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ESTONIA
A III

PART-REPORT

covering technical issues
on the capsizing on 28 September 1994
in the Baltic Sea
of the ro-ro passenger vessel

MV ESTONIA

The Joint Accident Investigation Commission
of Estonia, Finland and Sweden

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The Government of the Republic of
Estonia

Part-Report on the ESTONIA Disaster of 28 September 1994

Pursuant to an agreement concluded between Estonia, Finland and Sweden a "Joint Accident Investigation Commission" for the investigation of the capsizing of the passenger vessel ESTONIA on 28 September 1994 was set up on 29 September 1994. The Commission consists of three members from each state and is chaired by one of the Estonian members. Each state has appointed experts to assist the Commission.

This part-report covers main technical findings and conclusions. The final report to be issued later will also cover all other factors and circumstances contributing to the accident. The report is unanimous on all points.

for Estonia	**for Finland**	**for Sweden**
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Identical letters to:

The Council of State of the Republic of Finland
The Government of the Kingdom of Sweden

PART- REPORT

covering technical issues on
the capsizing on 28 September 1994 in the Baltic Sea
of the ro-ro passenger vessel

MV ESTONIA

The Joint Accident Investigation Commission

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In case of discrepancies between the Estonian, Finnish, Swedish and English texts, the English text is to be considered the authoritative version.

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Preface

Shortly before 2 a.m. on 28 September 1994 the Estonian ro-ro passenger vessel ESTONIA capsized and sank in the Baltic Sea whilst on a scheduled passage from Tallinn to Stockholm. A large number of lives were lost.

The accident is being investigated by a joint Estonian/Finnish/Swedish commission.

The Commission has previously concluded that the accident was initiated by the locking devices for the bow visor being unable to withstand the loads imposed during the prevailing speed, heading and sea conditions. This conclusion is still valid.

This part-report covers main technical findings and conclusions. The final report to be issued later will cover also all other factors and circumstances found to have contributed to the development of the accident. This will include inter alia operational practices, certification and inspections, stability information, weather conditions and training. Rescue operations and resources will be covered as well.

The content of the current part-report may be amended and editorially modified as part of the final report but it is anticipated that all facts and conclusions reported herein will remain unchanged in substance.

The Commission consists of the members and appointed experts listed on the opposite page.

Note

The present part report must be read with its restricted scope in mind and no conclusions about the causes of the accident should be drawn before the final report is available.

1. If not otherwise stated all times in the report are given in Estonian time = UTC + 2 hrs.

2. Weight (mass) and forces are in this report given in metric tons rather than SI-units.

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1 Introduction and Summary

1.1 Introduction

The Estonian-flagged ro-ro passenger vessel ESTONIA capsized and sank shortly before 2 a.m.on 28 September 1994 whilst on a scheduled voyage from Tallinn to Stockholm. The vessel had, according to available information, 989 passengers and crew members on board. 137 persons survived the accident.

The accident is being investigated by a joint Estonian/Finnish/ Swedish Commission, set up in accordance with a decision taken on 28 September 1994 at Turku by the prime ministers of the three countries. Under Estonian chairmanship the Commission has nine regular members, three from each country. Experts have been assigned to the Commission to ensure competence in all areas.

The present report is a part-report, covering the findings, conclusions and recommendations of the Commission regarding the technical causes and development of the accident. The final report will also cover all other factors and circumstances contributing to the development of the accident, including weather conditions, certification and inspections, stability information, operational practices, training and rescue operations and resources. It will also describe affected institutional organizations.

Several investigations by appropriate independent institutions have been initiated during the work. They include inter alia analysis of the weather and sea conditions, the wave induced motion of the ship, calculation of hydrodynamic forces in the bow area, metallurgical investigation of fractured surfaces from failed parts and investigation of an hydraulic actuator.

In reading this part-report it must be noted that the causes and conclusions quoted herein relate only to technical matters and do not describe or explain the full sequence of events nor any operational issues related to the accident.

1.2 The Vessel

The vessel was a ro-ro passenger ferry, built as yard newbuilding number 590 by Jos. L Meyer Werft of Papenburg in Germany for the Finnish ferry company Rederi AB Sally. She was delivered on 20 June 1980 under the name of VIKING SALLY and was put into service on the route between the port of Stockholm in Sweden and the ports of Mariehamn and Turku in Finland. After the Sally company merged with Effjohn Oy, the vessel was operated from April 1990 as SILJA STAR between Stockholm and Turku and from January 1991 as WASA KING on the routes between Vaasa and Umeå/Sundsvall in the Gulf of Bothnia.

The vessel was the second largest passenger ferry in the Baltic Sea in those days and was one of the first "jumbo" size ferries. A general arrangement drawing of the vessel is shown in Figure 1.

The vessel was acquired on 15 January 1993 by Estline Marine Co Ltd and was bareboat chartered to the Estonian company E-line Ltd. It was put into the service of Estline between Tallinn and Stockholm under the name of ESTONIA. The operations were conducted by Estonian Shipping Company Ltd under a management contract. The companies E-line Ltd and Estline were owned equally by the state owned Estonian Shipping Company Ltd and by the Swedish shipping company Nordström & Thulin AB. Technical management was subcontracted to Nordström & Thulin AB.

The vessel was built after a similar newbuilding, DIANA II, delivered to the Swedish shipping company Rederi AB Slite. The ESTONIA was longer by an extra midship section but the bow and stern areas were identical in the two vessels except for the length of the bulbous bow which was increased by 0.8 metres in the ESTONIA. Both ships were built to the rules of the classification society Bureau Veritas rules with class notation +I 3/3 E, Deep Sea, Ice IA, Car/Passenger Ferry + (AUT). The ESTONIA was modified in 1985 when the aft part of the hull below the waterline was rebuilt to increase buoyancy and stability.

Upon delivery from the yard the vessel was issued a Passenger Ship Safety Certificate in compliance with the Safety of Life at Sea (SOLAS) convention by the Finnish Authorities. The vessel was certified for short international voyages. The permitted number of passengers was linked to a note referring to short international voyages between Sweden and Finland (this note was introduced since certain life saving equipment complied with the 1974 issue of the SOLAS convention, not yet in force at the time, rather than the 1960 SOLAS convention). The vessel was under the statutory supervision of the Finnish Board of Navigation from the time of construction up to 14 January 1993. The administration had authorized Bureau Veritas to perform the related hull surveys and inspections. It was under Estonian supervision from 15 January 1993 to the time of the accident. The Estonian Board of Navigation had authorized Bureau Veritas to perform the statutory functions under the SOLAS and other international conventions.

The vessel had the following main particulars:

Length, over all 155.40 m	Propulsion power 17,600 kW
Length, between perpendiculars 137.40 m	Deadweight 3230 tons
Breadth, moulded 24.20 m	Light weight 9733 tons
Depth to bulkhead deck, moulded 7.65 m	Gross tonnage 15,598
Maximum draft 5.60 m	Max. number of passengers 2000
Number of decks 8	Max. service speed 21 knots

1.3 The Voyage

This section contains a brief summary of the voyage ending with the accident. A more detailed description of the voyage and analysis of operational and other aspects and the rescue operations will be given in the final report.

The vessel was on scheduled service between Tallinn and Stockholm with departure from Tallinn every second evening at 1900 hrs local time and arrival in Stockholm the following morning at 0900 hrs local time. The vessel departed from Stockholm on the same evening for arrival the following morning to Tallinn. The scheduled duration of the westbound voyage was 15 hours.

The vessel departed at 1915 hrs on 27 September 1994, carrying 803 passengers, 186 crew members and a load on car deck consisting, according to customs documentation, of 38 lorries and trailers, 25 trucks, 11 vans and 26 passenger cars with a combined weight of about 1000 tons. The lorries and trucks were loaded aft and the vessel had a departure trim of about half a metre by the stern. The vessel had one degree of starboard list at departure and the port ballast tank was full.

When the ESTONIA left Tallinn the wind was southerly, 8–10 m/s. Visibility was good, with rainshowers. As the voyage continued the wind increased gradually and veered to south-west. At midnight the weather conditions were wind south-west 15–20 m/s with a significant wave height of 3.5–4.5 metres. Visibility was generally more than 10 nautical miles.

The weather forcast for the midnight hours as received by the vessel predicted southwesterly wind, veering to west, velocity 15–20 m/s, increasing towards the morning, significant wave height 2.5–3.5 m.

The voyage proceeded as normal with moderate sea conditions and a heading of 262° along the Estonian coast. All four engines were operated at normal cruise power. The vessel turned at about 0030 hrs at a waypoint located about 59°20'N and 22°02'E to heading 287° for the continued passage to the Söderarm entrance to the Stockholm archipelago.

The sea conditions grew more severe as the vessel left the sheltered water along the Estonian coast. Speed was around 14.5 knots with some rolling and moderate to occasionally heavy pitching. The stabilizing fins had been activated when passing the waypoint. At about 0045 hrs the first indications of something abnormal were noted by several witnesses. Metallic sounds were heard in the vessel.

The engineer in the engine control room has stated that he later on – probably at about 0115 hrs – observed on the TV monitor that water was coming in at the sides of the forward ramp which appeared to be in closed position. Somewhat later again more severe metallic impact noises were heard and shortly thereafter the ship started to roll more severely, developing a starboard list.

Subsequently the bow visor separated from the bow and tilted forward over the stem. The forward ramp was pulled open by the visor due to mechanical interference and was finally fully opened, allowing large amounts of water to enter the car deck.

As the list increased passengers started to rush up the staircases and panic developed at many places. People who managed to get onto the boat deck received life jackets. Many passengers who had gone to sleep were trapped in their cabins and had no chance of getting out in time.

As the list increased to about 30 degrees the main engines tripped due to lack of lubricating oil pressure. The generator units stopped somewhat later and the emergency generator started automatically, supplying power to limited lights in public areas and on deck.

MAYDAY emergency signals were received at 0124 hrs by eleven shore and ship based radio stations in the area, including the MRCC station at Turku.

The vessel continued to heel over and the accomodation decks started to take on water at about 0130 hrs. Flooding of the accomodation continued with considerable speed and the starboard side of the bridge was submerged at about 0135 hrs as indicated by the chart room clock which had stopped at this moment. The list was at this stage more than 90 degrees.

Passengers who had managed to reach the boat deck and the outer side of the ship jumped or were swept into the water. Life rafts had been released or were released automatically as they became submerged and some people managed to get into them. The weather was severe during the night and caused additional loss of life. A total of 94 victims were collected from rafts and from the water in the area. A total of 137 survivors were picked up by helicopters and assisting ships during the night and the early morning hours.

The vessel made a port turn whilst the starboard list was developing. It has not been possible to ascertain what action was taken on the bridge at this stage. The ship lost propulsion and drifted, lying across the seas, whilst flooding continued. It sank completely at 0148 hrs when the last visible indication disappeared from the radar screen of a Finnish radar station. The position at the sinking was N59°22'.9, E21°41'.0. The wreck had turned to a heading of 95 degrees as she went down. The bow visor was later traced about one nautical mile west of the wreck.

A review has shown that weather conditions comparable to those during the night of the accident had occurred only once or twice before while the vessel was sailing from Tallinn to Stockholm.

2 Summary of Facts and Findings

2.1 Description of Affected Installations

2.1.1 The Bow Visor and Ramp Installation

This section describes the bow visor and ramp installation. The background and circumstances related to the location of the ramp are covered separately in Section 2.5.

The bow visor and ramp installation of the ESTONIA was of a configuration common at the time of building. The installation comprised an upward-opening bow visor and a loading ramp, hinged at main deck level and being closed in a raised position. In closed position the upper end of the ramp extended into a box-like structure on the deck of the visor.

The specific components related to the bow visor and ramp installations had been designed and supplied by von Tell AB, one of the established makers of such systems. The system included the complete ramp with hinges, operating and locking devices and the operating and locking devices for the bow visor as well as the hydraulic operation and control system for the complete installation. The incorporation of the system into the ship was shipyard design and installation work.

The general arrangement of the ramp and visor installation is shown in Figure 2.

2.1.1.1 The visor

The visor was the most forward part of the vessel's hull and was a steel structure similar to the normal bow structure of a vessel. The general shape and design is shown in Figure 3. The hull form had considerable flare in the bow area, typical for ro-ro vessels built at the time. The visor consisted mainly of the shell plating, being an extension of the ship's shell plating and contour, the deck part, the bottom part, the aft bulkhead and internal horizontal stringers, vertical partial bulkheads and transverse stiffeners. Two beams on deck extended aft of the visor aft end and carried the hinge arrangements for the pivoting points of the visor. The visor weighed about 55 tons.

The deck of the visor had a box-like housing between the two beams, enclosing the upper part of the ramp when the ramp was in closed position. The geometry was such that the ramp had to be in the fully closed position in order not to interfere with the visor during its opening and closing movement.

The visor pivoted around the two hinges on upper deck during its normal opening and closing movement. It was secured in the closed position by three hydraulically operated locking devices at its lower part. One of these was mounted on the forepeak deck and the other two on the aft side of the visor with mating parts in the hull front bulkhead. Additionally, two mechanical locking devices were located in the area of the hydraulic side locks. Three locating horns, one on the forepeak deck and two on the front bulkhead engaged recesses in the visor to absorbe lateral loads.

The visor was supported vertically in the closed position by the two deck hinges and further rested on three points on the forepeak deck. One of these was the solid stem post of the visor, resting on the ice-breaking stem on top of the bulbous bow, the other two were steel pads on the forepeak deck. The three locking devices kept the visor down in its closed position and the locating horns absorbed any side loads that might develop. Longitudinal loads were borne by the hinges and the locking devices and possibly by direct contact between the visor and the front bulkhead of the hull.

The visor was supported in open position by the two hinges and two parking devices, consisting of hydraulically operated bolts engaging lugs on the hinge beams.

Rubber seals supported by steel flat bars were installed on the forepeak deck and the front bulkhead, together making a continuous seal against which the visor abutted when closed.

The visor could not be seen from the bridge due to the protruding forward superstructure. The top of the bow flag pole could, however, be seen.

2.1.1.2 The bottom lock

The bottom locking arrangement is shown in Figure 4. It was sometimes called the "Atlantic lock" as it was not in common use in early ferries but was later introduced to enable similar ferries to cross open oceans. The "Atlantic lock" had become established by the time the ESTONIA was built. The locking device consisted of a locking bolt, movable horizontally in a transverse direction, guided in a bolt housing. In extended position the tip of the bolt engaged a support bushing. The bolt housing was fixed to the forepeak deck by means of two steel lugs and the bushing was installed in a third similar lug. A mating lug, attached to the visor itself, was located between the bolt housing and the support bushing when the visor was in the closed position and the extended bolt then engaged the hole in the mating lug.

Some overall dimensions of the lugs were given on an assembly drawing issued by the supplier of the locking devices but no manufacturing drawing seems to have existed.

The bolt was moved in the bolt housing between the retracted position and the extended position by means of a hydraulic actuator, operated from the control panel for the visor and the ramp as described in subparagraph 2.1.1.7. A spring-loaded mechanical plunger, perpendicular to the bolt, engaged grooves in the bolt in the open and closed position, respectively, thereby securing the bolt mechanically in its extreme positions, regardless of hydraulic pressure. The bolt was also locked hydraulically at any time because the hydraulic fluid was trapped in the system, regardless of whether the hydraulic system was under pressure or not.

Two magnetic-type limit switches were installed, being actuated by a magnet attached to the bolt. The switches were actuated when the bolt was in fully retracted position and fully extended position respectively. The hydraulic control system as well as the arrangement and functioning of the switches and the position indication and alarm system are covered separately in subparagraph 2.1.1.7. The mechanical switches of the original design had been replaced by the magnetic ones at an earlier stage in the history of the vessel.

The mating lug in the bottom structure of the visor consisted of a single steel lug, welded to a transverse beam of the visor bottom structure and supported by a bracket as shown in Figure 5. The lug had a hole for the locking bolt with an original diameter of 85 millimetres. The diameter of the hole had increased in service and after the accident the hole was oval with dimensions about 90 x 105 millimetres. The elongation may have been caused by wear or by yielding during the failure of the locking device.

The failure mode of the bottom lock installation and related findings are covered in paragraph 3.1.2.

2.1.1.3 The side locks

The side locks consisted of two lugs, mounted to the aft bulkhead of the visor and extending, when the visor was closed, into two recesses in the front bulkhead of the hull, one at each side of the ramp opening. In the closed position hydraulically operated bolts engaged holes in the visor lugs. The arrangement is shown in Figure 6. The hydraulic bolt installations were similar to that of the bottom lock, i.e. a bolt moving in a bolt housing and, when extended, engaging a support bushing. The visor lug inserted between the bolt housing and the support bushing. The bolt was moved by an hydraulic actuator. A mechanical friction plunger was installed. The position of the bolt, fully retracted and fully extended, was sensed by magnetic-type limit switches.

Additional hydraulic cylinders were installed at each side to push in a forward direction on the visor lugs when the visor was to open. This installation was intended to assist in breaking the visor open in case it had become stuck in the closed position due to icing.

The installation of the visor side lugs is shown in Figure 7. It has been noted by the Commission that no detailed drawing existed for these lugs and that their actual length along the attachment area to the visor was shorter than that indicated on general arrangement drawings for the locking installation. The lugs were welded to the aft side of the visor aft bulkhead with fillet welds. No welding details were given on any drawing.

Two vertical stiffeners were installed on the front side of the plating, separated by a distance slightly larger than the thickness of the lug itself.

These stiffeners were installed to satisfy a Bureau Veritas surveyor's requirement for "local reinforcement of the ship's structure by way of locking devices". No other arrangements were made in the design to transmit the forces from the lugs into the structure of the visor.

2.1.1.4 Manual visor locks

Two manual locks were installed, one at each side and mounted just below the hydraulic side locks. Each lock consisted of two lugs welded to the aft side of the visor and a hinged eye bolt with nut, mounted between two lugs in the front bulkhead. In closed position the eye bolt was swung into position between the two lugs in the visor and the nut was tightened down. The arrangement is shown in Figure 8. The locks had no remote position indicating devices.

The manual lock was described in the supplier's instructions booklet as "reserve". No advice was given anywhere in instructions by the maker, the shipyard or operators as to the use of these manual locks.

2.1.1.5 The deck hinges

The two beams on the deck of the visor extended about 3 metres aft of the aft edge of the visor deck. The ends of the beams carried the hinge arrangements. The hinge arrangement is shown in Figure 9. A heavy steel bushing was welded into a hole in each of the two side plates of each beam. The bushings had a bore, carrying a bronze bushing. The deck part of the hinge consisted of two lugs welded to the deck, carrying between them a steel housing. This deck part was located, in the installed arrangement, between the two bushings of a visor beam. A shaft was installed through the entire assembly, secured by locking plates bolted to the outer ends of the hinge bushings.

2.1.1.6 The loading ramp

The ramp was a steel design with four longitudinal beams and a number of transverse beams. A steel plate made up the upper surface of the ramp. Additional stiffeners were arranged between the main beams.

The ramp was longer than the available deck height and therefore protruded by about 1.5 metres above the level of the upper deck when in the raised, i.e. closed, position. This extension was enclosed in the box-like housing on the visor deck. Flaps at the tip of the ramp were hinged along the front end of the ramp and were controlled by means of steel cables to extend when the ramp was lowered. The cables were engaged on bellcranks at the ends of the flap axis. When the ramp was closed these flaps hung down to keep its total length as short as possible.

The ramp was hinged at its aft end to the hull structure by four hinges. Each hinge consisted of steel lugs welded to the hull and lugs welded to the aft beam of the ramp. Bushings and hinge pins made up the complete hinge installation. The outer hinges were heavier than the two inner ones.

Raised bars were welded onto the sides of the ramp. Fixed railings were mounted on each side.

The ramp was manoeuvered by two hydraulic actuators, one at each side. When in the raised, closed, position the ramp was pulled in by two locking hooks, engaging pins in the side beams of the ramp. These hooks were hydraulically operated via a lever mechanism arranged to move past its dead centre during the locking movement and stay in this mechanically secured position.

Two additional locking bolts were mounted along each side of the ramp. These were hydraulically operated, moving transversely in the ramp coaming. In the extended position they engaged box-like extensions on the ramp side bars.

All the locking devices had limit switches for their retracted and extended positions as described separately in subparagraph 2.1.1.7.

A rubber seal, supported by steel flat bars, was arranged in the ramp coaming and made up a weathertight seal against the surface of the ramp when the ramp was in the closed position.

2.1.1.7 Visor and ramp control system

A control system served the ramp and visor installation. The system was supplied by the maker of the ramp and visor actuating systems. It was described in an instruction booklet, issued by the supplier.

The control system consisted of a high-pressure hydraulic system with tank and two pumps plus the normal components of a hydraulic power system, providing hydraulic power to a control panel and to the operating and locking devices of the visor and the ramp. The control panel was mounted on the port side just inside the ramp. It contained manual control levers for separately operating:

- the visor bottom lock
- the visor side locks
- the ramp pull-in hooks and locking bolts
- the visor opening/closing
- the open visor parking plungers
- the ramp opening/closing.

There was no hydraulic or electric interlock between the devices, the indicator lamps being monitored by the operator for proper function of each step during opening or closing, before the next step was activated.

The indicator lamps were mounted on a panel located at the operating station and a second panel was installed on the bridge, in the front panel to the right of the seat of the Officer of the Watch.

The panels had red and green lights, powered via the limit switches on the actuators for the visor and ramp locking devices. Position switches were also installed to sense fully-closed ramp and fully-closed visor. Lights for the visor and the ramp were green only when the visor or the ramp, respectively, was fully closed, otherwise they were red. The lights for the locking devices were wired to be red when the locks were in the fully

retracted position and green when they were fully extended, locked. The bottom lock had a separate set of lights, the side locks one set of lights and the ramp locks one set of lights. The position switches for the side locks and for the ramp locks, respectively, were wired in series so that all the devices had to be in the correct end position before the relevant light came on. If one device was in an intermediate position no light would be on.

TV cameras were installed for monitoring the car deck. One of these monitored the forward ramp area. Display screens were installed in the engine control room and in the chart room on the bridge.

2.2 Summary of Observations on the Recovered Bow Visor and on the Wreck

2.2.1 General

No indications of structural deviations between the actual on board installations and the original design have been found. It has, however, not been possible to fully establish if any repair work has been carried out on the affected parts during the vessel's lifetime.

2.2.2 The Bow Visor

The visor was traced on the seabed and recovered. The main observations that were made on the visor after it had been brought ashore at Hanko in Finland are summarized below.

The visor shell plating had an extended indentation on its front side, slightly starboard of the stem.

The solid stem post had left the visor after separation of the welds.

The bottom of the visor was heavily pounded and distorted. The lug for the bottom lock was in place but the surrounding structure was heavily deformed. The hole in the lug was oval and the material showed signs of yielding.

The inner vertical bulkheads of the visor had indentations and score marks on the port side.

The upper cross-bar in the visor had heavy impact marks. Other cross-bars had lighter marks.

The aft bulkhead of the visor had various damage. In particular the recess for the port side locating horn had been torn completely open in the area below the recess.

Both side locking lugs had been torn out of the bulkhead, leaving rectangular holes in the plating.

The hinge bushings at the end of the hinge beams had separated from the beam side plates due to failure of the side plates and the welds around the bushings.

The bottom plates of the hinge beams had pounding and impact marks around the attachment lugs for the visor opening actuators and green paint marks. The lugs for the opening cylinders had heavy score marks on their starboard sides.

The box on the visor deck had impact damage to the port part of its aft inner wall, including bent and dented bulb bars.

The aft edges of the hinge beam bottom plates and the deck plating of the visor had heavy pounding marks.

The damage is illustrated in a series of photographs in Figure 10.

2.2.3 The Bow Area of the Hull

Diving and ROV inspections of the bow area of the wreck revealed certain damage to the hull and the installations in the bow area as summarized below.

The deck hinge fittings on deck were undamaged except for pounding marks on their forward faces. The visor parking support was undamaged.

The deck was torn open from the visor operating actuator openings and forward. The openings continued for some length down the front bulkhead. The deck damage was extensive with uneven fracture surfaces whereas the openings in the front bulkhead had rather clean cut contours.

The side lock lugs remained in their recesses, engaged on the locking bolts. Part only of the ripped-out visor aft plating seemed to remain attached to the lug bottom faces. The clearance between the lugs and the bolts was estimated by the diver to be about 10 millimetres.

Various damage to the front bulkhead was found and in particular to its lower part.

The bottom locking bolt housing was torn away as well as the support bushing. All three attachment lugs were fractured in their thinnest cross sections. The welds between the lugs and the housing and bushing respectively had failed. The locking bolt remained attached to the piston rod of the actuating cylinder.

There was various damage to the rubber seals and their supporting flat bars on the front bulkhead and, extensively, on the forepeak deck.

Pounding damage was recorded to the shell plating edges around the forepeak deck and to the ice-breaking stem on the bulbous bow. Various scratch marks were noted on the bulbous bow.

The loading ramp was slightly open, with a gap of about one metre at the top.

The two port side hinges at the bottom of the ramp were torn apart. Both hydraulic actuators for the ramp had failed in their rod end pieces. The actuators were in retracted position as when the ramp is closed.

Various deep indentations were found on the beams on the lower side of the ramp.

The ramp port side beam was damaged in several places, mostly towards the top end.

The lugs for the pull-in locking hooks were twisted. The hooks themselves could not be inspected closely.

The boxes on the ramp side bars, mating the bolts of the ramp side locks, were twisted to open position, except for the lower port side one. The side lock bolts were fully extended except for the lower port side one which was only partly extended.

The damage is illustrated in a series of photographs shown in Figure 11.

2.3 Parts Recovered for Examination

The visor was traced on the seabed and was recovered and brought ashore for investigation. Steel parts of the visor were removed for detailed examination from the attachment areas of the side locking lugs and the hinges. One hydraulic cylinder was removed for internal examination.

The attachment lugs for the bottom lock were removed from the wreck and brought to the surface. One hinge bushing was also recovered.

The locking bolt was removed from the actuator piston rod by divers on 4 December 1994 and brought to the surface. It was checked for wear and deformation. The bolt was straight. Only a slight difference in diameter was measured at the contact area between the bolt and the lug of the visor. The general diameter of the bolt was 79.8 millimetres whereas the minimum measurement across the contact area was 79.4 millimetres. No other damage to the bolt was noted.

When the bolt was recovered from the wreck it was attached to the piston rod of the hydraulic actuator which remained in place on the forepeak deck as shown in Figure 12. The hydraulic hoses were connected. The actuator was in fully extended, i.e. locked, position and the piston rod was bent upwards, away from the forepeak deck. The connecting pin could be withdrawn without difficulty and the bolt was brought to the surface.

2.4 Other observations

A student working temporarily in an on board maintenance team observed in August 1994 some cracks in the fillet welds between the hinge beam side plates and the hinge bushings.

The observed cracks were located in the lower section of the weld beads between the hinge beam side plates and the hinge bushings on the side facing the deck part of the hinge installation. One crack, about 100 millimetres long, and one shorter crack were observed in the starboard hinge lugs. One crack, about 60 millimetres long, was observed in one lug at the port hinge. The cracks were not visible when the visor was closed.

2.5 Location of the Collision Bulkhead and the Ramp

The ramp of the ESTONIA was located about 4.2 metres forward of the position for an upper extension of the collision bulkhead required by the SOLAS 1960 convention, valid at the time of building the vessel.

Thé Bureau Veritas rules valid at the time had not fully incorporated the SOLAS requirements regarding the upper extension of the collision bulkhead. Thus, the minimum 5 per cent of ship's length limit applicable to its location pursuant to SOLAS (1960) was not a requirement of the Bureau Veritas rules. The rules did, however, contain wording stating the the classification society head office may require an extension of the collision bulkhead to the forecastle deck.

The building specification for the vessel stated under a heading "Partial Collision Door" that "For the intended service not required by F.B.N." (Finnish Board of Navigation). The vessel was given a Passenger Ship Safety Certificate in compliance with SOLAS by the Finnish Authorities upon delivery from the yard. The extent of participation by representatives of the Finnish Administration during the construction of the vessel is still being investigated.

More detailed requirements for bow door and ramp installations were later given in the 1981 Amendments to the SOLAS convention and in the 1982 Unified Requirements by IACS (International Association of Classification Societies).

3 Analysis and Evaluation

3.1 The Bow Visor Attachment Devices – Strength Considerations

3.1.1 Design Basis and Requirements of the Classification Society

3.1.1.1 General requirements

The bow visor itself was built to scantling requirements specified in Bureau Veritas Rules of 1977. Compliance with these has not been verified in detail in this investigation.

The locking devices should, according to the Bureau Veritas rules valid at the time, cause the bow door to be "firmly secured". No detailed procedure for verifying the locking devices was given. Structural reinforcements were specified in general wording to be required at attachment points for cleats, hinges and jacks.

Two notes made by the Bureau Veritas examiner of the assembly drawing of the visor installation stated that "the locking devices to be subject of the approval of the National Authority" and "local reinforcement of the ship's structure in way of locking devices, cylinders and hinges to Surveyor's satisfaction".

The design load to be applied to the bow visor of a ro-ro vessel has been subject to continuous development based on new data and was not well established at the time of ESTONIA's construction.

3.1.1.2 Bureau Veritas rule requirements for the design load on the visor

The Bureau Veritas rules did not specify minimum pressure heads to be applied to the horizontal and vertical areas of the visor. These loads as calculated by the yard based on applied pressure heads amounted to 536 tons vertically and 381 tons horizontally. The origin of the applied pressure heads has not been identified. The applied loads were, however, of the same magnitude as those required by other classification societies at the time.

The loads were, in the calculations by the yard, applied evenly to the five attachment points, the hinges included, resulting in a calculated design load of 100 tons per attachment point. The Bureau Veritas rules did not include guidance on the calculation procedure to be applied as no load requirements were specified.

The procedure applied did not produce a set of forces being in static balance with the external forces. The load distribution is statically undertermined. A more detailed load distribution analysis would have shown a design load per locking device of about 135 tons. The pressure head to be applied was later more clearly defined and the value given in the 1982 Unified Requirements of IACS would have resulted in a design load for each locking device of about 200 tons.

The design load on each locking device was used for determining a minimum load carrying cross section of the attachment of each device. This was obtained by applying generally permissible stress levels. The calculations were not submitted to Bureau Veritas for examination. The calculation methodology included a nominal safety factor of about three against the assumed failure mode.

3.1.2 The Strength of the Bottom Lock Assembly

The bottom locking device failed in its attachments to the fore peak deck. The failure took place in the plate lugs carrying the bolt housing and the mating support bushing and in the weld around the housing and the bushing.

The failed lugs were recovered from the wreck and have undergone metallurgical and strength examination of the fractured surfaces and of the base material as will be reported in detail in an appendix to the final report. All indications are that the lugs failed in an overload condition with a low number of cycles. The general appearance of the failed lugs is shown in Figure 13. The failure in the weld was partly in the beads and partly through separation between the weld and the housing material. The thickness of the weld beads was about 3 millimetres.

The load-carrying capability of the bottom lock assembly has been estimated according to different calculations to be in the range from 90 to maximum 150 tons. The calculations take into account the cross section of the fractured surfaces of the lugs and a contribution from the weld joints.

The actual failure load was most likely less as the lugs may have failed in sequence. The gap between the housing and the bushing was 100 millimetres compared to the 60 millimetre thickness of the mating lug on the visor. The actual transverse position of the lug on the locking bolt would influence which lug would carry the major part of the load and thereby fail ahead of the other one. The deformation of the visor lug indicates that the single lug for the support bushing failed first.

It is understood from information given by the yard that the locking device assembly was manufactured as a shop subassembly that was subsequently welded to the forepeak deck. The assembly was welded using standard welding practice as no detailed drawing with welding data was issued for this subassembly.

To satisfy the design calculations of the yard, the lugs should have had a larger minimum cross section or the weld should have been made a full load-carrying joint, using appropriate manufacturing technique.

It is concluded that a load carrying cross section of the locking device, to satisfy the applied design load, was not incorporated in the actual installation.

3.1.3 The Strength of the Side Locks

The side locks failed at the attachment of the lugs to the visor aft plating. No detailed drawings have been found, that show the exact dimensions of the lugs, nor details of the welding of these to the visor plating. The lugs had a bottom length of about 380 millimetres as measured at the attachment remains on the visor, compared to about 480 indicated on general arrangement drawings.

The lugs were ripped out of the visor plating together with part of the plating itself, leaving rectangular holes with fracture surfaces in shear. The lugs remain in the wreck. The bottom surface of one of the lugs is shown in Figure 14.

The thickness of the aft plating of the visor was 8 millimetres. Two vertical stiffeners were added behind each lug at the request of the surveyor for local reinforcement of the structure in way of the locking devices. No other strength continuity was incorporated behind the lugs.

The load-carrying capability of the side lock cannot be calculated with certainty as it is statically undetermined. The force required to pull and break the lug away from the visor in a direction tangential to the rotation around the hinge points has, however, been estimated to be 90–120 tons.

It is concluded that the absence of sufficiently detailed manufacturing and installation instructions resulted in the calculated design load carrying capability not being incorporated. Only limited arrangements were made for transmitting the loads from the lugs to the structure of the visor.

3.1.4 Approval of the Locking Devices

A written request was made by the manufacturer of the ramp and the locking devices to the Finnish Board of Navigation for advice about which drawings the Administration wanted to see. The Administration responded that only where there was any doubt as to interpretation of applicable rules should drawings be submitted to the Administration. The Administration assumed that the classification society would take care of the routine examination. This correspondence refers to drawings produced by the maker of the ramp and associated parts and not the installation drawings of the shipyard. No indications have been found that any drawings were submitted to the Administration for special consideration.

In examining the arrangement drawings the Bureau Veritas surveyor made a remark that the arrangement of the locking devices should be subject to the approval of the national authority. No evidence has been found indicating that such installation drawings were submitted by the yard to the Finnish Administration.

A comment on the arrangement drawing by the surveyor further stated that the structural reinforcement behind the locking devices should be to the satisfaction of the attending surveyor. This comment seems to have been complied with and a note on the inspection records for the completed installation requests that two vertical stiffeners be welded on the front side of the visor plating.

3.1.5 The Hinges on Deck

The hinge bushings installed in the end lugs of the visor hinge beams had an ultimate load-carrying capacity in tension of about 350 tons at each hinge. This includes an estimated contribution from the weld joints. The weakest section was across the lugs and included the fillet weld around the hinge bushing. The normal load created while raising the visor was about 150 tons on each hinge. The reported cracks in these welds were in a location which was subjected to stress primarily as a result of wind loads during the visor's opening and closing and in particular if some twisting occurred as a consequence that the actuators did not move with the same velocity. The cracks had, due to their location, a rather limited effect on the assembly's capability to take forward directed loads.

The failure of the lugs at the hinges took place in tension. The fracture surfaces indicate that the failure took place in a monocyclic overload condition. The lugs and the welds of the hinge bushings have undergone metallurgical and strength investigation which will be reported in an appendix to the final report.

It is regarded as likely that the forces to cause the hinges to fail were created when the hinge arms started to contact the upper deck as a consequence of compression of the visor bottom structure. The leverage thereby created in combination with the mass forces generated when the visor was pounding on the forepeak deck were more than adequate to pull the hinges apart.

3.1.6 Contribution from the Manual Locks

The manual locks at each side consisted of two plate lugs and an eye bolt rotated to position between the lugs and tightened. The total load-carrying capability of the manual locks has been calculated to be about 70 tons each. If the manual locks had been applied they would to some extent have contributed to the overall load-carrying capability of the visor locks. The

fact that there were no instructions for their use indicates, however, that they were not regarded as part of the operational locking system.

3.1.7 The Visor Operating Actuators

The visor had two heavy-duty actuators for controlled opening and closing of the visor. These were connected to the visor hinge beams at a distance of 1.3 metres from the hinges and were mounted on reinforced horizontal platforms in the front structure of the hull. The actuators were connected hydraulically to a solenoid-type control valve, which was closed at all times except when the visor was being moved.

When sea loads started to open the visor, an upward load was also applied to the actuators, which resisted the opening movement. The leverage from the centre of attack of the sea loads compared to that of the actuators enabled a high pulling force to be transmitted to the actuators. The port side actuator was at this moment pulled out of the hull without being extended whilst the locked-in hydraulic fluid acted to transmit the force to the lower attachment of the unit. The vertical force to pull the support structure of the actuator out of the hull in shear has been estimated to be around 700 tons, taking into account the unsymmetrical attachment point of the load. The actuator has undergone a detailed investigation which will be reported in an appendix to the final report.

The seals in the starboard side actuator failed, preventing the hydraulic fluid from transmitting the load. The piston rod of this actuator was therefore extended and the actuator remained connected in the hull during the initial phase of the movement of the visor. The load initially taken by this actuator before the seals failed cannot be determined but will have been less than the above value of 700 tons.

3.2 The Ramp Locking Devices – Strength Considerations

The ramp was secured in the closed position by six locking devices, two pull-in hooks at the upper end and two locking bolts along each side of the ramp.

The upper pull-in hooks were in closed position as verified by video pictures of the actuator and lever mechanism. It has, however, not been possible to determine in which mode the hooks failed. An upper limit of the load-carrying capability of a hook may have been the load at which the metal in the contacting area between the hook and the mating pin started to yield. This load was approximately 20 tons. It is assumed that the pin slipped off the hook when yielding started in the hook material, as the bend-over angle of the hook tip was small.

The side securing bolts were, in locked position, extending into box-like structures, which were welded to the side bars of the ramp. These boxes were ripped open following failures in their welds. The force required to rip any one of these boxes open has been estimated to about 20 tons. One box, the lower port-side one, was not ripped open and it is assumed that the locking bolt was not fully engaged in this box. A question remains about the condition of this locking device at the time of the accident, but this did not have any effect on the overall development of the accident.

The securing devices failed sequentially as a result of load being applied first to the port side. A force applied to the top of the ramp from contact with the visor had a favourable leverage relative to that of the locking devices, reducing the force actually required to break the devices. The contact force required to deform the stiffeners in the deck box of the visor has been estimated to be about 50 tons.

3.3 Probable Failure Sequence of the Visor and the Ramp

The distribution of forces on the visor attachment points cannot be statically determined. A complete finite element analysis of the visor and the hull part of the attachment structure, taking into account all elasticity of the structures, would in theory permit calculation of forces at the individual attachment point, given that the external loads were known. Since the external loads are undeterminable and quickly variable in magnitude and location, no means exist for accurate calculation of the loads at each individual attachment point.

The most probable sequence of events during the failure has been reconstructed based on damage observations and calculations. Figure 15 illustrates this sequence as described below.

The three locking devices may have failed in any one sequence. The chance that they failed simultaneously has been considered to be small, taking into account the uncontrolled play at each locking bolt and the elasticity of the structure.

After failure of the bottom and side locks, the visor operating actuators resisted further opening movement. The leverage of the sea loads created sufficiently high loads on the actuators to cause these to be pulled out of the hull or to fail internally.

Following the failure of the locks and the actuators the visor was free to pivot around its hinge points. The lack of damage to the parking device on deck indicates that the visor did not at any moment rise to fully open position. Witness statements regarding sharp hammering noises from the bow area and water coming up between the visor and the deck indicate that the visor was pivoting up and down for some time. During this part of the

sequence the visor was beating on its three bottom resting pads, the main one being the visor stem post, which was in contact with the ice-breaking stem. The stem post separated from the visor due to failure of the attachment welds in consequence of this hammering. The violence of the pounding action caused the stem post to leave the visor with a considerable upward velocity, creating a sharp indentation in the front of the visor for a length of about 2 metres as shown in Figure 10.

After the solid stem post had separated from the visor there was no other strong point to take the vertical pounding, and the bottom part of the visor structure was deformed and compressed by about 0.2 metres by beating against the two remaining pads, the shell plating protusion around the forepeak deck and the locating horn.

As the visor was seating lower than normal due to the compression of the bottom part, the hinge beams started to contact the main deck, causing heavy upwards and forwards loads on the hinges, resulting in failure of these. The visor was also beating backwards against the lower part of the front bulkhead during this movement, adding to a forward pulling force at the hinges.

At this stage the visor was still in a position close to the normal one, guided because the attachment lugs for the lifting actuators were engaged in the openings in the deck. The visor continued to make vertical movements during this phase, indicated by various damage, e.g. the port-side locating horn tore a long opening in the visor aft bulkhead. It is also evident from damage to the aft end of the bottom plates of both visor hinge beams and the mating hinge fittings on deck that the visor was beating backwards heavily onto the hull. The aft edge of the visor deck plating was also beating backwards onto the edge of the hull deck, about evenly for the full width from port to starboard.

At a later stage, possibly due to accumulation of water inside the visor and due to the mass forces from the pitching of the vessel, the visor started to tilt forward with sufficient force to cause the attachment lugs for the lifting actuators to start cutting openings in the deck plating. During this gradual movement forward the aft wall of the box on the visor deck came in contact with the top of the ramp. As the sea load was on the port bow, the visor was turned somewhat to starboard, thereby causing the contact to be concentrated to the port side.

During the continued forward shift of the visor in a step by step beating movement, the lugs of the lifting actuators continued to cut slots in the deck plating, and the aft wall of the deck box started to push on the upper side of the ramp. The ramp locking devices failed sequentially. The upper pull-in hooks of the ramp may have disengaged due to the shock load in the structure created when the port side actuator was pulled out or later due to the bouncing around of the actuator in the area as the visor moved up and down. Both operating actuators for the ramp failed at their piston rod end fittings.

After this stage there was nothing to prevent the ramp from falling forward under its own weight and it opened to a position resting against the cross-beams inside the visor. The visor was still restrained in its forward movement by the lugs working their way through the deck plating. At this stage water was entering the car deck along the sides of the ramp as seen by the engineer on duty, although the ramp was still in a seemingly lifted position. The visor was probably water filled during this phase.

The visor continued this forward movement and the lugs, later also the piston rods, cut slots in the deck and in the front bulkhead. During this movement the visor was guided fore-and-aft by engagement with the ramp, resting on the cross-bars and between the inner longitudinal bulkheads of the visor. The port side sea loads caused heavy contact between the visor and the port side of the ramp, causing the two port-side ramp hinges to fail.

At a still later stage the visor may have jumped forward and bounced on the top of the bulbous bow, causing additional damage to the bottom structure of the visor. The visor was at this stage still guided by the ramp, now almost fully open, and by the starboard side lifting actuator. When the actuator was finally pulled out of the hull, the visor tumbled forward. When its deck was struck by waves it was slammed back against the bulbous bow of the vessel and thereafter slid downwards, causing an extended indentation and various scratch marks ont its front.

At this stage the ramp was fully open. Damage on the lower side of the ramp indicates that it struck the forepeak deck.

3.4 Forces Developing during the Failure

3.4.1 General Considerations

Forces required to break the visor open initially created an opening moment around the hinge points. This can only be achieved when sea loads are applied to the upper part of the visor, i.e. when a major part of the visor is submerged in a wave. The relevant sea loads and the wave conditions have been extensively investigated and simulated as described in detail in an appendix to the final report.

Damage indications show that the sea load came essentially from forward and on the port bow, causing the failure sequence to start with the visor opening, pivoting around its intact hinge points. An alternative failure mode could have been that the visor attachments were damaged by a substantially sideward load, twisting the visor off the hull. This scenario, however, is deemed less likely.

It cannot be determined with certainty what sea load was required to force the visor open. The three locking devices each had a failure load in the magnitude of 100 tons in the direction of movement of the particular lock when the visor was pivoting around the hinges.

The vertical force required to pull the port-side lifting actuator out of the hull has been estimated to be about 700 tons, however with a short moment

arm around the hinge points. The force required to fail the seals in the starboard side actuator may have been of any magnitude up to 700 tons.

The upper limit forces to fail the locking devices correspond to moments about the hinge axis of about 900, 450 and 450 ton-metres respectively, developing simultaneously, in sequence or with some overlap. The moment to fail the actuators was maximum about 900 ton-metres on each side, possibly developing simultaneously. The required moment on the starboard side actuator may, however, have been considerably less, due to failure of the seals. The forces to pull out the actuators, however, occurred only after the lower locks had failed, as there would have been some delay due to play in hinge pins and attachment pins and a compression effect in the hydraulic fluid.

The maximum opening moment to make the locking devices fail simultaneously was thus about 1800 ton-metres. However, due to elasticity of the structure and play at the locking bolts, the failing is more likely to have been progressive and the actual failure moment therefore significantly less. The maximum moment to subsequently break the actuators was of the same magnitude as that of the locks.

3.4.2 Comparison with Design Requirements

The design loads used in the original design work included a vertical load of 536 tons acting at a radius of 5.05 metres less the weight of the visor, 55 tons, acting at a radius of 4.9 metres and a horizontal force of 381 tons, acting with an arm of 2.86 metres below the hinge points. These forces together correspond to a visor opening moment of 1350 ton-metres. The failure load of the locks, as described above, was therefore not significantly higher than the design load on the visor.

Several incidents where the locking devices for a visor have failed have occurred over the years in other ferries. One such example is the near-sister vessel DIANA II in which the locking devices partly failed during a heavy weather voyage in the southern Baltic Sea in January 1993. Several other serious incidents which have occurred will be delt with in the final report as well as the apparent lack of efficient routines for extracting experience from such incidents.

It has been noted by the Commission that the design load requirements have gradually been increased and that, in particular, a major increase of stringency of the design load requirements and the calculation methodology was introduced in 1982 by IACS.

3.4.3 Sea and Speed Conditions Required to Create Crucial Forces

The sea load required to fail the lower locks and subsequently the hydraulic actuators may have been created under the prevailing speed and sea conditions. Extensive simulation of loads developing during various sea conditions and ship's speed have been carried out, as will be covered in detail in the final report. The sea conditions are based on those statistically probable for the wind conditions at the time of the accident. Any possible effect of bottom topography on the wave formation will also be evaluated.

In summary an external hydrodynamic load of the same magnitude as the design load was most likely sufficient to break the visor locking devices. Such wave loads, or even worse, may have been generated as extreme values under the prevailing conditions with a ship speed of 14–15 knots and a wave coming in on the port bow with an estimated significant wave height of 4.2–4.5 metres in combination with a modal wave period of 8–9 seconds.

3.5 Location of the Collision Bulkhead and the Ramp

3.5.1 Regulatory Requirements

The ramp arrangement of the ESTONIA and the absence of a correctly located upper extension of the collision bulkhead were typical of a large number of ferries built in the period from 1960 to the early 1980s. The arrangement did not comply with the regulations which had been in force since SOLAS 1948. It has not been concluded with certainty whether the practice that had developed over the years was based on acceptance of the ramp as a collision bulkhead despite a forward location or whether the requirement for an upper extension of the collision bulkhead was disregarded in its entirety.

Compliance with the requirements valid at the time regarding the extension of the collision bulkhead up to the forecastle deck would have significantly increased the possibilities for the vessel to survive the loss of the bow visor.

3.5.2 Design Considerations

The design arrangement incorporating a box on the deck of the visor for accomodating the top of the ramp was also the common solution on ro-ro ferries built during the same period. This arrangement, although not in violation of any rules, had crucial consequences when the ESTONIA's visor separated from the hull.

4 Conclusions

In reviewing the findings and studying relevant technical information the Commission has found that a number of design features and conditions contributed to the accident. Other contributory factors will be evaluated in the final report. In summary the Commission has at this stage concluded that

- The vessel capsized due to large amounts of water entering the car deck, loss of stability and subsequent flooding of the accomodation decks. The full-width open car deck contributed to this development.
- The accident occurred during heavy weather conditions. Sea conditions of equivalent severity had only existed once or twice before during the period the vessel had been in service between Tallinn and Stockholm on a westbound voyage.
- The bow visor locking devices failed due to loads generated by the hydrodynamic forces on the bow visor at the prevailing speed, heading and wave conditions.
- The visor locking devices were constructed with less strength than required according to calculations. It is believed that this discrepancy developed due to lack of sufficiently detailed manufacturing and installation instructions for certain parts of the devices.
- Following failure of the locking devices the visor pounded heavily on the stem structure before it separated from the hull. This pounding was clearly noticed by crew members and passengers.
- The failure of the bow visor caused the ramp to be forced open due to mechanical interference between the visor and the ramp, inherrent in the design. This design arrangement had crucial consequences for the development of the accident.
- The classification society design requirements concerning bow doors, valid at the time, were less detailed and demanding than later ones.
- The vessel had no upper extension of the collision bulkhead satisfying the regulations of SOLAS. No such extension was required by the national administration according to the building specification. The ramp did not satisfy the requirement of such an extension of the collision bulkhead.
- The industry's general experience of hydrodynamic loads on large ship structures was limited at the time of construction of the ESTONIA and full knowledge of the related problems was not available to the parties involved, including administrations, shipbuilders, operators and ship masters.

5 Recommendations

In reviewing all facts related to the technical circumstances of the accident the Commission recommends that all affected states

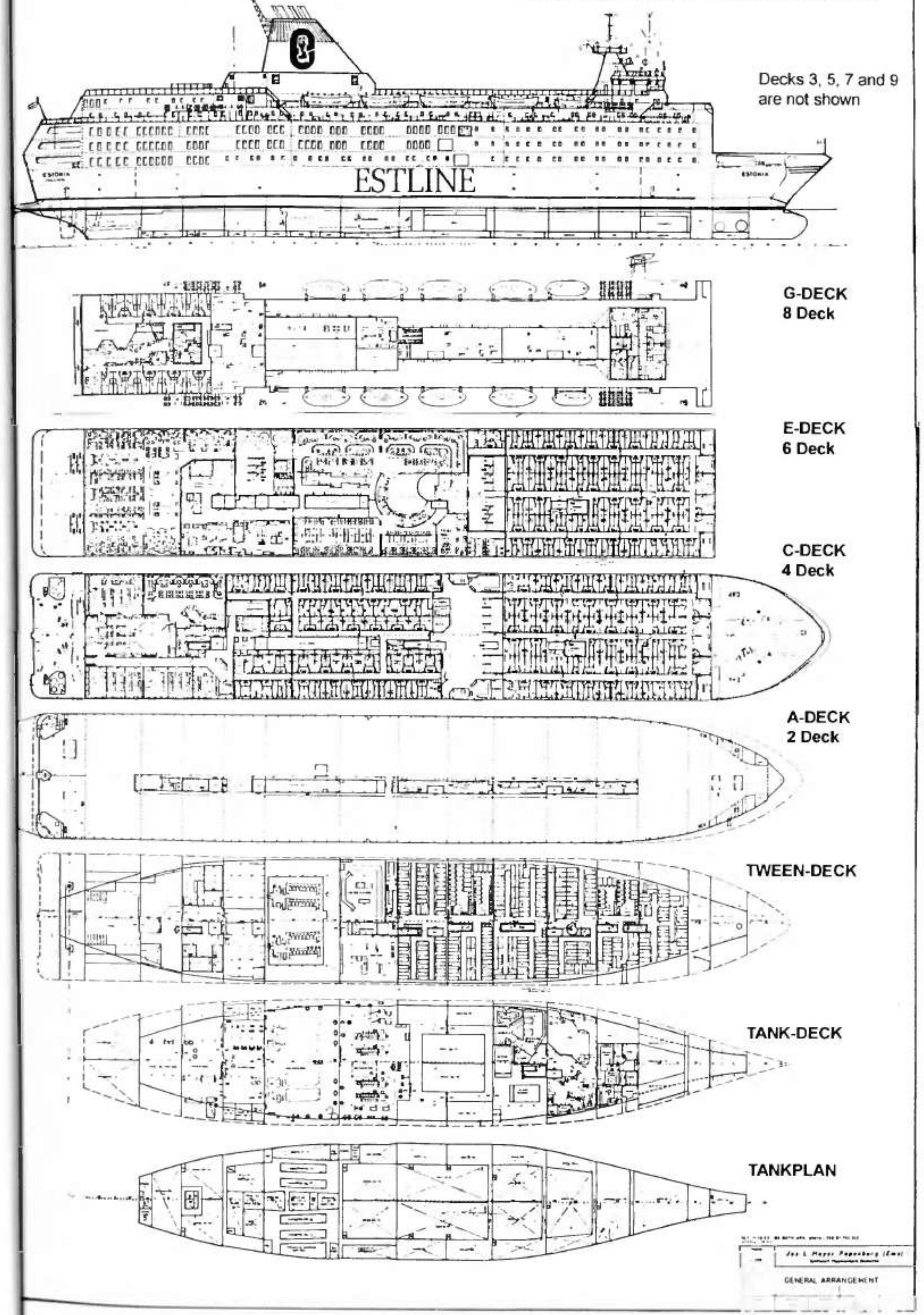
1. Require upgrading of existing ferry vessels to comply with current issues of international regulations as far as safety is concerned;

2. Require bow arrangements of ferries to have such design features incorporated that failure in a single barrier component, such as a visor, will not have crucial effects on the safety of the vessel, and

3. Require, in the shortest reasonable time scale, ro-ro ferries to have such arrangements incorporated that flooding of large deck areas cannot jeopardize the stability of the ship.

FIGURES

FIG 1 MV ESTONIA – General Arrangement



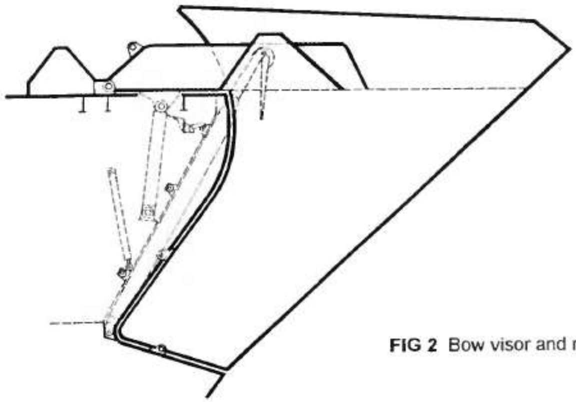
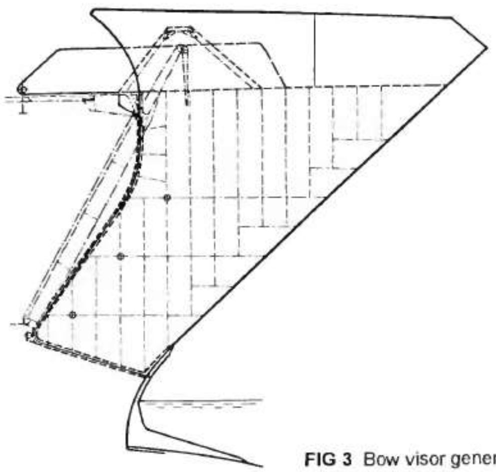


FIG 2 Bow visor and ramp installation



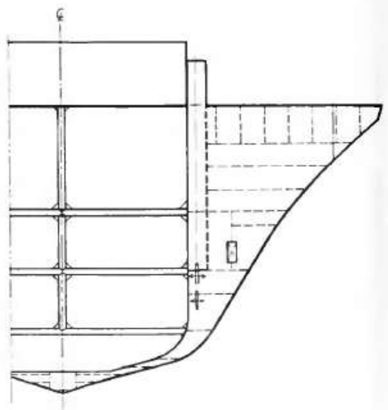
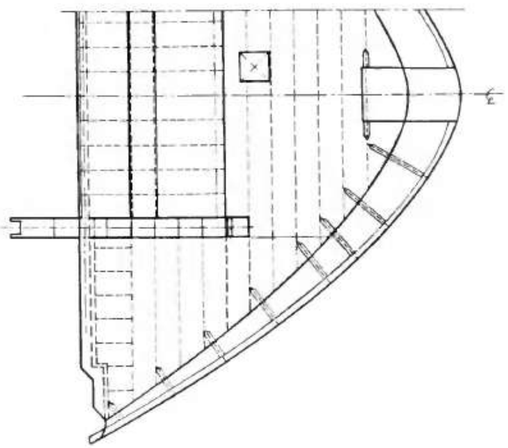
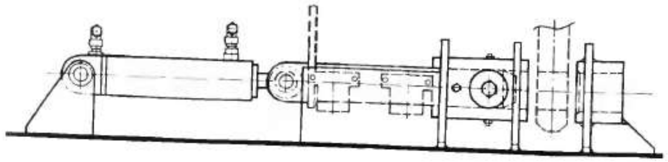


FIG 3 Bow visor general arrangement and structure





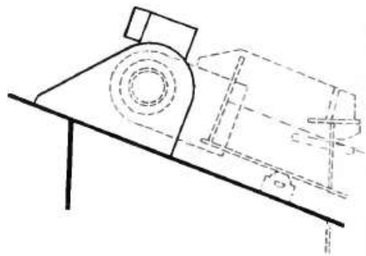


FIG 4 Bottom locking device

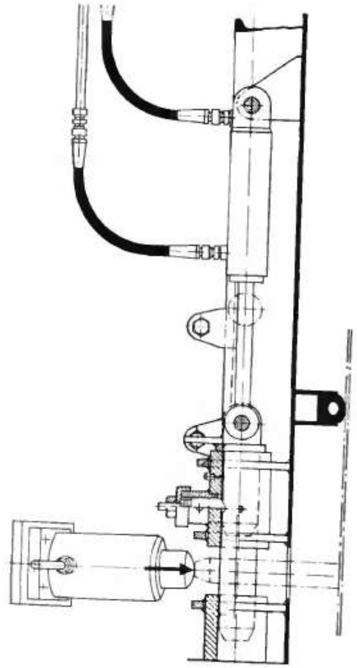


FIG 6 Side locking device, port and starboard

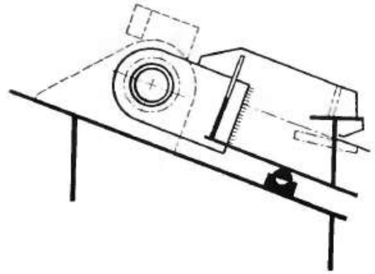


FIG 5 Lug of visor, mating the bottom locking device

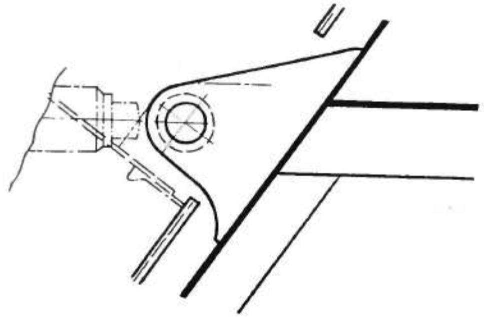


FIG 7 Lug of visor, mating the side locking device

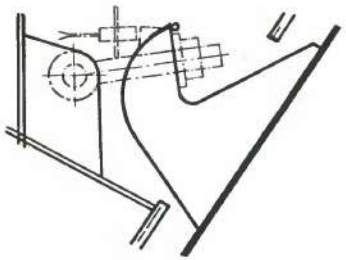


FIG 8 Manual locking device, port and starboard

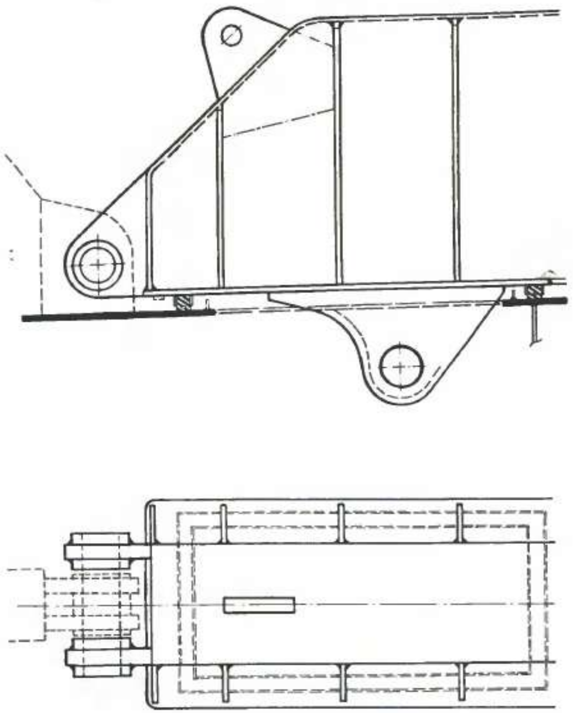


FIG 9 Arrangement of deck hinges and deck beams

Various damages to the bow visor

FIG 10.1
The bow visor as recovered and brought ashore

FIG 10.2
The visor starboard side actuator

FIG 10.3
Damage in the area of the hinge beam and the actuator attachment lug, starboard side

FIG 10.4 Damage to the bottom structure of the visor

FIG 10.5 The visor lug for the bottom lock

FIG 10.6 Damage to the aft wall of the visor deck box

FIG 10.7 Damage from separation of a side locking lug

FIG 10.8 A failed visor hinge

FIG 10.9 Damage to the visor front, including indications of separated stem post

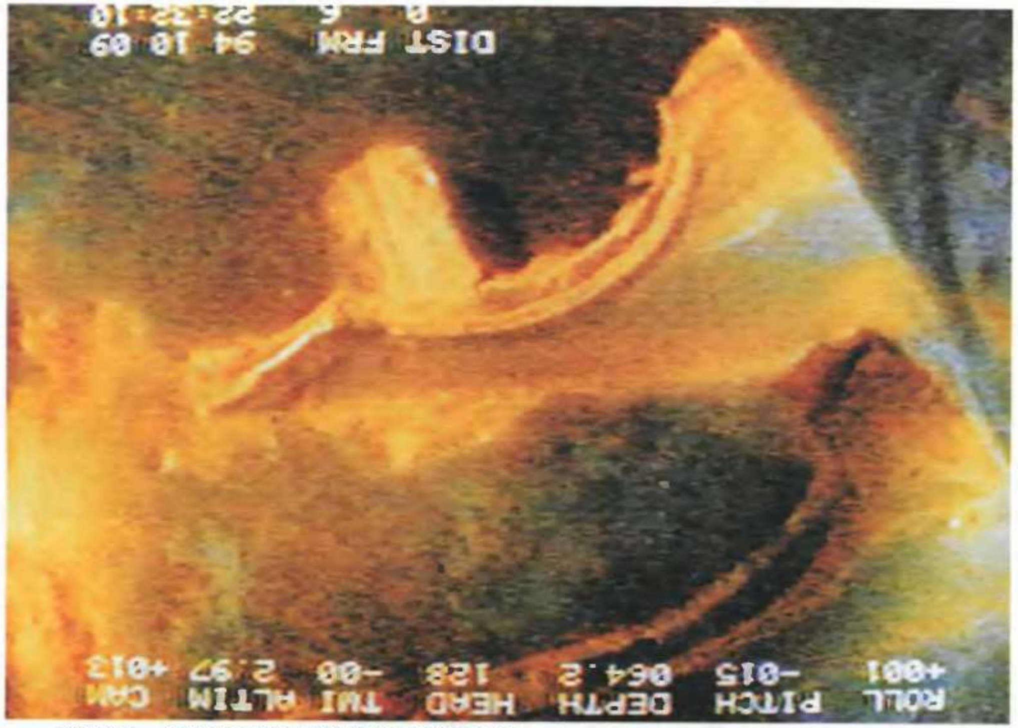


FIG 11.1 Failed mounting lugs for the bottom lock

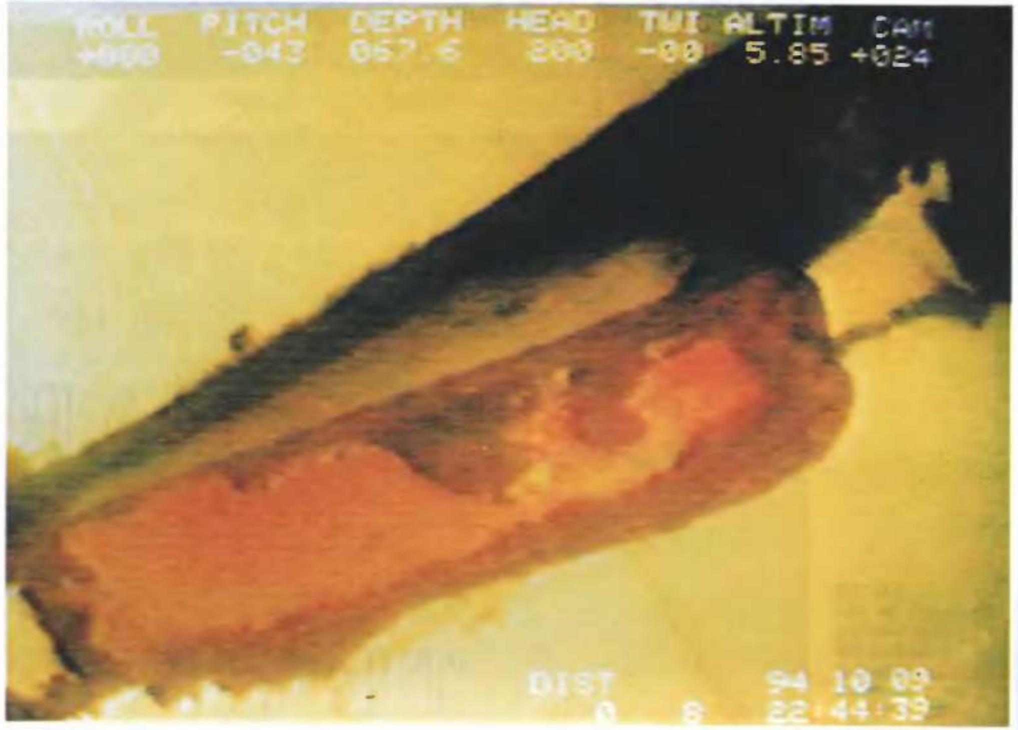


FIG 11.2 Bottom face of a side locking lug

FIG 11.3 Deck hinge fitting. One separated hinge bushing visible at bottom picture.

FIG 11.4 General damage on deck from beating by actuator attachment lugs

FIG 11.5 Damage on front bulkhead caused by actuator during movement of visor

FIG 11.6 Pull-in locking mechanism for ramp, shown in locked position

FIG 12 Locking bolt and failed mounting lugs for bottom locking device

FIG 13 Details of failed mounting lug for bottom locking device

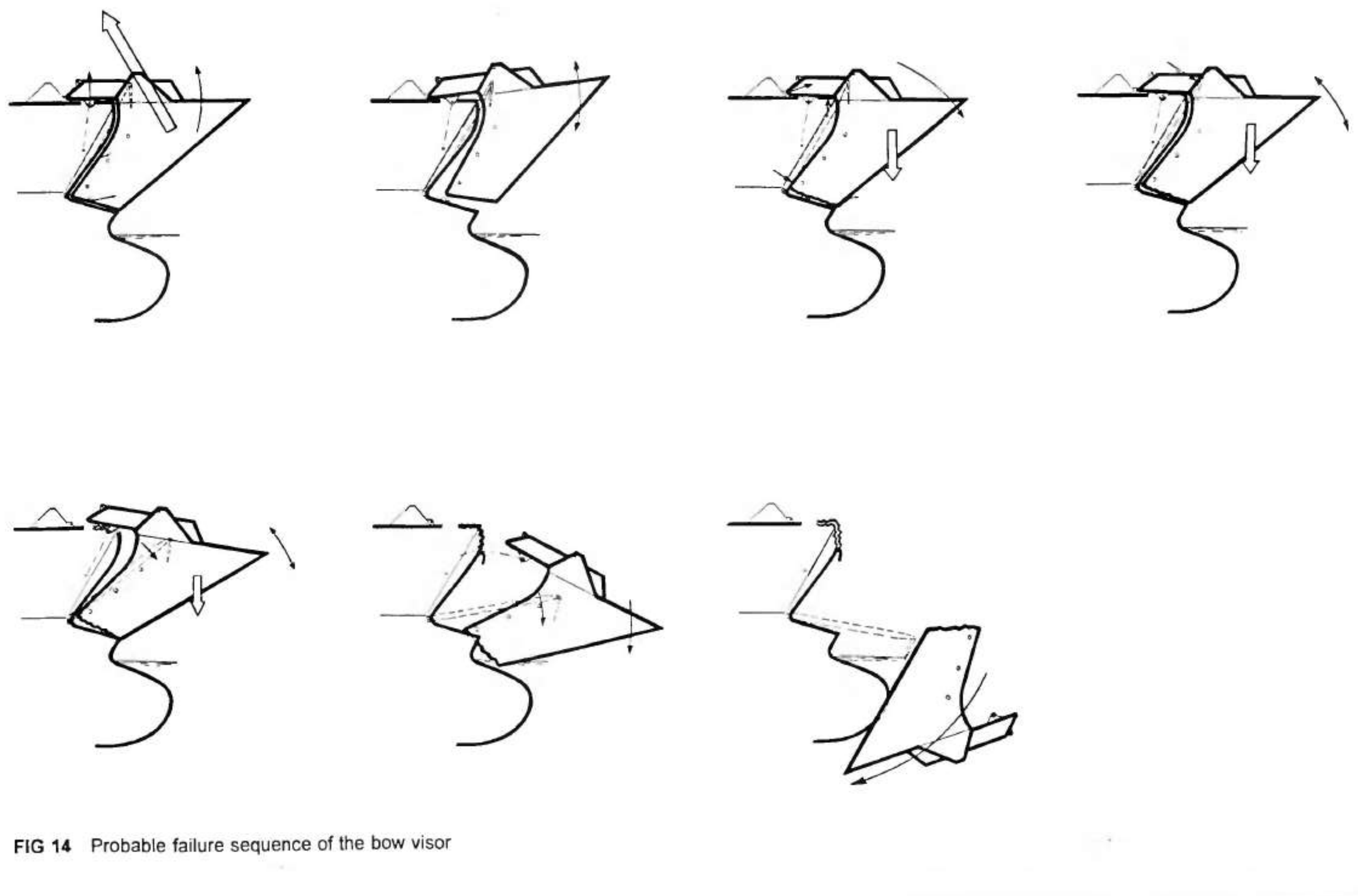


FIG 14 Probable failure sequence of the bow visor