CHALMERS

Research Study of Sinking Sequence of m/v ESTONIA

WP2.1 - Review of Evidence and Forming of Loss Hypothesis

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Technical Report

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SUMMARY

In the year of 2005 VINNOVA announced a call for research studies on the sinking sequence of m/v ESTONIA. A consortium headed by SSPA Sweden AB was awarded one project of which the Work Package WP2.1 – "Review of Evidence and Forming Loss Hypothesis" constitutes one of the initial tasks.

The purpose of WP2.1 – Review of Evidence and Forming Loss Hypothesis has been to, based on available facts and supported by hydrostatic stability calculations, establish some conceivable loss hypotheses which will constitute the basis for further and more comprehensive investigations including simulations and model tests.

In addition hereto, the outcome of this work is materialized through a Database containing testimonies and other relevant observations for further reference throughout the project. Furthermore, a hydrostatic model describing the m/v ESTONIA as used within the WP2.1 work, will also be utilized in dynamic stability analyses further on in the project.

The primary results of the Work Package WP2.1 are presented in the following chapters of the present report:

- A conceivable Course of Events is outlined in Chapter 2.4,
- Comments on Significant Observations are presented in Chapter 2.5,
- The Hydrostatic Stability Calculations are concluded in Chapter 4.4
- In Chapter 5, two plausible main loss hypotheses are proposed.

1 Introduction

1.1 Background

Following the dreadful accident 28 September 1994 when the RoPax vessel m/v ESTONIA capsized and foundered in the Baltic Sea and 853 lives were lost, the authorities of Estonia, Finland and Sweden including the Joint Accident Investigation Commission compiled and investigated evidences in terms of:

I. Interviews of survivals and other persons of relevance to the investigation,

II. ROV Underwater Operations when the wreck was filmed,

III. Tracing and Recovering of the Bow Visor,

IV. Diving Operations including a survey of the bow area and the navigation bridge.

Today the site of the wreck is classified as a sanctuary. Diving and other submarine activities in the region that could help to shed some additional light in the chain of events causing the disaster are thus not allowed. Consequently, a new sinking sequence study must be based on basically the same available factual material as back in the 1990:th.

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1.2 Purpose and Objective

The purpose of WP2.1 – Review of Evidence and Forming Loss Hypothesis has been to, based on available facts and supported by hydrostatic stability calculations, establish some conceivable loss hypotheses which will constitute the basis for further and more comprehensive investigations including simulations and model tests.

The main objective has been to form and put forward a first time track of a possible flooding sequence and to present supporting static stability calculations.

2 Review of Evidence

2.1 Evidence Material

In total 265 transcripts of testimonies as recorded during interrogations of 130 survivors, some of which interviewed at several different occasions, have been examined. Furthermore, transcripts of interviews with other persons than survivors considered to have some relevance to the capsizing and sinking sequence, have been reviewed.

In addition hereto, have also the digitized video recordings as made available to the public on the Riksarkivet's URL, consisting of about 53 minutes of ROV film material, been reviewed and relevant technical drawings and documents have been studied. A Reference List is presented in Chapter 6.

2.2 Quality of Evidence Material

When compared, the many different experiences made by people in a disastrous situation, some of which in a state of shock, will of course differ significantly, especially with regard to the time and duration of traumatic events. This divergence is even more pronounced as the accident develops. However, time reference for the initiation of an accident is normally more precise and coherent; people can relate to their whereabouts at the time for the initiation of an accident. Furthermore, when evaluating transcripts of the interrogations, the experience and skills of the interviewed persons must be taken into consideration.

It should be noted that the transcripts of the Estonian survivors have been translated to Swedish, in some cases based on a first translation in Finnish. In some of the transcripts it is even not clear whether the witness refers to Estonian time or to Swedish time.

Within this investigation any event having a time reference has been linked to other significant events into a network in which some plausible courses of events can be extracted. Some events are more distinct then others with regard to time and list reference, hence when linked to other significant observations a higher resolution and a somewhat more narrow timeframe can be established.

2.3 Database

In order to facilitate a systematic approach on the compilation and evaluation of the available evidence material related to the capsize and sinking of the m/v ESTONIA, a database was established. For the reasons of availability and simplicity the Microsoft software MS Access was selected, providing the possibility to filter, sort and present extracts of the data, using a SQL (Structured Query Language) code.

A number of fields considered relevant to the investigation were defined and sorted into tables where after relations between these field were established, see Figure 1

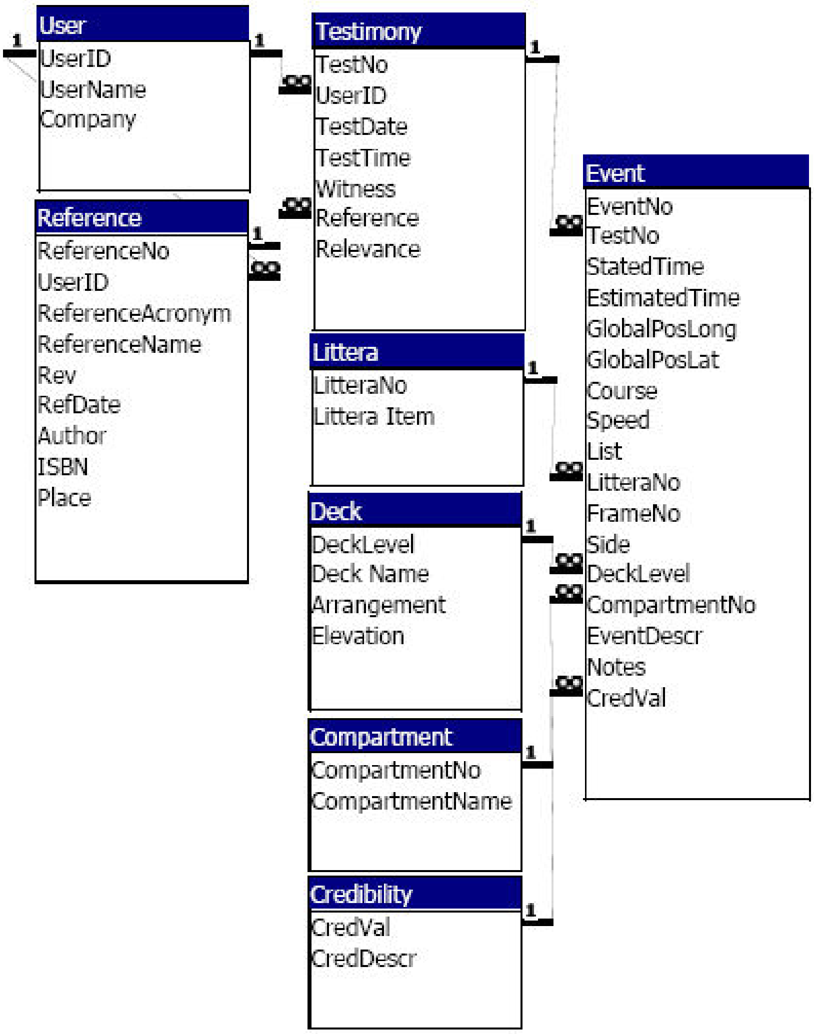

Figure 1 **Database Structure and Field Relations**

Following a first review of the material a second more directed assessment was carried out focusing on the following observations, see .

No.	**Time Period**	**Observation**
1	At Departure	Observations with regard to the lashing of cars, trucks and semi-trailers.
2	Sea Voyage prior to Initiation of Accident	Observations with regard to unusual / unexpected noise, ship performance or activities.
3	Experienced Initiation of Accident	Observations made in conjunction with and time reference for the experienced initiation of the accident.
4	Development of Floating Status	Specific values, estimates or geometrical information related to the increasing list and trim, and any corresponding time references pertaining hereto.
5	Flooding of Buoyant Hull Volumes	Observations of water ingress into the buoyant hull volumes below freeboard deck.
6	Observations made on Open Deck	Observations made on open deck related to ship's orientation towards wind and waves.
7	Observations made after Evacuation	Observations from liferafts related to the sinking of the vessel, stern or bow down etc.
8	Other Specific Observations	Other specific observations related to the accident but not in particular to the capsizing and sinking. The information sought for to be used as reference data to be linked with Items 1-7 as specified above.

Table 1 Database Search Items applied in Second Assessment

2.4 Course of Events

Based on the above assessment of testimonies the following first conceivable "Time Track" of significant events and observations, leading to the accident and consecutively the loss of m/v ESTONIA, can be established. It should again be noted that the time references are sometimes an estimation made based on other interlinked observations.

Estonian Time	Event / Observation
1994-Sep-27 19:15 hrs	m/v ESTONIA departs from Tallinn. The ship was carrying full deck payload. Cars were not lashed to the deck, only the car parking break and in some cases a gear constituted the securing. Some trucks and lorries were hindered from sliding by rubber chocks. Semi-Trailers were lashed by four web-lashings. Heavy weather was forecasted.
1994-Sep-28 00:00 hrs	m/v ESTONIA reaches the waypoint, the speed was 14.5 kts. After change in course, the wind was South-West veering to West and the waves were somewhat more westerly.
00:00 hrs	Some witnesses experience sliding noise from Car Deck (Dk. No.2), as if something was sliding from side to side, banging into the hull side. Another witness states that he experiences a bang close to midnight Estonian Time.
01:00 hrs	Witness in cabin on Deck No. 1 experiences hydraulic sound and relates this to visor and / or Ramp operation.
01:00 hrs	At least three witnesses experience change in ship motion. An increased roll motion is now more pronounced instead of pitching.
01:05 hrs	At least three heavy blows were noticed by at least 14 witnesses. One survivor experiences a heavy wave impact followed by 2-3 loud banging and scraping noises from the bow. Where after the ship heels over making loose items fall. Among other items one alarm clock that stopped 12:02AM when the battery fell off.
01:05 hrs	At least one full heel-over from side to side is experienced where after the ship ends up at a list of more than 15° to SB.
01:10 hrs	Many survivors testify about loose items falling over including heavy furniture. Some witnesses wake up by falling off their beds.

Estonian Time	Event / Observation
01:10 hrs	Shortly after pronounced list, when moving from SB aft to PS, one witness observed how the ship was slowing down and made a PS turn.
01:10 hrs	A reduction in ship's speed is noticed by several survivors, some of which states that just following the heavy blows and the initial list, the engine sound diminished or could no longer be sensed. At an unspecified point of time the Third Engineer in the Engine Control Room (ECR) observes that the engine speed has been reduced, from the Nav. Bridge controls, to just above idling speed.
01:10-01:15 hrs	At least six survivors experienced water on Deck No. 1 or water ingress at the sliding doors at Deck No. 2. None of them reported any massive flooding. Probably one of the last survivors from the Deck No. 1 accommodation hears the "Häire, Häire" from this deck level and still manages to ascend prior to any massive flooding.
01:15 hrs	At least 14 witnesses report about the faint alarm "Häire, Häire". An evaluation of these testimonies indicates a time reference for this alarm close to 01:15 and at a corresponding list reference of 30-40°.
01:15 hrs	The "Häire, Häire" alarm is overridden by the announcement from the Nav. Bridge "Mr. Skylight to number One and Two" which, according to the m/s ESTONIA's Safety Manual, is a Fire alarm at which specified crew members in the Safety Organisation should man the Fire Stations No. 1 fwd at Deck No. 8 and Fire Station No. 2 aft on the Car Deck
01:15 hrs	WT-sliding doors are remotely released from the Navigation Bridge.
01:15 hrs	Due to list and consequently loss of LO-pressure PS Main Engines (ME:s) tripped and stopped. Shortly after also the SB ME:s stopped.
01:20 hrs	The Auxiliary Engines (AE:s) tripped and stopped and consequently the lights went down for a second until the Emergency Genset started. The list is now more than 45°.
01:22 hrs	First Mayday is transmitted from m/v ESTONIA.
01:25 hrs	During the distress traffic m/v ESTONIA confirms having a Black-Out.

Estonian Time	Event / Observation
01:25 hrs	The third engineer climbs the Crew's staircase to Deck 8. When reaching the Emergency Generator Room the list is close to 90° and the Emergency Genset shuts down.
01:29 hrs	The last message in the distress traffic from m/v ESTONIA is transmitted.
>01:30 hrs	At some point the lowest part of the sinking ship touches-down on the seabed at a water depth of about 80m, thus most likely slowing down the sinking and impeding the full capsize.

2.4.1 List Development

In order to depict the variance in perception of the events the list development v:s time has been plotted, see Figure 2.

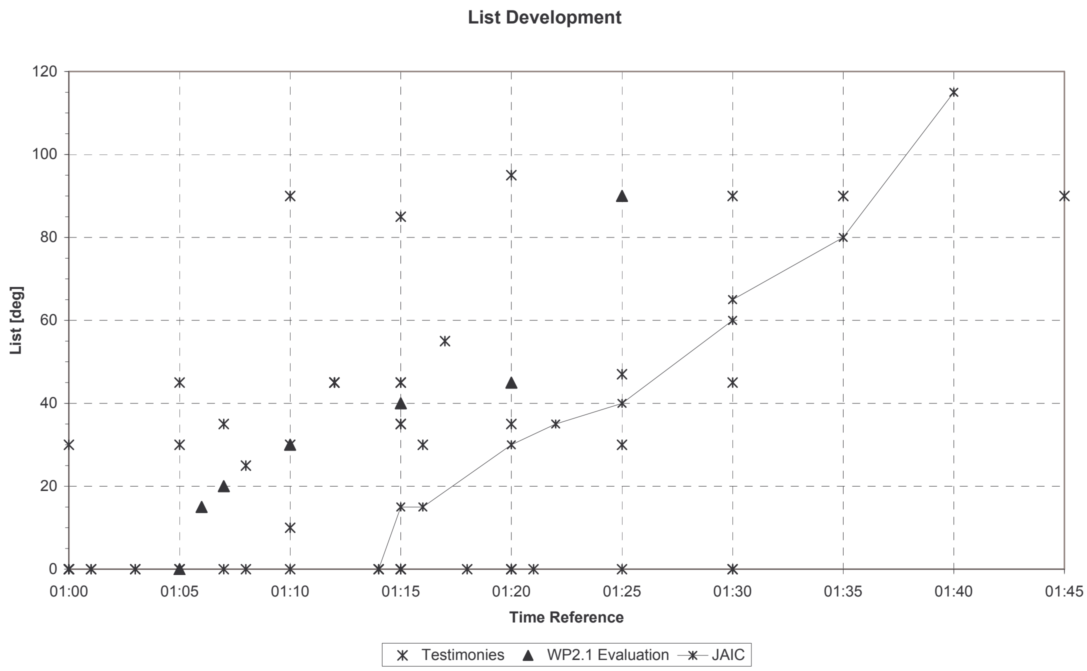

Figure 2 List Development

2.5 Comments on Significant Observations

2.5.1 Ship's Condition

According to one survivor, a truck driver who had frequently been traveling with the m/v ESTONIA, there were considerable problems locking and un-locking both the bow visor and the bow ramp at departure and arrival. Many times crew members had to work on the locks using sledge hammers. This testimony is also confirmed by several other witnesses interviewed by the German Group of Experts, [4]. Further according to [4], some passengers traveling with the m/v ESTONIA prior to the disaster have testified that during voyages in heavy weather there was always some amount of water on the Car Deck (Dk. No.2).

The day of the departure preceding the accident, 27 September 1994, two Swedish Maritime Administration surveyors performed an educational Port State Control exercise for some Surveyors of the Estonian Maritime Administration. The m/v ESTONIA was selected as subject vessel for the training exercise. Among other items, the survey the SMA Surveyors made the following notations, [10]:

- The Surveyors got the first impression that the ship was well managed and clean. However, the Surveyors could from some reason not be not provided with some important documentation such as the Ship's Stability Booklet, Damage Control Plan and the Cargo Securing Manual.

- On the Navigation Bridge, the so called MIME-Panel on which the indication of WT-closing was presented; displayed green light when the WT-doors were open. According to prevailing rules should the indication be green when the doors were closed. This seemed to cause some confusion also to the 1st Mate who was attending the educational survey.

- Some WT-doors were later tested locally and proved to function. However, it appeared as if the local controls, at least in the Machinery Spaces, were overridden by the panel on the Nav. Bridge; as soon as the WT-doors were closed locally they were immediately operated to open again. In the Deck No. 1 Passenger Accommodation area the WT-doors proved to function satisfactory.

- On the Car Deck and presumably in the Bow Thruster Room some hatches into to the watertight integrity were open. The impression was that the hatch covers had not been closed for quite some time. According to the SMA Surveyors were these covers closed after the SMA notation. At least one cover had to be forced into position to be closed.

- The SMA Surveyors confirmed a torn down rubber seal half a meter up at both sides of the bow ramp. When noted, the Chief told the Surveyors that the seal was to be removed at the next docking.

- As the impression was that the Ship was very clean, no inspection of scuppers was made.

- Some worn out and broken cargo lashing equipment was stowed together with functional lashing equipment. When noted, the Surveyor got the reply that the broken equipment was used "if necessary".

2.5.2 Noises

The interrogations, at least most of them, were held in accordance with a protocol that included the question about specific noise such as an explosion. Within the material none of the survivors have been found testifying any noise related to an explosion but rather to more a heavy hammering or banging metallic noise standing out from the sea impacts just prior to extensive heel-over. At least two witnesses also testify about noise from Car Deck (Dk. No.2) earlier the night of the accident. One of them relates the noise to a loose item sliding across the deck and smashing into the ship's sides.

During one interview when discussing water ingress at the sides of the bow ramp, the Third Engineer indicated that a container (intended for laundry) was located aft of the ramp, to some extent obstructing the view surveillance camera. Whether this container was lashed down to the deck or not is not given by any examined documentation.

2.5.3 Bow Visor

One testimony is given by a survivor who states that he observed green water on F'cle Deck and that "a large part of the F'cle was bouncing up and sinking. A transverse opening was noticed, through which much water was gushing up. The cascades of water seemed to be heavier on the starboard side".

2.5.4 Deteriorated Stability

Close to midnight, many witnesses experience a dramatic increase in the roll motion close. The ship heels over from side to side where after it rests for a moment at a significant list of more than 15°. Within less than two minutes the list increases causing loose items to fall over or to slide across the deck, even a rather heavy Casino Table starts to slide.

2.5.5 Water Ingress

At least six survivors experienced some water on Deck No. 1 or water ingress at the sliding doors at Deck No. 2. None of them reported any massive flooding. Probably one of the last survivors from the accommodation area at Deck No. 1 hears the "Häire, Häire" from this deck level and still manages to ascend without the experience of massive flooding.

While still in the ECR prior to ascending up to Deck No. 8, the System Engineer had the impression that the Officers on the Navigation Bridge were informed about water ingress somewhere into the hull and that the Bilge Pumps therefore were running. Since there was no bilge suction at Car Deck level and above, the water ingress indication should presumably have been originated from within the buoyant hull.

2.5.6 Alarms

The alarm “Mr. Skylight to Number One and Two” is, according to the m/v ESTONIA’s Safety Manual [8] a cryptic order to the Safety Organisation to man the fire stations one and two. Some crew members did start to execute the order but the fire station located on the Car Deck (Dk. No. 2) could of course not be manned.

In case of Collision, Grounding or Leakage the announcement, according to the m/v ESTONIA’s Safety Manual, [8], should be “Mr. Skylight One and Two Damage Control”. This announcement should according to [8] be preceded by the closing of all WT-doors. Following the alarm should the WT buoyant hull be searched from stem to stern.

2.5.7 Ship’s Route

In spite of the heavy weather at least three survivors testified that they had visual contact with two other vessels, presumably the m/v MARIELLA and the m/v SILJA EUROPA. One of these witnesses states that he could identify the m/v MARIELLA while evacuating the m/v ESTONIA.

In addition, the Second Officer on watch on the m/v MARIELLA keeps track on m/v ESTONIA on the radar. He also confirms having visual contact and states that he recognises the silhouette of m/v ESTONIA. The Second Officer furthermore testifies that in the corner of his eye he sees on the radar the track of a rather sudden and hasty PS turn of the m/v ESTONIA.

2.5.8 The Turn

A confirmation of a turn is given by the fact that at least three witnesses testify that the vessel, having a SB list, is inclining down towards the wind, i.e. at some stage the ship’s SB is side facing West or South-West. One survivor testifies that when the funnel starts to immerse a heavy smoke is covering some groups gathered on the vessel side shell. Another witness together with a group of passengers had the intention to launch a liferaft by sliding it down the PS side towards what seemed to be the leeward side. However, as the list exceeded 90 degrees the raft was actually launched against the wind and waves. Here at the windward side a lot of other rafts and lifebelts were gathered and thrown against the sinking ship.

According to the JAIC, [1], the diving inspection of the Wreck showed the rudders to be in hard Starboard position and the propellers were set to close to zero pitch.

2.5.9 The Sinking Development

When evaluating the testimonies, an average value of the estimated time from first perception of the accident to the foundering of ship is determined to 22 minutes. It should be noted that when the lowest part of the sinking ship touched-down on the seabed at a water depth of about 80m, the sinking development was most likely slowed down and the full capsize impeded.

30 survivors stated that the ship was sinking by stern. Out of these could eleven witnesses recall that the bow visor was missing. One witness testified that the bow was raised upwards and that the bulbous bow was the highest point. Nine survivors stated that the ship went down bow first. One of which stating that he could see the rudders and another that he saw the propellers.

2.5.10 Ship Wreck Details

The subsea activities as ordered by the Commission and carried out by Rockwater AS is summarized in the Condition Survey report, [9]. An limited internal inspection was executed on the Deck No:s 8 to 1. Among other observations the following can be noted:

- On Deck No. 8 the Stern Port Side quarter of the superstructure had sustained structural damage during the sinking. All cabins within this region had been destroyed. No casualties were found on the inspected area of Deck No. 8.

- On Deck No. 7, comprising Crew Accommodation, 11 PS cabins were inspected, in four of which a total of 12 casualties were sighted. The relatively high number of crew members that did not manage to escape from PS cabins on Deck No. 7 indicates a rather rapid development of the accident. Further down in the Ship the number of victims was increasing and congestions in stairwells were confirmed.

- Most of the cabins surveyed in Deck No. 1 were found to be intact, the exception being cabins 1005 and 1006 amidships.

- The only WT-door that was inspected, WT-Door 107, was found to be closed.

A further observation from the examination of the available video material is that many of the windows visual on the Port Side do not seem to be broken. The ROV is “flying” along the hull side using the blue stripes on the ship’s side as guidance for depth measurements, at which the ROV is operated to touchdown on certain window panes where after the depth is recorded. All windows passed by the ROV also gave searchlight reflections indicating that the panes were still intact.

The available film material could not reveal any information whether the Stern Ramps were closed or not.

3 Ship Status and Condition

In the present report a model for static stability analyses of m/v ESTONIA have been used. The stability calculations do not account for any dynamic affects e.g. waves, wind or maneuvering. It will also not capture the time scale of the events, apart from a few estimations of flood rates. It can however serve as a test platform of loss hypothesis where finding possible events is of importance, rather than high accuracy.

For this reason the ship is not modeled in a very high detail. Only larger compartments and tanks below the bulkhead deck are modeled. The car deck however is modeled accurately. The spaces above deck 4 are not used in the calculations.

The loading condition of the ship was taken from the JAIC supplements with a deduction for the weight of the bow visor. The hydrostatic particulars in intact condition are listed in Table 2.

Displacement	11902.6 ton
Draft (aft, mid, fwd)	5.65 m, 5.32 m, 4.98 m
List	0.16° SB
G'M	1.26 m
VCG	10.65 m
LCG	63.64 m fwd of AP

Table 2 Hydrostatic particulars of intact condition.

In traditional damage stability calculations, the spaces above the freeboard deck are considered to have no buoyancy at all. This is basically a correct assumption for these non water tight spaces, when static stability is regarded. In a real sinking scenario however, time will be a factor. Air needs to be evacuated from these spaces and replaced by floodwater. The total gross volume of the m/v ESTONIA is about six times larger than the intact displacement i.e. floodwater of about five times the weight of the ship will enter before the ship will sink.

The space below the bulkhead deck corresponds to a displacement of about 19 000 tonnes. 12 000 of these represent the mass of the intact ship. Consequently at least 7 000 tonnes of water must enter the spaces or the ship will not sink (this figure is in fact somewhat higher due to the buoyancy of the steel and outfit of the upper part of the ship).

In addition to flood points in the centre casing, the most important flood points for the loss hypothesis in the present report are:

- Ventilation ducts for spaces below the bulkhead deck which are located on the inside of the outer hull, each between two frames and with a size of approximately 800 by 350 mm, Figure 3 and Figure 15. They are located in SB/PS pairs: One pair for each of stern tube/store room and KaMeWa room and two pairs for the separator room and for natural exhaust of the main engine room. The inlets of these ducts are located below deck 4. These will be submerged at about 35° of heel.
- Car deck ventilators, terminating on deck 4. The ventilation openings are located at the ships sides just in front of the deck house and at the sides on the aft deck. These will be submerged at about 40° of heel.
- Four 800 by 350 mm exhaust ducts leading to the car deck, terminating in the ship sides below deck 4. These will be submerged at a heel angle of about 35° degrees.

The water level inside the car deck will be below the mean water line when the ventilation openings are reached and the water inflow will increase.

The rate of flow through the six machinery space ventilation ducts is estimated to a few hundred tons/min with a pressure head of one meter.

Located close to the forward and aft car deck ventilation openings on deck 4 are also exhaust/supply ventilation of bow thrusters and steering gear as well as staircases reaching the four casings in the corners of the car deck.

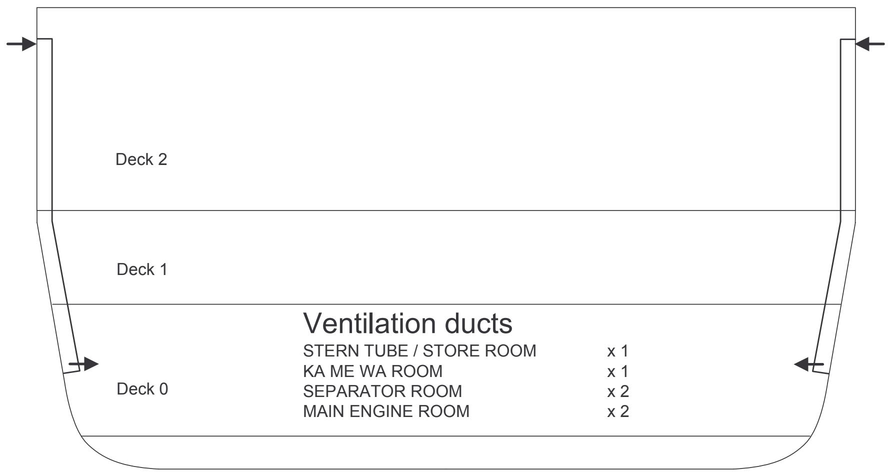

Figure 3 **Principle arrangement of ventilation ducts.**

4 Static Flooding Analysis

4.1 *Flooding into the Car Deck*

Water on the Car Deck (Dk. No.2) is considered to be the main cause for the rapid list development. Different facts influencing the flooding of the car deck is discussed below.

4.1.1 Through Bow Ramp Opening

Water entering the car deck through the bow ramp opening will remain on the car deck even if no consideration of dynamic effects is made. This is mainly due to the narrow ramp opening in the centre line. This opening will be above the mean water level and the flooded water will be accumulated at the side of the car deck. The ship also has a trim by stern and the forward part of the deck has a slight slope towards the stern.

Figure 4 show the spatial relationships between ramp opening, floodwater level on the car deck and the outside mean water level for different stages of flooding.

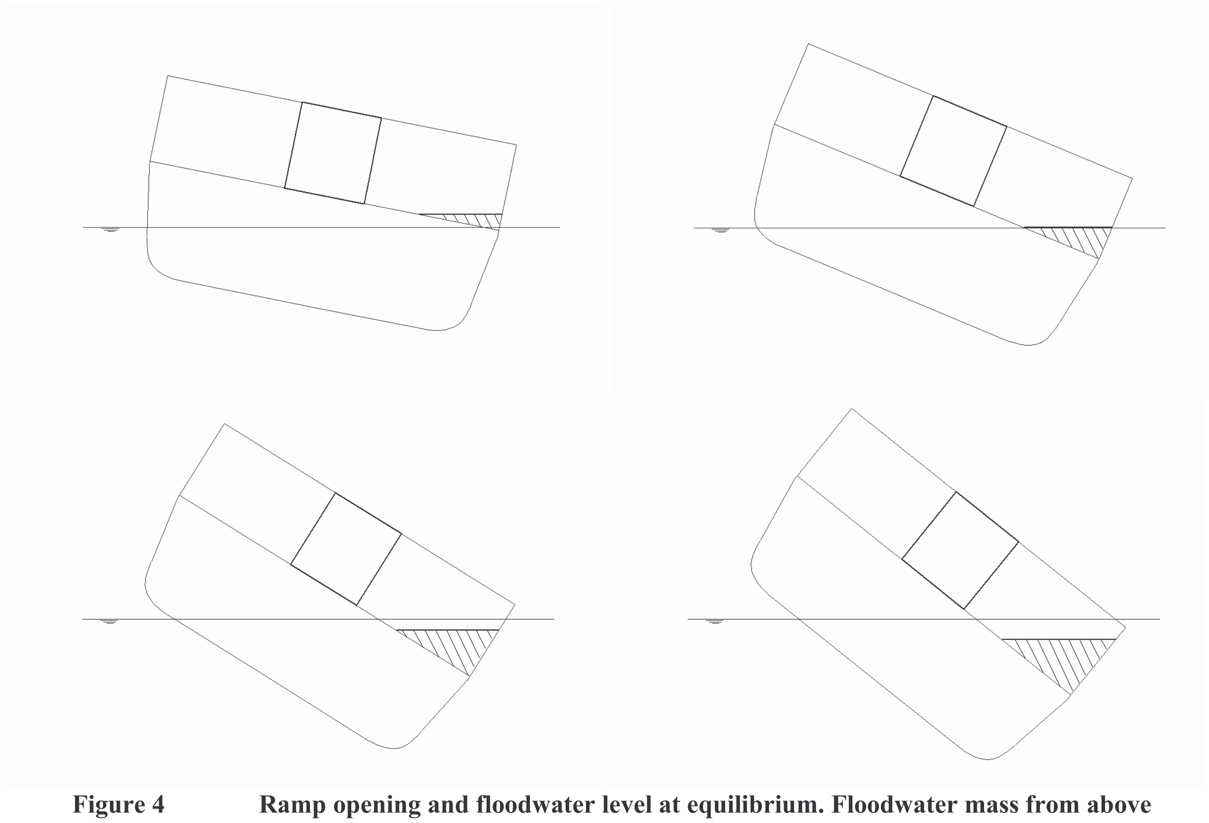

Figure 4 **Ramp opening and floodwater level at equilibrium. Floodwater mass from above left: 400 t, 1000 t, 1600 t, 1900 t.**

In all four stages of flooding in Figure 4, the floodwater level is below the lowest part of the ramp opening i.e. water entering through the ramp opening will be trapped on the car deck. However in the first stage, 400 tonnes of floodwater, the water level inside the car deck is higher than the mean water level. At this stage the outflow from the scuppers on the car deck will be at a maximum, with a pressure height of about one meter. At about 1000 tonnes of water the floodwater level will coincide with the mean water level. If more water enters the car deck the floodwater level in static equilibrium will be below the mean water level. This will allow additional flooding, driven by the pressure head, through any connecting opening (see below).

4.1.2 From Spaces Below

There also exists a possibility of flooding the car deck from the spaces below through the centre casing. If large parts of the forward accommodation spaces or aft machinery spaces are flooded the forward or aft end of the centre casing on the car deck will be below the still water line due to trim (and larger draft). This could enable flooding of the car deck through the spaces below. In this case, even if the free surface of the car deck is reduced due to large trim before flooding, negative stability due to water on deck could occur. Before the final stage of equilibrium of any of the above damages is reached, heeling angles beyond submersion of the bulkhead deck could take place. However non-return valves on the scuppers should hinder water inflow through these.

Examples of one aft and one forward damage are shown in Figure 5 to Figure 8. Both damages represent the minimum damage extent that will lead to submersion of the centre casing.

Figure 5 Symmetrical aft damage, equilibrium position.

Figure 5 shows the final equilibrium stage of a large aft damage case where the aft part of the centre casing is below the mean water line. Progressive flooding of the car deck will eventually lead to capsize. The damage includes the machinery spaces aft of the main engine room.

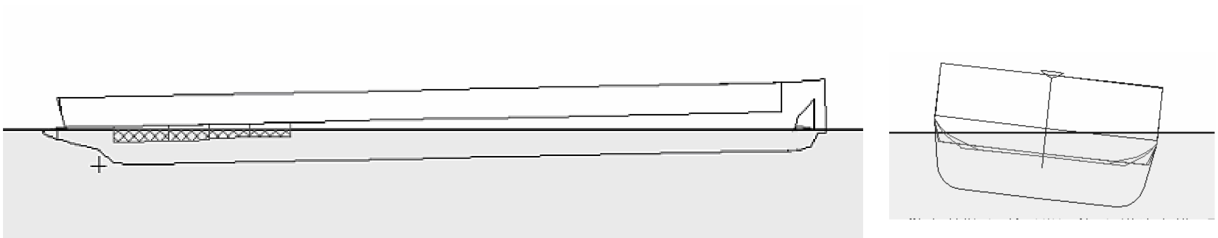

Figure 6 **Symmetrical aft damage, intermediate stage. (Lower compartments 50% full.)**

Figure 6 shows the same damage as above but at an intermediate stage of flooding where the three lower compartments are 50% full.

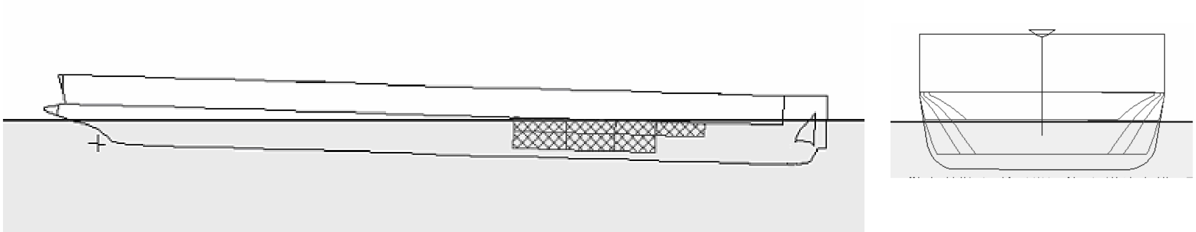

Figure 7 **Symmetrical forward damage, equilibrium position.**

Figure 7 shows the final equilibrium stage of a large damage in the forward accommodation area. The forward part of the car deck casing is below the mean water line. Progressive flooding of the car deck will eventually lead to capsize. The damage includes all but the two aft most compartments of the accommodation area below the bulkhead deck.

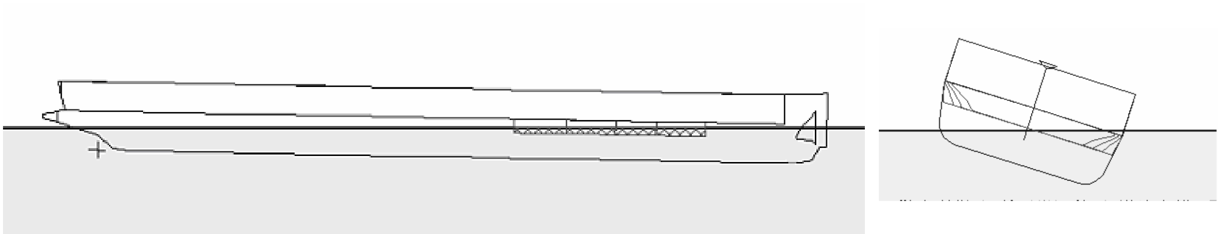

Figure 8 **Symmetrical forward damage, intermediate stage. (Lower compartments 50% full.)**

Figure 8 shows the same damage as above but at an intermediate stage of flooding where the three lower compartments are 50% full.

The flood rates involved in these scenarios could possibly alter the routs of the water and thereby change the outcome of the scenario.

At a later stage of flooding water would enter through four 800 by 350 mm exhaust ducts in the ship sides below deck 4, Figure 9, and the large car deck ventilators on deck 4. The ventilation openings on deck 4 are located at the ships sides just in front of the super structure and at the sides on the aft deck, Figure 11. The water level inside the car deck will be below the mean water line when these openings are reached, at about 40° of heel, and the water inflow will increase. Located close to these forward and aft openings are also exhaust/supply ventilation of bow thrusters and steering gear as well as staircases reaching the four casings in the corners of the car deck.

Figure 10 shows the floating position with approximately 1 900 tonnes of water on the car deck. Close to this position water will enter through ventilation on deck 4.

Figure 9 **Principle arrangement of car deck exhaust ventilation ducts.**

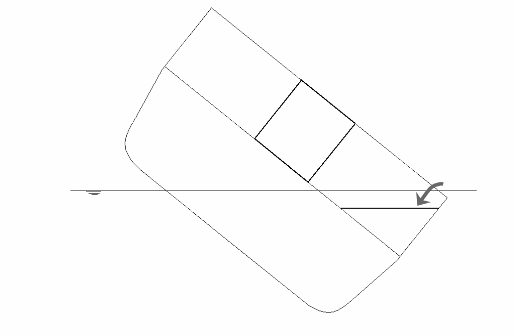

Figure 10 Water entering from car deck ventilation on deck 4.

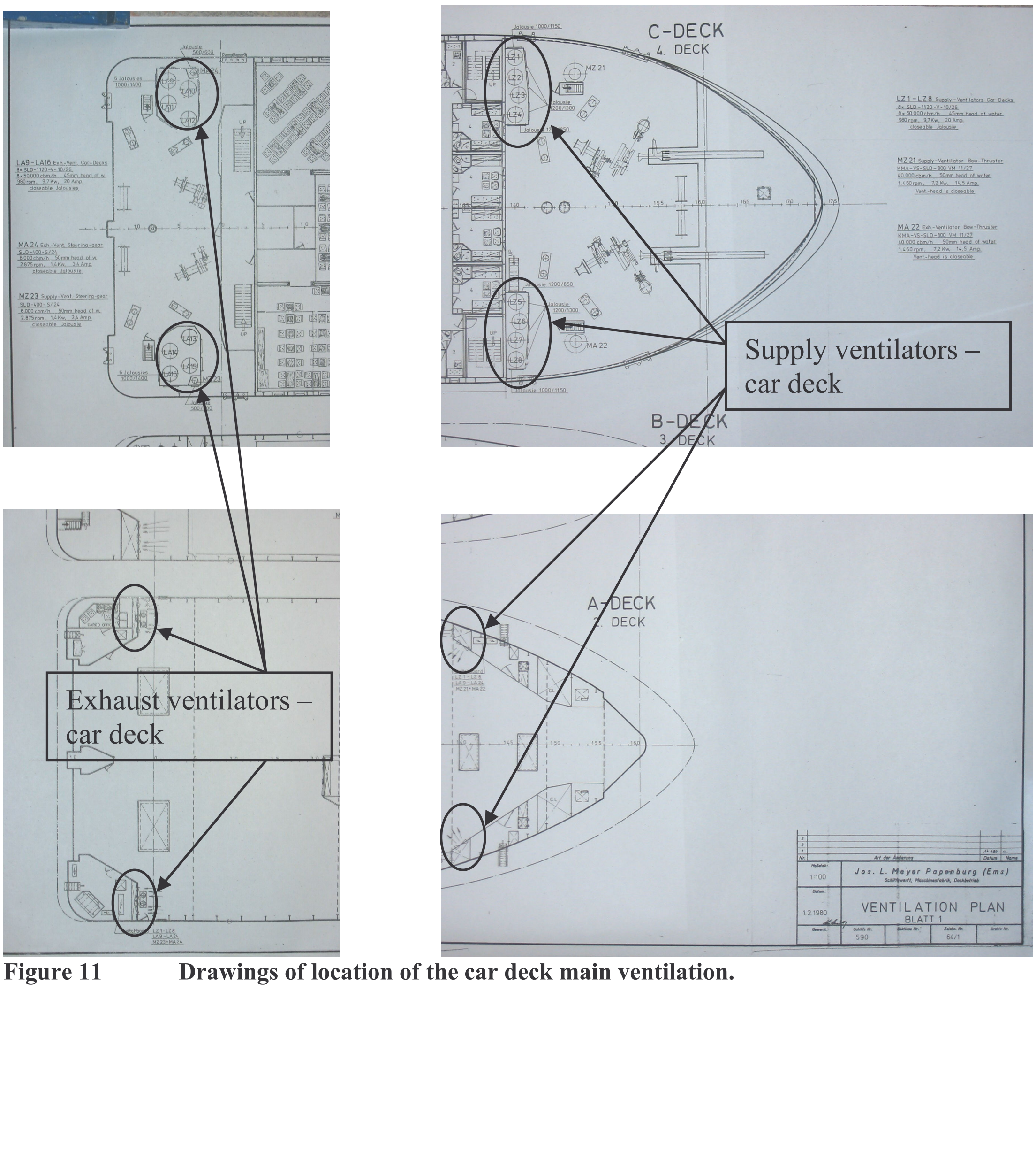

Figure 11 Drawings of location of the car deck main ventilation.

4.1.3 Estimate of Outflow through Scuppers

Twelve closable 4" scuppers were installed along each side of the deck. These scuppers were normally left open. An estimate of the flow rate through these scuppers gives a maximum outflow rate of less than 26 t/min, Appendix 2. (this is a conservative estimate the outflow was probably never this high). This can be compared to JAIC estimate of the inflow of water through the bow, 300-1200 t/min.

4.1.4 Cargo Shifting

Instructions to secure the heavy cargo carefully due to the forecast of heavy weather had been given. There are also witness reports that this was done. Substantial shifting of cargo however, must have taken place at some point in any scenario due to the observed large heel angles (>90°).

Table 3 shows the effect of cargo shifting in intact condition. Cargo shifting above one meter would imply shifting of cargo inside of the carriers, Figure 12.

Cargo shift (970 t) [m]	List [°]	Residual GM [m]
1	4	1.4
2	7	1.7
4	12	2.3

Table 3 Cargo shifting

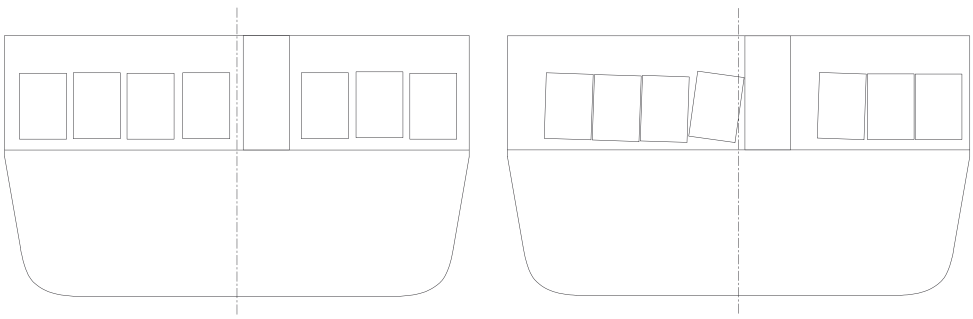

Figure 12 Shifting of cargo of about 1 meter.

Cargo shifting could also cause damages on the ventilation ducts leading to the machinery spaces below the bulkhead deck, located at the sides of the car deck.

4.2 Flooding into Spaces Below the Car Deck

4.2.1 Through Centre Casing

Water on the car deck will lead to an unstable equilibrium at zero heel and the ship will reach a stable equilibrium at a certain list angle to the SB or PS. If the amount of water on deck is small enough however, the energy from the waves will make the ship pass through the unstable upright position i.e. the ship will roll through both stable equilibriums. The floodwater will go from side to side passing the centre casing and some of the water could possibly flood through openings in the centre casing down to the compartments below. Figure 13 show the GZ curve of the intact ship around probable roll angles together with GZ curves for 100t and 200t of water on the car deck. The potential energy i.e. area under the curves will not alone govern the roll motion of the ship but the curves can serve as rough estimates of the above phenomenon.

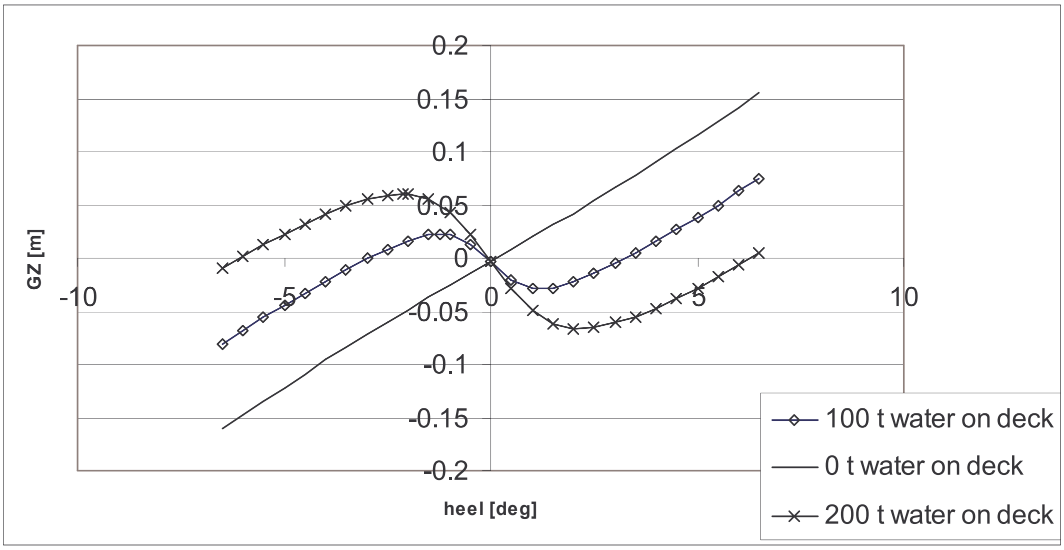

Figure 13 GZ curves with flooded car deck

Without flooding of the spaces below the bulkhead deck the centre casing would not be subjected to flooding, by hydrostatic pressure head, until a late stage where flooding of the accommodation spaces above the car deck has started. However if some parts of the spaces below the bulkhead deck was flooded in an earlier stage other parts could possibly be flooded through the centre casing before flooding of the above accommodation decks, due to large trim and immersion.

4.2.2 Through SB Ventilation Ducts

Ventilation ducts to spaces below the bulkhead deck are located on the inside of the outer hull. Each duct is located between two frames and is approximately 800 by 350 mm large. They are located in SB/PS pairs: One pair for each of stern tube/store room and KaMeWa room and two pairs for the separator room and for natural exhaust of the main engine room. The inlets of these ducts are located below deck 4, Figure 14.

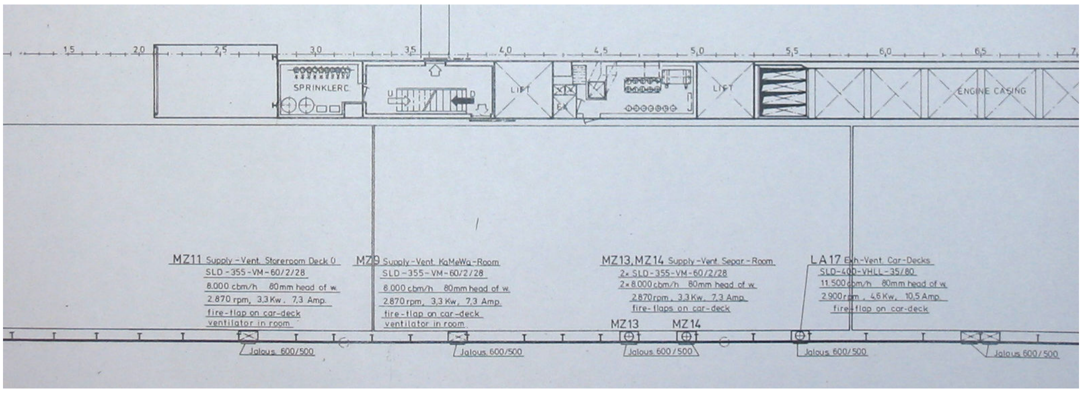

Figure 14 **SB ventilation ducts on car deck. Centre casing at the top of the figure and SB side at the bottom**

In a scenario with water on deck only, these inlets will be submerged at a heel angle of 35-40 deg and about 1800 tonnes of water on deck, see Figure 15. The rate of flow through these six ducts is roughly estimated to a few hundred t/min with a pressure head of two meters, Appendix 2. This flood rate could be high enough for flooding of 7000 t during the sinking scenario. However these spaces can only contain up to about 4500 tonnes of water i.e. additional flooding below the bulkhead deck is necessary for the ship to sink. Damages on these ducts due to e.g. cargo shifting could have caused flooding from the car deck at an earlier stage.

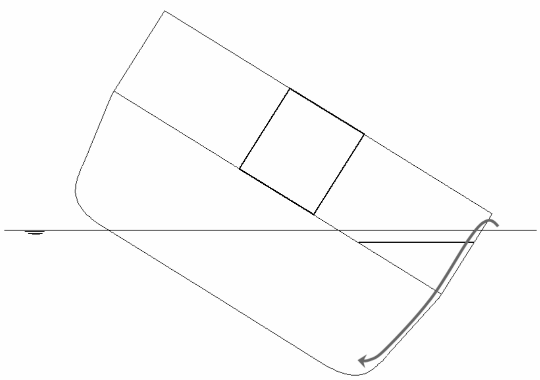

Figure 15 **Flooding of spaces below the bulkhead deck through ventilation ducts.**

4.2.3 Through Damage Below Waterline

The flooding of the car deck from below as described earlier would imply a damage in the buoyant hull below the water line.

4.3 Flooding into Spaces Above the Car Deck

The sequence of flooding of the non water tight spaces above the car deck is important for the timing of the sinking scenario and might also affect the sequence of flooding of the spaces below. When these spaces are reached however, the process is irreversible, the ship will eventually capsize.

The flow rates will also be important for the capsizing scenario i.e. without this buoyancy the ship will capsize very fast (seconds instead of tens of minutes between 40-180 deg).

4.4 Conclusions

Some major conclusions from the hydrostatic calculations together with chapter references:

- Water flooding into the car deck through bow ramp opening would not flood out. The water level would be below the mean water level during most of the flooding sequence, allowing further flooding through any additional opening, Chapter 4.1.1.

- Spaces below the car deck were flooded by at lest 7000 tonnes of water, Chapter 3.

- These spaces could have been flooded through ventilation ducts at the ship side, Chapter 4.2.2.

- Sloshing effects might account for partial flooding of the accommodation spaces below the car deck, Chapter 4.2.1.

- The car deck could have been flooded from the spaces below through the centre casing, 4.1.2.

- The sequence of flooding of the non water tight spaces above the car deck is important for the timing of the sinking scenario, Chapter 4.3.

5 Loss Hypotheses

The loss hypotheses presented below cover the sinking process from the first incident of flooding of the hull to the incident where the entire hull is under the surface. However the details of the course of events are presented with a limited resolution. The hypotheses will serve as a first starting point in the project and will be refined as the project progresses. Two main scenarios are outlined supported by the review of testimonies and the static calculations in chapter 2 and 4 of the present report. The scenarios are differing in how the water first entered the hull.

Using the information from

- testimonies from survivors
- status and conditions of the hull
- static calculations of sequential stability calculations

possible scenarios for the sinking sequence of M/V Estonia are suggested. The two possible main scenarios for the sinking are:

A) Due to water on the car deck with an intact underwater part of the hull or

B) A damage in the watertight hull with consecutive flooding of the car deck.

Combinations of these two main scenarios are also possible.

5.1 A: (Intact hull)

Main reason for water ingress on Car Deck: Bow visor locks fail, visor vertical motions cause the hinges to break where after the visor rests on the ramp top. Eventually the visor falls off and the ramp opens completely.

Phase 1.1: Wave impacts on visor cause a gap at the ramp sides and water is entering the car deck while the visor is still resting on the ramp. Roll angle is increased, water pouring down through lift shafts and staircases until list to SB of about 10 degrees.

This hypothesis could be supported by the testimony of among others the System Engineer and third engineer who both stated that a huge amount of water was pressing in from the sides of the ramp.

At least six survivors experienced water on Deck No. 1 or water ingress at the sliding doors at Deck No. 2. None of them reported any heavy flow causing massive flooding.

Phase 1.2: Bow visor opens the ramp fully when it falls off and at first wave impact a large amount of water is entering the car deck. Roll angle is increased, water is pouring down through lift shafts and staircases until list to SB of about 10 degrees.

At least six survivors experienced water on Deck No. 1 or water ingress at the sliding doors at Deck No. 2. None of them reported any heavy flow causing massive flooding.

Phase 2: Throttle is pulled down and ship is turned to port while water is still entering through the open bow ramp. When stopped with SB side against the waves the list has increased to 30 degrees.

Shortly after first heel over and list one witness moves from SB aft to PS and observes ship slowing down and turning to PS.

Phase 3.1: SB ventilation ducts are damaged by cargo shifting and / or collapse due to static water pressure. The list at this phase is close to 35°.

Phase 3.2: Water is flooded down through SB ventilation ducts to machinery spaces below freeboard deck. Smaller car deck exhaust ducts are submerged allowing consecutive water ingress. Subsequently car deck ventilators on the F'cle and poop decks are submerged allowing additional water ingress. At this phase the list exceeds 35-40°.

Phase 3.3: Above in combination with damaged WT-integrity (For example damaged SB fin stabilizer) which would increase the water inflow rate.

Phase 4.1: The list is increased and reserve buoyancy provided by the superstructure is needed to prevent capsize. Windows are subsequently damaged and list is increasing to 90 degrees. Aft windows are damaged and aft doors are submerged and flooding the lower deck areas in combination with flooding through centre casing.

At least one survivor testifies that he heard the breaking sound of windows in the accommodation.

Phase 4.2: In addition water tight doors may not be closed causing flooding of compartments below freeboard deck and / or the centre casing is immersed allowing consecutive flooding of the compartments below freeboard deck through primarily the sliding doors.

Phase 5: Ship is sinking with stern first and with a list of 180 degrees.

At least 30 survivors stated that the ship was sinking by stern.

5.2 B: (Damaged hull.)

Main reason for primary flooding into hull: Large hull damage and subsequently flooding the car deck through the lift shaft in centre casing due to static pressure head.

A witness has testified that the MER was dry when he ascended at a list exceeding 70°. At least six survivors experienced water on Deck No. 1 or water ingress at the sliding doors at Deck No. 2. None of them reported any heavy flow causing massive flooding. Hereby it is concluded that only a damage aft of the MER would be likely.

Phase 1: Increasing amount of water is entering the car deck from the damaged spaces below through openings in the centre casing. Roll angle is increased, water is pouring down in forward part through lift shafts and staircases until list to SB of about 10 degrees.

At least six survivors experienced water on Deck No. 1 or water ingress at the sliding doors at Deck No. 2. None of them reported any heavy flow causing massive flooding.

Phase 2: Throttle is pulled down and ship is turned to port. Large amounts of water is still entering through the aft end damage. When stopped with SB side against the waves the list has increased to 30 degrees.

Phase 3.1: SB ventilation ducts damaged by cargo shifting and / or collapse due to static water pressure.

Phase 3.2: Water is flooded down through SB ventilation ducts to the MER. Smaller car deck exhaust ducts are submerged allowing consecutive water ingress. Subsequently aft car deck ventilators on open deck are submerged allowing additional water ingress.

Phase 4.1: The list is increased and reserve buoyancy provided by the superstructure is needed to prevent capsize. Windows are subsequently damaged and list is increasing to 90 degrees. Aft windows are damaged and aft doors are submerged and flooding the lower deck areas in combination with flooding through centre casing.

At least one survivor testifies that he heard the breaking sound of windows in the accommodation.

Phase 4.2: In addition water tight doors may not be closed causing flooding of compartments below freeboard deck and / or the centre casing is immersed allowing consecutive flooding of the compartments below freeboard deck through primarily the sliding doors.

Phase 5: Ship is sinking with stern first and with a list of 180 degrees.

At least 30 survivors stated that the ship was sinking by stern.

6 References

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Sprint 001 – 21:18-21:48
Sprint 001B – 17:41-17:52
Sprint 001B - 19:02-19:07
Sprint 001B – 20:22-20:37
Sprint 002
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[10] Transcript of conversation with SMA Surveyors at the Accident Commission Office, 02-Nov-1994
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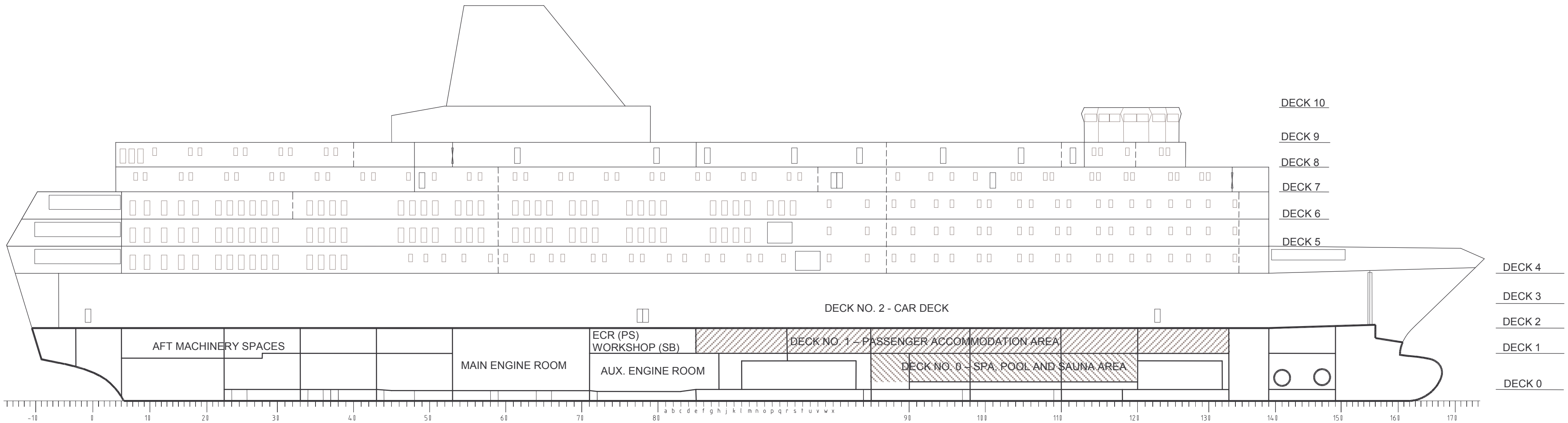
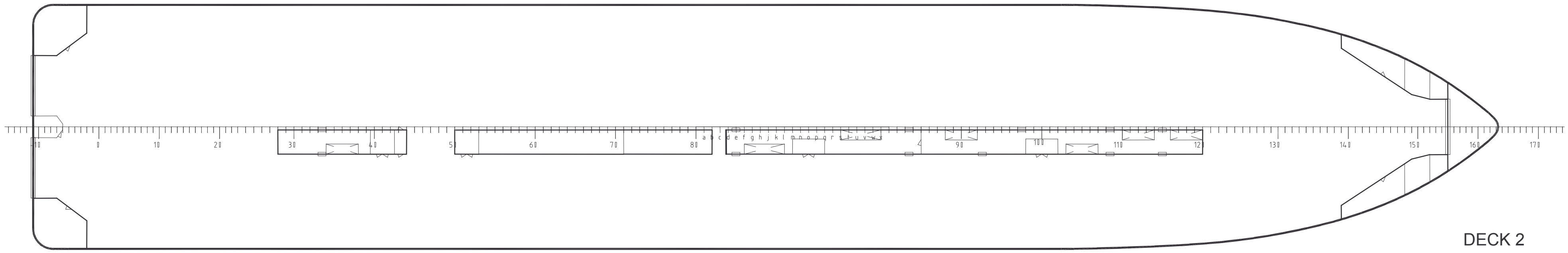
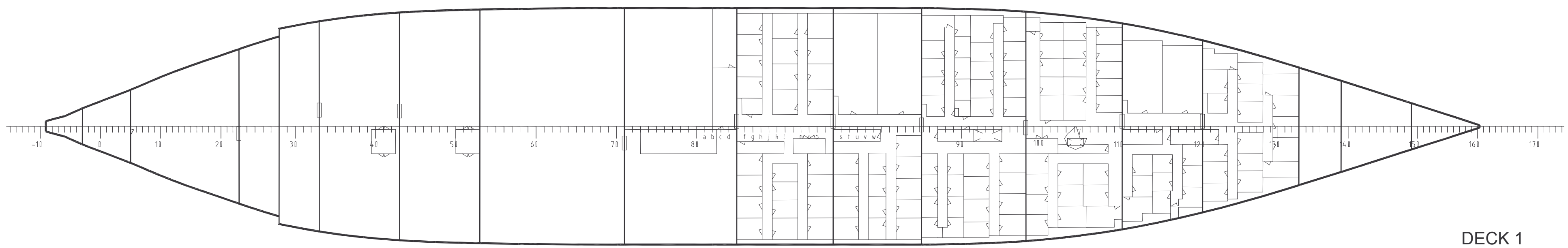
Appendix 1 – m/v ESTONIA GENERAL ARRANGEMENT – OVERVIEW WT-INTEGRITY





DECK 2



DECK 1

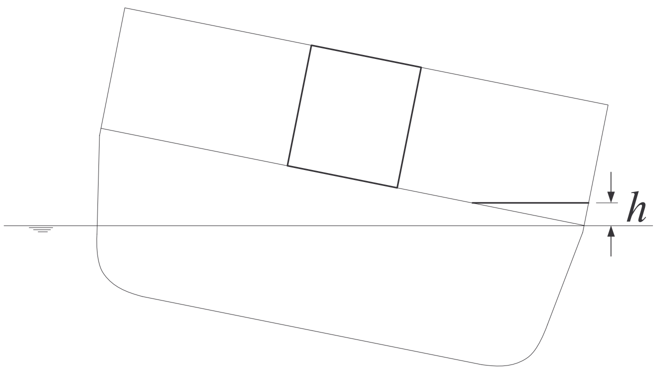
Appendix 2 – Estimate of flood rates

The possible outflow from the scuppers on the car deck is calculated in a simplistic way by use of Bernoulli's equation:

$$Q = k \cdot \sqrt{2 \cdot g \cdot h} \cdot A_{tot}$$

where,
Q = flood rate
k = flow coefficient
h = pressure height
A_{tot} = area of scuppers

The pressure height is determined from the floating position depicted below.



This floating position, with about 400 tonnes of water on the car deck, represents the largest possible static pressure head due to water on the deck, with $h \approx 1$m.

$A_{tot} \approx 0.097$ m^2 (12 scuppers, dia 4 inch)
$k = 1$ (high estimate)

The outflow rate Q will be 0.43 m^3/s or 26 t/min.

A rough estimate of the flood rate through ventilation ducts can be calculated the same way:

$A_{tot} = 1.68$ m^2 (6 ducts, 800 by 350 mm)
$k = 0.5$
$h = 2$ m

The outflow rate Q will be 5.26 m^3/s or 319 t/min.