REPORT

Subject	Report
MV Estonia Foundering tests	4006 4100-4
	Project manager Björn Allenström
Customer/Contact VINNOVA	Author Björn Allenström Michael Leer-Andersen
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Foundering tests in wind and waves have been carried out with a model of MV Estonia in SSPA manoeuvring and sea-keeping basin (MDL). The model was specially designed and manufactured to represent the full scale ship MV Estonia as much as possible in a foundering situation.

SSPA Sweden AB

Claes Källström
Vice President
Head of SSPA Research

Björn Allenström
Vice President

SSPA Sweden AB

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SUMMARY

The present report describes the foundering tests carried out within the SSPA consortium. The aim with these tests was twofold: to validate the simulations carried out within the project (see [4] to [6]), and to strengthen the understanding of the foundering by use of physical experiments.

In the work the information coming from different testimonies (see [7] has played a certain role. As an example it can be mentioned that the SSPA consortium has considered that the ship sank with the stern first as the most probable sinking scenario.

The agreement regarding the most probable foundering scenario when the model tests are compared with computer simulation (see [4] to [6]) is quite satisfactory.

From the model tests it is also shown that it is very important to have a full scale like ventilation of the ship for air evacuation and that it is necessary to scale air compressibility.

1 INTRODUCTION

The present report describes the foundering tests carried out within the SSPA consortium. The aim with these tests was twofold: to validate the simulations carried out within the project (see [4] to [6]), and to strengthen the understanding of the foundering by use of physical experiments.

In the work the information coming from different testimonies (see [7] has played a certain role. As an example it can be mentioned that the SSPA consortium has considered that the ship sank with the stern first as the most probable.

2 SHIP AND MODEL PARTICULARS

2.1 Main data

The model 3191-A was manufactured according to information from the Joint Accident Investigation Commission final report [1] and from Meyer Werft. In this report the following expressions are used to describe the model:

- the model up to deck 2 (car deck) is called ‘below car deck’
- deck 2 up to deck 4 is called ‘car deck’
- deck 4 and above is called ‘superstructure’

The model was manufactured from different materials: hull was manufactured from carbon fibre, interior parts from keel to deck 4 level in reinforced plastic and Plexiglas, and superstructure in aluminium.

The hull of the model including the fore body and ramp is the same as was used in the previous tests, see SSPA report 40064100-1 (see [2]). Model scale is 1:40.00. The model drawings are shown in Figures 3 to 9.

The ramp was like before remote controlled. When the ramp was open it was forced to stay open by use of a magnetic plate. The two electrical motors driving the propellers and the rudders were radio controlled like two valves placed in the bottom of the model, one fore and one aft, to be able to adjust for air compressibility in model scale, se below. It would have been desirable to use 10-15 remote controlled valves. This would, however, increased the technical complexity so much that it was rejected.

The main data of the ship at the tests are given below.

Table 1: Main data of MV Estonia

		Ship	**Model**
Lbp	[m]	137.4	3.435
Beam	[m]	24.2	0.605
Draft, aft	[m]	5.61	0.140
Draft, fwd	[m]	5.17	0.129
Displacement	[tonnes]	12 046	0.1864
Block coefficient	[-]	0.683	0.683
LCB (fwd of Lbp/2)	[m]	-4.66	-0.116
LCB (% rel Lbp/2)	[%]	-3.39	-3.39
VCG	[m]	10.62	0.2655
GM (corrected)	[m]	1.17	0.02925
Radius of gyration (kxx)	[m]	8.954 (0.37*B)	0.224
Radii of gyration (kyy/kzz)	[m]	37.1 (0.27*Lbp)	0.928
Rudders:			
Area (one rudder), movable	[m^2]	8.75	0.00542
Area (one rudder), total	[m^2]	10.85	0.00678
Rudder height	[m]	4.00	0.100
% of Lbp · T per rudder	[%]	2.93	2.93
Rudder rate	[°/sec]	2.321	
Max rudder angle	[°]	35	35

SSPA stock propeller models were used at the tests:

Table 2: SSPA stock propeller data

Diameter (model scale)	0.1044 m
Diameter (full scale)	4.18 m
No of blades, Z	4
Pitch P/D at 0.7R	0.806
Blade area ratio	0.611

2.2 Interior arrangement

All decks and main bulkheads were represented in the ship model except deck 3 (hanging car deck) and the small parts of deck 5, 6 and 7 located behind the superstructure, see Fig. 8. All compartments could be filled with water during the foundering except a number of tanks that were regarded as void spaces. These are shown in figure 1, all located below car deck.

When building the model for the foundering there were three main tasks to consider:

- the displacement of the model has to be correct
- the permeability of the model must be as full scale like as possible
- the scaling of air compressibility model/full scale has to be handled like the ventilation of air

The first demand, correct displacement, is relatively easy to accomplish. However, the permeability of the MS Estonia is not completely known. Permeability is here defined as a figure from 0 to 1 where 1 means that the whole available volume can be filled with water. Since in practice the walls containing the volume must have a thickness, this figure must be below 1. In a room with lots of goods that won't be filled with water, e.g. a storage room, the figure is as low as 0.6. Because of the problem not knowing the permeability of M/S Estonia when she foundered, early in the project it was decided that the permeability according to IMO's regulations for performing damage stability tests should be used. In Fig. 2 this permeability is shown. This gives, taking into consideration the spaces that cannot be filled (see Fig. 1), that the permeability for the three main parts of the ship is:

Below car deck:	0.88
Car deck:	0.90
Superstructure:	0.95

The total volume of the full scale ship is 78 006 m^3. The amount of water that can enter the ship is 72 106 m^3. The overall permeability for the ship is then 0.92. This means that when the ship is totally filled with water 8% of its volume is still giving a displacement in the water. The volume of the void spaces are 4218 m^3. The weight of the ship in water is then calculated according to below. Here it is assumed a water density of 1000kg/ m^3 :

Weight of the total volume of the ship in water:	78 006 tons
Ships weight (in air) at departure:	-11 930 tons
Weight of water entering the ship:	-72 106 tons
Weight of water representing void spaces:	+ 4218 tons
Remaining weight:	- 1812 tons

1812 tons corresponds to a weight in water for the model of 28.3 kg, which was checked before the tests.

The air compressibility must be considered in scale model tests of foundering scenarios. In the foundering air is trapped. In Stockholm Agreement 'Appendix C - Guidance on Application of Stockholm Agreement' it is prescribed that it is not allowed to trap air to improve the floatability. In the present tests these guidelines are not applicable. In the SOLAS resolution adopted 29 November 1995 regarding regulations for performing damage stability tests it is prescribed that the model should be as full scale like as possible. This is more applicable and therefore the model was built as good as possible to represent a reasonable air evacuation, see below. However, since the air cannot be compressed in model scale in the same way as in full scale, some air had to be ventilated manually.

A number of tests were carried out where the model capsized, trapped air and remained floating upside down. The volume of this trapped air was measured, and a mean value was found to be around 40 liters. Also the pressure of the trapped air was measured. The scaling laws give for the present situation that about 20% of the trapped air should be evacuated to give a proper remaining amount of trapped air in the model, see Appendix 1. In this case around 8 liters could be let out in order to fulfill the scale laws. The two valves in the bottom of the model were calibrated giving a flow of 6.7 liters each per minute at the actual pressure. This means that one valve could be held open a little more than 1minute during the test.

2.2.1 Below car deck

The material used below car deck was carbon fibre for the hull, reinforced plastic for the bulkheads and Plexiglas for the deck. The thickness of the material was between 3 and 4 mm, ensuring that the flow through openings wasn't affected in model scale. Thinner material would have been beneficial, but to be sure that the model should withstand all stresses in the foundering this was not possible. This caused a somewhat too low permeability below car deck. The permeability according to IMO should have been 0.88, instead the model had 0.78. The balance in permeability fore/aft was however correct. To achieve this, in some of the rooms aft (specially those with permeability of 0.6) foam plastic material were put in to reduce the permeability.

The different compartment modeled on tank and tween deck are shown in Fig. 3. In each compartment there were possibilities to reach the watertight doors by use of hatches, see Fig. 12. These hatches were also used when the model were emptied from water after each test. From the simulations (see [4]) it was shown that the ship didn't sink within a reasonable time frame having the watertight doors closed. This was one of the reasons why the tests were carried out with the watertight doors open. Only one door was closed, the one forward of the engine control room on tween deck. The other reason was that with the doors closed only a small amount of the trapped air could be evacuated in order to model the air compressibility.

Each room could be flooded through the different staircases, lifts, emergency exits etc. that are shown on the drawings and according to the full scale ship.

Ventilation of the different rooms was modeled as good as possible according to the full scale drawings available. The most important ventilation shafts for the water ingress was the ones going down from the both sides of the ship just below deck 4 (first deck in the superstructure), inside car deck and down to room Nos. 311, 411, 519, and 611. These shafts were scaled and they were also important for air evacuation. Also to room 1014 a similar ventilation shaft was modeled, however, this ventilation came from the port side of the ship so it didn't influence the flooding but played a role in the air evacuation. Also ventilation from deck No. 4 into the car deck fore and aft played a significant role in the foundering as well as ventilation of the steering room and bow thruster room.

The evacuation of air was arranged so that in each watertight section, air could pass from tween deck to tank deck when the ship model was upside down. Only a small hole of 5 mm were made in each section. This was necessary because of the problem with air compressibility in model scale which is explained above. Since there were only valves at the bottom of the model, the only way to let air out was to let it reach the tank deck.

Ventilation of air was also arranged according to the ventilation and AC system onboard. This was arranged so that from each watertight section a small hose (5 mm diameter) lead up to deck 8 level, but instead of having the hoses going up midships, which would have been more full scale like, the hoses was going up behind the superstructure. When the model was heeled up to 90 degrees these hoses were then below water surface and no more air could escape this way.

2.2.2 Car deck

From practical reason an extra deck below the real deck No. 4 had to be installed in the model. As stated above the permeability of the car deck should be 0.90, for the model the figure became 0.94, somewhat compensating for the too low figure below car deck. Also on car deck all doors, lifts etc in the center casing and other spaces were modeled properly allowing water flood the compartment below car deck. All these doors were open. Aft of the center casing there is a lift going down to tween deck. The door to this lift was assumed open and the movable threshold was down. Therefore a minor opening was made to represent a gap and letting water flow down to room R321. The doors leading from car deck and into the center casing were open in the model tests since these doors are not watertight.

2.2.3 Superstructure

The superstructure was manufactured in aluminum to give the whole model a correct permeability. On starboard side all windows and doors were possible to have open (see Fig. 10), as well as all doors fore and aft in the superstructure. Since it was not possible in a controlled way to release trapped air in the superstructure, 5 holes (diameter 5 mm) were drilled on port side close to deck level 4,5 and 6 at frames 20, 52, 75, 85 and 110. These holes allowed some air trapped in the superstructure to escape when the heel angle reached 150-160 degrees. Before that the air could escape through other openings such as doors.

From the simulations carried out it was shown that having two big windows open (size 1500*600 mm) on each deck 4,5 and 6 an adequate heel development was found. This was also used in the model tests, see Fig. 11. The two second last windows on deck 4, 5 and 6 were open during the tests. Also all doors facing aft in the superstructure on port side and the one facing forward was open. This was mainly for air evacuation.

It was discussed if these windows should be opened by remote control during the foundering, but having received information from the Glass Research Institute in Växjö, Sweden that it is probable that these windows can break already with a pressure corresponding to a water column of 5 meters, knowing that there are substantial dynamic forces involved it can be assumed that these windows will break when they are very close the waterline, i.e. in the region of 40 degrees heel angle.

3 TEST ARRANGEMENT

The foundering tests was carried out in the Maritime Dynamics Laboratory (MDL).

MDL has a basin with the dimensions 88 m x 39 m with variable water depth up to 3 m. At these tests the water depth was 2.25 m. Wave generators for regular and irregular long-crested waves are installed on two perpendicular sides of the basin. A multi-motion carriage, normally used for data logging and model control, spans the whole basin. In this test the carriage was only used to carry a wind battery, chasing the model. The wind was calibrated to give a full scale mean wind speed of 18 m/s. The water depth corresponded to 90 m in full scale at the tests. The waves used was the same as in the previous tests:

Significant wave height,	$H_{1/3}$:	4.3 m
Peak wave period,	Tp:	8.3 s

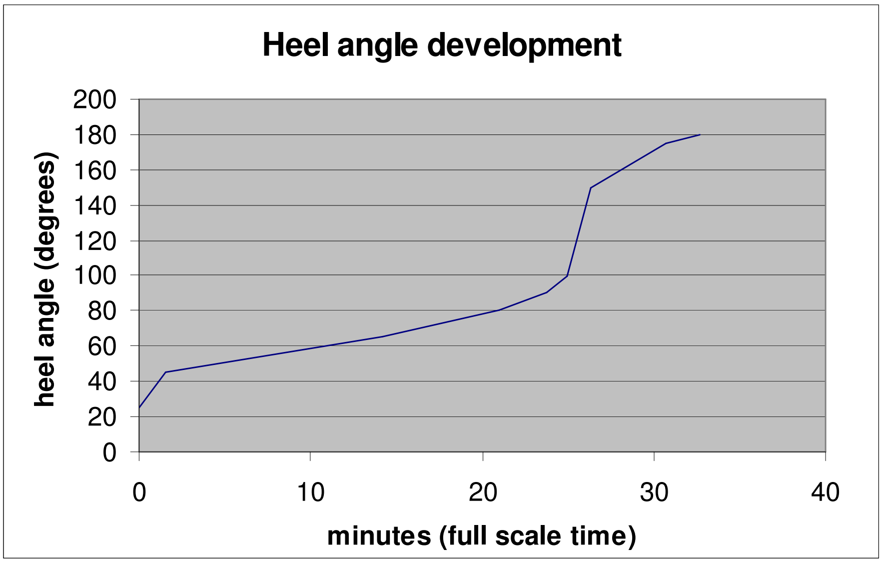
4 TESTS CARRIED OUT AND RESULTS

A video showing the foundering is presented with the final report, see [8]. The tests started with the model close to the end of the basin and steamed against the waves with an angle of approx. 10 degrees from port side. The wind came also from port side with an approx. angle of 40 degrees. When the model reached the position +10 m (10 m south of the midpoint in the basin) the ramp was opened, see Fig. 14, and the propeller thrust was somewhat reduced, in the order of 10%. Immediately the heel increased due to the water entering on car deck, and starboard rudder was used to keep her on course. When the model reached a heel angle of approx. 25 degrees a port turn was initiated. The heel increased all the time in the turn, see Fig. 15, and when the turn had reach around 100 degrees the propellers were stopped. The model then stopped very quickly and started to drift in wind and waves 90 degrees to the waves . The position of the model was then approx. +22, i.e. from the ramp was opened and to the model was drifting the full scale distance was approx. 500 meters. When the drift was steady (within 5 minutes in full scale time) the wind was turned of not having the model to drift too fast not to reach the end of the basin before it sank.

From [3] it was known that the wave drift speed was about one knot in 45 degrees heel angle. This was now also the case, but at the final stage of the foundering with a heel angle about 150 degrees the wave drift speed was about the half. When the model was just floating it had turned from the heading 90 degrees to the waves and was instead drifting with the stern towards the waves. Now the drift speed was very low. The drift distance in the laboratory (without wind) was approx. 40 meters corresponding to 1600 meters in full scale. Some tests were carried out with the wind battery working all the time, then the model reached the end of the basin which represented a drift distance of 2200 meters in full scale.

Several tests under the same conditions were carried out to assure the repeatability of the tests. In the final phase of the foundering, when the model had reach a heel angle of 150-160 degrees, see Fig. 16, the aft valve was opened less then one minute to compensate for air compressibility. The ship model sank with stern first and rested with the aft part of the superstructure on the bottom of the basin. The forward part of the ship model with the bulb was now still above the surface, see Fig. 16. In this position the forward valve was opened a few seconds and now also the bow sank. This means that the amount of air ejected from the model was in the order of 8 litres.

The heel angle development during the tests is shown in the figure below.



As mentioned above, the tests were carried out several times to assure that the test result is robust. Very small differences in the behaviour from one test to another were observed. The plot above is intentionally started at the heel angle 25 degrees. Here is the ramp completely open. The SSPA consortium has adopted the possibility that the ramp was partly open before the visor fell off and then completely opened the ramp. Due to practical reasons this was not possible to demonstrate in the laboratory. The initial phase of the foundering could be several minutes, in the laboratory it took only one minute full scale time to go from almost no heel to 25 degrees heel when the ramp opened.

As soon as the model reached a heel angle of about 40 degrees water started to fill the aft rooms Nos. 311, 411, 519, and 611 on tank deck through the ventilation shafts described above which is shown in the video mentioned above. At the same time water flooded deck 4. This explain the relatively slow increase in heel angle until the model reach 90-100 degrees, see Fig. 15. From this point the heel increases rapidly up to about 150 degrees.

5 CONCLUSIONS

The agreement regarding the most probable foundering scenario when the model tests are compared with computer simulation (see [4] to [6]) is quite satisfactory.

From the model tests it is also shown that it is very important to have a full scale like ventilation of the ship for air evacuation and that it is necessary to scale air compressibility. This is an area where further research is required.

6 REFERENCES

[1] The Joint Accident Investigation Commission of Estonia, Finland and Sweden, 'Final report on the capsizing on 28 September 1994 in the Baltic Sea of the ro-ro passenger vessel MV ESTONIA'. Edita Ltd. Helsinki 1997.

[2] Allenström, B., Thorsson, Sune '**MV Estonia,** Manoeuvring tests and Bow Ramp Flooding tests' SSPA report 40064100-1.

[3] Allenström, B. '**MV Estonia,** Bow ramp flooding tests with complete car deck' SSPA report 40064100-2.

[4]Jasionowski, A. "PROTEUS3 Simulations" (preliminary title)

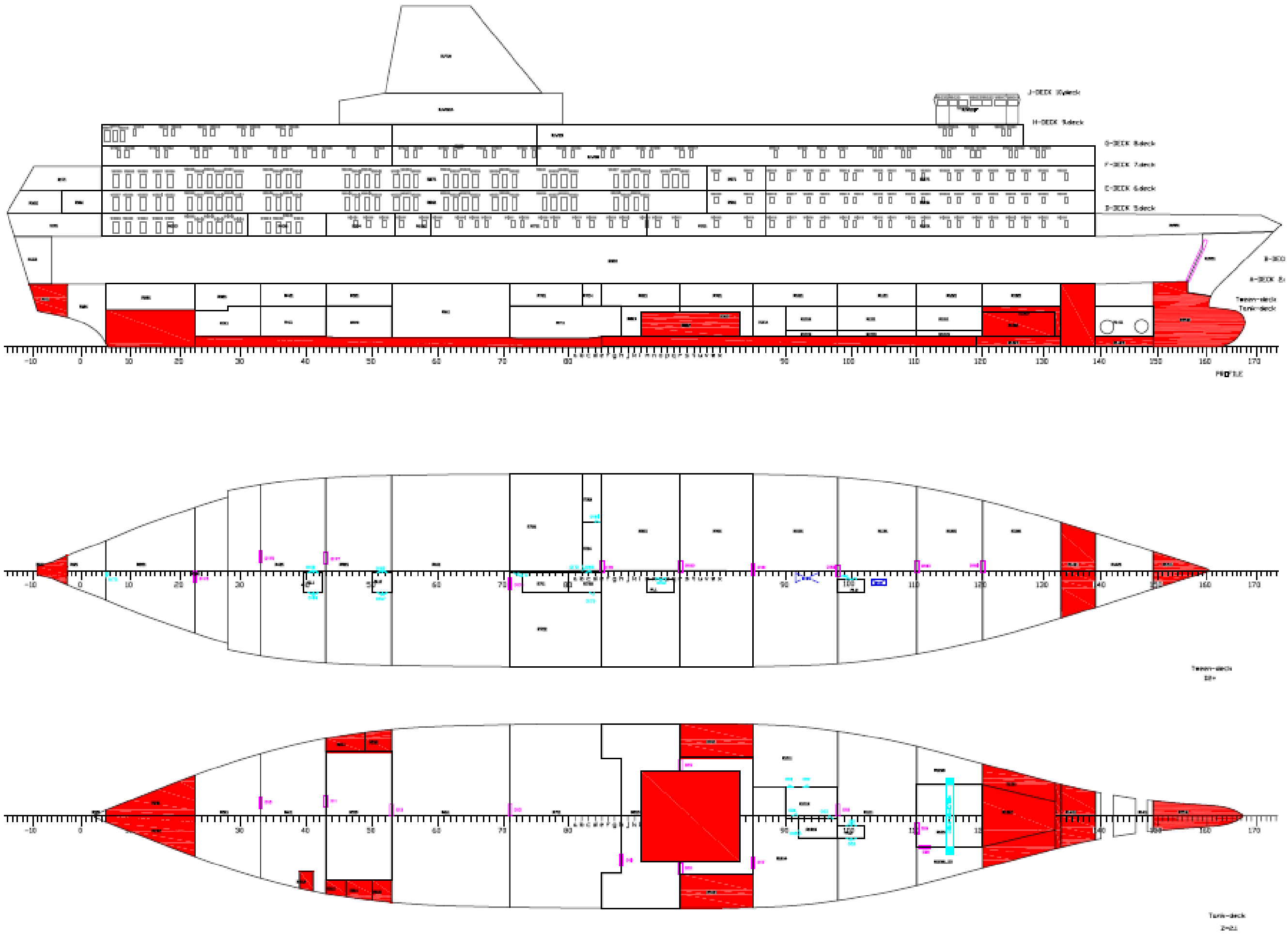
[5] Ottosson, P: "SEAMAN simulations of course of events before foundering", SSPA Report 4006 4100 – 3, April 2008.

[6] Schreuder, M: “WP4.1-4.3 Numerical simulations of foundering scenarios”, Department of Shipping and Marine Technology, Chalmers, Technical Report, April 2008.

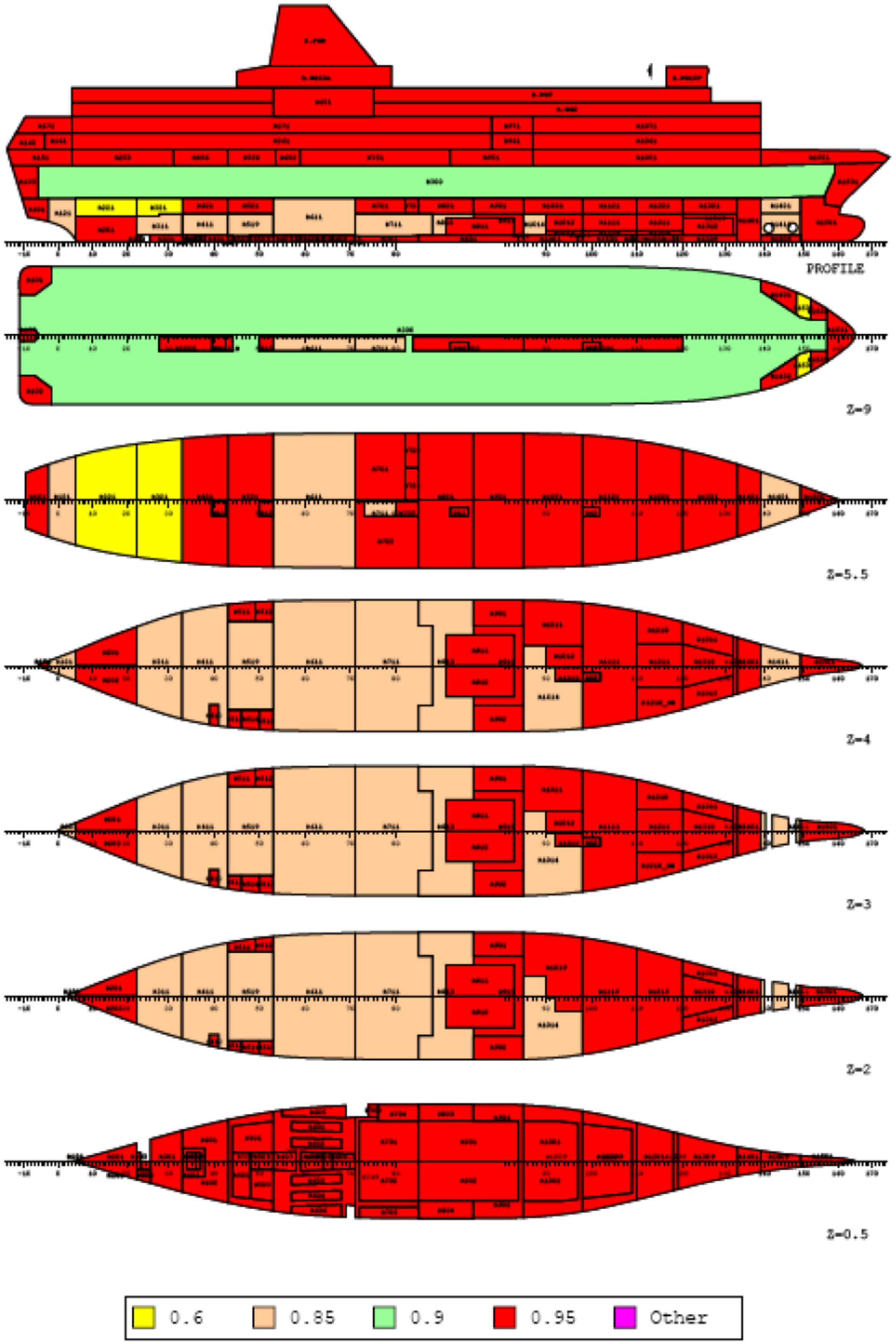
[7] Bergholtz, J, Rutgersson, O, Schreuder, M: “WP2.1 Review of evidence Report No. 2 Conceivable course of events”, Department of Shipping and Marine Technology, Chalmers, Technical Report, March 2008.

[8] Allenström, B, Bergholtz, J, Blok, J J, van Daalen, E F G, Jasionowski, A, Källström, C, Ottosson, P, Rutgersson, O, Schreuder, M, Vassalos, D: ”The sinking sequence of MV Estonia”, SSPA Research Report No. 134, ISBN 91-86532-47-2, ISSN 0282-5805, May 2008.

SSPA	M/S Estonia Ship model 3191-A Void spaces marked red	Figure 1 Report 4006 4100-4



	M/S Estonia Permeability according to IMO	Figure 2
		Report 4006 4100-4



M/S Estonia

Ship model 3191-A

Figure 3	
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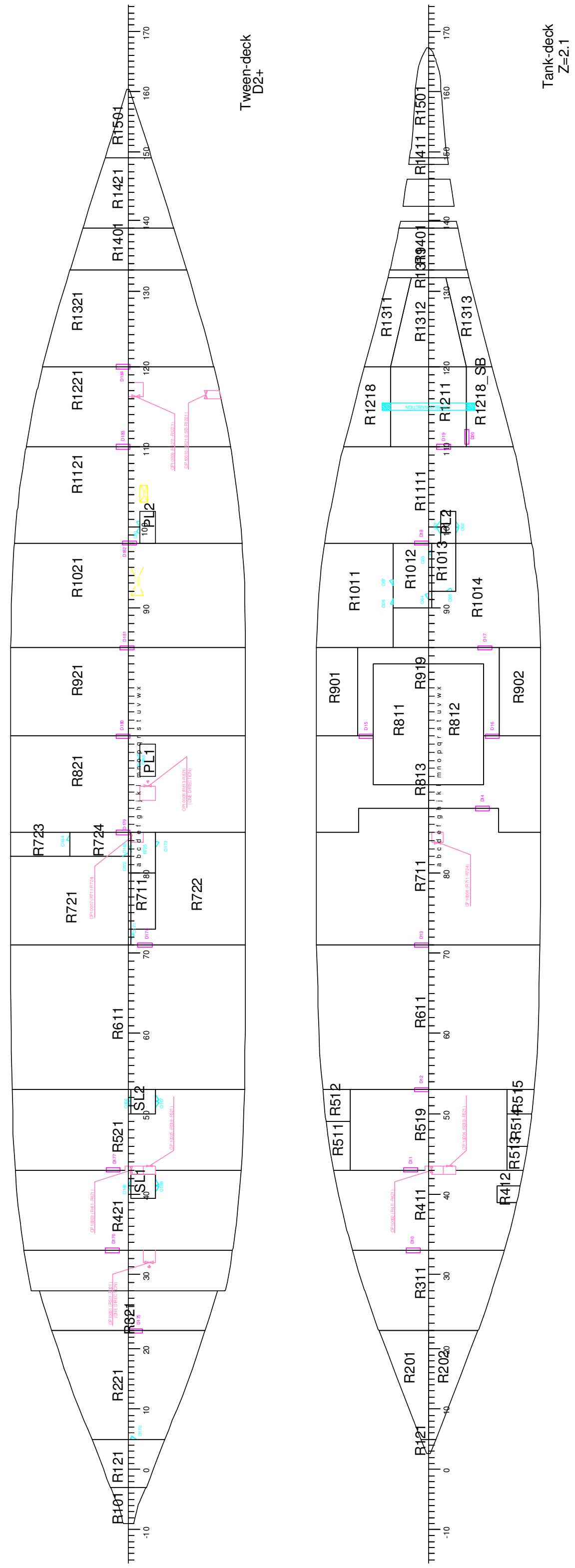
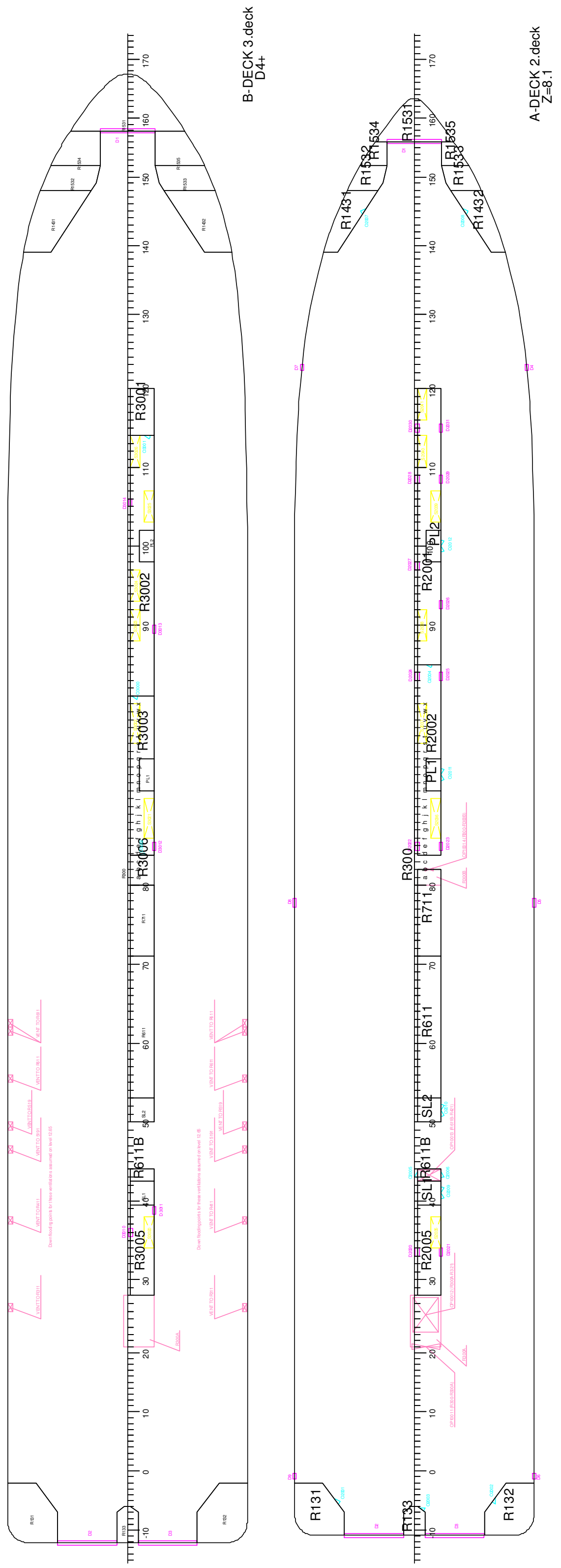
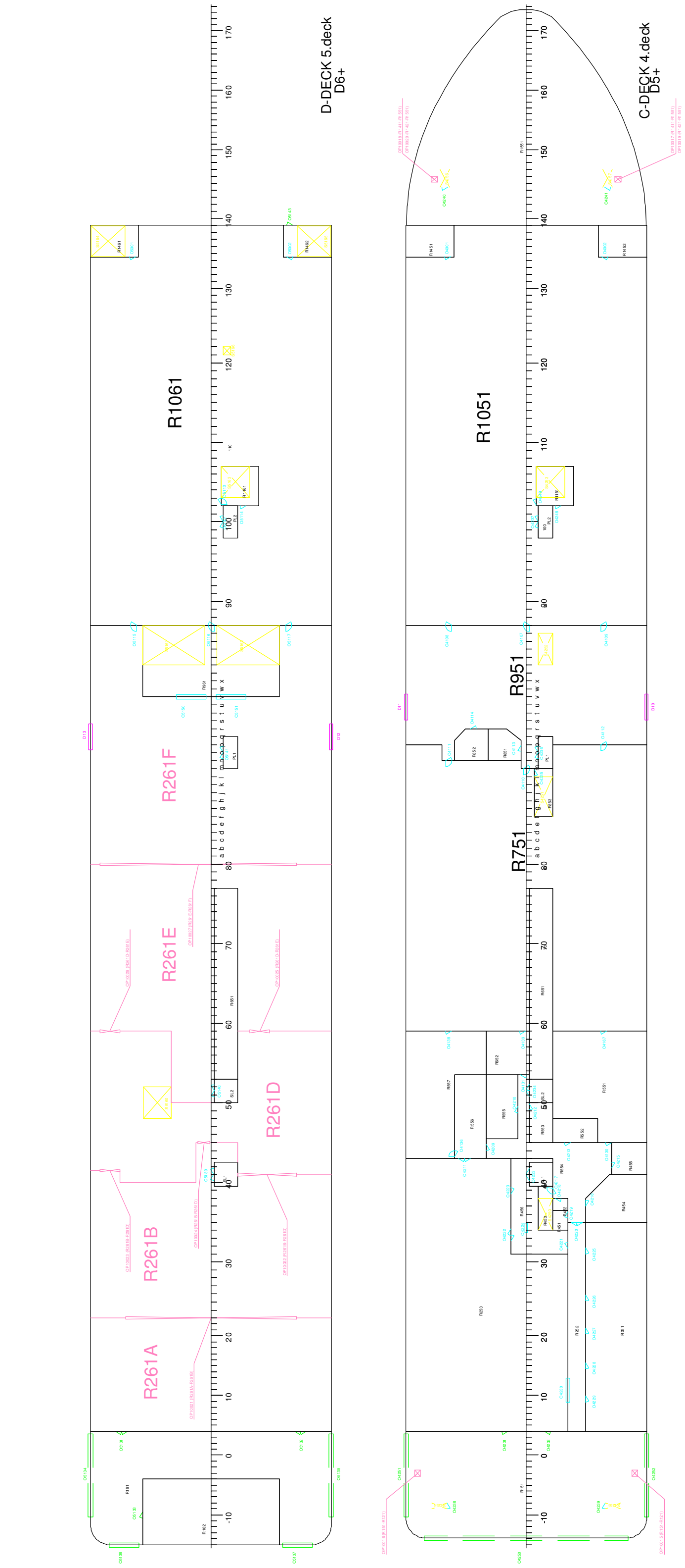


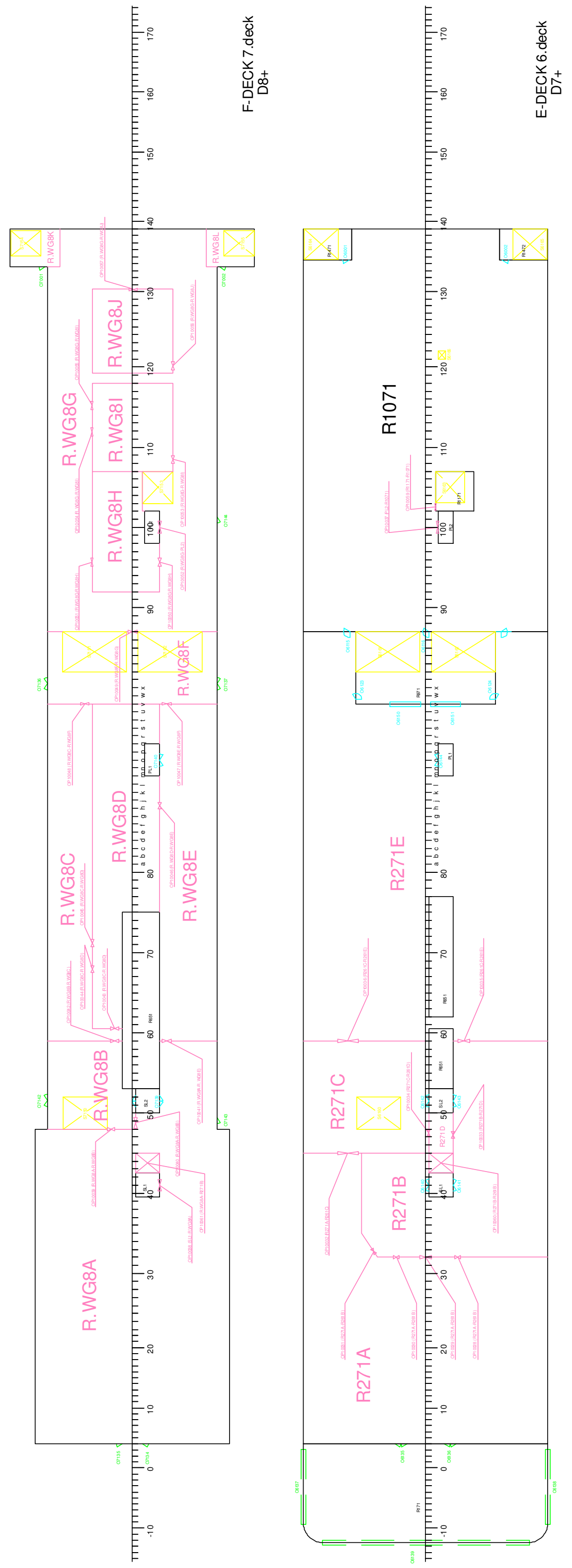
SSPA	M/S Estonia Ship model 3191-A Car deck	Figure 4 Report 4006 4100-4



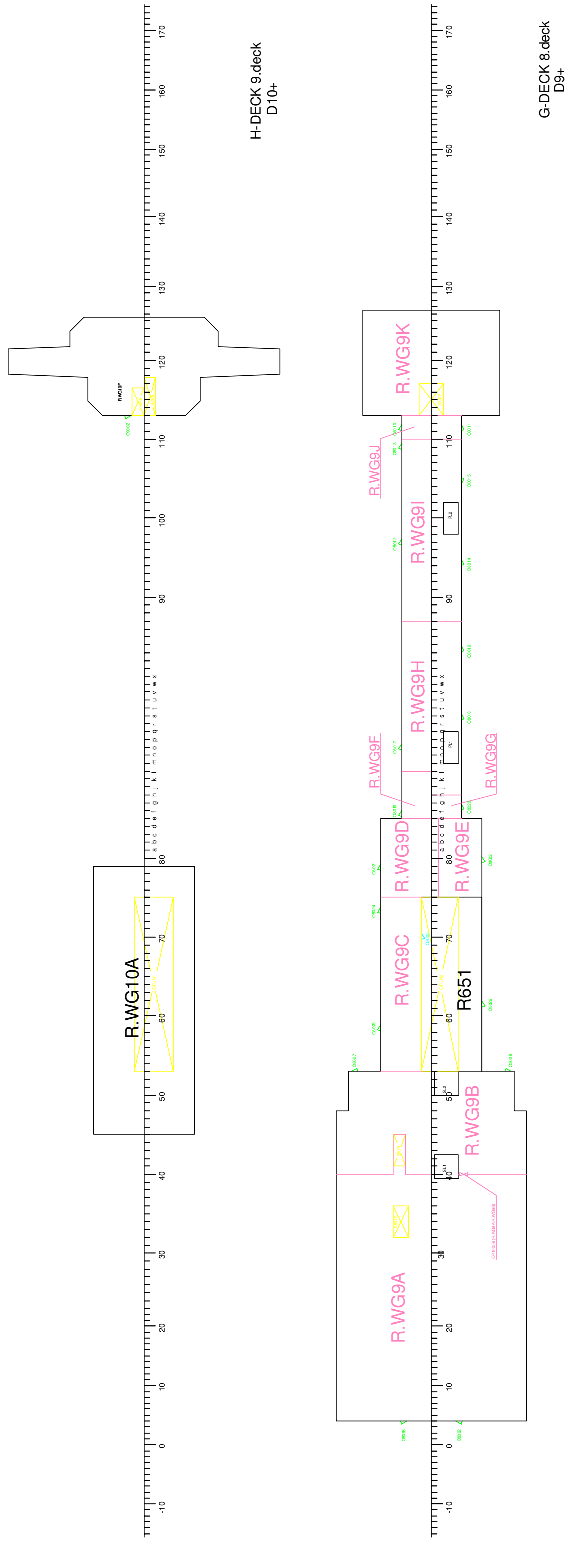
SSPA	**M/S Estonia** Ship model 3191-A Deck 4 and 5	Figure 5 Report 4006 4100-4



	M/S Estonia Ship model 3191-A Deck 6 and 7	Figure 6 Report 4006 4100-4



M/S Estonia Ship model 3191-A Deck 8 and 9	Figure 7 Report 4006 4100-4



M/S Estonia

Ship model 3191-A

Side view

Figure 8

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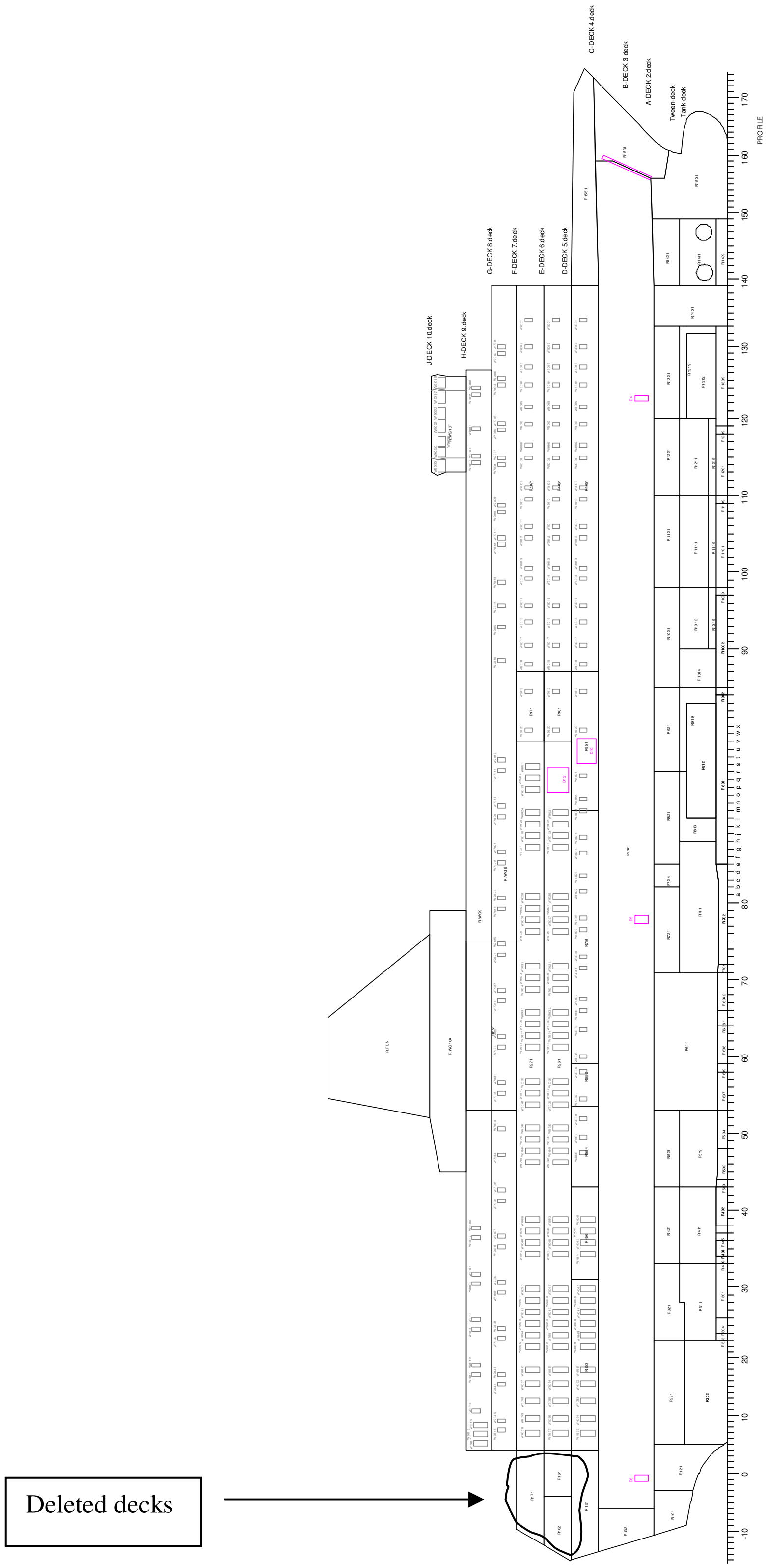

M/S Estonia

Ship model 3191-A

Fore and aft view

Figure 9

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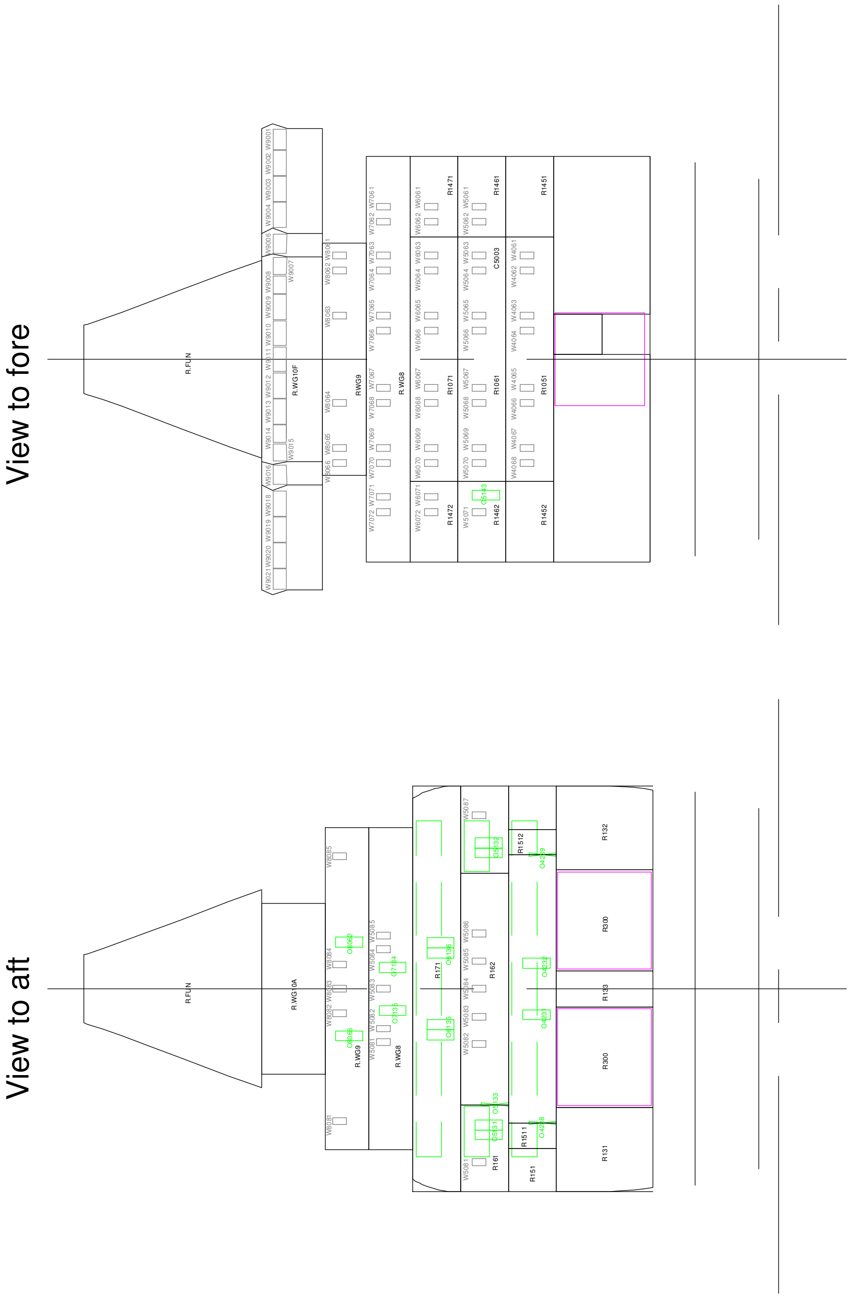
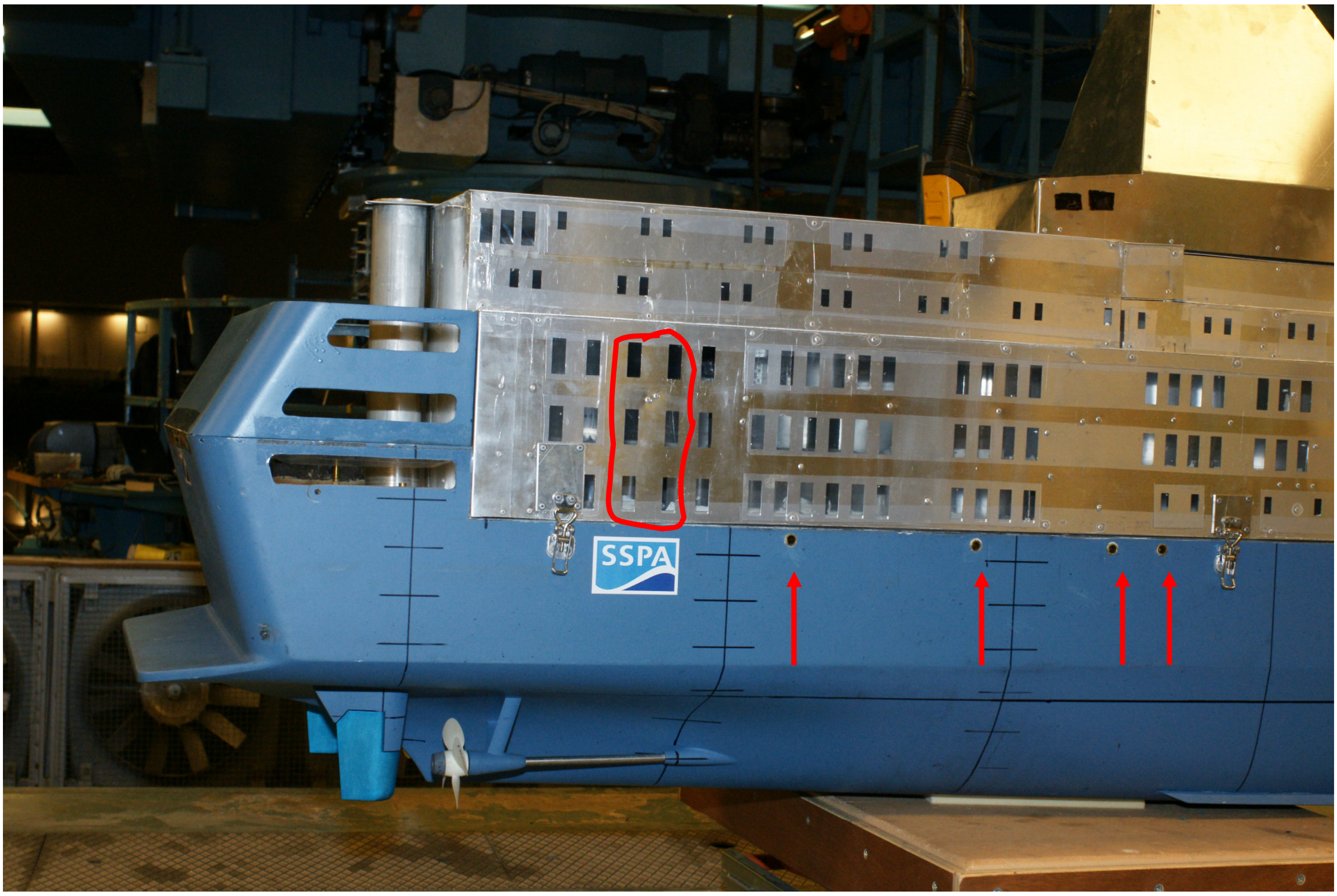
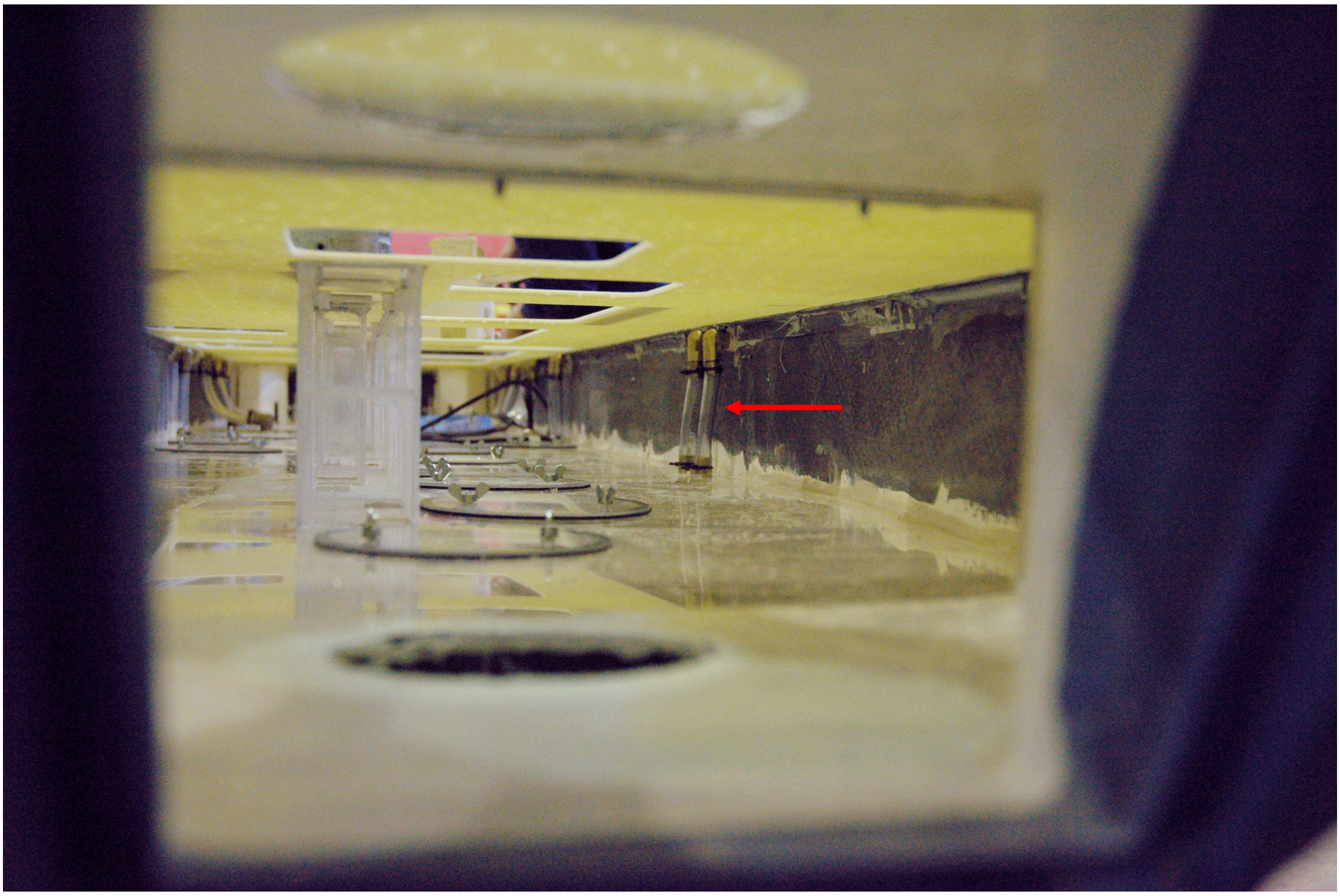


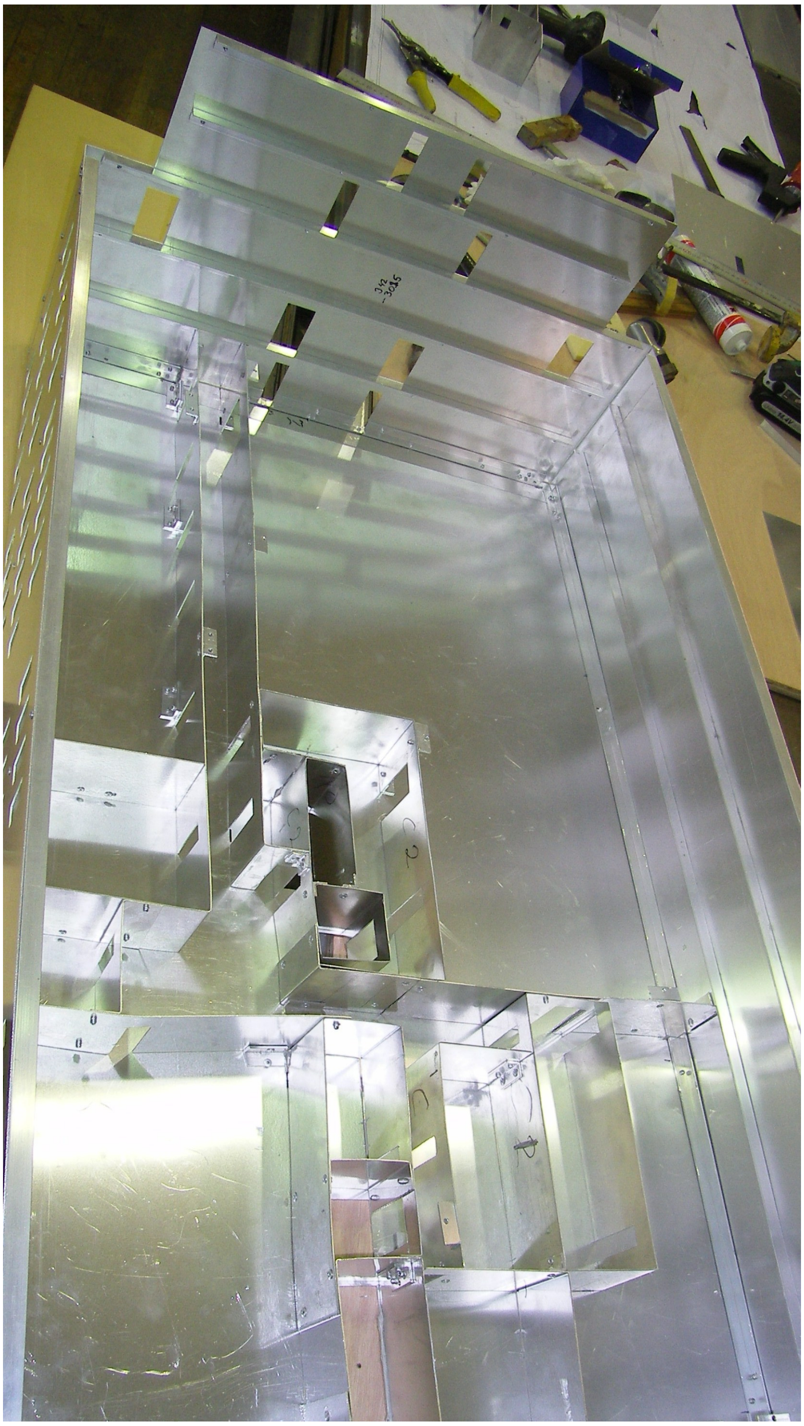
The ship model of MS Estonia. In the background the Maritime Dynamics Laboratory with the wind battery mounted on the carriage.



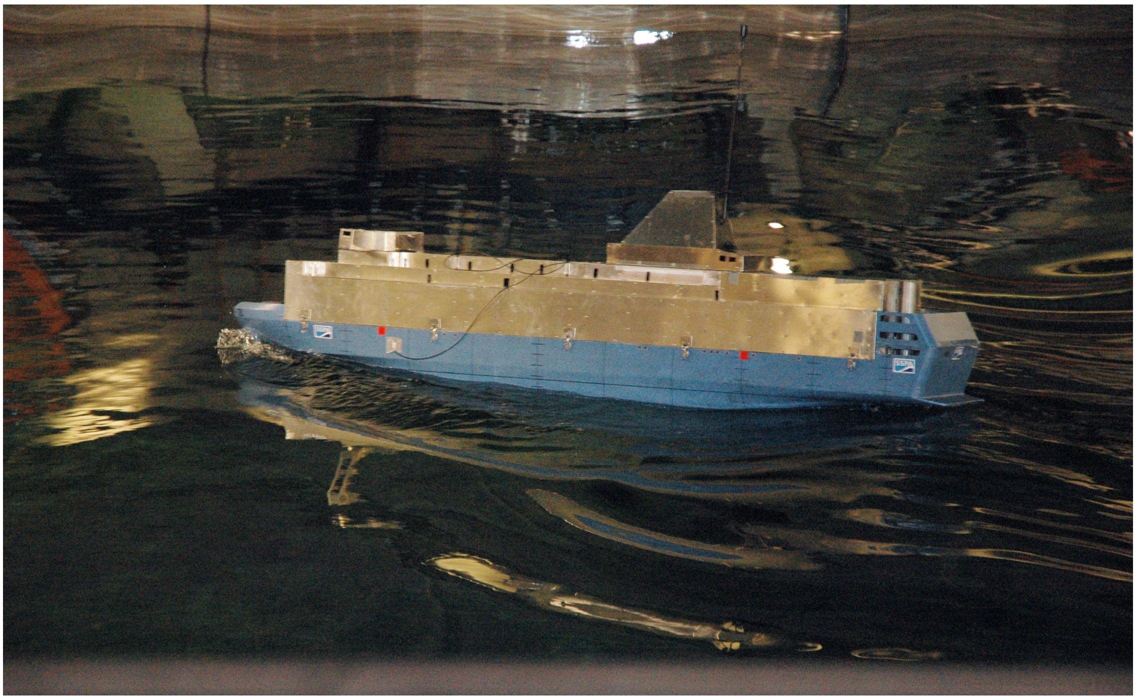
The afterbody of the ship model. The 6 marked windows was the only windows open during the test. The arrows indicates the openings for the ventilation shafts.



Interior of the ship model looking through the bow ramp into the car deck. The center casing in Plexiglas reach up to the 'extra' deck 4 installed. A number of round hatches can be seen on deck 2 (car deck). The ventilation shafts are represented by hoses through the car deck and down to tank deck (arrow).

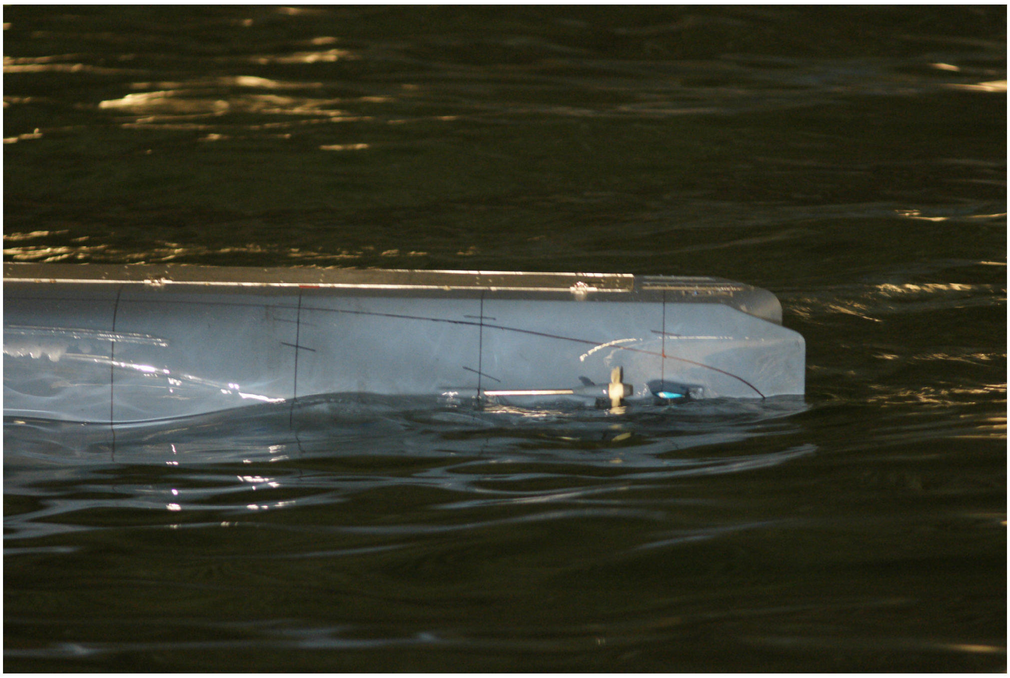


Manufacturing of the superstructure in aluminium. Aft part of deck 4 where water first entered.



Bow ramp has opened and the water floods the car deck giving a heel angle of 25 degrees within 10 seconds (one minuter in full scale)

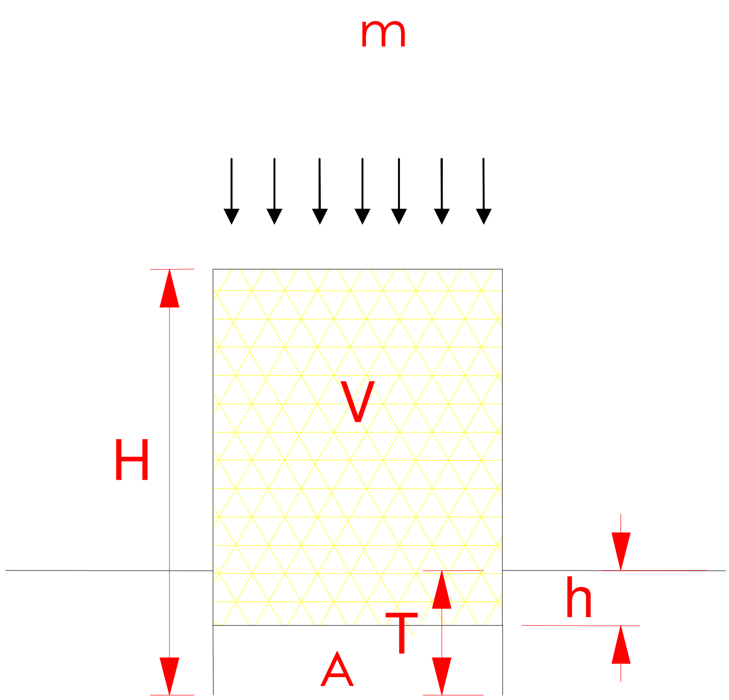
The port turn is almost completed and the heel angle is close to 45 degrees.



The ship model is drifting with a heel angle of 90 degrees. Soon the heel angle rapidly increases to about 150 degrees.

Ship model in heel angle 150-160 degrees. Due to scale effects in air compressibility air was ejected from a calibrated valve at the stern of the model.

Final phase of the foundering. The stern has rested at the bottom of the basin and air is escaping from the car deck. Due to practical reasons the ramp was forced open during the tests, but would have been closed by gravity by now.



Hydrostatic pressure: $p_{surface} = \rho g \Delta h + p_{atm}$ (1)

Air Volume: $V = A(H - T + \Delta h)$ (2)

Initial condition: $p_{atm} HA = p_{surface} V$ (3)

Forces: $F_{boyancy} = \rho g V_{water} = \rho g \Delta h A \qquad F_{gravity} = mg$

$F_{boyancy} = F_{gravity} \quad \Leftrightarrow \Delta h = \frac{m}{\rho A}$ (4)

$$p_{atm} HA = (\rho g \Delta h + p_{atm}) V = (\rho g \Delta h + p_{atm}) A(H - T + \Delta h)$$

$$= \rho g \Delta h A(H - T + \Delta h) + p_{atm} A(H - T + \Delta h)$$

$$0 = \rho g \Delta h A(H - T + \Delta h) + p_{atm} A(\Delta h - T)$$

$$0 = mg(H - T + \frac{m}{\rho A}) + p_{atm}A\left(\frac{m}{\rho A} - T\right)$$

$$p_{atm}AT + mgT = mg(H + \frac{m}{\rho A}) + p_{atm}\frac{m}{\rho}$$

$$T = \frac{mg(H + \frac{m}{\rho A}) + p_{atm}\frac{m}{\rho}}{p_{atm}A + mg}$$

The following numbers are known

m_{model}=186.4kg

A=0.87m^2 (based on geometrical considerations of where air is trapped)

H=V/A=0.0460m

V=40liters (known from the model tests, by releasing and measuring the trapped air volume)

However as the model is already partly submerged, at the time in the sinking sequence of interest (fully capsized and not sinking further), using the full mass of the model is incorrect. As the model displaces water (from walls and non-flooded cavities), the weight of the submerged volume should be used as m.

The weight of the model fully submerged is 28.3kg (measured from model tests without air trapped), therefore the correct weight to use would be between 28.3-186.4kg. The air pressure from the air outlets was measured during static tests ($p_{surface}$=700Pa above atmospheric pressure), which together with (1) and (4) can reveal the actual weight of the model before air is released.

$$m = \frac{Ap_{surface}}{g} = 88.5kg$$

Using the following scaling laws

$m_{full}=\lambda^3 m_{model}$, $H_{full}=\lambda H_{model}$, $A_{full}=\lambda^2 A_{model}$

 can be calculated for both full and model scale with λ=40, where variables in the below equations without subscript refer to model scale.

$$T_{full} = \frac{\lambda^4 mg(H + \frac{m}{\rho A}) + p_{atm}\lambda^3\frac{m}{\rho}}{p_{atm}\lambda^2 A + \lambda^3 mg} = \lambda\frac{\lambda mg(H + \frac{m}{\rho A}) + p_{atm}\frac{m}{\rho}}{p_{atm}A + \lambda mg} \dots$$

$$= \lambda\frac{\lambda \cdot 88.5kg \cdot 9.81\,m/s^2\left(0.046m + \frac{88.5kg}{1025\,kg/m^3 \cdot 0.87m^2}\right) + 1.01 \cdot 10^5\text{Pa} \cdot \frac{88.5kg}{1025\,kg/m^3}}{1.01 \cdot 10^5\text{Pa} \cdot 0.87m^2 + \lambda \cdot 88.5kg \cdot 9.81\,m/s^2}$$

$$= \lambda \cdot 0.1121m$$

$$T = \frac{mg(H + \frac{m}{\rho A}) + p_{atm}\frac{m}{\rho}}{p_{atm}A + mg}$$

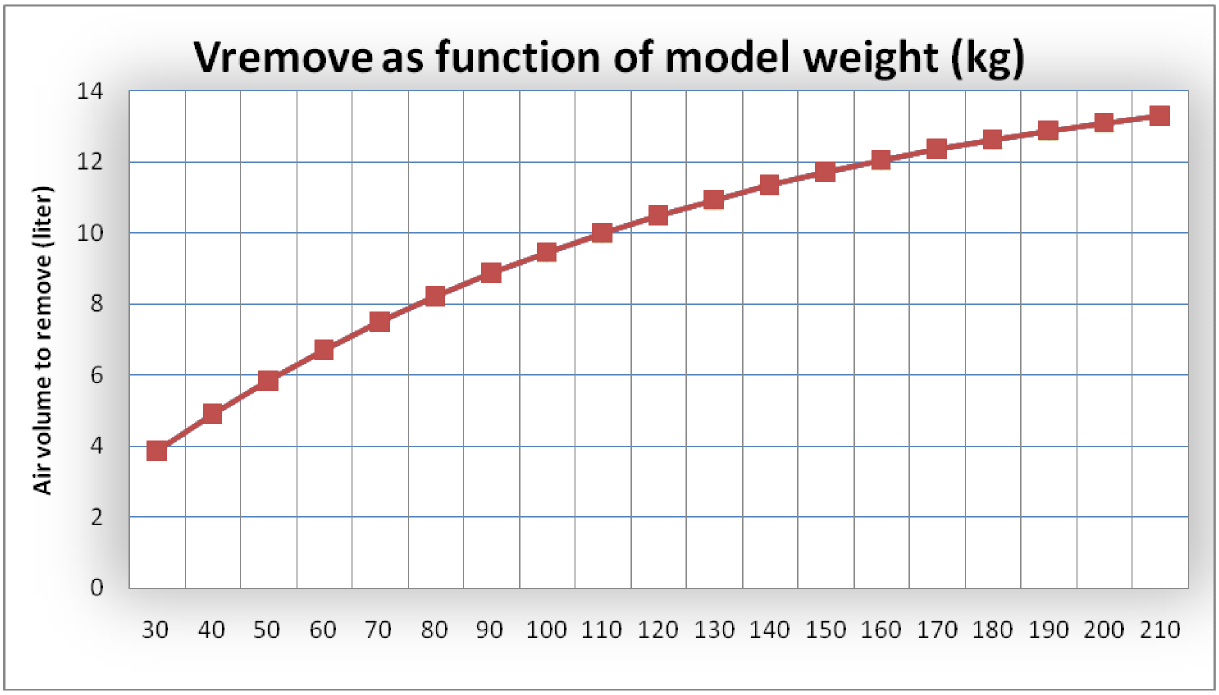
$$= \frac{88.5kg \cdot 9.81\, m/s^2 \left(0.046m + \frac{88.5kg}{1000\, kg/m^3 \cdot 0.87m^2}\right) + 1.01 \cdot 10^5\text{Pa} \cdot \frac{88.5kg}{1000\, kg/m^3}}{1.01 \cdot 10^5\text{Pa} \cdot 0.87m^2 + 88.5kg \cdot 9.81\, m/s^2}$$

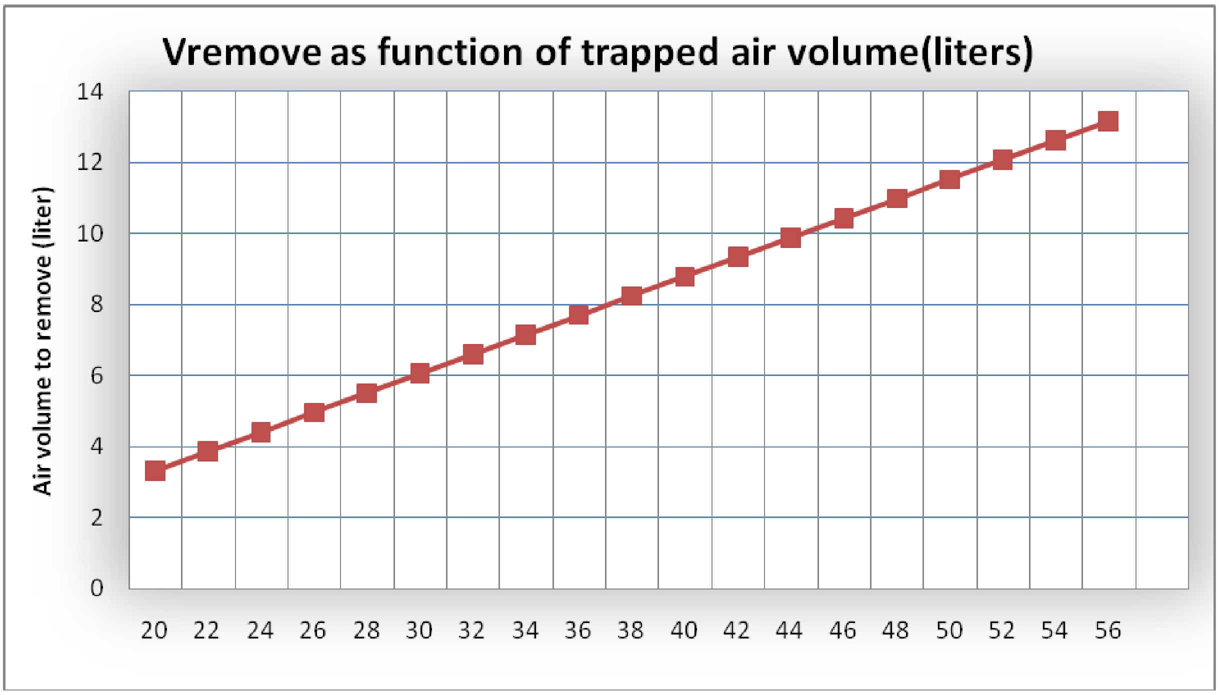
$$= 0.1022m$$

Scale effect to balance is $T_{full} = \lambda T_{scale}$ and the air volume to remove will be

$$V_{remove} = A\left(\frac{T_{full}}{\lambda} - T_{model}\right) = 0.87m^2(0.1122m - 0.1022m) = 8{,}7\text{liter}$$

Below the air volume to remove because of scale effects in compressibility is shown as a function of trapped air volume and the weight of the capsized model. This is to illustrate that even though the weight of the capsized model and the trapped air volume is not known exactly, the change in air volume to remove is not very large (m should be known within a few kilograms because of the pressure measurement, trapped air volume was measured to be between 35-45 liters between different tests).





Vremove as function of trapped air volume(liters)
Air volume to remove (liter)
0
2
4
6
8
10
12
14
20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54 56