	14590.12	14692.25	15059.56	-4.85	3.47	12.13	293.55	3004.85	-9.05	126348.4	4232255.	30802.4	0.489	31.02	0.916	0.700
6.40	14740.80	14843.98	15215.08	-4.89	3.50	12.15	293.00	3016.65	-9.03	127468.1	4267519.	31059.1	0.490	31.14	0.919	0.702

20.3 Stability cross curves from the Stability Booklet of Hull No. S590

JOS. L. Meyer Papenburg EMS Building No. 590				-CROSS CURVES OF STABILITY – (KN – VALUES) SMOOTH WATER			
DRAFT BK	DISPL. SEA-W.	INCLINATION (DEGREES)					
(M)	(T)	10	20	30	45	60	75
3.50	7256	2.33	4.73	6.68	8.66	9.66	9.31
3.55	7377	2.31	4.71	6.67	8.66	9.66	9.30
3.60	7498	2.30	4.70	6.66	8.65	9.66	9.30
3.65	7619	2.29	4.68	6.65	8.65	9.65	9.29
3.70	7741	2.28	4.66	6.63	8.65	9.65	9.28
3.75	7863	2.26	4.65	6.62	8.65	9.64	9.27
3.80	7985	2.25	4.63	6.61	8.65	9.64	9.26
3.85	8108	2.24	4.62	6.60	8.65	9.63	9.25
3.90	8231	2.23	4.60	6.59	8.65	9.63	9.24
3.95	8355	2.22	4.59	6.58	8.65	9.62	9.23
4.00	8479	2.21	4.57	6.56	8.65	9.61	9.22
4.05	8604	2.20	4.56	6.55	8.65	9.61	9.21
4.10	8729	2.19	4.54	6.54	8.65	9.60	9.20
4.15	8854	2.18	4.53	6.53	8.65	9.59	9.19
4.20	8980	2.17	4.52	6.52	8.65	9.58	9.18
4.25	9106	2.16	4.50	6.51	8.65	9.54	9.18
4.30	9233	2.16	4.49	6.50	8.65	9.56	9.17
4.35	9360	2.15	4.48	6.49	8.65	9.55	9.16
4.40	9487	2.15	4.47	6.48	8.65	9.54	9.15
4.45	9615	2.14	4.45	6.47	8.64	9.53	9.13
4.50	9743	2.14	4.4	6.46	8.64	9.52	9.12
4.55	9872	2.13	4.4	6.45	8.64	9.51	9.1
4.60	10001	2.13	4.42	6.44	8.64	9.50	9.10
4.65	10131	2.13	4.41	6.43	8.63	9.49	9.09
4.70	10262	2.12	4.40	6.42	8.63	9.47	9.08
4.75	10394	2.12	4.39	6.41	8.62	9.46	9.07
4.80	10526	2.12	4.38	6.40	8.62	9.45	9.06
4.85	10659	2.12	4.37	6.39	8.61	9.44	9.05
4.90	10793	2.11	4.36	6.38	8.61	9.42	9.04
4.95	10927	2.11	4.35	6.37	8.60	9.41	9.03
5.00	11063	2.11	4.34	6.36	8.59	9.40	9.02
5.05	11198	2.11	4.33	6.35	8.59	9.38	9.00
4.10	11335	2.11	4.32	6.34	8.58	9.37	8.99
5.15	11472	2.11	4.31	6.33	8.57	9.35	8.98

JOS. L. Meyer Papenburg EMS Building No. 590		-CROSS CURVES OF STABILITY – (KN – VALUES) SMOOTH WATER					
DRAFT BK	DISPL. SEA-W.	INCLINATION (DEGREES)					
(M)	(T)	10	20	30	45	60	75
5.20	11610	2.11	4.30	6.32	8.56	9.34	8.97
5.25	11749	2.11	4.29	6.31	8.55	9.32	8.96
5.30	11888	2.11	4.28	6.30	8.54	9.31	8.95
5.35	12028	2.11	4.27	6.29	8.53	9.29	8.93
5.40	12169	2.11	4.27	6.28	8.52	9.27	8.92
5.45	12311	2.11	4.26	6.27	8.51	9.26	8.91
5.50	12455	2.11	4.25	6.26	8.50	9.24	8.90
5.55	12599	2.11	4.24	6.26	8.49	9.22	8.89
5.60	12744	2.11	4.23	6.25	8.48	9.21	8.87
5.65	12889	2.11	4.23	6.24	8.47	9.19	8.86
5.70	13035	2.11	4.22	6.23	8.46	9.17	8.85
5.75	13182	2.10	4.21	6.22	8.44	9.16	8.83
5.80	13330	2.10	4.20	6.21	8.43	9.14	8.82
5.85	13478	2.10	4.20	6.21	8.42	9.12	8.81
5.90	13627	2.10	4.19	6.20	8.40	9.10	8.80
5.95	13776	2.10	4.18	6.19	8.39	9.09	8.78
6.00	13926	2.10	4.17	6.18	8.38	9.07	8.77
6.05	14077	2.10	4.16	6.17	8.36	9.05	8.76
6.10	14229	2.10	4.16	6.16	8.35	9.03	8.74
6.15	14381	2.10	4.15	6.16	8.33	9.01	8.73
6.20	14534	2.10	4.14	6.15	8.32	9.00	8.72
6.25	14688	2.10	4.14	6.14	8.30	8.98	8.70
6.30	14842	2.10	4.13	6.13	8.29	8.96	8.69
6.35	14997	2.10	4.13	6.12	8.27	8.94	8.68
6.40	15153	2.10	4.12	6.11	8.26	8.92	8.66

20.4 Detailed Cross Curves of Stability Including the Ducktail

Yard number:	Ship name:	Date:
590	Estonia	

Trim	:	0.000 m (positive forward)
Density Sea Water	:	1.025 t/m3
Keel Thickness	:	0.025 m
Shell plating factor	:	1.007 m

STABILITY CROSS TABLES (FIXED TRIM)

T AP Metre	Dis.SW Ton	Kn 5 Metre	Kn 10 Metre	Kn 20 Metre	Kn 30 Metre	Kn 45 Metre	Kn 60 Metre	Kn 75 Metre	T FP Metre
2.000	3787.9	1.665	3.214	5.570	7.118	8.597	9.300	9.437	2.000
2.050	3897.8	1.636	3.166	5.527	7.101	8.603	9.328	9.440	2.050
2.100	4008.2	1.609	3.120	5.484	7.084	8.609	9.356	9.442	2.100
2.150	4119.0	1.583	3.076	5.444	7.066	8.614	9.383	9.443	2.150
2.200	4230.2	1.558	3.034	5.404	7.050	8.619	9.410	9.443	2.200
2.250	4341.8	1.534	2.993	5.365	7.033	8.624	9.436	9.443	2.250
2.300	4453.9	1.511	2.955	5.327	7.017	8.629	9.462	9.442	2.300
2.350	4566.5	1.489	2.917	5.291	7.001	8.633	9.485	9.440	2.350
2.400	4679.4	1.468	2.881	5.255	6.985	8.637	9.507	9.438	2.400
2.450	4792.8	1.448	2.847	5.221	6.969	8.640	9.527	9.436	2.450
2.500	4906.6	1.428	2.813	5.187	6.954	8.643	9.545	9.433	2.500
2.550	5020.7	1.410	2.781	5.155	6.938	8.646	9.562	9.429	2.550
2.600	5135.2	1.392	2.750	5.123	6.923	8.648	9.577	9.425	2.600
2.650	5250.1	1.375	2.720	5.093	6.908	8.650	9.590	9.421	2.650
2.700	5365.3	1.358	2.691	5.063	6.893	8.652	9.602	9.416	2.700
2.750	5480.8	1.343	2.663	5.035	6.878	8.654	9.613	9.411	2.750
2.800	5596.7	1.328	2.636	5.007	6.864	8.656	9.623	9.406	2.800
2.850	5712.8	1.313	2.610	4.981	6.849	8.657	9.631	9.400	2.850
2.900	5829.4	1.299	2.584	4.955	6.835	8.658	9.638	9.394	2.900
2.950	5946.2	1.285	2.560	4.931	6.821	8.660	9.645	9.388	2.950
3.000	6063.3	1.272	2.536	4.907	6.807	8.661	9.650	9.382	3.000
3.050	6180.8	1.260	2.513	4.884	6.793	8.661	9.654	9.375	3.050
3.100	6298.6	1.248	2.490	4.862	6.779	8.662	9.658	9.368	3.100
3.150	6416.7	1.236	2.469	4.841	6.766	8.662	9.660	9.361	3.150
3.200	6535.2	1.225	2.448	4.821	6.752	8.662	9.662	9.354	3.200
3.250	6653.9	1.214	2.428	4.801	6.739	8.662	9.663	9.346	3.250
3.300	6773.1	1.204	2.408	4.781	6.726	8.661	9.663	9.338	3.300
3.350	6892.5	1.194	2.390	4.762	6.713	8.661	9.663	9.330	3.350
3.400	7012.3	1.184	2.372	4.744	6.700	8.660	9.662	9.322	3.400
3.450	7132.4	1.175	2.355	4.726	6.687	8.659	9.660	9.314	3.450
3.500	7252.8	1.166	2.338	4.708	6.674	8.658	9.658	9.305	3.500
3.550	7373.6	1.157	2.323	4.691	6.662	8.658	9.655	9.297	3.550
3.600	7494.8	1.149	2.307	4.674	6.650	8.657	9.651	9.288	3.600
3.650	7616.2	1.141	2.293	4.657	6.637	8.656	9.647	9.279	3.650
3.700	7738.1	1.133	2.279	4.641	6.625	8.655	9.643	9.270	3.700
3.750	7860.3	1.126	2.266	4.626	6.613	8.654	9.638	9.261	3.750
3.800	7982.9	1.119	2.253	4.611	6.601	8.653	9.632	9.252	3.800

STABILITY CROSS TABLES (FIXED TRIM)

T AP Metre	Dis.SW Ton	Kn 5 Metre	Kn 10 Metre	Kn 20 Metre	Kn 30 Metre	Kn 45 Metre	Kn 60 Metre	Kn 75 Metre	T FP Metre
3.850	8105.8	1.112	2.241	4.596	6.589	8.652	9.626	9.242	3.850
3.900	8229.2	1.106	2.229	4.582	6.578	8.651	9.620	9.233	3.900
3.950	8352.9	1.100	2.218	4.568	6.566	8.651	9.613	9.223	3.950
4.000	8477.0	1.094	2.208	4.554	6.555	8.650	9.605	9.213	4.000
4.050	8601.6	1.088	2.198	4.541	6.543	8.649	9.598	9.203	4.050
4.100	8726.5	1.083	2.189	4.528	6.532	8.649	9.589	9.193	4.100
4.150	8851.8	1.078	2.180	4.516	6.521	8.648	9.581	9.183	4.150
4.200	8977.6	1.073	2.172	4.503	6.510	8.648	9.572	9.173	4.200
4.250	9103.8	1.068	2.164	4.491	6.499	8.647	9.563	9.163	4.250
4.300	9230.4	1.064	2.157	4.480	6.488	8.647	9.553	9.153	4.300
4.350	9357.5	1.060	2.150	4.468	6.477	8.645	9.543	9.142	4.350
4.400	9485.0	1.056	2.144	4.457	6.467	8.643	9.533	9.132	4.400
4.450	9613.0	1.052	2.138	4.446	6.456	8.641	9.522	9.121	4.450
4.550	9870.5	1.046	2.128	4.425	6.435	8.634	9.500	9.100	4.550
4.600	9999.9	1.043	2.124	4.415	6.425	8.630	9.488	9.089	4.600
4.650	10129.9	1.040	2.121	4.405	6.415	8.626	9.477	9.078	4.650
4.700	10260.4	1.038	2.118	4.395	6.405	8.621	9.464	9.067	4.700
4.750	10391.4	1.036	2.115	4.385	6.395	8.616	9.452	9.056	4.750
4.800	10523.1	1.034	2.113	4.375	6.385	8.610	9.439	9.044	4.800
4.850	10655.3	1.032	2.111	4.366	6.375	8.604	9.426	9.033	4.850
4.900	10788.2	1.031	2.109	4.356	6.365	8.597	9.412	9.022	4.900
4.950	10921.6	1.030	2.108	4.347	6.355	8.590	9.399	9.010	4.950
5.000	11055.8	1.029	2.107	4.338	6.346	8.582	9.385	8.999	5.000
5.050	11190.6	1.029	2.106	4.329	6.336	8.575	9.370	8.987	5.050
5.100	11326.2	1.028	2.106	4.321	6.327	8.566	9.356	8.975	5.100
5.150	11462.5	1.028	2.105	4.312	6.317	8.558	9.341	8.964	5.150
5.200	11599.7	1.028	2.105	4.303	6.308	8.549	9.325	8.952	5.200
5.250	11737.7	1.029	2.105	4.295	6.298	8.539	9.310	8.940	5.250
5.300	11876.5	1.029	2.105	4.286	6.289	8.530	9.294	8.928	5.300
5.350	12016.2	1.030	2.105	4.278	6.280	8.520	9.277	8.915	5.350
5.400	12156.7	1.031	2.106	4.270	6.271	8.509	9.261	8.903	5.400
5.450	12298.2	1.033	2.106	4.262	6.262	8.499	9.244	8.891	5.450
5.500	12440.6	1.034	2.106	4.254	6.253	8.488	9.228	8.878	5.500
5.550	12584.0	1.036	2.107	4.246	6.244	8.476	9.211	8.865	5.550
5.600	12728.4	1.037	2.107	4.239	6.235	8.465	9.193	8.853	5.600
5.650	12873.7	1.039	2.108	4.231	6.226	8.453	9.176	8.840	5.650
5.700	13020.0	1.041	2.108	4.224	6.217	8.440	9.158	8.827	5.700
5.750	13167.2	1.043	2.109	4.217	6.208	8.428	9.140	8.814	5.750
5.800	13315.4	1.045	2.109	4.210	6.199	8.415	9.123	8.801	5.800
5.850	13464.5	1.048	2.110	4.203	6.191	8.402	9.105	8.787	5.850
5.900	13614.7	1.050	2.110	4.197	6.183	8.388	9.086	8.774	5.900
5.950	13765.9	1.052	2.110	4.190	6.174	8.374	9.068	8.760	5.950
6.000	13918.0	1.054	2.111	4.184	6.166	8.360	9.050	8.747	6.000
6.050	14071.0	1.056	2.111	4.178	6.159	8.346	9.031	8.733	6.050
6.100	14224.9	1.058	2.111	4.172	6.151	8.331	9.012	8.719	6.100
6.150	14379.7	1.060	2.111	4.166	6.144	8.316	8.994	8.705	6.150
6.200	14535.3	1.062	2.111	4.160	6.136	8.301	8.975	8.691	6.200
6.300	14849.1	1.065	2.111	4.149	6.123	8.270	8.937	8.662	6.300
6.350	15007.3	1.067	2.111	4.144	6.116	8.254	8.918	8.647	6.350
6.400	15166.4	1.068	2.111	4.139	6.110	8.238	8.899	8.632	6.400
6.450	15326.3	1.070	2.110	4.134	6.103	8.222	8.880	8.617	6.450
6.500	15487.1	1.071	2.110	4.129	6.097	8.205	8.861	8.602	6.500

20.5 Detailed Hydrostatic Particulars Including the Ducktail

Yard number:	Ship name:	Date:
590	Estonia	

HYDROSTATIC TABLES

T AP Metre	Dis.SW Ton	Dis.FW Ton	LCB m.f.AP	TCB m.f.CL	VCB m.a.BL	LCF m.f.AP	KM.T m.a.BL	T FP Metre
2.000	3842.8	3749.1	65.993	-6.E-10	1.062	65.935	18.982	2.000
2.050	3952.9	3856.5	65.991	-6.E-10	1.089	65.923	18.662	2.050
2.100	4063.5	3964.4	65.989	-4.E-10	1.116	65.911	18.359	2.100
2.150	4174.5	4072.7	65.987	-5.E-10	1.142	65.896	18.071	2.150
2.200	4286.0	4181.4	65.985	-2.E-10	1.169	65.881	17.798	2.200
2.250	4397.8	4290.6	65.982	8.4E-11	1.196	65.865	17.539	2.250
2.300	4510.2	4400.1	65.979	2.5E-11	1.223	65.848	17.293	2.300
2.350	4622.9	4510.1	65.975	2.4E-11	1.250	65.831	17.059	2.350
2.400	4736.1	4620.5	65.972	3.2E-11	1.277	65.812	16.836	2.400
2.450	4849.6	4731.4	65.968	3.8E-11	1.304	65.790	16.617	2.450
2.500	4963.6	4842.6	65.963	3.7E-11	1.331	65.766	16.390	2.500
2.550	5077.9	4954.1	65.958	3.6E-11	1.357	65.741	16.170	2.550
2.600	5192.6	5066.0	65.953	3.6E-11	1.384	65.716	15.956	2.600
2.650	5307.7	5178.2	65.948	-9.E-14	1.411	65.690	15.751	2.650
2.700	5423.0	5290.7	65.942	-9.E-14	1.438	65.663	15.553	2.700
2.750	5538.7	5403.6	65.936	-9.E-14	1.465	65.635	15.363	2.750
2.800	5654.7	5516.8	65.930	-8.E-14	1.492	65.605	15.181	2.800
2.850	5771.1	5630.3	65.923	-8.E-14	1.519	65.573	15.006	2.850
2.900	5887.7	5744.1	65.916	-8.E-14	1.546	65.541	14.837	2.900
2.950	6004.7	5858.3	65.908	-8.E-14	1.572	65.508	14.676	2.950
3.000	6122.0	5972.7	65.900	-8.E-14	1.599	65.474	14.521	3.000
3.050	6239.7	6087.5	65.892	-8.E-14	1.626	65.436	14.372	3.050
3.100	6357.6	6202.6	65.883	-7.E-14	1.653	65.399	14.229	3.100
3.150	6475.9	6318.0	65.874	-7.E-14	1.680	65.361	14.091	3.150
3.200	6594.5	6433.7	65.864	-7.E-14	1.707	65.323	13.959	3.200
3.250	6713.5	6549.7	65.854	-7.E-14	1.734	65.281	13.833	3.250
3.300	6832.7	6666.1	65.844	-7.E-14	1.761	65.239	13.711	3.300
3.350	6952.3	6782.8	65.833	-7.E-14	1.788	65.195	13.595	3.350
3.400	7072.3	6899.8	65.822	-7.E-14	1.815	65.149	13.483	3.400
3.450	7192.5	7017.1	65.810	-7.E-14	1.841	65.103	13.376	3.450
3.500	7313.2	7134.8	65.798	-6.E-14	1.868	65.052	13.273	3.500
3.550	7434.1	7252.8	65.786	-6.E-14	1.895	65.000	13.175	3.550
3.600	7555.5	7371.2	65.773	-6.E-14	1.922	64.948	13.080	3.600
3.650	7677.1	7489.9	65.759	-6.E-14	1.949	64.896	12.990	3.650
3.700	7799.2	7608.9	65.745	-6.E-14	1.976	64.843	12.903	3.700
3.750	7921.5	7728.3	65.731	-6.E-14	2.003	64.788	12.820	3.750
3.800	8044.3	7848.1	65.716	-6.E-14	2.030	64.733	12.741	3.800
3.850	8167.5	7968.3	65.701	-6.E-14	2.057	64.673	12.666	3.850
3.900	8291.0	8088.8	65.685	-6.E-14	2.085	64.610	12.594	3.900
3.950	8414.9	8209.7	65.669	-5.E-17	2.112	64.549	12.525	3.950
4.000	8539.3	8331.0	65.652	-1.E-14	2.139	64.482	12.459	4.000
4.050	8664.0	8452.7	65.635	-2.E-14	2.166	64.415	12.397	4.050
4.100	8789.1	8574.8	65.617	-3.E-14	2.193	64.349	12.337	4.100
4.150	8914.7	8697.2	65.598	-2.E-14	2.220	64.271	12.280	4.150
4.200	9040.6	8820.1	65.579	4.2E-14	2.248	64.189	12.227	4.200

T AP Metre	Dis.SW Ton	Dis.FW Ton	LCB m.f.AP	TCB m.f.CL	VCB m.a.BL	LCF m.f.AP	KM.T m.a.BL	T FP Metre
4.250	9167.1	8943.5	65.560	8.1E-14	2.275	64.109	12.176	4.250
4.300	9293.9	9067.2	65.539	7.5E-14	2.302	64.026	12.128	4.300
4.350	9421.2	9191.4	65.518	1.8E-13	2.329	63.937	12.082	4.350
4.400	9549.0	9316.1	65.496	4.9E-13	2.357	63.841	12.040	4.400
4.450	9677.2	9441.2	65.474	8.2E-13	2.384	63.743	11.999	4.450
4.500	9805.9	9566.7	65.451	1.1E-12	2.412	63.644	11.960	4.500
4.550	9935.1	9692.8	65.426	1.5E-12	2.439	63.542	11.923	4.550
4.600	10064.8	9819.3	65.401	2.2E-12	2.467	63.436	11.888	4.600
4.650	10195.1	9946.4	65.376	3.0E-12	2.494	63.326	11.855	4.650
4.700	10325.8	10074.0	65.349	3.9E-12	2.522	63.219	11.823	4.700
4.750	10457.2	10202.1	65.322	4.9E-12	2.550	63.098	11.795	4.750
4.800	10589.1	10330.8	65.293	6.2E-12	2.577	62.973	11.769	4.800
4.850	10721.6	10460.1	65.264	7.6E-12	2.605	62.847	11.746	4.850
4.900	10854.8	10590.1	65.233	9.2E-12	2.633	62.718	11.726	4.900
4.950	10988.6	10720.6	65.202	1.1E-11	2.661	62.585	11.709	4.950
5.000	11123.1	10851.8	65.169	1.2E-11	2.689	62.441	11.695	5.000
5.050	11258.3	10983.7	65.136	7.6E-12	2.717	62.284	11.683	5.050
5.100	11394.3	11116.4	65.101	8.8E-12	2.745	62.109	11.675	5.100
5.150	11531.0	11249.8	65.064	2.8E-12	2.773	61.929	11.671	5.150
5.200	11668.6	11384.0	65.026	3.1E-12	2.802	61.745	11.669	5.200
5.250	11807.0	11519.0	64.987	-5.E-13	2.830	61.556	11.671	5.250
5.300	11946.2	11654.8	64.945	-4.E-12	2.858	61.362	11.678	5.300
5.350	12086.3	11791.5	64.903	-6.E-13	2.887	61.167	11.687	5.350
5.400	12227.4	11929.1	64.859	-8.E-13	2.916	60.971	11.701	5.400
5.450	12369.3	12067.6	64.813	1.1E-13	2.945	60.784	11.719	5.450
5.500	12512.2	12207.0	64.766	2.8E-13	2.973	60.600	11.741	5.500
5.550	12656.1	12347.4	64.718	4.5E-13	3.002	60.419	11.765	5.550
5.600	12800.9	12488.7	64.668	6.3E-13	3.032	60.241	11.793	5.600
5.650	12946.7	12630.9	64.617	8.2E-13	3.061	60.068	11.822	5.650
5.700	13093.5	12774.1	64.565	1.0E-12	3.090	59.902	11.854	5.700
5.750	13241.2	12918.2	64.512	1.2E-12	3.119	59.744	11.888	5.750
5.800	13389.8	13063.2	64.458	1.4E-12	3.149	59.559	11.922	5.800
5.850	13539.5	13209.3	64.403	1.6E-12	3.178	59.368	11.954	5.850
5.900	13690.2	13356.3	64.347	1.8E-12	3.208	59.196	11.985	5.900
5.950	13841.8	13504.2	64.290	2.0E-12	3.238	59.046	12.014	5.950
6.000	13994.4	13653.1	64.232	2.2E-12	3.268	58.910	12.041	6.000
6.050	14147.9	13802.8	64.173	2.4E-12	3.298	58.795	12.068	6.050
6.100	14302.2	13953.4	64.115	2.6E-12	3.328	58.692	12.094	6.100
6.200	14613.5	14257.0	63.997	3.1E-12	3.388	58.507	12.154	6.200
6.250	14770.4	14410.1	63.938	3.3E-12	3.418	58.418	12.189	6.250
6.300	14928.1	14564.0	63.880	3.6E-12	3.448	58.333	12.228	6.300
6.350	15086.7	14718.8	63.821	3.8E-12	3.478	58.248	12.271	6.350
6.400	15246.2	14874.4	63.762	4.0E-12	3.509	58.166	12.317	6.400
6.450	15406.6	15030.8	63.704	4.3E-12	3.539	58.089	12.367	6.450
6.500	15567.8	15188.1	63.645	4.5E-12	3.569	57.593	12.454	6.500
6.600	15894.3	15506.6	63.521	5.0E-12	3.631	57.656	12.492	6.600
6.650	16058.5	15666.8	63.462	5.3E-12	3.661	57.705	12.503	6.650
6.700	16223.2	15827.5	63.403	5.5E-12	3.692	57.768	12.511	6.700
6.750	16388.5	15988.8	63.347	1.7E-12	3.722	57.847	12.515	6.750
6.800	16554.4	16150.6	63.292	1.0E-17	3.753	59.814	12.320	6.800
6.850	16716.2	16308.5	63.259	2.0E-17	3.783	59.894	12.300	6.850
6.900	16878.6	16466.9	63.227	1.9E-16	3.813	59.975	12.310	6.900
6.950	17041.5	16625.9	63.196	6.1E-18	3.842	60.055	12.321	6.950
7.000	17205.0	16785.4	63.167	9.3E-18	3.872	60.134	12.332	7.000

20.6 Tank Filling

'11 '06 18:28 FAX +358 9 16067811 ONNETTOMUUSTUTKINTAKESK 003

ESTONIA
B 33

SHK Statens haverikommission
Board of Accident Investigation

TELEFAX MESSAGE

From: B Stenstrom, chief maritime accident investigator,
fax No. +46 8 737 58 42
To: SSPA, VTT
Attention: Peter Ottosson, Tuomo Karppinen
Fax number: 031 63 96 24, 009358 0 455 0619
Date: 30 nov 1994
Number of pages (incl this one): 1

ESTONIA, lastkondition

Har fått följande beräknade uppgifter om vätskor vid olyckstillfället:
tank 10, 108 m3
tank 11, 108 m3
daytank 36, 25 m3
settl.tank 38, 20 m3, totalt 261 m3 IFO 180 bunker

tank 41, 10 m3
tank 18, 32 m3, totalt 42 m3 MDO

tank 20, 10 mr, totalt 10 m3 gas oil

tank 1, 175 m3
tank 13 + 14, 183 m3, totalt ballast 358 m3

Häri ingår inte färskvatten och andra servicetankar, förmodar det kan vara rimligt att räkna dessa halvfulla.

Lastmanifestet upptar 34 lastbilar/trailers med en sammanlagd längd av 607 meter och en totalvikt av 970 ton. Den sammanlagda fillängden på bildäck är 940 meter, fördelat på 7 filer (3 om styrbord, 4 om babord). Lastbilarna stod akteröver och resten av filerna var enl uppgift i stort sett fyllda med personbilar.

Detta bör räcka med tillräcklig noggrannhet för beräkningarna

Återkommer om girdata.

Mvh

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Education	
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University Education	1999 - 2004 Studied Naval Architecture at Hamburg University of Technology (TUHH), Germany
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