Norwegian Safety Investigation Authority

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Loss of propulsion and near grounding of Viking Sky, Hustadvika, Norway 23 March 2019

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The Norwegian Safety Investigation Authority (NSIA) has compiled this report for the sole purpose of improving safety at sea.

The object of a safety investigation is to clarify the sequence of events and causal factors, elucidate matters of significance for the prevention of maritime accidents and improvement of safety at sea, and to publish a report with possible safety recommendations. The NSIA shall not apportion any blame or liability.

Use of this report for any other purpose than for improvements of the safety at sea shall be avoided.

Photo: Frank Skorgenes

Legal authority for the Norwegian Safety Investigation Authority's activities is found in Section 473 of the Act of 24 June 1994 No 39 (the Norwegian Maritime Code); cf. the Regulations of 11 January 2008 No 30 on public investigations of accidents and incidents under Section 473 of the Maritime Code.

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Notification of the accident

At 1445 Saturday 23 March 2019, the Norwegian Safety Investigation Authority (NSIA), was informed by the Norwegian Maritime Authority (NMA) that the cruise ship *Viking Sky* had experienced a blackout, causing loss of propulsion and steering, in the Hustadvika area of the Norwegian coast, and were drifting towards shore. The NSIA was continuously updated by the Joint Rescue Coordination Centre (JRCC), the police and Wilhelmsen Ship Management, until the ship arrived Molde, where it moored at around 1625 in the afternoon of 24 March.

During Sunday 24 March, the NSIA was in contact with the United Kingdom's Marine Accident Investigation Branch (MAIB), the United States Coast Guard (USCG) and the United States' National Transportation Safety Board (NTSB). It was decided to initiate a safety investigation into the accident, led by the NSIA.

On 25 and 26 March, 15 representatives of the NSIA, MAIB, USCG and NTSB arrived in Molde and Kristiansund to initiate the investigation.

Summary

In the afternoon of 23 March 2019, the cruise vessel *Viking Sky* experienced a blackout, causing loss of propulsion and steering, during a storm in the Hustadvika area of the Norwegian coast. The vessel is estimated to have come within a ship's length of running aground with 1,374 persons on board, and the accident had the potential to develop into one of the worst disasters at sea in modern times.

The accident was caused by insufficient lubricating oil in all of the operating diesel generators' lubricating oil sump tanks, in combination with pitching and rolling in rough seas. The investigation has identified operational, technical, and organisational safety issues that in different ways contributed to the blackout.

The blackout recovery was time consuming, and it took 39 minutes from the blackout until both propulsion motors were operational and the ship had sufficient power available to maintain between 1 to 5 knots ahead. Blackout drills had been carried out, but recovery from a full blackout without a standby generator had never been drilled on board. The engineers were therefore faced with a situation they were not practised in managing. The situation was stressful, the control system was complex, and a specific sequence of actions was needed. Insufficient training likely contributed to why the blackout recovery was time consuming.

When *Viking Sky* left Tromsø 21 March 2019, with one out of four diesel generators unavailable, both crew and passengers were unknowingly exposed to an increased risk as the vessel did not have the redundancy required under the Safe Return to Port (SRtP) regulations. As *Viking Sky* did not comply with the applicable safety standards, it should not have departed Tromsø under the prevailing circumstances.

Main findings

Viking Sky suffered a blackout when all three operational diesel generators (DGs) were shut down by their protection systems responding to low lube oil pressures. The low lube oil pressure was due to low levels of lube oil in the sump tanks in combination with the vessel motion, causing the lube oil suction pipe opening to be exposed to air. The vessel encountered strong winds and heavy seas, as forecast, but the vessel motion at the time of the first engine shutdown was significantly below the design criteria.

Since the departure from Tromsø two days before, no oil had been transferred into the DG sump tanks even though low lube oil level alarms went off both for DG2 and DG4 during the voyage, and the heavy weather checklist, that included an item requesting the lube oil sump tank levels to be optimised, was logged as completed.

None of the vessels in the fleet of five sister vessels had been provided with instructions on correct lube oil sump tank filling levels or alarm setpoints. In June 2016, the engineers working on board the sister vessel *Viking Sea* requested information from MAN regarding the recommended oil levels. MAN was unable to give a clear answer as the tanks were designed by the shipyard and not by them. The shore organisation of the ship management company was made aware of the email exchange between *Viking Sea* and MAN. However, no guidance on correct filling levels or alarm set points was issued by the ship management company until after the accident on *Viking Sky.*

The remote lube oil sump tank level monitoring system was complex, and the resulting onboard measurements were inaccurate and unreliable. The engineering crew on board *Viking Sky* had gradually lost confidence in the remote monitoring system. Since the level alarms were generated by the remote readings, the crew did not take the level alarms as a true indication of the actual level.

The combination of economic considerations, underestimation of consumption, the lack of confidence in the remote tank monitoring system and the lack of instructions regarding the correct filling and alarm setpoints, probably resulted in the lube oil levels and alarm settings decreasing over time. The safety issues related to lube oil level management observed onboard *Viking Sky* were likely the result of underlying organisational safety issues.

The shipyard, the classification society and SINTEF Ocean have conducted independent Computational Fluid Dynamics (CFD) analyses on the DG lube oil sump tank design following the accident. All three indicated that there were situations within the parameters of the design criteria where the lube oil suction pipe is likely to be exposed to air. Hence, the lube oil sump tank design was non-compliant with the SOLAS requirement for safe operation under vessel inclination (SOLAS Chapter II-1, Part C, Regulation 26.6).

Simulations using the vessel motion recorded at the time of the first engine shutdown indicate that the accident would likely not have occurred had the lube oil sump tanks been filled to the highest level recommended by the engine manufacturer. The recorded vessel motion was, however, significantly below the design criteria specified in SOLAS.

The shipyard's design process did not effectively ensure that the lube oil sump tanks complied with all applicable rules, regulations, and recommendations. Likewise, the plan approval process of the classification society was ineffective and did not ensure that the sump tank design, which is critical to safe engine operation, was compliant. Further, no technical guideline or industry standard for application of the SOLAS requirement existed, making design and verification difficult.

The actual limitations associated with the lube oil sump tank design in terms of dynamic inclination angles or corresponding sea conditions had not been calculated. The crew therefore did not have the safety critical information necessary to know the limits of safe operation.

The alarm system in the engine control room did not differentiate between critical and less critical alarms. Troubleshooting was therefore challenging when a total of approximately 1,000 alarms sounded within the first 10 seconds after the blackout. Several issues related to design and configuration of the alarm system are likely to have had a negative impact on the effectiveness and efficiency of engineering officers on watch. At the time of the construction of *Viking Sky*, there were no standards available giving specific criteria for the design of engine room alarm systems in the maritime industry.

The complex and extended helicopter operation was carried out effectively with no accidents or casualties, however both the first rescue helicopter and the first tug arrived after the vessel would have grounded if propulsion had not been regained. This underlines the importance of not losing propulsion and steering and of avoiding situations where an evacuation is required, in particular for large passenger vessels.

The ship management company was aware of the forecast weather and that one DG was not available prior to the vessel's departure from Tromsø. However, they did not instruct the vessel to stay in port. The ship management company had no guidelines or procedures in their safety management system (SMS) regarding how to handle planned or unplanned unavailability of a DG with respect to the SRtP requirements. In the absence of such support from the shore organisation, the decision to sail or stay in port ultimately fell on the decision makers on board. However, none of these individuals have mentioned any concern related to SRtP. Consequently, crew and passengers on board *Viking Sky* were unknowingly exposed to an increased risk as the vessel set to cross Hustadvika, known as a *notoriously dangerous area*[1], in a forecast storm without the redundancy required.

It is possible that the *Viking Sky* could have experienced a blackout also with all four engines available if the lube oil level was low on all four lube oil sump tanks, including for DG3. This is, however, not a reason not to comply with the SRtP regulations.

The vessel's owner, ship management company, classification society, the administration of the flag state, the shipyard and the engine manufacturer were informed about the non-compliant sump tank design as soon as it was discovered by the NSIA. The owner was strongly encouraged to take remedial action to ensure that the fleet of vessels were operating in compliance with applicable rules and regulations. The classification society and the administration of the flag state were likewise encouraged to require appropriate remedial action to be taken. Following the accident, the ship management company has implemented a new procedure for lube oil management, aimed at maintaining higher lube oil levels. It is uncertain whether the new procedure fully remedy the safety issue as it is not supported by any calculation to document compliance with the SOLAS requirement or other operational limitations.

The NSIA issues a total of 14 safety recommendations to relevant parties. These are aimed at addressing the identified safety issues that have not been resolved prior to the publication of this safety investigation report.

[1] *According to the Admiralty Sailing directions, see section 1.6*

Norsk sammendrag

Om ettermiddagen den 23. mars 2019 fikk cruiseskipet Viking Sky en blackout, og mistet dermed fremdrift og styring, under en storm på vei over Hustadvika. Det er anslått at skipet bare var ca. en skipslengde fra å grunnstøte, og med 1 374 personer om bord hadde ulykken potensiale til å bli en av de verste katastrofene til sjøs i moderne tid.

Ulykken skyldtes for lavt oljenivå i alle de operative dieselgeneratorenes smøreoljetanker, i kombinasjon med stamping og rulling i høy sjøgang. Undersøkelsen har avdekket operasjonelle, tekniske og organisatoriske sikkerhetsproblem som på ulike måter bidro til at skipet fikk blackout.

Gjenopprettingen etter blackouten var tidkrevende, og det tok 39 minutter å få begge fremdriftsmotorene i drift slik at skipet hadde nok kraft til å opprettholde en fart på mellom 1 og 5 knop. Det hadde tidligere blitt utført blackout-øvelser om bord, men aldri basert på full blackout uten noen standby-generator tilgjengelig. Maskinistene ble derfor stilt overfor en situasjon de ikke hadde trent på å håndtere. Situasjonen var stressende, kontrollsystemet var komplekst, og det var behov for å utføre bestemte handlinger i en gitt rekkefølge. Utilstrekkelig opplæring bidro sannsynligvis til at gjenopprettingen ble tidkrevende.

Da Viking Sky forlot Tromsø 21. mars 2019, med en av fire dieselgeneratorer ute av drift, var både mannskapet og passasjerene uvitende om at de var utsatt for økt risiko, ettersom skipet ikke hadde den redundansen som kreves i henhold til Safe Return to Port-regelverket (SRtP). Viking Sky oppfylte ikke gjeldende sikkerhetsstandarder og skulle derfor ikke ha forlatt Tromsø under de rådende omstendigheter.

Hovedfunn

Viking Sky fikk en blackout da alle de tre operasjonelle dieselgeneratorene (DG) ble stengt ned på grunn av for lavt smøreoljetrykk. Det lave oljetrykket skyldtes for lavt nivå av smøreolje i sumptankene, i kombinasjon med skipets bevegelser, noe som førte til at sugerørsåpningen ble eksponert for luft. Forholdene med sterk vind og store bølger var varslet, men skipets bevegelser da den første motoren stengte ned var godt innenfor det skipet var designet for.

Det var ikke etterfylt olje på sumptankene siden avgangen fra Tromsø to dager tidligere, selv om alarmer for lavt oljenivå ble utløst for DG2 og DG4 underveis, og Heavy Weather Checklist, der et av punktene var optimalisering av smøreoljenivåene, ble logget som fullført.

Ingen av skipene i flåten på fem søsterskip hadde fått instruksjoner om korrekte fyllingsnivå eller alarminnstillinger for smøreoljetankene. I juni 2016 ba maskinistene på søsterskipet Viking Sea om informasjon fra MAN om anbefalte fyllingsnivå. MAN kunne ikke gi dem et klart svar, ettersom det var verftet som hadde designet tankene. Rederiets landorganisasjon ble gjort kjent med e-postutvekslingen mellom Viking Sea og MAN. Det ble imidlertid ikke gitt noen veiledning om korrekte fyllingsnivå eller alarminnstillinger før etter ulykken med Viking Sky.

Overvåkingssystemet for nivået på smøreoljetankene var komplekst, og målingene som ble foretatt om bord var unøyaktige og upålitelige. Maskinistene om bord på Viking Sky hadde gradvis mistet tilliten til tankovervåkingssystemet. Ettersom nivåalarmene ble aktivert på bakgrunn av disse fjernavlesningene, anså ikke mannskapet alarmene som en indikasjon på det faktiske oljenivået.

Kombinasjonen av økonomiske hensyn, undervurdering av forbruk, manglende tillit til tankovervåkingssystemet og mangelen på instrukser om korrekte fyllingsnivå og alarminnstillinger førte trolig til at smøreolje- og alarmnivåene ble redusert over tid. Sikkerhetsproblemene knyttet til håndtering av smøreoljenivået på Viking Sky var trolig et resultat av underliggende organisatoriske sikkerhetsproblemer.

Verftet, klasseselskapet og SINTEF Ocean har alle gjennomført uavhengige CFD-analyser (Computational Fluid Dynamics) av smøreoljetankenes design etter ulykken. Alle analysene konkluderte med at det kunne oppstå situasjoner innenfor designparametrene der sugerørsåpningen sannsynligvis ville bli eksponert for luft. Designet var derfor ikke i samsvar med SOLAS-kravet til sikker operasjon under krenging (SOLAS kapittel II-1, del C, regel 26.6).

Simuleringer basert på fartøyets bevegelser da den første motoren stengte ned, tyder på at ulykken sannsynligvis ikke ville ha skjedd dersom smøreoljetankene hadde vært fylt til det høyeste nivået anbefalt av motorfabrikanten. Fartøyets bevegelser var imidlertid betydelig mindre enn designkriteriene spesifisert i SOLAS.

Verftets designprosess sikret ikke at smøreoljetankene var designet i henhold til alle gjeldende regler, forskrifter og anbefalinger. Klasseselskapets godkjenningsprosess var heller ikke god nok og sikret ikke at tankdesignet, som er kritisk for sikker operasjon av motorene, var i samsvar med kravene. Videre fantes det ingen teknisk veiledning eller industristandarder for hvordan SOLAS-kravet skulle følges i praksis, noe som gjorde design og verifikasjon vanskelig.

Tankdesignets faktiske begrensninger med hensyn til dynamiske krengevinkler eller samsvarende sjøforhold, var ikke beregnet. Mannskapet hadde derfor ikke den sikkerhetskritiske informasjonen de trengte for å kjenne til grensene for sikker operasjon.

Alarmsystemet i maskinkontrollrommet skilte ikke mellom kritiske og mindre kritiske alarmer. Det var derfor utfordrende å feilsøke når til sammen ca. 1 000 alarmer ble utløst i løpet av de første 10 sekundene etter blackouten. Flere problemer knyttet til alarmsystemets design og konfigurasjon har trolig hatt negativ innvirkning på de vakthavende maskinistenes utførelse av sine oppgaver. Da Viking Sky ble bygget, fantes det ingen tilgjengelige standarder som spesifiserte kriterier for design av alarmsystem i maskinrom i den maritime næringen.

Den komplekse, langvarige helikopterevakueringen ble gjennomført på en effektiv måte uten ulykker eller omkomne, men både det første redningshelikopteret og den første slepebåten ankom etter at fartøyet ville ha grunnstøtt dersom de ikke hadde lyktes med å gjenopprette fremdriften. Dette understreker viktigheten av ikke å miste fremdrift og styring og å unngå situasjoner der evakuering er nødvendig, særlig for store passasjerskip.

Rederiet var kjent med værvarselet og at en av dieselgeneratorene var ute av drift før skipet forlot Tromsø. De beordret imidlertid ikke skipet om å holde seg i havn. Rederiet hadde ingen retningslinjer eller prosedyrer i sitt sikkerhetsstyringssystem for hvordan en planlagt eller ikke-planlagt nedstengning av en dieselgenerator skulle håndteres med hensyn til SRtP-kravene. I mangel av slik støtte fra landorganisasjonen falt beslutningen om å fortsette seilasen eller bli i havn på ledelsen om bord. Ingen av dem har imidlertid nevnt noen bekymringer knyttet til SRtP. Uten å vite det ble følgelig mannskapet og passasjerene på Viking Sky utsatt for økt risiko da skipet krysset Hustadvika, et notorisk farlig område[2], i dårlig vær og uten påkrevd redundans.

[2] *I følge Admiralty Sailing directions, see section 1.6*

Det er mulig at en blackout kunne oppstått selv med alle de fire motorene tilgjengelig, dersom oljenivået var lavt i alle de fire smøreoljetankene, inkludert for DG3. Dette er imidlertid ingen grunn til ikke å overholde SRtP-regelverket.

Så snart det ble oppdaget, informerte Havarikommisjonen skipets eier, rederiet, klasseselskapet, flaggstaten, verftet og motorfabrikanten om at designet på sumptankene ikke oppfylte regelkravene. Eieren ble sterkt oppfordret til å iverksette tiltak for å sikre at flåten opererte i samsvar med gjeldende regler og forskrifter. Klasseselskapet og flaggstaten ble også oppfordret til å kreve iverksettelse av utbedrende tiltak. Etter ulykken har rederiet utarbeidet en ny prosedyre for smøreoljehåndtering, med sikte på å opprettholde høyere smøreoljenivå. Det er usikkert om den nye prosedyren fullt ut løser sikkerhetsproblemet, da den ikke understøttes av noen beregninger som dokumenterer overholdelse av SOLAS-kravet eller andre operasjonsbegrensninger.

Havarikommisjonen fremmer i alt 14 sikkerhetstilrådinger til relevante aktører. Disse retter seg mot å løse sikkerhetsproblemene som ikke har blitt løst før denne rapporten publiseres.

About the investigation

Purpose and method

The NSIA has classified this accident as a very serious marine casualty. The purpose of this investigation has been to clarify the circumstances of the accident and identify safety issues and contributing factors. The NSIA has also considered what can be done to improve safety and prevent the recurrence of similar accidents and consequences in the future.

The investigation was conducted in line with the NSIA's framework and analysis process for systematic safety investigations (the NSIA method[3]).

Organisation of the investigation

The safety investigation into this accident was conducted in accordance with the Norwegian Maritime Code, chapter 18 II implementing IMO Resolution MSC.255(84) Casualty Investigation Code (CIC) and Directive 2009/18/EC of the European Parliament and of the council of 23 April 2009.

The Norwegian Safety Investigation Authority (NSIA) has been the lead investigating authority. The United Kingdom (UK), the United States of America (USA), Australia and Italy were considered Substantially Interested States (SIS) in accordance with the Norwegian Maritime Code section 474. The United Kingdom's Marine Accident Investigation Branch (MAIB), the United States Coast Guard (USCG) and the United States' National Transportation Safety Board (NTSB) worked with the NSIA, as representatives of the SIS. In addition to the MAIB, NTSB and USCG, the Australian Transport Safety Bureau (ATSB) assisted in collecting evidence for the investigation.

The investigating authorities worked closely with Wilhelmsen Ship Management, Viking Ocean Cruises, Fincantieri S.p.A., MAN Energy Solutions (MAN)[4], Wärtsilä, Lloyd's Register (LR), the Norwegian Maritime Authority (NMA), the Norwegian Costal Administration (NCA) and other interested parties.

On 12 November 2019 an interim report on the accident was published by the Norwegian Safety Investigation Authority, with contributions from the MAIB, the NTSB and the USCG.

Sources of information

The facts are based on interviews with the vessel's crew and passengers, examination of technical shipboard systems, VDR, CCTV, the JRCC's operations log, the Norwegian Coastal Administration's AIS log, information obtained from the Norwegian Maritime Authority, the owner, the shipping company, the shipyard, equipment makers, the classification society, the Norwegian Meteorological Institute, and other sources.

The investigation report

The first section of the report, Factual information, describes the sequence of events, associated data and information gathered in connection with the accident, and the NSIA's examinations and related findings.

The second section, Analysis, describes the NSIA's assessments and analyses of the sequence of events and contributing factors, on the basis of factual information and examinations carried out.

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[3] *See https://www.nsia.no/About-us/Methodology*

[4] *Changed name from MAN Diesel & Turbo in 2018*

Details and factors that are found to be less relevant in to understanding and explaining the accident are not discussed in depth.

The report ends with the NSIA's conclusions and safety recommendations.

1. Factual information

1. Factual information

1.1 Introduction

On the afternoon of 23 March 2019, the cruise vessel *Viking Sky*, on its way from Tromsø, experienced a blackout, causing loss of propulsion and steering, in 24 m/s winds (BF9, strong gale force)[5] with gusts to 29 m/s in the Hustadvika area of the Norwegian Coast. The captain immediately sent out a Mayday as the ship drifted towards the shore.

Figure 1: The voyage from Tromsø, until Viking Sky experienced problems and eventually was moored alongside in Molde. Illustration: The Norwegian Coastal Administration AIS / NSIA

[5] Based on average wind speed registered by the VDR in the period 1349 to 1359. For Beaufort (BF) wind scale, see Appendix H.

1.1.1 THE VESSEL

Viking Sky was a cruise vessel with diesel electric propulsion, with length overall (LOA) 228.3 m. The vessel was built at Fincantieri S.p.A (Fincantieri) at Ancona shipyard in Italy and was delivered in January 2017.

Figure 2: Viking Sky. Photo: Viking Ocean Cruises

Viking Sky was the third in the Viking Star class of cruise vessels. From 2018 to 2024, seven additional sister ships have joined the fleet.

Viking Sky was certified for 954 passengers and a maximum total number of people on board of 1,453. At the time of the accident, there were 915 passengers and 459 crew, a total of 1,374 people, on board. Most of the passengers were US (602) and UK (197) citizens, followed by Australians (69) and other nations (47).

1.1.2 VESSEL OWNER, SHIP MANAGER, FLAG STATE AND CLASSIFICATION SOCIETY

1.1.2.1 Vessel owner

Viking Sky was owned by Viking Ocean Cruises. Viking Ocean Cruises will be referred to as the owner throughout the report.

1.1.2.2 Ship management company

Wilhelmsen Ship Management provided technical ship management for *Viking Sky*. Wilhelmsen Ship Management will be referred to as the ship management company throughout the report.

1.1.2.3 Flag state

Viking Sky was flying the Norwegian flag and was registered in the Norwegian International Ship Register. The Norwegian Maritime Authority (NMA) is the administrative and supervisory authority in matters related to safety of life, health, material assets and the environment on vessels flying the Norwegian flag.

1.1.2.4 Classification society

Lloyd’s Register (LR) is the classification society responsible for the approval of the design of *Viking Sky* and its sister vessels. In addition, Lloyd’s Register is delegated responsibility for the survey and issuance of statutory certificates as recognised organisation (RO) by the Norwegian Maritime Authority.

1.2 Sequence of events

1.2.1 TIMESTAMPS USED IN THE REPORT

Unless otherwise stated, local time (UTC +1) is used in this report.

Information and evidence have been gathered from various systems on board. The investigation has identified time offsets between these systems, the three most important of these are shown in Table 1.

Table 1: Viking Sky time offsets. Source: NSIA

System name	Difference between UTC system time
Voyage Data Recorder (VDR)	Accurate 00:00:00
Integrated Automations System (IAS)	Add 00:01:36 to system time to get UTC
Closed Circuit TV (CCTV)	Add 00:00:27 to system time to get UTC

All known time offsets are taken into account to make sure the sequence of events is correct, which is crucial to correctly understand the accident.

Due to the time offsets, small deviations from timestamps stated in documentation from other parties might occur.

In addition to known time offsets, there is some uncertainty associated with timestamps due to sampling time and time delays on signals between the different systems on board. Hence, timestamps are mainly given with minute precision as this is considered to give sufficient detail for the reader to understand the sequence of events during the accident.

1.2.2 THE VOYAGE

Viking Sky had started the last of six Northern Light cruises in Bergen on 14 March 2019. These cruises included the ports of Narvik, Alta, Tromsø, Bodø and Stavanger. The ship left Tromsø at around 2200 on 21 March, scheduled to arrive in Bodø on 22 March. The plan was then to call at Stavanger on 24 March before crossing the North Sea south to London, which was the final stop on this cruise.

When the ship left Tromsø there were two licensed Norwegian coastal pilots on board. One of them had been on board since Lødingen on the way north, while the other boarded the ship in Tromsø. Using pilots was mandatory for parts of the voyage. Both pilots had sailed on *Viking Sky* several times before and were familiar with the ship and crew.

One of the four diesel generator sets, DG3, was temporarily out of service due to a recent failure of the engine's turbocharger (for details on the engine configuration, see section 1.7.1). New parts had been ordered and were due to be delivered on board in Stavanger. A service technician was already on board to prepare for the work.

The planned route was reviewed by the captain, the rest of the bridge team and the pilots prior to departure from Tromsø. The lack of one engine and the weather conditions were assessed as part of the voyage planning. According to notes made in the Navigation checklist for voyage planning (checklist B07), strong winds and rough seas were expected.

The weather was fine at the time of departure. At 0111, while passing the island of Senja, the lubricating oil low level alarm on the DG2 registered on the vessel Integrated Automation System (IAS) in the engine control room (ECR). The alarm was acknowledged by the engineer on watch after two seconds and returned to normal condition after a little more than a minute. The voyage was otherwise uneventful southbound towards Bodø. The wind was forecast to increase over the afternoon and into the evening of 22 March, and the captain was concerned that they would struggle to leave the quay in Bodø, taking into account the weather forecast and the tugboat capacity available. Therefore, in consultation with the ship management company on the morning of the 22nd, he decided to cancel the visit to Bodø and head directly for Stavanger, as done for three out of the five previous voyages. Information was given to the passengers that the call at Bodø was cancelled due to the forecast of deteriorating weather.

At approximately 1340 on 22 March, the staff captain, on the captain's instruction, informed the crew by e-mail about the forecast weather and instructed them to start preparing the vessel for the deteriorating weather conditions, by securing loose items in their respective areas.

For the rest of the day, the vessel sailed inshore until they reached Rørvik right after midnight, see Figure 3. On the journey from Rørvik to Trondheim the wind reached gale force[6] and the wave height was in the range 4–6 metres, according to the deck log book. They headed south at a reduced speed of 10–12 knots to make the voyage as comfortable as possible for the passengers.

[6] *Gale force (BF8) corresponds to 17.2–20.7 m/s according to the Beaufort (BF) wind scale, see Appendix H.*

Figure 3: Viking Sky sailing inshore from Bodø until passing Rørvik. Illustration: The Norwegian Coastal Administration AIS / NSIA

1.2.3 EVENTS LEADING UP TO THE BLACKOUT

As *Viking Sky* was entering the Trondheim fairway at around 0600 on 23 March, the wind had increased to strong gale[7] from the southwest. The ship headed straight into the wind and waves transiting the Trondheim fairway. In this area the ship was less exposed to wind and sea. However, the captain expected the weather to deteriorate in the afternoon and evening, in line with the weather forecasts. Later that morning, the captain therefore ordered the checklist *B10 Navigation in heavy weather* to be completed.

During the 04–08 watch, the IAS in the engine control room (ECR) registered approximately 50 alarms in total. These included two lubricating oil level alarms on the DG4 sump tank, see Figure 4. There was one low level alarm at 0502, and then a new low level alarm was registered two hours later at 0704.

During the 08–12 watch, there were approximately 150 audible alarms in total, whereas two more low level alarms were registered on DG4, both within a minute at 0904. Out of the approximately 150 alarms, 88 were tank level warnings that all registered, were acknowledged and returned to normal condition within 2 minutes at around 0845. These warnings were likely caused by a short term pressure fluctuation at one of the barometric reference sensors or a temporary faulty signal.[8]

The four low lube oil level alarms were acknowledged with no further action taken by the engineer on watch. They all reverted to pre-alarm condition within one minute and were cleared from the screen by the alarm system. For a detailed description of the alarm system, see section 1.10.

[7] Strong gale force (BF9) corresponds to 20.8–24.4 m/s according to the Beaufort (BF) wind scale, see Appendix H.
[8] Since a large number of sensors provided a warning at the same time, they were almost certainly related to the common barometric reference sensors, and not to each individual tank level sensor. The tank level sensors are programmed to provide a warning if the difference in reading between the two barometric reference sensors exceeds a set limitation. The warnings cleared within 2 minutes, indicating that the issue was no longer present.

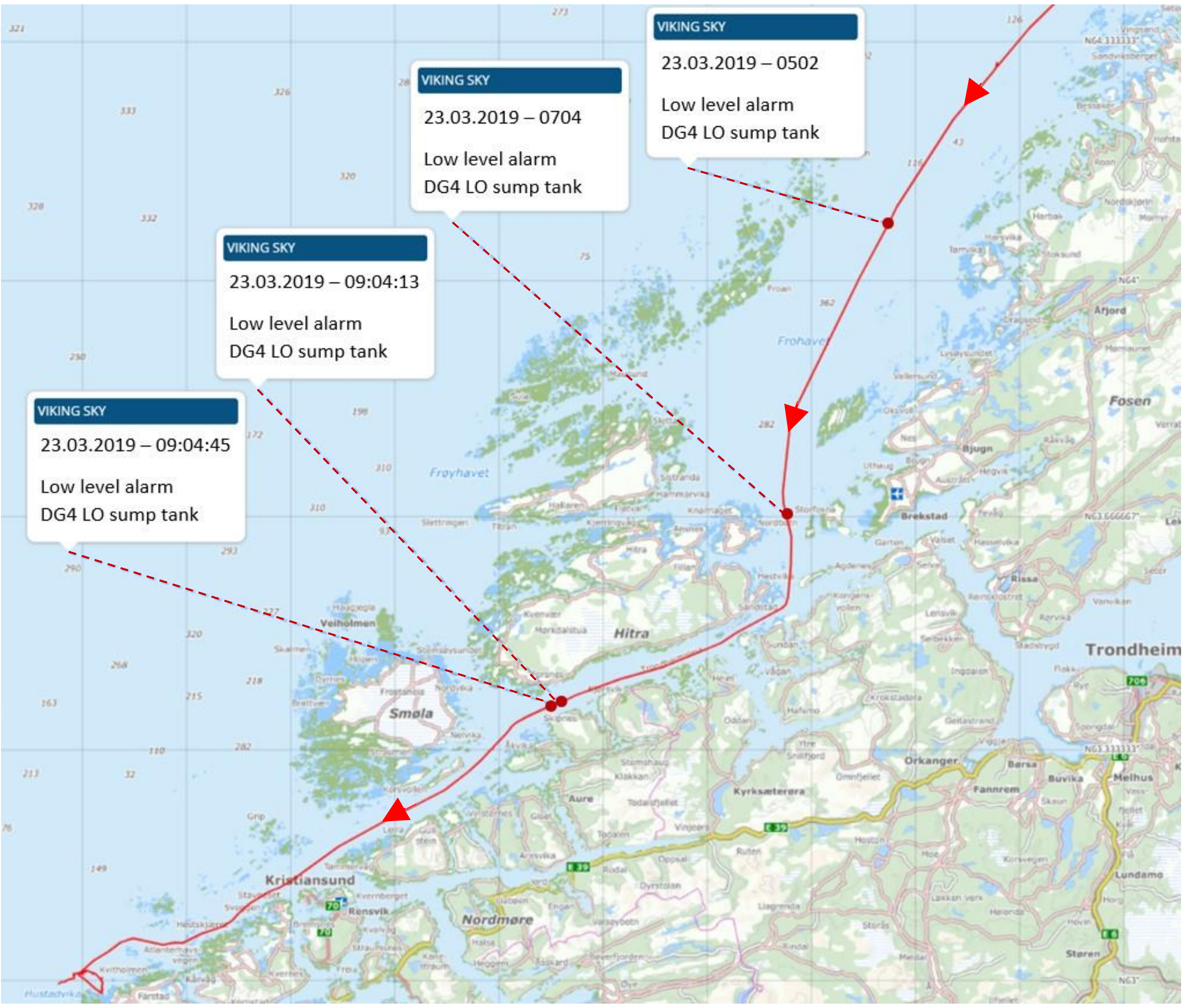
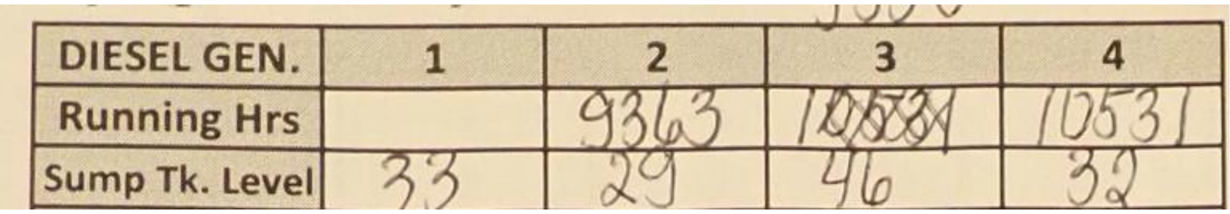


Figure 4: Lube oil sump alarms in the time period from 0502 until 0904. Illustration: The Norwegian Coastal Administration AIS / NSIA

During the 08–12 watch one of the engineers routinely measured the various tank levels. This included manual soundings of the diesel generators lube oil sump tanks. The measured levels were considered normal and logged in the noon report. No lubrication oil was added at this time.



DIESEL GEN.	1	2	3	4
Running Hrs		9363	[illegible]	10531
Sump Tk. Level	33	29	46	32

Figure 5: Extract from noon report from 08–12 watch on 23 March 2019. Tank level given in cm. Source: Wilhelmsen

When *Viking Sky* passed Kristiansund just before noon, one of the pilots was transferred to the passenger list and left the bridge as he only held a certificate as far as Kristiansund. A new pilot was scheduled to come on board from a pilot boat when they passed Ålesund. At this point, the captain informed the passengers about the weather forecast over the PA system.

The average wind speed was 30 m/s (BF11, violent storm force)[9] with gusts to 41 m/s when the vessel started to cross Hustadvika at 1230. Under the prevailing wind conditions and with the vessel's planned course, the waves and wind hit the ship on the starboard bow. At this point, the waves were in the range of 4–6 metres, according to the deck log book. Occasional higher waves were observed, and the weather conditions were continuously assessed. Data from onboard sensors show that the vessel was rolling to between 1 and 2 degrees with some maximum movements to around 5 degrees roll. The crew continued to attend to their normal duties on board and lunch service continued in the restaurants.

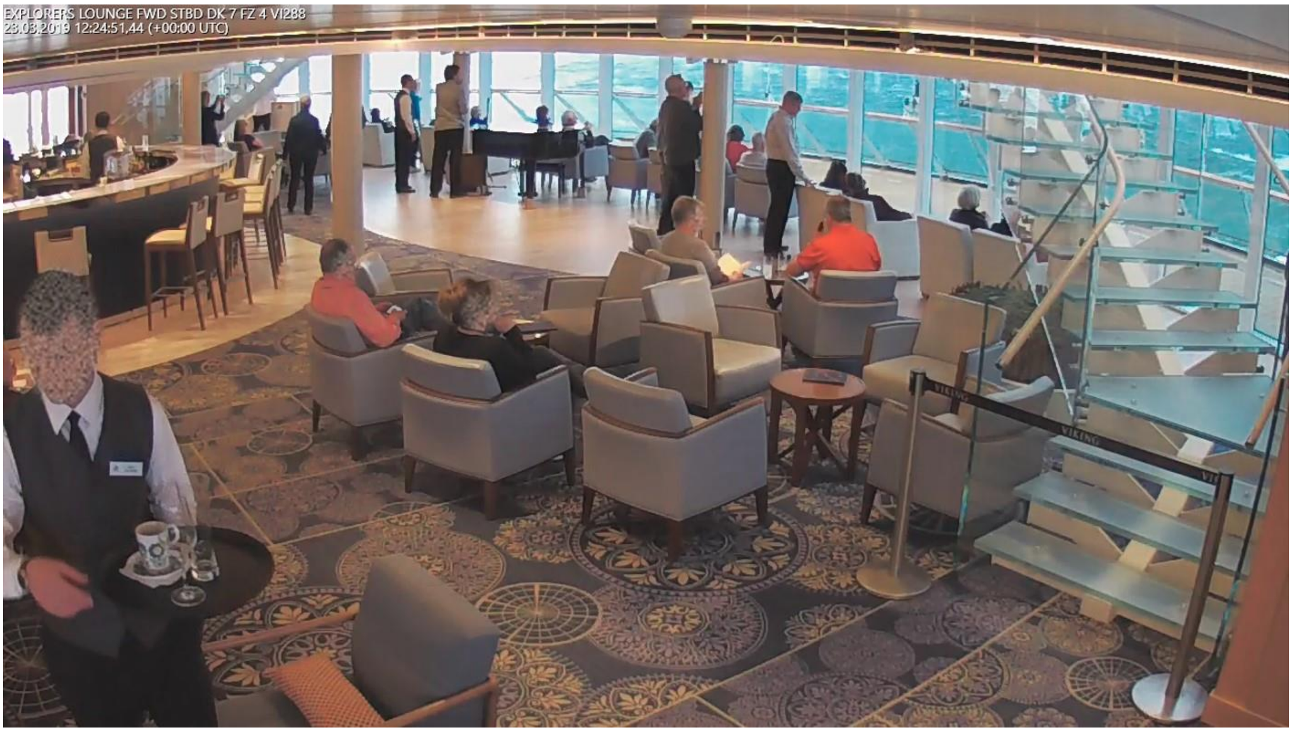


Figure 6: Entering Hustadvika at approximately 1230. Passengers having drinks and watching the weather and view from the Explorers' Lounge, forward on deck 7. View is looking forward and to port. Photo: CCTV

The heavy weather checklist was recorded as completed in the deck log book at 1317. The checklist contained 44 items within the departments navigation and communication, stability and stress, engine room, accommodation and deck. The list included an item on optimising the DG lube oil sump tank levels.

In the period from around 1330 onwards, increasingly more sea spray was observed. The rolling increased somewhat to about 3–4 degrees with maximum movements of approximately 6 degrees roll.

At 1337, DG4's low lube oil pressure and automatic load reduction alarms sounded. This indicated that the lube oil pressure on the engine had dropped below the acceptable limit and that the system was shedding electrical load from DG4 to DGs 1 and 2 in an attempt to ensure continued operation. The alarms were acknowledged with no further action by the engineer on watch, before reverting to their pre-alarm conditions within a minute and being cleared from the screen by the alarm system. At 1340, DG1 registered a low low lube oil sump tank level alarm, which was acknowledged and cleared from the alarm system within 8 seconds.

[9] Based on average wind speed registered by the VDR in the period 1220 to 1230. For Beaufort (BF) wind scale, see Appendix H

CCTV and VDR recordings show that the pilot and the officer on watch appeared outwardly unconcerned at this time, sitting in the chairs on the bridge and having a conversation. In the Explorers' Lounge and the restaurant, service continued as normal.

At 1345, DG4 shut down, followed by DG2 a few seconds later. The alarms indicating that these shutdowns were both due to low lube oil pressure were registered in the event log some 8 seconds after the shutdown alarms. During this period approximately 50 alarms registered in the engine room alarm system. Immediately after the shutdown of DGs 4 and 2, the engineer on watch informed the chief engineer by telephone and the latter came down to the ECR approximately 6 minutes later.

The vessel now lost speed to below 6 knots, which led to the automated retraction of the stabilisers, exacerbating the vessel's motion in the heavy seas. The roll angles increased to 4–6 degrees with maximum movements of approximately 12 degrees. The service continued in the restaurants, but the waiters started to clear tables not in use.

Figure 7: Crew telling passengers to move to carpeted area after chairs starting to slide sideways on the hard floor in the Explorers' Lounge right after DG4 and DG2 shutdown. Photo: CCTV

At 1356, approximately 11 minutes after the shutdowns, DG2 was successfully restarted and the stabilisers were manually deployed to the operational position. Less than three minutes later, at 13:58:31, DG1 and DG2 shut down, causing a blackout and loss of propulsion and steering.

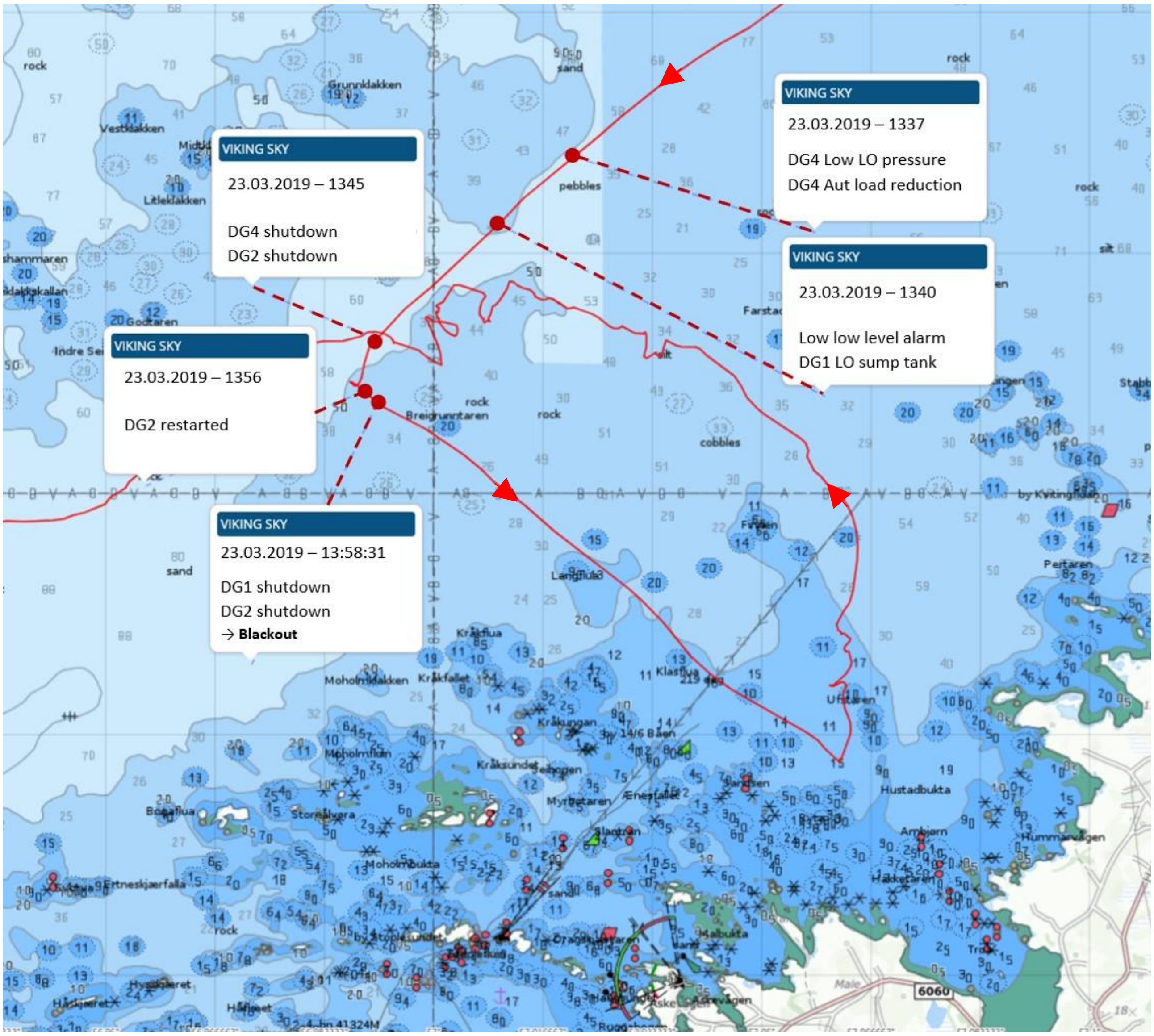


Figure 8: Events from 1337 until blackout. Illustration: The Norwegian Coastal Administration AIS / NSIA

1.2.4 BLACKOUT RECOVERY

During the 10 seconds following the blackout, approximately 1,000 alarms registered in the engine room alarm system as a result of the blackout. The vessel's emergency diesel generator started within 4 seconds, and power was established to the emergency switchboard 16 seconds later.

Numerous alarms also sounded on the bridge and some loose equipment fell down due to the vessel motion. The bridge team realised all engines had stopped and were immediately in contact with the ECR to establish how long the vessel would be without propulsion. The cause of the shutdowns was not immediately apparent to the engineers, and they were therefore unable to estimate when it would be possible to restore power.

Having assessed the situation, the captain broadcast a Mayday at 1400. He then instructed the crew to drop both anchors, and the crew were deployed to prepare them. A few minutes later, they started to lower the starboard anchor, and then the port anchor, both with ten shackles in the water. However, the anchors did not hold, and the ship continued to drift. The average wind during this period was 24 m/s (BF9, strong gale force)[10] with gusts to 35 m/s. The ship drifted towards the shore at an average speed of about 4 knots, dragging the anchors along the seabed.

Figure 9: Viking Sky drifting towards the shore. Photo: Eva Frisnes

Upon the broadcast of Mayday, the JRCC launched a major rescue operation and started scrambling resources on a large scale, see section 1.2.5.

At the time of the blackout the vessel experienced several large rolling movements to around 14 degrees. In the Explorers' Lounge on deck 7 furniture slid sideways on the hard floor and ceiling plates fell down. In the restaurant on deck 2, chairs and tables also started to slide, and passengers moved from the chairs to the fixed sofas.

Figure 10: Ceiling plates falling down in the Explorer's Lounge at the time of the blackout. Photo: CCTV

[10] *Based on average wind speed registered by the VDR in the period 1400 to 1410. For Beaufort (BF) wind scale, see Appendix H.*

In the engine department, the engineers focused on restarting the diesel generators, but the efforts were unsuccessful. After some time, they realised that the shutdowns might be caused by low lube oil pressure. At around 1412 they began transferring lube oil from the storage tank to the sump tanks. Priority was given to DG2 which was the largest of the DGs (see further details on the engine configuration in section 1.7.1).

When restarted, the DGs kept shutting down as they still had active shutdown alarms due to low lube oil pressure. When the oil level was sufficient to ensure stable oil supply to the engine's lube oil pump, the lube oil pressure was restored, and the alarm condition was no longer present. However, to allow remote operation, the control system required the alarm to be reset locally prior to a local start of the engine, but also a reset in the ECR. A few attempts to restart and connect the engines to the switchboard failed as these steps were not carried out in the correct order. In addition, the speed of the engines had to be synchronised for the engines to be connected to the main switchboard and operate in parallel. This was challenging as the speed of the first engine that was connected to the switchboard was fluctuating, as the load on the propulsion system varied due to the weather conditions.

At 1413, the General Alarm was activated on the captain's instruction and the passengers and crew began to muster. One of the pilots took over communication with the JRCC and rescue personnel, and the staff captain initiated preparations for helicopter evacuation of passengers. The captain communicated with the onshore organisation and kept the passengers informed over the PA system. The other pilot on board had the conn.

At 1422 DG2 was successfully restarted and connected to the Main Switch Board (MSB) in local manual control mode. At this time, the ship was in the immediate vicinity of several shallows and rocks, see Figure 11 and Figure 12.

Figure 11: Viking Sky in the immediate vicinity of several shallows and rocks. Photo: Eva Frisnes

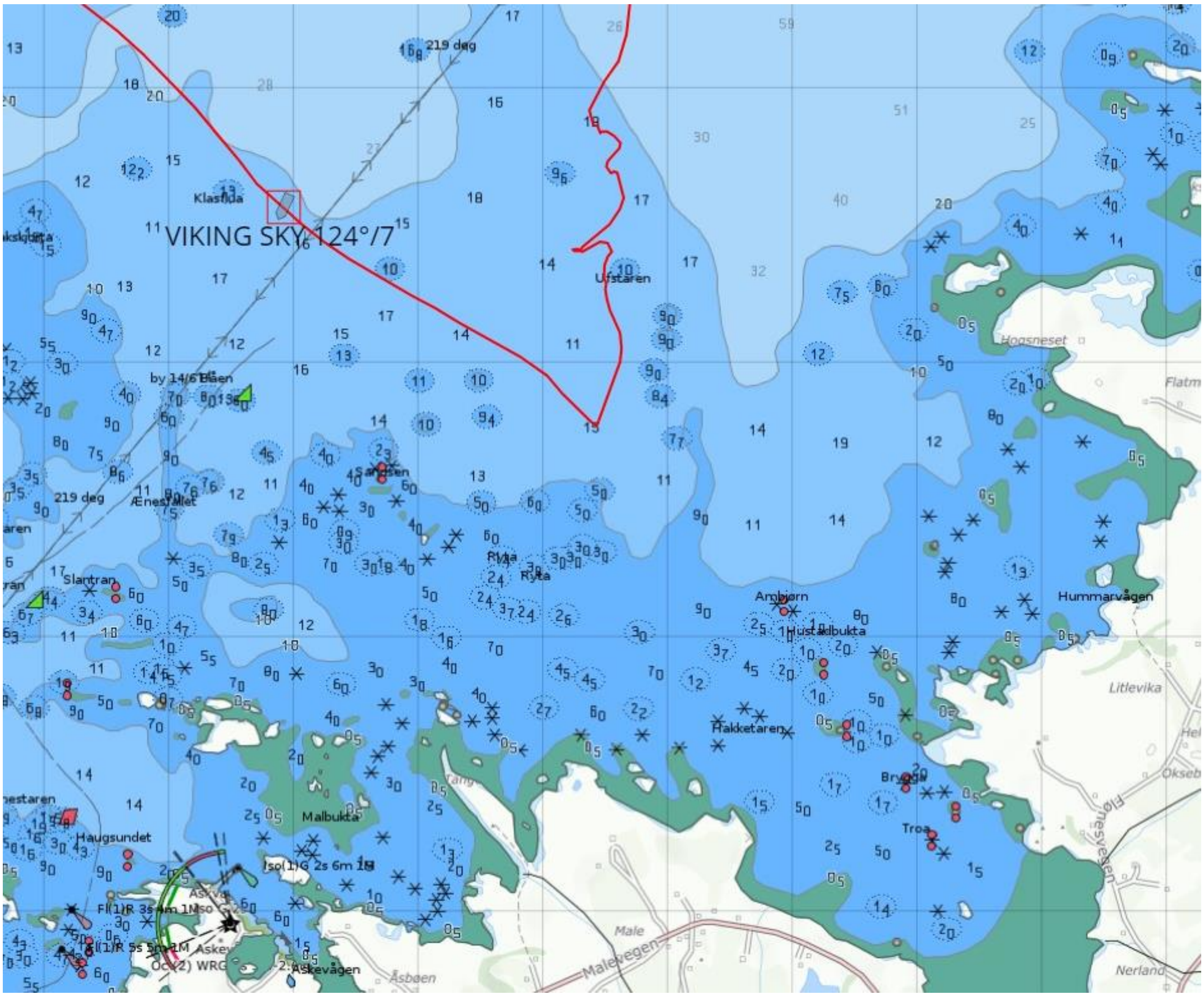


Figure 12: Viking Sky at 1422, in area with shallow banks and rocks. Source: The Norwegian Coastal Administration AIS

At 1427, the vessel drifted over a rock charted at 10 metres depth, as illustrated in Figure 13. The vessel's draft was approximately 6.5 m and the average wave height was estimated to 4–6 m according to the entry in the deck log book. According to a weather report from the Norwegian Meteorological Institute the significant wave height was 8–9 m in the area at the time.

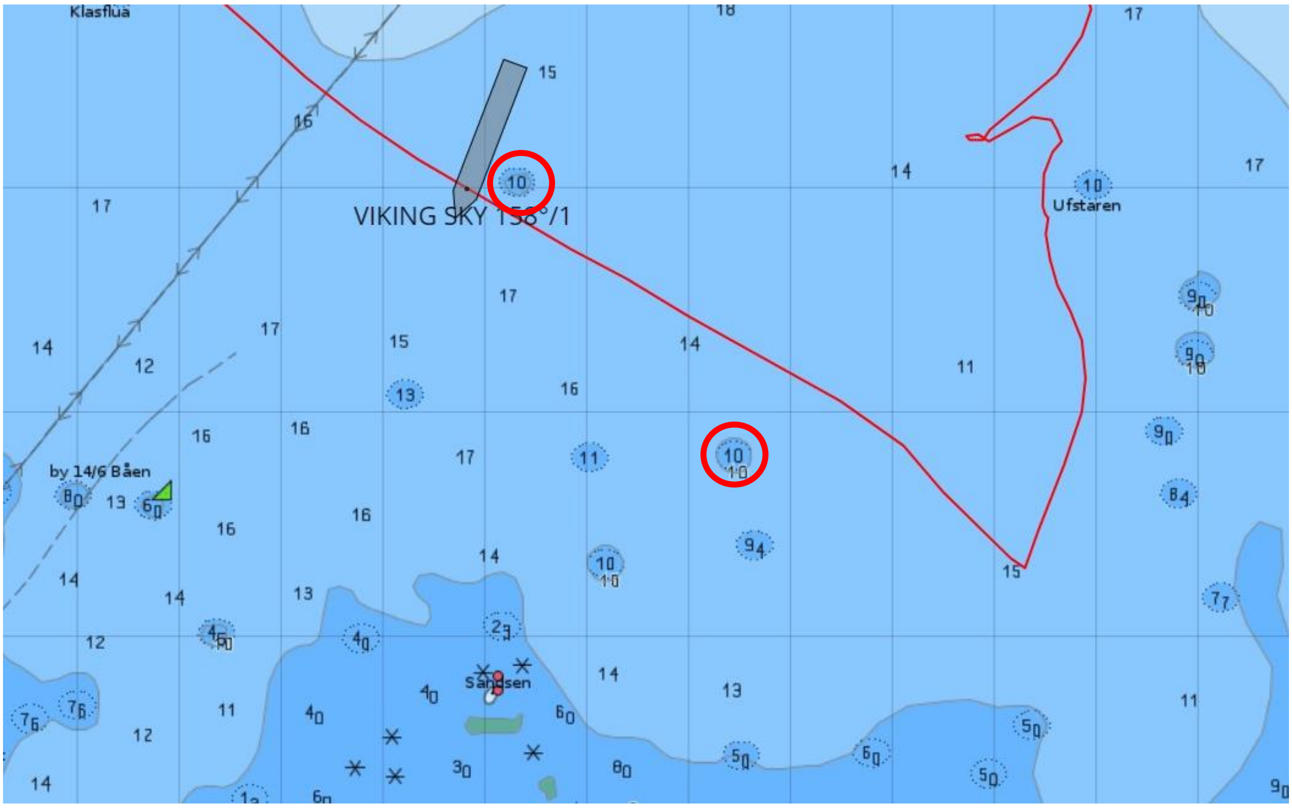


Figure 13: Viking Sky at 1427, drifting over a rock at a depth of 10 metres. Source: The Norwegian Coastal Administration AIS

The main focus of the engineers was to get the propulsion motors and the propellers powered to prevent the ship from running aground. At 1431, port propulsion motor was connected. From approximately 1437, both propulsion motors were operational and sufficient power was available to maintain between 1 to 5 knots ahead. At this time, the vessel had drifted to within a ship's length of running aground, see Figure 14.

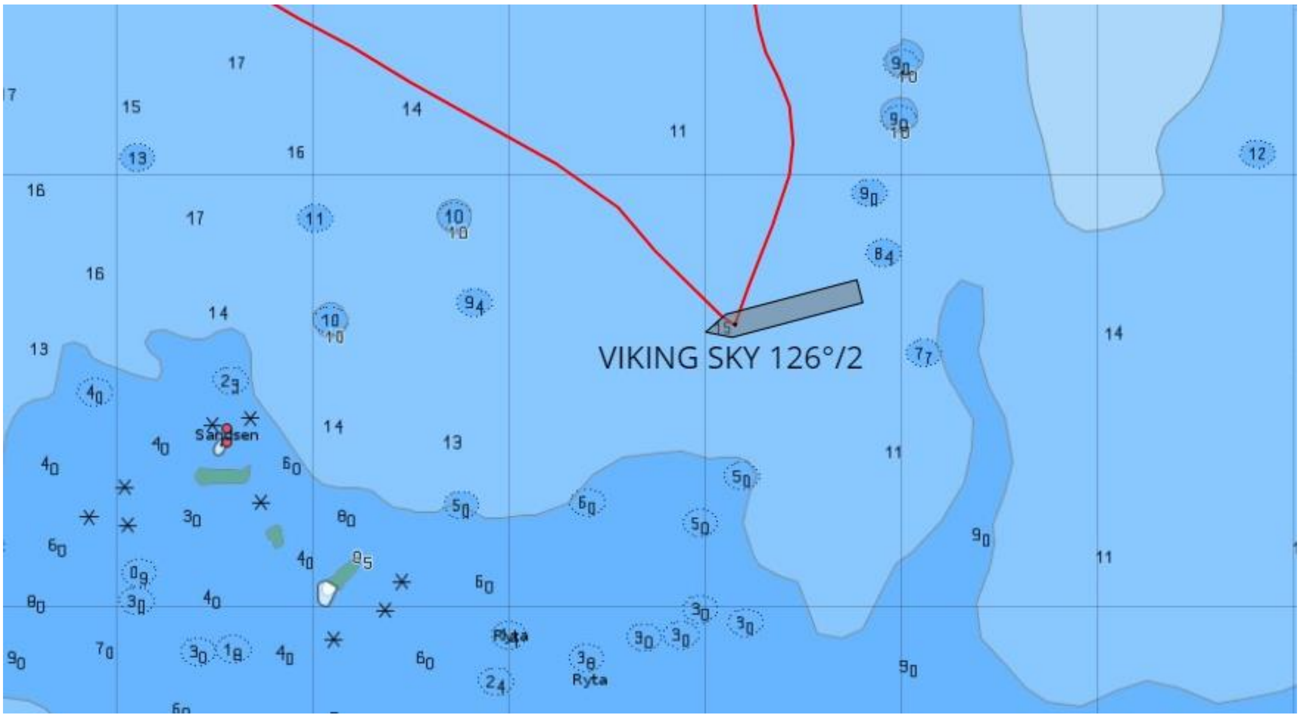


Figure 14: Viking Sky at 1437, a ship's length from running aground. Source: The Norwegian Coastal Administration AIS

Upon request from the captain, the chief engineer took manual control of the propulsion motors to prevent overspeed shutdowns when the vessel's propellers came clear of the water as the vessel moved in the heavy seas. An electrician was instructed to stand by at the propulsion motor controls to quickly reset the overspeed trips when they occurred.

Electric power for lights and navigational and communication systems were available on the bridge throughout. The captain gave regular updates to the passengers and crew over the PA system, including information about the helicopter evacuation and that the lifts on board were not to be used.

DG4 and DG1 were restarted and connected to the MSB in automatic load-sharing mode at 1524 and 1546 respectively, see Figure 15. Due to the proximity of the vessel to shallow waters and a concern that there might be an issue with the engines' control system, the engineers did not want to risk another blackout by attempting to switch DG2 to automatic. DG2 was therefore left in manual mode which meant that the electrical load on DG2 had to be manually controlled and did not automatically share load with DG1 and DG4. Only some load was taken by DG1 and DG4, while DG2 was taking most of the load.

At approximately 2046, DG2 again shut down on low lube oil pressure. Additional lube oil was pumped into its sump tank. After switching the DG to remote control and automatic load sharing mode, it was successfully restarted and connected to the MSB after about 5 minutes. DG1, DG2 and DG4 were now all running, and the power management system automatically shared the load between them.

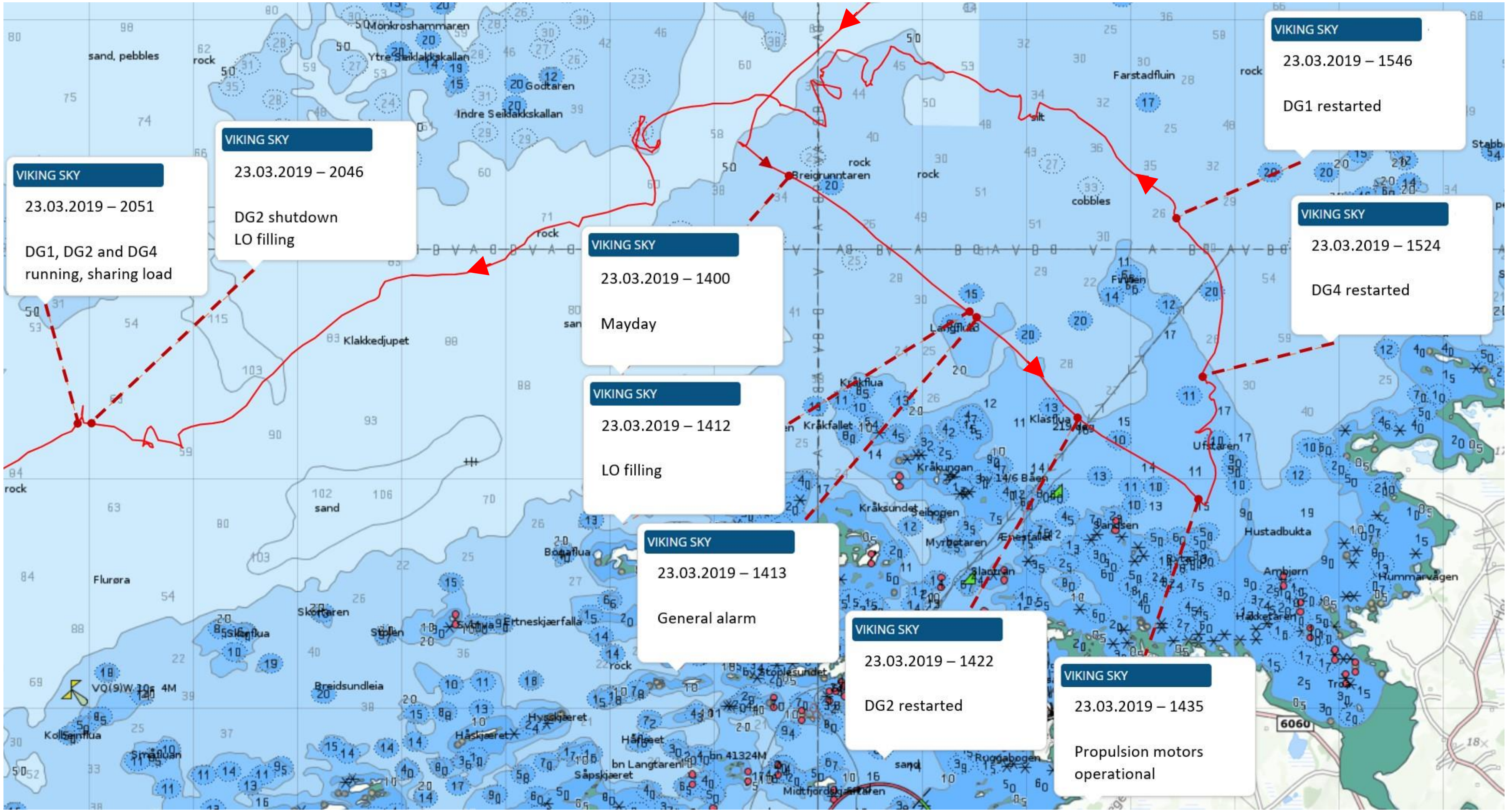


Figure 15: Events during restoration of power. Source: The Norwegian Coastal Administration AIS / NSIA

1.2.5 MUSTERING, EVACUATION AND RESCUE OPERATION

Upon the Mayday signal at 1400, the JRCC mobilised a rescue command group comprising representatives of the key collaborating parties and led by the police. The command group's remit was to have overall management and coordination responsibility in connection with the accident. The rescue operation, including maritime intervention and rescue by helicopter, the evacuation of passengers and their reception and handling on shore, is covered in detail in a report published by the Norwegian Directorate for Civil Protection (DSB)[11]. The NSIA's investigation mainly focuses on the activities on board and the rescue operations' interface with the vessel.

Shortly after the Mayday signal, helicopters and vessels with capacities to assist were scrambled and directed towards *Viking Sky*, without any delay. The coast guard vessel *KV Njord*, which later was assigned the role of *on scene coordinator* (OSC), left Kristiansund at 1415 and headed towards the scene of the accident.

On board the ship, two predetermined assembly stations were established, assembly station A in the theatre forward on deck 2 and assembly station B in the main restaurant aft on deck 2, see Figure 16 and Figure 17. The passengers gathered at these stations after the general alarm sounded at 1413.

Figure 16: Assembly station A in the theatre forward, deck 2. Photo: NSIA

Figure 17: Assembly station B in the main restaurant aft, deck 2. The photo only shows a section of the muster area. Photo: NSIA

At 1426, *Viking Sky* reported to the JRCC that it had dropped both anchors, but that neither of them held. *Viking Sky* therefore reported to the JRCC that they wanted to evacuate passengers as

[11] *Rapport: Evaluering av Viking Sky-hendelsen, ISBN 978-82-7768-502-1 (PDF), DSB (2020). Report: Assessment of the Viking Sky Incident, ISBN 978-82-7768-511-3 (PDF), DSB (2021).*

soon as possible. Due to the weather, the captain, supported by the pilots, considered it too dangerous to evacuate the passengers and crew in the vessel's lifeboats or by transfer to other vessels. The captain, in consultation with the JRCC, therefore decided to initiate evacuation by helicopter as soon as they were in place.

At about 1500, the vessel encountered a series of particularly large waves. A large wave struck the door between the starboard side forward of the main restaurant and the outer starboard side embarkation deck. The wave impact dislodged and pushed the door inwards into the assembly station where some passengers were struck by the door sustaining injuries. Cold seawater entered the assembly station knocking many passengers to the floor and dislodging unsecured furniture, consisting mostly of tables and chairs. Since the assembly station was in the dining room, large quantities of loose objects such as bottles, glasses, cutlery, dishes and food service items were thrown about and broken. Most of the injuries sustained by the passengers occurred in connection with this accident. The damaged metal door remained lying on the floor in assembly station B, see Figure 23.

All of the passengers at assembly station B were relocated to spaces in the atrium which was forward of assembly station B on both deck 1 and 2 midship, or the main theatre assembly station A on deck 2.

The pre-defined and primary area for receiving helicopters and hoisting passengers was on the port side of deck 8, just outside the exit door, see Figure 18. An additional space for evacuation was considered in order to increase capacity by allowing two helicopters to perform the hoist operation simultaneously, but this was considered too risky due to the weather and the vessel's movements, see Figure 19.

Figure 18: Primary hoisting area, port side, deck 8. Photo: NSIA

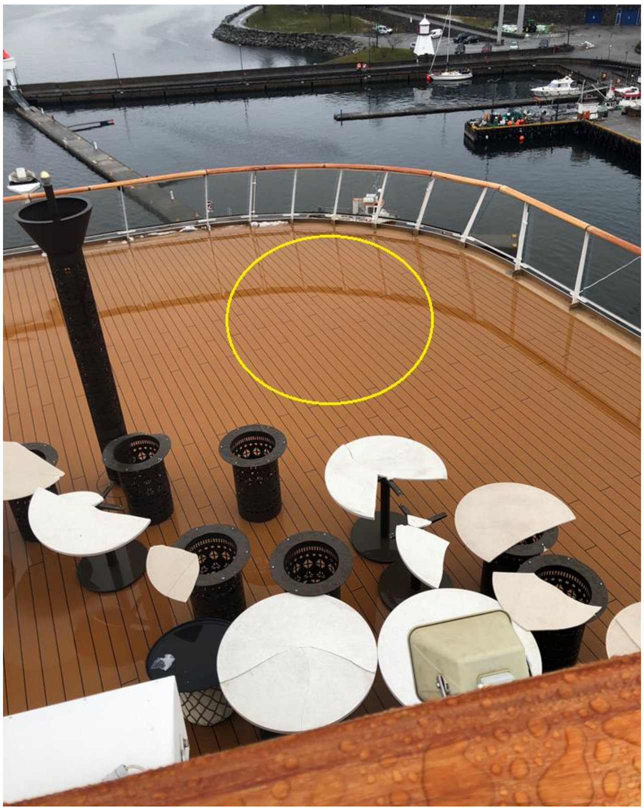


Figure 19: Secondary hoisting area, aft, deck 7. For safety reasons, this area was never used. Photo: NSIA

A total of six rescue helicopters were involved in the evacuation. The helicopter that was stationed the closest took off from Kristiansund, which is only around 40 km from Hustadvika. The five remaining helicopters all took off from helicopter bases along the coast, from Stavanger in the south to Ørlandet in the north.

The first helicopter was in position above the vessel at 1503, and the crew manoeuvred the vessel to give the helicopters the best possible working conditions for the evacuation of passengers. After the helicopter crew had made visual observations from above the ship, and conducted an assessment of the hoist operation, they reported that they were 'ready to hoist'. The crew was in place on deck to receive the guide line from the helicopter, and a rescue crewman was hoisted down. The first helicopter hoisting operation took place a few minutes later, approximately 1 hour 20 minutes after the Mayday signal. Injured passengers were hoisted up together with a rescue crewman. Many of the other hoist operations were carried out as tandem lifts to save time and increase capacity. After a while, the crew of *Rescue5* decided to position a rescue crewman on board the vessel to organise the rescue work and optimise the operation.

The operation was performed as a series of continuous airlifts by helicopters that flew back and forth between a hold position, *Viking Sky* and the onshore reception centre located only about 2 km away where they delivered the rescued passengers and refuelled. The operation was therefore organised in a way that ensured full utilisation of resources.

Figure 20: Helicopter hoisting operation. Photo: Eva Frisnes

The coast guard vessel *KV Njord* reached *Viking Sky* at approximately 1640, having been assigned the role of *on scene coordinator* (OSC). The tugboat *Vivax* arrived at around 1705 and stayed in the vicinity of *Viking Sky*, which at this time had sufficient power to manoeuvre slowly outwards towards deeper waters.

A separate emergency call was made shortly before 1900, this time from the cargo ship *Hagland Captain*, which had suffered a blackout about 2 NM east of *Viking Sky*. One of the helicopters that was helping to rescue passengers from *Viking Sky* was diverted to the cargo vessel. This had no practical consequences for the rescue rate of passengers, as five helicopters were still involved in the evacuation from *Viking Sky*.

At around 1945, it was decided that the tugboat *Ocean Response*, which was about 4–5 hours away, would head towards *Viking Sky*, as it was considered that the ship had sufficient bollard pull and size to handle a tow of *Viking Sky* together with *Vivax*.

When *Viking Sky* reached deeper waters shortly after all available DGs (DG1, DG2 and DG4) were functioning at around 2100, the port anchor was winched in first, revealing that the anchor flukes had been torn off. There were difficulties winching in the starboard anchor because the anchor chain was lying across the bulb of the bow and astern on the port side. It was therefore decided to pay out the whole chain and slip the chain from its bitter end[12]. This took place just before 2230. *Ocean Response* arrived at the vessel at 0245. The weather was still rough, and it was decided to postpone the fastening of the towlines until after daylight.

Towlines were eventually secured on board both fore (*Ocean Response*) and aft (*Vivax*) at about 0830, although the vessel maintained its own propulsion. At approximately 0915, the captain decided to stop the helicopter evacuation. According to the JRCC, a total of 460 passengers had been evacuated in the continuous helicopter evacuation throughout the night. *Viking Sky* now turned shoreward and slowly made its way to Molde, where it moored at around 1625 in the afternoon of 24 March. Figure 21 and Figure 22 show events during the evacuation and rescue operation.

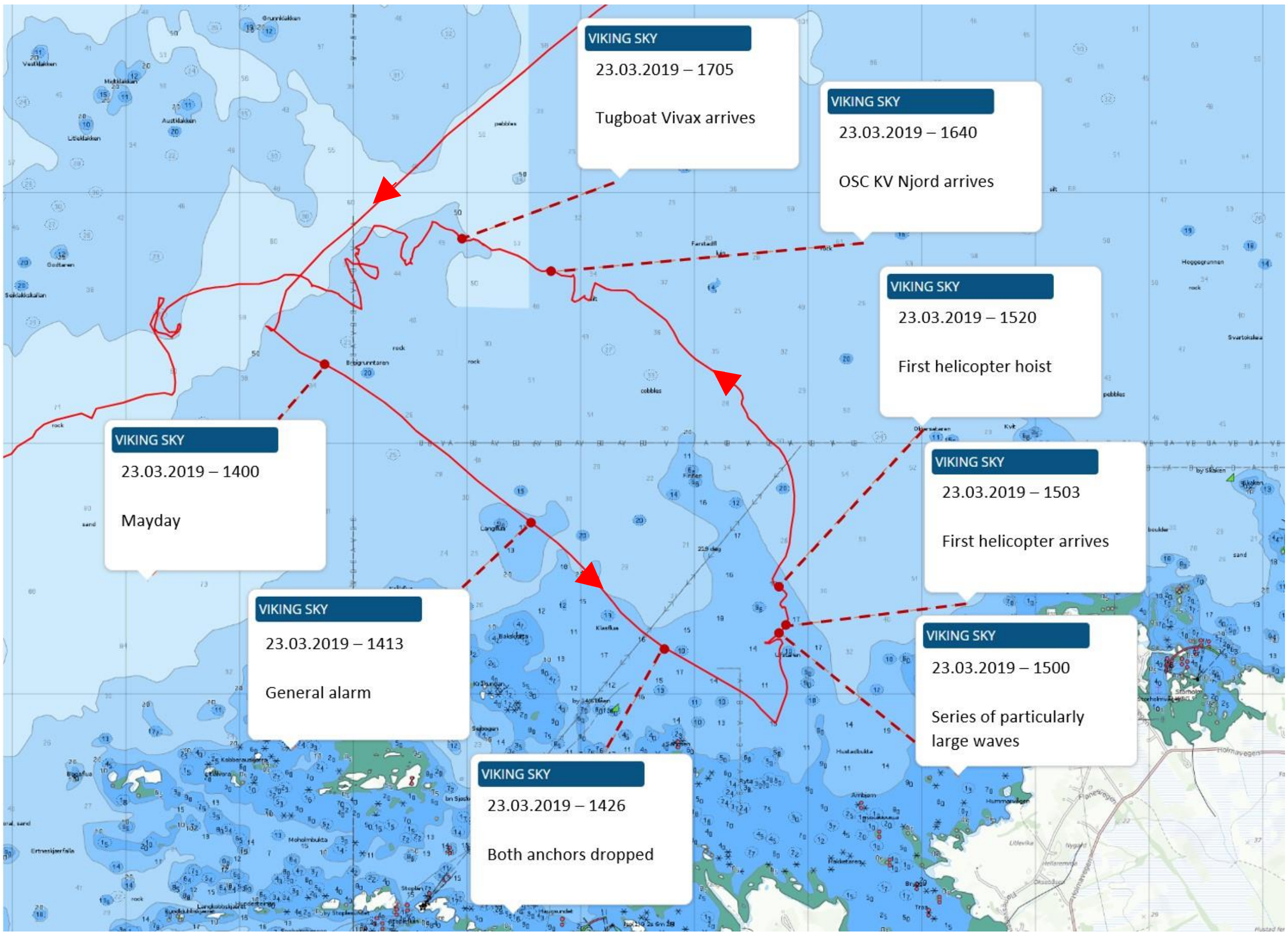


Figure 21: Events during evacuation and rescue operation, 1400–1705. Source: The Norwegian Coastal Administration AIS / NSIA

[12] Bitter end: The inboard end of the anchor cable that is secured to a strong point normally with some form of quick-release arrangement to allow the cable to be safely slipped in the event of an emergency.

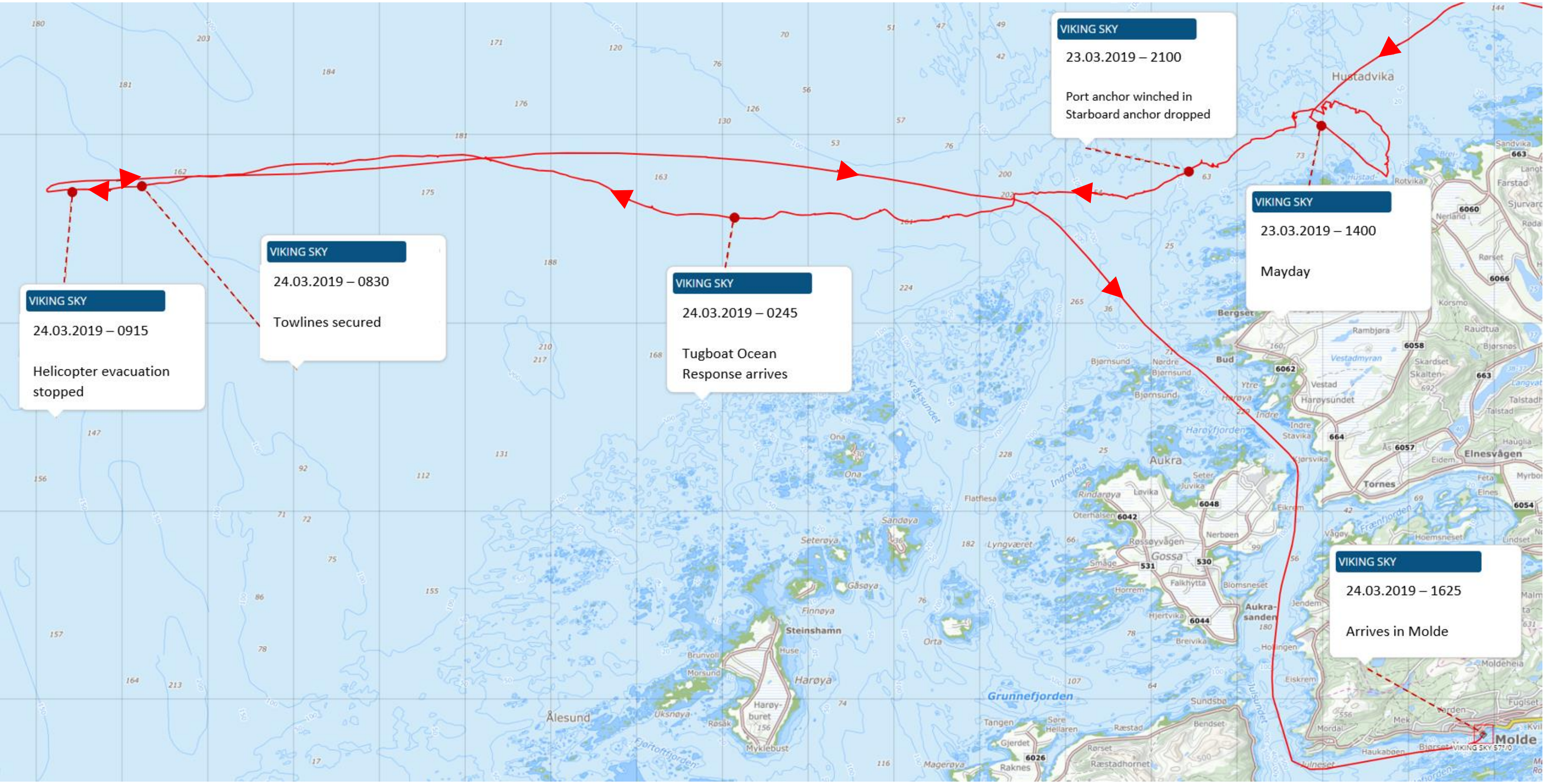


Figure 22: Events during evacuation and rescue operation, 2100–1625. Source: The Norwegian Coastal Administration AIS / NSIA

1.3 Injuries

The NSIA has registered 19 injuries to passengers during the accident, one of which was regarded as a serious injury. The injured passengers were taken care of on board and after the evacuation sent to different hospitals and emergency treatment centres in the area for further treatment. One passenger was flown to a hospital in Bergen.

No crew members were reported injured during the accident.

Table 2: Injuries. Source: JRCC

Injuries	Crew	Passengers	Other
Fatal	-	-	-
Serious	-	1	-
Minor/none	-	18	-

1.4 Damage to vessel and equipment

Witness accounts and CCTV footage indicate that most of the damages to the ship and interior occurred in connection with, or within an hour or so after the blackout.

There were some cracked windows on deck 7. The door from the outside deck on the starboard side into the restaurant on deck 2 was broken due to a wave impact shortly after 1500, see Figure 23. This is also considered the most likely time for all the damage on the starboard side to have occurred, including lifeboat no. 3, see Figure 24, all the lifeboat davit control stations, the gangway bracket, the railings from D2 to D3 and the lifejacket boxes. The starboard stabiliser was also damaged.

Figure 23: Broken door in the restaurant at deck 2. Photo: NSIA

Figure 24: Damage to lifeboat on starboard side. Photo: NSIA

As detailed in section 1.2.5, the port anchor was damaged, and the starboard anchor and chain were let go.

The NSIA does not have a full overview of all the damage to the interior, but witness accounts and CCTV footage have revealed damage in the restaurant after its door to the open deck was dislocated. In addition to ceiling plates that fell down, loose items and unsecured furniture also caused damage in parts of the ship.

1.5 Weather, sea conditions and vessel motion

1.5.1 WEATHER AND SEA CONDITIONS

Information on weather and sea conditions is obtained from various sources, and both weather reports prior to the accident and observed conditions during the accident are assessed:

- The Norwegian meteorological institute
- Norwegian Coastal Administration AIS
- Voyage Data Recorder, VDR
- Video surveillance system, CCTV
- Deck log book
- Witness statements, videos and observations from crew, passengers and other relevant actors

The weather forecasts available prior to departure from Tromsø on the evening of Thursday 21 March, reported near gale (BF7)[13] to gale (BF8) force winds 20 m/s from south/southwest Friday on the southbound voyage towards Bodø. Forecasts from Friday morning reported gale force (BF8) winds up to storm (BF10) 25 m/s and significant wave heights up to 7 metres on the further voyage towards Rørvik midnight Friday.

Several, almost identical weather reports and special alerts were broadcast for the area from Salten (Bodø) to Møre and Romsdal (Hustadvika) during Friday and Saturday. For the area including Hustadvika, storm force (BF10) winds 25 m/s from southwest with gusts up to 30–35 m/s and wave heights up to 8–11 metres were forecast for 23 March, the day of the accident.

The investigation shows that the weather and sea conditions were as forecast. Details are presented in the sequence of events.

1.5.2 VESSEL MOTION

Viking Sky's VDR did not record inclination angles, nor was it required to do so, see section 1.7.5. The main source of information regarding the vessel motion is recordings of heel and trim registered by sensors in the vessel's fuel efficiency management system, Eniram. The purpose of these sensors and their measurements was not to inform the decision-making process on board, nor was it to assist in casualty investigations. However, according to the supplier, the sensors were calibrated to 20 degrees inclination, which is more than the highest registered motion during the interval of interest.

Analysis of the data has revealed that the signals are influenced by noise. In connection with post-accident computational fluid dynamics (CFD) calculations, SINTEF Ocean closely analysed the data for an interval of 5 minutes around the time of the first engine shut down and found that the

[13] *For the Beaufort wind scale, see Appendix H*

noise was primarily above 1 Hz frequency. The noise had a relatively small influence on the roll angle, but for the purpose of the CFD calculations a low pass filter with a cut-off of 0.8 Hz was used to remove all frequencies above 0.8 Hz.

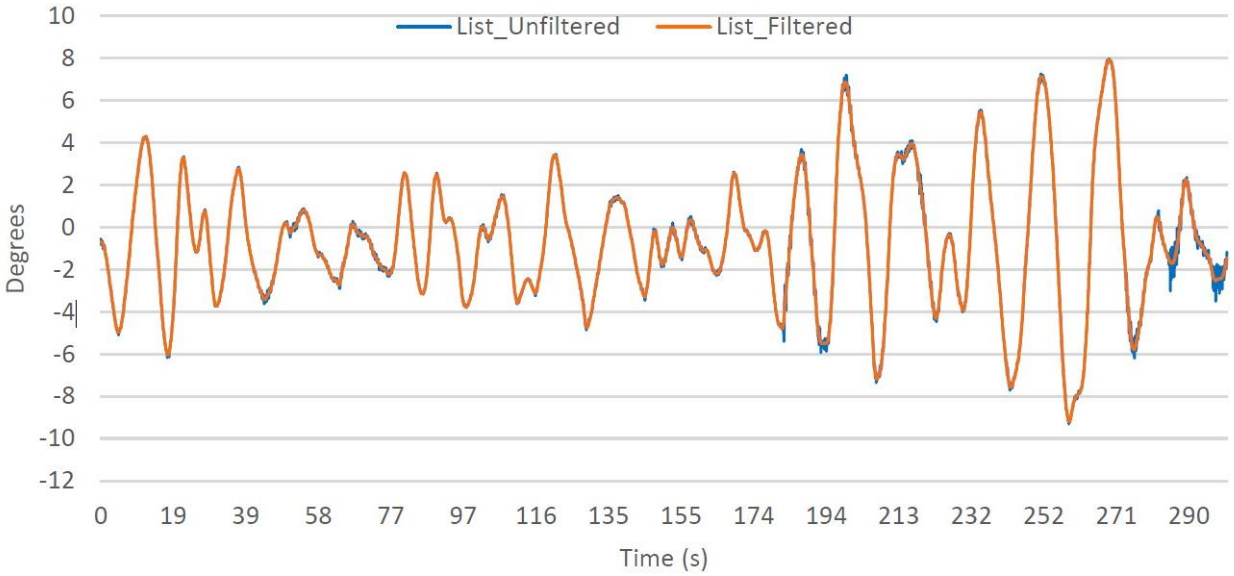


Figure 25: Angle of list (roll), filtered and unfiltered signal. Source: Eniram data / SINTEF Ocean's CFD report

The approximate angles of inclination at various periods of the sequence of events, as specified in section 1.2, are taken from the Eniram dataset. For the purpose of establishing these approximate angles of inclination no filter was applied to the signal.

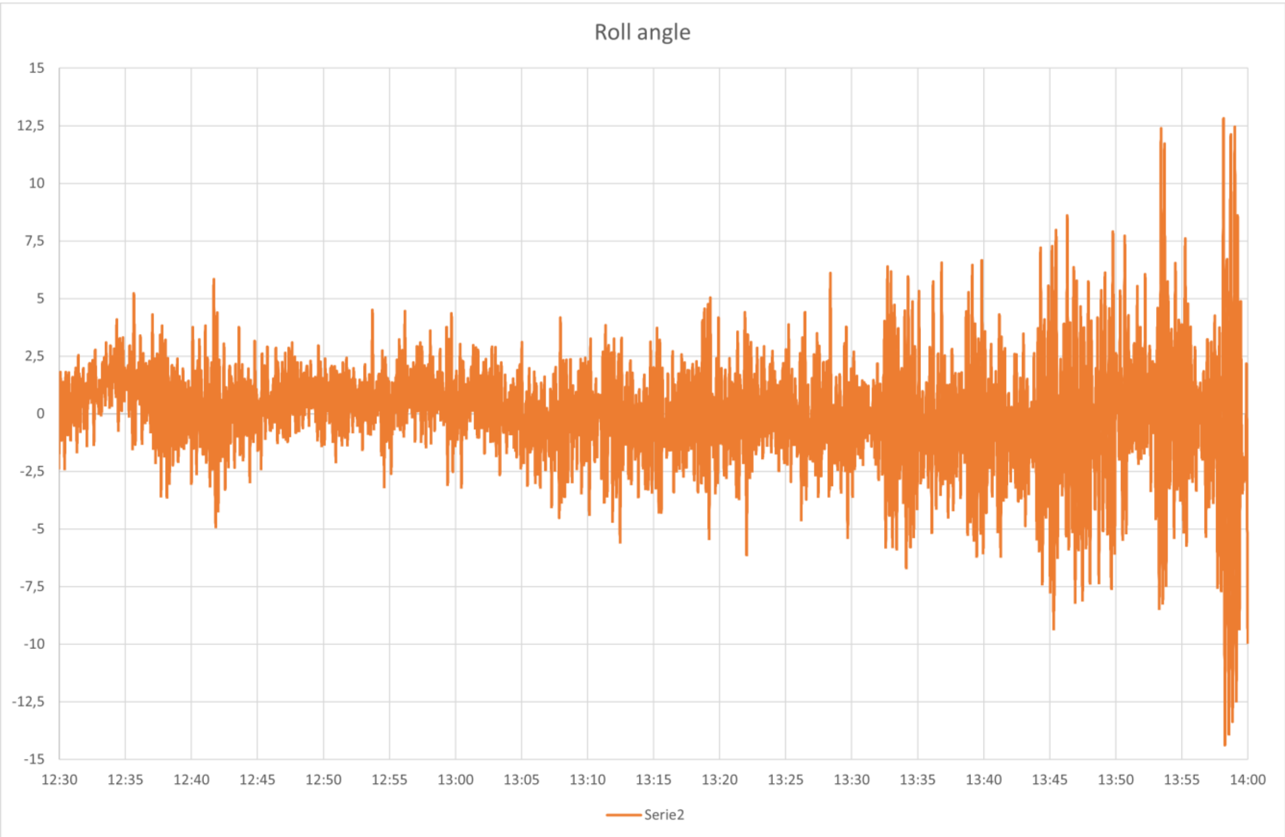


Figure 26: Roll angle registered by Eniram 1230 to 1400 LT. Source: Eniram/NSIA

Viking Sky entered Hustadvika at approximately 1230 LT, experienced the first engine shut down at 1345 and the blackout at 1358. As described in the sequence of events and as shown in the graphical representation of the Eniram recordings in Figure 26, the angle of roll increased over this period and reached approximately 14 degrees at the time of the blackout.

1.6 Description of waters in Hustadvika

Hustadvika is the western part of the fairway between Bud and Kristiansund, see Figure 27.

The *Admiralty Sailing Directions* state:

> *Area 11, Hustadvika (63°00.00’N 7°00.00’E) is a notoriously dangerous area; the coast is completely exposed to the weather and extensive shoals lie offshore. Strong winds from SW to NW raise a large steep swell with hollow breaking seas, especially during the out-going tidal stream. These conditions are likely to be particularly severe in the area of Budadjupet between Bjørnsund (62°53.75’N 6°48.96’E) and Kolbeinsflua, 5 miles NNE. Breaking surf is reported to occur throughout the whole area.*

A similar description is available in the *Norwegian Pilot Guide*, Volume 4. According to this publication, the description is to a significant extent based on a research project aiming to improve safety for smaller vessels in heavy seas. A survey was also conducted, where pilots and fishing professionals were asked about areas with unusually challenging wave conditions. Hustadvika was frequently emphasized, and the publication describes the area as one of the most dangerous and talked-about stretches of the Norwegian coast.

The raster chart for Hustadvika included a warning about “Dangerous Waves”, with reference to *Norwegian Pilot Guide* and *Admiralty Sailing Directions*. The electronic navigational charts (ENC) did not include the same warning at the time of the accident. The ENC was updated to include the warning in October 2019.

Viking Sky followed the main fairway when crossing Hustadvika on the day of the accident.

Figure 27: Hustadvika. Source: The Norwegian Coastal Administration

1.7 Machinery and equipment

1.7.1 POWER GENERATION

1.7.1.1 Diesel generators

The electric power generation on board *Viking Sky* comprised four diesel generators (DGs) manufactured by MAN.

The vessel was equipped with two types of DGs, the smaller (DG1 and DG4) were 9-cylinder inline engines each capable of supplying 5,040 kW electric power, the larger (DG2 and DG3) were 12-cylinder V-engines, each capable of supplying 6,720 kW. *Viking Sky* had two separate engine rooms, and there were one large and one small DG in each engine room, DG1 and DG2 in the forward engine room and DG3 and DG4 in the aft engine room, see Figure 28 and Figure 29. The engine rooms were in different watertight compartments and separated by A60 class boundaries for fire protection.

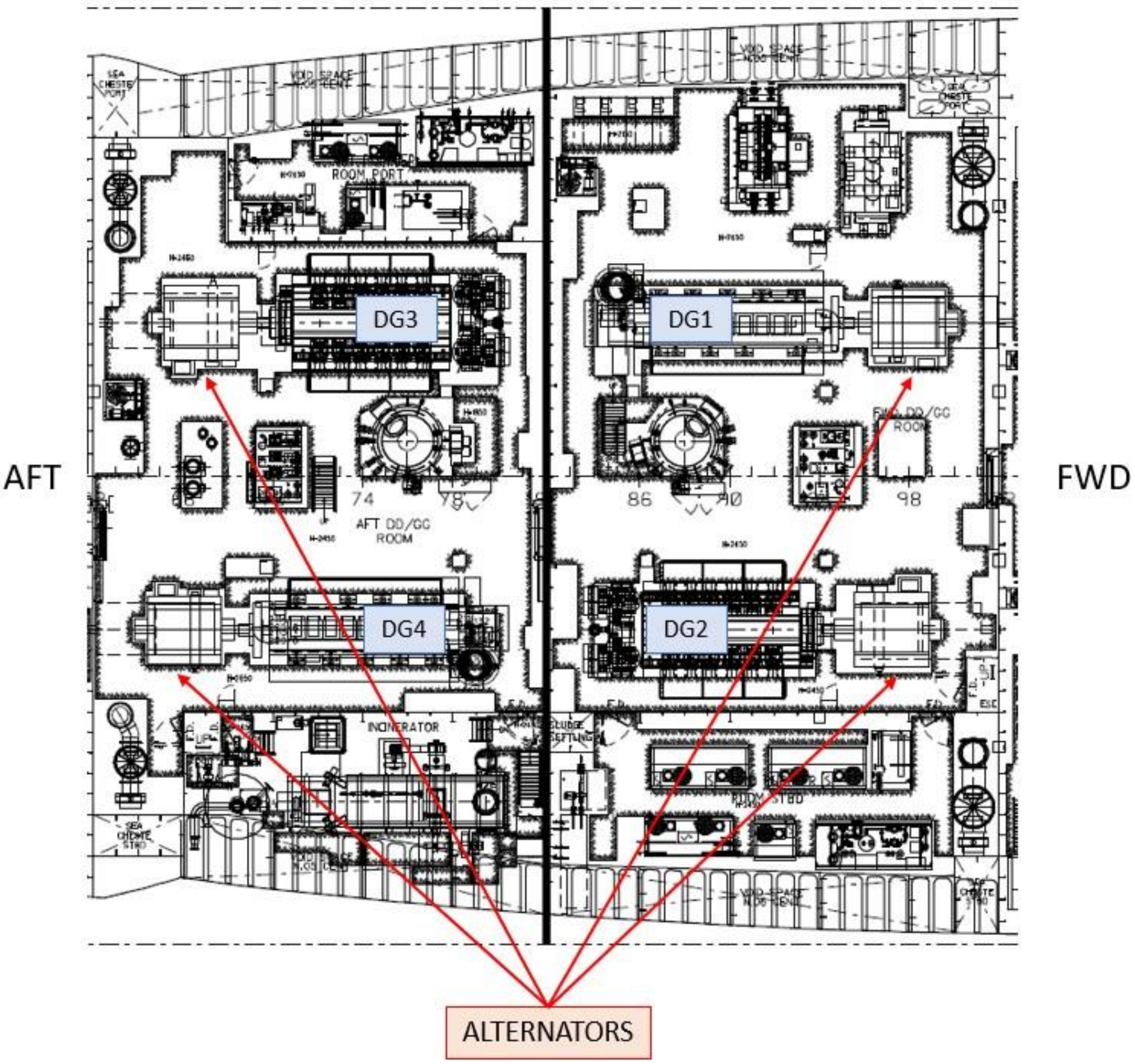


Figure 28: Extract from the vessel's General Arrangement, showing the positioning of the DGs. Illustration: Fincantieri/NSIA

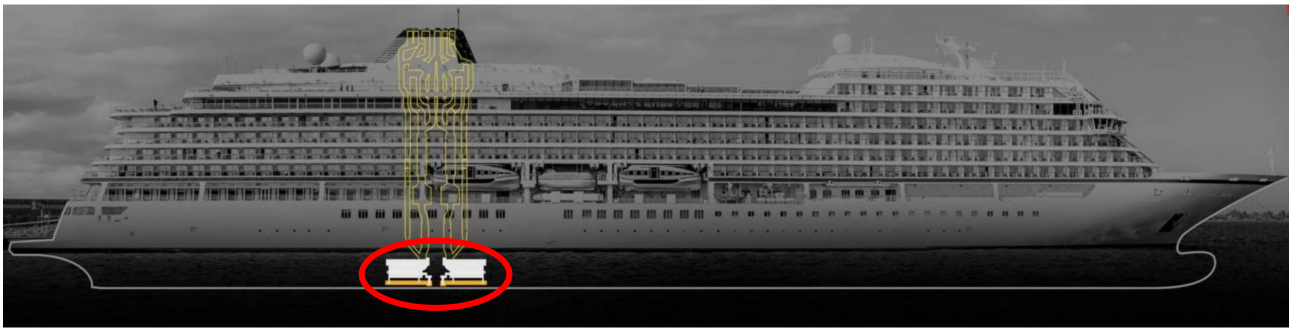


Figure 29: Viking Sky in profile, showing location of the DGs and the lube oil sump tanks. Illustration: Adobe Stock/Fincantieri/NSIA

1.7.1.2 Lubrication system

For each DG, the lubricating oil (lube oil) system consisted of an engine-driven pump for forced lubrication of bearings, turbochargers and other engine components, an oil cooler (heat exchanger) and automatic oil filters. In addition, there was an electrically-driven pre-lubrication pump, used to ensure adequate lubrication during start-up, see Figure 30. All DGs also had their own by-pass lube oil cleaning circuit with individual lube oil purifiers.

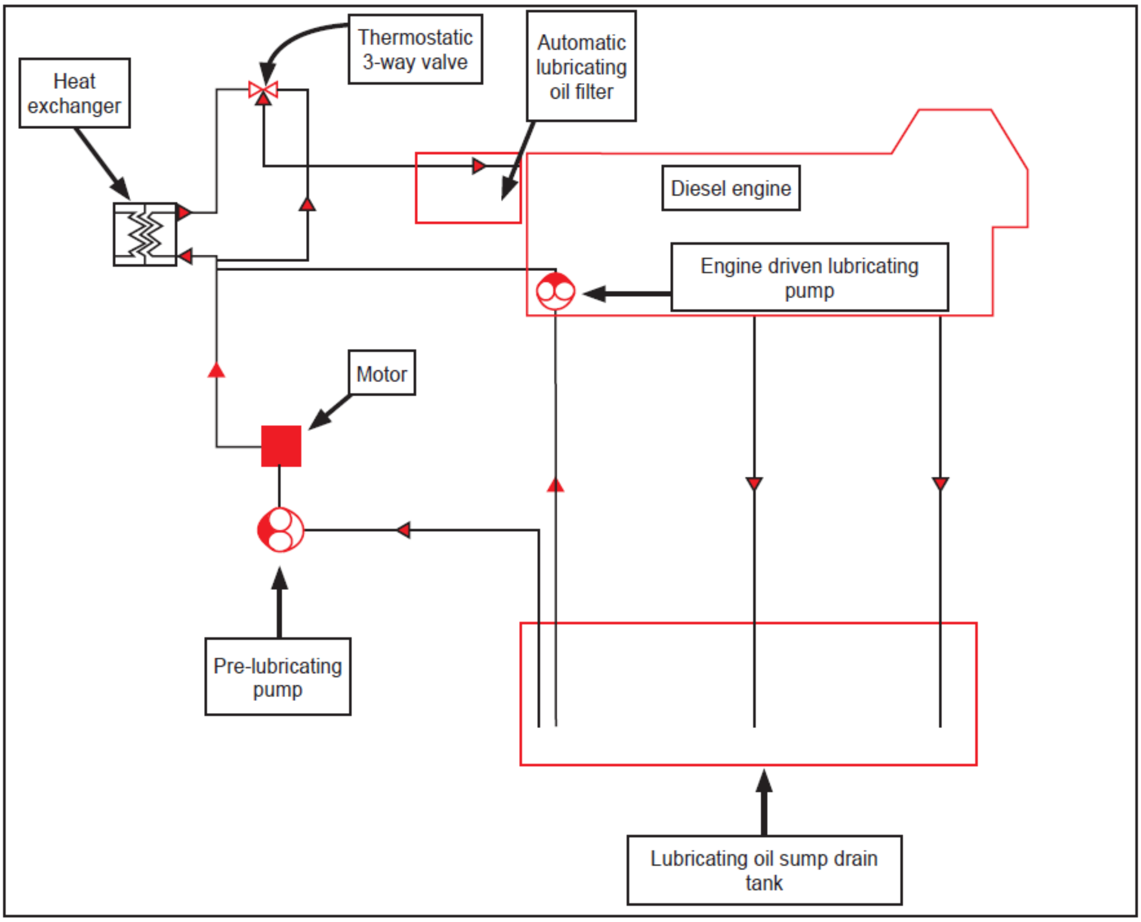


Figure 30: Schematic drawing of the diesel generator lubricating oil system. Illustration: NSIA

The DGs were of a dry sump design with separate lube oil sump tanks located directly below the engines.

The lube oil sump tank design is described in further detail in section 1.8.1.

The vessel had two lube oil transfer pumps of 10 m^3/hour capacity each: one for transferring clean oil to the DGs sump tanks and the other for transferring oil from the DGs sump tanks to the dirty oil tank.

1.7.1.3 Lubricating oil monitoring

The oil level in the lube oil sump tanks were measured both automatically by built-in level sensors in a remote monitoring system and manually using a sounding tape. The automatic measurements would generate alarms if the measured level was below or above defined alarm levels. The lube oil level remote monitoring system is described in further detail in section 1.10 and lube oil level management is described in section 1.12.

The diesel engines were equipped with independent control and monitoring systems that included monitoring of the lube oil pressure at the engine and turbocharger lube oil inlets. The system was programmed to give low lube oil pressure alarms if the pressure dropped below certain levels, including an automatic slow-down of the engine at a set pressure and automatic shutdown of the engine should the lube oil pressure fall to a critically low level. The purpose of the automatic shutdown was to protect the engine from damage caused by insufficient lubrication. The automatic shutdown was programmed with a four second delay. According to the engine manufacturer the purpose of the delay was to avoid unwanted shutdowns due to short pressure fluctuations that typically do not harm the engine as long as they stay below the time limit. This is not saying that the suction pipe inlet may be exposed to air at any time. MAN has informed that the suction pipe inlet must remain fully submerged in oil at all times. Even a brief exposure of the suction pipe inlet opening to air can cause a significant pressure drop in the engine’s lube oil of more than 4 seconds.

1.7.2 POWER DISTRIBUTION

The electrical distribution system consisted of two 6.6 kV main switchboards (MSBs) positioned in the forward and aft engine rooms with interconnecting circuit breakers, six transformers for engine room auxiliary machinery, various low voltage substations, an emergency DG and an emergency switchboard. The generated voltage was 6.6 kV. Four air conditioning compressors, a stern thruster and two bow thrusters operated directly on 6.6 kV. All other engine room auxiliary machinery operated on 690 V.

The forward MSB was designated as ‘primary’ and the aft MSB as ‘secondary’. The forward MSB synchronisation panel had a control selector switch for each of the interconnecting tie circuit breakers and DGs 1 and 2. These switches had three positions: Local Manual, Local Automatic and Remote Automatic. The forward MSB also had control selector switches for DGs 3 and 4. These switches had two positions: Local Manual and Local Automatic. The aft MSB had three-position control selector switches for DGs 3 and 4 and a transfer switch to pass control of DGs 3 and 4 to the forward MSB.

Under normal conditions both MSBs were connected by tie circuit breakers. However, in case of failure or the requirement to carry out maintenance work, the switchboards could be operated independently with the tie circuit breakers open. The tie breakers had opened automatically during the blackout on 23 March and were closed manually during the blackout recovery process.

The electrical systems – including DG circuit breakers – were monitored by general protection modules.

1.7.3 POWER MANAGEMENT

1.7.3.1 General description

Viking Sky was equipped with a Wärtsilä NACOS VALMATIC Platinum Integrated Automation System (IAS), a distributed process control and monitoring system. The power management system (PMS) was an integral part of the IAS. Its main functions included:

- Monitoring of shutdown status originating from MSB.
- Priority and sequence selection of automatic start or stop depending on load demand.
- Synchronisation at the MSB.
- Unbalanced load sharing.
- Managing the load sharing of DGs in the event of load reduction or shutdown.
- Activation of preferential trips to cut power to non-essential circuits in the event of load reduction or shutdown.
- Prevention of overloading by limiting the power output of main propulsion motors.

The PMS also monitored the MSB breakers, blocked heavy load demanding equipment during blackout restart, controlled the MSB tie breakers and evaluated the power available before allowing large loads to be connected.

1.7.3.2 Automatic blackout recovery

Viking Sky's PMS provided an automated blackout recovery system. In the event of a blackout, the sequence of events would be as follows:

1. The tie breakers connecting the two MSBs would open as soon as the low voltage protection system detected a loss of voltage.
2. The emergency diesel generator would start and connect to the emergency switchboard.
3. The standby generators would start up and connect to their respective MSB.
4. The operator would request the load transfer from the emergency switchboard to the forward MSB.
5. The interconnecting breakers between the MSBs would close.

The blackout recovery system was designed to work under all combinations of running/standby DG operation and MSB configuration (connected or isolated from each other), but not when no standby generator was available.

Although blackout drills were carried out by the crew of *Viking Sky*, the scenario when no standby generators were available had never been drilled.

1.7.4 PROPULSION

Viking Sky's main propulsion system comprised two fixed pitch propellers directly driven by in-line variable speed electric motors.

The rated output power of each propulsion motor was 7,250 kilowatt (kW) at 143 revolutions per minute (rpm).

1.7.5 ELECTRONIC INCLINOMETER

Resolution MSC.363(92), *Performance standards for electronic inclinometers*, apply to all electronic inclinometers intended to support the decision-making process on board as well as assist in and facilitate maritime casualty investigations by providing information about the roll period and the heel angle of the ship. *Viking Sky* was not required to be, nor was it fitted with an electronic inclinometer type-approved according to this standard and providing recordings to the VDR.

As the VDR did not have any recordings from an electronic inclinometer, data from the vessel's fuel efficiency management system, Eniram, was used as input to simulations performed as part of the investigation, see section 1.5.2. Extracting data of sufficient quality was both complex and time consuming.

Whether or not it should be mandatory for ships to carry electronic inclinometers, has been discussed in several sub-committees of IMO (MSC, NSCR, III) over the past years. In document MSC 101/21/14 from 2019, Germany proposed that container ships and bulk carriers of 3,000 gross tonnage, should be fitted with electronic inclinometers. Passenger ships were used as examples in the support documentation, MSC 101.INF.9, but there was no recommendation to introduce the requirement for such vessels.

Following an accident involving the container ship *MSC Zoe* in 2019, see section 1.15.2, the investigation report recommended that all container ships should install electronic inclinometers as a support for the captain and crew, but also for the purpose of safety investigation. This was similar to a recommendation from the investigation report following an accident involving the cruise ship *Crown Princess* in 2006, see section 1.15.1.

The III Sub-Committee in its 7th session[14] supported mandatory carriage of electronic inclinometers and recommended to expand the requirement to all SOLAS ships of 3,000 gross tonnage and upwards, including passenger ships. It also recommended that the data should be recorded on the VDR to support safety investigations. The Sub-Committee noted that the *Viking Sky* investigation provided an excellent example of where an electronic inclinometer recorded on the VDR would have been highly beneficial for the investigation.

The outcome from the III Sub-Committee were brought forward by MSC to the NCSR 9[15], and the result was NCSR 9/18, providing a revised draft SOLAS amendments for the mandatory carriage of electronic inclinometers on container ships and bulk carriers. China commented on the draft, supporting that the requirement should also be set for passenger ships for the purpose of safety investigations. Regarding the proposal to expand the mandatory carriage of electronic inclinometers to all SOLAS ships of 3,000 gross tonnage and upwards, the majority of the delegations that took the floor did not support the expansion, noting that no appropriate justification had been provided for the use of electronic inclinometers in other types of ships, other than for marine casualty investigation purposes. Hence, MSC 106[16] concluded that the requirement should only apply to container ships and bulk carriers of 3,000 gross tonnage and upwards.

1.7.6 LIFEBOATS

Viking Sky had four lifeboats for 235 persons each, two lifeboats for 150 persons each and in addition 19 life rafts for 35 persons each which give a total capacity for the lifeboats/-rafts of 1,905 persons, equally distributed on each side.

[14] Sub-Committee on Implementation of IMO Instruments (III), 7th session, July 2021
[15] Sub-Committee on Navigation, Communication and Search and Rescue (NCSR), 9th session, June 2022
[16] Maritime Safety Committee, 106th session, November 2022

Lifeboat no. 3 on starboard side, the rescue boat on starboard side and all control stations for lifeboat davits on starboard side were damaged during the accident, probably shortly after 1500, see section 1.4.

Regardless of the damage that occurred later, the lifeboats were not in use during the evacuation as the captain considered the weather too rough and therefore not advisable to lower the lifeboats and life rafts.

There have been continuous discussions in IMO with respect to life-saving appliances, including lifeboats. In 2006, Japan submitted a proposal (MSC 82/21/7) to IMO for a systematic approach to the requirements of life-saving appliances. One of the aspects they highlighted, was that SOLAS chapter III and the LSA Code set some requirements to operation in heavy weather for Marine Evacuation Systems (MES)[17] and fast rescue boats, but not to lifeboats, although they are expected to be used in same environmental conditions. This initiative led to MSC.1/Circ.1212/Rev. 1 (Appendix 5), which introduced a further description of existing requirements to function and performance, i.a.:

> *All ships should provide for a safe abandonment of all persons.*
>
> *All ships should provide for safe launching of survival craft both in a seaway and when the ship is adrift.*

In 2017, Germany submitted a proposal to IMO (MSC 98/20/9) that supported the initiative from Japan in 2006 and requested a full revision of SOLAS chapter III and the LSA code. Norway submitted comments (MSC 98/20/14) to support this proposal. The result was that the MSC 98[18] agreed on a revision of the requirements to remove gaps, inconsistencies and ambiguities in SOLAS chapter III and the LSA code. A correspondence group was established to draft the revision.

The work was delayed due to the corona pandemic but was restarted at a meeting in Hamburg in 2022 and the work is still on-going.

Rescue equipment, including lifeboats, is also discussed in the report *Cruise traffic in Norwegian waters and adjacent sea area*, published 23 February 2022 by a government-appointed committee after the *Viking Sky* accident. The following recommendations are given by the committee:

> *Although the cruise ship will often be the safest place to stay during a serious incident, it is sometimes necessary to evacuate the ship. Proper rescue equipment on board a cruise ship can be crucial in reducing the risk of loss of life. Today's requirements for rescue equipment are not sufficiently adapted to the conditions that may arise during cruise voyages.*
>
> *The committee has therefore given recommendations on clearer requirements for rescue equipment. The Norwegian authorities should also stimulate research and innovation with respect to rescue equipment, including lifeboats. The cruise industry should ensure that new and safer technology for lifeboats and rescue equipment is used.*

The NSIA supports these recommendations and also the revision of SOLAS chapter III and the LSA code. It is considered important to remove unreasonable differences in the requirements to different life saving appliances regarding weather criteria.

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[17] SOLAS defines a Marine Evacuation System (MES) as an appliance for the rapid transfer of persons from the embarkation deck of a ship to a floating survival craft.
[18] Maritime Safety Committee, 98th session, June 2017

1.7.7 ANCHOR EQUIPMENT

Both anchors on *Viking Sky* were deployed after the blackout as a last resort as part of the emergency response, yet the vessel continued drifting.

The International Association of Classification Societies Ltd. (IACS) is an umbrella organisation for classification societies, of which Lloyd's Register (LR) is also a member. The IACS issues specific requirements and limitations relating to the design and construction of anchor arrangements.

The following is cited from IACS Req. 2007:

> *The anchoring equipment required herewith is intended for temporary mooring of a vessel within a harbour or sheltered area when the vessel is awaiting berth, tide etc.*
>
> *The equipment is therefore not designed to hold a ship off fully exposed coasts in rough weather or to stop a ship which is moving or drifting. In this condition the loads on the anchoring equipment increase to such a degree that its components may be damaged or lost owing to the high energy forces generated, particularly in large ships.*

The regulations are based on the assumption that the seabed provides a good holding ground for the anchor, and that, under normal circumstances, a vessel will use only one bow anchor and chain. The design criteria are based on an assumed current speed of 2.5 m/sec, wind speed of 25 m/sec and that the paid-out length of anchor chain is between 6 and 10 times the water depth.

As the anchor equipment is not designed to hold a ship off fully exposed coasts in rough weather or to stop a ship which is moving or drifting, the NSIA has chosen not to investigate this in further detail.

1.8 Lubricating oil sump tank design and approval

1.8.1 GENERAL DESCRIPTION OF ACTUAL TANK DESIGN

The diesel generators were of a dry sump design with separate lube oil sump tanks located directly below the engines and with similar footprint as the engine, see Figure 31.

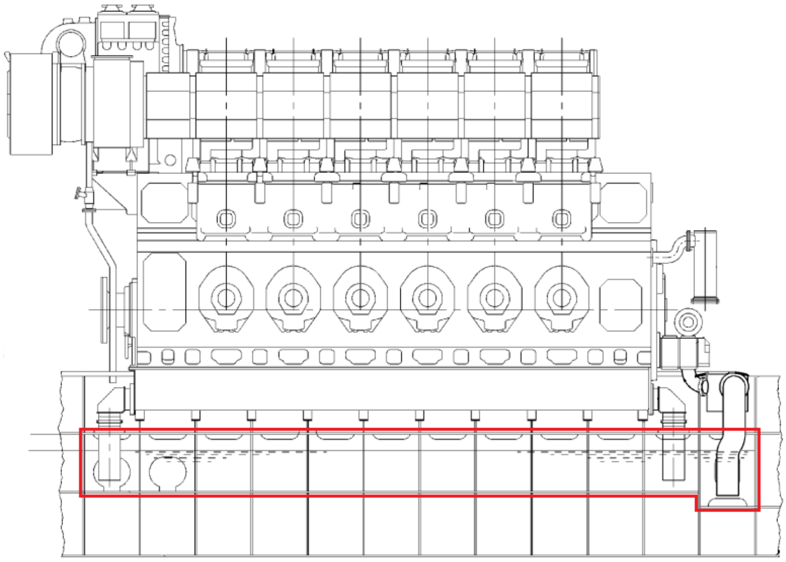

Figure 31: Diesel engine and sump tank (indicated in red) side view. Source: MAN/NSIA

The sump tanks were designed and fabricated by the ship builder, Fincantieri. The tanks had a series of transverse baffles and one longitudinal partition as shown in the below sketch taken from the lube oil service system functional diagram. The engines and sump tanks were fitted with their centerlines parallel to the longitudinal axis of the vessel.

CODE	DESCRIPTION	ND
1	SUCTION PIPE SERVICE PUMP	250
2	OIL RETURN FROM ENGINE	200
3	SECTION PIPE STAND-BT PUMP	125
4	OIL RETURN FROM ENGINE	200
5	SEPARATOR RETURN PIPE	—
6	VENT	100
7	VENT	100
8	SEPARATOR SUCTION PIPE	—

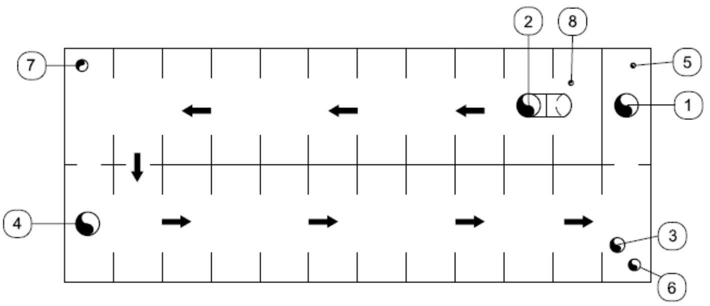

Figure 32: Extract from "Lube oil service system functional diagram", showing a sump tanks' baffle and pipework arrangement seen from above. Extract: Fincantieri

The engine-driven oil pumps took suction from the lube oil sump tank below the engines' free ends, with oil returns located at both the free and alternator ends. The lube oil returns from the engines to the free ends were separated by a partition from the main lube oil pump suctions, see Figure 32.

1.8.2 SOLAS REGULATION

SOLAS Chapter II-1, Part C contains regulations relevant to machinery installations on passenger and cargo ships.

Regulation 26.6 stipulates:

> *Main propulsion machinery and all auxiliary machinery essential to the propulsion and the safety of the ship shall, as fitted in the ship, be designed to operate when the ship is upright and when inclined at any angle of list up to and including 15˚ either way under static conditions and 22.5˚ under dynamic conditions (rolling) either way and simultaneously inclined dynamically (pitching) 7.5˚ by bow or stern. The Administration may permit deviation from these angles, taking into consideration the type, size and service conditions of the ship.*[19]

The SOLAS regulation specifies the dynamic pitch and roll amplitudes (i.e., 22.5° roll and 7.5° pitch simultaneously), under which the machinery shall be able to operate safely. The regulation does not provide information on the period, duration or pattern of the movement over time to be used for the application or verification of compliance with the regulation.

As far as the NSIA is aware, no technical guideline or industry standard for application of the SOLAS requirement exists. The Norwegian Maritime Authority, Lloyd's Register and Fincantieri have confirmed that they are not aware of any such supporting methodology either.

[19] *SOLAS II-1, Part C, Regulation 26.6*

1.8.3 CLASS RULES AND IACS UNIFIED REQUIREMENTS

LR Class Rules Part 5, Chapter 1, Section 3.7 states that "*Main and essential auxiliary machinery is to operate satisfactorily under the conditions as shown in Table 1.3.2 Inclination of ship"*. The table is shown in the below Figure 33.

Installations, components	Angle of inclination, degrees, *see* Note 1			
	Athwartships		Fore-and-aft	
	Static	Dynamic	Static	Dynamic
Main and auxiliary machinery essential to the propulsion and safety of the ship	15	22,5	5 *see* Note 2	7,5
Emergency machinery and equipment fitted in accordance with Statutory Requirements	22,5 *see* Note 3	22,5 *see* Note 3	10	10

Note 1. Athwartships and fore-and-aft inclinations may occur simultaneously.

Note 2. Where the length of the ship exceeds 100 m, the fore-and-aft static angle of inclination may be taken as:

$\frac{500}{L}$ degrees

where L = length of ship, in metres.

Note 3. In ships for the carriage of liquefied gas and of liquid chemicals the emergency machinery and equipment fitted in accordance with Statutory Requirements is also to remain operable with the ship flooded to a final athwartships inclination to a maximum angle of 30°.

Figure 33: Lloyd's Register's Rules and Regulations Table 1.3.2 Inclination of ship. Source: Lloyd's Register

The International Association of Classification Societies (IACS) Unified Requirements (UR) M46 Rev. 1 (valid at the time of construction), attached in Appendix B, has a similar wording and table, stating the same inclination angles as shown in the above table.

In addition to the angles of inclination required under the SOLAS regulation, the Class Rules and IACS UR M46 have specified a static fore-and-aft inclination (trim) angle of 5°, except for ships that exceed 100 m in length (L), for which the fore-and-aft static angle of inclination may be taken as 500/L degrees. For *Viking Sky*, LR calculated this trim angle as 2.56° and Fincantieri as 2.54°.

Moreover, LR Rules Part 1, Chapter 2, Sec 5.1.5 states that LR Type Approval is subject to the understanding that the manufacturer's recommendations and instructions for the product are fulfilled.

LR Rules Part 5, Chapter 2, Section 7 on Control and monitoring of main, auxiliary and emergency engines, contains requirements for a lube oil sump tank low level alarm and an automatic shutdown for low pressure at the engine lube oil inlet.

1.8.4 ENGINE MANUFACTURER'S RECOMMENDATIONS

The engine manufacturer, MAN, produced project guides with information and data for design, installation, operation, and maintenance of plants incorporating MAN diesel engines. According to the engine manufacturer, the version of the project guide valid at the time of design for *Viking Sky* is Version 2.8, dated 2011-12-23.

Section 2.2.5 of the project guide is entitled *Engine Inclination* and contains the illustration shown in Figure 34.

2.2.5 Engine inclination

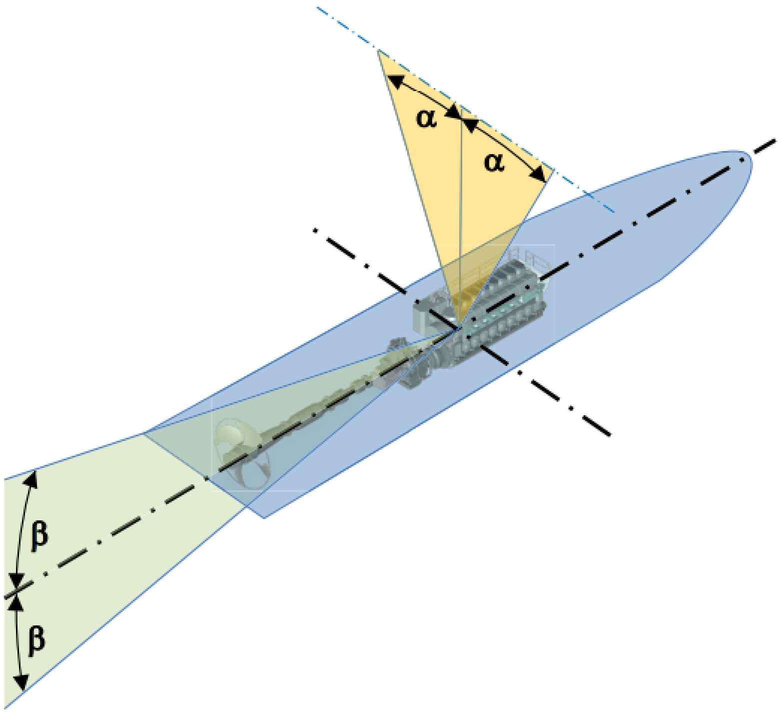

Figure 2-5 Angle of inclination

Legend	
α	Athwartships
β	Fore and aft

Max. permissible angle of inclination [°][1]					
Application	Athwartships α		Fore and aft β		
	Heel to each side (static)	Rolling to each side (dynamic)	Trim (static)[2]		Pitching (dynamic)
			L < 100 m	L > 100 m	
Main engines	15	22.5	5	500/L	7.5

Table 2-6 Inclinations

[1] Athwartships and fore and aft inclinations may occur simultaneously.

[2] Depending on length L of the ship.

Figure 34: MAN project guide engine inclination diagram. Extract: MAN

The *Engine and operation* section of the MAN project guide included table 2-32, see Figure 35, indicating the minimum effective capacities for lube oil sump tanks (referred to as lube oil service tanks) as 4.5m^3 for the 9 cylinder engines and 6.0m^3 for the 12 cylinder engines.

Service tanks	Installa-tion[1] height	Minimum effective capacity									
	m	m³									
No. of cylinders	**-**	**6**	**7**	**8**	**9**	**10**	**12**	**14**	**16**	**18**	**20**
Cooling water cylinder	6 ... 9	0.5					0.7				
Lube oil in Baseframe[2]	-	3.0	3.5	4.0	4.5	5.0	6.0	7.0	8.0	9.0	10
Lube oil in Baseframe[3]	-	5.0	6.0	6.5	7.5	8.0	9.5	11.0	12.0	13.5	14.5

Table 2-32 Service tanks capacity

[1] Installation height refers to tank bottom and crankshaft centre line.
[2] Marine engines with attached lube oil pump.
[3] Marine engines with free-standing lube oil pump; capacity of the run-down lube oil tank included.

Figure 35: MAN project guide minimum effective capacity. Extract: MAN

Section 5.2 of the project guide is dedicated to the Lube Oil System. In section 5.2.2 *Lube oil system description*, it is stated that

> *The main purpose for the service tank is to separate air and particles from the lube oil, before being pumped back to the engine. For the design of the service tank the class requirements have to be taken in consideration. For design requirements of MAN Diesel & Turbo see "Section 5.2.5: Lube oil service tank, page 5-35".*

Section 5.2.5 *Lube oil service tank* includes more details regarding recommended tank design, see Figure 36.

5.2.5 Lube oil service tank

The lube oil service tank is to be arranged over the entire area below the engine, in order to ensure uniform vertical thermal expansion of the whole engine foundation.

To provide for adequate degassing, a minimum distance is required between tank top and the highest operating level. The low oil level should still permit the lube oil to be drawn in free of air if the ship is pitching severely

- 5° longitudinal inclination for ship's lengths ≥ 100 m
- 7.5° longitudinal inclination for ship's lengths < 100 m

A well for the suction pipes of the lube oil pumps is the preferred solution.

The minimum quantity of lube oil for the engine is 1.0 litre/kW. This is a theoretical factor for permanent lube-oil-quality control and the decisive factor for the design of the by-pass cleaning. The lube oil quantity, which is actually required during operation, depends on the tank geometry and the volume of the system (piping, system components), and may exceed the theoretical minimum quantity to be topped up. The low-level alarm in the service tank is to be adjusted to a height, which ensures that the pumps can draw in oil, free of air, at the longitudinal inclinations given above. The position of the oil drain pipes extending from the engine oil sump and the oil flow in the tank are to be selected so as to ensure that the oil will remain in the service tank for the longest possible time for degassing.

Draining oil must not be sucked in at once.

Figure 36: Extract from the engine project guide. Extract: MAN

These recommendations are further explained in the same chapter of the project guide, through illustrations with design details. The full illustrations may be found in the project guide annexed to the report. The extracts shown in Figure 37 to Figure 39 contain the information most relevant to the investigation.

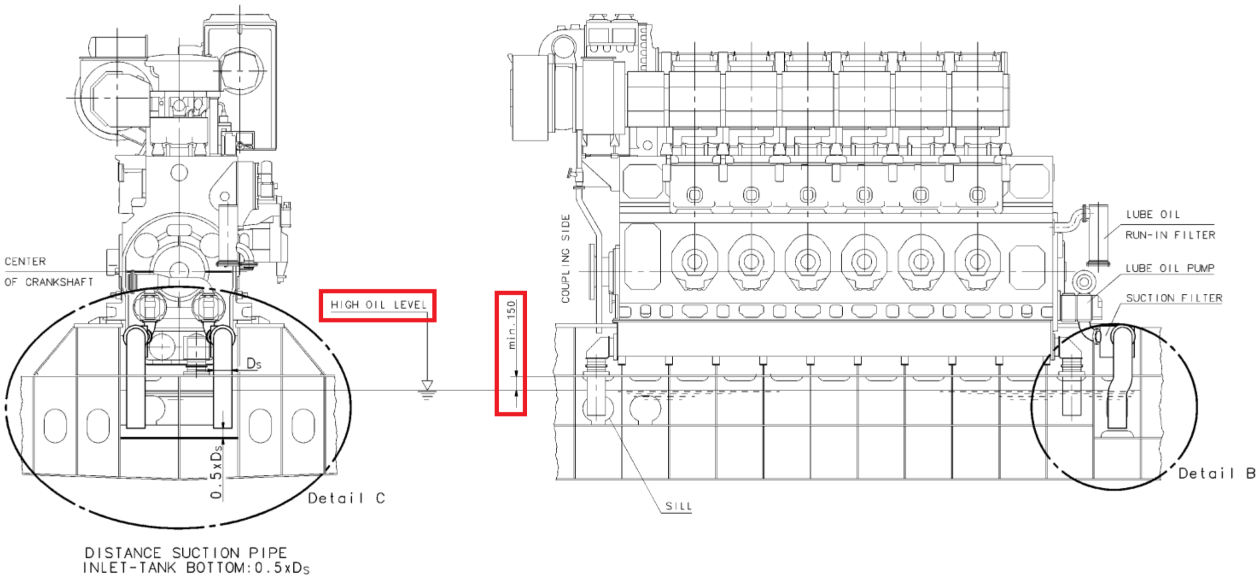

Figure 37: Extract from the MAN project guide showing the high oil level to be min 150 mm below the tank top. Extract: MAN

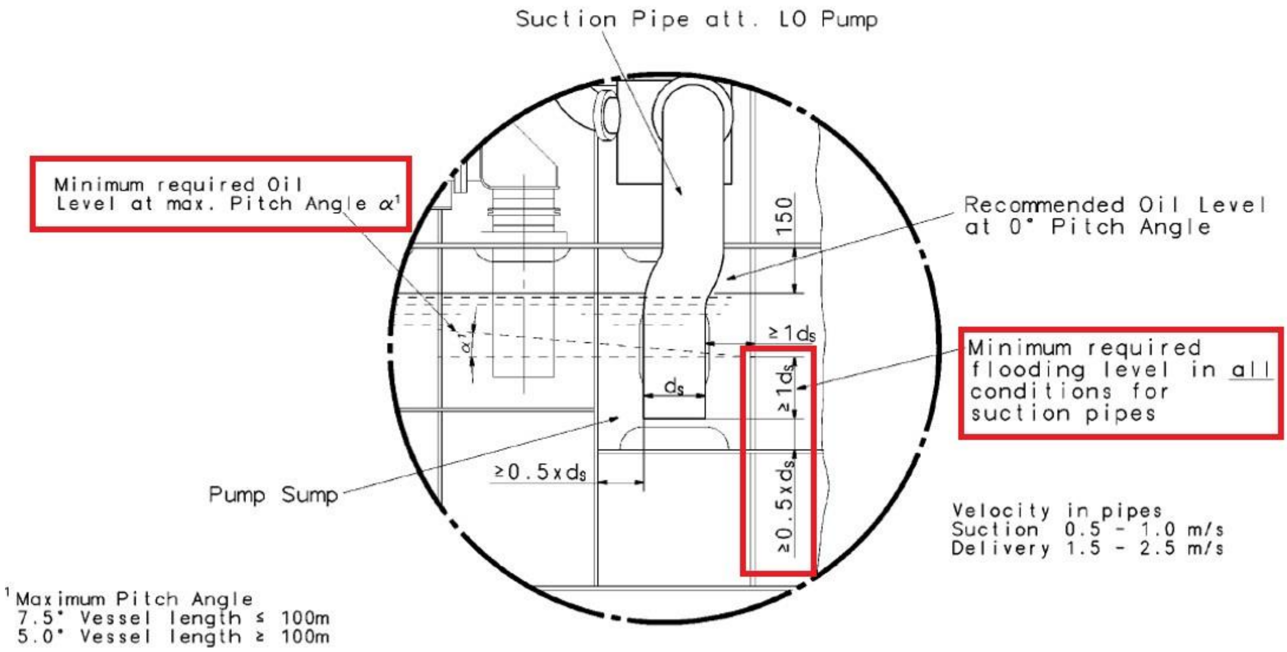

Figure 38: MAN project guide lubricating oil suction pipe detail. Extract: MAN

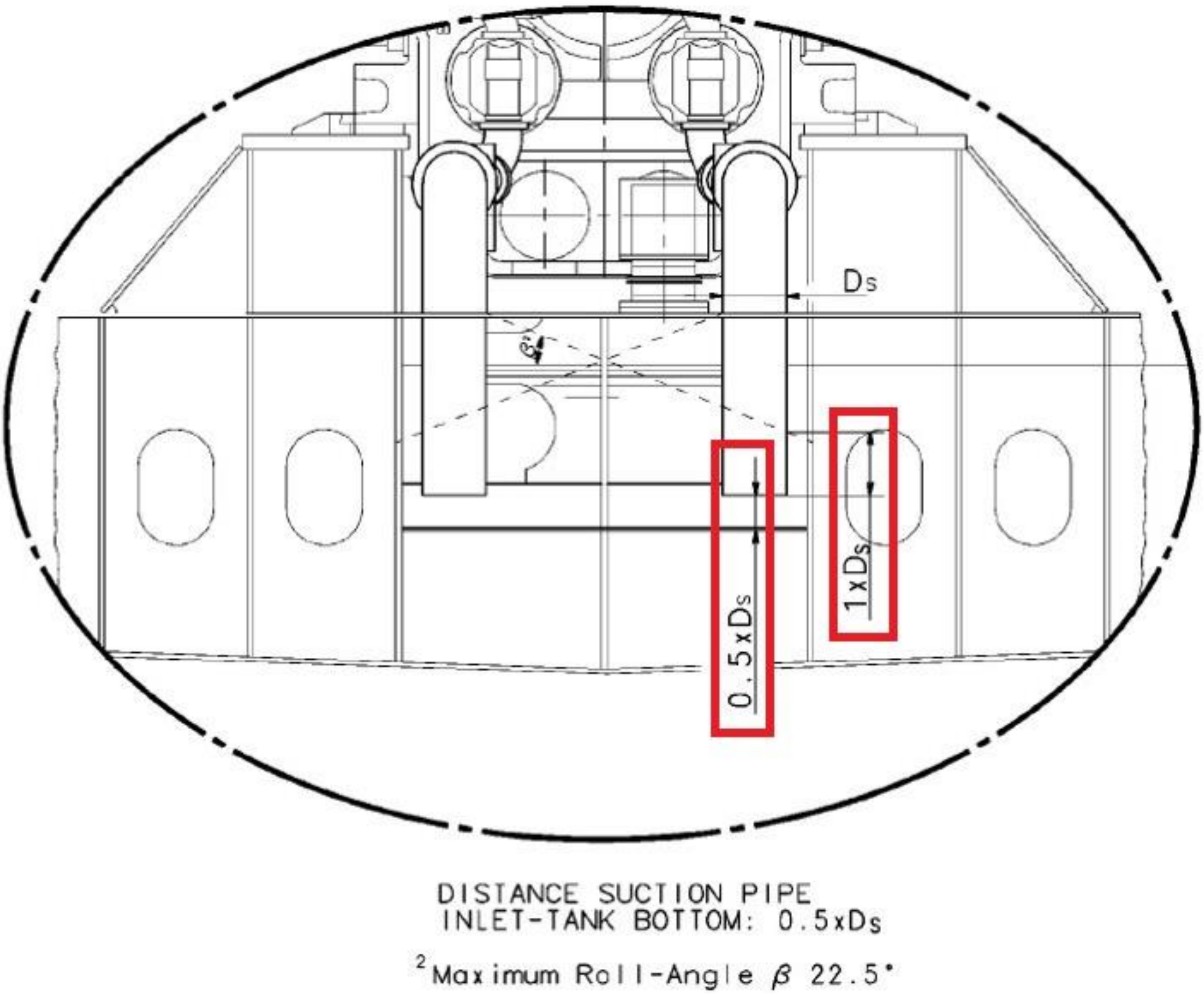

Figure 39: MAN project guide lubricating oil suction pipe detail. Extract: MAN

As shown in the above illustrations:

- the high oil level was to be maintained minimum 150 mm below the top of the lube oil sump tank.
- the minimum filling level should ensure that the suction pipe opening is still submerged by a depth equal to one pipe diameter when statically inclined to the required angles of roll (β = 22.5°) and pitch (α = 5° for vessels over 100m in length).
- the suction inlet should be positioned a minimum of half the suction pipe diameter above the tank bottom, preferably in a suction well.

The NSIA has had extensive communication with MAN throughout the investigation, i.a. to make sure the project guide is correctly understood. MAN has confirmed that the intention of the above quoted recommendations of the project guide Section 5.2.5 is to ensure suction of oil free of air under the static and dynamic angles of inclination required by Class.

The recommendations are meant as a guidance for designers to ensure the tank design is safe and in compliance with Class Rules. Project specific tank design, e.g. by use of sloshing simulations may however result in other equivalent solutions.

MAN has however confirmed that the suction pipe inlet must be fully submerged at all times. A time wise short exposure to air can cause a pressure drop which may lead to severe engine damage.

With respect to lube oil consumption, Figure 40 shows the information provided in the project guide.

2.8.2 Lube oil consumption

Engine 32/44CR

560 kW/cyl.; 720/750 rpm

Specific lube oil consumption . . . . . 0.5 g/kWh

Total lube oil consumption [kg/h][1]										
No. of cylinders	**6L**	**7L**	**8L**	**9L**	**10L**	**12V**	**14V**	**16V**	**18V**	**20V**
Speed 720/750 rpm	1.7	2.0	2.2	2.5	2.8	3.4	3.9	4.5	5.0	5.6

Table 2-23 Total lube oil consumption 32/44CR

[1] Tolerance for warranty +20 %.

Note!
As a matter of principle, the lubricating oil consumption is to be stated as total lubricating oil consumption related to the tabulated ISO full load output (see *"Section 2.3: Ratings (output) and speeds, page 2-21"*).

Figure 40: Lube oil consumption. Source: MAN

1.8.5 YARD DESIGN

Figure 41 represents the geometry of lube oil sump tank 5S, which supplies DG4. The main geometry is similar for all sump tanks, therefore Figure 41 is used to illustrate the sump tanks as designed by the yard.

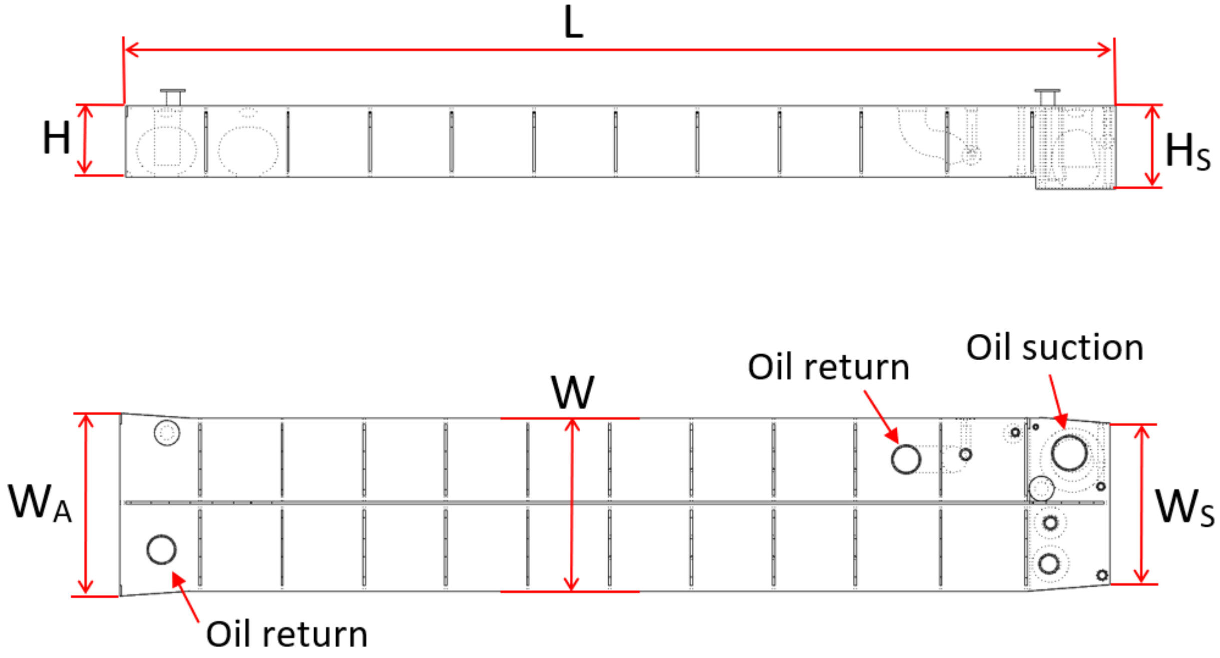

Figure 41: Side and top view of lube oil sump tank 5S, supplying DG4. Illustration: Fincantieri

Table 3 provides the main dimensions according to the drawings from the yard.

Table 3: Lube oil sump tanks main dimensions. Source: Fincantieri/NSIA

Sump tank (DG)	6P (DG1)	6S (DG2)	5P (DG3)	5S (DG4)
Length (L), mm	8,370	8,370	8,370	8,370
Height (H), mm	600	650	650	600
Height, Suction end (H_S), mm	700	750	750	700
Width, Alternator end (W_A), mm	1,485	1,849	1,849	1,567
Width, Main section (W), mm	1,485	1,685	1,685	1,485
Width, Suction end (W_S), mm	1,270	1,270	1,477.5	1,377.5
Total sump tank volume, m^3	7.4	9	9.1	7.4

The dimensions in Table 3 are nominal dimensions taken from the steel drawings without making corrections for plate thicknesses. The listed tank volumes are the actual tank volumes indicated by the yard. The total tank volumes calculated by use of the above listed nominal dimensions may therefore differ marginally from the listed tank volumes.

The suction pipes of all sump tanks are 250 mm diameter ending in a “trumpet shaped” opening of 350 mm at a distance of 175 mm above the bottom of the tank. As shown by the above illustrations and table of dimensions, the section of the tank where the suction pipe is located is 10 cm deeper than the rest of the length of the tank.

The shipyard has informed that they designed the sump tanks to meet Class requirements, while at the same time paying the necessary attention to the engine manufacturer’s recommendations and the existing structural constraints. Communication with the shipyard has revealed that the requirements and recommendations taken into consideration during the design phase were the following:

- Minimum static inclination angles, as required under LR Class Rules and IACS UR M46, of 15° heel and 2.54° trim (equal to 500/L, where L is the length of the vessel).
- The engine manufacturer’s recommended minimum lube oil quantity of 1 liter/kW.
- Minimum ullage (free space above highest oil level) of 150 mm.

The information shown in Figure 42 was submitted to the investigation by the shipyard as documentation of compliance with Class Rules and Manufacturer’s Recommendations.

LUBE OIL SUMP TANKS - COMPLIANCE WITH RULES

Lloyd's Register Reg. Part 5, Chapter 1, Section 3, par. 3.7 Inclination of ship (Table 1.3.2)

Required Angle of inclination: **15.0 degrees (Athwartships), 500/L = 500/196.6 = 2.54 degrees (Fore-and-aft)**

HULL	CCODE	ROOM NAPA	Description	Frame Min	Frame Max	Vol. Max m^3	Min. Vol. Request by Rules m^3	Min Vol. required by MAN m^3
6236 VIKING	LO05P	R0532	LUBE OIL SUMP N.05 PORT	69	81	9.10	4.92	6.7
	LO05S	R0531	LUBE OIL SUMP N.05 STBD	69	81	7.40	4.61	5.04
	LO06P	R0634	LUBE OIL SUMP N.06 PORT	83	95	7.40	4.60	5.04
	LO06S	R0633	LUBE OIL SUMP N.06 STBD	83	95	9.00	4.77	6.7

Figure 42: Documentation from yard to document compliance with Rules and Recommendations. Source: Fincantieri

1.8.6 DESIGN APPROVAL

Lloyd's Register (LR) is the classification society responsible for the approval of the design of *Viking Sky* and its sister vessels. In addition, Lloyd's Register is delegated responsibility for the follow up of statutory requirements (e.g. SOLAS Regulations) as recognised organisation (RO) by the Norwegian Maritime Authority (NMA).

The diesel engines installed on board *Viking Sky* were Type Approved by LR. As part of the Type Approval process, the engine manufacturer is to document compliance with the Rule requirement on static and dynamic angles of inclination. The detailed design of the lube oil sump tanks was not part of the Type Approval as the tanks are not an integrated part of the engine. The engine manufacturer however produces project guides with information and data for design, installation, operation, and maintenance of plants incorporating its diesel engines. This project guide contained a number of recommendations pertinent to the sump tank design, as described in section 1.8.4.

As part of the Type Approval process, LR stamped the project guide for the engines as "Examined". The stamped version of the project guide submitted to the investigation by LR is numbered Version 1.0 and dated 2010-04-16. The version of the document submitted to the NSIA by the engine manufacturer as the relevant version for the time of design of the vessel was numbered Version 2.8 and dated 2011-12-23. The recommendations and data referred to in this report are the same in the two versions of the document.

The approval of the sump tanks, being designed and built by the shipyard in this case, is part of the design approval of the ship. There has been extensive communication with LR about this during the investigation. LR has i.a. provided the following statement regarding the sump tank design approval process:

> *In accordance with Lloyd's Register's Rules for the Classification of Ships, Part 1, Chapter 2, Paragraph 5.1.5, it is a requirement that shipbuilders install engines in accordance with the manufacturers' instructions. Where the shipbuilder does not follow this requirement, they are to advise LR accordingly. With reference to the engines installed on this vessel, LR received information submitted by the shipbuilder, Fincantieri, during design showing modifications to the engines' lubricating oil arrangements carried out at the engine manufacturer's request. LR concludes that the lubricating oil arrangements had, therefore, been reviewed by the engine manufacturer and, on the basis of the drawing modifications made and in the absence of any further notification from the engine manufacturer or shipyard to LR, the design satisfied the engine manufacturer's instructions.*

To summarise, LR did not verify that the sump tank design was in compliance with applicable rules and regulations or in accordance with the manufacturer's recommendations during the design approval process.

LR assumed that the lube oil arrangements satisfied the engine manufacturer's recommendations based on information that the lube oil arrangement was modified following comments from the engine manufacturer and the absence of a notification that the recommendations in the project guide were not followed.

The yard and the engine manufacturer have submitted documentation of communication between the parties regarding the lube oil arrangement. The yard presents the communication as evidence that the engine manufacturer had approved the sump tank design. The engine manufacturer does not describe the process as an approval but as a review where they provided comments relevant to the characteristics shown in the documents. The engine manufacturer has stated that the information provided by the yard was not sufficiently detailed to do an analysis of reasonable lube oil filling levels assuming applicable inclination angles.

1.8.7 POST-ACCIDENT CALCULATIONS OF LUBE OIL SUMP TANK DESIGN

After the accident, several calculations have been made in an attempt to compare the actual sump tank design with the applicable Class Rules, the SOLAS Regulation and the engine manufacturer's recommendations.

1.8.7.1 NSIA's application of the engine manufacturer's recommendations

The NSIA has made a calculation to compare the design of the sump tanks to the design recommendations of the MAN project guide. The NSIA has been in close dialogue with the engine manufacturer throughout the investigation and the engine manufacturer has confirmed that the relevant recommendations are correctly understood as applied in the below calculation.

The design criteria considered are the following:

a) The minimum oil filling level should ensure that the suction pipe opening is submerged by a depth equal to one pipe diameter when inclined to the required angles of pitch (α = 5°) and roll (β = 22.5°).

b) Minimum 150 mm between the highest oil filling level and the tank top.

The design criteria are found in section 5.2.5 of the MAN project guide that, according to MAN, was applicable at the time of design for *Viking Sky* Version 2.8, dated 2011-12-23, included in Appendix D.

Figure 37, Figure 38 and Figure 39 in section 1.8.4, taken from the project guide, illustrate the criteria. Figure 43 below shows a side view and a top view of the yard's 3D-model of sump tank 5S, supplying DG4.

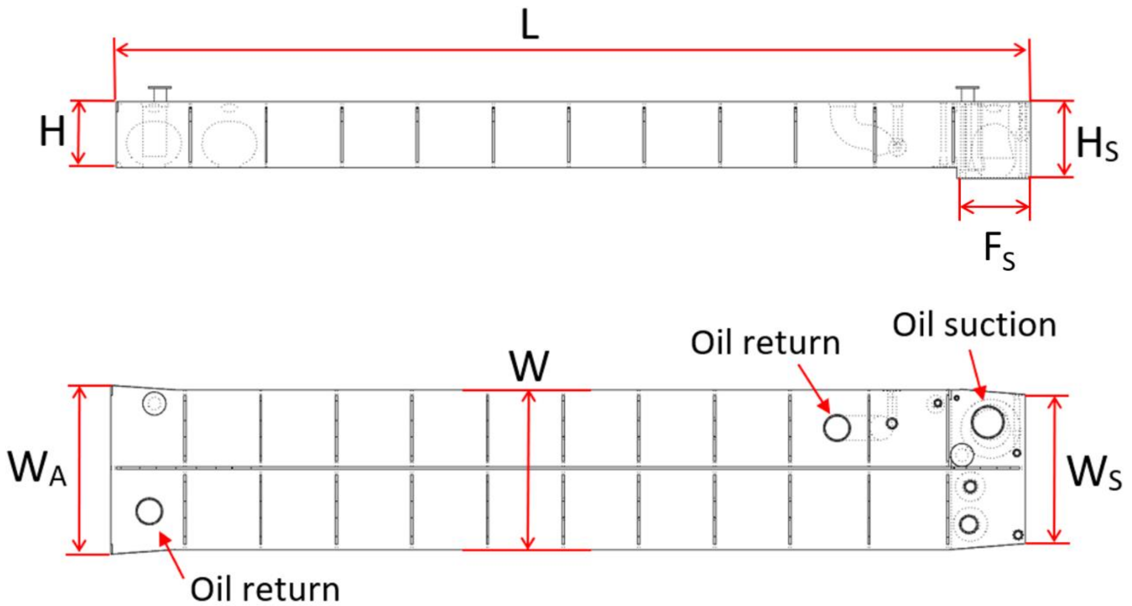

Figure 43: Side and top view of lube oil sump tank 5S, supplying DG4. Illustration: Fincantieri

All lube oil sump tanks are similar in shape. Table 4 provides the main dimensions highlighted in above illustration for each tank.

Table 4: Lube oil sump tanks main dimensions. Source: Fincantieri/NSIA

Sump tank (DG)	6P (DG1)	6S (DG2)	5P (DG3)	5S (DG4)
Tank length (L), mm	8,370	8,370	8,370	8,370
Tank height (H), mm	600	650	650	600
Tank height, suction end (H_S), mm	700	750	750	700
Width, alternator end (W_a), mm	1,485	1,849	1,849	1,567
Width, main section (W), mm	1,485	1,685	1,685	1,485
Width, suction end (W_S), mm	1,270	1,270	1,477.5	1,377.5
Frame spacing, suction end (F_S), mm	720	720	720	720
Total tank volume (V_{Tot}), m^3	7.4	9	9.1	7.4

Figure 44 and Figure 45 provide details relevant to the suction end of the tank, the suction pipe position and indicate the minimum required flooding level in all conditions and the maximum oil filling level (minimum ullage) according to the MAN recommended design criteria.

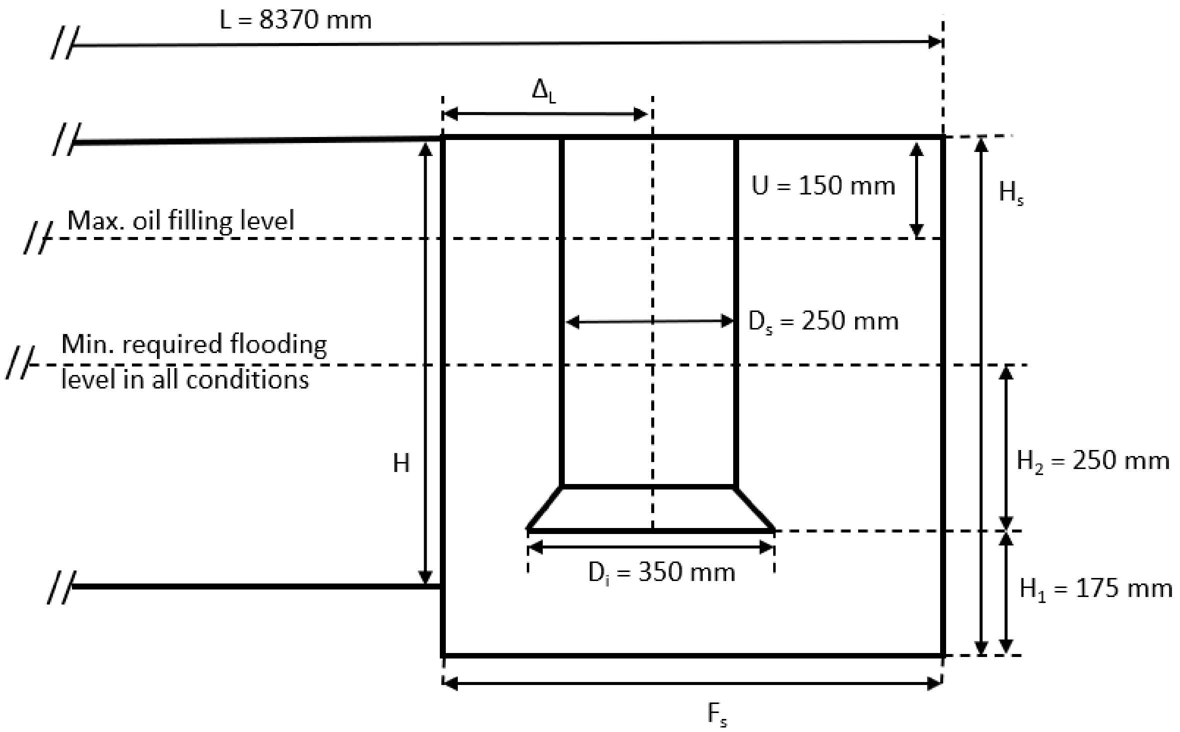

Figure 44: Longitudinal section view of suction end. Illustration: NSIA

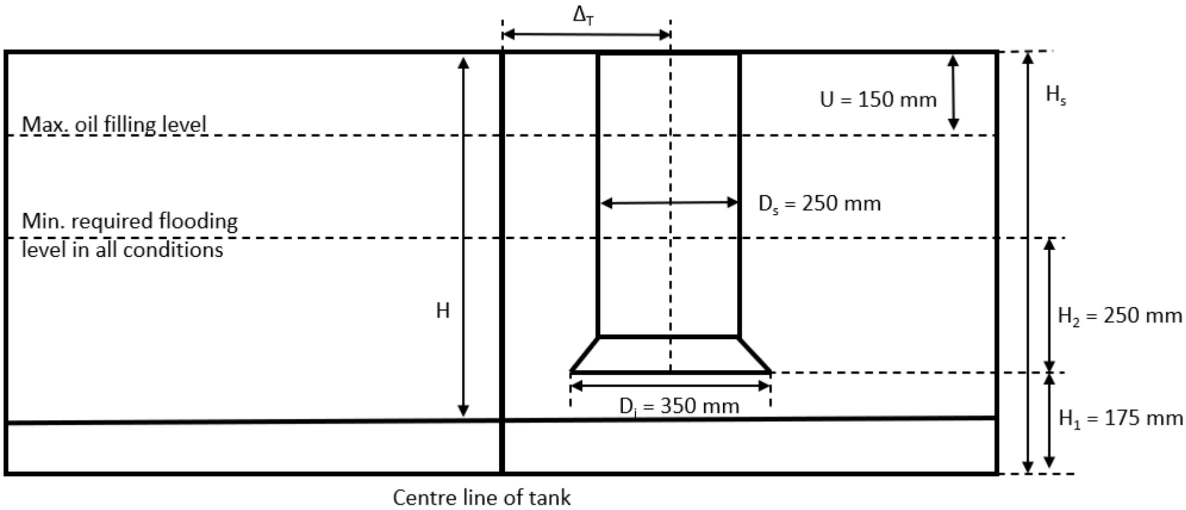

Figure 45: Transverse section view of suction end. Illustration: NSIA

Inclination of the tank caused the level of oil in a given point to increase or decrease. To find the minimum oil filling height necessary to ensure the minimum required flooding level in all conditions, it is necessary to calculate the reduction in oil level due to pitch angle α and roll angle β, $H_α$ and $H_β$ respectively. This is found by the following trigonometrical calculations:

$$H_α = L_α * \tan α$$

$$H_β = L_β * \tan β$$

Where $L_α$ and $L_β$ are the distances from the far edge of the suction pipe inlet to the longitudinal and transverse center of the tank respectively. See Figure 46 and Figure 47.

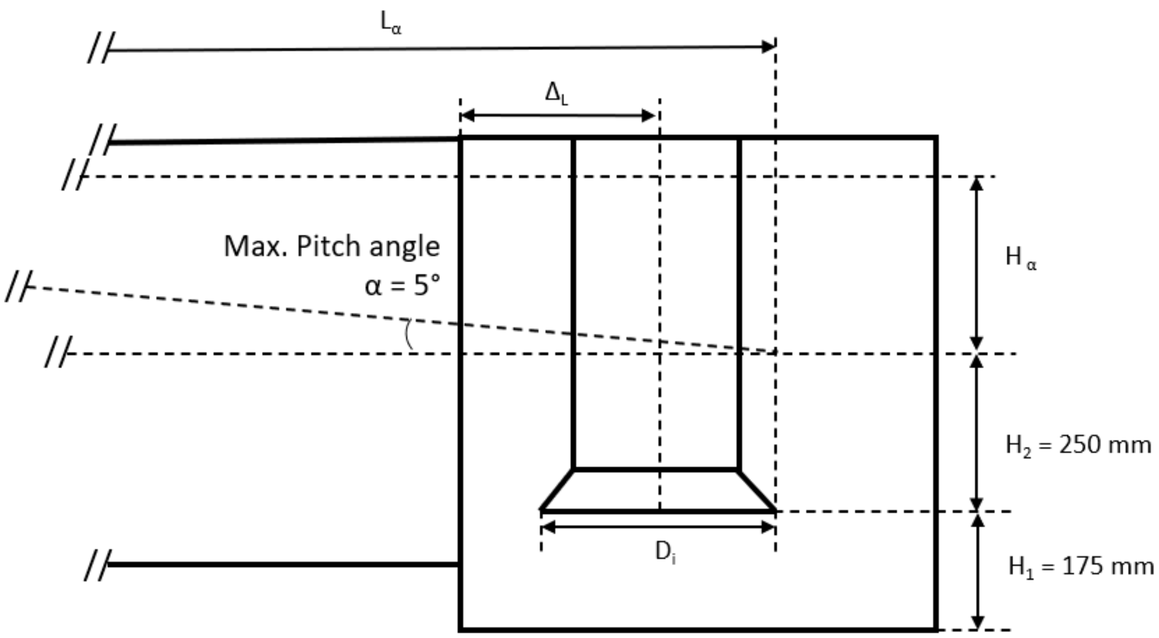

Figure 46: Dimensions relevant to calculate oil level reduction due to pitch, $H_α$. Illustration: NSIA

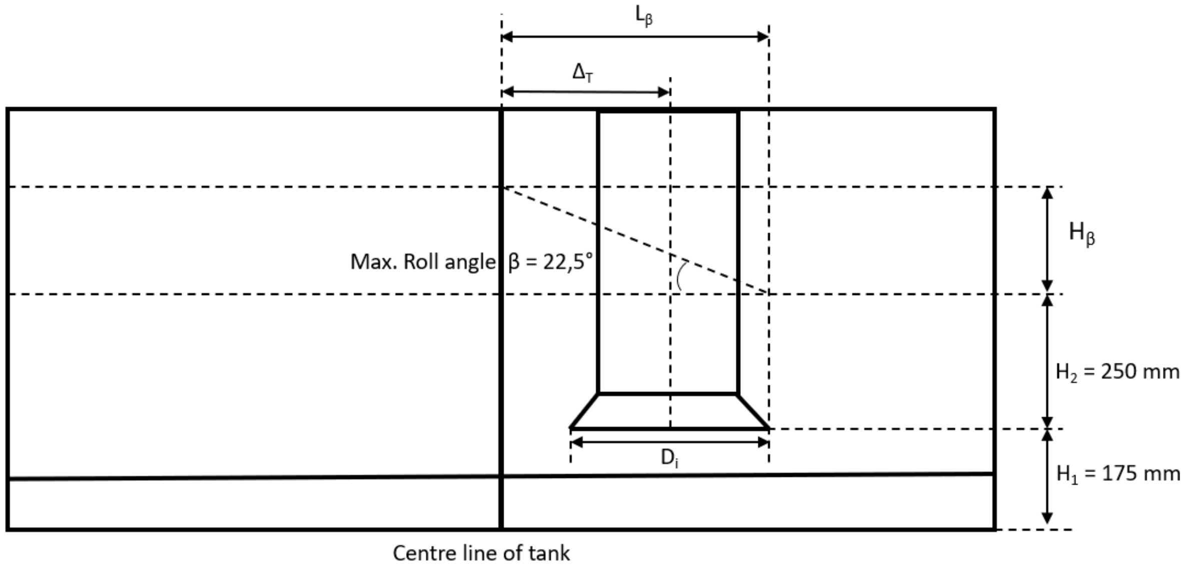

Figure 47: Dimensions relevant to calculate oil level reduction due to roll, H_β. Illustration: NSIA

L_α and L_β, the distances from the far edge of the suction pipe inlet to the longitudinal and transverse center of the tank respectively, can be calculated as follows:

$$L_\alpha = 0.5 * L - F_S + \Delta_L + 0.5 * D_i$$

$$L_\beta = \Delta_T + 0.5 * D_i$$

Consequently, the reduction in oil level due to pitch angle α and roll angle β, H_α and H_β respectively, are found by the following calculations:

$$H_\alpha = L_\alpha * \text{Tan } \alpha = (0.5 * L - F_S + \Delta_L + 0.5 * D_i) * \text{Tan } \alpha$$

$$H_\beta = L_\beta * \text{Tan } \beta = (\Delta_T + 0.5 * D_i) * \text{Tan } \beta$$

Table 5: Lube oil sump tanks dimensions. Source: Fincantieri

Sump tank (DG)	6P (DG1)	6S (DG2)	5P (DG3)	5S (DG4)
Tank length (L), mm	8,370	8,370	8,370	8,370
Frame spacing, suction end (F_s), mm	720	720	720	720
Suction pipe inlet diameter (D_i), mm	350	350	350	350
Dist. suction pipe centre to adjacent transverse boundary (Δ_L), mm	238	260	203	354
Dist. suction pipe centre to centre line of tank (Δ_T), mm	246	300	305	415
Dist. far edge of suction pipe inlet to longitudinal center of tank (L_α), mm	3,878	3,900	3,843	3,994
Dist. far edge of suction pipe inlet to transverse center of tank (L_β), mm	421	475	480	590
Reduction in oil level due to pitch angle (H_α), mm	339	341	336	349
Reduction in oil level due to roll angle (H_β), mm	174	197	199	244

For each tank, the resulting minimum oil filling height (F_{min}) and minimum tank height (H_{min}) are calculated as follows, as illustrated in Figure 48.

$$F_{min} = H_1 + H_2 + H_\alpha + H_\beta$$

$$H_{min} = F_{min} + U$$

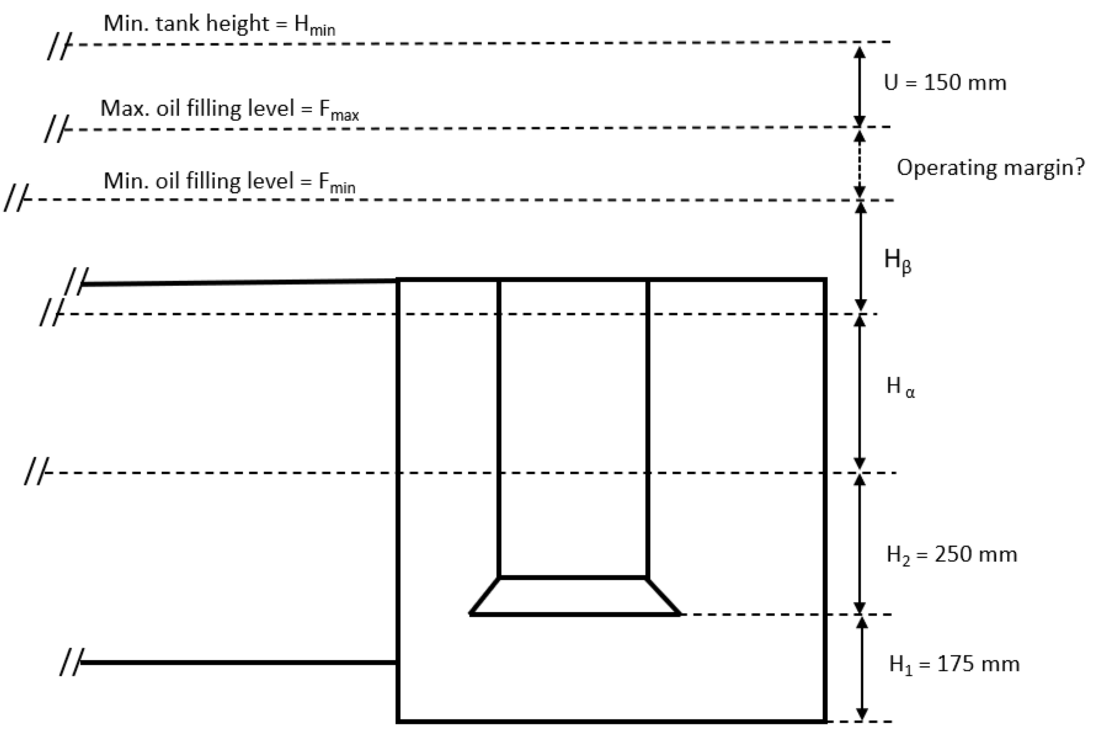

Figure 48: Minimum oil filling and tank height. Illustration: NSIA

Table 6: Minimum oil filling and tank height. Source: NSIA

Sump tank (DG)	6P (DG1)	6S (DG2)	5P (DG3)	5S (DG4)
Min. oil filling height (F_{min}), mm	939	963	960	1,019
Min. tank height (H_{min}), mm	1,089	1,113	1,110	1,169
Actual tank height, suction end (H_s), mm	700	750	750	700
Actual tank height / min tank height, %	64%	67%	68%	60%

As displayed in Table 6, all the tanks are 60–68% of the minimum calculated tank height to fulfil the design criteria recommended by MAN. Hence, the tank design does not fulfil the design criteria recommended by MAN in the engines' project guide.

It should be noted that the sump tank 5S (DG4) needs 70 mm higher oil filling level than the sump tank 6P (DG1) to have the same margin against exposure to air of the suction pipe inlet. This is due to the substantially larger transverse offset of the suction pipe, which increased the effect of roll considerably.

The minimum filling and tank heights above are calculated without any addition for an operating margin. In other words, the minimum and maximum filling levels are identical. In reality there should be added an operating margin, i.a. to allow for consumption between oil refilling and to take into account the uncertainty of manual and remote level readings to ensure the level does not fall below the minimum recommended level due to reading errors.

MAN has no specific recommendation regarding the operating margin, but the project guide indicate a consumption of 2.5 kg/h for the 9L (small) and 3.4 kg/h for the 12V (large) engines, based on continuous operation and full load. This may be converted to a number of mm of oil consumed per day or per week by use of the oil density (~ 900kg/m^3) and through an equivalent oil volume/mm for each tank deducted from the sounding tables. Table 7 provides indicative values from the sounding tables.

Table 7: Oil volume per filling height. Source: NSIA

Sump tank (DG)	6P (DG1)	6S (DG2)	5P (DG3)	5S (DG4)
Oil volume at 55 cm filling height (m^3)	5.8	6.5	6.6	5.8
Oil volume at 45 cm filling height (m^3)	4.6	5.1	5.2	4.6
Litres / mm	12	14	14	12

Table 8 use the above estimated value of oil volume per mm filling height to convert the nominal consumption from mass per hour to mm per day or week:

Table 8: Table of consumption. Source: NSIA

DG	Kg/h	l/h	l/24 h	l/week	l/mm	mm/24 h	mm/week
DG1 / DG4 (9L)	2.5	2.78	66.7	467	12	5.6	39
DG2 / DG3 (12V)	3.4	3.78	90.7	635	14	6.5	45

As shown in Table 8, the nominal consumption of lube oil is 39 mm per week for the small and 45 mm per week for the large engines, based on continuous full load operation.

1.8.7.2 CFD calculation by the shipyard

As the documentation submitted by the shipyard, see section 1.8.5, did not include documentation of compliance with the required dynamic inclination angles according to SOLAS and Class Rules nor with all the relevant design recommendations of the MAN project guide, the NSIA requested the shipyard to produce and submit such documentation, if possible. An oil sump tank analysis report was received, see Appendix E, which included the results of both static simulations and dynamic CFD simulations.

The static simulation, using the Class Requirement for static inclination (2.54° trim and 15° heel), indicates a minimum filling level leaving 230 to 308 mm free air above the oil level as shown in Figure 49. As the extract shows, the shipyard finds the lube oil sump tank 5S (DG4) to have the least margin, requiring 75 mm higher oil filling level than the sump tank 6P supplying the other small engine (DG1). Sump tank 5S (DG4) was therefore chosen for the dynamic simulation.

						Static Filling (Trim 500/L°, Heel 15 °)		
Free CCODE	ROOM NAPA	Description	Frame Min	Frame Max	Vol. Max	Vol. Requested by the Static Rule	Filling	Free air above oil level
					m3	m3	%	mm
LO05P	R0532	LUBE OIL SUMP N.05 PORT	69	81	9.10	4.92	54.1	303
LO05S	R0531	LUBE OIL SUMP N.05 STBD	69	81	7.40	4.61	62.3	230
LO06P	R0634	LUBE OIL SUMP N.06 PORT	83	95	7.40	4.60	62.2	305
LO06S	R0633	LUBE OIL SUMP N.06 STBD	83	95	9.00	4.77	53.0	308

Figure 49: Table of results of static simulations, extract from the shipyard's calculation report. Source: Fincantieri

The dynamic simulation of lube oil behaviour in sump tank 5S (DG4) was carried out by applying harmonic pitch and roll motion with the amplitudes prescribed by SOLAS and Class, 7.5° pitch and 22.5° roll. Two simulations were made, both with a 10 second period for both pitch and roll motions, with maximum roll and pitch occurring simultaneously either with the motions in phase or in opposite phase.

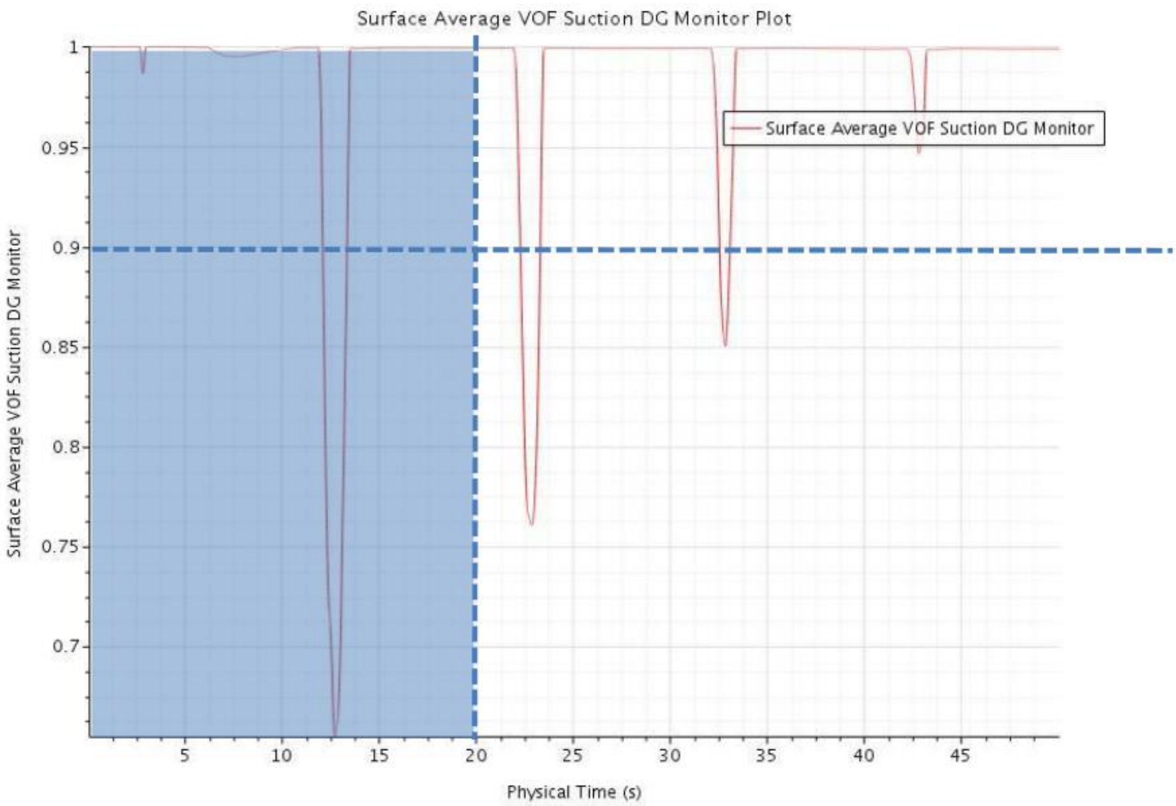

Figure 5: time dependent behaviour of the VOF on the suction pipe in the "Design Scenario" with motions in phase.

Figure 50: Oil fraction at suction pipe inlet area, extract from the shipyard's calculation report. Source: Fincantieri

The red graph represents the fraction of the suction pipe inlet opening that is covered by oil. An oil fraction of 1 indicates that the suction pipe inlet opening is fully covered by oil. When the graph indicates a steep drop, the edge of the inlet opening has been exposed to air and the fraction of the opening exposed to oil therefore decreases.

The results indicate partial exposure to air of the suction pipe inlet opening for a period of approximately 1 second. The shipyard concluded that this guaranteed the capability of the engine to operate at the extreme conditions prescribed by the Rules, since the duration of suction of air is less than the 4 seconds delay of the pressure sensor activating the engines shutdown in case of low oil pressure.

The NSIA disagrees that the design may be compliant with the SOLAS Regulation if the suction pipe is exposed to air, even for short periods. This is further discussed in the analysis section of the report, see section 2.4.1.

The NSIA also question the choice of 10 seconds as period for the dynamic motion. Since the SOLAS requirement does not specify any limitations and in the absence of any approved test standard or industry guidance on the parameters of the dynamic motion, the NSIA is of the opinion that the least favourable, realistic, dynamic motion should be used.

1.8.7.3 CFD calculation by SINTEF Ocean for NSIA

The NSIA decided to carry out independent CFD calculations similar to those made by the yard in order to study the case more closely. The yard shared the data model and other necessary documents as requested.

The NSIA contracted SINTEF Ocean, an institute of SINTEF, one of Europe's largest independent research organisations, to carry out CFD simulations of lubricating oil in lube oil sump tank 5S (DG4).

The primary goal of the simulations was to evaluate the likelihood of the lube oil suction pipe being exposed to air, with the highest oil filling level recommended by the engine maker, if *Viking Sky* was subject to vessel motion as specified in the dynamic requirements of SOLAS, Chapter II-1, Part C Regulation 26.6 (i.e., 7.5° pitch and 22.5° roll simultaneously).

SINTEF Ocean commenced the study by searching for the most unfavourable, yet realistic, vessel motion within the criteria set out by the SOLAS Regulation. The simulations established that the worst-case scenario likely occur at the ship's natural roll period of 17.5 seconds, with a 45° phase shift between pitch and roll.

With the highest oil filling level recommended by the engine maker, this resulted in the suction pipe being completely exposed to air, see Figure 51, for about 4 seconds and partially exposed to air for approximately 6 seconds as illustrated by Case 10 in Figure 52.

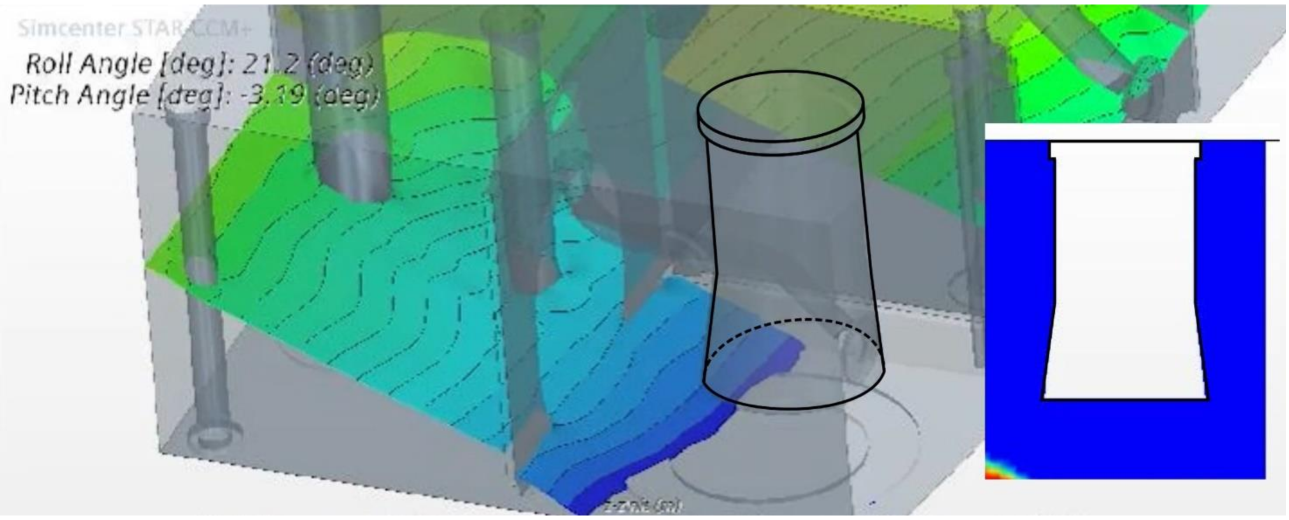

Figure 51: Illustration from the CFD simulation showing the suction pipe completely exposed to air. The multi-coloured surface represents the surface of the oil. The illustration in the box to the right shows a 2D side view of the suction pipe. Source: SINTEF Ocean/NSIA

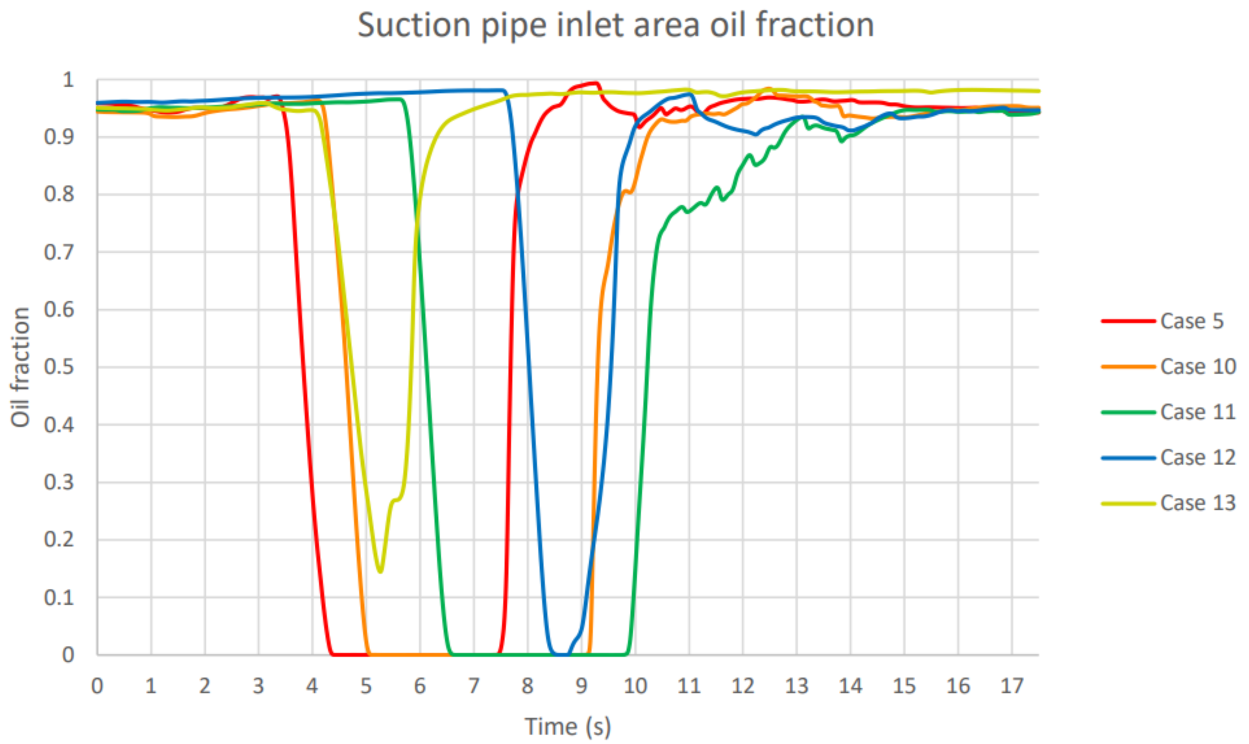

Figure 52: Oil fraction at suction pipe inlet area. Case 10 represents the worst case. Source: SINTEF Ocean's CFD calculation

The coloured graphs in the above Figure 52 represent the fraction of the suction pipe inlet opening that is covered by oil. An oil fraction of 1 indicates that the suction pipe inlet opening is fully covered by oil. Due to a slight mixture of air in the oil, this fraction remains slightly below 1 even when the inlet opening is fully submerged in the mixed fluid. When the graph indicates a steep drop, the edge of the inlet opening has been exposed to air and the fraction of the opening exposed to oil therefore decreases. When the graph reaches the value of 0, the complete opening of the suction pipe inlet is exposed to air. The different cases represent different input parameters, as specified in the report in Appendix F.

SINTEF Ocean simulated the oil behaviour in the lube oil tanks by means of harmonic sinusoidal motion with the maximum amplitudes prescribed by SOLAS. The simulations were run until a periodic behaviour for the oil motion was reached and only results from the last motion period (17.5 seconds) is presented in the above Figure 52 and in below Figure 53.

Figure 53 shows the same simulation results as Figure 52, but the coloured graphs indicate the oil level at the suction pipe. The dotted horizontal line shows the height of the suction pipe inlet and the 0-level indicate the tank bottom. When the graph crosses below the dotted line, the oil no longer reaches the suction pipe opening and the suction pipe is consequently exposed to air.

As the graphs represent a full motion period (17.5 seconds) after periodic behaviour is reached, the oil level is in constant motion and fluctuates around the filling level (55 cm) up to the tank height at 70 cm.

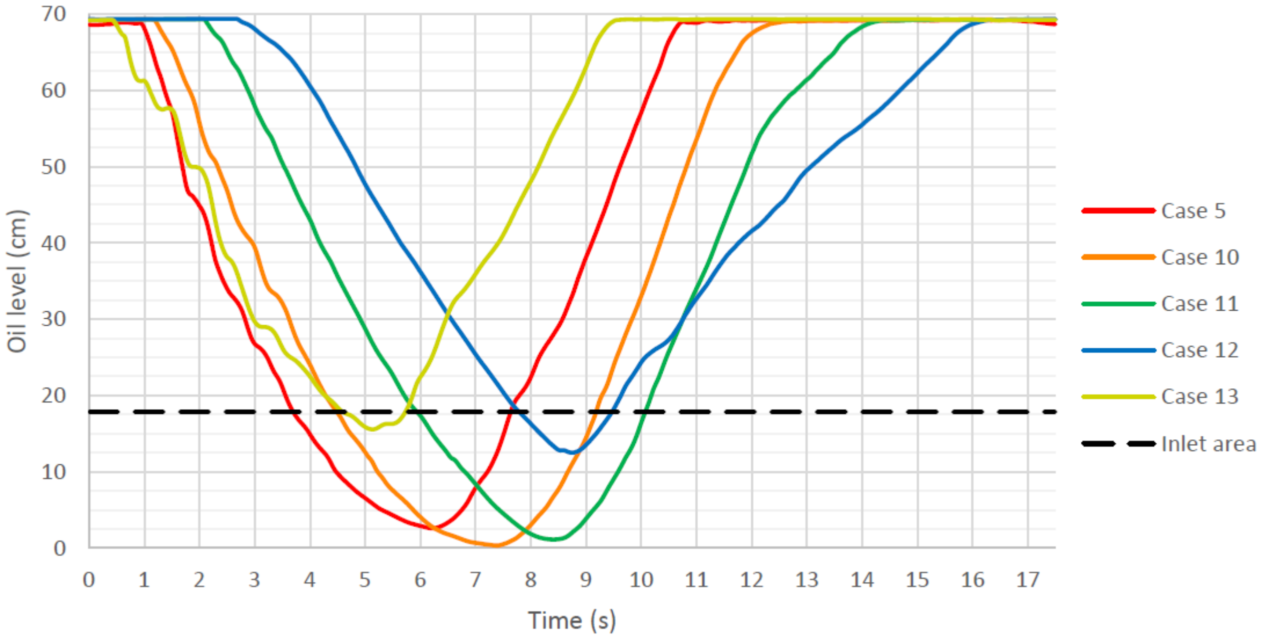

Figure 53: Oil level at suction pipe. Case 10 represents the worst case. Source: SINTEF Ocean's CFD calculation

In addition, simulation cases that include the estimated actual filling level and recorded motion experienced by *Viking Sky* during the time of the accident were carried out. The purpose of these simulations was to evaluate the validity of the simulation model by comparing the results with the actual events as logged by the alarm system on board.

These simulations showed that the suction pipe would be exposed to air at about the same time as the ship experienced engine shutdown signals according to the alarm log. These simulation results are presented in Chapter 4.4 of the SINTEF Ocean CFD calculations report, see Appendix F. This supports the validity of the simulation results.

Further, a simulation case combining the highest oil filling level recommended by the engine manufacturer and the recorded vessel motion was carried out to evaluate if the oil suction pipe was likely to have been exposed to air under such conditions.

The results indicate that the suction pipe inlet area would remain submerged by approximately 20 cm of oil or more throughout the duration of the simulation.

The simulations were carried out without circulation of oil as it proved difficult to achieve stable simulations when suction of air occurred. An investigation into the effect of oil circulation showed a reduced level of oil around the suction pipe in the range of 0 to 5 cm. This indicates that the suction pipe inlet area would be exposed to air somewhat earlier than what was found in the simulations.

A study of the sensitivity to the oil's properties (dependent on temperature) and the vessels centre of motion was also carried out. These showed that the uncertainty due to those parameters is insignificant.

The full report from SINTEF Ocean is attached in Appendix F.

1.8.7.4 CFD calculation by class

The classification society Lloyd's Register has carried out independent CFD simulations of the lube oil sump tank 5S (DG4).

LR has shared the report, Appendix G, and presented the results of these calculations to the NSIA and the MAIB. The simulations are based on an irregular wave pattern for which the maximum vessel inclinations exceed the required amplitudes stipulated by SOLAS and Class Rules, but the maximum pitch and roll angles do not occur simultaneously. Four cases are simulated to include the least favourable wave heading both for roll angle and for pitch angle, with and without translatory motion. Each case simulates a 30-minute scenario.

The results of all four simulation cases indicate exposure of the suction pipe to air a various number of times and for different durations. For the case which seems to be the worst of the four, 19 events of suction of air are detected with duration of up to 5 seconds.

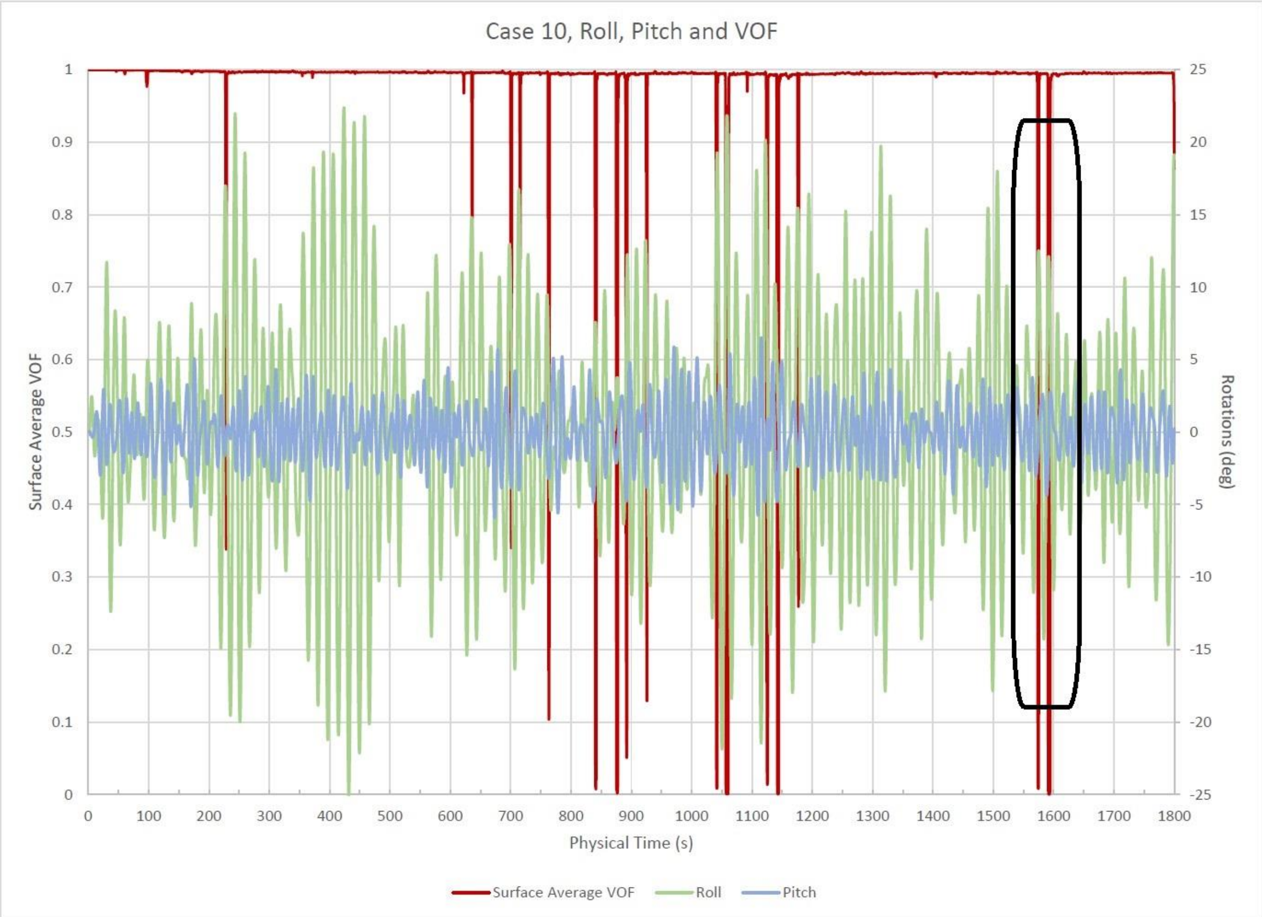

Figure 54: Graphical representation of results of CFD analysis from Lloyd's Register. Source: Lloyd's Register

The blue graph represents the pitch angle and the green graph represents the roll angle. Both of these are linked to the y-axis on the right side of the diagram. The red graph represents the fraction of the suction pipe inlet opening that is covered by oil and is linked to the y-axis shown on the left side of the diagram. Whenever the red graph drops below 1 the suction pipe inlet opening is partially exposed to air. When the red graph reaches the value of 0, the complete opening of the suction pipe inlet is exposed to air. LR has informed that the suction of air events have a duration of approximately 1.2 to 5 seconds each for the above illustrated case. Several of the events of suction of air seem to occur while the pitch and roll angles are less than the angles prescribed by the SOLAS regulation, as indicated by the black circle in the above graphical representation.

LR has not included circulation of oil nor quantified or qualified the effect of it in the simulations.

LR considered the results representative and realistic and concluded that *"the inlet exposure to air events are considered negligible in terms of number and duration."* LR further concluded that there is no evidence of the tank design being non-compliant with SOLAS or contributing to the accident.

1.9 Available information on sump tank filling levels

1.9.1 THE ENGINE MANUFACTURER'S PROJECT GUIDE

The MAN project guide for the diesel engines was available on board *Viking Sky.* As detailed in section 1.8.4, the project guide includes several pieces of information regarding lube oil levels or quantities.

According to section 5.2.5 *Lube oil service tank* of the project guide, the minimum recommended lube oil quantities were based on two separate requirements:

- The minimum quantity required to ensure oil quality, based on the DGs' design output in kW:

  The minimum quantity of lube oil for the engine is 1.0 litre/kW. This is a theoretical factor for permanent lube-oil-quality control and the decisive factor for the design of the by-pass cleaning. The lube oil quantity, which is actually required during operation depends on the tank geometry and the volume of the system (piping, system components), and may exceed the theoretical minimum quantity to be topped up.

On *Viking Sky* 1l/kW equated to 5.04 m^3 for DGs 1 and 4, and 6.72 m^3 for DGs 2 and 3.

- The minimum oil level required to ensure that the lube oil pump can draw in oil, free of air, in all design conditions.

  This requirement is further detailed through explanatory illustrations. These show that the high oil level was to be maintained minimum 150 mm below the top of the lube oil sump tank to ensure adequate degassing. The minimum filling level should ensure that the suction pipe opening is still submerged by a depth equal to one pipe diameter when statically inclined to the required angles of roll (β = 22.5°) and pitch (α = 5° for vessels over 100 m in length). The suction inlet should be positioned a minimum of half the suction pipe diameter above the tank bottom, preferably in a suction well.
  The corresponding minimum oil level or volume must therefore be calculated based on the actual sump tank geometry and suction pipe position. The result of such calculation was not available on board, but was carried out by the NSIA post-accident – see section 1.8.7.1.

1.9.2 INFORMATION SUPPLIED BY THE SHIPYARD

The shipyard was responsible for the design and construction of the sump tank. The only documentation of a ship specific minimum lube oil volume supplied by the shipyard was a table inserted on the last of six pages of a drawing entitled "Lube oil Service System Functional Diagram", see Figure 55.

SUMP TANKS CAPACITIES			
ENGINE		MAN MIN. RACCOMENDED TANK CONTENT - m^3	DESIGNED CAPACITY m^3
ITEM	TYPE		
XB/274A	09L32	5.04	6.4
XB/274B	12V32	6.72	8
XB/274C	12V32	6.72	8
XB/274D	09L32	5.04	6.4

Figure 55: Table extract from "Lube oil Service System Functional Diagram". Source: Fincantieri

The minimum recommended tank content specified in the above table equals 1l/kW, the minimum volume specified by the engine manufacturer to maintain lube oil quality and are not based on the tank geometry and the quantity required to ensure that the oil pump maintain suction of oil in all design operating conditions.

1.9.3 INFORMATION ON LUBE OIL LEVEL MANAGEMENT IN THE SMS

As far as the investigation has established, neither *Viking Sky's* safety management system (SMS) or any operational manual or procedures provided any guidance or information regarding minimum, maximum or "normal" lube oil levels nor what the lube oil level alarm set points should be.

The SMS mentioned lube oil levels twice in connection with heavy weather situations:

- The Ship Safety Management Manual Chapter 7.3 was entitled *Heavy Weather Precautions* and had a sub-chapter 7.3.9 *Engine room* that contained the following statement:

  Oil levels in the sumps of main machinery are to be checked and topped up to prevent loss of lubrication to excessive rolling, with due allowance to prevent spillage / overflow.

- The SMS also contained a checklist entitled *B10 Navigation in heavy weather* with a sub-section dedicated to *Engine room* in which the following checkpoint was listed:

  18) Oil levels in sumps………..………..Optimized □

1.9.4 AWARENESS OF THE ENGINE CREW

The investigation has found that the engineers on board were generally not familiar with any of the information listed in the above sections 1.9.1 to 1.9.3 nor with any other instructions or guidance regarding minimum lube oil levels or alarm setpoints. Upon request, some of the members of the engine crew stated 50%–60% or 3 to 5 m^3 as the normal filling level, whilst others were unable to provide a number or range for what the lube oil level was expected to be under normal operation.

In June 2016, one of the engineers working on board *Viking Sea* requested information from MAN regarding the recommended oil quantities for the engines. MAN responded with a reference to the table in the project guide indicating the minimum tank capacities of 6.0 and 4.5 m^3 for the large and small engines, respectively. MAN further specified that it was the shipyard's responsibility to design the lube oil sump tanks and that there should be documentation from the shipyard which indicates the correct oil level. The shore organisation of the ship management company was made aware of the email exchange between *Viking Sea* and MAN at the time. However, no guidance on correct filling volumes or alarm set points was issued by the ship management company until after the accident on *Viking Sky.*

1.10 Lubricating oil level remote monitoring system

Viking Sky was equipped with a Smart-Electro Pneumatic (EP) Level gauge system from Wärtsilä for remote tank monitoring of the lube oil sump tanks. One separate system was installed per tank.

The system consisted of level sensors in each tank that measured a liquid pressure, converted the pressure to oil height and added the offset of the sensor (height above tank bottom) to find the filling level. The filling level was sent via the IAS to NAPA which computed a corresponding volume, corrected for measured ship heel and trim. The volume was returned from NAPA to the IAS, displayed on relevant graphical display mimics and used to generate the lube oil volume alarms. In this report, these will be referred to as lube oil level alarms, as this is the term that is generally used. As the alarm shall be set based on what is identified to be the critical level for operation, the objective of ensuring a sufficient amount of lube oil in the tanks are achieved independent of whether level or volume is measured as long as consistency is ensured.

The lube oil sump low level alarm is a Class requirement, ref. LR Rules Pt. 5 Ch.1, Sec. 7.6.

The block diagram in Figure 56 is a functional description of the remote monitoring system. The Smart EP level module, IAS, NAPA and Eniram will be further described in the following sections.

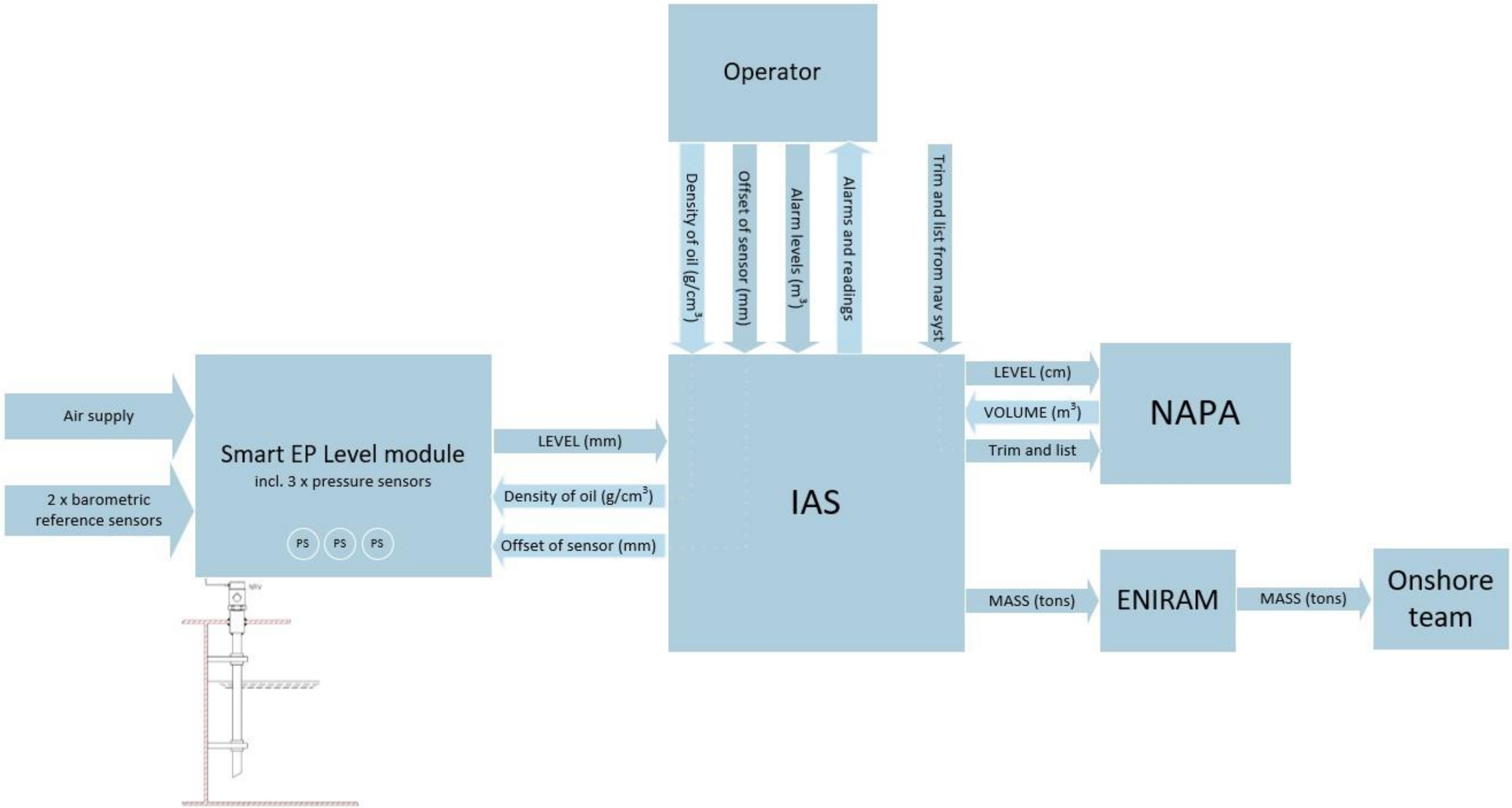

Figure 56: Functional block diagram, lube oil level remote monitoring system. Illustration: NSIA

1.10.1 TANK LEVEL SENSOR MODULE

The Smart EP level module is a sensor system delivered by Wärtsilä APSS srl. It is based on the bubble tube principle, where hydrostatic pressure of the lube oil is continuously measured by introducing compressed air from an external air supply into the tank via a pipe.

The installation of the sensor system in the lube oil sump tank is shown in Figure 57. As shown in the figure, the tube is installed with an offset, measured as the distance from the end of the tube down to the tank bottom. In addition to the external air supply, the module requires input from two barometric reference sensors for measurement correction.

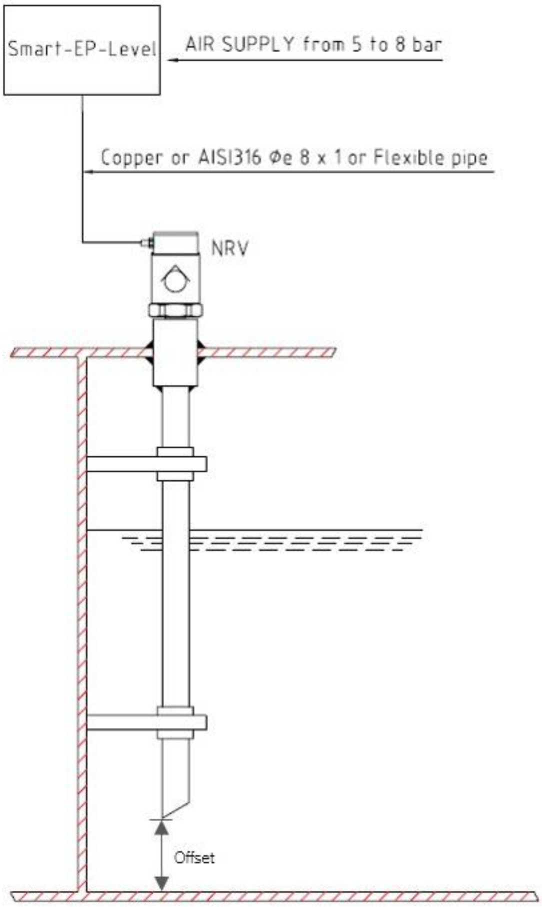

Figure 57: Installation of the level gauge system in the lube oil sump tank. Extract: The system data sheet, S-SEPL-TM-V21. Rev. 20, Wärtsilä APSS srl.

The hydrostatic pressure measured in the tank is converted to an oil height based on the density of the oil input by the operator in the IAS. The offset of the sensor is added and the resulting filling level, measured in millimetres (mm), is sent to the IAS.

The EP level sensor system comes in two different versions, one for tanks up to 15 metres and one for tanks up to 30 metres. The version for tanks up to 15 metres is installed for the lube oil sump tanks, and according to the manual, this version of the EP level system has a maximum error of +/- 15 mm H_2O or +/- 0.1% of the full range of the sensor. This corresponds to 16.7 mm lube oil, using a density of 900 kg/m^3, which represents 200 litres for sump tanks 6P (DG1) and 5S (DG4) and 233 litres for sump tanks 6S (DG2) and 5P (DG3). For the sump tanks in question, the sensors should measure an oil column of up to ca. 0.5 m. The corresponding uncertainty being minimum +/- 3.3% as compared to +/- 0.1% for an application corresponding to the maximum range of the sensor.

In addition to this error due to measurement uncertainty, there will be drifting of the signal over time. The manufacturer has put a requirement in the manual that the system is calibrated every two years to maintain accuracy but has not quantified the maximum drifting of the measurement in between calibrations.

The smart EP level module is installed on several other tanks on board the ships.

1.10.2 INTEGRATED AUTOMATION SYSTEM, IAS

Viking Sky was equipped with a Wärtsilä NACOS VALMATIC Platinum Integrated Automation System (IAS), which is a distributed process control and monitoring system. The system is event-based, which means that the system values are updated only on change in a state, not on predetermined time intervals.

The following operator inputs were required for remote monitoring of the sump tanks:

- Offset of the sensor tube (mm)
- Density of the oil (g/cm^3)
- Alarm levels (m^3); low low (LL), low (L), high (H) and high high (HH)

These values could be adjusted in the IAS by any of the engineers, with no means of identifying what had been changed, by whom, when or why.

The IAS received a filling level measured in millimetres from the EP level sensor module. The level was rounded and sent to NAPA as a level measured in centimetres. This introduced a measurement uncertainty of maximum 0.5 cm, which corresponds to 60 litres for sump tanks 6P (DG1) and 5S (DG4) and 70 litres for sump tanks 6S (DG2) and 5P (DG3).

After heel and trim compensation in NAPA, the signal was again received by the IAS and compared to the alarm levels set by the operator.

Upon a level signal outside the predefined alarm levels, the system gave an audible alarm. Upon failure in the sensor system, the system gave a warning, also sounding like an alarm.

The alarms had the parameters ON DELAY and OFF DELAY, given in seconds, and set up by the operator in the ECR. ON DELAY defined how long the alarm condition should be active before an alarm was triggered and was used to prevent alarm conditions of a short duration from triggering an alarm. If the ON DELAY for the high alarm (H) was set to 5 seconds, this meant that there had to be a high level of lube oil for 5 seconds or more for the alarm to be triggered. This prevented temporary sloshing of oil above the alarm limit from triggering a high level alarm. Similarly, OFF DELAY defined how long an alarm should be active after the system had returned to the normal condition. OFF DELAY was used to give the operator time to become aware of the alarm and ensure that it was not triggered again within the defined time period. Similar to the level alarm values, the ON and OFF DELAY values have also been changed several times on board.

An alarm situation resulted in an alarm sounding in the ECR and the alarm showed up in the IAS alarm list, as shown in Figure 58. A further description of the alarm system is given in section 1.11.

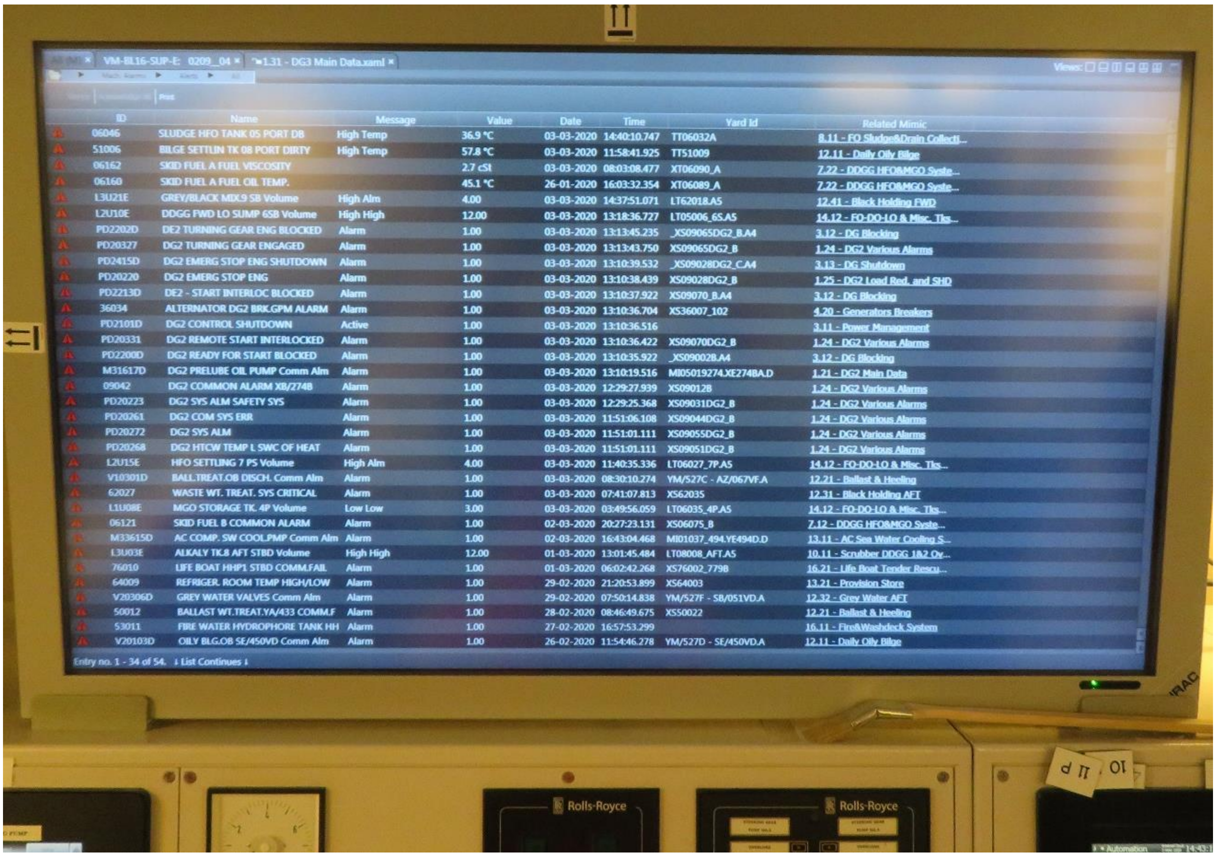

Figure 58: Alarm list as presented to the operators in the ECR. Photo: NSIA

The alarms were also shown in the relevant mimics. An example from the power management mimics is shown in Figure 59, where a red alarm triangle and text describing the alarm indicates low lube oil pressure approximately 2 minutes after DG2 shutdown.

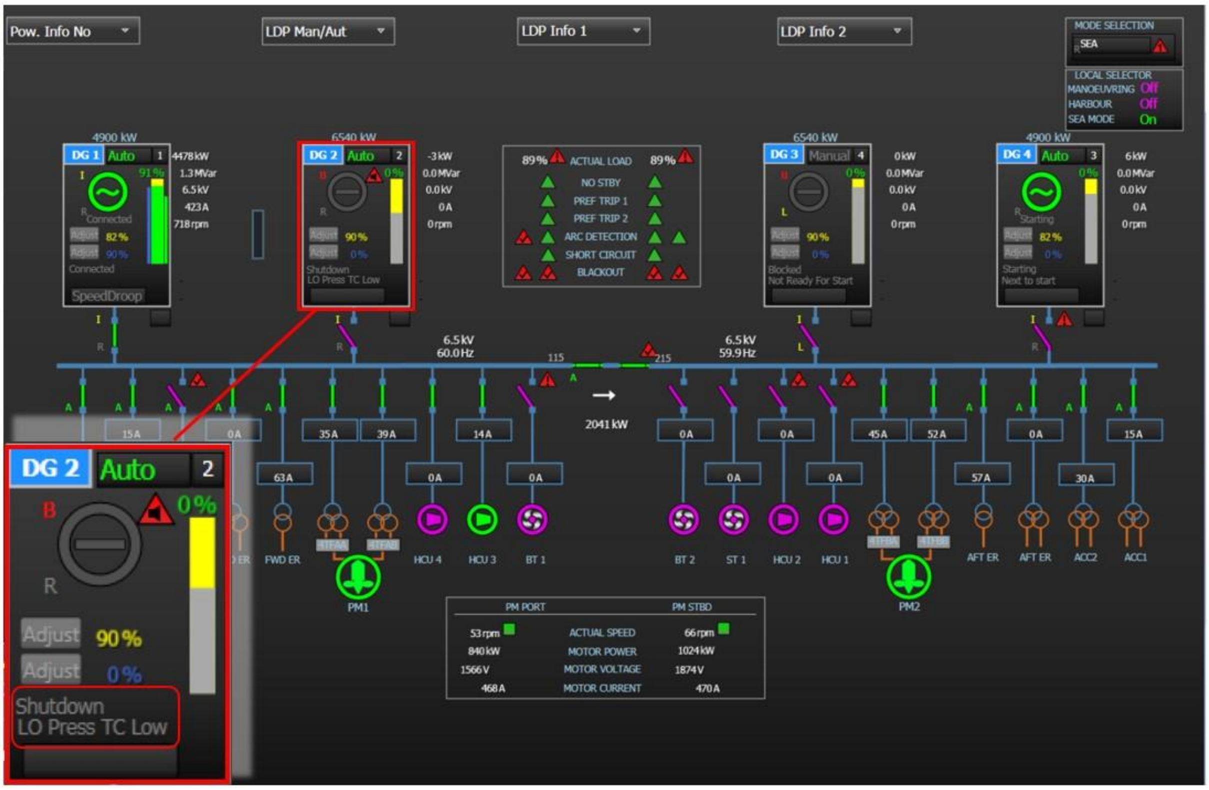

Figure 59: Extract from the power management mimics, showing the low lube oil alarm. Source: IAS/NSIA

Figure 60 and Figure 61 shows how levels and corresponding alarms were shown in relevant mimics. These two figures show the tank level at the time of the DG4 shutdown at 1345, with details for sump tank 5S (DG4) highlighted. The volume for 5S (DG4) is based on heel and trim compensated and rounded data from NAPA, stated to be 1.8 m^3. This corresponds to 24% filling level. The graphical representation of the filling level, represent the direct level measurement of the EP Level Module[20], shown to be approximately 40%, see Figure 62.

Figure 60: Extract from the tank mimics, showing the tank levels. Source: IAS/NSIA

[20] Not heel and trim compensated, and not rounded.

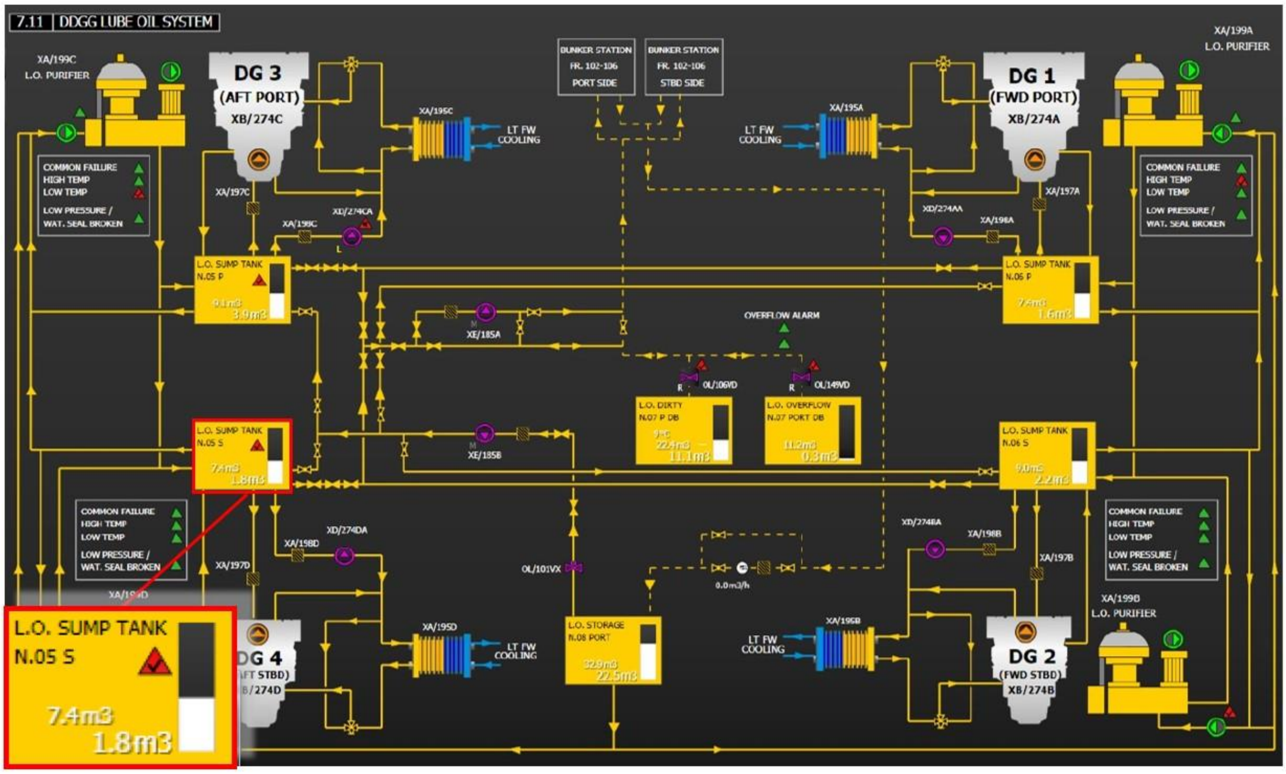

Figure 61: Extract from the lube oil system mimics, showing the tank levels. Source: IAS/NSIA

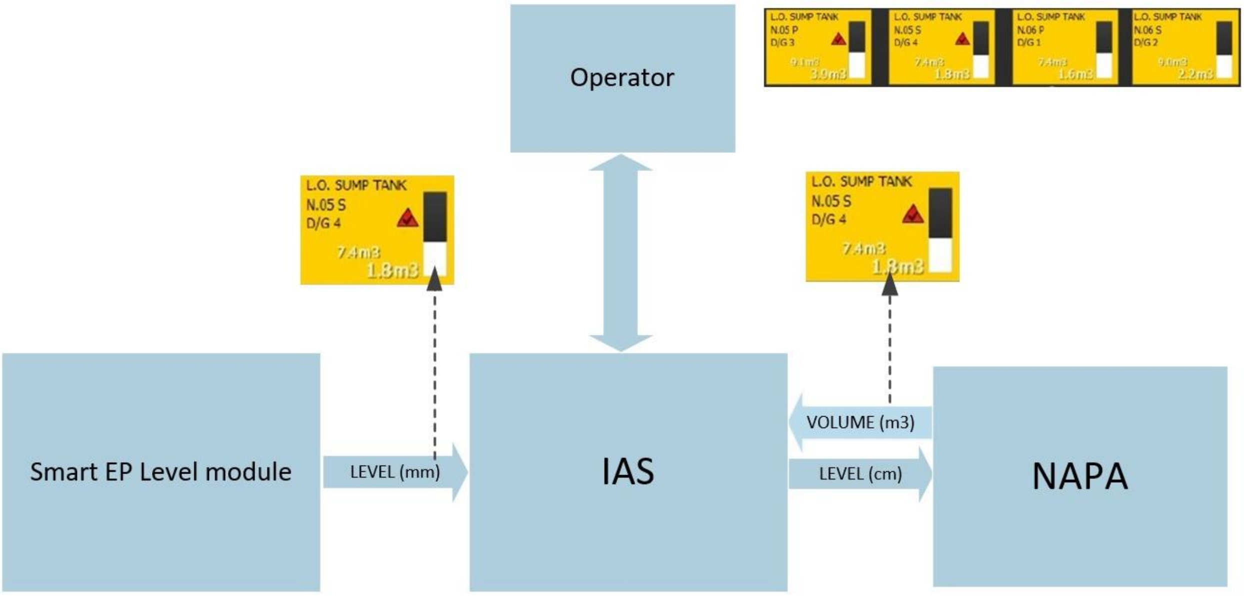

Figure 62: Inconsistency in volume shown in mimics. Source: IAS/NSIA

1.10.2.1 Level alarm and delay values

The investigation has shown that the level alarm and delay values have been changed several times on board both *Viking Sky* and its sister vessels. As examples, values set on board *Viking Sky* prior to delivery, a few months after delivery and two days after the accident, are shown in Table 9, Table 10 and Table 11.

Table 9: Level alarm and delay values, Viking Sky 21.02.2017. Source: Wärtsilä

Lube oil sump tank	Low Low level			Low level			High level			High High level		
	Value	Delay On	Delay Off	Value	Delay On	Delay Off	Value	Delay On	Delay Off	Value	Delay On	Delay Off
6P (DG1)	1.0 m^3	5 s	5 s	4.5 m^3	5 s	5 s	6.8 m^3	5 s	5 s	7.0 m^3	5 s	5 s
6S (DG2)	2.0 m^3	5 s	5 s	3.0 m^3	5 s	5 s	8.3 m^3	5 s	5 s	8.6 m^3	5 s	5 s
5P (DG3)	2.0 m^3	5 s	5 s	3.0 m^3	5 s	5 s	9.0 m^3	5 s	5 s	9.0 m^3	5 s	5 s
5S (DG4)	1.0 m^3	5 s	5 s	3.0 m^3	10 s	5 s	6.9 m^3	10 s	5 s	7.1 m^3	10 s	5 s

Table 10: Level alarm and delay values, Viking Sky 12.07.2017. Source: Wärtsilä

Lube oil sump tank	Low Low level			Low level			High level			High High level		
	Value	Delay On	Delay Off	Value	Delay On	Delay Off	Value	Delay On	Delay Off	Value	Delay On	Delay Off
6P (DG1)	2.0 m^3	5 s	5 s	3.0 m^3	5 s	5 s	6.9 m^3	5 s	5 s	7.2 m^3	5 s	5 s
6S (DG2)	2.0 m^3	5 s	5 s	3.0 m^3	5 s	5 s	8.3 m^3	5 s	5 s	8.8 m^3	5 s	5 s
5P (DG3)	2.0 m^3	5 s	5 s	2.5 m^3	5 s	5 s	8.3 m^3	5 s	5 s	8.8 m^3	5 s	5 s
5S (DG4)	2.0 m^3	5 s	5 s	3.0 m^3	15 s	5 s	6.9 m^3	10 s	5 s	7.2 m^3	5 s	5 s

Table 11: Level alarm and delay values, Viking Sky 26.03.2019. Source: Wilhelmsen

Lube oil sump tank	Low Low level			Low level			High level			High High level		
	Value	Delay On	Delay Off	Value	Delay On	Delay Off	Value	Delay On	Delay Off	Value	Delay On	Delay Off
6P (DG1)	2.5 m^3	5 s	5 s	3.0 m^3	10 s	5 s	6.5 m^3	5 s	5 s	6.6 m^3	5 s	5 s
6S (DG2)	3.0 m^3	5 s	5 s	3.5 m^3	10 s	60 s	8.3 m^3	5 s	5 s	8.5 m^3	5 s	5 s
5P (DG3)	3.0 m^3	5 s	5 s	3.5 m^3	10 s	60 s	7.0 m^3	5 s	5 s	8.0 m^3	5 s	5 s
5S (DG4)	2.5 m^3	5 s	5 s	3.0 m^3	10 s	5 s	5.6 m^3	10 s	5 s	7.2 m^3	5 s	5 s

1.10.3 NAPA

Viking Sky had a NAPA Loading Computer installed. This is a stability instrument primarily intended as an instrument for the crew to plan and optimise load and stability. According to NAPA, the loading computer has not been designed with the intention of generating output to critical alarms outside of the computer itself.

NAPA was connected to the IAS from which it automatically received the lube oil sump tank level, measured in centimetres. NAPA calculated the tank volumes based on the following:

- 3D geometry of the tank, received from the shipyard and based on design drawings
- liquid level data from the level sensor in the tank, and
- the ships current floating position (heel and trim), based on input data from onboard draft sensors.

The volume data, rounded to the closest 100 litres (0.1 m^3), was then transferred back to the IAS. This rounding resulted in a maximum error of 0.05 m^3.

In October 2018, it was identified that the aft draft sensor was sending erroneous readings to NAPA. This was affecting the level correction done by NAPA and thus also led to wrong volume calculations. The issue was resolved by reconfiguring the NAPA loading computer to ignore the signal from the draft sensors and use the heel and trim sensor data directly in the calculation. In December 2023 the issue with the draft sensor was resolved and the system was reconfigured to its original setup, using the draft sensors as input.

The investigation has identified that there was an error in the 3D model geometry for sump tank 6P (DG1) as it indicated a total tank height of 75 cm instead of 70 cm and a well area of 15 cm depth instead of 10 cm depth. This caused an error in the calculations. The IAS further holds tank capacity tables that are used for conversion of oil level to volume in case the NAPA loading computer is unavailable. The tank capacity table for sump tank 6P (DG1) has the same error as the 3D model. The below sketches illustrate the effect of the erroneous model:

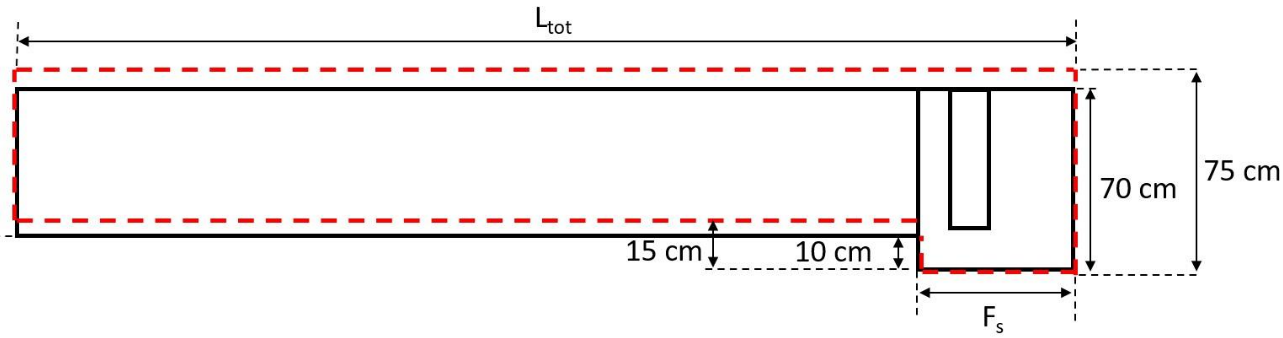

Figure 63: Actual tank (black contour) and the erroneous model (red dotted line). Illustration: NSIA

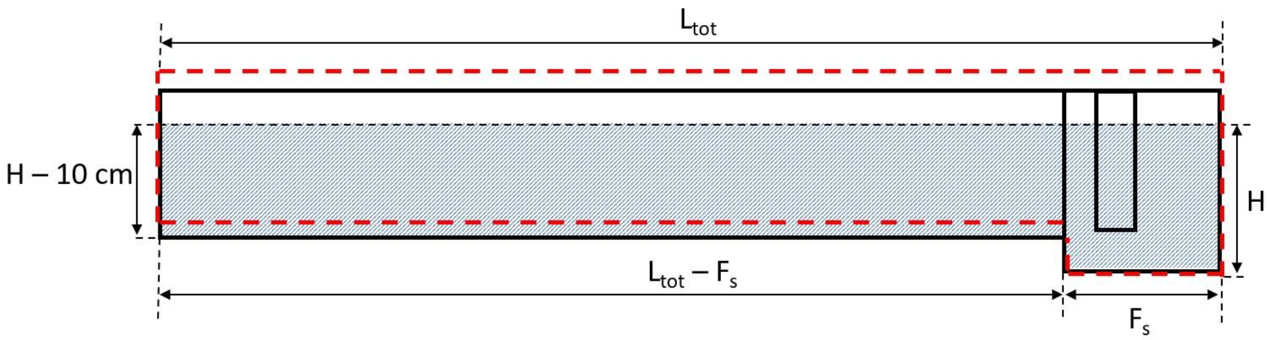

Figure 64: Actual oil volume for a given oil filling height "H". Illustration: NSIA

The width of the tank varies slightly over the length of the tank, but for the sake of this simplified demonstration we consider the width of the tank equivalent to "W" for the full length of the tank "L_{tot}". "F_s" is the length of the frame spacing that constitutes the well area. In this case, the actual volume "V" of oil for a given filling height "H" equals:

$V = W \times H \times F_s + W \times (H-10) \times (L_{tot} - F_s)$

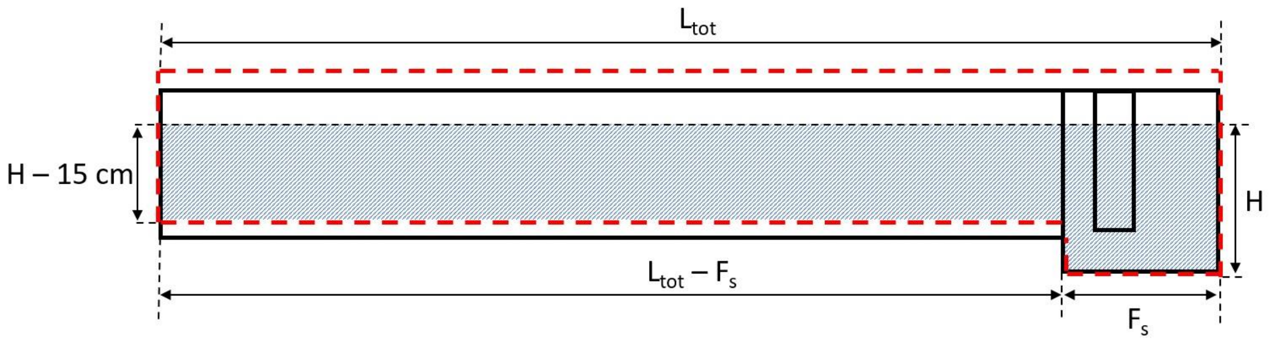

Figure 65: Oil volume calculated by use of the erroneous model for a given oil filling height "H". Illustration: NSIA

The oil volume calculated by use of the erroneous model for a given oil filling height "H" equals:

$V = W \times H \times F_s + W \times (H\text{-}15) \times (L_{tot} – F_s)$

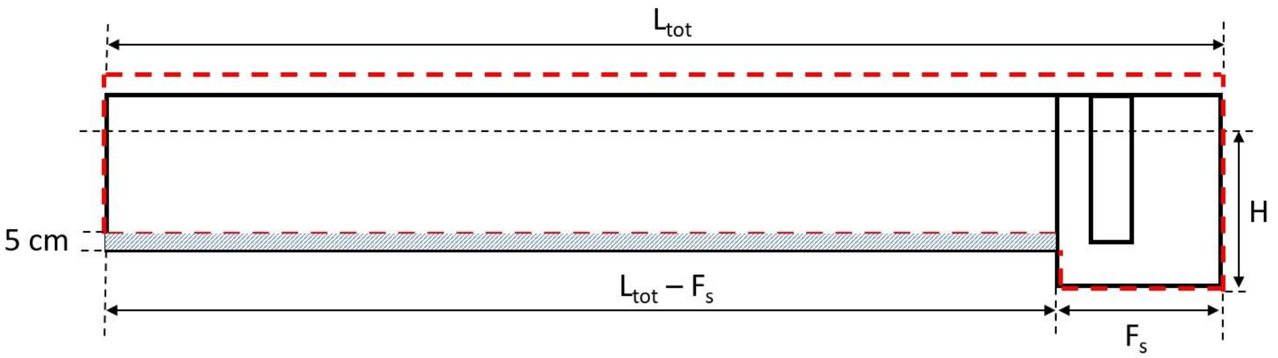

Figure 66: Difference in oil volume between a correct and the erroneous model. Illustration: NSIA

The difference in oil volume, as shown in above sketch, equals:

$V_{diff} = W \times 5 \times (L_{tot} – F_s)$

By use of the actual tank dimensions, the resulting difference in volume is 568 litres. As indicated by the above illustrations, the effect of the erroneous model being used on board is that the calculation will return a value 568 litres less than the actual oil volume for any given oil height. This represents 7.7% of the total tank volume.

1.10.4 ENIRAM

Eniram is an onboard and onshore energy management system with operational optimisation and fuel saving as main purpose. Inclinometers are part of the system, for the purpose of calculation of dynamic heel and trim of the vessel. Limited, processed information from Eniram is available by touch screen on the bridge and in the engine control room (ECR). Raw data from IAS, the navigation system and from Eniram inclinometers is transferred from onboard to shoreside automatically and selected data is accessible from an Eniram online portal.

The lube oil sump tanks content was converted from volume to mass in IAS and sent to Eniram. The mass, measured in tons, were available onshore through the Eniram online portal.

1.10.5 INSTALLATION OF LEVEL SENSOR

1.10.5.1 Distance between sensor tubes and operational pipes

According to the technical manual, the horisontal distance between the smart EP level tubes and operational pipes must not be less than 280 mm, to avoid disturbances and to ensure a reliable value.

According to as-built drawings received from the yard, these are the closest distances measured between the level tube and operational pipes in each tank:

- 6P (DG1) – all distances are over 280 mm
- 6S (DG2) – all distances are over 280 mm
- 5P (DG3) – all distances are over 280 mm
- 5S (DG4) – 209 mm between level tube and oil suction

1.10.5.2 Offset

The offset is the height from the tank bottom to the bottom of the sensor tube, see Figure 57. The design offset for the sensor tubes in the lube oil sump tanks for *Viking Sky* and its sister vessels was 60 mm. According to the yard, the actual as-built height may vary due to available pipe-length and accuracy during welding. The offset value in the IAS is adjusted on board during commissioning, aligning the volume from the level transmitter with the volume from manual soundings.

The offset was not considered a critical value on board, and both crew and service personnel used the offset as a dynamic value to “calibrate” the level sensor by aligning the manual and remote readings when required.

The offset values set on board *Viking Sky* 12.07.2017 and 26.03.2019 are shown in Table 12.

Table 12: Offset values, Viking Sky. Source: Wärtsila/Wilhelmsen

Lube oil sump tank (DG)	Offset Value 12.07.2017	Offset Value 26.03.2019
6P (DG1)	110.0 mm	80.0 mm
6S (DG2)	60.0 mm	80.0 mm
5P (DG3)	110.0 mm	80.0 mm
5S (DG4)	90.0 mm	80.0 mm

1.10.6 UNCERTAINTY OF THE REMOTE MONITORING SYSTEM

The total, known uncertainty for the remote monitoring system is as shown in Figure 67. It consists of the maximum error for each contributing system which is based on the known measurement uncertainty and rounding in the transactions, as described in the previous sections.

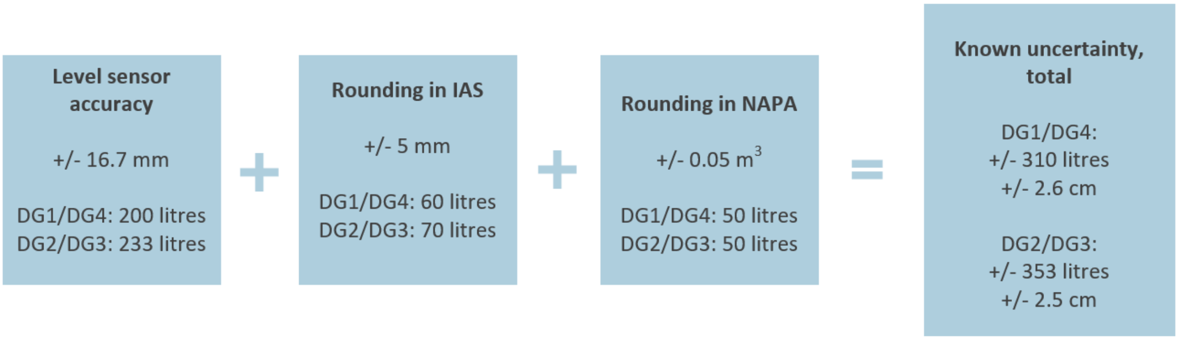

Figure 67: Known, total uncertainty for the remote monitoring system. Illustration: NSIA

Due to the known error in the 3D model, the volume calculation will return a value 568 litres less than the actual oil volume for any given oil height for 6P (DG1). This will come in addition to the uncertainty shown in Figure 67.

The following are further identified contributions to the uncertainty which has not been possible to quantify:

- Drifting of signal from the sensor element over time.
- Uncertainty in the onboard draft sensors used in the heel and trim compensation in NAPA.
- Too short distance between sensor tube and operational pipe for DG4.

Wrongly set manual inputs will also add to the uncertainty:

- Incorrect offset
- Incorrect density of oil

1.10.7 ASSESSMENT OF TANK CONTENT DATA STORED ONSHORE

The investigation has secured the tank content data stored onshore for *Viking Sky* and four sister vessels. The database contained an hourly average value for each tank from 1 January 2017. Prior to this date, for the vessels of the fleet in service at that time, the database only held a daily average value. A close analysis of the data has revealed a significant number of individual data points that are clearly erroneous. There are also periods for which the trend of the data is inexplicable.

Due to these observations and the specified uncertainties in section 1.10.6, the NSIA finds the data not sufficiently trustworthy to be used to draw any conclusions unless there are other sources of information to corroborate the data. The investigation has not looked into the data handling on shore in sufficient detail to establish if the tank content data made available to the onshore organisation "in real time" was already unreliable or if there may be other reasons for the observations stated above.

On the day of delivery of *Viking Sky*, 25.01.2017, a printout was made from the IAS with an overview of all tanks content. The below figure shows an extract with the lube oil sump tanks content.

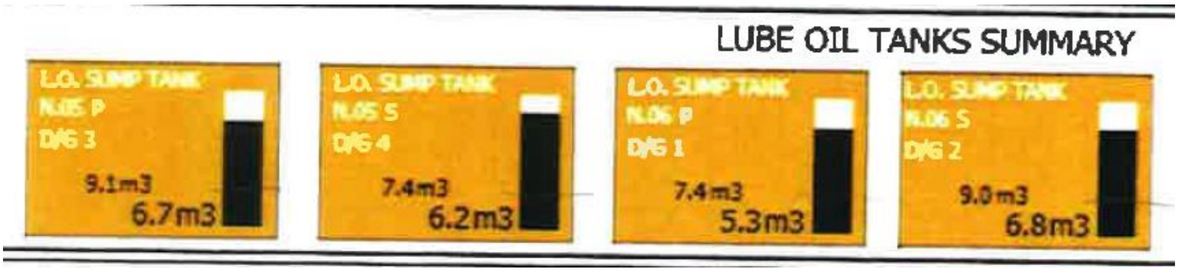

Figure 68: Extract from printed tanks summary on day of delivery. Source: Wilhelmsen

1.11 Alarm system design and management

1.11.1 GENERAL

The alarm and monitoring system on board a ship should enable the crew to operate the vessel efficiently and safely. The system should act as a support for the operators and inform of abnormal conditions in the machinery and systems under monitoring.

The alarm and monitoring system on board *Viking Sky* was an integral part of the Wärtsilä NACOS VALMATIC Platinum Integrated Automation System (IAS). The IAS recorded and raised all the alarms and events associated with the vessel's machinery, receiving signals either directly, or from local systems dedicated to individual equipment. These were then shown in visual form to operators via displays in the ECR. See examples in section 1.10.2.

The DGs had their own alarm monitoring and shutdown system: MAN's diesel engine Safety and Control System (SaCoS). When displayed on the IAS, SaCoS alarms were preceded by the text 'Common alarm'.

In the event of a serious electrical fault in a DG, the general protection module would send shutdown signals directly to SaCoS, which in turn would shut down the engine concerned. In the event of a critical mechanical issue such as lube oil low pressure, cooling water temperature or overspeed, SaCoS would shut down the engine concerned. Concurrently, it would generate a set of alarms for the IAS. While the shutdown of a DG would register immediately on the IAS, the cause of the shutdown would appear as alarms once the relevant alarms reached the top of the alarm system's buffer. This could take several seconds, due to cyclic reading between the various systems and interfaces.

1.11.2 STANDARDS AND GUIDELINES FOR DEVELOPMENT OF ALARM SYSTEMS

At the time of the construction of *Viking Sky*, there were no standards available giving specific criteria for the design of engine room alarm systems in the maritime industry. The only guidance in place, explicitly for this industry, was the IMO Code on Alerts and indicators, 2009. This IMO Code is intended to provide general design guidance and to promote uniformity of type, location and priority for those alerts and indicators which are required by SOLAS and other statutory regulations, but it does not provide guidance on alarm management beyond that scope. In developing an alarm system in high-risk land-based industries, the following aspects were given consideration[21]:

- Human Machine Interface specification
- Human Machine Interaction style guide

[21] *Office for Nuclear Regulation. Human Factors Integration. NS-TAST-GD-058-Revision 3. March 2017. N.B. These are similar to those used in transportation modes such as aviation.*

- User experience, usability assessments and trials
- Evidence from user-based design assessments
- Usability / interaction standards.

To ensure the inclusion of these aspects in product development, a user-centred design development and design process was considered to facilitate the best possible user experience. ISO standard 9241-210:2019, *Human-centred design for interactive systems*, defined six fundamental principles that formed the basis of the user-centred design process:

1. **Design is based on understanding users, their tasks and their environment:** It is not enough to have a vague impression of the product's target group. User-centred design requires deep immersion into the lives of users.
2. **Users are involved throughout the entire development and design process:** This is one of the main differences to other approaches. Users are not just invited to assess a finished product, rather their opinions are the basis for development.
3. **The design process is guided by user ratings:** Users evaluate every prototype and every beta version, and this feedback is used to develop the product.
4. **The process is iterative:** The process steps in product development are performed non-linearly and repeatedly. Feedback from users can make multiple iterations of individual phases necessary.
5. **The entire user experience is taken into account:** The aim of user-centred design is not to make using a product as simple as possible. Instead, the process takes a broader view of the user experience. Products should evoke positive emotions, offer genuine solutions and encourage users to use them repeatedly.
6. **The project team is multi-disciplinary:** User-centred design requires close cooperation across disciplines. There is no room for silo mentalities in product development. User requirements can only be implemented optimally if copywriters, graphic designers, and programmers share their different perspectives.

1.11.3 ALARMS MANAGEMENT, REQUIREMENTS AND GUIDANCE

1.11.3.1 Bridge alert management

The International Maritime Organization's (IMO) Resolution MSC.302(87), Adoption of Performance Standards for Bridge Alert Management (BAM), adopted in 2010, included the following in its stated purpose:

- *to harmonise the priority, classification, handling, distribution and presentation of alerts, to enable the bridge team to devote full attention to the safe operation of the ship and to immediately identify any alert situation requiring action to maintain the safe operation of the ship.*
- *to avoid unnecessary distraction of the bridge team by redundant and superfluous audible and visual alarm announcements.*
- *to reduce the cognitive load on the operator by minimising the information presented to which* is necessary to assess the situation.

MSC.302(87) required the BAM implementation to prioritise alerts as:

> *1. Emergency alarms when an immediate danger to human life or to the ship exists.*
>
> *2. Alarms that require immediate action to avoid a hazardous situation.*
>
> *3. Warnings for conditions not immediately hazardous, but may develop into one.*
>
> *4. Cautions to make the bridge team aware of a condition that has deviated from the normal.*

For alert handling purposes they are categorised as A, B and C alerts.

- Category A alerts require the user to access the individual equipment's alarm system for further information.
- Category B, where no additional information is required other than that presented at an integrated central system.
- Category C, where the alert cannot be acknowledged from the bridge – as in the case of engine room alerts.

In addition, the BAM also requires the following features:

- Alert messages of different priorities to be distinguishable from each other.
- If all alerts cannot be displayed simultaneously, there should be a means to inform the user of the same.
- It should be possible to return to the display containing the highest priority alerts by a single user action.
- 'Aggregate alerts', which combine multiple individual alerts of the same kind, should be available.

No similar requirements were made of engine room alarm systems.

1.11.3.2 Airline industry requirements

The European Aviation Safety Agency's publication *Certification Specification and Acceptable Means of Compliance for Large Aeroplanes* contains section AMC 25.1322 Flight Crew Alerting.

Under the section Flight Crew Alerting Philosophy, AMC 25.1322 states:

> *When developing a flight crew alerting system, use a consistent philosophy for alerting conditions, urgency and prioritisation, and presentation.*

Alerts were to be categorised as warning, caution or advisory. A consistent alert presentation scheme was required, comprising the location of the alert, combinations of alert mechanism, such as aural signals with unique tones, visual displays with colour and graphical coding for the three categories of alarms as well as tactile or haptic methods.

On the subject of unwanted alerts, the document states:

> *… the impact of frequent False or Nuisance alerts increases the flight crew's workload, reduces the flight crew's confidence in the alerting system, and affects their reaction in case of a real alert.*

1.11.3.3 Guidance

The Engineering Equipment and Materials Users Association's (EEMUA) publication entitled *Alarm systems – a guide to design, management, and procurement* (also referred to as EEMUA 191) included input from the UK's Health and Safety Executive (HSE) and was an accepted guide to good practice for all aspects of alarm systems. Much of the guidance was generic and the guide had been used successfully as a basis for training in transport sectors and in the nuclear industry.

Following an explosion at the refinery at Milford Haven in 1994, see section 1.15.5, the UK HSE published a separate information sheet, *Better Alarm Handling*. This stated that an effective alarm system should:

- *Alert, inform and guide the operators, allowing them to correctly diagnose problems in order to keep the process within safe parameters.*
- *Prevent shutdowns that are unnecessary.*
- *Present the operator with only relevant and useful alarms.*
- *Highlight critical alarms by prioritisation.*
- *Be designed ergonomically and should allow time for the operator to respond.*

1.11.4 ALARM SYSTEM DESIGN AND MANAGEMENT ON VIKING SKY

During the investigation into this accident, the design and management of the ECR alarm system on board *Viking Sky* has been assessed through the following:

- Review of the event list and alarm list logs.
- Heuristic evaluation of the configuration and use of the alarm and monitoring system, carried out on a sister vessel.
- Reviews performed on board both *Viking Sky* and sister vessels.
- Interviews of ECR operators.
- Review of CCTV footage from the ECR.

1.11.4.1 Alarm system design and configuration observations

The following observations were made of the design and configuration of the alarm system:

- All alerts had equal priority, and the annunciation of each alarm was achieved by an audible signal and a line displayed on the alarm screen. An alarm indicating that the refrigerator room door had been open for too long, had for example the same priority as an alarm indicating lube oil pressure shutdown.
- Alarms were raised for non-operational systems, e.g. DG3 LO level, and level alarms sounded despite it being unavailable due to ongoing turbocharger maintenance.
- There was no grouping of alarms.
- The alarm line displayed on the screen had a red flashing icon to its left, which stopped flashing when acknowledged by the engineer on watch. The alarm line cleared once the alarm condition ceased to exist.
- During normal operation in port and at sea, it was not unusual for a large number, often two or three full screens, of acknowledged alarm lines to be present.
- An observation from *Viking Sky,* but also for sister vessels, is that the total number of alarms appeared high.

- There were approximately 50 alarms during the 4–8 watch and approximately 150 alarms during the 8–12 watch 23 March.
- Between the shutdown alarms for DG4 and DG2 and their low lube oil pressure alarms being displayed some 8 seconds later, approximately 50 other various alarms were registered.
- During the 10 seconds following the blackout, approximately 1,000 alarms registered in the engine room alarm system as a result of the blackout.
- Subsystems generated and displayed a line identified as 'Common alarm' before the cause of the alarm was displayed.
- The alarm system displayed both level alarms[22] and level warnings for tank readings. Level alarms indicated volume outside predefined alarm limits, while level warnings indicated internal errors in the sensor system.
- Alarm messages were sometimes cryptic and ill-defined and operators acknowledged that there were occasions when they had to look them up or ask a colleague.
- The alarm system did not provide any guidance on how to address specific alarms.
- The alarm setpoints could be adjusted in the IAS by any of the engineers, with no means of identifying what had been changed, by whom, when or why.

1.11.4.2 Alarm system management observations

The following observations were made of the alarm management on *Viking Sky*:

- Alarm set points were changed several times from delivery of the ship.
- The operators were observed acknowledging alarms seemingly without any registration or further follow-up. This applied both for acknowledging of individual alarms and several alarms in one operation.
- After the blackout, the operators in the ECR were mainly using the power management mimics and the engine mimics.

1.12 Lubricating oil level management

Based on information provided by engine crew on board, ranging from chief engineer to motorman, and by shore based technical personnel in the ship management company, the NSIA has investigated how the lube oil level in the sump tanks was managed during operation. Besides information from interviews and meetings, electronic data from databases, printouts from the IAS and manually logged data has been scrutinised.

Several parameters were mentioned as relevant to the management of the lube oil level in the sump tanks. These were:

- The minimum lube oil level necessary to ensure suction of oil under vessel inclinations.
- The lube oil quality.
- Lube oil consumption.
- Economy.

[22] *Termed Volume Alarm in the IAS, see section 1.10*

1.12.1 MINIMUM LUBRICATING OIL LEVEL REQUIRED TO ENSURE SUCTION OF OIL

The lube oil level is measured both remotely and manually.

The sump tank levels were continuously monitored by a remote sounding system that provided the input to real time indications of the oil volumes as graphical displays (mimics) in the IAS and compared to the alarm set points, see section 1.10.

Several engineers have mentioned that the remote readings regularly differed significantly from the manual tank soundings and therefore were perceived as unreliable. The level sensors were calibrated by service technicians in November 2018, but according to the engineers the measurements again differed from the manual soundings after a short time. The lack of confidence in the remote readings resulted in a lack of confidence in the tank level alarms as well, since these were triggered by the same sensors. The NSIA has received information that the lube oil level alarms sounded frequently, in particular during bad weather, but that this did not trigger any particular action or adjustment of oil levels as the alarms were perceived as not trustworthy.

Manual tank soundings were taken every morning by the motorman during the 0800–1200 watch. The measurements were noted in cm on the *Daily noon report-form* and handed over to the engineer on watch (EOW) in the ECR. The EOW converted the measured tank soundings from cm to m^3 by use of the sounding tables available in the ECR. These soundings were also aggregated to give a daily total lube oil carried figure for the vessel, which was sent to the ship management company ashore. The ship management company also received monthly performance reports from each vessel. These contained, among several other technical performance parameters, information on the consumption of DG lube oil.

To compensate for the perceived unreliability of the remote readings, the frequency of manual soundings was increased from daily to once every watch. However, as described in section 1.9.3 above, the engineers did not know what the minimum oil level was supposed to be, and the ship management company had not provided any instruction or guidance to the vessel regarding minimum lube oil levels or alarm setpoints. The manual soundings were therefore noted but they were not compared to any minimum or reference values.

Table 13 contains the oil level measured for the three operational DGs on the day of the accident and the two days before. The manual soundings are quoted from the *Daily noon report-form* and the remote readings from printouts of mimics with tank levels from the IAS.

Table 13: Manual soundings and remote level monitoring on the day of the accident and the two days before. Source: Wilhelmsen/NSIA

Date	**Sump tank (DG)**	**6P (DG1) (m^3)**	**6S (DG2) (m^3)**	**5S (DG4) (m^3)**
21.03.2019	Manual sounding	3.3	4.9	4.0
	Remote reading	2.5	4.2	3.5
22.03.2019	Manual sounding	3.0	2.8	3.0
	Remote reading	2.5	2.6	2.1
23.03.2019	Manual sounding	3.1	3.0	3.0
	Remote reading	2.3	2.7	1.9

The figures in Table 13 illustrate the significant difference between the remote and manual soundings.

Another observation is the large decrease in volume seen from the 21st to the 22nd for DG2 and DG4. Most of this difference is due to these two engines being stopped on the 21st as the vessel was alongside in Tromsø, only running on DG1, while on the 22nd all three DGs were running. A significant amount of lube oil circulates in pipes and systems during engines' running condition and some of this oil will return to the sump tank when the engine is stopped or in standby. Soundings of sump tanks under controlled conditions have established the variation due to this effect to be approximately 0.8 m^3 and 1.2 m^3 for the small and large engines respectively.

Other variation is likely due to the uncertainty of the measurements and consumption, see section 1.12.3. The engine crew has estimated the uncertainty in manual soundings to be +/- 1 cm. The NSIA has witnessed lube oil soundings taken on board sister vessels and consider the uncertainty of the manual soundings likely to be at least the +/- 1 cm stated by crew. For the large sump tanks serving DG2 and DG3, 1 cm of oil height amounts to approximately 140 litres of oil. For the smaller tanks serving DG1 and DG4, 1 cm amounts to approximately 120 litres of oil. The uncertainty in remote readings, described in detail in section 1.10, are estimated to at least 310 litres (or 2.6 cm) for DG1 and DG4, and 353 litres (or 2.5 cm) for DG2 and DG3. In addition, the remote reading for the tank serving DG1 has a constant error due to the erroneous 3D-model resulting in the calculated volume being 568 litres (or 4.7 cm) too low.

The crew and technical staff ashore are of the opinion that the manual soundings are the most reliable. The NSIA agrees to this in this case and has therefore chosen to use the manual soundings from the morning of the 23rd as the assumed oil level and volume in the tanks at the time of the accident, see Table 14.

Table 14: Manual tank soundings in cm and corresponding volume in m³ from the day of the accident. Source: Wilhelmsen/NSIA

Sump tank (DG)	6P (DG1)	6S (DG2)	5S (DG4)
Oil height (cm)	33	29	32
Oil volume (m^3)	3.1	3.0	3.0

1.12.2 LUBRICATION OIL QUALITY

Lube oil samples were taken regularly, analysed onboard, and periodically sent ashore for a broader analysis by a specialised laboratory. While most of the parameters were usually within the recommended limits, the Total Base Number (TBN) – an indication of the reserve alkalinity of the oil – would sometimes fall below the recommended minimum level. Both engine crew and technical shore staff have reported that this was a concern as the TBN fell below the recommended minimum level faster than expected. This would trigger the exchange of part of the volume of oil in the subject tank to increase the TBN. It was common practice to discard a certain volume of oil and refill a somewhat larger volume to compensate for presumed oil consumption.

Both engine crew and shore staff has indicated that the lube oil exchange was mainly managed based on the TBN level.

1.12.3 LUBRICATING OIL CONSUMPTION

The general impression of both crew and technical shore staff was that the engines – still being new and of a modern design – consumed very little oil, although no one knew or would estimate the actual consumption when asked.

As shown in section 1.8.7.1, the nominal consumption specified by the engine manufacturer was 467 litres/week and 635 litres/week for the small and large engines, respectively. Both on board and shore based technical staff found this surprisingly high when confronted with this number.

The investigation has not been able to establish the exact oil consumption of the engines, but data samples indicate that the actual consumption is likely in the range of the nominal consumption specified by the engine manufacturer.

1.12.4 ECONOMIC CONSIDERATIONS

The cost of exchanging lube oil due to low TBN alone – when oil samples were otherwise ok – was mentioned as a source of annoyance.

The NSIA was also informed that maintaining an oil level higher than strictly necessary would be to run an unnecessary economic risk as there is always a possibility that the complete volume of oil in a tank had to be discarded, e.g. in the case of a water leakage or other contamination.

1.12.5 FILLING OF LUBRICATING OIL AFTER THE BLACKOUT

The NSIA has received a handwritten note of the oil volumes transferred during the afternoon and evening of 23 March 2019, after the blackout occurred. The note indicated the refilling volumes as shown in Table 15.

Table 15: Refilling volumes 23 March 2019. Source: Wilhelmsen/NSIA

Sump tank (DG)	6P (DG1)	6S (DG2)	5S (DG4)
Volume refilled (m^3)	3.2	4.4	3.2

As described in section 1.10.7, the remote tank level measurements stored in the Eniram database ashore are considered unreliable and is therefore not seen as a trustworthy source in itself. The NSIA has still decided to look at the data from the day of the accident to see if they correlate with the numbers on above mentioned note. The increase in oil levels indicated by the stored data is not significantly different from the data noted by the crew.

1.13 Safe return to port

1.13.1 SRTP REGULATIONS

The Safe Return to Port (SRtP) regulations in SOLAS Chapter II-1 Regulation 8-1 and II-2 Regulation 21 entered into force 1 July 2010. The purpose was to establish design criteria to ensure systems are available for a ship to return to port under its own propulsion after a fire or flooding casualty, while providing for a safe area for persons on board.

The overall intention of the regulations was to increase the safety level of passenger ships and reduce the likelihood of an evacuation. This is achieved through more redundant and segregated system arrangements, providing increased robustness and fault tolerance, and establishing procedures for system restoration and recovery.

The SRtP regulations were introduced due to an increasing concern of the operational risk of passenger ships, based on increasing size of vessels and number of passengers, previous accidents of fire in passenger ships, cruises in more remote and exposed areas and the risk associated with lifeboat evacuation, see section 1.7.6.

The basic philosophy is that the ship itself should be the safest place for all persons on board in all situations and to avoid evacuation for as long as possible. In case of evacuation, time and technical systems must be available to support orderly evacuation.

The regulations set clear requirements to the design of essential systems on board:

> ***Regulation 8-1.*** *A passenger ship shall be designed so that the systems specified in regulation II-2/21.4 (i.e. essential systems) remain operational when the ship is subject to flooding of any single watertight compartment.*

> ***Regulation 21.*** *This regulation provides design criteria for a safe return to port of the ship under its own propulsion after a fire casualty that does not exceed the casualty threshold, where the fire casualty threshold is defined as being the loss of the space of origin up to the nearest A-class boundary if the space is protected by a fixed fire-fighting system, or the loss of the space of origin and adjacent spaces up to the nearest A-class boundaries which are not part of the space of origin.*

As propulsion, steering and electrical power production are defined as essential systems, redundancy is required. Propulsion engines and electrical generators will have to be distributed in at least two separate engine rooms, and all essential auxiliaries for propulsion and electrical power production must be sufficiently segregated.

As the regulations are goal based and given on a quite high level, supplementary guidance and interpretations from the IMO are provided in circulars developed in the Marine Safety Committee (MSC), whereas the primary guidance to the design requirements is the MSC.1/Circ.1369 (2010).

The MSC.1/Circ.1369 links the design requirements to the ship operation and recommends operational limitations to comply with the regulations. It recommends that propulsion in SRtP situations is sufficient to provide a speed of 6 knots while heading into Beaufort[23] 8 weather conditions:

> ***II-2/21.4.1 Propulsion. Interpretation 18.***
>
> *Following a fire casualty within the threshold, the ship should be able to maintain an adequate speed for sufficient time to permit the ship's planned safe return to port in sea and wind conditions acceptable to the Administration taking into account the intended area of operation. A minimum speed of 6 knots while heading into Beaufort 8 weather and corresponding sea conditions is recommended. Configuration for power generation and propulsion in the worst case scenario in terms of casualty cases should be verified during normal sea trials.*

According to the circular, the ship systems' capabilities should be included in the list of operational limitations issued to passenger ships.

Only the SRtP redundancy requirement for propulsion, steering and power is regarded relevant for this investigation. Other requirements from the SRtP regulation will not be covered by this report.

1.13.2 SRTP IMPLEMENTATION FOR VIKING SKY

As part of the plan approval process Lloyd's Register, *Viking Sky*'s classification society, conducted a Safe Return to Port (SRtP) assessment and certified that *Viking Sky* was designed to the requirements for SRtP.

In the document *Ship description in Safe Return to Port*, prepared by the yard and approved by the owner and the classification society, reference is given to interpretation 18 in the MSC.1/Circ.1369 and to the ship's specification stating a minimum safe speed of 6 knots for heading into Beaufort 8 weather conditions. An *Electric load analysis report* was prepared to define the required propulsion load to achieve the defined minimum speed. According to this analysis, the total power required in an SRtP situation (loss of one engine room) with minimum speed 6 knots is 8,824 kW.

As described in section 1.7.1.1, *Viking Sky* had two separate engine rooms, located in different watertight compartments, separated by an A class boundary. There were one large DG (6,720 kW) and one small DG (5,040 kW) in each engine room. The total power generation capacity in each engine room therefore exceeded the total power required for SRtP, thus the vessel fulfilled the SRtP design requirements with respect to propulsion power redundancy and capacity. In case of loss of any one DG, the remaining power capacity of the affected engine room would be below the total power required for SRtP, hence no longer in compliance with the regulations.

On 16 March 2019, DG3 suffered a turbocharger failure, rendering the DG inoperable. As demonstrated above, the vessel was consequently no longer in compliance with the SRtP regulations. This degradation of equipment was not reported to the administration of the flag state nor the classification society as required (SOLAS Chapter I Regulation 11).

[23] *For the Beaufort wind scale, see Appendix H*

Viking Sky had previously experienced two turbocharger failures (DG1 and DG4) in June 2018. During the two months prior to the failure of *Viking Sky*'s DG3 turbocharger there were five turbocharger failures on three of the sister vessels. Since September 2016 the five sister vessels in the fleet had experienced a total of 33 turbocharger issues of various category and severity.

Defects that affect the safety of the ship and/or compliance with rules or regulations should be reported and the ship should stay in port until repair is performed or exemption to sail is granted (SOLAS Chapter I Regulation 11). An application for exemption should be sent from the shipping company to the recognised organisation (RO)[24], which in turn would perform an assessment and send a recommendation to the administration of the flag state. The flag state could in turn grant an exemption, possibly with restrictions, limiting the range and environmental conditions within which the vessel would be permitted to operate.

At the time of the accident there were no guidelines or procedures in the safety management system (SMS) regarding how to handle planned or unplanned unavailability of a DG with respect to the SRtP requirements. According to the internal investigation report prepared by the ship management company following the accident, limitations with regards to SRtP was never considered, and only after the accident a risk assessment based on one engine out of operation was made, see section 1.16.5.2.

[24] An RO is a classification society which has been authorised and recognised by the Administration under a written agreement to undertake statutory surveys and issue statutory Certificates on the Administration's behalf

1.14 Passenger questionnaire

The NSIA sent out a survey to passengers following the accident. The survey was distributed to approximately 500 e-mail addresses and had a response rate of more than 80%. All responses have been reviewed and evaluated and they are all important pieces to understand the individual passenger's experiences during the accident.

The replies have given valuable input to the investigation team. The NSIA believes that it gave a representative picture of how the passengers experienced the accident, as well as contributing to specific answers to certain matters of significance to the investigation. In addition to the survey, interviews were conducted with some of the passengers.

1.15 Relevant previous accidents

1.15.1 CROWN PRINCESS

On 18 July, 2006, the cruise ship *Crown Princess* had a heeling accident in the Atlantic Ocean off port Canaveral, Florida. The vessel’s automatic steering system began a turn to port, and in an effort to counter the effects of a perceived high rate of turn, the automatic steering mode were disengaged. Manual turning of the wheel first to port and then from port to starboard several times caused a heel at a maximum angle of about 24°, resulting in injuries to 298 passengers and crewmembers.

As the VDR did not record heel angles, the investigation team from the NTSB had to determine the *Crown Princess*’s maximum angle of heel from images taken by video cameras installed on the vessel for purposes other than accident investigation.

Data that accurately record a vessel’s angle of heel can considerably assist those attempting to understand the nature of a heeling event. The NTSB therefore concludes that the *Crown Princess* accident demonstrates the need for obtaining and archiving data on vessel angles for heel and recommends that the Coast Guard propose to the International Maritime Organization that it mandate the recording on voyage data recorders of heel angles through the complete range of possible values.

1.15.2 MSC ZOE

On 1 January, 2019, the container ship *MSC Zoe* experienced constant rolling and loss of a total of 342 containers whilst sailing on the North Sea, on its way from Portugal to Bremerhaven in Germany. The main cause of the loss of containers was the high stability at which the ship was sailing in storm and shallow waters.

On board *MSC Zoe,* a mechanical inclinometer was installed to provide information to the crew about the actual heel angle of the ship. The investigation concluded that the mechanical inclinometer is not a good instrument to determine the real roll angles a ship experiences, as the instrument is sensitive to accelerations.

Based on the findings from the investigation, it was recommended to generate an obligation on all container ships to install electronic inclinometers or similar systems to measure and display this information in real-time to the captain/crew, and for ships with mandatory equipped VDR to record actual roll angle, roll period and accelerations for the purpose of safety investigations.

1.15.3 EL FARO

On 1 October, 2015, the cargo vessel *SS El Faro* was on a regular route from Jacksonville, Florida, to San Juan, Puerto Rico, when it foundered and sank in the Atlantic Ocean about 40 nautical miles northeast of Acklins and Crooked Island, Bahamas. The ship had sailed directly into the path of Hurricane Joaquin, carrying a crew of 33. All those aboard perished in the sinking.

The *El Faro* developed a significant list mainly caused by the strong wind on the vessel's beam. The list most likely caused the lube oil suction pipe bellmouth to be exposed to air, resulting in a loss of lube oil pressure and subsequent shutdown of the propulsion plant.

The NTSB investigation found that the lube oil level was not maintained in accordance with the vessel's operating manual and that it had probably not been raised before or during the heavy weather. The NTSB concluded that the crew was most likely unaware of the operational limitations with respect to inclination and that the company provided no guidance to the engineers about list induced operation limitations of the engine and about raising the level of lube oil in the main engine sump before heavy weather.

1.15.4 RMS QUEEN MARY 2

In September 2010, *RMS Queen Mary 2* suffered an explosion in its aft MSB harmonic filter compartment due to the deterioration of capacitors installed to absorb harmonic currents in the high voltage system. The vessel blacked out and lost all four of its propulsion motors for nearly an hour. Fortunately, there were no injuries and the vessel drifted in open sea, clear of any hazards to navigation.[25]

The investigation into this accident established that, during the watch before the accident, the duty engineer had accepted approximately one alarm every minute. He had received a series of alarms indicative of impending anomalies in the propulsion system around 36 minutes before the explosion, and although these were accepted, no action was taken. The shipowner was recommended to review the alarm system and to take actions to prioritise those alarms that had the potential to affect the vessel's safety so that operators could recognise complex system failures and respond appropriately.

1.15.5 TEXACO MILFORD HAVEN REFINERY

The 1994 explosion and fires at the Texaco Milford Haven refinery injured 26 people and caused damages of around £48 million and significant production loss. Key factors that emerged from the UK HSE's investigation[26] were:

- There were too many alarms and they were poorly prioritised.
- The control room displays did not help the operators to understand what was happening.
- There had been inadequate training for dealing with a stressful and sustained plant upset.

In the last 11 minutes before the explosion the two operators had to recognise, acknowledge and act on 275 alarms.

[25] https://www.gov.uk/maib-reports/catastrophic-failure-of-capacitor-in-aft-harmonic-filter-room-on-passenger-cruise-ship-rms-queen-mary-2-off-barcelona-spain
[26] https://www.hse.gov.uk/comah/sragtech/casetexaco94.htm

1.16 Measures implemented

1.16.1 NORWEGIAN MARITIME AUTHORITY

On 27 March 2019 the Norwegian Maritime Authority issued a Safety Message on risk assessment of critical systems which asked:

> *all shipping companies to take the necessary precautions to ensure the supply of lubricating oil to engines and other critical systems under expected weather conditions. This should be done in collaboration with the engine supplier and included as part of the ship's risk assessments in the safety management system.*[27]

1.16.2 THE CLASSIFICATION SOCIETY – LLOYD'S REGISTER

LR has implemented two measures with relevance for the accident:

1. A Plan Approval Circular, included at Appendix I, – an internal instruction to the Plan Approval community of LR – pertaining to design appraisal of main and essential auxiliary machinery for operation under conditions of static and dynamic inclination has been issued. The circular require:
    - With immediate effect, design appraisal of main and essential auxiliary machinery for operation under the conditions of static and dynamic inclination defined in the Rules is to establish that:
        - the item of machinery is capable of operating satisfactorily at the defined angles of inclination; and
        - that the item of machinery is to be installed in accordance with the machinery manufacturer's instructions, recommendations or guidance relating to operation when inclined.
    - Where not apparent from information submitted, a written confirmation should be requested from the shipyard.
2. Initiation of a task within the IACS Machinery Panel, to revise IACS's UR M46 to establish Unified Requirements in respect of the following:
    - to ensure that main propulsion machinery and all auxiliary machinery that are essential to the propulsion and the safety of the ship shall be capable of operation under the effects of expected pitch, heave and roll motions.
    - Equipment manufacturers are to submit details of the requirements/recommendations for installation of the machinery and equipment onboard to ensure satisfactory operation in service under the required static and dynamic conditions.
    - Shipbuilders are to submit details demonstrating that the installation of the machinery and equipment onboard is in accordance with manufacturer's requirements/recommendations.

[27] *Translated from Norwegian, original text available at https://www.sdir.no/contentassets/6a7de0c70733442a9e654767897b4c65/sikkerhetsmelding-om-risikovurdering-av-kritiske-systemer.pdf?t=1568816231988*

1.16.3 THE INTERNATIONAL ASSOCIATION OF CLASSIFICATION SOCIETIES – IACS

IACS UR M46 rev. 3, see Appendix C, was published in august 2023 and will enter into force on ships contracted for construction on or after 1 January 2025.

The revised UR M46 specifies that effects of acceleration and motions shall be taken into account. It requires ship builders to identify and document the ship accelerations and motions periods the machinery may experience. It also requires machinery and equipment manufacturers to document that their machinery or equipment can operate under the required static and dynamic conditions at least at these levels of accelerations.

The revised UR M46 further requires machinery and equipment manufacturers to document details of the requirements/recommendations for installation of the machinery and equipment onboard to ensure satisfactory operation in service under these required static and dynamic conditions. It also requires shipbuilders to submit details demonstrating that the installation of the machinery and equipment onboard is in accordance with manufacturer's requirements/recommendations.

1.16.4 THE YARD – FINCANTIERI S.P.A

Fincantieri has informed the NSIA of the following two measures:

- *Following this experience, our technical department is verifying the approval of sump tanks design by the supplier with higher formality.*
- *An internal check on all projects did not reveal any critical issues regarding lubricating oil sump tank design.*

A flow chart of the revised design process that includes a verification that the details of the sump tanks are in accordance with the suppliers' recommendations has been submitted, see Appendix J.

1.16.5 THE SHIP MANAGEMENT COMPANY – WILHELMSEN SHIP MANAGEMENT

28 June 2019, the ship management company issued a *Preliminary Investigation Report* into the blackout on board *Viking Sky.* The report included a number of findings and a list of recommendations and improvements. Implemented measures with relevance to the topics discussed in the NSIA report are presented in the following.

1.16.5.1 Heavy Weather

The ship management company has updated checklist *B10 Navigation in Heavy weather*, and chapter 7.3 in the SSMM, *Heavy Weather Precautions,* with some clarifications and additions. There is now a requirement that the captain should, together with the heads of departments (HOD), conduct a ship and voyage specific risk assessment for the intended voyage.

1.16.5.2 Safe Return to Port

The ship management company has implemented the following measures related to Safe Return to Port:

- An SRtP procedure is included in the Operational Manual Cruise Vessel (OMCV). This procedure states that Class/Flag should be notified in case of any planned or unplanned maintenance or damage of essential systems.
- Risk assessments for planned and unplanned unavailability for one small or one large engine are prepared, including weather limitations for such operation:
  - A limitation up to Beaufort 6 is set in case of unavailability of one large engine.
  - A limitation up to Beaufort 8 is set in case of unavailability of one small engine

1.16.5.3 Sump tank filling levels and alarm settings

The ship management company has implemented the following measures related to the sump tank filling levels and alarm settings:

- Instructions on sump tank filling levels under normal and heavy weather conditions, including level alarm settings, has been issued to the vessels. See attached in Appendix K, form CVP-101.
- A revised change of watch form for the engine department has been issued. This includes the minimum recommended sump tank level next to the space allocated for noting the manual tank sounding. See attached in Appendix L, form CVE-100.

1.16.5.4 Alarm management

The ship management company has implemented the following measures related to alarm management:

- Changes in the procedure for change of watch in OMCV, 7.15.7. The EOW shall ascertain from the engineer relieved, status of any active alarms and of any changes in set points, supressed or inhibited alarms.
- A change log is developed for recording of all permanent and temporary changes to IAS set points, including inhibited alarms. All changes shall be approved. Electronic logging of changes to offset and sump tank level alarm settings is implemented.

1.16.5.5 Automation system and blackout recovery

The ship management company has implemented the following measures related to blackout recovery:

- A ship-specific blackout recovery procedure, CVP-100, is developed, see Appendix M. The procedure is implemented as a wall poster in the ECR.
- Software is updated, including a new mimic, implemented on a separate screen, showing only blackout related alarms.
- According to the updated *Emergency drills and Training* Matrix, CVDE-64, a blackout recovery drill is performed minimum twice per year, including full recovery, with no standby generator available.

2. Analysis

2. Analysis

2.1 Introduction

The purpose of the analysis is to determine the contributing factors and circumstances of the accident as a basis for making recommendations to prevent similar accidents occurring in the future.

Viking Sky was less than a ship length from running aground in harsh weather and cold waters with more than 1,300 persons on board. The accident had the potential to develop into one of the worst disasters at sea in modern times. It is with this seriousness and potential in mind that the accident has been investigated. The fact that it ended relatively well has provided a unique opportunity to investigate an accident of disastrous potential with the benefit of having access to large amounts of data, an intact ship and live witnesses who can account for the situation they experienced.

Figure 69: Viking Sky in close vicinity to shore and several shallow banks. Photo: Frank Skorgenes

As this analysis will demonstrate, operational issues were a significant contributor to the situation that unfolded. However, the NSIA has not found any indication of deliberate wrongdoing or of any one consciously taking excessive risk. Further, to simply blame the operators would be a mistake as the key to safety learning lies in understanding why the people acted the way they did.

The analysis will therefore take a closer look at both the operational side and decision making, but also technical and organisational aspects to shed light on the context in which the individuals acted.

Viking Sky left Tromsø with two pilots on board in the evening of 21 March 2019 southbound for Bodø and then Stavanger. According to the weather forecast, strong winds and rough seas were expected. One of the diesel generators was unavailable due to a recent turbocharger breakdown and it was decided to cancel the visit to Bodø as the captain was concerned that they would struggle to leave the quay. For the area including Hustadvika, storm force (BF10)[28] winds 25 m/s from southwest with gusts up to 30–35 m/s and wave heights up to 8–11 metres were forecast for 23 March, the day of the accident. Hustadvika is referred to as a *notoriously dangerous area* both by *The Admiralty Sailing direction* and the *Norwegian Pilot Guide*, see section 1.6. Even though this description to a significant extent is based on a research project aiming to improve safety for smaller vessels in heavy seas, the area is also reputed to be one of the most dangerous and talked-about stretches of the Norwegian coast, hence larger vessels should also be particularly attentive under the forecast weather and sea conditions. The decision to sail will be discussed in detail in section 2.2.

Even though the heavy weather checklist, that included an item requiring the lube oil sump tank levels to be optimised, was logged as completed, and despite the fact that low lube oil level alarms went off both for DG2 and DG4 during the voyage southbound from Tromsø, no oil had been transferred into the DG sump tanks in the days preceding the accident.

Viking Sky suffered a blackout, causing loss of propulsion and steering, while crossing Hustadvika at 13:58:34 on 23 March 2019, when all three operational DGs were automatically shut down. The engines' protection systems were responding to low lube oil pressures caused by insufficient lube oil level in the sump tanks. The direct causes of the blackout will be analysed in section 2.3.

The low lube oil levels are the main focus area of this analysis. In order to identify effective remedial measures, it is important to understand why the lube oil levels were low on the day of the accident. The investigation has taken a broad approach, looking into both technical and operational factors, and has uncovered several safety issues that in different ways may have contributed to this practice. These will be analysed in further detail in the following sections:

- Lube oil sump tank design and approval, section 2.4.
- Lube oil level operating instructions, section 2.5.
- Lube oil remote monitoring system, section 2.6.
- Alarm system, section 2.7.
- Lube oil level management, section 2.8.

In the 10 seconds immediately following the blackout, a total of approximately 1,000 alarms went off in the IAS. Recovery from a blackout without a standby generator had never been drilled on board. The engineers were therefore faced with a situation they could not readily recognise and were not practised in managing.

It took about 14 minutes from the blackout until refilling of lube oil was started. The engineers struggled to restart and connect the DGs, and the first DG was connected to the MSB almost 24 minutes after the blackout, and it took another 9 minutes further to restore any propulsive power.

During this time, the vessel drifted to within a ship's length of running aground despite the attempt to arrest its drift by deploying both anchors. The blackout recovery is analysed in section 2.9 and the evacuation and rescue operation is analysed in section 2.10.

[28] *For Beaufort (BF) wind scale, see Appendix H.*

2.2 The decision to sail

Viking Sky was built for international voyages with no operating restrictions. Witness accounts and electronic evidence such as CCTV footage, VDR recordings and vessel motion data from the Eniram system indicate that the vessel handled the heavy weather conditions rather well up until the first engine shutdown. After the first shutdown the vessel had less available power to counter the rough seas, hence the vessel was pitching and rolling increasingly. This was further exacerbated after the blackout, as the vessel drifted towards the shore without any propulsion or steering.

It was decided not to lower the lifeboats, as lifeboats were not considered a safe means of evacuation in such rough weather close to shore, see section 1.7.6 for further details. A rescue by tugboats is dependent on the availability of tugs with sufficient towing capacity close enough to the scene of the accident. During this event, the first tug arrived long after the vessel would have grounded if propulsion had not been regained. Similarly, helicopters cannot be counted upon to constitute an efficient means of evacuation, even if available in the vicinity, as they have insufficient capacity to evacuate the large number of people on board a cruise ship. See section 2.10 for an analysis of the evacuation and rescue operation.

This demonstrates the importance of not losing propulsion and steering, in particular for large passenger vessels.

The Safe Return to Port (SRtP) regulations, as described in section 1.13.1, were introduced due to a growing concern of the operational risk of passenger ships, based on increasing size of vessels and number of passengers, previous accidents of fire in passenger ships, cruises in more remote and exposed areas and the risks associated with lifeboat evacuation. It specifically aims to reduce the likelihood of situations where an evacuation of a passenger vessel is required, i.a. through increased redundancy of essential systems like propulsion.

Viking Sky fulfilled the SRtP design requirements with respect to propulsion power redundancy and capacity as long as all four engines were available. In case of loss of any one DG, the remaining power capacity of the affected engine room would be below the total power required for SRtP, hence the vessel would no longer be in compliance with the regulations.

Five days prior to the departure from Tromsø, one out of four diesel generators (DG3) became unavailable due to a turbocharger failure. The resulting reduced power capacity rendered the vessel non-compliant with SRtP, however, no notification to the classification society and the administration of the flag state was made.

To comply with the SRtP regulation, the vessel would have had to repair the damaged DG or an exemption to sail had to be granted. Such an exemption would normally require the operator to submit i.a. a description of the planned itinerary with a specific risk assessment, taking into consideration the weather forecast, which reported storm force (BF10)[29] winds 25 m/s from southwest with gusts up to 30-35 m/s for the crossing of Hustadvika.

The design requirements of the SRtP regulations and associated interpretations may be seen as a safety barrier to reduce the likelihood of a situation where an evacuation of a passenger vessel is required. As described in section 1.13.1, the regulations clearly state that there should be two separate engine rooms, and that each engine room need the necessary capacity to bring the ship safely back to port in case of fire or flooding. As far as the investigation has found, this barrier was intact in that the vessel was designed and built in compliance with this requirement.

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[29] *For Beaufort (BF) wind scale, see Appendix H.*

Another barrier is the organisation on shore, whose role is to ensure that regulations are implemented and to give operational support. The organisation on shore was informed about the unavailability of DG3 but did not instruct the ship to stay in port despite the forecast weather. Neither did they notify the administration of the flag state nor the classification society, as required (SOLAS Chapter I Regulation 11).

The organisation on shore had not sufficiently implemented the SRtP regulations into the safety management system to support the crew making decisions on board. At the time of the accident there were no guidelines or procedures in the safety management system (SMS) regarding how to handle planned or unplanned unavailability of a DG with respect to the SRtP requirements. According to the internal investigation report prepared by the ship management company following the accident, limitations with regards to SRtP was never considered. Had the SRtP regulations been implemented and audited within the safety management system, it would have indicated to the decision makers that the vessel should not have left port, increasing the likelihood that this would be the outcome. The NSIA is of the opinion that the shore organisation of the ship management company did not provide adequate support to the vessel.

The decision makers on board the vessel may be considered yet another barrier. As described above, this barrier would have benefited from direct support from shore or indirect support by means of adequate decision support tools such as clear provisions in the SMS. Training and awareness around SRtP could also have strengthened this barrier. In absence of such support from the organisation, the decision to sail or stay in port ultimately depended on these individuals.

None of the decision makers on board, including senior officers on the bridge and in the engine department, have mentioned any concern related to SRtP. None have reported that not leaving port was an option. The reason for this, and for the limited support from the organisation on shore, is not known, but there are several possible contributing factors.

It is unclear whether the decision makers on board and the technical support staff on shore had sufficient knowledge of the SRtP regulation. Low risk awareness and conflicting goals, i.e. how passenger satisfaction and arriving at destination to schedule may be in conflict with safety precautions, may also have played a role. As pointed out in the first paragraph of this section, the vessel handled the rough weather conditions relatively well as long as sufficient propulsion power and steering was available. It is likely that the senior officers on board had experienced this previously and therefore had confidence in the vessels ability to cope with heavy weather, reducing the perceived risk represented by such adverse conditions. It is also possible that the people on board judged the absence of an instruction from the shore organisation to stay in port as a pressure to proceed as planned.

Even though the SRtP regulations don’t specifically address a scenario like the one *Viking Sky* experienced, the NSIA is of the opinion that departing Tromsø with one out of four DGs unavailable represented an unacceptable risk to the crew and passengers on board given the forecast weather conditions the vessel was to experience. As the vessel did not comply with the internationally agreed minimum safety standard as required by SOLAS, it should not have departed Tromsø under the prevailing circumstances. Had the vessel experienced a flooding or fire incident during this voyage, the ramifications of which SRtP was designed to mitigate, the ship would have been at a disadvantage in that it was sailing without the necessary redundancies. This means that in case the intact engine room was lost due to fire or flooding, the ship would not have been able to produce the total power required for Safe Return to Port.

The vessel did not fulfil the SRtP requirements when leaving port, but it is still possible *Viking Sky* could have experienced a blackout also with all four engines available if the lube oil level was low on all four lube oil sump tanks, including for DG3. This is, however, not a reason not to comply with the SRtP regulations, rather it underlines the importance of ensuring a sufficient oil level, as further discussed in this analysis.

Following the accident, the ship management company has implemented several measures regarding SRtP, see section 1.16.5.2. The requirement to notify the class or flag in case of any defect of essential systems has been included in the new SRtP procedure in the safety management system. Risk assessments for planned and unplanned unavailability of either a small or a large engine have also been prepared, including weather limitations for such operation. According to these risk assessments the weather limitation with one large engine unavailable is Beaufort 6. Hence, provided the revised procedure is implemented and followed, the ship management company will not anymore plan to nor request a permission to sail through a weather system like the one forecast for Hustadvika at the time of departure from Tromsø with one large engine unavailable.

2.3 The blackout

Viking Sky suffered a blackout at 13:58:34, when all three operational DGs were shut down by their protection systems within a period of 15 minutes. The alarm log shows that the engines' protection systems were responding to low lube oil pressures. Both the manual tank soundings and the remote tank level readings indicate that the lube oil level was low in all the lube oil sump tanks, see section 1.12 and Table 16.

Table 16: Manual and remote tank soundings on the day of the accident. Source: Wilhelmsen/NSIA

Date	Sump tank (DG)	6P (DG1) (m^3)	6S (DG2) (m^3)	5S (DG4) (m^3)
23.03.2019	Manual sounding	3.1	3.0	3.0
	Remote reading	2.3	2.7	1.9

Even though the heavy weather checklist, that included an item requesting the lube oil sump tank levels to be optimised, was logged as completed, and despite the fact that low lube oil level alarms went off both for DG2 and DG4 during the voyage southbound from Tromsø, no oil had been transferred into the DG sump tanks in the days preceding the accident.

Viking Sky handled the prevailing weather conditions fairly well, but at times the vessel did roll and pitch noticeably. The motions registered in the Eniram system shows accentuated roll and pitch amplitudes immediately before the engines' shutdowns. A CFD simulation of the accident conditions, using the registered ship motion and the estimated actual lube oil filling level for the DG4, indicates that the lube oil suction pipe opening would likely be exposed to air, and oil suction would therefore be lost, at the time of the blackout.

Based on the above factors, the NSIA concludes that the low lube oil pressure that caused the engine shutdowns and subsequent blackout was the result of the loss of lube oil suction. Further, that the loss of lube oil suction was the result of the low levels of lube oil in the sump tanks in combination with the vessel motion, causing the lube oil suction pipe opening to be temporarily exposed to air. The NTSB investigation into the sinking of the cargo vessel *SS El Faro* northeast of Bahamas 1 October 2015, see section 1.15.3, revealed similar contributing factors.

The vessel encountered strong winds and heavy seas, and the vessel motion at the time of the first engine shutdown was in the range of 1 degree pitch and 10 degrees roll. This is significantly below the design criteria specified in SOLAS of 7.5 degrees pitch and 22.5 degrees roll simultaneously. The vessel motion later increased, but this must be seen in connection with reduced or lost propulsion and is therefore considered in part a consequence of the first shutdowns. The low lube oil levels are therefore considered decisive for the outcome and will be the main focus area of this analysis.

2.4 Lubricating oil sump tank design and approval

Section 1.8 provides a detailed description of relevant rules, regulations and recommendations, as well as the actual tank design and post-accident calculations made to evaluate compliance of the tank design.

As demonstrated in Section 1.8 and summarised in below Table 17, the LR Class Rules and IACS Unified Requirements are largely the same as the SOLAS Regulation.

Table 17: Summary of requirements for inclination angles under which main and auxiliary machinery essential to the propulsion and safety of the ship shall be able to operate. Source: NSIA

	Angle of inclination (°)*			
	Athwartship		Fore-and-aft	
Regulation	Static (heel)	Dynamic (roll)	Static (trim)	Dynamic (pitch)
SOLAS Ch. II-1, Pt. C, Reg. 26.6	15	22.5	-	7.5
IACS UR M46	15	22.5	5**	7.5
LR Class Rules	15	22.5	5**	7.5

* Athwartships and fore-and-aft inclinations may occur simultaneously
** Where the length of the ship (L) exceeds 100 m, the fore-and-aft static angle of inclination may be taken as 500/L

The SOLAS regulation specifies the dynamic roll and pitch amplitudes (i.e., 22.5° roll and 7.5° pitch simultaneously), under which the machinery shall be able to operate safely. However, the regulation does not provide information on the period, duration or pattern of the movement over time to be used for the application or verification of compliance with the regulation. No technical guideline or industry standard for application of the SOLAS requirement exists.

The engine manufacturer's project guide contains design recommendations intended to ensure compliance with the Class Rules and SOLAS requirement, that are easy to apply using a simple static calculation. These are presented in Section 1.8.4. MAN has informed the NSIA that the recommendations in their project guide may be conservative, and that the detailed design should be calculated and decided by the responsible designer, the shipbuilding yard.

2.4.1 YARD DESIGN

As described in Section 1.8.5, the shipyard used the LR Class Rules' requirement for safe operation under static inclination as criteria for the design of the sump tanks. The inclination angles considered were therefore 15° heel and 2.54° trim. The requirement for safe operation under dynamic inclination (22.5° roll and 7.5° pitch) was not considered.

Further, the yard took into consideration the engine manufacturer's recommended minimum lube oil volume for design of the by-pass cleaning of 1 l/kW, a requirement that is intended to ensure acceptable lube oil quality. The design recommendations intended to ensure suction of oil free of air under dynamic inclination were not taken into consideration.

According to calculations made by the NSIA, presented in section 1.8.7.1, applying the engine manufacturer's relevant design recommendations show that the different lube oil sump tanks were 60–68% of the calculated minimum tank heights necessary to theoretically fulfil the design criteria recommended by MAN – see results in below Table 18. Hence, the tank design did not fulfil the design criteria recommended by MAN in the engines' project guide.

Table 18: Minimum oil filling and tank height. Source: NSIA

Sump tank (DG)	6P (DG1)	6S (DG2)	5P (DG3)	5S (DG4)
Min. oil filling height (F_{min}), mm	939	963	960	1,019
Min. tank height (H_{min}), mm	1,089	1,113	1,110	1,169
Actual tank height, suction end (H_s), mm	700	750	750	700
Actual tank height / min tank height, %	64%	67%	68%	60%

Even though the SOLAS regulation does not specifically state any acceptance criteria, it requires the propulsion machinery to be able to operate under specified angles of dynamic inclination. The intention of the regulation must be understood as that the propulsion machinery should be expected to operate safely without risk of shutting down due to the effects of dynamic inclination as long as the angles of inclination do not exceed those stated in the regulation.

Any exposure to air of the suction pipe inlet opening represents a risk of loss of lube oil pressure and subsequent shutdown, malfunction or even severe damage to the engine. It should therefore be considered outside of the acceptance criteria for compliance with the SOLAS regulation.

As presented in sections 1.8.7.2 to 1.8.7.4, the shipyard, the classification society and SINTEF Ocean (on behalf of the investigation) have carried out CFD simulations of the lube oil behavior under dynamic inclination of the vessel. The simulations have used somewhat different approaches, but all three indicate that within the parameters of the design criteria there are situations where the suction pipe is likely to be exposed to air. The NSIA therefore concludes that the lube oil sump tank design must be considered non-compliant with the SOLAS regulation.

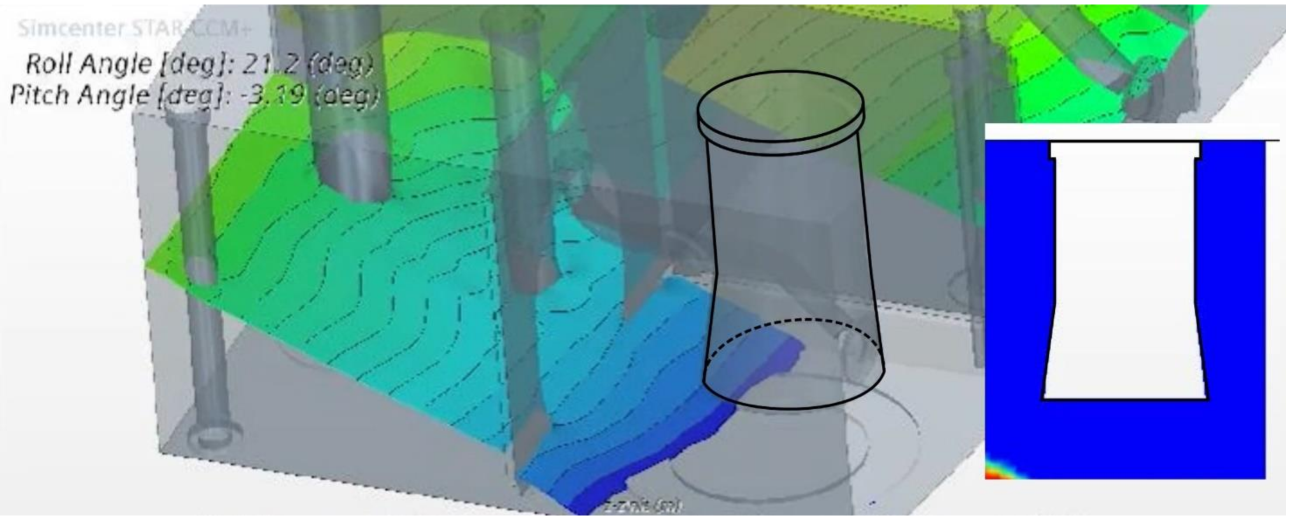

Figure 70: Illustration from the CFD simulation showing the suction pipe completely exposed to air. The multi-coloured surface represents the surface of the oil. The illustration in the box to the right shows a 2D side view of the suction pipe. Source: SINTEF Ocean/NSIA

The shipyard has stated that it disagrees with the conclusion and argues that it is unrealistic for a cruise vessel of the size of *Viking Sky* to ever encounter vessel inclination of the amplitudes specified in the SOLAS regulation. The SOLAS regulation however explicitly specifies the possibility for the administration of the flag state to permit deviation from these angles, taking into consideration the type, size and service conditions of the ship. No such deviation has been requested or granted, thus the main rule of the SOLAS regulation must be considered applicable.

The NSIA has however pointed out that the implementation of operational restrictions may be among the possible remedial actions.

The NSIA concludes that the yard did not take the SOLAS Requirement for safe operation under vessel inclination (SOLAS Chapter II-1, Part C, Regulation 26.6) fully into account in the design of the lube oil sump tanks. It is further found that the yard did not use the correct Class Rules or recommendations from the engine manufacturer to calculate the necessary minimum volume of lube oil necessary to ensure safe operation under dynamic inclination angles. The resulting sump tank design is found to be non-compliant with the SOLAS regulation.

The shipyard has argued that the engine manufacturer had approved the sump tank design without any comments to the effect that the design was non-compliant with the relevant recommendations. The engine manufacturer has stated that the information provided by the yard was not detailed enough to do an analysis of reasonable lube oil filling levels assuming applicable inclination angles and that this is usually not part of the design review. The NSIA has received the documentation that was exchanged between the parties at the time. After an initial review of the documentation the NSIA decided not to investigate this aspect any further. The main reason for that is that the tank design was within the scope of the yard, yet the yard has not provided any calculations carried out prior to the accident that take into account the required angles of dynamic inclination specified in SOLAS nor the recommendations from the engine maker to ensure suction of oil free of air under dynamic inclination angles.

The NSIA finds that the design process of the shipyard did not effectively ensure that the lube oil sump tanks complied with the SOLAS requirement for safe operation under dynamic inclination. The shipyard has provided a flow chart of a revised design process that includes a verification that the details of the sump tanks are in accordance with the suppliers' recommendations and approved by the engine supplier, see section 1.16.3. However, the shipyard has since continued to deliver sister vessels of the same series with no modifications to the lube oil sump tank design or construction. The NSIA therefore does not see this as an effective corrective action or adequate documentation of a resilient design process that ensures compliance with SOLAS. Similarly, the yard has stated that an internal check on all projects did not reveal any critical issues regarding lubricating oil sump tank design, but the statement has not been supported by any documentation to that effect. A Safety Recommendation is issued to Fincantieri in this respect, see Safety Recommendation Marine No. 2024/06T in chapter 4.

As mentioned in section 1.8.7.3 and specified in further detail in Appendix F, a simulation case combining the highest oil filling level recommended by the engine manufacturer and the vessel motion recorded at the time of the first engine shutdown, indicates that the suction pipe inlet area would remain submerged by approximately 20 cm of oil or more throughout the duration of that simulation. It is therefore likely that the accident would not have occurred had the lube oil sump tanks been filled to this level. The vessel motion at the time was in the range of 1 degree pitch and 10 degrees roll, which is significantly below the design criteria specified in SOLAS of 7.5° pitch and 22.5° roll simultaneously.

2.4.2 DESIGN APPROVAL

The classification society Lloyd's Register was not only responsible for the verification of compliance with the Classification Rules, but also with the SOLAS Requirement as part of the delegated authority for issuance of statutory certificates and conduct of related surveys as recognised organisation on behalf of the Norwegian Maritime Authority.

According to LR Rules, it is a requirement that shipbuilders install engines in accordance with the manufacturers' instructions. Where the shipbuilder does not follow this requirement, they are to advise LR accordingly. LR did receive information from the shipbuilder, showing modifications to the engines' lube oil arrangements including comments by the engine manufacturer. LR concluded that the lube oil arrangements had been reviewed by the engine manufacturer and, in the absence of any further notification, assumed the design satisfied the engine manufacturer's instructions.

The sump tank design is critical to safe engine operation and the plan approval process of a classification society is intended to be an important barrier to ensure adequate and compliant design of safety critical features. Lloyd's Register did not independently verify, nor request confirmation of or documentation of, compliance with either the engine manufacturer's instructions, the SOLAS regulation or LR's own class rules. As demonstrated in the above section 2.4.1, the tank design did not comply with any of these. The NSIA therefore concludes that LR's plan approval process was ineffective and did not constitute the barrier it should.

LR has issued a Plan Approval Circular, as described in section 1.16.2. This Circular instructs the plan approval engineer to positively verify that the item of machinery is to be installed in accordance with the machinery manufacturer's instructions, recommendations or guidance relating to operation when inclined. Where not apparent from information submitted, a written confirmation should be requested from the shipyard.

The NSIA finds this action insufficient. The option of a written confirmation of compliance by the shipyard effectively eliminates the role of Class as an independent third party verification and merely represents a disclaimer. This investigation has demonstrated that the shipyard had not fully taken into consideration either the Class Rules or the engine manufacturer's instructions, thus there is reason to believe that the implementation of the Plan Approval Circular would not have made any difference. A Safety Recommendation is issued to Lloyd's Register in this respect, see Safety Recommendation Marine No. 2024/07T in chapter 4.

2.4.3 IMPLICATIONS FOR VESSELS IN OPERATION

As demonstrated in the above section 2.4.1, the NSIA investigation has concluded that the lube oil sump tank design is non-compliant with the SOLAS regulation. Consequently, *Viking Sky* and its sister vessels are built with lube oil sump tanks that do not comply with the applicable rules and regulations, and therefore the vessels themselves do not operate in compliance with the premises of their certification.

This finding was communicated to the vessel's owner, ship management company, classification society, administration of the flag state and to the shipyard and engine manufacturer as soon as it was discovered. The owner was strongly encouraged to take remedial action to ensure that the fleet of vessels was operating in compliance with applicable rules and regulations. The classification society and the administration of the flag state were likewise encouraged to require such remedial actions to be taken. The NSIA emphasised to all parties the fact that the relevant SOLAS regulation specifically allows for exemptions from the main rule. Remedial action is therefore not limited to redesigning and modifying the tanks. Another conceivable option could be to establish the actual limitations of the current design in terms of dynamic inclination angles and corresponding sea conditions, implement operating restrictions accordingly and request exemption from the SOLAS regulation on that basis – either as a permanent measure or as a temporary measure until modifications are in place. It is also possible that minor modifications to the tanks or suction pipes in combination with less restrictive operating instructions could be a viable solution. It is not the role of the NSIA to prescribe the solution, thus the investigation has not looked further into these or other possible options or calculated the actual limitations of the current tank design.

The ship management company has implemented a new procedure for lube oil management to maintain higher lube oil levels. The new procedure includes increased filling levels up to 80 mm below the tank top, but no documentation has been made available to support that the increased filling levels ensure compliance with SOLAS. Furthermore, the new procedure is not in accordance with the recommendation stated in the engine manufacturer's project guide of always allowing minimum 150 mm air above the oil. According to MAN, the main reason for not filling oil above the prescribed level is to allow sufficient degassing of the oil before it reaches the suction pipe. Insufficient degassing could lead to cavitation on the pump, reduced lubrication of the engine and potential serious engine damage or shutdown. Another risk from excessive filling of the tank is that ventilation between the sub-compartments of the tank may be obstructed, potentially leading to detrimental pressure increase from the degassing.

In December 2023, upon request from the owner of *Viking Sky*, the engine manufacturer issued a statement, see Appendix N, confirming that no irregularities in the lubricating oil supply to the engines had been observed nor any damages had occurred since start of the above mentioned procedure in 2019. MAN further states that, consequently, MAN considers that such an increased lubricating oil level with a reduced air gap level is not disturbing the reliable operation of the engines. MAN has confirmed to the NSIA that the statement should not be interpreted as saying that the increased level solves the potential problem of sucking in air during rolling and pitching of the vessel. MAN has analysed recorded lubricating oil pressures after the accident but has not had information regarding the corresponding vessel inclination angles.

Clear instructions regarding the lube oil filling and alarm levels are probably perceived as an advantage to the crew. The actual limitations associated with these filling levels in terms of dynamic inclination angles or corresponding sea conditions have however not been calculated. The crew on board the vessels therefore still don't have the safety critical information necessary to know what the limits for safe operation are. It is likely that the crew is under the possibly false impression that the levels prescribed by the new procedure rectifies the safety issue and ensures compliance with applicable rules and regulations.

The new procedure exceeds the recommendations stated in the manufacturer's project guide and is not supported by any risk assessments or calculations. Most importantly, it is not documented that the increased oil levels lead to compliance with the SOLAS regulation nor what the associated operating limitations are. It is therefore uncertain whether the revised procedure fully remedy the safety issue.

The safety issue related to the non-compliant sump tanks originated at the shipyard, was not detected by the classification society, and now it is in the hands of the owner of *Viking Sky* and its sister vessels. The owner of the vessels are therefore recommended to take necessary action to ensure the vessels are compliant with the SOLAS regulation, see Safety Recommendation Marine No. 2024/08T in chapter 4. The owner is recommended to seek necessary support from the shipyard and engine manufacturer as well as approval by the classification society and the administration of the flag state.

Likewise, the classification society and the administration of the flag state are recommended to require remedial action from the owner of the vessels to ensure the vessels operate safely and in compliance with the SOLAS regulation, see Safety Recommendations Marine No. 2024/09T and 2024/10T in chapter 4.

2.4.4 SOLAS REGULATION

Neither SOLAS nor IACS UR M46 provide all the necessary information to assess whether the design of the sump tanks is compliant or not, as important parameters like roll and pitch periods or a dynamic motion pattern over time is not provided.

Rev. 3 of IACS UR M46, see Appendix C, entering into force in January 2025, specifies that ship accelerations and motions periods shall be identified and documented. This is an improvement, yet still insufficient to unambiguously interpret and apply the SOLAS requirement, as demonstrated by the different interpretations made by Fincantieri, SINTEF Ocean and LR in connection with this investigation. Fincantieri and SINTEF Ocean simulated the oil behaviour in the lube oil tanks by means of harmonic sinusoidal motion with the maximum amplitudes prescribed by SOLAS, while LR applied an irregular wave pattern for which the maximum vessel inclinations exceed the required amplitudes stipulated by SOLAS and Class Rules, but the maximum pitch and roll angles do not occur simultaneously.

The NSIA is not aware of any other supporting technical standard or recognised method for application of the requirement. This investigation has shown that calculations and simulation results may be interpreted in different ways. A well-defined technical standard would likely eliminate such ambiguity or at least reduce it to a minimum. The NSIA finds the lack of guidance to be a safety issue as it is unclear how compliance with this safety critical requirement should be documented and verified.

The NSIA has, together with SINTEF Ocean, carried out simulations according to a method that, we believe, provide realistic results in the framework of the SOLAS regulation. There may be other means and methods to demonstrate compliance, and the adopted method is not meant to represent a suggested solution or proposed standard approach. However, the NSIA finds that there should be a technical standard or harmonised method to document and verify compliance with this safety critical requirement. The NSIA therefore issues a safety recommendation to the Norwegian Maritime Authority to raise this matter in the IMO in order to mitigate this safety issue, see Safety Recommendation Marine No. 2024/11T in chapter 4.

Likewise, IACS, having adopted the SOLAS regulation in its Unified Requirement M46, is recommended to develop a technical guideline on the application of this regulation see Safety Recommendation Marine No. 2024/12T in chapter 4.

2.4.5 ELECTRONIC INCLINOMETER

Viking Sky was not required to be, nor was it, fitted with a type-approved electronic inclinometer providing recordings to the VDR, see section 1.7.5. Hence, inclination angle data from the vessel's fuel efficiency management system, Eniram, was used as input to simulations performed as part of the investigation, see section 1.5.2. Extracting data of sufficient quality was both complex and time consuming, and the sensors only measured angles of inclination up to 15°.

Whether it should be mandatory for ships to carry electronic inclinometers providing readings to the VDR, has been discussed in IMO over the past years. The NSIA agrees that it isn't critical for safe navigation of passenger ships. However, it can improve safety at sea, as easy access to data that accurately record a vessel's inclination through the complete range of possible values can considerably assist in casualty investigations.

The NSIA concludes that the *Viking Sky* accident demonstrates that an electronic inclinometer providing recordings to the VDR would provide more efficient and reliable results and therefore would be beneficial for safety investigations. The investigations of the accidents with *MSC Zoe* and *Crown Princess* support this conclusion.

The NSIA submits one safety recommendation to the Norwegian Maritime Authority concerning electronic inclinometers; see Safety Recommendation Marine no 2024/13T in chapter 4.

2.5 Operating instructions for lubricating oil levels and alarm setpoints

Sections 1.9.1 to 1.9.3 describe in detail the information available in the engine manufacturer's project guide, the information supplied by the yard, and the information on lube oil level management in the SMS. The only specific source of information available on board, was a table of minimum lube oil volume inserted on the last of six pages of a drawing by the shipyard, see Figure 71.

SUMP TANKS CAPACITIES			
ENGINE		MAN MIN. RACCOMENDED TANK CONTENT - m^3	DESIGNED CAPACITY m^3
ITEM	TYPE		
XB/274A	09L32	5.04	6.4
XB/274B	12V32	6.72	8
XB/274C	12V32	6.72	8
XB/274D	09L32	5.04	6.4

Figure 71: Table from "Lube oil Service System Functional Diagram". Source: Fincantieri

The minimum recommended tank content specified in the above table equals 1l/kW, the minimum volume specified by the engine manufacturer to maintain lube oil quality. This is substantially lower than the quantity required to ensure that the oil pump maintain suction of oil in all design conditions. The lube oil levels onboard were however kept at even lower levels than this, which indicates that the ship's engineers probably were not familiar with this information.

The SMS mentioned lube oil levels twice in connection with heavy weather situations. These stated that the oil levels should be "checked and topped up" and "optimized", respectively. This had limited value as a specific required minimum level was not mentioned anywhere.

Section 1.9.4 points out that the engineers on board were generally not familiar with any of the above-mentioned information, nor with any other instructions or guidance regarding minimum lube oil levels or alarm setpoints.

In June 2016, the engineers working on board *Viking Sea* requested information from MAN regarding the recommended oil levels. MAN was unable to give a clear answer as the tanks were designed by the shipyard and not by them. The shore organisation of the ship management company was made aware of the email exchange between *Viking Sea* and MAN. However, no guidance on correct filling volumes or alarm set points was issued by the ship management company until after the accident on *Viking Sky.*

The investigation has found that the fleet of Viking cruise vessels was operated for years without the crew or shoreside personnel knowing the correct lube oil sump tank filling levels or alarm setpoints. With the exception of the question raised from the *Viking Sea*, the NSIA has found no evidence that this was of concern to anyone on board or ashore – at least not enough to ensure operating instructions were developed, distributed and implemented. Consequently, it was not only one engineer or one team of engineers onboard *Viking Sky* who accepted to operate this way.

The NSIA see the lack of available operating instructions as an organisational safety issue that likely contributed to the lube oil levels being too low. A clear instruction would serve as an additional barrier and increase the chances that the crew would maintain correct oil levels and alarm settings. This safety issue has likely been present onboard all the sister vessels since delivery and the NSIA is of the opinion that it is the responsibility of the shore organisation to ensure that the vessels are provided with correct and concise operating instructions of this kind. The on board lube oil level management is further discussed in section 2.8.2.

The ship management company have implemented a new procedure for lube oil levels and alarm settings. This is discussed in detail in section 2.4.3. As pointed out in that section of the report, the sump tanks are significantly shallower than recommended and the tank design is non-compliant with SOLAS. For this reason, as much as the NSIA supports the initiative of keeping the oil levels high, the operating instructions need to be revised once the tank design issue is properly resolved. Hence, a safety recommendation is issued to Wilhelmsen Ship Management, see Safety Recommendation Marine No. 2024/14T in chapter 4.

2.6 Lubricating oil level remote monitoring system

As demonstrated in Section 1.10 the remote monitoring system was complex and had an inherent level of uncertainty due to factors like sensor accuracy and rounding of the measurement during signal processing.

In addition, the level measurements depended on the manually set parameters for oil density and sensor offset. The sensor offset represents the physical fixed distance from the bottom of the tank to the bottom of the level sensor tube, see Figure 72. This will never actually change unless the sensor tube is cut loose and rewelded in a different position.

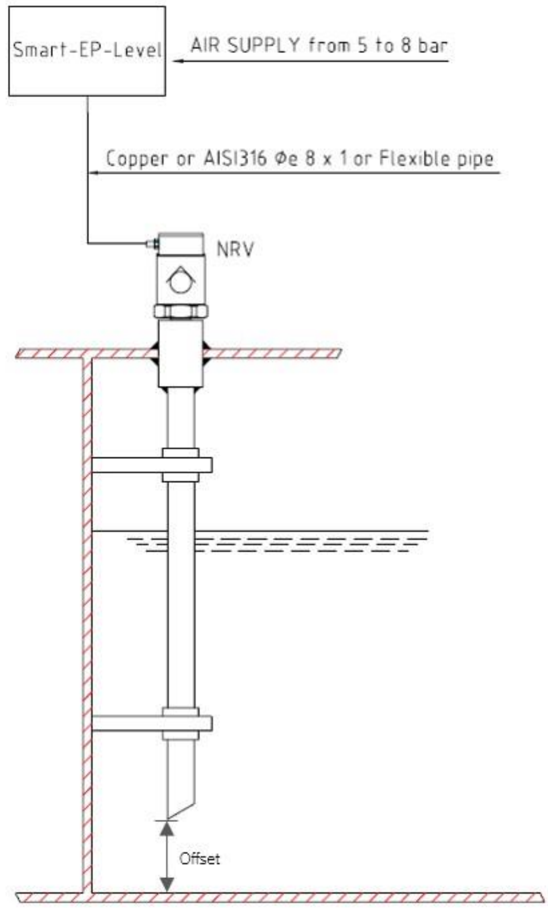

Figure 72: Illustration showing the physical offset. Extract: The system data sheet, S-SEPL-TM-V21. Rev. 20, Wärtsilä APSS srl.

The shipyard has explained that the design offset for *Viking Sky* and its sister vessels was 60 mm. However, the importance of the offset and its direct influence on the accuracy of the level measurements was not recognised. Therefore, the as-built offset could vary, and the actual offset was never measured or recorded. Furthermore, the shipyard systematically made adjustments to the offset value in the IAS during commissioning to align the manual and remote level readings. In a similar manner, both the crew and service engineers from the equipment maker has later altered the offset value to "calibrate" the manual and remote measurements. By doing so, a measurement error that was caused by an unknown reason was masked by introducing an additional error. "Calibrating" the manual and remote level readings through manipulation of the offset merely aligns the two measured values for that exact oil level. As soon as the level of oil changed, the remote measurements would diverge from the manual soundings and the crew would again experience the system as "out of calibration".

Moreover, the equipment maker recommends the sensor tube to be installed at a minimum distance apart from the oil suction pipe, to avoid that the measurement is influenced by hydrodynamic effects from these. The NSIA has found that the yard has not respected this minimum distance for the sump tank 5S (DG4). Neither the yard nor the equipment maker is able to quantify the effect of this, if any, and the NSIA has not investigated this further. It is however clear that the yard's practice of installing the sensor tubes has not taken the equipment makers recommendations into account.

The investigation has found that the 3D-model of sump tank 6P (DG1) was erroneous and caused NAPA to return a value 568 litres less than the actual oil volume for any given oil height for DG1. This represents 7.7% of the total tank volume and depending on the filling level this could easily constitute an error in excess of 10% of the measurement. This significant error caused confusion among engineers on board several of the vessels in the fleet. The issue has been raised with the shore organisation of the ship management company several times over the past years. The ship management company has further raised the issue with the yard, but no solution has been implemented. The NSIA has also informed the yard of this finding, but the yard claims that the resulting error is only 46 litres. The NSIA disagrees and maintains that the error made is in the order of 568 litres as demonstrated by the calculation in section 1.10.3.

Another issue that might have caused confusion was the presentation of oil content in the tank level mimics, as described in section 1.10.2. The investigation has shown that the graphical illustration of the tank content did not correctly represent the filling level given as a percentage. Depending on whether the operator observed the content based on the number or the graphical illustration, the actual tank level may not be perceived. The difference between the two would vary but was at times shown to be sufficiently large to cause confusion on what was the actual level, hence leading to loss of confidence in the level measurements.

As described in section 1.10.1, the sensor system used is dimensioned for pressures up to 15 metres water column. For the sump tanks in question, the sensors measure an oil column of only ca. 0.5 metres. The corresponding uncertainty being minimum +/- 3.3% as compared to +/- 0.1% for an application corresponding to the maximum range of the sensor. In other words, the uncertainty for this application is more than 30 times greater than that of the full range of the sensor.

The investigation has found that the engine crew on board *Viking Sky* had gradually lost confidence in the remote monitoring system. The sensors had been calibrated but the crew still found the remote readings to differ significantly from manual soundings. Since the level alarms were generated by the remote readings, the crew subsequently did not take the level alarms as a true indicator of the actual level. The NSIA believe the errors and the significant uncertainty of the remote lube oil level readings described above significantly contributed to this loss of confidence in the remote level readings and associated alarms. This is considered a safety issue as it is critical that the crew receive trustworthy information on lube oil levels, and that the related lube oil alarms are triggered correctly. The low lube oil level alarm is also a Class and SOLAS requirement, and it should be set no lower than the minimum level necessary to ensure both adequate oil quality and safe operation under the static and dynamic inclination angles for which the ship is designed to operate.

The owner is therefore recommended to carry out a systematic and holistic review of the remote lube oil sump tank level monitoring system and ensure the vessels are fitted with an accurate and trustworthy remote monitoring system, see Safety Recommendation Marine No. 2024/15T in chapter 4. Likewise, a safety recommendation is issued to the shipyard to ensure accurate and trustworthy remote monitoring systems are provided for all future vessels, see Safety Recommendation Marine No. 2024/16T in chapter 4.

2.7 Alarm system design and management

2.7.1 ALARM SYSTEM AND MANAGEMENT ON BOARD VIKING SKY

An effective alarm system should support the engineering team's decisions and help in triaging the alarms to the corrective action needed. The IAS raised and recorded all the alarms and events associated with the vessel's machinery, receiving signals either directly, or from local systems dedicated to individual equipment. The result was that the ECR operators were responsible for monitoring a large number of alarms, likely too many for an operator to handle, given the design and configuration of the alarm system. The scope of the alarms was very wide – from swimming pool temperature alarms and open refrigerator doors to highly critical alarms, such as the low lube oil sump tank alarm.

The modality of alerts – visual and/or auditory – was not adequately considered for different types of alarms. Variation in pitch and timing of auditory alarms was not used to distinguish alarms and colour was not used to distinguish alarms in priority. As there were no priority according to criticality and no grouping of alarms, the alarm system offered limited support to understand the situation and the associated risk. The fact that there was no grouping of alarms slows problem solving and requires operators to remember information from one part of the system to compare with others. Operators managed this issue by pre-loading many sub-system pages that represent ship sub-systems to provide the information that is needed to problem solve or monitor status. However, having to filter information over several displays leads to an increased risk of missing key information between pages, demonstrating that problem solving tasks may not be performed effectively and efficiently.

For the user interface to offer sufficient support, the operators need a good knowledge of the ship's IAS and its behaviours in relation to the engineering systems represented to develop a good mental model. This learning process takes time to embed within long-term memory and for operators to learn the system functionality. Hence, this must be taken into account in design and configuration of the alarm system, but also in training of operators.

There was no alarm philosophy to support operators in their tasks, and the alarm system did not provide any guidance on how to address specific alarms and no response instructions were provided with the alerts to support operators' problem-solving. The information provided by the alarms was sometimes also perceived as cryptic or confusing. This may link to an increased risk of operators addressing alarms inappropriately.

As observed during the investigation into the accident on board *Queen Mary 2* and other serious accidents in industries ashore, see section 1.15.4, a high frequency of alarms can quickly overwhelm the operators, causing them to miss critical alarms that precede a major accident.

On *Viking Sky*, the design and configuration of the alarm system resulted in a large number of alarms for the operators to monitor and act upon, leading to a reduced sensitivity to alarms. This is seen in the period prior to the blackout, where operators are observed acknowledging alarms, seemingly without any registration or further follow-up. This applied both for acknowledging of individual alarms and several alarms in one operation.

The four lube oil sump tank related alarms that sounded on the morning of 23 March, and the one lube oil sump tank alarm the night before, were not remarked upon during the subsequent watch changeovers. Approximately 50 alarms during the 04–08 watch, and approximately 150 the watch after was not unusual, and working in a control room with, at times, almost constant alarms was a normal situation for the operators.

At the time of the blackout on board *Viking Sky*, the task load[30] on the engineers would have been very high, increasing the risk of information being missed. As approximately 1,000 alarms registered in the ECR during the first 10 seconds following the blackout, it is clear that the operators were not able to investigate and act on them all. Their working memories would have become increasingly saturated by the quantity of visual and auditory information from the operational systems being shown on different systems, causing delays to their perceptual and memory processing capacity, impacting their ability to recognise the issues and take appropriate

[30] Task load is the demands imposed by the task, workload the available mental resource to meet the task demand. From. (2017) Matthews, G., Reinerman-Jones, L. Workload Assessment: How to Diagnose Workload Issues and Enhance Performance, 1st edition. ed. Human Factors and Ergonomics Society.

corrective action. The design and configuration of the alarm interface produced unacceptable workload which would have had a negative effect on engineers' processing ability to the extent that it is very likely to have decreased their problem-solving and decision making ability. In situations like a blackout where the alarm burden is extremely high, priority and grouping of alarms are of specific importance.

The NSIA's observations are also supported by the internal report by the ship management company where it is stated that the configuration of the alarm system provided an incomplete understanding of the risks. As they found there were too many alarms and lack of criticality indicators, they stated that a further study into configuration of the alarm system was recommended.

The investigation has highlighted several design and configuration issues that were likely to have a negative impact on the effectiveness and efficiency of engineering officers on watch. Given the number of issues identified and their nature, the NSIA submits a safety recommendation to Viking Ocean Cruises to carry out an operator centric design and configuration review aimed at reducing the risk of overload and confusion leading to required actions being missed, see Safety Recommendation Marine No. 2024/17T in chapter 4.

2.7.2 STANDARDS AND GUIDELINES

In the two decades leading up to this accident, there had been significant development in sensor technology and associated monitoring systems. The monitoring systems on cargo ships and tankers were originally limited to critical systems, and consequently the number of alarms to be handled by the watchkeeping engineers was limited and manageable. Passenger ships such as *Viking Sky* had an extensive set of engineering systems designed to comply with safety and environmental regulations, while also catering to the comfort of large numbers of passengers and crew. This resulted in a highly instrumented environment where every system was monitored and had alarms set.

Despite this development and a growing need for guidance, there were no specific standards or guidelines for development of alarm systems or alarm management in engine control rooms available.

For many years the airline industry had required a structured approach to cockpit alarm management, and a substantial set of guidance and international standards existed on the subject.

The IMO also recognised the issues relating to bridge operations and, in 2010, adopted Resolution MSC.302(87), Performance Standards for Bridge Alert Management (BAM).

A vessel with a limited number of systems and without extensive monitoring could perhaps cope without adhering to a structured and harmonised approach. However, for a large passenger vessel with thousands of equipment sensors, tanks and interconnected sub-systems that generate frequent and persistent alarm conditions, a rigorous approach to alarm management is essential.

Ships' engine room alarm management had not been subject to any regulation equivalent to the BAM performance standards, with the result that many of these systems, such as the alarm system on *Viking Sky* and its sister vessels, did not have an optimal design and configuration. The cumulative effect of multiple systems and subsystems had resulted in excessive alarms that hindered rather than assisted the watchkeeping engineers.

The NSIA recommends that the Norwegian Maritime Authority make a proposal to the IMO that an engine room alarm management performance standard shall be developed, see Safety Recommendation Marine No. 2024/18T in chapter 4.

2.8 Lubricating oil level management

2.8.1 REDUCTION IN LUBRICATING OIL LEVELS AND ALARM SETTINGS OVER TIME

It has proven difficult to establish the actual filling levels or how they varied over time as the investigation has found the remote level monitoring system unreliable. Records of manual soundings for a few weeks prior to the accident have been collected.

There are also printouts of the tank summary from the day of delivery of the vessel, including lube oil sump tank levels. Even though these values come from the remote monitoring system, there is reason to believe that they correlate with manual soundings of that day as the sensors were calibrated to match with the manual soundings during commissioning. The tank levels as stated in Table 19 are therefore considered the likely lube oil sump tank levels on the day of delivery of the vessel and the day of the accident.

Table 19: Lube oil filling levels on day of delivery and day of the accident. Source: Wilhelmsen

Sump tank (DG)	Filling level on day of delivery (from tank summary)	Filling level on day of the accident (manual sounding)
6P (DG1)	5.3 m^3	3.1 m^3
6S (DG2)	6.8 m^3	3.0 m^3
5P (DG3)	6.7 m^3	N/A
5S (DG4)	6.2 m^3	3.0 m^3

The NSIA assumes that the DG1 was the only running generator at the time the tank summary was printed as the vessel was alongside and there would probably only be one small generator running. The DG1 has a significantly lower filling level than the other tanks, which is due to the oil circulating in the engine and auxiliary systems when the engine is running. On the day of the accident all the three available engines were running.

The alarm settings on board on the day of the accident were not recorded before they were changed and, at the time, there was no log of such changes. Still, the low level alarms have been set below the remote level readings from the day of the accident, see Table 20, as the tanks were not in alarm condition when the remote readings were taken. This shows that the alarm levels have been reduced significantly after the vessel was delivered.

Table 20: Low level alarms for sump tanks over time, compared to remote level measurements at the day of the accident. Source: NSIA/Wilhelmsen/Wärtsilä

Sump tank (DG)	Low Level Alarm 21.02.2017	Low Level Alarm 12.07.2017	Remote level readings 23.03.2019
6P (DG1)	4.5 m^3	3.0 m^3	2.3 m^3
6S (DG2)	3.0 m^3	3.0 m^3	2.7 m^3
5P (DG3)	3.0 m^3	2.5 m^3	N/A
5S (DG4)	3.0 m^3	3.0 m^3	1.9 m^3

The alarm system monitored a large number of machinery and appliances on board and without any prioritisation of alarms or indication of criticality, the crew experienced a generally high alarm burden. As described in section 1.10 the engine crew had gradually lost confidence in the remote sump tank level monitoring system and the associated level alarms. This in turn led to an acceptance of these alarms sounding regularly, normalising them.

The situation was exacerbated by:

- The lack of instructions for minimum lube oil levels and alarm set points.
- The sump tank level alarm settings from the time of delivery were not documented.
- The alarm set points could be changed by any of the engineers on board, with no means of identifying what had been changed, by whom, when or why the changes had been made.
- The crew had never experienced the consequences of low lube oil levels.

The result was that the engine crew did not always replenish lube oil when the low lube oil level alarm sounded as would be the desirable practice. The crew also lowered the low lube oil level alarm settings, see Table 20, probably to reduce the alarm burden.

2.8.2 ON BOARD LUBRICATING OIL LEVEL MANAGEMENT

The engine crew had different understandings of how the lube oil levels were managed and what the minimum level should be. Some mentioned a minimum volume in cubic metres while others referred to a percentage of tank filling. No one could provide accurate numbers with certainty or refer to any instruction, procedure or other reference. Manual soundings were noted but they were not compared to any minimum or reference values. Several crew members claimed that the engines consumed very little oil, although no one would quantify the actual consumption.

Lube oil samples were taken regularly, and the results showed that the TBN would sometimes fall below the recommended minimum level. Interviews with engine crew and shore staff indicated that exchange of lube oil was mainly managed based on the TBN level. It seems it was common practice to discard a certain volume of oil whenever the TBN dropped below the minimum level and refill a somewhat larger volume. The general impression was that the engines – still being new and of a modern design – consumed very little oil and that this practice was sufficient to maintain an appropriate filling level.

The cost of exchanging lube oil due to low TBN alone – when the oil sample was otherwise ok – was mentioned as a source of annoyance. It was also mentioned that maintaining an oil level higher than strictly necessary would be to run an unnecessary economic risk as there is always a possibility that it could become necessary to renew the complete volume of oil – e.g. in the case of a water leakage or other contamination of the oil.

The investigation has found that the primary parameter for lube oil management was the TBN, but when oil was discarded and refilled to increase the TBN there was no reference filling level to maintain. It seems like reaching an acceptable TBN was the dimensioning criteria. The combination of the economic considerations, the underestimation of consumption, the lack of confidence in the remote tank monitoring system and the lack of instructions on correct filling and alarm levels thereby likely resulted in the lube oil levels and alarm settings decreasing over time. The NSIA therefore finds that the on board lube oil level management was ineffective and did not ensure sufficient levels of lube oil in the sump tanks.

Still, these factors do not fully explain why the crew did not top up the lube oil sump tanks before entering the announced heavy weather or why they did not act on the low lube oil level alarms during that voyage.

The NSIA has not found any indication of deliberate wrongdoing or of any one consciously taking excessive risk. The NSIA has considered whether competence could be a contributing factor, but keeping sufficient lube oil levels in an engine's sump tank is a basic task for any engineer. Even if there is no available information regarding recommended filling levels, a low level alarm being triggered should logically be followed up by the replenishment of oil rather than the reduction of the level alarm setting.

The NSIA believes the lack of instructions on correct lube oil level and alarm settings, the alarm system with its sub-optimal user interface, the unreliable tank level monitoring system and the economic considerations were factors that negatively influenced the on board lube oil level management. These factors were present on board several or all sister vessels, thus the safety issues related to lube oil level management observed onboard *Viking Sky* are likely the result of underlying organisational safety issues.

The ship management company noted in their internal investigation report that they had *"invited external safety culture specialists to look into our office organisation aiming for a thorough study into our role in the incident."* Investigating safety culture is a complex and resource demanding endeavour and the NSIA has not undertaken this as part of an already complex and extensive investigation. The NSIA however finds the safety issues related to lube oil level management to confirm the benefit of and need for such an external review of the organisation and its culture. The results of the announced safety culture study were therefore requested as they could be of relevance to the investigation. In August 2022, the NSIA was informed that this study had been dismissed as unnecessary and therefore not carried out after all.

In January 2024 Wilhelmsen Ship Management informed that a safety culture survey by an external consultant had been conducted in June 2023. Wilhelmsen has not shared the report from the study, thus the NSIA cannot evaluate the relevance of the study pertaining to the findings described in this report.

2.9 Blackout recovery

As discussed in section 2.3, the investigation has found that the blackout was caused by low lube oil pressure due to insufficient lube oil levels in the sump tanks of all the DGs in combination with the vessel motion in the rough weather. As the vessel lost speed and started to drift, the vessel motion further increased. It was therefore necessary to increase the level of lube oil in the sump tanks in order to regain uninterrupted oil suction and sufficient oil pressure at the engines.

The electronic evidence recovered from the IAS show that it took 14 minutes from the blackout until refilling of the lube oil sump tanks was started. Still, the engineers continued to struggle to restart and connect the DGs, and the first DG was connected to the MSB about 10 minutes later. It took another 9 minutes further to restore any propulsive power. When eventually all the DGs had been successfully connected to the MSB, DG2 was left in manual load sharing mode with DG1 and DG4, which were in automatic mode. The vessel drifted across shallows and rocks and came to within a ship's length of running aground before sufficient propulsion power was restored to turn the vessel and slowly move towards deeper waters, see Figure 73 and section 1.2.4.

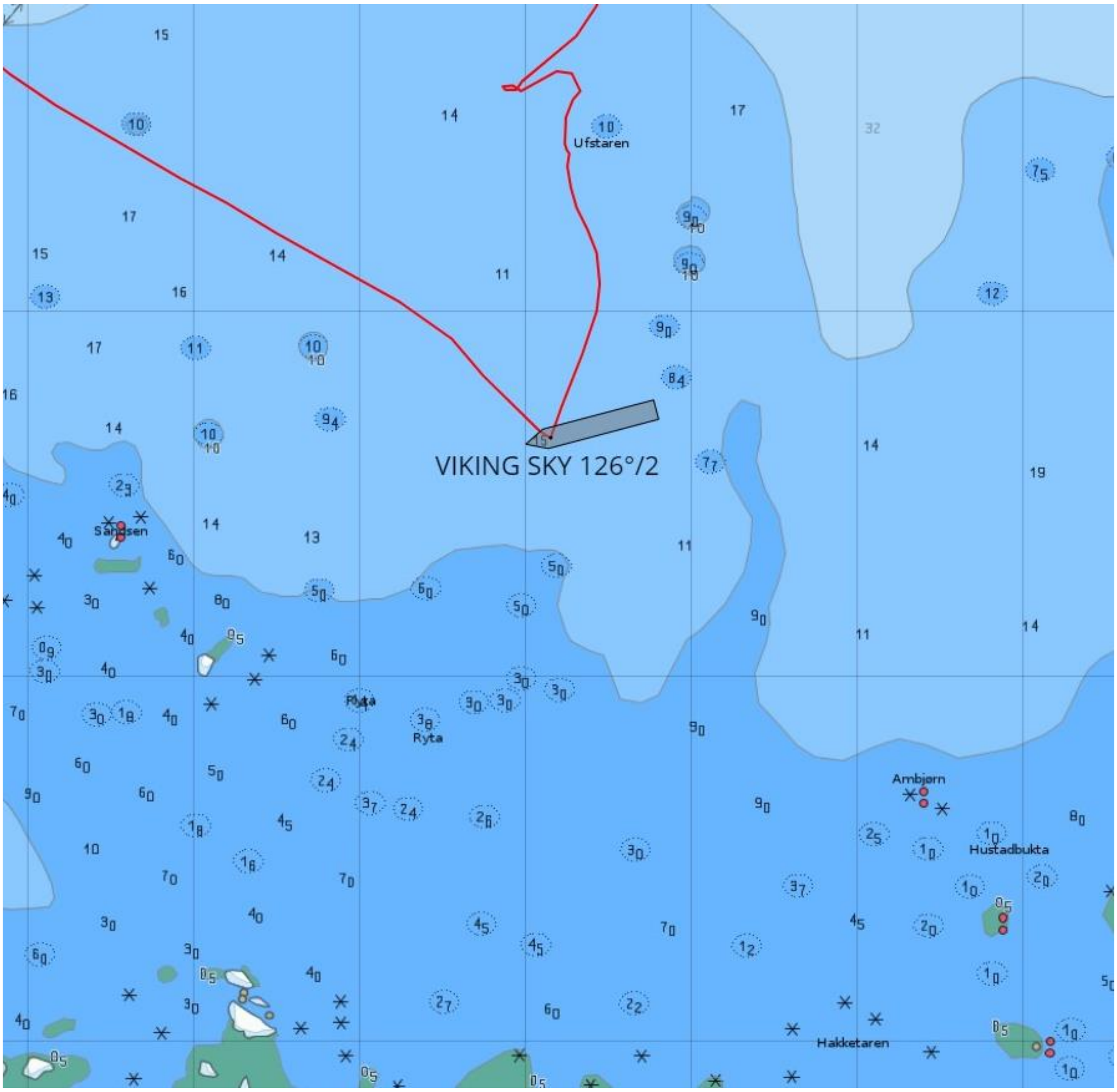

Figure 73: Viking Sky in close vicinity to several shallow banks, drifting towards shore. Source: The Norwegian Coastal Administration AIS

The alarm system did not differentiate between critical and less critical alarms. Troubleshooting was therefore challenging when a total of approximately 1,000 alarms went off in the IAS within the first 10 seconds after the blackout. A discussion of the role of the alarm system and its room for improvement is found in section 2.7. Also, recovery from a blackout without a standby generator had never been drilled on board. The engineers were therefore faced with a situation they were not practised in managing.

Even though the alarm system could have been of better assistance to the engineers in the troubleshooting process, this does not fully explain why it took about 14 minutes from the blackout until filling of the sump tanks commenced. Both the low lube oil level alarms and the low lube oil pressure alarms and shutdowns are displayed by red triangles and printed messages in the relevant mimics in the IAS. Moreover, this information was available at the time of the first shutdowns 13 minutes earlier.

One of the reasons that the troubleshooting was time consuming, might have been that the situation was perceived as stressful and that priority was put on restarting the engines rather than investigating the reasons why they shut down.

Once DG2 was successfully restarted locally and manually connected to the MSB, the engine crew had made so many unsuccessful attempts to restart, connect and transfer the engine to remote automatic control that they left it in manual. It was left in manual mode after it was also reset in the IAS and therefore could have been successfully transferred to remote control and automatic load sharing. The situation was clearly stressful, the control system was complex and a specific sequence of actions was needed, see section 1.2.4. Therefore, competence and training were clearly needed to be able to efficiently cope with emergency situations. The NSIA has found that the crew likely had insufficient training in this specific area and that this was a contributing factor to why it took 39 minutes from the blackout until both propulsion motors were operational and the ship had sufficient power available to maintain between 1 to 5 knots ahead. The investigation has not looked further into the domain of competence and training nor into the ship management company's competence management.

As described in section 1.16.5.5, the ship management company has implemented several measures related to blackout recovery.

In addition to interviews with crew, CCTV images from the ECR and electronic data from the VDR and the IAS has provided important information to shed light on this accident. Still, it has been difficult to fully understand some important aspects, i.a. why it took so long before filling of oil was started. It would likely have been much easier to understand had there been recordings of the sound in the ECR. Even though the engineers have been helpful and willing to share their recollections and impressions, human memory is not flawless and it may be particularly hard to remember all that happened correctly and in the right order after a stressful situation like this one.

The sound from the ECR was not recorded either on the VDR or the CCTV. This could have provided valuable insights and contributed to better understanding the safety issues present. The NSIA believe that recording of the sound in the ECR may be of great value in many accident investigations, in particular in the most serious accidents where lives - and therefore also witness accounts - are lost. The sound on the bridge is already recorded to the VDR and the NSIA recommends that the Norwegian Maritime Authority make a proposal to the IMO that the VDR performance standard is amended to also include recording of sound from the ECR, see Safety Recommendation Marine No. 2024/19T in chapter 4.

2.10 Evacuation and rescue operation

As the weather was considered too rough and the ship was too close to shore to use the lifeboats at the time of the blackout, see section 1.2.5 and 1.7.6, evacuation of passengers by helicopters was initiated.

As seen from the sequence of events in section 1.2.5, the first helicopter arrived at the scene approximately one hour after the blackout and 25 minutes after they had restored power, see Figure 74.

The helicopters were located not too far from Hustadvika, the closest as near as 40 km from the scene. They arrived as fast as possible without delay, and the complex and extended helicopter operation was carried out effectively with no accidents or casualties. As the blackout happened close to shore in a populated area, it was a short helicopter flight from the ship to the reception centre that was set up.

According to the JRCC, a total of 460 passengers had been evacuated in the continuous helicopter evacuation throughout the night, meaning that approximately 1/3 of all persons on board were rescued during the 18 hours long operation. This shows that in the event of immediate danger to life, helicopters have too little capacity compared to the large number of persons on board a cruise ship.

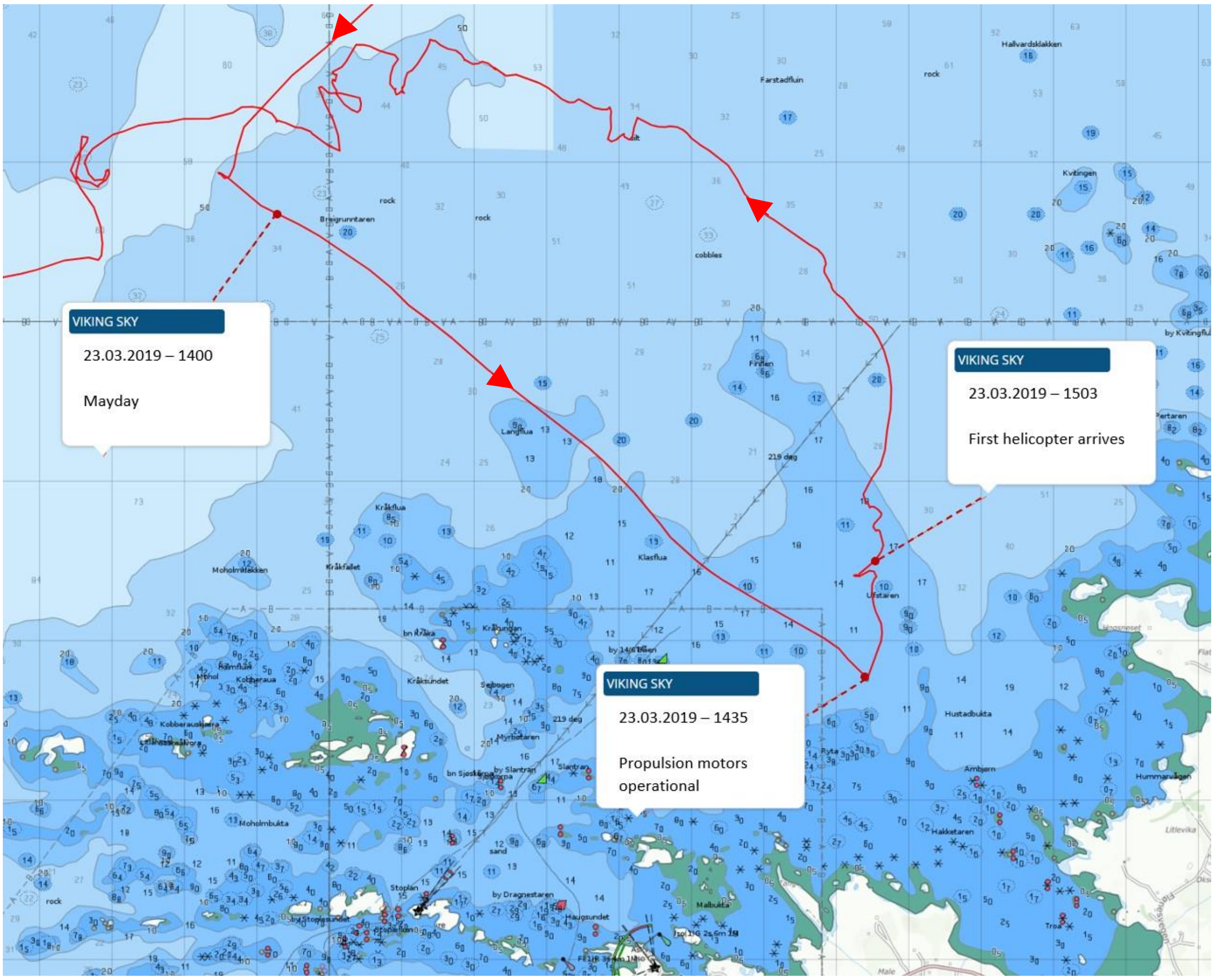

Figure 74: Arrival of first helicopter. Source: The Norwegian Coastal Administration/NSIA

The first tugboat arrived more than three hours after the blackout. *Viking Sky* had at that time sufficient power to manoeuvre slowly outwards towards deeper waters. Nearly three hours later, it was decided that a tugboat with larger bollard pull should head towards *Viking Sky.*

Since the weather was still rough and the situation was not considered as critical when the larger tugboat arrived later that night, towlines were not secured until 0830 the next morning.

Depending on where along the long Norwegian coast a blackout happens, and how far the nearest tug with sufficient capacity is, it might take a long time for a tugboat to arrive at the scene.

Despite the fact that helicopters were located and available nearby, had *Viking Sky* not been able to restore propulsion power at the time they did, the vessel would have grounded before helicopters or tugboats arrived at the scene. It is impossible to precisely predict the outcome of such a grounding, but it clearly had the potential to develop into a disaster with a high number of casualties.

This underlines the importance of not losing propulsion and steering and of avoiding situations where an evacuation is required, in particular for large passenger vessels. This was discussed in more detail in section 2.2.

The following three reports are all initiated by the *Viking Sky* accident and have similar conclusions regarding evacuation and rescue:

- The Norwegian Directorate for Civil Protection (DSB): *Assessment of the Viking Sky incident,* Report, 1 September 2021.

  This assessment covers all aspects of the rescue operation, including maritime intervention and rescue by helicopter, the evacuation of passengers, and their reception and handling on land.

  DSB's assessment confirms the broad understanding that the rescue operation was successful with regard to the evacuation of passengers from the cruise ship, and their reception and management on land. However, they present 22 lessons learned with corresponding recommendations of follow-up measures. For none of the lessons learned they have any reason to believe it had any negative consequences for the outcome of the situation.

- Official Norwegian Reports NOU 2022: 1 Excerpt. *Cruise traffic in Norwegian waters and adjacent sea area*, 23 February 2022.

  This publication is a translation from official Norwegian report prepared by a Government-appointed committee (the Cruise Committee), which submitted its report to the Ministry of Justice and Public Security on 23 February 2022. The report covers maritime safety and emergency preparedness challenges associated with cruise traffic in Norwegian waters and adjacent sea areas, and presents 66 recommended risk-reducing measures, including what the cruise industry itself can contribute.

  The Cruise Committee concludes that it is not possible to dimension an emergency preparedness and response system that takes into account an accident involving a cruise ship with several thousand passengers on board and have therefore emphasised probability-reducing measures to reduce the risk of cruise traffic.

- The Norwegian Coastal Administration (NCA): *Analysis of additional risk associated with cruise traffic along the Norwegian coast outside the summer season,* Report, prepared by DNV for the Norwegian Coastal Administration, 27 May 2020.

  The report discusses special challenges of cruise activity in the Svalbard area and the coast of mainland Norway during the winter months.

  The NCA concludes that dimensioning the emergency response apparatus for a major incident involving a cruise ship with hundreds or thousands of people on board would be very expensive and inexpedient. The report therefore primarily recommends risk-reducing measures that focus largely on preventive measures to make voyages safer.

3. Conclusions

3. Conclusions

3.1 Main conclusion

In the afternoon of 23 March 2019, the cruise vessel *Viking Sky* experienced a blackout, causing loss of propulsion and steering, in 24 m/s winds (BF9, strong gale force)[31] with gusts to 29 m/s in the Hustadvika area of the Norwegian coast. The vessel is estimated to have come within a ship's length of running aground with more than 1,300 persons on board, and the accident had the potential to develop into one of the worst disasters at sea in modern times.

The accident was caused by insufficient lubricating oil in all of the operating diesel generators' lubricating oil sump tanks, in combination with pitching and rolling in rough seas. The investigation has identified operational, technical, and organisational safety issues that in different ways contributed to the blackout.

The blackout recovery was time consuming, and it took 39 minutes from the blackout until both propulsion motors were operational and the ship had sufficient power available to maintain between 1 and 5 knots ahead. The situation was stressful, the control system was complex and a specific sequence of actions was needed. Insufficient training likely contributed to why the blackout recovery was time consuming.

When *Viking Sky* left Tromsø 21 March 2019, with one out of four diesel generators unavailable, both crew and passengers were unknowingly exposed to an increased risk as the vessel did not have the redundancy required under the Safe Return to Port (SRtP) regulations. As *Viking Sky* did not comply with the applicable safety standards, it should not have departed Tromsø under the prevailing circumstances.

3.2 Investigation results

3.2.1 THE BLACKOUT

- *Viking Sky* suffered a blackout when all three operational diesel generators (DGs) were shut down by their protection systems responding to low lube oil pressures.
- The low lube oil pressure was due to low levels of lube oil in the sump tanks in combination with the vessel motion, causing the lube oil suction pipe opening to be exposed to air.
- No oil had been transferred into the DG sump tanks even though low lube oil level alarms went off both for DG2 and DG4 during the voyage, and the heavy weather checklist, that included an item requesting the lube oil sump tank levels to be optimised, was logged as completed.
- The vessel encountered strong winds and heavy seas, as forecast, but the vessel motion at the time of the first engine shutdown was significantly below the design criteria.

3.2.2 LUBRICATING OIL SUMP TANK DESIGN AND APPROVAL

- The shipyard did not take into account the required angles of dynamic inclination specified in SOLAS and class rules nor the recommendations from the engine manufacturer to ensure suction of oil free of air under dynamic inclination angles.

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[31] *Based on average wind speed registered by the VDR in the period 1349 to 1359. For Beaufort (BF) wind scale, see Appendix H.*

- The lube oil sump tanks were 60–68% of the calculated minimum tank heights necessary to theoretically fulfil the design criteria recommended by MAN in the engines' project guide. Hence, the tank design did not fulfil the design criteria recommended by MAN.
- The shipyard, the classification society and SINTEF Ocean have carried out CFD simulations, all three indicating that within the parameters of the design criteria there are situations where the suction pipe is likely to be exposed to air, hence the lube oil sump tank design was non-compliant with the SOLAS regulation.
- Simulations using the vessel motion recorded at the time of the first engine shutdown indicate that the accident would likely not have occurred had the lube oil sump tanks been filled to the highest level recommended by the engine manufacturer. The recorded vessel motion was however significantly below the design criteria specified in SOLAS.
- The SOLAS regulation explicitly specifies the possibility for the administration of the flag state to permit deviation from the required angles of inclination, taking into consideration the type, size and service conditions of the ship. No such deviation had been requested or granted.
- The design process of the shipyard did not effectively ensure that the lube oil sump tanks complied with the SOLAS requirement for safe operation under dynamic inclination.
- Lloyd's Register's plan approval process was ineffective and did not ensure that the sump tank design, which is critical to safe engine operation, was compliant with the applicable rules and regulations.
- The actual limitations associated with the tank design in terms of dynamic inclination angles or corresponding sea conditions had not been calculated. The crew on board the vessels therefore did not have the safety critical information necessary to know the limits of safe operation.
- The SOLAS regulation specifies the dynamic pitch and roll amplitudes under which the machinery shall be able to operate safely. However, neither SOLAS nor IACS UR M46 provide unambiguous information on the period, duration or pattern of the movement over time to be used for the application or verification of compliance with the regulation.
- No technical guideline or industry standard for application of the SOLAS requirement exists. This lack of guidance is a safety issue as it is unclear how compliance with the requirement should be documented and verified.

3.2.3 OPERATING INSTRUCTIONS FOR LUBRICATING OIL LEVELS AND ALARM SETPOINTS

- *Viking Sky* and the sister vessels were operated without instructions regarding correct lube oil sump tank filling levels or alarm setpoints.
- Only one of the sister vessels requested guidance from the shore organisation on this matter, a safety critical factor to be managed by the crew on board.
- Even though the shore organisation was made aware of this issue in 2016, no guidance on correct filling volumes or alarm set points was issued until after the accident on *Viking Sky*.
- The lack of available operating instructions is an organisational safety issue that likely contributed to the lube oil levels being maintained too low.
- The ship management company has implemented a new procedure for lube oil management to maintain higher lube oil levels. It is uncertain whether the new procedure fully remedy the safety issue as it is not supported by any calculation to document compliance with SOLAS or other operational limitations.

3.2.4 LUBRICATING OIL LEVEL REMOTE MONITORING SYSTEM

- The as-built sensor pipe offset, representing the physical fixed distance from the bottom of the tank to the bottom of the level sensor tube, was not recorded by the shipyard. The importance of the offset and its direct influence on the accuracy of the level measurements was not recognised.
- The design was not according to the equipment makers recommended minimum distance between the sensor tube and oil suction pipe for sump tank 5S (DG4).
- The 3D-model used to convert the level measurements to oil volumes for DG1 was erroneous, causing a significant measurement error.
- The remote lube oil sump tank level monitoring system was complex and the resulting onboard measurements inaccurate and unreliable.
- The engine crew on board *Viking Sky* had gradually lost confidence in the remote monitoring system. Since the level alarms were generated by the remote readings, the crew subsequently did not take the level alarms as a true indicator of the actual level.

3.2.5 ALARM SYSTEM DESIGN AND MANAGEMENT

- The ECR operators were responsible for monitoring a large number of alarms, too many for an operator to handle, given the design and configuration of the alarm system.
- The alarms were not grouped and had no priority according to criticality.
- Several issues related to design and configuration of the alarm system likely had a negative impact on the effectiveness and efficiency of engineering officers on watch.
- At the time of the construction of *Viking Sky,* there were no standards available giving specific criteria for the design of engine room alarm systems in the maritime industry.

3.2.6 LUBRICATING OIL LEVEL MANAGEMENT

- The exchange of lube oil was mainly managed based on the Total Base Number (TBN) level and the oil consumption of the engines was underestimated.
- The on board lube oil level management was ineffective and did not ensure sufficient levels of lube oil in the sump tanks.
- The combination of economic considerations, the underestimation of consumption, the lack of confidence in the remote tank monitoring system and the lack of instructions on correct filling and alarm levels probably resulted in the lube oil levels and alarm settings decreasing over time.
- The safety issues related to lube oil level management observed onboard *Viking Sky* were likely the result of underlying organisational safety issues.

3.2.7 BLACKOUT RECOVERY

- The alarm system did not differentiate between critical and less critical alarms. Troubleshooting was therefore challenging when a total of approximately 1,000 alarms went off in the IAS within the first 10 seconds after the blackout.
- Blackout drills had been carried out, but recovery from a full blackout without a standby generator had never been drilled on board. The engineers were therefore faced with a situation they were not practised in managing.

- It took 14 minutes from the blackout until refilling of the lube oil sump tanks was started, 10 more minutes to restart and connect the first DG and another 15 minutes before both propulsion motors were operational and the ship had sufficient power available to maintain between 1 to 5 knots ahead.
- The situation was stressful, the control system was complex and a specific sequence of actions was needed. Insufficient training likely contributed to why the blackout recovery was time consuming.
- Recording of sound from the ECR could have provided valuable insights and contributed to better understanding the safety issues present during blackout recovery.

3.2.8 EVACUATION AND RESCUE OPERATION

- The lifeboats were not lowered, as lifeboats were not considered a safe means of evacuation in such rough weather close to shore.
- The complex and extended helicopter operation was carried out effectively with no accidents or casualties, however both the first rescue helicopter and the first tug arrived after the vessel would have grounded if propulsion had not been regained.
- This underlines the importance of not losing propulsion and steering and of avoiding situations where an evacuation is required, in particular for large passenger vessels.

3.2.9 THE DECISION TO SAIL

- Five days prior to the departure from Tromsø, DG3 became unavailable due to a turbocharger failure, rendering the vessel non-compliant with the Safe Return to Port (SRtP) regulations.
- The ship management company was aware of the unavailability of an engine yet did not instruct the vessel to stay in port.
- The ship management company had no guidelines or procedures in the safety management system (SMS) regarding how to handle planned or unplanned unavailability of a DG with respect to the SRtP requirements.
- Crew and passengers on board *Viking Sky* were unknowingly exposed to an increased risk as the vessel set to cross Hustadvika, known as a *notoriously dangerous area*, in a forecast storm without the redundancy required.
- It is possible that the *Viking Sky* could have experienced a blackout also with all four engines available if the lube oil level was low on all four lube oil sump tanks, including for DG3. This is, however, not a reason not to comply with the SRtP regulations.

3.2.10 ELECTRONIC INCLINOMETER

- *Viking Sky* was not required to be, nor was it fitted with a type-approved electronic inclinometer providing recordings to the VDR. Hence, inclination angle data from the vessel’s fuel efficiency management system, Eniram, was used in the investigation.
- An electronic inclinometer providing recordings to the VDR would provide more efficient and reliable results and therefore would be beneficial for safety investigations and may contribute to improve safety at sea.

4. Safety recommendations

4. Safety recommendations

The Norwegian Safety Investigation Authority proposes the following safety recommendations[32] for the purpose of improving safety at sea:

Safety Recommendation Marine No. 2024/06T

On 23 March 2019 *Viking Sky* was less than a ship length from running aground during a storm in Hustadvika, Norway. With more than 1,300 persons on board, the cruise ship suffered a blackout due to loss of lubricating oil pressure caused by insufficient lube oil in the engines' sump tanks.

The investigation has shown that the lube oil sump tank design did not comply with SOLAS II-1, Part C, Regulation 26.6 and LR Class Rules Part 5, Chapter 1, Section 3.7 on safe operation under dynamic inclination nor with the recommendations of the engine manufacturer. The sump tank design is critical to safe engine operation, yet the shipyard's design process did not effectively ensure that the lube oil sump tanks complied with the SOLAS requirement for safe operation under dynamic inclination.

The Norwegian Safety Investigation Authority recommends that Fincantieri review and strengthen the design process to ensure that lube oil sump tanks are designed and built in compliance with the SOLAS regulation and Class Rules in the future. Fincantieri is also recommended to investigate if any other ships designed at the yard may have non-compliant lube oil sump tanks and take necessary action if relevant.

Safety Recommendation Marine No. 2024/07T

On 23 March 2019 *Viking Sky* was less than a ship length from running aground during a storm in Hustadvika, Norway. With more than 1,300 persons on board, the cruise ship suffered a blackout due to loss of lubricating oil pressure caused by insufficient lube oil in the engines' sump tanks.

The investigation has shown that the lube oil sump tank design did not comply with SOLAS II-1, Part C, Regulation 26.6 and LR Class Rules Part 5, Chapter 1, Section 3.7 on safe operation under dynamic inclination nor with the recommendations of the engine manufacturer. The sump tank design is critical to safe engine operation, yet Lloyd's Register did not independently verify compliance with either the engine manufacturer's instructions, the SOLAS regulation or LR's own Class Rules.

The Norwegian Safety Investigation Authority recommends that Lloyd's Register review and strengthen the plan approval process to ensure that lube oil sump tanks are designed and built in compliance with the SOLAS regulation and Class Rules.

[32] *The Ministry of Trade, Industry and Fisheries has the overall responsibility for following up the safety recommendations.*

Safety Recommendation Marine No. 2024/08T

On 23 March 2019 *Viking Sky* was less than a ship length from running aground during a storm in Hustadvika, Norway. With more than 1,300 persons on board, the cruise ship suffered a blackout due to loss of lubricating oil pressure caused by insufficient lube oil in the engines' sump tanks.

The investigation has shown that the lube oil sump tank design did not comply with the SOLAS II-1, Part C, Regulation 26.6 and LR Class Rules Part 5, Chapter 1, Section 3.7 on safe operation under dynamic inclination nor with the recommendations of the engine manufacturer. The operational limitations associated with the tank design in terms of dynamic inclination angles or corresponding sea conditions have not been calculated. The crew on board the vessels therefore didn't have the safety critical information necessary to know the limits of safe operation.

The Norwegian Safety Investigation Authority recommends that Wilhelmsen Ship Management, in cooperation with Viking Ocean Cruises, take necessary action to ensure the vessels are compliant with the SOLAS regulation through calculation and implementation of operating restrictions associated with the current tank design, modification of the tank design, or a combination of both.

Safety Recommendation Marine No. 2024/09T

On 23 March 2019 *Viking Sky* was less than a ship length from running aground during a storm in Hustadvika, Norway. With more than 1,300 persons on board, the cruise ship suffered a blackout due to loss of lubricating oil pressure caused by insufficient lube oil in the engines' sump tanks.

The investigation has shown that the lube oil sump tank design did not comply with the SOLAS II-1, Part C, Regulation 26.6 and LR Class Rules Part 5, Chapter 1, Section 3.7 on safe operation under dynamic inclination nor with the recommendations of the engine manufacturer. The operational limitations associated with the actual tank design in terms of dynamic inclination angles or corresponding sea conditions have not been calculated. The crew on board the vessels therefore didn't have the safety critical information necessary to know the limits of safe operation.

The Norwegian Safety Investigation Authority recommends that Lloyd's Register require action to ensure *Viking Sky* and its sister vessels are compliant with the SOLAS regulation and LR Class Rules through calculation and implementation of operating restrictions associated with the current tank design, modification of the tank design, or a combination of both.

Safety Recommendation Marine No. 2024/10T

On 23 March 2019 *Viking Sky* was less than a ship length from running aground during a storm in Hustadvika, Norway. With more than 1,300 persons on board, the cruise ship suffered a blackout due to loss of lubricating oil pressure caused by insufficient lube oil in the engines' sump tanks.

The investigation has shown that the lube oil sump tank design did not comply with the SOLAS II-1, Part C, Regulation 26.6 and LR Class Rules Part 5, Chapter 1, Section 3.7 on safe operation under dynamic inclination nor with the recommendations of the engine manufacturer. The operational limitations associated with the actual tank design in terms of dynamic inclination angles or corresponding sea conditions have not been calculated. The crew on board the vessels therefore didn't have the safety critical information necessary to know the limits of safe operation.

The Norwegian Safety Investigation Authority recommends that the Norwegian Maritime Authority require action to ensure *Viking Sky* and its sister vessels are compliant with the SOLAS regulation through calculation and implementation of operating restrictions associated with the current tank design, modification of the tank design, or a combination of both.

Safety Recommendation Marine No. 2024/11T

On 23 March 2019 *Viking Sky* was less than a ship length from running aground during a storm in Hustadvika, Norway. With more than 1,300 persons on board, the cruise ship suffered a blackout due to loss of lubricating oil pressure caused by insufficient lube oil in the engines' sump tanks.

The investigation has shown that the lube oil sump tank design did not comply with the SOLAS II-1, Part C, Regulation 26.6 and LR Class Rules Part 5, Chapter 1, Section 3.7 on safe operation under dynamic inclination nor with the recommendations of the engine manufacturer. The SOLAS regulation specifies the dynamic pitch and roll amplitudes under which the machinery shall be able to operate safely. However, neither SOLAS nor IACS UR M46 provide unambiguous information on the period, duration or pattern of the movement over time to be used for the application of, or verification of compliance with, the regulation. No technical guideline or industry standard for application of the SOLAS requirement exists.

The Norwegian Safety Investigation Authority recommends that the Norwegian Maritime Authority make a proposal to the International Maritime Organization (IMO) that a technical guideline on the application of SOLAS Chapter II-1, Part C, Regulation 26.6 shall be developed.

Safety Recommendation Marine No. 2024/12T

On 23 March 2019 *Viking Sky* was less than a ship length from running aground during a storm in Hustadvika, Norway. With more than 1,300 persons on board, the cruise ship suffered a blackout due to loss of lubricating oil pressure caused by insufficient lube oil in the engines' sump tanks.

The investigation has shown that the lube oil sump tank design did not comply with the SOLAS II-1, Part C, Regulation 26.6 and LR Class Rules Part 5, Chapter 1, Section 3.7 on safe operation under dynamic inclination nor with the recommendations of the engine manufacturer. The SOLAS regulation specifies the dynamic pitch and roll amplitudes under which the machinery shall be able to operate safely. However, neither SOLAS nor IACS UR M46 provide unambiguous information on the period, duration or pattern of the movement over time to be used for the application of, or verification of compliance with, the regulation. No technical guideline or industry standard for application of the SOLAS requirement exists.

The Norwegian Safety Investigation Authority recommends that Lloyd's Register make a proposal to the International Association of Classification Societies (IACS) that a technical guideline on the application of SOLAS Chapter II-1, Part C, Regulation 26.6 shall be developed.

Safety Recommendation Marine No. 2024/13T

On 23 March 2019 *Viking Sky* was less than a ship length from running aground during a storm in Hustadvika, Norway. With more than 1,300 persons on board, the cruise ship suffered a blackout due to loss of lubricating oil pressure caused by insufficient lube oil in the engines' sump tanks.

The investigation has shown that the lube oil sump tank design did not comply with the SOLAS II-1, Part C, Regulation 26.6 and LR Class Rules Part 5, Chapter 1, Section 3.7 on safe operation under dynamic inclination nor with the recommendations of the engine manufacturer. *Viking Sky* was not required to be, nor was it fitted with a type-approved electronic inclinometer providing recordings to the VDR. Hence, inclination angle data from the vessel's fuel efficiency management system was used in the investigation. An electronic inclinometer providing recordings to the VDR would more efficiently provide reliable data for safety investigations and may thereby contribute to improve safety at sea.

The Norwegian Safety Investigation Authority recommends that the Norwegian Maritime Authority make a proposal to the International Maritime Organization (IMO) that inclinometer information compliant with the technical requirements of resolution MSC.363(92) is recorded on the VDRs of all SOLAS ships with a gross tonnage of 3,000 and above.

Safety Recommendation Marine No. 2024/14T

On 23 March 2019 *Viking Sky* was less than a ship length from running aground during a storm in Hustadvika, Norway. With more than 1,300 persons on board, the cruise ship suffered a blackout due to loss of lubricating oil pressure caused by insufficient lube oil in the engines' sump tanks.

The investigation has shown that the lube oil sump tank design did not comply with the SOLAS II-1, Part C, Regulation 26.6 and LR Class Rules Part 5, Chapter 1, Section 3.7 on safe operation under dynamic inclination nor with the recommendations of the engine manufacturer. The ship management company has implemented a new procedure for lube oil management to maintain higher lube oil levels. It is uncertain whether the revised procedure fully remedy the safety issue as it does not document that the increased oil levels lead to compliance with the SOLAS regulation nor what the operating limitations associated with the increased oil levels are. The crew on board the vessels therefore don't have the safety critical information necessary to know the limits of safe operation with respect to dynamic inclination angles or corresponding sea conditions.

The Norwegian Safety Investigation Authority recommends that Wilhelmsen Ship Management, develop and implement a new procedure for lube oil level management, and calculate and implement the associated operating restrictions, to ensure safe operation in compliance with the SOLAS requirement and in accordance with the engine manufacturer's recommendations.

Safety Recommendation Marine No. 2024/15T

On 23 March 2019 *Viking Sky* was less than a ship length from running aground during a storm in Hustadvika, Norway. With more than 1,300 persons on board, the cruise ship suffered a blackout due to loss of lubricating oil pressure caused by insufficient lube oil in the engines' sump tanks.

The investigation has shown that the remote lube oil sump tank level monitoring system was complex and the resulting on board measurements inaccurate and unreliable. The as-built sensor pipe offset, representing the physical fixed distance from the bottom of the tank to the bottom of the level sensor tube, was not recorded by the shipyard. The yard did not take into account the equipment maker's recommended minimum distance between the sensor tube and oil suction pipe. In addition, the 3D-model used to convert the level measurements to oil volumes for diesel generator 1 (DG1) was erroneous, causing a significant measurement error.

The Norwegian Safety Investigation Authority recommends that Wilhelmsen Ship Management, in cooperation with Viking Ocean Cruises, carry out a systematic and holistic review of the remote lube oil sump tank level monitoring system and ensure the vessels are fitted with an accurate and trustworthy remote monitoring system.

Safety Recommendation Marine No. 2024/16T

On 23 March 2019 *Viking Sky* was less than a ship length from running aground during a storm in Hustadvika, Norway. With more than 1,300 persons on board, the cruise ship suffered a blackout due to loss of lubricating oil pressure caused by insufficient lube oil in the engines' sump tanks.

The investigation has shown that the remote lube oil sump tank level monitoring system was complex and the resulting on board measurements inaccurate and unreliable. The as-built sensor pipe offset, representing the physical fixed distance from the bottom of the tank to the bottom of the level sensor tube, was not registered. The yard did not take into account the equipment maker's recommended minimum distance between the sensor tube and oil suction pipe. In addition the 3D-model used to convert the level measurements to oil volumes for DG1 was erroneous, causing a significant measurement error.

The Norwegian Safety Investigation Authority recommends that Fincantieri carry out a systematic and holistic review of the remote lube oil sump tank level monitoring system and take the necessary actions to ensure that future vessels are fitted with a sufficiently accurate and trustworthy remote lube oil sump tank level monitoring system.

Safety Recommendation Marine No. 2024/17T

On 23 March 2019 *Viking Sky* was less than a ship length from running aground during a storm in Hustadvika, Norway. With more than 1,300 persons on board, the cruise ship suffered a blackout due to loss of lubricating oil pressure caused by insufficient lube oil in the engines' sump tanks.

The investigation has found several design and configuration issues related to the engine control room alarm system that likely had a negative impact on the effectiveness and efficiency of engineering officers on watch.

The Norwegian Safety Investigation Authority recommends that Wilhelmsen Ship Management, in cooperation with Viking Ocean Cruises, carry out an operator centric design and configuration review of the engine room alarm system and implement identified improvements.

Safety Recommendation Marine No. 2024/18T

On 23 March 2019 *Viking Sky* was less than a ship length from running aground during a storm in Hustadvika, Norway, with more than 1,300 persons on board, as it suffered a blackout due to loss of lubricating oil pressure caused by insufficient lube oil in the engines' sump tanks.

The investigation has found several design and configuration issues related to the engine control room alarm system that likely had a negative impact on the effectiveness and efficiency of engineering officers on watch. Ships' engine room alarm management are not subject to any regulation equivalent to the Bridge Alert Management (BAM) performance standards, with the result that many of these systems, such as the alarm system on *Viking Sky* and its sister vessels, do not have an optimal design and configuration.

The Norwegian Safety Investigation Authority recommends that the Norwegian Maritime Authority make a proposal to the International Maritime Organization (IMO) that an engine room alarm management performance standard shall be developed.

Safety Recommendation Marine No. 2024/19T

On 23 March 2019 *Viking Sky* was less than a ship length from running aground during a storm in Hustadvika, Norway. With more than 1,300 persons on board, the cruise ship suffered a blackout due to loss of lubricating oil pressure caused by insufficient lube oil in the engines' sump tanks.

The blackout recovery was time consuming, and it took 39 minutes from the blackout until both propulsion motors were operational and the ship had sufficient power available to maintain between 1 and 5 knots ahead. It has been difficult to understand why it took so long before filling of oil was started and why the crew continued to struggle to restore power and propulsion. Recording of sound from the engine control room could have provided valuable insights and contributed to better understanding the interaction in the engine control room and the safety issues present.

The Norwegian Safety Investigation Authority recommends that the Norwegian Maritime Authority make a proposal to the International Maritime Organization (IMO) that the VDR performance standard is amended to also include recording of sound from the engine control room.

Norwegian Safety Investigation Authority
Lillestrøm, 18 March 2024

Abbreviations

Abbreviations

AC	Alternating Current
AIS	Automatic Identification System
ATSB	Australian Transport Safety Bureau
BAM	Bridge Alert Management
CCTV	Closed Circuit Television
CFD	Computational Fluid Dynamics
CIC	Casualty Investigational Code
CoCoS	Computer Controlled Surveillance Engine Diagnostics System
DC	Direct Current
DG	Diesel Generator
DSB	Norwegian Directorate for Civil Protection
ECR	Engine Control Room
EEMUA	Engineering Equipment and Materials Users Association
ENC	Electronic Navigation Charts
EOW	Engineer on Watch
EP	Electro-pneumatic
HSE	Health and Safety Executive
IACS	International Association of Classification Societies
IAS	Integrated Automation System
III	Implementation of IMO Instruments
IMO	International Maritime Organization
JRCC	Joint Rescue Coordination Centre
LO	Lubrication Oil
LOA	Length Overall
LPP	Length between Perpendiculars
LR	Lloyd’s Register
LSA	Life-Saving Appliance

MAIB	Marine Accident Investigation Board
MES	Marine Evacuation System
MSB	Main Switch Board
MSC	Maritime Safety Committee
NCA	Norwegian Coastal Administration
NIS	Norwegian International Ship Register
NMA	Norwegian Maritime Authority
NSCR	Navigation, Communication and Search and Rescue
NSIA	Norwegian Safety Investigation Authority
NTSB	National Transportation Safety Board
OMCV	Operational Manual Cruise Vessel
OSC	On Scene Coordinator
PA	Public Address system
PMS	Power Management System
RO	Recognised Organisation
RPM	Revolutions Per Minute
SaCoS	Safety and Control System
SIS	Substantially Interested State
SMS	Safety Management System
SRtP	Safe Return to Port
TBN	Total Base Number
TPA	Thermal Protective Aids
UK	United Kingdom
UR	Unified Requirement
US	United States
UTC	Coordinated Universal Time
USCG	United Stated Coast Guard
VDR	Voyage Data Recorder

Appendices

Appendix A Details of the vessel and the accident

Vessel	
Name	Viking Sky
Flag state	Norway/NIS
Classification society	Lloyd's Register
IMO Number/Call signal	9650420/LAYU7
Type	Passenger
Year of build	2017
Owner	Viking Ocean Cruises AS
Operator / Responsible for ISM	Wilhelmsen Ship Management (Norway) AS
Construction material	Steel
Length	228.37 m
Gross tonnage	47,842
Safe manning	167
The voyage	
Port of departure	Tromsø, Norway
Port of destination	Stavanger, Norway
Type of voyage	Coastal
Cargo	Cruise ship
Persons on board	1,374
Information about the accident	
Date and time	23 March 2019 at 1358
Type of accident	Machinery failure
Location/position where the accident occurred	63˚ 00.3' N, 006˚ 59.6' E
Place on board where the accident occurred	Machinery space
Injuries/deaths	19 passengers injured
Damage to ship/environment	See section 1.4
Ship operation	On passage
At what point in the voyage was the vessel	Mid-water
The external environment	Average wind speed 24 m/s SW (BF9, strong force)[33] with gusts to 29 m/s, significant wave height 4-6 m (according to the deck log book)/ 8–9 m (according to weather report from the Norwegian Meteorological Institute)

[33] Based on average wind speed registered by the VDR in the period 1349 to 1359. For Beaufort (BF) wind scale, see Appendix H.

Appendix B IACS Unified Requirement M46 Rev. 1 2002

M46
(1982)
(Rev.1
June
2002)

Ambient conditions - Inclinations

M46.1 The ambient conditions specified under M46.2 are to be applied to the layout, selection and arrangement of all shipboard machinery, equipment and appliances to ensure proper operation.

M46.2 Inclinations

Installations, components	Angle of inclination [°][2]			
	Athwartships		Fore-and-aft	
	static	dynamic	static	dynamic
Main and auxiliary machinery	15	22,5	5[4]	7,5
Safety equipment, e.g. emergency power installations, emergency fire pump and their devices Switch gear, electrical and electronic appliances[1] and remote control systems	22,5[3]	22,5[3]	10	10

NOTES:

1. Up to an angle of inclination of 45° no undesired switching operations or operational changes may occur.

2. Athwartships and fore-end-aft inclinations may occur simultaneously.

3. In ships for the carriage of liquefied gases and of chemicals the emergency power supply must also remain operable with the ship flooded to a final athwartships inclination up to maximum of 30°.

4. Where the length of the ship exceeds 100m, the fore-and-aft static angle of inclination may be taken as 500/L degrees where L = length of the ship, in metres, as defined in UR S2.

The Society may consider deviations from these angles of inclination taking into consideration the type, size and service conditions of the ship.

End of Document

Appendix C IACS Unified Requirement M46 Rev. 3 2023

M46
(1982)
(Rev.1 June 2002)
(Rev.2 Dec 2018)
(Rev.3 Aug 2023)

Ambient conditions – Inclinations and Ship Accelerations and Motions

M46.1 General

The ambient conditions specified under M46.2 and M46.3 are to be applied to the layout, selection and arrangement of ~~all~~ shipboard machinery, equipment and appliances (addressed in this UR) to ensure proper operation.

Note:

1. The requirements of UR M46 Rev.2 are to be uniformly implemented by IACS Societies on ships contracted for construction on or after 1 January 2020.

2. The requirements of UR M46 Rev.3 are to be uniformly implemented by IACS Societies on ships contracted for construction on or after 1 January 2025.

~~2~~3. The "contracted for construction" date means the date on which the contract to build the vessel is signed between the prospective owner and the shipbuilder. For further details regarding the date of "contract for construction", refer to IACS Procedural Requirement (PR) No. 29.

M46
(cont)

M46.2 Inclinations

Inclinations applied to respective components are as follows.

Installations, components	Angle of inclination [°][2]			
	Athwartships		Fore-and-aft	
	static	dynamic	static	dynamic
Main and auxiliary machinery	15	22.5	5[4]	7.5
Safety equipment, e.g. emergency power installations, emergency fire pump and their devices Switch gear, electrical and electronic appliances[1] and remote-control systems	22.5[3]	22.5[3]	10	10

Notes:

1. No undesired switching operations or operational changes are to occur.
2. Athwartships and fore-and-aft inclinations may occur simultaneously.
3. In ships for the carriage of liquefied gases and of chemicals, the emergency power supply must also remain operable with the ship flooded to a final athwartships inclination up to maximum of 30°.
4. Where the length of the ship exceeds 100m, the fore-and-aft static angle of inclination may be taken as 500/L degrees where L = length of the ship, in metres, as defined in UR S2.

The Society may consider deviations from these angles of inclination, taking into consideration the type, size and service conditions of the ship.

M46.3 Shipboard accelerations

3.1 Main propulsion and steering machinery and auxiliary machinery that is essential to the propulsion and steering, and the safety of the ship shall be capable of operation under the effects of acceleration and motions.

3.2 The requirements in M46.4 to M46.6 apply where documented evidence of equipment suitability is specifically required by other relevant URs for such equipment or requested by the Classification Society.

M46.4 Documentation

4.1 For ships subject to the SOLAS Convention, ship builders are to identify and document the ship accelerations and motions periods to which machinery and equipment might be subjected to. The expected accelerations and ship motions periods are to be within machinery and equipment manufacturers requirements. The estimations are to consider vessel type, machinery or equipment location and expected service conditions.

M46
(cont)

M46.5 Evaluation of equipment suitability

5.1 Machinery and equipment manufacturers are to submit evidence to the Classification Society that their machinery or equipment can operate under the required static and dynamic conditions stated in M46.2 and at least at the levels of shipboard accelerations as stated in M46.4 and/or specified in the relevant URs. Documentation of satisfactory performance shall take the form of:

.1 Report of testing under representative conditions; or

.2 Report of theoretical verification using recognised computational techniques accompanied by detailed and relevant validation data: or

.3 Historical data which provides relevant demonstration of satisfactory experience in service.

M46.6 Installation and operation

6.1 Machinery and equipment manufacturers are to submit details of the requirements /recommendations for installation of the machinery and equipment onboard to ensure satisfactory operation in service under the required static and dynamic conditions as described in M46.2 and at least at the levels of shipboard accelerations as stated in M46.4 and/or specified in the relevant URs.

Note: Consideration should be given for positioning machinery in order to minimize the dynamic load on bearings due to ship motion.

6.2 Shipbuilders are to submit details demonstrating that the installation of the machinery and equipment onboard is in accordance with manufacturer's requirements /recommendations.

End of Document

Appendix D MAN Project guide – section 5.2.5

5.2.5 Lube oil service tank

The lube oil service tank is to be arranged over the entire area below the engine, in order to ensure uniform vertical thermal expansion of the whole engine foundation.

To provide for adequate degassing, a minimum distance is required between tank top and the highest operating level. The low oil level should still permit the lube oil to be drawn in free of air if the ship is pitching severely

- 5° longitudinal inclination for ship's lengths ≥ 100 m
- 7.5° longitudinal inclination for ship's lengths < 100 m

A well for the suction pipes of the lube oil pumps is the preferred solution.

The minimum quantity of lube oil for the engine is 1.0 litre/kW. This is a theoretical factor for permanent lube-oil-quality control and the decisive factor for the design of the by-pass cleaning. The lube oil quantity, which is actually required during operation, depends on the tank geometry and the volume of the system (piping, system components), and may exceed the theoretical minimum quantity to be topped up. The low-level alarm in the service tank is to be adjusted to a height, which ensures that the pumps can draw in oil, free of air, at the longitudinal inclinations given above. The position of the oil drain pipes extending from the engine oil sump and the oil flow in the tank are to be selected so as to ensure that the oil will remain in the service tank for the longest possible time for degassing.

Draining oil must not be sucked in at once.

The man holes in the floor plates inside the service tank are to be arranged so as to ensure sufficient flow to the suction pipe of the pump also at low lube oil service level.

The tank has to be vented at both ends, according to *"Section: Engine supply systems – Crankcase vent and tank vent"*.

Lube oil preheating

Preheating the lube oil to 40 °C is effected by the preheater of the separator via the free-standing pump. The preheater must be enlarged in size if necessary, so that it can heat the content of the service tank to 40 °C, within 4 hours.

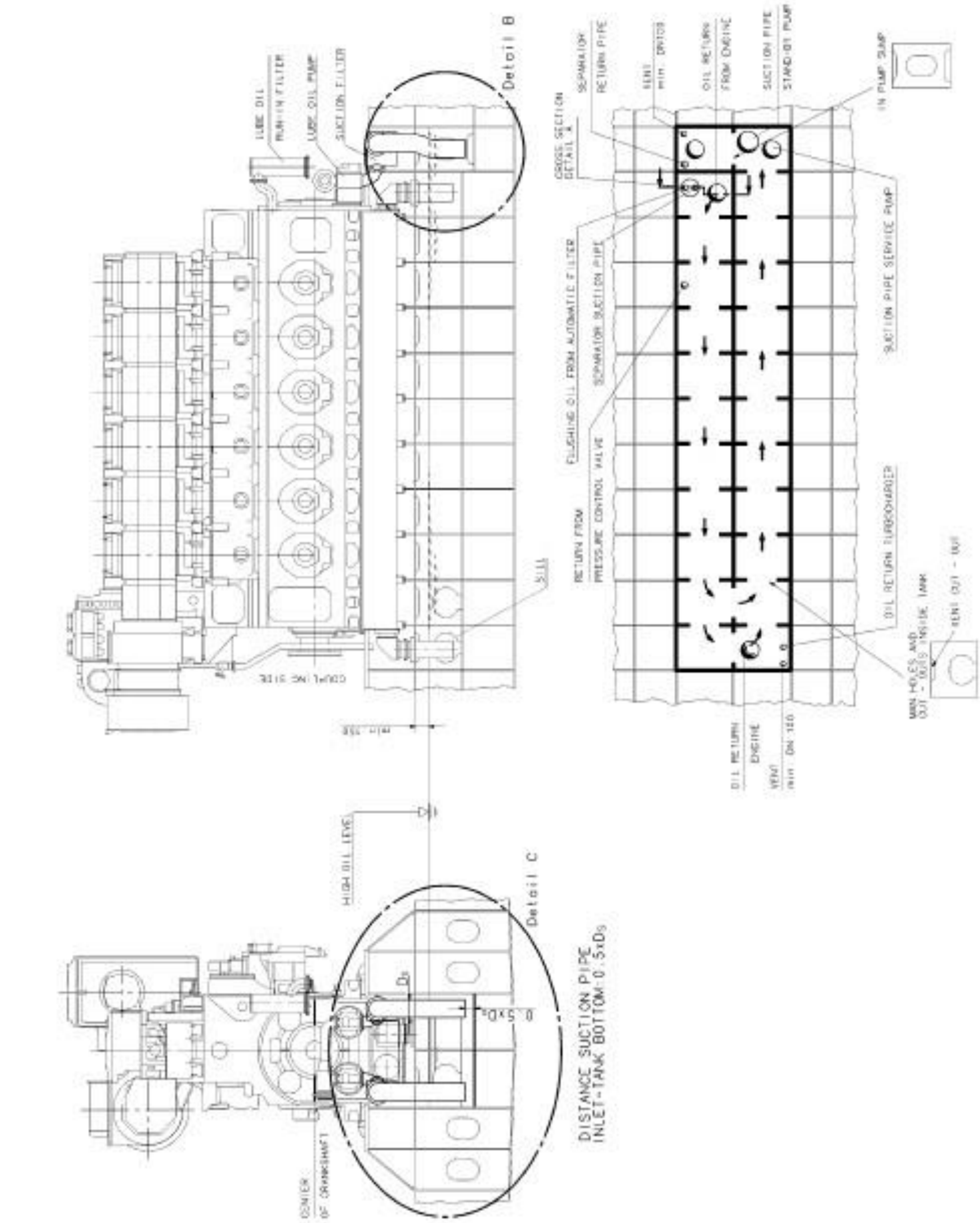

Figure 5-8 *Lube oil service tank_1*

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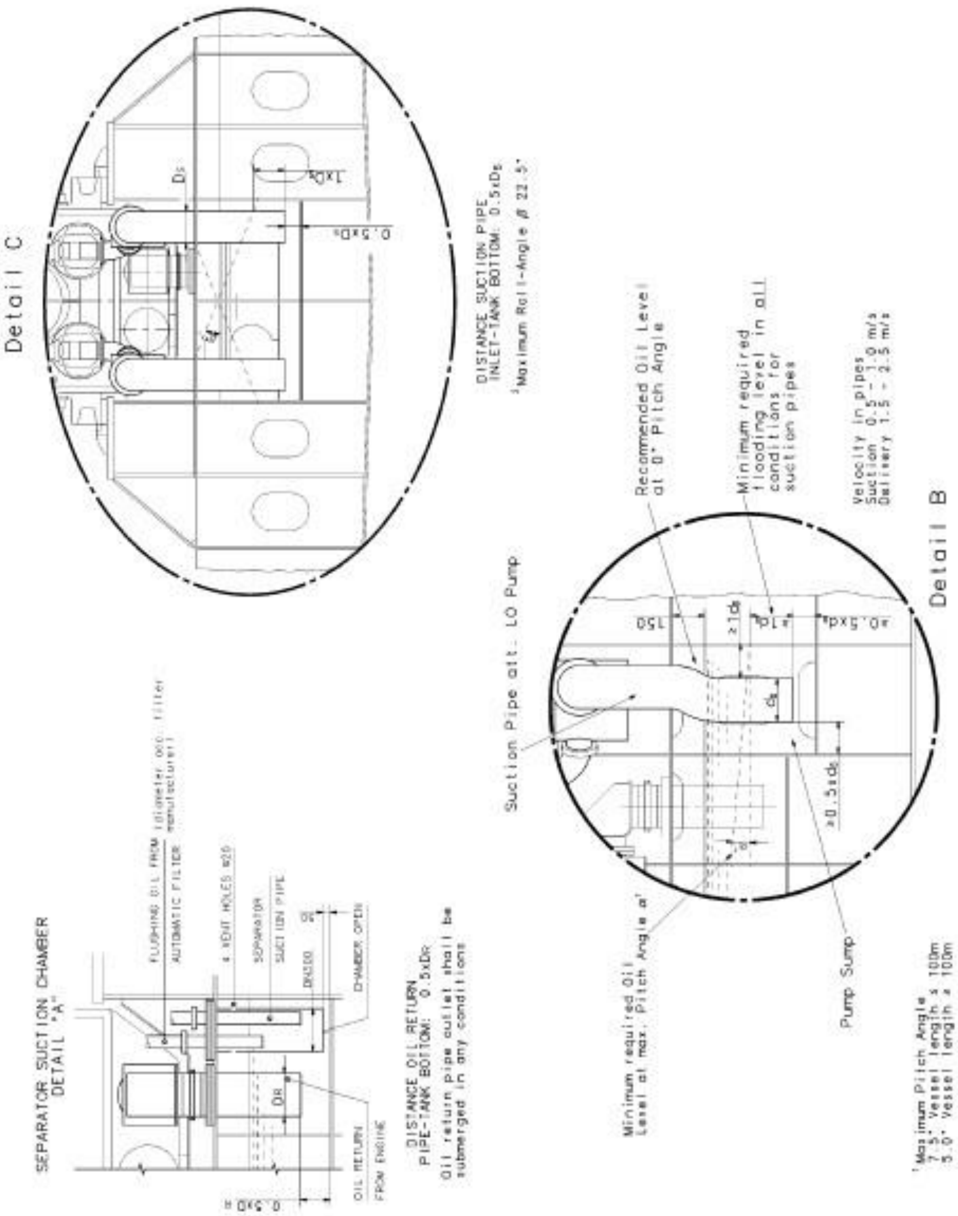


Figure 5-9 *Lube oil service tank_2*

Appendix E Fincantieri CFD

The Appendix is available at NSIA's website.

Appendix F SINTEF Ocean CFD

The Appendix is available at NSIA’s website.

Appendix G Lloyd's Register CFD

The Appendix is available at NSIA's website.

Appendix H Beaufort wind scale

Wind				
Force – Beaufort scale	Wind speed		Description	
	knots	m/s	Norwegian	English
0	> 1	0.0–0.2	Stille	Calm
1	1–3	0.3–1.5	Flau vind	Light air
2	4–6	1.6–3.3	Svak vind	Light breeze
3	7–10	3.4–5.4	Lett bris	Gentle breeze
4	11–16	5.5–7.9	Laber bris	Moderate breeze
5	17–21	8.0–10.7	Frisk bris	Fresh breeze
6	22–27	10.8–13.8	Liten kuling	Strong breeze
7	28–33	13.9–17.1	Stiv kuling	Near gale
8	34–40	17.2–20.7	Sterk kuling	Gale
9	41–47	20.8–24.4	Liten storm	Strong gale
10	48–55	24.5–28.4	Full storm	Storm
11	56–63	28.5–32.6	Sterk storm	Violent storm
12	64–	32.7–	Orkan	Hurricane

Appendix I Lloyd's Register Plan Approval Circular

Plan Approval Circular

20 July 2020 **PAC 2020/05**

FOR INTERNAL USE ONLY

Effective: **1 August 2020**

Supersedes: **NA**

Title: **Design appraisal of main and essential auxiliary machinery for operation under conditions of static and dynamic inclination**

Prepared: [redacted]	Reviewed: [redacted]	Approved: [redacted]

1. Application

1.1. This Plan Approval Circular (PAC) applies to the design appraisal of main and essential auxiliary machinery for operation under conditions of static and dynamic inclination.

2. Background

2.1. The Rules require that main and essential auxiliary machinery is to operate satisfactorily under defined angles of inclination, in particular:

- *Rules and Regulations for the Classification of Ships - Pt 5, Ch 1, 3.7 Inclination of ship*
- *Rules and Regulations for the Classification of Special Service Craft - Pt 9, Ch 1, 4.2 Inclinations of the craft*
- *Rules and Regulations for the Classification of Naval Ships - Vol 2, Pt 1, Ch 3, 4.6 Inclination of ship*
- *Rules and Regulations for the Classification of Offshore Units - Pt 5 Ch 1, 2.1 Inclination of unit*

2.2. In accordance with SOLAS II-1/Regulation 26.6, main and essential auxiliary machinery is that deemed to be essential to the propulsion and safety of the ship.

2.3. For satisfactory operation in service, it is necessary that:

a) the item of machinery is capable of operating satisfactorily at the defined angles of inclination; and
b) that the item of machinery is installed in accordance with the machinery manufacturer's instructions, recommendations or guidance relating to operation when inclined.

2.4. Verification of the requirement during design appraisal is generally based on review of documentation, submitted by the machinery manufacturer, confirming that the machinery is capable of operation under the defined angles of inclination in accordance with 2.3.a) above.

2.5. Unless notified otherwise by the shipyard, it is expected that the machinery is installed in accordance with the machinery manufacturer's instructions, recommendations or guidance in accordance with 2.3b) above without further design appraisal.

Lloyd's Register

Published by Rules & Procedures Publishing Team, Technical Policy Group

2.6. Recent in-service experience however suggests that verification of the requirement during design appraisal needs to positively establish that both 2.3.a) and 2.3.b) above are satisfied.

3. Requirements

3.1. With immediate effect, design appraisal of main and essential auxiliary machinery for operation under the conditions of static and dynamic inclination defined in the Rules is to establish that:

a) the item of machinery is capable of operating satisfactorily at the defined angles of inclination; and

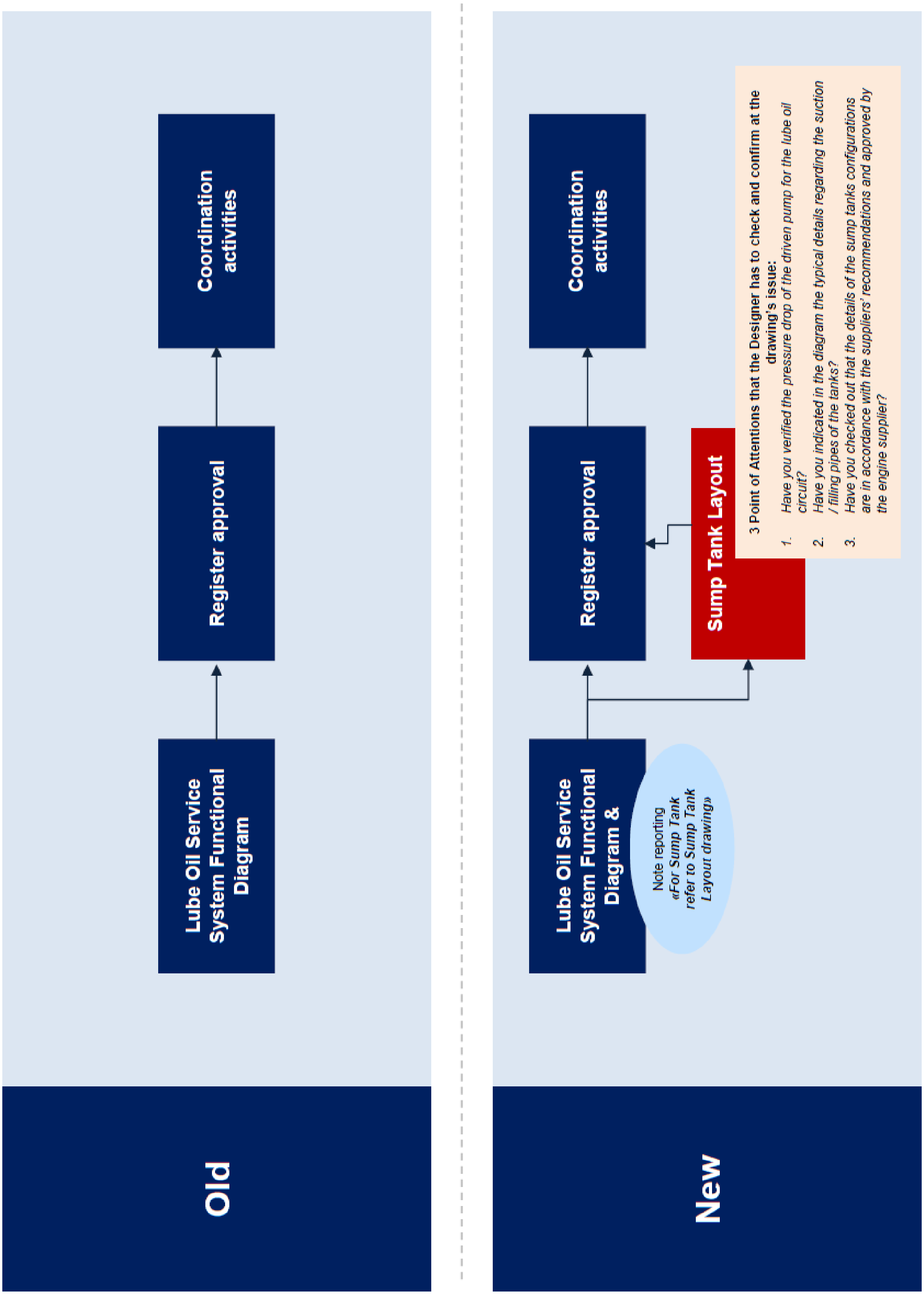
b) that the item of machinery is to be installed in accordance with the machinery manufacturer's instructions, recommendations or guidance relating to operation when inclined.

3.2. Where not apparent from information submitted, a written confirmation should be requested from the shipyard.

4. Effective date

4.1. This Plan Approval Circular is effective 1 August 2020.

Appendix J Fincantieri, revised design process – flow chart



Appendix K CVP-101 – Instruction on sump tank filling levels

Wilhelmsen

CVP-101
Rev. 10/20

Viking Ocean Cruises
Diesel Generator - Lub. Oil Levels

Normal condition					
sump tank name:	sump tank for:	minimum level engine running		Corresponding level engine stopped	
		cm	m^3	cm	m^3
6 PORT	DG 1	53	5.6	60	6.4
6 STBD	DG 2	58	6.9	67	8.1
5 PORT	DG 3	58	7.0	67	8.2
5 STBD	DG 4	53	5.6	60	6.4

- routine manual sounding: 4 X sounding >> average
- manual sounding value to be enterred in CVE-100 & Engine Logbook

note: normal top-up quantity - 200 ~ 300 ltr (0.2 ~ 0.3 m^3)

sump tank name:	sump tank for:	recommended filling level **heavy weather** with engine running	
		cm	m^3
6 PORT	DG 1	62	6.6
6 STBD	DG 2	67	8.1
5 PORT	DG 3	67	8.2
5 STBD	DG 4	62	6.6

note: Sump overflow risk to be evaluated and mitigated prior stopping engine

Level Alarm Settings	**DG1**	**DG2**	**DG3**	**DG4**
	m3	m3	m3	m3
HH	6.8	8.4	8.5	6.8
H	6.5	7.7	7.8	6.5
L	4.5	5.9	6.0	4.9
LL	4.2	4.8	4.9	4.6

Position on board: Engine Control Room

Appendix L CVE-100 – Change of Watch form

CVE-100
Rev. 09/22

WILHELMSEN SHIP MANAGEMENT

VOC ENGINE – CHANGE OF WATCH FORM
(Ref. OMCV 7.15)

Date (DD-MM-YY)		Change of Watch (hh:mm)	

Running DG's	1	2	3	4

Running RO's	Fwd	Aft

Running EVAP'S	Fwd	Aft	SOx Scrubber	Fwd	Aft	Boiler	Fwd	Aft

Running HFO SEP	1	2	3	4

Running MGO SEP	Fwd	Aft

Running LUB SEP	1	2	3	4	Running INCINERATOR	1

Running AC Chillers	1	2	3	4

Fresh Water	PW 12P	PW 12S	PW 13C	PW 13P	PW 13S	PW 14C	PW 14P	PW 14S	DW 05C	DW 06C
Production/ bunkering										
Consumption										

Stabilizers Mark if they are In (I) or out (O)	0/I
Port	
Starboard	

GW/Bilge	Over board	Holding tank
Bilge Sep.		
Scanship		

NM	Inside	Outside
12		
4		

HFO/ MGO Consumption	HFO 10P	HFO 11P	HFO 11S	MGO 02P	MGO 02S	MGO 04P	MGO 10S

FWD Engine room		AFT Engine room	
HFO	MGO	HFO	MGO

Lub. oil sump tank levels (manual soundings)		
DG 1 / 6P		(min. 5.6m³)
DG 2 / 6S		(min. 6.9m³)
DG 3 / 5P		(min. 7.0m³)
DG 4 / 5S		(min. 5.6m³)

Remarks / Work in progress:

Relived EOW (sign)

Relieving EOW (Sign)

Appendix M CVP-100 – Blackout recovery procedure

WILHELMSEN SHIP MANAGEMENT CVP-100 REV 12/19

Black Out Recovery Procedure

Condition: All DGs are in auto mode and have stopped or disengaged.
Indication: The system fails to auto restart and restore DG power within 2 minutes.
Objective: Restore sufficient DG power for propulsion and essential systems.

The Chief Engineer or Engineer on Duty should coordinate this procedure from the ECR.

1) If the emergency generator does not start within 5 seconds, send somebody up to trouble shoot and try to start it
2) Keep the bridge regularly informed of the progress
3) Establish communication with engineer(s) attending engines locally
4) Open PMS screen page 3.12 DG BLOCKING
   a) Check for active start blockings
   b) If needed, correct problems

Note: PMS screen 3.13 DG SHUTDOWN and 3.14 DG LOAD DOWN could help to troubleshoot.

5) Clear start blockings in:
   a) MAN Local Operating Panel (LOP)
   b) PMS

Note: Reset MAN LOP alarms before resetting PMS alarms.

Caution: *Do not try to connect a DG before clearing blocking alarms. DGs will shut down again if detecting blocking alarms.*

6) Tell electricians to reset any active alarms locally on forward and aft main switchboard breakers

Note: Connecting the bus tie breaker with active alarms can cause another shut down. If in doubt, consider keeping the bus tie breaker open.

7) Make sure available DGs are in auto mode
8) If the auto start sequence does not engage after 30 seconds:
   a) Set one DG in local mode on MAN LOP
   b) Verify or set local mode in PMS
   c) Start the DG manually

Note: It is best to start DG2 or DG3 first but consider the condition of the DGs and then decide.

   d) If needed, connect one DG manually
      - Adjust RPM
      - Adjust voltage

Warning!
Do not switch DGs to auto before clearing all start blocks. This avoids new shut downs.

Note: Discuss with the bridge and find the best option for how to proceed.
We may start propulsion carefully even with only one DG.

9) Prepare propulsion
   a) Transfer propulsion control to ECR
   b) Set propulsion to zero

Note: Focus on one propulsion line first.

10) Clear any active propulsion alarms:
   a) On local alarm panels
   b) On PMS
11) Confirm propulsion is ready for start
12) Start one propulsion line

Caution: *Do not exceed DG load capabilities. Start with DEAD SLOW and coordinate load carefully with the bridge.*

13) Make sure essential equipment has connected automatically
   a) If needed, consider if it is safe to connect equipment manually
14) Continue trouble shooting
15) If needed, start and connect additional DGs

■■ Completed ■■

Position on board: ECR

Appendix N MAN statement

MAN Energy Solutions

MAN Energy Solutions SE, 86224 Augsburg, Germany

To whom it may concern

Augsburg, 15 Decemberr 2023

Ref. LO- Level- Viking Ocean Cruises

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Viking Ocean Vessels – Lube Oil Level in Sump Tanks

Dear Customer,

In agreement with MAN ES, the Operator of the Viking Ocean Vessels, Wilhelmsen Ship Management, has operated for more than 4 years all engines across the Fleet with increased Lubricating Oil levels. Each engine sump tank has been filled to such a level that the air gap between Lubricating Oil and upper tank frame was reduced to a minimum of 80mm in heavy weather (LO De-foaming space).

Herewith MAN ES confirms, that since start of the above mentioned procedure in 2019 up to now, no irregularities in the lubricating oil supply to the engines have been observed nor any damages have occurred to the engines themselves or the attached lubricating oil auxiliaries.

Consequently, MAN considers that such an increased lubricating oil level with a reduced air gap level is not disturbing the reliable operation of the engines.

Yours sincerely,
MAN Energy Solutions

[redacted]
Head of Project management
MAN ES PrimeServ O&M

[redacted]
Project manager
MAN ES PrimeServ O&M