TECHNICAL REPORT

KYSTVERKET NORWEGIAN COASTAL ADMINISTRATION

SALVAGE OF U864 - SUPPLEMENTARY STUDIES - STUDY NO. 1: CORROSION

REPORT NO. 23916-1

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DET NORSKE VERITAS

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TECHNICAL REPORT

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Summary:

The German submarine U-864 was torpedoed by the British submarine Venturer on February 9 1945 and sunk approximately two nautical miles west of the island Fedje in Hordaland. U-864 was carrying about 67 metric tonnes of metallic mercury that implies a threat to the marine environment. In September 2007 The Norwegian Costal Administration commissioned Det Norske Veritas to further investigate different alternatives to salvage the wreck and remove the mercury from the seabed.

The main objectives of the study have been to assess the corrosion degradation of steel containers for mercury still located in the keel of U-864 and of those containers which were not fractured during the explosions and became partly or fully embedded in seabed sediments. In addition, the effect of corrosion on the structural integrity of the hull in case of salvage was to be assessed.

DNV's main conclusion is: It is not expected that damage by corrosion will affect the overall integrity of the hull during salvage within the next ten years, or that corrosion has caused any significant increase in mercury contamination of the sediments. Capping will reduce future corrosion rate of the containers. Further exposure will eventually lead to penetration of mercury containers but accumulation of corrosion products is expected to largely encapsulate the mercury.

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The German submarine U-864 was torpedoed by the British submarine Venturer on February 9 1945 and sunk approximately two nautical miles west of the island Fedje in Hordaland. U-864 was carrying about 67 metric tonnes of metallic mercury that implies a threat to the marine environment.

In September 2007 The Norwegian Costal Administration commissioned Det Norske Veritas to further investigate different alternatives to salvage the wreck and remove the mercury from the seabed.

1 SUMMARY

This report is *Supplementary Study No. 1: Corrosion,* one of twelve supplementary studies supporting the overall report regarding U-864 (Det Norske Veritas Report No. 23916) prepared by Det Norske Veritas (DNV).

The main objectives of the study have been to assess the corrosion degradation of steel containers for mercury still located in the keel of U-864 and of those containers which were not fractured during the explosions and became partly or fully embedded in seabed sediments. The present condition and the future development of corrosion of these objects were to be considered to assess if or when these containers will start leaking mercury as a result of corrosion. In addition, the effect of corrosion on the structural integrity of the hull in case of salvage was to be assessed.

Of the two mercury containers retrieved and examined, the one fabricated by welding of steel plate material had developed a pinhole leak in a weld, whilst the other type in forged steel had an 80% local reduction in wall thickness (initially 5 mm) that most likely would have developed a pinhole leak within 10-20 years if left on the seabed. Both areas have been exposed to shallow marine sediments promoting corrosion attack by 'Microbiologically Induced Corrosion' (MIC) probably associated with Sulphate Reducing Bacteria (SRB).

For mercury containers stored in flooded compartments of the keel and without convective exchange of seawater, the corrosive conditions are less severe and it is assumed that few containers, if any at all, have developed leaks due to corrosion. Even if containers have been locally penetrated by corrosion, accumulation of corrosion products will retard leakage of mercury, especially for containers embedded in sediments.

Capping of the wreck could initially stimulate bacterial activity, and hence increase corrosion by supply and/or redistribution of organic material. However, after one or a few years, the instantaneous supply of organic materials has been used up and supply of new organic material is prevented by the capping. This should gradually reduce the average corrosion rate to the order of 0.01 mm/yr. Eventually, the wall of the containers may still become penetrated by corrosion but a scale of corrosion products and mineral particles will form and more or less' encapsulate' the liquid mercury that has not yet reacted with seawater forming a barely soluble compound as mercury chloride.

DNV's overall conclusion is:

It is not expected that damage by corrosion will affect the overall integrity of the hull during salvage within the next ten years, or that corrosion has caused any significant increase in mercury contamination of the sediments. Capping will reduce future corrosion rate of the containers. Further exposure will eventually lead to penetration of mercury containers but accumulation of corrosion products is expected to largely encapsulate the mercury.

DNV's supporting conclusions are:

C1. **The corrosion of the forged container was localised and related to bacterial activity in the seabed (MIC) and with an average (60 years') corrosion rate of 0.07 mm/yr. On other areas, the average corrosion rate was 0.02 mm/yr or less. (This container had not developed any leakage)**

C2. **The corrosion rate of the welded container for mercury (related to MIC) was more or less uniform with an average corrosion rate estimated to 0.03 mm/yr. A pinhole leakage had developed in a weld.**

C3. **The steel cylinder for pressurised air was severely corroded (by MIC) as both uniform and localised corrosion attack with an average corrosion rate estimated to 0.05 mm/yr and 0.12 mm/yr, respectively. The cylinder wall had been penetrated by corrosion.**

C4. **It is estimated that the maximum average corrosion rates of structural steel components of the hull freely exposed to steel and exposed to stagnant water in closed compartments are 0.04 mm/yr and 0.02 mm/yr, respectively.**

C5. **As per today, any contribution of corrosion on mercury contamination of the seabed is marginal; i.e. compared to the effects of the initial explosion(s) expected to have caused fracturing of mercury containers**

C6. **Capping will reduce future corrosion rate of the containers. Eventually, the wall of the containers may become penetrated by corrosion but a scale of corrosion products and mineral particles will form and more or less 'encapsulate' the liquid mercury.**

C7. **The current amount of leaking mercury due to corrosion is expected to be minimal. Mercury containers freely exposed to seawater may have developed pinhole leaks.**

C8. **It is not expected that local damage due to corrosion will affect the overall integrity of the hull during salvage.**

C9. **After capping the overall residual rate of corrosion on the hull is expected to decrease to the order of 0.01 mm/yr**

The rest of *Supplementary Study No. 1: Corrosion* details the arguments behind the conclusions.

Den tyske ubåten U-864 ble torpedert av den britiske ubåten Venturer den 9. februar 1945 og sank omtrent to nautiske mil vest for øya Fedje i Hordaland. U-864 var lastet med omtrent 67 tonn med metallisk kvikksølv som utgjør en fare for det marine miljøet.

I September 2007 tildelte Kystverket Det Norske Veritas oppdraget med å nærmere utrede ulike alternativer for heving av vrak og fjerning av kvikksølv fra havbunnen.

2 SAMMENDRAG

Denne rapporten er *Tilleggsutredning nr. 1: Korrosjon*, en av tolv tilleggsutredninger som understøtter hovedrapporten vedrørende U-864 (Det Norske Veritas Report No. 23916) utarbeidet av Det Norske Veritas (DNV).

Det viktigste formålet med studien har vært å bedømme korrosjonsskadene på de stålbeholderne som inneholder metallisk (flytende) kvikksølv, som fortsatt er til stede i kjølen på U-864, og til de beholderne som ikke ble oppsprekket av eksplosjonene ved torpederingen, men ble spredt ut omkring vraket og som er helt eller delvis innleiret i sedimenter. Nåværende og fremtidig utvikling av korrosjonen på disse beholderne skal analyseres for å vurdere om eller når beholderne kan komme til å lekke kvikksølv grunnet korrosjon. I tillegg skal effekten av korrosjon på mekanisk reststyrke til skroget ved en eventuell heving vurderes.

Av de to beholderne for kvikksølv som var blitt hentet opp, hadde den som var laget av sveiste stålplater en lekkasje i form av et lite hull i en sveis (helt eller delvis forårsaket av korrosjon), mens den som var smidd hadde et mindre korrodert område med opp til 80 % reduksjon av opprinnelig veggtykkelse (antatt 5mm), som i løpet av 10-20 år sannsynligvis vil utvikle seg til en lekkasje. Begge områdene med korrosjon hadde vært tildekket av sedimenter og har dermed vært utsatt for mikrobiell korrosjon, mest sannsynlig av sulfat-reduserende bakterier (SRB). For de kvikksølv beholderne som fortsatt er på plass i kjølen med innelukket sjøvann, vil de korrosive betingelsene være mindre, og det antas at få eller ingen beholder har utviklet lekkasje som følge av korrosjon. Også om enkelte beholder skulle ha blitt lokal penetrert av korrosjon, og spesielt for de som er tildekket av sedimenter, vil akkumulering av korrosjonsprodukter på ståloverflaten motvirke en lekkasje av kvikksølv til omgivelsen.

En tildekking av vraket vil initialt kunne stimulere bakterievekst og dermed korrosjon ved tilførsel av organisk material. Derimot etter noen tid, når den initiale tilførselen av organisk material er blitt konsumert, vil aktiviteten bli lavere enn før tildekkingen fordi tilførsel av nytt organisk material vil forhindres. Det antas da at korrosjonen vil reduseres til i størrelsesorden 0,01 mm/år.

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DNV sin overordnede konklusjon er:

Det er ikke forventet at skade som følge av korrosjon vil påvirke integriteten til skroget ved heving i løpet av de neste ti år, eller at korrosjon har forårsaket signifikant økning av kvikksølvkontamineringen av bunnsedimenter. Tildekking vil redusere fremtidlig korrosjon av kvikksølvbeholderne. Ytterligere eksponering vil med tiden gi penetrering av beholderne, men akkumulering av korrosjonsprodukter på overflaten vil derved innkapsle kvikksølvet.

DNV underbygger denne konklusjonen med:

C1. **Korrosjonsangrep på den smidde beholderen for kvikksølv var lokal og forårsaket av bakteriell aktivitet i det øvre sedimentlaget på havbunnen. Gjennomsnittlig korrosjonshastighet (for 60 års eksponering) har i dette området vært 0,07 mm/år, mens den på andre områder av beholderen har vært maks. 0,02 mm/år. Denne beholderen har ikke utviklet noen lekkasje.**

C2. **Korrosjonsangrepet på den sveiste beholderen for kvikksølv (også forårsaket av bakterier) var stort sett jevn med en gjennomsnittlig estimert hastighet 0,03 mm/år. Et punktformet hull hadde utviklets seg i en sveis.**

C3. **Den smidde beholderen for trykkluft var forholdsvis sterkt korrodert (også bakteriekorrosjon). Korrosjonen som var både lokal og jevn hadde en estimert middelverdi på 0,05 mm/år og 0,12 mm/år for jevn respektive lokal korrosjon. Beholderen var perforert av korrosjon.**

C4. **Det ble estimert at strukturelle komponenter på skroget som er vært fritt eksponert for sjøvann har hatt en middels korrosjonshastighet som har vært maksimalt 0,04 mm/år, mens den for komponenter eksponert for innelukket stagnant sjøvann har vært maksimalt 0,02 mm/år.**

C5. **Bidraget til kvikksølvforurensingen av sjøbunnen pga korrosjon av beholderne antas å være marginal sammenlignet med den kontaminering som oppstod ved eksplosjonen(e) i forbindelse med torpederingen.**

C6. **Tildekking vil redusere fremtidlig korrosjon av kvikksølvbeholderne. Med tiden vil beholderne kunne bli gjennomtæret av korrosjon, men et skall av korrosjonsprodukter og mineralpartikler vil dannes og mer eller mindre 'innkapsle' kvikksølvet.**

C7. **Den eksisterende lekkasjen av kvikksølv som følge av korrosjon er forventet å være minimal. Kvikksølvbeholdere som er fritt utsatt for sjøvann kan ha utviklet lokal punktlekkasje. Andre beholdere er forventet å være tette.**

C8. **Det er ikke forventet at lokal skade som følge av korrosjon vil påvirke den overordnede integriteten til skroget ved heving.**

C9. **Etter tildekking er den gjenværende korrosjonsraten på skroget forventet å avta til 0.01 mm/år.**

Resten av *Tilleggsutredning nr. 1: Korrosjon* utdyper argumentene bak konklusjonene.

3 INTRODUCTION

3.1 Background

The German submarine U-864 was sunk by the British submarine Venturer on 9 February 1945, approximately 2 nautical miles west of the island Fedje in Hordaland (Figure 3-1). The submarine was on its way from Germany via Norway to Japan with war material and according to historical documents; U-864 was carrying about 67 metric ton of metallic (liquid) mercury, stored in steel canisters in the keel. The U-864, which was broken into two main parts as a result of the torpedo hit, was found at 150-175 m depth by the Royal Norwegian Navy in March 2003. The Norwegian Costal Administration (NCA) has, on behalf of the Ministry of Fisheries and Coastal Affairs, been performing several studies on how the risk that the mercury load constitutes to the environment can be handled. In December 2006 NCA delivered a report to the Ministry where they recommended that the wreck of the submarine should be encapsulated and that the surrounding mercury-contaminated sediments should be capped. In April 2007 the Ministry of Fisheries and Coastal Affairs decided to further investigate the salvaging alternative before a final decision is taken about the mercury load.

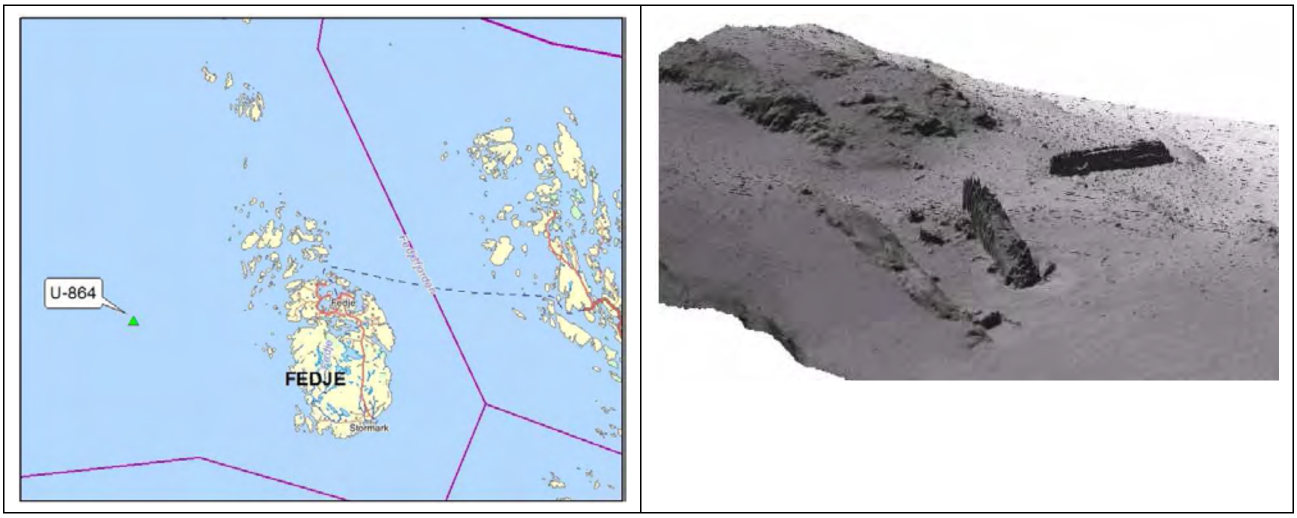

Figure 3-1 Location (left) and a sonar picture of the wreck of U-864 on seabed (right) (from Geoconsult).

3.2 DNV's task

In September 2007 NCA commissioned Det Norske Veritas (DNV) the contract to further investigate the salvaging alternative. The contract includes:

- DNV shall support NCA in announcing a tender competition for innovators which have suggestions for an environmentally safe/acceptable salvage concept or technology. Selected innovators will receive a remuneration to improve and specify their salvage concept or technology.

- DNV shall support NCA in announcing a tender competition for salvage contractors to perform an environmentally justifiable salvage of U-864.
- DNV shall evaluate the suggested salvage methods and identify the preferred salvage method.
- The preferred salvage method shall be compared with the suggested encapsulation/capping method from 2006. (DNV shall give a recommendation of which measure that should be taken and state the reason for this recommendation.)
- DNV shall perform twelve supplementary studies which will serve as a support when the decision is taken about which measure that should be chosen for removing the environmental threat related to U-864. The twelve studies are:

1. *Corrosion*. Probability and scenarios for corrosion on steel canisters and the hull of the submarine.
2. *Explosives.* Probability and consequences of an explosion during salvaging from explosives or compressed air tanks.
3. *Metal detector*. The possibilities and limitations of using metal detectors for finding mercury canisters.
4. *The mid ship section*. Study the possibility that the mid section has drifted away.
5. *Dredging*. Study how the mercury-contaminated seabed can be removed around the wreck with a minimum of spreading and turbidity.
6. *Disposal*. Consequences for the environment and the health and safety of personnel if mercury and mercury-contaminated sediments are taken up and disposed of.
7. *Cargo.* Gather the historical information about the cargo in U-864. Assess the location and content of the cargo.
8. *Relocation and safeguarding.* Analyse which routes that can be used when mercury canisters are relocated to a sheltered location.
9. *Monitoring.* The effects of the measures that are taken have to be documented over time. An initial programme shall be prepared for monitoring the contamination before, during and after salvaging.
10. *Risk related to leakage.* Study the consequences if mercury is unintentionally leaked and spreading during a salvage or relocation of U-864.
11. *Assessment of future spreading of mercury for the capping alternative*. The consequences of spreading of mercury if the area is capped in an eternal perspective.
12. *Use of divers.* Study the risks related to use of divers during the salvage operation in a safety, health and environmental aspect and compare with use of ROV.

3.3 Scope of this report

This report is *Supplementary Study No. 1: Corrosion.*The mercury had been stored in steel containers in the keel of U-864. Some of the containers were fractured as a result of the torpedoing, resulting in extensive contamination of the seabed around the wreck. However, a main part of the containers are believed to be more or less intact in those parts of the keel that were not damaged, whilst some further intact containers are assumed to be distributed around the wreck. During the surveys on U-864 by Geoconsult and by KMT Tyr, two containers for mercury and one cylinder for pressurised gas (first believed to contain mercury) were retrieved. Efforts to examine the keel for the status of remaining mercury containers had to be interrupted when the hull section examined showed signs of instability.

3.3.1 Objectives

According to the invitation to tender (3.2.1), the main objectives of this study are:

- Assess long term corrosion of steel in seawater and in marine sediments (chapter 4)
- Examination of objects retrieved from seabed sediments around the hull of U-864 (chaper 5)
- Assessment of present and future corrosion degradation of hull and mercury containers (chapter 6)

3.3.2 Scope

The scope has included the following activities:

- Review of previously prepared documents containing information on corrosion of the hull and objects retrieved from U-864.
- Review of video recordings of the hull.
- Review of photographic documentation from the salvage (1993) and later exposition of U-534 which was sunk in Skagerak in 1944.
- Examinations of objects retrieved from U-864 in 2006, including a forged steel container for mercury, a welded container for mercury and a cylinder for pressurised air.
- Review of literature and DNV in-house experience on the long-term corrosion degradation of steel in seawater and in marine sediments.

Some assessments of the corrosion degradation of components in steel and other alloys associated with the U-864 torpedoes are contained in *Supplementary Study No.2: Explosives*.

4 LONG TERM CORROSION OF STEEL IN SEAWATER AND IN MARINE SEDIMENTS

4.1 General

When a steel surface is exposed to seawater, corrosion degradation will start almost instantaneously, unless:

- the steel surface is efficiently shielded from the corrosive environment by a protective coating (organic or metallic), or
- cathodic protection is applied, or
- the steel component is in a special alloy making it resistant to corrosion by seawater for a limited or extended period of time.

It is probable that the seawater exposed hull of U-864, being fabricated in a weldable C-steel, had a corrosion protective coating specially designed for marine applications. The mercury containers may also have had some coating but hardly of a type suited for long term exposure to a marine environment. The coating applied on seawater exposed hull areas (including internal ballasting tanks) was probably based on a synthetic or vegetable oil and as such subject to biodegradation in seawater and in upper parts of marine sediments. Still, depending of the type of coating and coating application parameters (number of coating layers, total thickness, etc.), areas with largely intact coating after the sinking of U-864 may have been protected from general corrosion for a period of one or more decades. In case the mercury containers were coated, the coating may have had some significant effect on containers contained in any flooded but otherwise still intact compartments in the keel but hardly on any surfaces with 60 years' free exposure to seawater or marine sediments outside the hull. It is expected that after 60 years of exposure, there are hardly any remainders of coating significantly affecting the future corrosion degradation of the hull or the mercury containers.

4.2 Corrosion Forms and Mechanisms of Steel in Seawater

Corrosion degradation of rolled, forged or cast C-steel surfaces freely exposed to seawater is generally rather uniform in character; i.e. unless the corrosion reflects the degradation of a corrosion protective coating. On the other hand, it is not uncommon that welds are preferentially attacked. This was previously related to 'galvanic effects' between a 'less noble' weld and a 'more noble' base material. However, there is increasing evidence that this preferential corrosion is rather due to the microstructure of welds being more susceptible than that of rolled surfaces. Galvanic corrosion may result from metallic coupling of a C-steel surface to a component in e.g. a Cu-base alloy or a stainless steel. If the surface area ratio 'more noble' (i.e. higher free corrosion potential in seawater) to 'less noble' (i.e. lower free corrosion potential in seawater) is large (one or higher), the corrosion rate may become quite high, especially during an initial exposure to seawater when the surface of the 'more noble' component is largely free from corrosion products and marine growth. For 'galvanic corrosion' of steel in seawater, the corrosion attack of rolled, forged or cast surfaces is typically uniform; however, any welds of rolled material may suffer selective corrosion attack as referred to above. Another possible factor affecting the form and rate of corrosion of C-steel in seawater is abrasion between any sliding surfaces as for suspended anchor chains in constant motion (‘abrasion corrosion’). As a result of the continuous removal of corrosion products and any other corrosion retarding deposits in such areas, very high local corrosion rates (of the order of 1 mm/year) may be obtained. However, no such conditions apply for the components being considered in this study.

For C-steel surfaces exposed to sediments, any corrosion will typically occur as scattered single or colonies of *pits* with a rather shallow depth (depth typically 1/3 to 1/5 of the diameter of the pit). Occasionally the pits overlap to form grooves or larger surfaces with more uniform attack. This form of corrosion is typical for *Microbiologically Induced Corrosion* (MIC).

Another corrosion form for steel in seawater is cracking related to corrosion in combination with either static stresses (‘stress corrosion cracking’) or cyclic stresses (‘corrosion fatigue’). As to stress corrosion cracking, the C-steel materials used for structural components of the hull and the mercury container are not susceptible when exposed to seawater or marine sediments and there are no cyclic stresses imposed that could lead to corrosion fatigue. ‘Deep pitting’ (i.e. depth larger than the pit diameter) is very unlikely to occur for the components and materials being considered.

Although not a corrosion mechanism per definition, mercury may cause ‘liquid metal embrittlement’ of certain metals and alloys, including aluminium base alloys; however, C-steel and other ferrous alloys are immune to this form of degradation.

Based on the considerations above, the forms of corrosion to be considered for structural components of the hull and the mercury containers are *uniform corrosion*, discrete or overlapping *shallow pitting* and further, *preferential weld corrosion* for those components that are welded. The latter corrosion may be either uniform or localised.

4.3 Corrosion Rates of Steel Surfaces Exposed to Seawater

The primary corrosive agent contained is seawater is oxygen. Depending on the temperature, seawater in equilibrium with air of atmospheric pressure dissolves about 6-9 ppm (weight) of oxygen. At large water depths, the oxygen content may diminish due to consumption by oxidation of organic matter and in certain seawater basins, narrow and deep fjords with little exchange of seawater, etc. it may become completely consumed and replaced by hydrogen sulphide from bacterial activity. In open waters of the North Sea, however, an oxygen concentration of 7-8 ppm extends to the sea bottom.

The initial corrosion of a bare C-steel surface exposed to seawater is determined by convective mass transfer of oxygen to the corroding surface being determined primarily by the flow rate of the seawater. During the first hours and days of corrosion, this initial corrosion may have a rate that corresponds to 1 mm/yr or even more. However, as a result of this initial corrosion, a thin rust layer is formed on the surface, retarding the further mass transfer of oxygen and hence, the rate of corrosion. The corrosion process is further affected by a microscopic biofilm consisting of oxygen consuming bacteria and later on, depending of depth and access of daylight, a algae, fungi plus hydroids, tube building amphipods, barnacles and other animal species eventually forming a macroscopic layer of marine growth eventually excluding any direct access of oxygen to the underlying steel surface. During the first year of exposure, the average corrosion rate is typically about 0.1 mm/yr. With further exposure, the corrosion rate gradually decreases further until a steady-state rate is reached after about 10 years of exposure and with a rate **consistently lower than 0.1 mm/yr**, eventually approaching a few hundreds of a millimetre per year; i.e. as a mean corrosion rate for a larger surface area. There is insufficient knowledge about the actual mechanism of this low residual corrosion but it is probable that it is primarily related to the metabolism of certain organisms in the macroscopic layer of biologic growth, possibly in combination with some residual oxygen reaching parts of the steel surface by diffusion.

In contrast, for C-steel exposed to a marine atmosphere (i.e. without any biologic growth), corrosion is only retarded by the accumulation of corrosion products ('rust') being subject to periodic spalling and erosive wear by wind and precipitation. Another factor affecting the corrosion degradation in marine atmospheres is the frequency and duration of periods without precipitation in combination with a low relative humidity, retarding corrosion by insufficient moisture in the rust layer and hence, low electrolytic conductivity at the steel surface. In marine atmospheres, the corrosion rate of C-steel is typically about 0.1 mm/yr. The highest corrosion rate is obtained in a 'splash zone' or 'tidal zone' were a steel surface is intermediately wetted by seawater followed by freely exposure to air. As a result of this, the mean long-term corrosion rate in this zone may readily amount to 0.3 mm/yr.

4.4 Corrosion Rates of Steel Surfaces Exposed to Seabed Sediments

Seabed sediments originate from three primary sources:

- Terrestrial and freshwater sources (inorganic and organic materials)
- Marine sources (e.g. calcareous and organic materials from marine organisms)
- Human activities (disposal of waist containing organic and/or non-organic materials)

In shallow sediments, steel surfaces will be exposed to some biologic activity which will vary considerably, especially in coastal areas such as fresh water estuaries and harbours. In such sediments, oxygen and hence 'aerobic bacteria' (i.e. oxygen consuming bacteria) will only occur in the uppermost layer (about 1-10 cm depending on the type of sediment and supply or organic materials) where the corrosive conditions for steel will be similar to those on surfaces with marine growth freely exposed to seawater. Deeper in the sediments where oxygen has been consumed but with supply of organic material, 'anaerobic bacteria' (using e.g. sulphate or nitrogen for their respiration in stead of oxygen) may cause corrosive conditions by their metabolism, whilst deeper down without supply of organic materials, steel surfaces do not suffer any significant corrosion degradation (the mean corrosion rate is expected to be of the order of **0.01 mm/yr** or less on average).

In the upper sediments with aerobic bacteria, corrosion of C-steel is mostly associated with *Sulphate Reducing Bacteria* (SRB). The detailed mechanism of Microbiolgically Induced Corrosion (MIC) associated with SRB is still disputed. Some theories are based on the cathodic corrosion reaction being hydrogen evolution stimulated by enzymes ('hydrogenase' type), organic acids or some corrosive phosphorous compound produced by SRB; other mechanisms are based on ferrous sulphide or other compounds formed by SRB and stimulating a cathodic reaction associated with reduction of oxygen. Irrespective of the corrosion mechanism, the corrosion form is discrete pits but more often colonies of partly overlapping shallow pits with a typical corrosion rate of some tenths of a millimetre per year. However, with ample supply of organic material (e.g. estuaries in shallow tropical waters, polluted harbour basins and depositions of drilling mud), the time averaged maximum corrosion rate may amount to **1 mm/yr** or even more; at least for a limited period of time (<10years). A more typical long term (> 10 years) corrosion rate in the North Sea would be of the order of **0.1 mm/yr**.

5 EXAMINATION OF OBJECTS RETRIEVED FROM SEABED SEDIMENTS AROUND THE HULL OF U864

5.1 Forged Container for Mercury

DNV's conclusion on this topic are:

C1. The corrosion of the forged container was localised and related to bacterial activity in the seabed (MIC) and with an average (60 years') corrosion rate of 0.07 mm/yr. On other areas, the average corrosion rate was 0.02 mm/yr or less. (This container had not developed any leakage)

The forged container (total height about 370 mm; external diameter about 140 mm) was subject to a detailed examination after retrieval in 2005, including visual examination and measurements of depth of corrosion, Magnetic Particle Investigation (MPI), testing of tensile properties and hardness, chemical analysis and examination of microstructure /1/. It was reported that about 40% of the container was covered by a thick layer of hard marine fouling. (It is assumed by DNV that this corresponds to area of the container being exposed above the seabed). Under this layer, there were no signs of significant corrosion. Visual signs of loss of wall thickness were, however, found in other areas (i.e. presumably those facing the seabed sediments) with a minimum residual thickness of 0.9 mm whilst the original thickness amounted to about 5 mm, corresponding to an average local corrosion rate of **0.07 mm/yr**. There were no signs of corrosion on internal surfaces of the container which still contained mercury when retrieved. MPI did not reveal any cracking. The measured hardness and yield strength was about HV 160 and 200 MPa, respectively and the tensile strength about 600 MPa. The chemical analysis showed 0.19C, 0.16Si, 0.66Mn, 0.040P, 0.032S, 0.13Ni and 0.06Cu. This analysis result is as expected for a 60 year old steel object.

The remainders of the container were examined by DNV in the offices of the Norwegian Coastal Administration (NCA) in Horten. Figs. 1 and 2 show segments which had been cut through the area with maximum corrosion that occurred in the form of overlapping shallow pits. (The external surfaces of the container had been grit blasted to remove corrosion products). Fig. 3 shows the top section of the container with its threaded plug. It was estimated that the average metal loss by corrosion was 1 mm maximum, corresponding to a mean corrosion rate (i.e. averaged for both time and total surface area) of maximum **0.02 mm/yr**. However, in the area covered by hard marine fouling, the corrosion rate has hardly exceeded **0.01 mm/yr**.

5.2 Welded Container for Mercury

DNV's conclusion on this topic are:

C2. The corrosion rate of the welded container for mercury (related to MIC) was more or less uniform with an average corrosion rate estimated to 0.03 mm/yr. A pinhole leakage had developed in a weld.

The container was in the form of a cylinder with an external diameter of about 130 mm and a height of 250 mm approximately. The shell had a longitudinal seam weld (width about 6 mm) and with the circular bottom and top plates welded to the shell. The top plate had an internally threaded opening welded to the plate (see Fig. 4). The container was examined by DNV in the offices of NCA in Horten. DNV has been informed by NCA that the container was found during dredging work and that it contained some seawater, in addition to mercury. It had not been cleaned from corrosion products and examined for corrosion damage. The corrosion products appeared to be quite uniformly distributed and there were no signs of any hard marine fouling; hence, it appeared that the whole container had been covered by sediments; see Figs 5-6. Without removal of the corrosion products, it was not practical to accurately estimate the average and maximum corrosion. However, examination indicated that the maximum local corrosion was less than on the forged container (which had a metal loss up to 4 mm) whilst the average corrosion rate may have been higher, possibly 2 mm giving a time averaged mean corrosion rate of about **0.03 mm/yr**.

There was no apparent preferential corrosion of the welds, although a leak had developed as a pore (about 3 mm in diameter) in the top plate to shell weld. It is assumed that this leak has been due to a local low thickness, possibly a crater pore of the weld in that area. A white deposit was observed in the leak area and in the threaded area of the top plate (see Fig. 5). It is assumed that this deposit is mercury chloride (HgCl or $HgCl_2$) formed by the reaction between metallic mercury and leaking seawater.

5.3 Steel Cylinder for Pressurised Gas

DNV's conclusion on this topic are:

C3. The steel cylinder for pressurised air was severely corroded (by MIC) as both uniform and localised corrosion attack with an average corrosion rate estimated to 0.05 mm/yr and 0.12 mm/yr, respectively. The cylinder wall had been penetrated by corrosion.

The steel cylinder was received for examination in the laboratories of DNV. It had a length of about 900 mm and a diameter of 200 mm approximately (Fig. 7). With a heavy deposit of corrosion products (ferric rust), it appeared uniformly corroded; however, the cylinder wall had been penetrated by corrosion at one location (Fig. 8). The flask appeared to be full with organic material. Ultrasonic examination showed an average residual thickness of the cylinder wall of about 3 mm and a maximum thickness of 5 mm. In comparison, a larger gas cylinder (shell diameter about 250 mm) had a thickness of 5 mm. Assuming that the initial shell thickness of the retrieved cylinder was 6 mm, the average uniform corrosion rate had been **0.05 mm/year**. Assuming that the cylinder was penetrated by corrosion 10 years ago, the local corrosion rate was as high as **0.12 mm/yr.**

5.4 Hull Structural Components

DNV's conclusion on this topic are:

C4. It is estimated that the maximum average corrosion rates of structural steel components freely exposed to steel and exposed to stagnant water in closed compartments are 0.04 mm/yr and 0.02 mm/yr, respectively.

A review of the photographic documentation of U-534 (on public display in Hartlepool, UK) shows that the hull structural components are in remarkable good condition. There is no information that corrosion damage to structural components caused any problems during the salvage. For plate and beam surfaces that had been freely exposed to seawater, it is a general estimate that the metal loss has not exceeded 2 mm, which gives a uniform corrosion rate of max. **0.04 mm/year**. Surfaces flooded by seawater but sheltered from convective supply of fresh seawater (internal tanks) appeared almost unaffected by corrosion and the average metal loss should then be max. **0.02 mm/yr.**

The video recordings of U-864 give a general impression of that the primary steel components visualised are in a 'good' condition but do not allow any quantitative estimates of loss of component thickness by corrosion.

A review of literature and data file on the long term corrosion of C-steel in seawater did not give much relevant information. However, in the October 2007 issue of Materials Performance /2/, there is a paper on the preservation of components from the USS *Monitor* which sunk in a storm off the coast of South Carolina in 1862. From 1998 and onwards, some major components of the vessel have been retrieved, including the gun turret in steel weighing about 120 tonnes. It is reported that "*The turret displayed limited evidence of corrosion damage*" and that the steel surfaces had been "*mineralised*" by corrosion products embedding particles of silt and hard marine fouling (also referred to as 'concretions'). The mean corrosion rates of the outer and inner surfaces of the turret were estimated to **0.04mm/year and 0.02 mm/year**, respectively. (The corrosion deterioration increased markedly after the retrieval as a result of free exposure to oxygen and with large amounts of salts and sulphur compounds contained in the corrosion product layer. A similar effect could be noticed on the photographic documentation of U-534).

6 ASSESSMENT OF PRESENT AND FUTURE CORROSION DEGRADATION OF HULL AND MERCURY CONTAINERS

6.1 Mercury Containers in the Keel and in the Surrounding Sediments

DNV's conclusions on this topic are:

C5. **As per today, any contribution of corrosion on mercury contamination of the seabed is marginal; i.e. compared to the effects of the initial explosion(s) causing fracturing of mercury containers**

C6. **Capping will reduce future corrosion rate of the containers. Eventually, the wall of the containers may become penetrated by corrosion but a scale of corrosion products and mineral particles will form and more or less 'encapsulate' the liquid mercury.**

C7. **The current amount of leaking mercury due to corrosion is expected to be minimal. Mercury containers freely exposed to seawater may have developed pinhole leaks. Other containers are expected to be closed.**

The two mercury containers that have been located and retrieved were of different types and it cannot be excluded that also other types have been used. The welded container had been penetrated by corrosion; however, only a small pinhole leak had developed and it is assumed that corrosion products and external sediments have prevented any leakage of mercury to the environment. For the forged container, the wall thickness had been reduced in one area to barely 1 mm. If the corrosion in this area would have remained active, a pinhole leak would have developed within another say 10-20 years; however, since the corroding area was facing the seabed, no major leakage of mercury would have occurred. The two mercury containers above have been exposed to 'worst case' condition for corrosion subsea; i.e. in shallow sediments subject to continuous supply of organic materials and consequently with high bacterial activity causing corrosion. It is further possible that oxygen in the seawater may interact to enhance corrosion. The conditions will be similar for any containers contained in keel compartments that were damaged during the explosion(s) and became more or less freely exposed to supply of seawater containing oxygen and organic materials. Hence, such compartments are likely to have containers which have developed, or will develop pinhole paths for leaks, although the amounts of leaking mercury due to corrosion should be small or moderate. For mercury containers stored in any intact keel compartments that are seawater flooded but sealed off from convective supply of organic materials and oxygen, the corrosive conditions will be very mild and it is unlikely that any corrosion has penetrated the wall of these containers. Based on the consideration above, it is assumed that as per today, any contribution of corrosion on mercury contamination of the seabed is marginal; i.e. compared to the effects of the initial explosion(s) causing fracturing of mercury containers.

For mercury containers located in seabed and in the keel, the corrosion process will continue, causing multiple pinhole leak paths but not necessarily any major leakage of mercury to the environment; the leak path being sealed by corrosion products and for containers in the seabed, also by mineral particles becoming embedded in the corrosion products.

Capping of the wreck could initially stimulate bacterial activity, and hence corrosion by supply and/or redistribution of organic material. However, after one or a few years, the instantaneous supply of organic materials has been used up and supply of new organic material is prevented by the capping. This should gradually reduce the average corrosion rate to less than **0.01 mm/yr**. Eventually, the wall of the containers may become penetrated by corrosion but a scale of corrosion products and mineral particles will form and more or less ‘encapsulate’ the liquid mercury that has not yet reacted with seawater forming a barely soluble compound.

6.2 Hull

DNV’s conclusions on this topic are:

C8. **It is not expected that local damage due to corrosion will affect the overall integrity of the hull during salvage.**
It was estimated (ref C4) that the mean uniform corrosion rate of structural components has not exceeded 0.04 mm/yr and 0.02 mm/yr for surfaces freely exposed to seawater and surfaces exposed to stagnant water in flooded tanks, respectively. For local corrosion of surfaces in shallow marine sediments, the corrosion rate may have been of the order of 0.1 mm/yr but it is assumed that such corrosion will not affect the overall integrity of the hull sections during a salvage operation.

C9. **After capping the overall residual rate of corrosion on the hull is expected to decrease to the order of 0.01 mm/yr**

Based on the corrosion rates referred to in section 4 and other considerations, it is estimated that the average corrosion rate of structural components of the hull (i.e. those affecting the integrity of the hull during a salvage operation) has not exceeded **0.04 mm/yr** (90% probability). For structural components contained in closed compartments (i.e. without free exchange of seawater) the corresponding corrosion rate is estimated to max. **0.02 mm/yr** (90% probability). For components exposed to shallow seabed sediments the maximum local corrosion rate may well have amounted to **0.1 mm/yr** but such local damage is assumed not to affect the overall integrity of the hull during a salvage operation.

Without salvage and capping, the above estimated corrosion rate will apply for a future exposure to seawater and seabed sediments; however, after a capping the corrosion rates should gradually decrease to approach a residual rate of the order of **0.01 mm/yr**.

7 REFERENCES

/1/ AGR Emi Team AS report IIN1912-19 (2005.11.14): "*Teknisk rapport etter undersøkelse av kvikksølvbeholder merket U864*"

/2/ C.S. Brossia et al: "*Corrosion Mitigation of USS Monitor Artefacts*", Materials Performance, October 2007, p. 56

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APPENDIX A

PHOTOGRAPHIC DOCUMENTATION

Figure A-1 Segment cut from bottom forged mercury coatiner (diameter 140 mm) through area with maximum metal loss. (All external surfaces have been grit blasted)

Figure A-2 Shell segment of forged mercury container cut through area with maximum metal loss

Figure A-3 Top section of forged container for mercury

Figure A-4 Welded mercury container (diameter 130 mm)

Figure A-5 Top section of welded mercury container (Leak area at the periphery to the left)

Figure A-6 Bottom section of welded mercury container

Figure A-7 Steel cylinder for pressurised gas (diameter 200 mm)

Figure A-8 Close up of pressurised gas cylinder wall penetrated by corrosion

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TECHNICAL REPORT

KYSTVERKET NORWEGIAN COASTAL ADMINISTRATION

SALVAGE OF U864 - SUPPLEMENTARY STUDIES - STUDY NO. 2: EXPLOSIVES

REPORT NO. 23916-2

REVISION NO. 01

DET NORSKE VERITAS

DET NORSKE VERITAS

TECHNICAL REPORT

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Client: Kystverket (Norwegian Coastal Administration)	Client ref.: Hans Petter Mortensholm

Summary:

The German submarine U-864 was torpedoed by the British submarine Venturer on February 9 1945 and sunk approximately two nautical miles west of the island Fedje in Hordaland. U-864 was carrying about 67 metric tonnes of metallic mercury that implies a threat to the marine environment. In September 2007 The Norwegian Costal Administration commissioned Det Norske Veritas to further investigate different alternatives to salvage the wreck and remove the mercury from the seabed.

As the U-864 was on a mission in a time of war, it is expected that it had full weapons load when torpedoed. The ordnance that is assessed to do most harm if detonated, are the torpedoes (27), 105 mm anti ship grenades (202), and demolition charges (assumed 500 kg). U-864 is expected to have had a large amount of pressurised air stored on cylinders when torpedoed. Most of this is assumed emptied when the hull was split in at least two parts after the torpedo detonated.

This study is assessing the risks related to explosives and pressurised air present when either salvaging or capping U-864.

DNV's main conclusion is: Removal of ordnance from U-864 is considered as a complex, though feasible, operation by the Norwegian Defence Authorities. The explosives are assessed not able to self detonate during salvage.

Report No.: 23916-2	Subject Group:	
Report title: Salvage of U864 - Supplementary studies - Study No. 2: Explosives		
Work carried out by: Nicolaj Tidemand (M.Sc), Carl Erik Høy-Petersen (M.Sc), Thomas Sydberger (Ph.D) The Norwegian Defence		
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TECHNICAL REPORT

The German submarine U-864 was torpedoed by the British submarine Venturer on February 9 1945 and sunk approximately two nautical miles west of the island Fedje in Hordaland. U-864 was carrying about 67 metric tonnes of metallic mercury that implies a threat to the marine environment.

In September 2007 The Norwegian Costal Administration commissioned Det Norske Veritas to further investigate different alternatives to salvage the wreck and remove the mercury from the seabed.

1 SUMMARY

This report is Study No. 2: Explosives, one of twelve supplementary studies supporting the overall report regarding U-864 (Det Norske Veritas Report No. 23916) prepared by Det Norske Veritas (DNV).

As the U-864 was on a mission in a time of war, it is expected that it had full weapons load when torpedoed. The ordnance that is assessed to do most harm if detonated, are the torpedoes (27), 105 mm anti ship grenades (202), and demolition charges (assumed 500 kg). U-864 is expected to have had a large amount of pressurised air stored on cylinders when torpedoed. Most of this is assumed emptied when the hull was split in at least two parts after the torpedo detonated.

This study is assessing the risks related to explosives and pressurised air present when either salvaging or capping U-864.

The Norwegian Defence Authorities (NDA) is responsible for removal of ordnance in Norway. The Norwegian Naval EOD Command (MDK) is the executing unit, and shall be involved during operations on U-864 to identify loose ordnance that could be uncovered, assess the risk for the involved personnel, the operation and the environment, and then conduct appropriate measures to eliminate or minimize the risk.

DNV's overall conclusion is:

Removal of ordnance from U-864 is considered as a complex, though feasible, operation by the Norwegian Defence Authorities. The explosives are assessed not able to self detonate during salvage.

DNV's supporting conclusions are:

Salvage:

C1. **Removal of ordnance from U-864 is considered as a complex, though feasible, operation by the Norwegian Defence Authorities.**

C2. **The explosives are assessed not able to self detonate during salvage.**

C3. **A torpedo explosion when salvaging U-864 may inflict fatalities and loss of equipment which is considered a disastrous effect. The probability of such incident is only considered a theoretical possibility and the Norwegian Defence Authorities do not have any records of such incidents occurring in prior operations of this type.**

C4. The risk of rupture of pressurised air cylinders as a result of a salvage operation is assessed to insignificant and is not expected to have any impact on an operation.

Capping:

C5. Explosives and pressurised air do not present a risk for involved personnel during and after a capping operation.

C6. The only identified major environmental risks during and after capping are related to explosives in the torpedoes. The probability that these explosives will detonate is assessed to be only theoretically possible.

Corrosion:

C7. The risk of an ignition as a result of corrosion on components associated with the explosives is assessed to be insignificant.

The rest of supplementary Study No. 2 “Explosives” details the arguments behind the conclusions.

TECHNICAL REPORT

Den tyske ubåten U-864 ble torpedert av den britiske ubåten Venturer den 9. februar 1945 og sank omtrent to nautiske mil vest for øya Fedje i Hordaland. U-864 var lastet med omtrent 67 tonn med metallisk kvikksølv som utgjør en fare for det marine miljøet.

I September 2007 tildelte Kystverket Det Norske Veritas oppdraget med å nærmere utrede ulike alternativer for heving av vrak og fjerning av kvikksølv fra havbunnen.

2 SAMMENDRAG

Denne rapporten er Studie nr. 2: Eksplosiver, en av tolv tilleggsutredninger som understøtter hovedrapporten vedrørende U-864 (Det Norske Veritas Report No. 23916) utarbeidet av Det Norske Veritas (DNV).

Da U-864 var på oppdrag under krigshandlinger, er det forventet at den hadde full våpenlast da den ble torpedert. Våpnene som vil gjøre mest skade dersom de eksploderer, er torpedoene (27), 105 mm anti-overflate granater (202), og demoleringsladninger (antatt 500 kg). U-864 er forventet å ha hatt store mengder trykkluft lagret på flasker da den ble torpedert. Mesteparten av dette er antatt å ha blitt tømt da skipet ble delt i minst to deler etter at torpedoen detonerte.

Forsvaret er ansvarlig for fjerning av våpen i Norge. Minedykkerkommandoen (MDK) er den utøvende enheten, og skal være involvert under operasjoner på U-864 for å kunne identifisere våpengjenstander, vurdere dets risiko for involvert personell, operasjon og miljø, og å gjennomføre hensiktsmessig tiltak for å fjerne eller minimere risikoen.

DNV sin overordnede konklusjon er:

Fjerning av eksplosiver fra U-864 er vurdert å være en rutineoperasjon av Forsvaret. Eksplosivene er vurdert å ikke kunne selvdetonere i forbindelse med heving.

DNV sine underbyggende konklusjoner er:

Heving:

C1. **Fjerning av eksplosiver fra U-864 er vurdert å være en rutineoperasjon av Forsvaret.**

C2. **Eksplosivene er vurdert å ikke kunne selvdetonere i forbindelse med heving.**

C3. **En torpedoeksplosjon i forbindelse med heving av U-864 kan medføre omkomne og tap av utstyr hvilket regnes å være en katastrofal hendelse. Sannsynligheten for en slik hendelse er vurdert kun å være teoretisk mulig og Forsvaret har ingen erfaring med slike hendelser i tidligere operasjoner av denne typen.**

C4. **Risikoen for at trykkluftflasker revner på grunn av hevingsoperasjonen er vurdert å være usignifikant og er forventet å ikke ha noen innvirkning på en operasjon.**

Tildekking:

C5. Eksplosiver og trykkluft utøver ingen risiko for involvert personell under og etter en tildekkingsoperasjon.

C6. Den eneste identifiserte miljørisikoen under og etter en tildekkingsoperasjon er forbundet med eksplosivene i torpedoene. Sannsynligheten for at disse eksplosivene vil detonere er vurdert kun å være teoretisk mulig.

Korrosjon:

C7: Risikoen for en detonasjon på grunn av korrosjon av komponenter tilknyttet eksplosivene er vurdert å være usignifikante.

Resten av Studie nr. 2: Eksplosiver utdyper argumentene bak konklusjonene.

3 INTRODUCTION

3.1 Background

The German submarine U-864 was sunk by the British submarine Venturer on 9 February 1945, approximately 2 nautical miles west of the island Fedje in Hordaland (Figure 3-1). The submarine was on its way from Germany via Norway to Japan with war material and according to historical documents; U-864 was carrying about 67 metric ton of metallic (liquid) mercury, stored in steel canisters in the keel. The wreck of U-864 which was broken into two main parts as a result of the torpedo hit was found at 150-175 m depth by the Royal Norwegian Navy in March 2003. The Norwegian Costal Administration (NCA) has on behalf of the Ministry of Fisheries and Coastal Affairs been performing several studies on how the risk that the mercury load constitutes to the environment can be handled. In December 2006 NCA delivered a report to the Ministry where they recommended that the wreck of the submarine should be encapsulated and that the surrounding mercury-contaminated sediments should be capped. In April 2007 the Ministry of Fisheries and Coastal Affairs decided to further investigate the salvaging alternative before a final decision is taken about the mercury load.

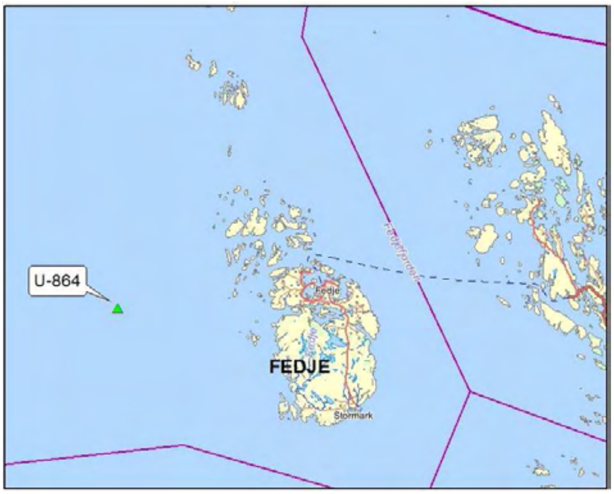


Figure 3-1 Location (left) and a sonar picture of the wreck of U-864 on seabed (right) (from Geoconsult).

3.2 DNV's task

In September 2007 NCA commissioned Det Norske Veritas (DNV) the contract to further investigate the salvaging alternative. The contract includes:

- DNV shall on the behalf of NCA announce a tender competition for contractors which have suggestions for an environmentally safe/acceptable salvaging technology. Selected contractors will receive a remuneration to prepare their suggestions.

- DNV shall evaluate the suggested salvage methods. DNV shall identify the preferred salvage method.
- The preferred salvage method shall be compared with the suggested encapsulation/capping method from 2006. (DNV shall give a recommendation for which measure that should be taken and state the reason for this recommendation.)
- DNV shall perform twelve supplementary studies which will serve as a support when the decision is taken about which measure that should be chosen for removing the environmental threat related to U-864. The twelve studies are:

1. *Corrosion*. Probability and scenarios for corrosion on steel canisters and the hull of the submarine.
2. *Explosives.* Probability and consequences of an explosion during salvaging from explosives or compressed air tanks.
3. *Metal detector*. The possibilities and limitations of using metal detectors for finding mercury canisters.
4. *The mid ship section*. Study the possibility that the mid section has drifted away.
5. *Dredging*. Study how the mercury-contaminated seabed can be removed around the wreck with a minimum of spreading and turbidity.
6. *Disposal*. Consequences for the environment and the health and safety of personnel if mercury and mercury-contaminated sediments are taken up and disposed of.
7. *Cargo.* Gather the historical information about the cargo in U-864. Assess the location and content of the cargo.
8. *Relocation and safeguarding.* Analyse which routes that can be used when mercury canisters are relocated to a sheltered location.
9. *Monitoring.* The effects of the measures that are taken have to be documented over time. An initial programme shall be prepared for monitoring the contamination before, during and after salvaging.
10. *Risk related to leakage.* Study the consequences if mercury is unintentionally leaked and spreading during a salvage or relocation of U-864.
11. *Assessment of future spreading of mercury for the capping alternative*. The consequences of spreading of mercury if the area is capped in an eternal perspective.
12. *Use of divers.* Study the risks related to use of divers during the salvage operation in a safety, health and environmental aspect and compare with use of ROV.

3.3 Scope of this report

This report is Supplementary Study No. 2: *"Explosives"*. The main objectives of this supplementary study are to:

- assess the quantity of explosives and pressurised air on board the U-864 (chapter 4)
- assess the amount of corrosion to the explosives and pressurised air cylinders (chapter 5)
- assess the risk of explosion during salvage and capping of the U-864 (chapter 6)
- address operational requirements by the NDA (chapter 7)

The overall risks related to salvage and capping of U-864 are identified by DNV and NDA in relation to the following areas:

- Personnel
- Operation
- Environment

4 THE QUANTITY OF EXPLOSIVES AND PRESSURISED AIR ON BOARD THE U-864

When assessing risk concerning explosives, it is vital to know in what kind of weapons the explosives are placed. Explosives itself only have a *shock wave* effect, while ordnance both have a *shock wave* and various kinds of *fragmentation bomb* effects. In the rest of this study both explosives and ordnance are named *ordnance.* Demolition charges are by definition only explosives not ordnance, but are in this report included in the term *ordnance* for simplicity.

The Norwegian Armed Forces (NAF) is responsible for demilitarization of explosives and ordnance in Norway, and MDK is the executing unit. NAF shall be involved in the operation for capping or salvaging U-864 (more information on this topic in chapter 7). MDK are the experts on explosives and ordnance, and have expertise and experience in handling pressurised air[1] cylinders. To ensure correct basis, NAF has played a major role in this supplementary study.

In November 2007 DNV and MDK visited Denmark to get insight to knowledge about the experiences the Danish Naval EOD Command built during the salvage of the submarine U-534 (type IX C/40) outside Denmark in 1993. U-534 is a similar, but approximately 11 metres shorter, submarine to U-864 which was a type IX D/2 submarine, and assumed to have carried about the same armament and type of pressurised air cylinders. Where limited information about the ordnance on board a type IX D/2 submarine is found, DNV has based the assessments on what was found on board U-534. DNV and MDK also visited the submarine U-995 (Type VII submarine, similar to type IX D/2 but approximately 20 m shorter) in Laboe (Germany) to acquire information about storage rooms, torpedo tubes, where to find pressurised air cylinders, as well as how removal of explosives from the submarine could be carried out if salvaging U-864.

As the U-864 was on a mission in a time of war, it is assumed that it had full weapons load when leaving Bergen - both for self defence measures and attacking merchant vessels. This is supported by Jürgen Oesten /1/. He was the commanding officer on a similar submarine (U-861) as U-864 and completed the same mission that U-864 was intended to carry out. Where alternatives exit, the worst-case scenario is used when deciding which type of ordnance U-864 carried when leaving Bergen.

Table 4-1 summarises the NDA's assessment on the armament and pressurised air on board U-864. For detailed information on this topic, see Appendix B.

[1] The term *air* is in this supplementary study used for all types of gas stored on a cylinder. Compressed air is the most common gas used, although containers with pure O^2 are also present.

Table 4-1 Ordnance and pressurised air assessed to be on board U-864

Ordnance			
Item	**Number / Weight**	**Storage**	**Conclusion**
Torpedoes	27	Assessed to be stored: Outside the pressure hull: 12 stored underneath the casing. Inside the pressure hull: 4 in the torpedo tubes fore, 6 in fore torpedo room, 2 in the torpedo tubes aft, 3 in the aft torpedo room.	**Salvage** When the submarine is raised towards the surface, the ambient pressure will be reduced. It is assessed only theoretically possible that this will cause a detonation of explosives. The possibility of a leakage from the pressurised air cylinder will increase during ascent (caused by reduction of the ambient pressure) and is assed to be remote. **Capping** The possibility of a detonation during capping, without a greater external influence, is assessed only to be theoretically possible. If a high pressure air cylinder starts leaking, due to corrosion, it is assessed that a rupture of the pressurised air cylinder is unlikely.
105 mm	202	Assessed to be stored: Outside the pressure hull: 32 by the 105 mm cannon. Inside the pressure hull: 170 divided in the two storage rooms below the central and the galley.	It is assessed that the risk concerning 105 mm ammunition is insignificant when salvaging or capping.
37 mm	1150	Assessed to be stored outside the pressure hull and in internal magazines. 60 projectiles under ”winter-garden” (aft of tower).	May contain a tracer in base, which will self destruct the projectile if it burns out. **Salvage** Should be kept wet until they are removed from the wreck, and kept wet until moved to the deposit site. It is assessed that the risk concerning 37 mm ammunition is insignificant when salvaging. **Capping** It is assessed that the risk concerning 37 mm ammunition is insignificant when capping.
20 mm	3060	Assessed to be stored outside the pressure hull and in internal magazines.	**Salvage** Should be kept wet until they are removed from the wreck, and kept wet until moved to the deposit site. It is assessed that the risk concerning 20 mm ammunition is insignificant when salvaging. **Capping** It is assessed that the risk concerning 20 mm ammunition is insignificant when capping.

Demolition charges	500 kg TNT	Assessed to be stored in the ammunition magazines	**Salvage/capping** Demolition charges are safe to handle when salvaging or capping. It is assessed that the risk concerning demolition charges are insignificant when salvaging or capping.
Small arms ammunition	3000	Assessed to be stored throughout the submarine	**Salvage/capping** Small arms ammunition safe to handle when salvaging or capping. It is assessed that the risk concerning small arms ammunition is insignificant when salvaging or capping.
Hand grenades	30	Assessed to be stored throughout the submarine	Usually stored separately (stick and grenade). Explosives might be very sensitive, due to picric acid. **Salvage** If salvaged, avoid drying. The longer the submarine is stored in a dry environment, the more sensitive the grenade will be. It is assessed that the risk concerning stick grenades are insignificant when salvaging. **Capping** It is assessed that the risk concerning stick grenades are insignificant when capping.
Pressurised air cylinders			
Item	**Volume / pressure**	**Location**	**Conclusion**
Ballast tanks	Unknown / 200 bar	Unknown	Assessed empty due to missing mid section where the main ballast blow panel is placed. **Salvage/capping** It is assessed that the risk concerning high pressure air for ballast tanks are insignificant when salvaging capping.
BIBS	Unknown / 200 bar	Unknown	Assessed likely pressurised. **Salvage/capping** It is assessed that the risk concerning BIBS is insignificant when salvaging or capping.
Starting air for engines	Unknown / 40 bar	Assessed close to engines	Assessed likely empty. **Salvage/capping** It is assessed that the risk concerning starting air for diesels is insignificant when salvaging or capping.
Oxygen tanks	13 x 50 l. / 200 bar	Assessed to be located aft of toilet and in fore section	Assessed likely pressurised. **Salvage/capping** It is assessed that the risk concerning oxygen tanks are insignificant when salvaging or capping.

5 THE AMOUNT OF CORROSION TO THE EXPLOSIVES AND PRESSURISED AIR CYLINDERS

DNV's conclusions are:

C7. The risk of an ignition as a result of corrosion on components associated with the explosives is assessed to be insignificant.

The effects of corrosion on mercury canisters and primary structural components of the hull fabricated in C-steel is the subject of another study (Supplementary Study No.1 "Corrosion"). For explosives containing components within and outside of the hull, torpedoes with internal cylinders or other canisters for pressurised air are of primary concern. The torpedoes are expected to have components both internally and externally that are fabricated in other materials than C-steel, primarily copper-base alloys like brass (CuZn alloys) and bronze (CuSn alloys), possibly also stainless steel (FeCr and/or FeCrNi alloys). Some Cu alloys are highly corrosion resistant in marine environment and therefore well suited to be used for parts of the torpedo propulsion mechanism exposed to seawater during storage outside the hull. A typical corrosion rate of such alloys is 0.001-0.005 mm/yr and the form of corrosion is uniform. For the initially dry internal of the torpedoes, other Cu-alloys with poor or marginal resistance to seawater; e.g. 'ordinary' brass and pure copper may have been used. Brasses that are not alloyed for marine application may suffer rapid degradation by selective leaching of zinc (dezincification) or stress corrosion cracking if exposed to seawater. It is assumed that the initially dry internals of the torpedoes have been flooded by seawater due to biodegradation and/or corrosion of seals which has affected detonation and propulsion mechanisms so that they are no longer operative. Hence, the components for ignition of explosives should rather become inactivated than activated by corrosion.

As reported in Supplementary Study No.1 "Corrosion", a steel cylinder for pressurised air found partly buried in sediments outside of the wreck was found to be severely corroded, the shell wall being penetrated by corrosion. The high corrosion rate (about 0.12 mm/yr and 0.05 mm/yr for local and uniform corrosion, respectively) was related to high bacterial activity in the sediments due to free supply of organic material, nutrients, possibly in combination with oxygen. On the other hand, leakage of seawater into the internal of torpedoes is not expected to have affected the integrity of any pressurised air cylinders in steel contained in them. (It is possible that a major part of the pressurised air has escaped through the loss of sealing function at the associated valves or by pinhole leakage of pressurised piping). As discussed in Supplementary Study No.1 "Corrosion", the two alternative corrosion mechanisms are:

1. Oxygen consuming corrosion.
2. Microbiologically induced corrosion (MIC) related to either aerobic or anaerobic bacteria.

Corrosion due to oxygen or aerobic bacteria is very much restricted by the slow supply of dissolved oxygen by leaking seawater, whilst the activity of bacteria (aerobic and anaerobic) is limited by the slow supply of organic material and nutrients. Without a corrosive agent, galvanic interaction between components in C-steel and other alloys contained within the shells of the torpedoes is not an issue. The steel cylinders for pressurised air are assumed to have a minimum thickness of 5 mm and if still pressurised, a metal loss extending over a larger surface area and with a depth of a few mm may cause a rupture in combination with some external action e.g. reducing the external pressure by 15 bars during the retrieval of a hull section. However, a more likely long term failure mode is a localised corrosion attack ultimately penetrating the cylinder wall and causing a pinhole leak and being virtually unaffected by a reduction of the external pressure. It is therefore assessed unlikely that such a leakage is triggered by a salvage operation.

Taking into account the expected form of corrosion and the potential corrosion rate, plus the relatively high probability that much of the pressurised air has already escaped by leakage, the probability of a rupture of a cylinder with pressurised air (including the cylinder contained within the shell of the torpedoes) as a result of a salvage operation is assessed to be remote. The probability of corrosion of other components associated with the explosives and causing ignition of the explosives are assessed extremely remote.

Figure 5-1 Steel canister for pressurised air (diameter 200 mm)

6 THE RISK OF EXPLOSION DURING SALVAGE AND CAPPING OF THE U-864

DNV has facilitated the risk analysis, while professionals on armament and disposal of explosives from the NAF have assessed the risks. The result of risk analysis for salvage and capping will be presented in the following chapters. A complete risk matrix is presented in Appendix A.

DNV's conclusions are:

Salvage:

C1. Removal of ordnance from U-864 is considered a as routine operation by the Norwegian Defence Authorities.

C2. The explosives are assessed not able to self detonate during salvage.

C3. A torpedo explosion when salvaging U-864 may inflict fatalities and loss of equipment which is considered a disastrous effect. The probability of such incident is only considered a theoretical possibility and the Norwegian Defence Authorities do not have any records of such incidents occurring in prior operations of this type.

C4. The risk of rupture of pressurised air cylinders as a result of a salvage operation is assessed to insignificant and is not expected to have any impact on an operation.

Capping:

C5. Explosives and pressurised air do not present a risk for involved personnel during and after a capping operation.

C6. The only identified major environmental risks during and after capping are related to explosives in the torpedoes. The probability that these explosives will detonate is assessed to be only theoretically possible.

The overall risks related to salvage and capping of U-864 are identified by DNV and NDA in relation to the following areas:

- Personnel
- Operation
- Environment

6.1 Objective and scope

The objective for this risk analysis is to evaluate the risks in conjunction with handling the ordnance and pressurised air cylinders on board U-864, both for salvaging and capping. For a salvage operation will this include all phases from the start of the operation (1.0 Preliminary study) until all the explosives have been brought out of the wreck and away from the wreck site (99.1 Removal of explosives), see Figure 6-1.

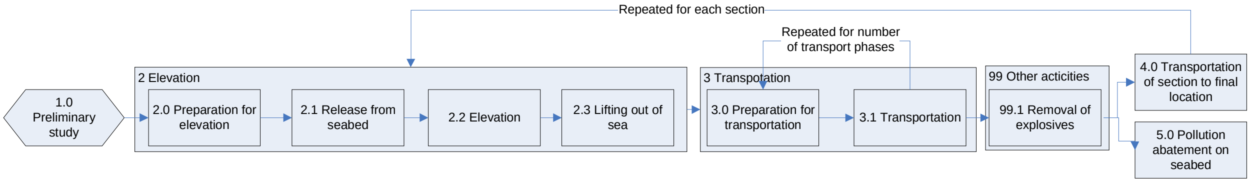


Figure 6-1 General description of a salvage process

The risk analysis for a capping process will include all processes from the start of the operation (1.0 Preliminary study) until all operations on the seabed have been completed (8.0 Demobilisation), see Figure 6-2.

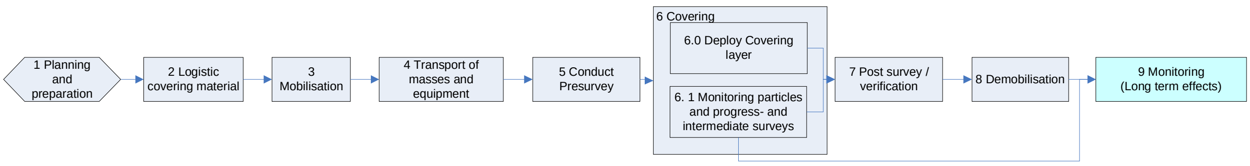


Figure 6-2 General description of a capping process

6.2 Definition of scales for probability and consequences

The following scales are used for assigning probability and consequences, respectively.

Table 6-1 Scale used on assigning probability

Likely	>50% Expected during an operation of this type.
Reasonably probable	10% < p <50% May be expected during an operation of this type.
Unlikely	0,5% < p <10% May occur but not to be expected during an operation of this type.
Remote	0,01% < p <0,5% Possible but with very low probability.
Extremely Remote	0,0001% < p <0,01% No experience that this has occurred.
Theoretically Possible	0,00001% < p <0,0001% Only theoretically possible. No experience that this has occurred.

Table 6-2 Scale used on assigning consequences

Minor	**Personnel**	Personnel injury without medical certificate.
	Operational	Not a substantial damage to equipment, cost less than 100.000 NOK. No delay.
	Environment	Discharge which has no influence for the environment. Do not need any special measures, nor reporting to the Norwegian Pollution Control (SFT).
Severe	**Personnel**	Personnel injury with medical certificate, but not permanent injured.
	Operational	Damage on equipment: 100.000 < NOK < 1.000.000. Delay < 3days.
	Environment	Minor discharge which has no permanent influence on the environment and can be handled by simple measures. Must be reported to the SFT.
Fatal	**Personnel**	Personnel injury with medical certificate > 1 month, permanent injury or fatality. Situations that *might* result in the mentioned result.
	Operational	Damage on equipment: 1.000.000 < NOK <10.000.000. Delay < 1 week.
	Environment	Discharge which need substantial measures. Might result in permanent damage to the environment.
Catastrophic	**Personnel**	Considerable personnel injury and/or fatalities (> 1 person).
	Operational	Loss of vessel/equipment. Operation aborted, considerable delays < 1 month. Needs re-planning.
	Environment	Considerable irreversible damage to the environment as a result of spill.
Disastrous	**Personnel**	A greater number of fatalities and injured.
	Operational	The operation fails. Considerable delay. Re-planning before restart of the project. Loss of main equipment.
	Environment	Considerable irreversible damage to the environment as a result of spill at larger and/or protected zones.

A risk is defined as the product of probability and consequence. The matrix in Figure 6-3 indicates that a risk's criticality is increasing from the lower left corner (theoretically possible and minor consequences) to the top right corner (likely and disastrous consequences).

It is although important to note that the numbers are subjective and ordinal within the same column or row. Two different risks' criticality can therefore not be directly compared with each other, even if they have the same number (criticality). Thus criticality of 4 is not twice as dangerous as a criticality of 2. When defining actions, each risk must be considered individually and not based on the criticality alone. The colours in the matrix do not indicate acceptance levels.

Likely	6	7	8	9	10
Reasonably Probable	5	6	7	8	9
Unlikely	4	5	6	7	8
Remote	3	4	5	6	7
Extremely Remote	2	3	4	5	6
Theoretically Possible	1	2	3	4	5
⇧ Probability **Consequence ⇨**	**Minor**	**Severe**	**Fatal**	**Catastrophic**	**Disastrous**

Figure 6-3 Risk matrix with criticality

Risks in the green area are considered *insignificant*, risks in the yellow area are considered *significant* while risks in the red area are considered *critical.*

6.3 Risk analysis for a salvage operation

DNV's conclusions are:

C1. Removal of ordnance from U-864 is considered a as routine operation by the Norwegian Defence Authorities.

C2. The explosives are assessed not able to self detonate during salvage.

C3. A torpedo explosion when salvaging U-864 may inflict fatalities and loss of equipment which is considered a disastrous effect. The probability of such incident is only considered a theoretical possibility and the Norwegian Defence Authorities do not have any records of such incidents occurring in prior operations of this type.

C4. The risk of rupture of pressurised air cylinders as a result of a salvage operation is assessed to insignificant and is not expected to have any impact on an operation.

The overall risks for salvaging U-864 based on the risks identified by DNV and NDA are:

Personnel

During the first part of a salvage operation, when the wreck is on seabed, no risks to personnel have been identified. When the wreck reaches surface, and for the rest of the salvage operation, it is assessed that personnel will be exposed to risks concerning explosions.

The probability of a torpedo explosion is only assessed as theoretically possible, but may result in several fatalities. Explosions of ordnance are assessed to be remote, but may result in permanent personal injuries.

The probability of explosions due to burst of pressurized air cylinder are assessed as unlikely, but may result in personal injury.

Clearing of ordnance from the wreck after salvage is the most dangerous activity for personnel, however use of experienced personnel reduces the risk for personnel to an acceptable level.

Operation

Explosion of a torpedo warhead, which is considered only theoretically possible, is assessed to damage both the wreck and the salvor's equipment to such a degree that the operation may have to be aborted or substantially delayed.

Explosion of one unit of fixed ordnance is assessed unlikely, and assessed not to pose a threat to the operation.

Leakage or rupture of pressurised cylinders is assessed not to have any severe impact on the operation.

Environment:

If a torpedo warhead explodes, which is assessed only theoretical possible, mercury canisters may rupture and result in increased mercury pollution on the seabed.

The effect of an explosion of single items of fixed ordnance is assessed to have minor consequences to the environment. If the explosion is inside the wreck, it may have no consequences to the environment.

6.3.1 Identified risks

The identified risks related to salvaging U-864, associated with explosives and pressurised air, and their respective criticality is displayed in Figure 6-4. It is important to note that risks that have a different criticality for different phases are only counted once – it is the salvage phase with the most critical risk that is displayed. Information about the identified risks is listed in Table 6-3 on page 19.

Likely					
Reasonably Probable					
Unlikely	R-09, R10				
Remote	R-11				
Extremely Remote	R-02, R-03, R-04		R-14		
Theoretically Possible	R13, R-30	R-07, R-08	R-16		R-05, R-06, R-12, R-15
⇧ Probability **Consequence ⇨**	**Minor**	**Severe**	**Fatal**	**Catastrophic**	**Disastrous**

Figure 6-4 Potential risks associated with explosives and pressurised air (salvage)

Table 6-3 Identified risks related to salvage

Risk	Name	Description	Comments (significant risks only)
R-02	Elements hits loose ordnance objects on the seabed that explodes.	Hitting loose ordnance when working on seabed and/or the hull.	
R-03	Hitting ordnance inside the hull or around the hull resulting in explosion.	Hit loose ordnance as a result of drilling or positioning of lifting equipment.	
R-04	Rupture in pressurised air cylinder in torpedoes positioned outside the wreck or as a result of drilling through the hull. Or other pressure thanks in the wreck.	Hit pressurised air cylinder can as a result of drilling or positioning of lifting equipment.	
R-05	Explosives in torpedoes explode as a result of shifting position.	Movement of torpedoes resulting in explosion. Torpedoes are expected to be secured for operations at sea, and torpedoes in torpedo tubes might not be affected as they are not able to be moved. Torpedoes stored inside hull in storage compartment might be stored close together. If one such torpedo explodes, it might lead to explosion of adjacent torpedoes.	It is assessed that as a result of the wreck's condition it is only theoretically possible that shifting position will initiate an explosion. If this occurs, the consequence may be that one torpedo warhead detonates which may blow away part of the hull, damage equipment and cause spreading of mercury.
R-06	Torpedoes explode as a result of structure failure.	Collapse of the hull or the torpedo results in an explosion due to explosives exposed to powerful shock when the submarine's hull or the torpedo itself collapses.	It is assessed that as result of wreck's condition it is extremely remote that structures will fail in a way that leads to torpedo detonation. If this occurs, the consequence may be that one torpedo warhead detonates which may blow away part of the hull, damage equipment and cause spreading of mercury.
R-07	Ordnance explodes as a result of shifting position.	Powerful movement results in ordnance to explode.	
R-08	Ordnance explodes as a result of structure failure.	A major structure fails exposing ordnance can lead to shock, impact or pinching which result in explosion. As the structure weakens due to corrosion, the probability of structural failure will increase.	

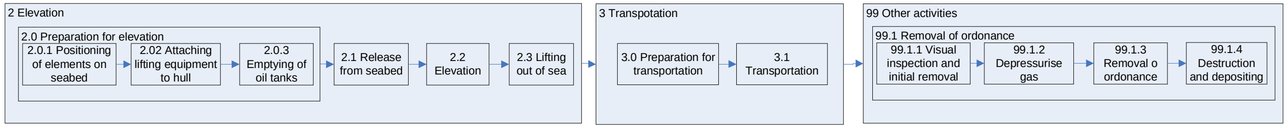
Risk	Name	Description	Comments (significant risks only)
R-09	Pressurised air cylinder rupture as a result of structural failure.	Collapse of the hull or the torpedo results in rupturing of pressurised air cylinders.	
R-10	Pressurised air cylinder start leaking air as a result of structural failure or reduced ambient pressure.	The hull of the pressurised air cylinders and/or its valve is weakened due to corrosion, which results in leakage of compressed air.	
R-11	Pressurised air cylinder rupture as a result of reduced ambient pressure.	Risk increases until surface is broken as the ambient pressure decreases. The hull of the cylinder and/or its valve is weakened due to corrosion, which results in a pressurised air cylinder rupture.	
R-12	Rupture of pressurised air cylinder influence torpedoes onboard resulting in explosion.	Risk increases until surface is broken as the ambient pressure decreases. The hull of the cylinder and/or its valve is weakened due to corrosion, which results in a torpedo pressure air cylinder to rupture, which leads to a detonation of the torpedo's explosives.	It is assessed theoretically possible that a rupture of a pressurised air cylinder will lead to explosion of a torpedo. If this occurs, the consequence may be that one torpedo warhead detonates which may blow away part of the hull, damage equipment and cause spreading of mercury.
R-30	Rupture of pressurised air cylinder influence ordnance onboard resulting in explosion.	Risk increases until surface is broken as the ambient pressure decreases. The hull of the cylinder and/or its valve is weakened due to corrosion, which results in a rupture of a pressure air cylinder, which leads to a detonation of ordnance.	
R-13	Reduced pressure result in separation of ordnance resulting in personnel injury or an explosion.	Unitary rounds can be separated in shell and casing as a result of reduced ambient pressure. It might result in an explosion.	
R-14	Ordnance explodes due to handling.	Ordnance explodes due to exposure of sufficient external influence.	

Risk	Name	Description	Comments (significant risks only)
R-15	Torpedoes explode due to handling.	Ordnance explodes due to exposure of sufficient external influence.	It is assessed extremely remote that torpedoes explode due to handling. If this occurs, the consequence may be that one torpedo warhead detonates which may blow away part of the hull, damage equipment and cause spreading of mercury.
R-16	Pressurised air cylinder rupture during placement of charges.	To depressurise tanks small explosive charges will be used. Due to corrosion, pressurised air cylinder ruptures when charges are set off.	

6.3.2 Risk assessment

Table 6-4 on the next page shows all risks identified by DNV and NDA and their respective criticality during a salvage operation. Only the highest criticality for each risk (either personnel, operational or environmental) per phase is displayed. A complete risk matrix, including probability and consequences for people, the operation and the environment, can be found in Table 8-1 in Appendix A.

Table 6-4 Identified salvage risks and their respective criticality (see Figure 6-3 for scale for criticality)



Risk	Name	Criticality (see Figure 6-3)											
R-02	Elements hits loose ordnance objects on the seabed that explodes.	2	2										
R-03	Hitting ordnance inside the hull or around the hull resulting in explosion.		2	2									
R-04	Rupture in pressurised air cylinder in torpedoes positioned outside the wreck or as a result of drilling through the hull. Or other pressure thanks in the wreck.		2	2									
R-05	Explosives in torpedoes explode as a result of shifting position.				4	4	5		5			4	
R-06	Torpedoes explode as a result of structure failure.				4	4	5						
R-07	Ordnance explode as a result of shifting position.				1	1	1		1	2		2	
R-08	Ordnance explode as a result of structure failure.				1	1	2						
R-09	Pressurised air cylinder rupture as a result of structural failure.				4	4	3						

		2 Elevation						3 Transpotation		99 Other activities			
		2.0 Preparation for elevation								99.1 Removal of ordonance			
		2.0.1 Positioning of elements on seabed	2.02 Attaching lifting equipment to hull	2.0.3 Emptying of oil tanks	2.1 Release from seabed	2.2 Elevation	2.3 Lifting out of sea	3.0 Preparation for transportation	3.1 Transportation	99.1.1 Visual inspection and initial removal	99.1.2 Depressurise gas	99.1.3 Removal o ordonance	99.1.4 Destruction and depositing
Risk	**Name**	**Criticality (see Figure 6-3)**											
R-10	Pressurised air cylinder start leaking air as a result of structural failure or reduced ambient pressure.				3	4	4						
R-11	Pressurised air cylinder rupture as a result of reduced ambient pressure.				3	3	3						
R-12	Rupture of pressurised air cylinder influence torpedoes onboard resulting in explosion.				4	4	5		5		4		
R-30	Rupture of pressurised air cylinder influence ordnance onboard resulting in explosion.				1	1	1		1		1		
R-13	Reduced pressure result in separation of ordnance resulting in personnel injury or an explosion.						1			4			
R-14	Ordnance explode due to handling.							4		4		4	
R-15	Torpedoes explode due to handling.											5	
R-16	Pressurised air cylinder rupture during placement of charges.										3		

6.4 Risk analysis for a capping operation

DNV's conclusions are:

C5. Explosives and pressurised air do not present a risk for involved personnel during and after a capping operation.

C6. The only identified major environmental risks during and after capping are related to explosives in the torpedoes. The probability that these explosives will detonate is assessed to be only theoretically possible.

The overall risks for capping U-864 based on the risks identified by DNV and NDA are:

Personnel:
As the operation will be performed from the surface with remote control, no risks to personnel have been identified.

Operation:

The probability for a torpedo explosion during capping is assessed theoretically possible, and may result in loss of salvor's equipment on seabed and longer operational delays.

Environment:

Short term:

Explosions during capping are assessed to be theoretically possible. The consequences may be spreading of mercury. Mercury canisters may rupture and result in increased mercury pollution on the seabed.

Long term:

As the structure of the submarine will weaken, collapse of the hull can lead to torpedo explosion, but this is only assessed as theoretically possible. The weight of capping can influence the outcome. The consequences may be breaching of the capping. Mercury may be spread. Mercury canisters may rupture and result in increased mercury pollution on the seabed.

6.4.1 Identified risks

The identified risks related to capping U-864, associated with explosives and pressurised air, and their respective criticality is displayed in Figure 6-5. It is important to note that risks that have a different criticality for different phases are only counted once – it is the capping phase with the most critical risk that is displayed. Information about the identified risks is listed in Table 6-5 on page 26.

Likely					
Reasonably Probable					
Unlikely					
Remote					
Extremely Remote	R-48				
Theoretically Possible	R-49, R-50				R-51, R-53
⇧ Probability Consequence ⇨	**Minor**	**Severe**	**Fatal**	**Catastrophic**	**Disastrous**

Figure 6-5 Potential risks associated with explosives and pressurised air (Capping)

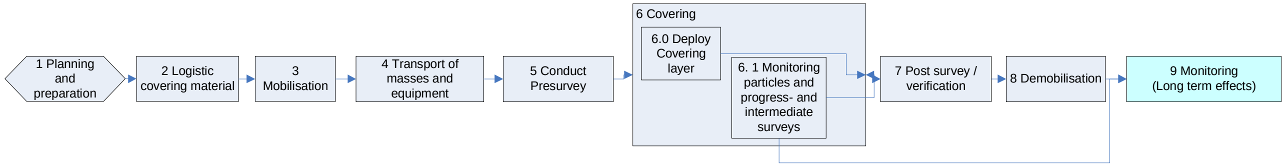
Table 6-5 Identified risks related to capping

Risk	Name	Description	Comments (significant risks only)
R-48	Elements hits loose ordnance objects on the seabed that explodes.	Hitting loose ordnance when working on seabed and/or the hull.	
R-49	Ordnance inside the hull explodes as a result of a hull collapse.	A major structure failure exposing ordnance can lead to shock, impact or pinching which result in explosion. As structures weakens due to corrosion the probability of structural failure increases.	
R-50	Pressurised air inside or outside the hull rupture as a result of a hull collapse.	Collapse of the hull results in rupture of a pressurised air cylinder.	
R-51	Pressurised air inside or outside the hull rupture as a result of a hull collapse and influence the torpedoes resulting in an explosion.	Collapse of the hull results in rupture of a pressurised air cylinder, which lead to a torpedo explosion.	It is assessed theoretically possible that a rupture of a pressurised air cylinder, as a result of a hull collapse, will lead to explosion of a torpedo. The consequences may be that one torpedo warhead detonates and blow away part of the hull. It is assumed that corrosion of tanks will lead to air leakage before the hull collapses. Release of oxygen air inside the wreck may theoretically enhance the self ignition of explosives.
R-53	Torpedoes inside or outside the hull explodes as a result of a hull collapse.	The hull structure collapses and exposes the ordnance to shock, impact or pinching which result in explosion. Due to the collapse, torpedo explosives might be brought together leading to explosion of several torpedo war heads at the same area, though maximum 6 torpedoes.	It is assumed that the hull will collapse eventually due to corrosion. At that time most of the protective structures around the torpedoes are assumed defect due to corrosion. The explosives may be more exposed to external effects like impact, intrusion or pinching, which may result in explosion of one, or in worst case, maximum six torpedoes. The weight of the capping will increase the force, but is not expected to have a significant on the risk.

6.4.2 Risk assessment

Table 6-6 on the next page shows all risks identified by DNV and NDA and their respective criticality when capping. Only the highest criticality for each risk (either personnel, operational or environmental) per phase is displayed. A complete risk matrix, including probability and consequences for people, the operation and the environment, can be found in Table 8-2 in Appendix A.

Table 6-6 Identified capping risks and their respective criticality (see Figure 6-3 for scale for criticality)



Risk	Name	Criticality (see Figure 6-3)									
R-48	Elements hits loose ordnance objects on the seabed that explodes					2	2	2	2		2
R-49	Ordnance inside the hull explodes as a result of a hull collapse						1				1
R-50	Pressurised air inside or outside the hull rupture as a result of a hull collapse										1
R-51	Pressurised air inside or outside the hull rupture as a result of a hull collapse and influence the torpedoes resulting in an explosion						5				5
R-53	Torpedoes inside or outside the hull explodes as a result of a hull collapse						5				5

7 OPERATIONAL REQUIREMENTS BY THE NDA

The Norwegian Defence Authorities (NDA) is responsible for removal of ordnance in Norway. The Norwegian Naval EOD Command (MDK) is the executing unit, and shall be involved during operations on U-864. NDA Systems Management Division will also be involved during planning. To secure that a capping or salvage operation is conducted safely, and especially removal of ordnance from the wrecks if salvaged, MDK has some operational requirements a contractor must take into account. The operational requirements for a salvage operation will be described in chapter 7.1, and likewise for capping in chapter 7.2.

7.1 Operational demands – salvage 4

Figure 7-1 states the MDK's requirements to the contractor:

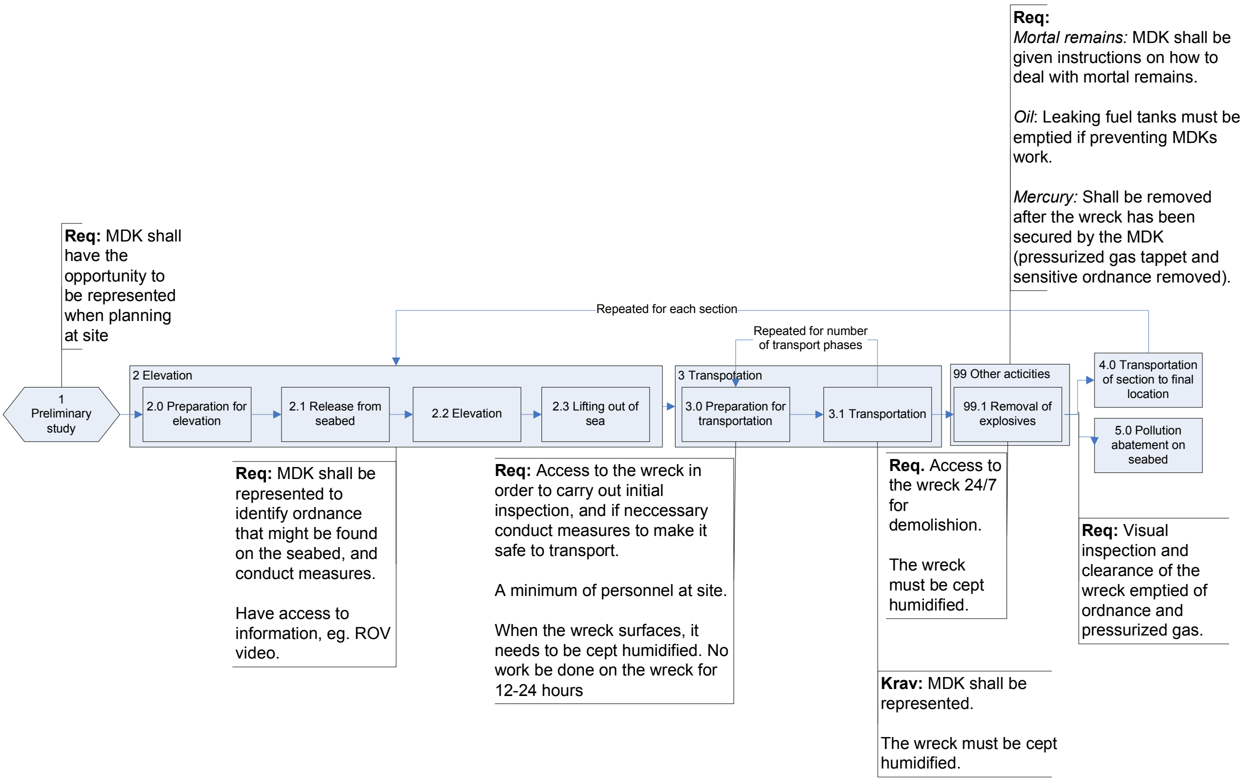


Figure 7-1 MDK's operational requirements during a salvage operation

In general, the MDK must be involved during the whole salvage operation in order to identify loose ordnance that could be uncovered, assess the risk for the involved personnel, the operation and the environment, and then conduct appropriate measures to eliminate or minimize the risk.

The number of MDK personnel represented will vary during the operation. MDK must have access to the wreck 24 hours per day during removal of explosives (phase 99.1). When this work is completed, MDK will inspect the wreck and state it as cleared.

Removal of the explosives from site and demolishing are MDKs responsibility, not the contractor's.

During operation there is a requirement of a 2 km safety zone when dealing with the explosives.

7.2 Operational demands - capping

In general, the MDK must be involved during the whole salvage operation in order to identify loose ordnance that could be uncovered, assess the risk for the involved personnel, the operation and the environment, and then conduct appropriate measures to eliminate or minimize the risk. If explosives are found, MDK might demand that the operation is halted until the situation is cleared.

MDK only need to be represented by one person on site, but might need to increase the staff if explosives are found or incidents with explosives occur.

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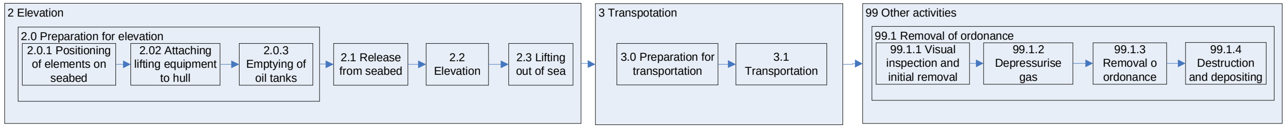
APPENDIX

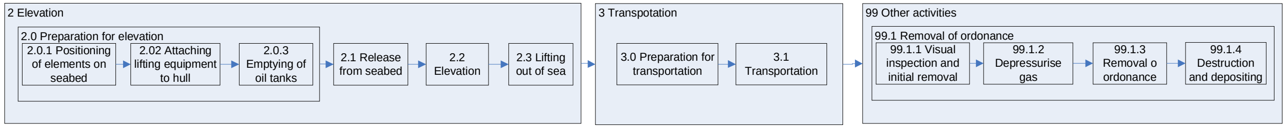
A
RISK ANALYSIS

- o0o -

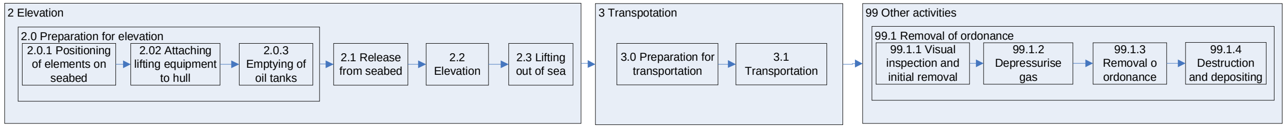
Table 8-1 Complete risks matrix for a salvage operation



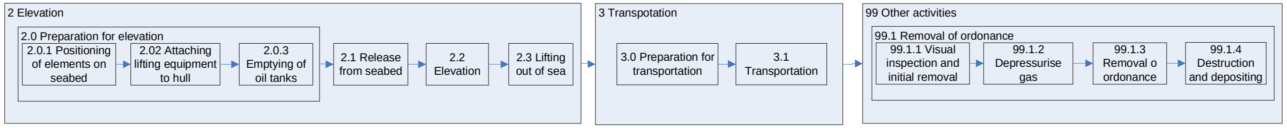
Risk	Name		Criticality (see Figure 6-3)											
R-02	Elements hits loose ordnance objects on the seabed that explodes	P												
		O	ER/M 2	ER/M 2										
		E	ER/M 2	ER/M 2										
R-03	Hitting ordnance inside the hull or around the hull resulting in explosion	P												
		O		ER/M 2	ER/M 2									
		E		ER/M 2	ER/M 2									
R-04	Rupture in pressurised air cylinder in torpedoes positioned outside the wreck or as a result of drilling through the hull. Or other pressure thanks in the wreck	P												
		O		ER/M 2	ER/M 2									
		E		ER/M 2	ER/M 2									
R-05	Explosives in torpedoes explode as a result of shifting position	P						TP/DA 5		TP/DA 5			TP/CA 4	
		O				TP/CA 4	TP/CA 4	TP/DA 5		TP/FA 3			TP/FA 3	
		E				TP/CA 4	TP/CA 4	TP/DA 5		TP/DA 5			TP/FA 3	
R-06	Torpedoes explode as a result of structure failure	P						TP/DA 5						
		O				TP/CA 4	TP/CA 4	TP/DA 5						



Risk	Name		Criticality (see Figure 6-3)											
		E				TP/CA 4	TP/CA 4	TP/DA 5						
R-07	Ordnance explode as a result of shifting position	P						TP/M 1		TP/M 1	TP/S 2		TP/S 2	
		O				TP/M 1	TP/M 1	TP/M 1		TP/M 1	TP/M 1		TP/M 1	
		E				TP/M 1	TP/M 1	TP/M 1		TP/M 1	TP/M 1		TP/M 1	
R-08	Ordnance explode as a result of structure failure	P						TP/S 2						
		O				TP/M 1	TP/M 1	TP/M 1						
		E				TP/M 1	TP/M 1	TP/M 1						
R-09	Pressurised air cylinder rupture as a result of structural failure	P						U/M 4						
		O				U/M 4	U/M 4	U/M 4						
		E				U/M 4	U/M 4	U/M 4						
R-10	Pressurised air cylinder start leaking air as a result of structural failure or reduced ambient pressure	P												
		O				R/M 3	U/M 4	U/M 4						
		E				R/M 3	U/M 4	U/M 4						
R-11	Pressurised air cylinder rupture as a result of reduced ambient pressure	P												
		O				R/M 3	R/M 3	R/M 3						
		E				R/M 3	R/M 3	R/M 3						

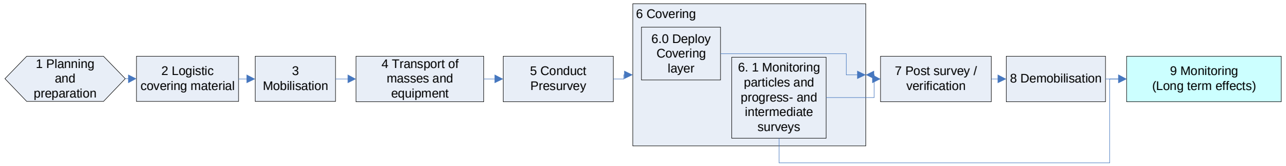


Risk	Name		Criticality (see Figure 6-3)											
R-12	Rupture of pressurised air cylinder influence torpedoes onboard resulting in explosion	P						TP/DA 5		TP/DA 5		TP/CA 4		
		O				TP/CA 4	TP/CA 4	TP/DA 5		TP/FA 3		TP/FA 3		
		E				TP/CA 4	TP/CA 4	TP/DA 5		TP/DA 5		TP/FA 3		
R-30	Rupture of pressurised air cylinder influence ordnance onboard resulting in explosion	P						TP/M 1		TP/M 1		TP/M 1		
		O				TP/M 1	TP/M 1	TP/M 1		TP/M 1		TP/M 1		
		E				TP/M 1	TP/M 1	TP/M 1		TP/M 1		TP/M 1		
R-13	Reduced pressure result in separation of ordnance resulting in personnel injury or an explosion	P						TP/M 1			U/M 4			
		O						TP/M 1			U/M 4			
		E						TP/M 1			U/M 4			
R-14	Ordnance explode due to handling	P							ER/F 4		ER/F 4		ER/F 4	
		O							ER/F 4		ER/F 4		ER/F 4	
		E							ER/S 3		ER/S 3		ER/S 3	
R-15	Torpedoes explode due to handling	P											TP/DA 5	
		O											TP/DA 5	
		E											TP/S 2	
R-16	Pressurised air cylinder	P										TP/F 3		

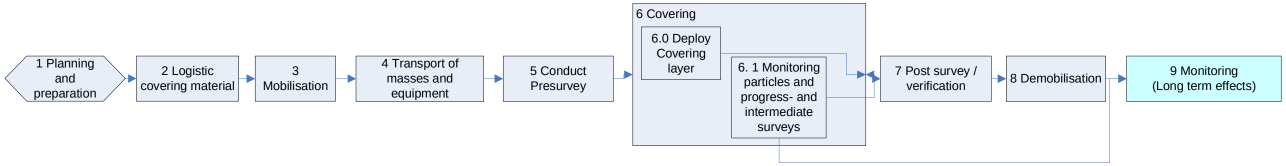


Risk	Name		Criticality (see Figure 6-3)											
	rupture during placement of charges	O										TP/S 2		
		E										TP/S 2		

Table 8-2 Complete risks matrix for a capping operation



Risk	Name		Criticality (see Figure 6-3)									
R-48	Elements hits loose ordnance objects on the seabed that explodes	P										
		O					ER/M 2	ER/M 2	ER/M 2	ER/M 2		ER/M 2
		E					ER/M 2	ER/M 2	ER/M 2	ER/M 2		ER/M 2
R-49	Ordnance inside the hull explodes as a result of a hull collapse	P										
		O						TP/M 1				TP/M 1
		E						TP/M 1				TP/M 1
R-50	Pressurised air inside or outside the hull rupture as a result of a hull collapse	P										
		O						TP/M 1				TP/M 1
		E						TP/M 1				TP/M 1
R-51	Pressurised air inside or outside the hull rupture as a result of a hull collapse and influence the torpedoes resulting in an explosion	P										
		O						TP/CA 4				TP/CA 4
		E						TP/DA 5				TP/DA 5
R-53	Torpedoes inside or outside the hull explodes as a result of a hull	P										
		O						TP/CA 4				TP/CA 4



Risk	Name		Criticality (see Figure 6-3)									
	collapse	E						TP/DA 5				TP/DA 5

APPENDIX

B
ARMAMENT AND PRESSURIZED AIR

8.1 Armament /6/

Literature found on German submarines and their armament is not always consistent when it comes to the type of armament used. When working with ordnance, the general rule is to plan for worst case scenario. The type of armament considered most dangerous for accomplishing a capping or salvage operation is therefore assumed in the following chapters. Likewise the highest number of each type of ordnance has been chosen.

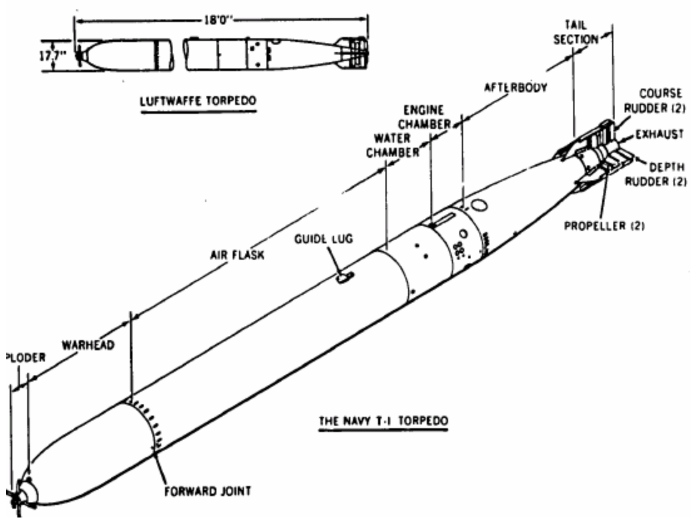
Armament on board U-534 has been used when information about the armament of U-864 has been limited.

8.1.1 Torpedoes

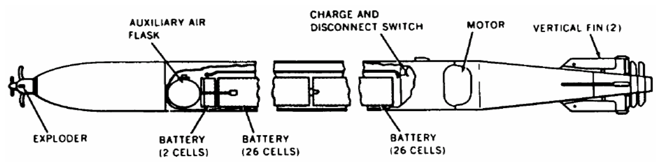
Type	T1 (G7A) or T3 (G7E)
Number	27 (confirmation by Oesten /1/)
Weight of explosives	650 pound = 295 kg hexanite (TNT equivalent factor varies dependent on mixture of hexanitrodeiphenylamine, aluminium and TNT, but >1) The T1 torpedo contains a pressurised air cylinder of 670 litres, pressure 200 bars
Fuse	Exploder type PI G7A AZ (impact), PI G7A MZ (magnetic)
Functionality	

Figure 8-1 The torpedo G7e /3/

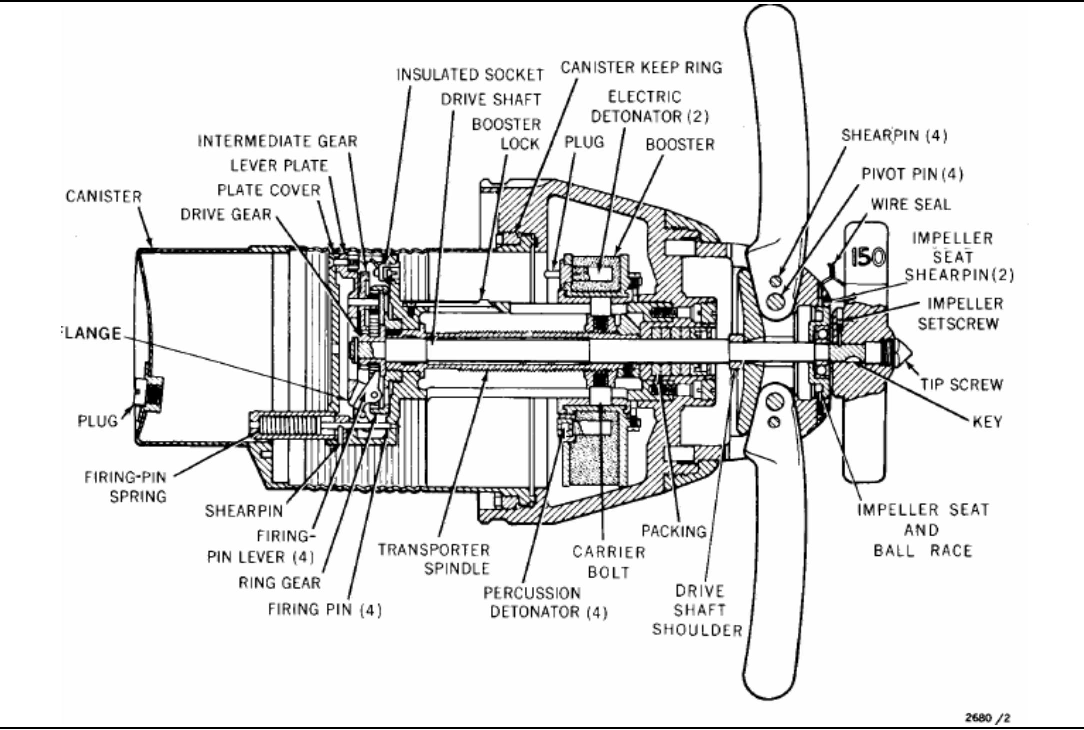
T 1 combustion engine



T 3 electrical engine



Exploder



Storage

In total 27 torpedoes can be stored on the submarine. 12 of these are stored on the outside of the pressure hull underneath the casing (see Figure 8-3, page B-4).
Inside the submarine: 4 torpedoes in the torpedo tubes fore (see Figure 8-2, page B-4) and 6 in fore torpedo room, 2 torpedoes in the torpedo tubes aft and 3 in the aft torpedo room.

Conclusion

Based on different engine system, the T1 torpedo has a combustion engine and contains a pressurised air cylinder. T3 is an electric driven torpedo and contains one small high pressure cylinder. Assumes similar type of explosives have been used in both types of torpedoes. Based on experience, the explosive should still be stable, and functional. In all types of exploder (fuzes) for these types of torpedoes. The explosive chain is mechanically separated (broken) when the torpedo has not been fired.

Based on worst case, all risk evaluations are based on torpedo type T1. Assumes that all torpedoes inside the pressure hull has an exploder (fuze) installed in the warhead, and the air cylinder in these torpedoes are assumed to be pressurised. If the structure of the pistol is intact, the torpedo is assessed safe to handle. Based on experience from WWII German ordnance, the explosives are assessed still stable and no decrease in effect of the explosives. If the high pressure air cylinder ruptures, it is assessed only theoretical possibility that it results in a detonation of the explosives in the torpedo.

Salvage

When the submarine is raised towards the surface, the ambient pressure will be reduced. It is assessed only theoretically possible that this will cause a detonation of explosives.

The possibility of a leakage from the pressurised air cylinder will increase during ascent (caused by reduction of the ambient pressure) and is assed to be remote.

Capping

The possibility of a detonation during capping, without a greater external influence, is assessed only to be theoretically possible.

If a high pressure air cylinder starts leaking, due to corrosion, it is assessed that a rupture of the pressurised air cylinder is unlikely.

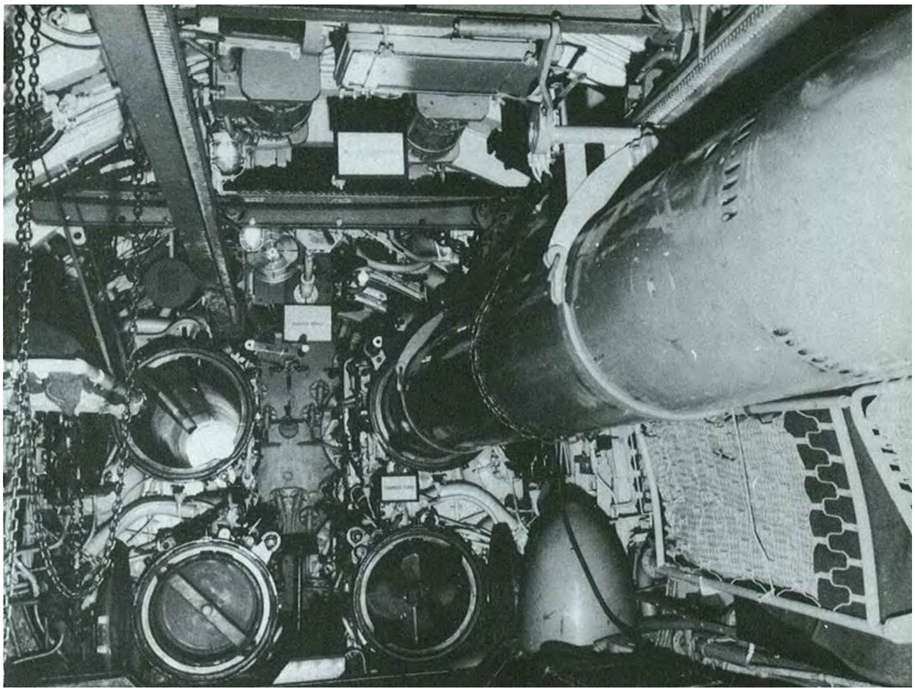


Figure 8-2 U-505 (Type IX C, fore torpedoroom) /4/.. In front are the four torpedo tubes. In the ceiling to the right is a torpedo ready to be loaded into the tube. The torpedoroom in a Type IX D/2 is similar.

Figure 8-3 The after deck of U-166, a type IX C submarine (similar to U-864, but approximately 11 metres shorter) /7/. This picture shows the wooden trapdoors on each side which torpedoes are stored beneath. A total of 12 torpedoes is expected to have been stored like this on U-864.

8.1.2 105mm

Type	Utof 105/45
Number	Total 202
Weight of explosives	High Explosive (unit weight 23,3 kg), High explosive weight approximately 1,4 kg Armour piercing (23.3 kg), high explosive weight approximately 1,16 kg Star shell (14,7 kg), explosive weight unknown, contains no high explosive. 1,5 -2 kg propellant.
Fuse	Type Kz C/28, Gr.Z m.V Iz and Zt.Z s/30 impact and time fuze. Contains very small amounts of explosives
Functionality	Explosives are assessed still functional. Fuze mechanism is assessed likely functional.
Storage	Total 202. 32 stored outside the pressure hull close to the 105mm cannon (see Figure 8-4), 170 divided in two different ammunition storages onboard. One storage area below the central (may have blown away when the submarine was torpedoed) and one below the galley (underneath of the 105mm cannon).
Conclusion	**Salvage / Capping** • It is assessed that the risk concerning 105 mm ammunition is insignificant when salvaging or capping.

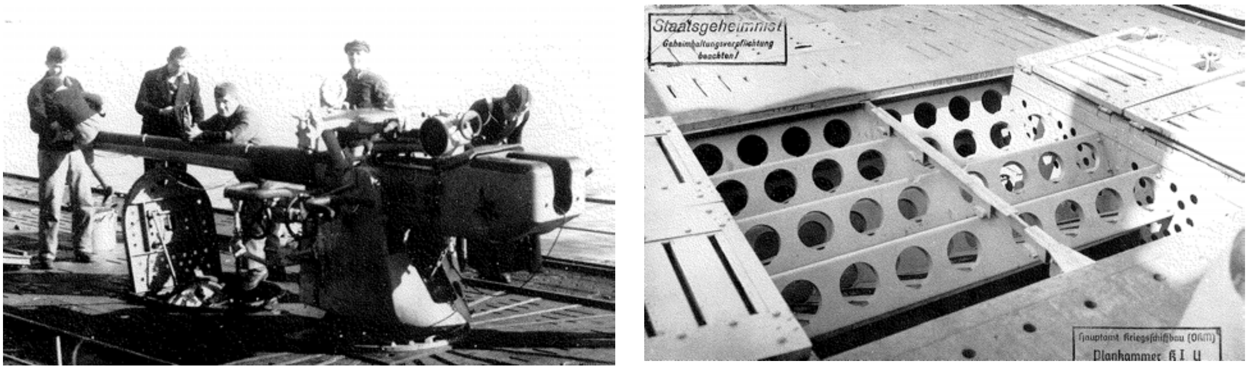


Figure 8-4 Left: U-506's (type IX C) 105 mm cannon, similar to that of U-864. Right: storage for 32 Utof 105/45 grenades, located at the 105 mm cannon on the ceising /2/.

8.1.3 37 mm (based on numbers from U 534)

Type	Assumed to be general purpose high explosive projectiles.
Number	1150
Weight of explosives	575 kg total weight, explosive weight: approximately 10-20%
Fuse	Most likely impact
Functionality	Explosives will be functional
Storage (maximum)	Probably stored outside the pressure hull and in internal magazines. 60 projectiles under ”winter-garden” (aft of tower).
Conclusion	May contain a tracer in base, which will self destruct the projectile if it burns out. **Salvage** • Should be kept wet until they are removed from the wreck, and kept wet until moved to the deposit site. • It is assessed that the risk concerning 37 mm ammunition is insignificant when salvaging. **Capping** • It is assessed that the risk concerning 37 mm ammunition is insignificant when capping.

8.1.4 20 mm

Type	20mm Flac 30/42 cannon
Number	Unknown (U 534: 3060)
Weight of explosives	Unknown (U 534: total weight 612 kg, estimated explosive weight 100 kg)
Fuse	Impact
Functionality	-
Storage	Probably stored both outside hull and in inside magazines.
Conclusion	May contain a tracer in base, which will self destruct the projectile if it burns out. May also contain a self-destroying fuze. **Salvage** • Should be kept wet until they are removed from the wreck, and kept wet until moved to the deposit site. • It is assessed that the risk concerning 20 mm ammunition is insignificant when salvaging. **Capping** • It is assessed that the risk concerning 20 mm ammunition is insignificant when capping.

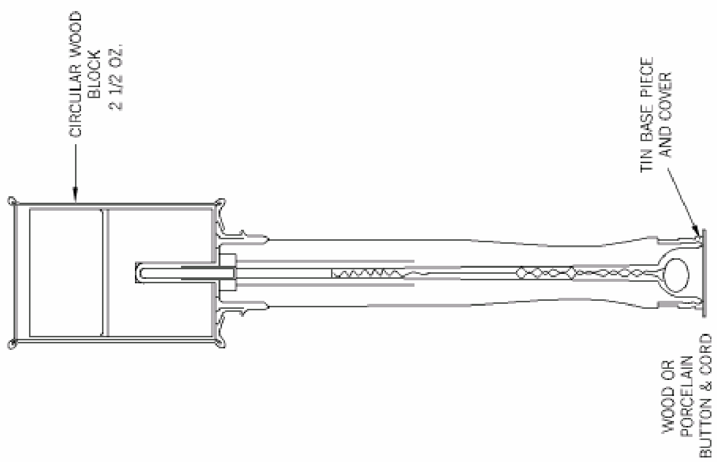
8.1.5 Demolition charges

Type	High Explosive
Number	Unknown
Weight of explosives	500 kg TNT (based on experience from U 534)
Fuse	Detonator and safety fuze stored separately
Functionality	Pull igniter
Storage	Probably in ammunition magazines
Conclusion	**Salvage/capping** • Demolition charges are safe to handle when salvaging or capping. • It is assessed that the risk concerning demolition charges are insignificant when salvaging or capping.

8.1.6 Small arms ammunition (SAA)

Type	7,65 mm, 9 mm, 8 mm
Number	3000 (Found onboard U 534)
Weight of explosives	-
Fuse	-
Functionality	-
Storage	Throughout the submarine (based on experience from U 534)
Conclusions	**Salvage/capping** • Small arms ammunition safe to handle when salvaging or capping. • It is assessed that the risk concerning small arms ammunition is insignificant when salvaging or capping.

8.1.7 Hand grenade

Type	Stick grenade
Number	30 (Found onboard U 534)
Weight of explosives	Approx 100 g each
Fuse	Unknown
Functionality	
Storage	Unknown, found on several places during the salvage of U-534
Conclusion	Usually stored separately (stick and grenade). Explosives might be very sensitive, due to picric acid. **Salvage** • If salvaged, avoid drying. The longer the submarine is stored in a dry environment, the more sensitive the grenade will be. • It is assessed that the risk concerning stick grenades are insignificant when salvaging. **Capping** • It is assessed that the risk concerning stick grenades are insignificant when capping.

8.2 Pressurised air cylinders

All submarines need a large amount of compressed air, mainly to force the water out of the main ballast tanks when the submarine is surfacing, and secondly to regulate the submarine's buoyancy. In addition to this, the submarine has got compressed air to start the engines, for BIBS-system (Build In Breathing System) and in addition cylinders with compressed oxygen.

8.2.1 High pressure air for ballast tanks

Type	Pressurised air cylinder
Volume	Unknown
Pressure	200 bar
Location	Unknown
Conclusion	Assessed empty due to missing mid section where the main ballast blow panel is placed. **Salvage/capping** • It is assessed that the risk concerning high pressure air for ballast tanks are insignificant when salvaging capping.

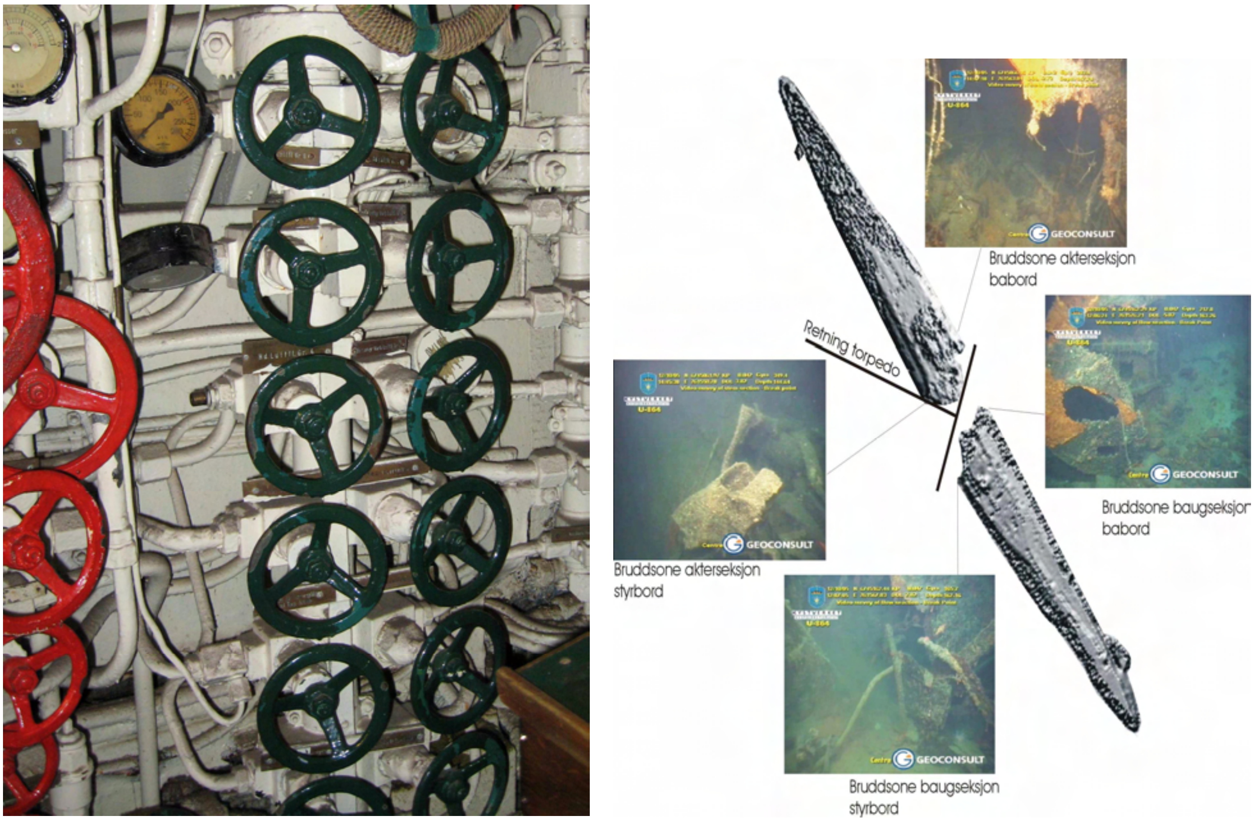


Figure 8-5 Left: U-995's main ballast blow panel in the central similar to that of U-864. Right: An illustration of where U-864 was split into two parts. This shows that the central is missing, including the main ballast blow panel /5/.

8.2.2 BIBS (Built In Breathing System)

Type	Pressurised air cylinder
Volume	Unknown
Pressure	200 bar
Location	Unknown
Conclusion	Assessed likely pressurised. **Salvage/capping** • It is assessed that the risk concerning BIBS is insignificant when salvaging or capping.

8.2.3 Starting air for diesel engines

Type	Pressurised air cylinder
Volume	Unknown
Pressure	Assumed 40 bars,
Location	Close to engines
Conclusion	Assessed likely empty. **Salvage/capping** • It is assessed that the risk concerning starting air for diesels is insignificant when salvaging or capping.

8.2.4 Oxygen tanks (O^2)

Type	Pressurised air cylinder
Volume	13 x 50 l (IX C class)
Pressure	200 bar
Location	Aft of toilet and in fore section
Conclusion	Assessed likely pressurised. **Salvage/capping** • It is assessed that the risk concerning oxygen tanks are insignificant when salvaging or capping.

TECHNICAL REPORT

KYSTVERKET
NORWEGIAN COASTAL ADMINISTRATION

SALVAGE OF U864 - SUPPLEMENTARY STUDIES - METAL DETECTOR

REPORT NO. 23916-3
REVISION NO. 02

DET NORSKE VERITAS

DET NORSKE VERITAS

TECHNICAL REPORT

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Date of first issue:	Project No.:
2008-07-04	23916
Approved by: Carl Erik Høy-Petersen, Senior Consultant	Organisational unit: DNV Consulting
Client: Kystverket (Norwegian Coastal Administration)	Client ref.: Hans Petter Mortensholm

Summary:

The German submarine U-864 was torpedoed by the British submarine Venturer on February 9 1945 and sunk approximately two nautical miles west of the island Fedje in Hordaland. U-864 was carrying about 67 metric tonnes of metallic mercury that implies a threat to the marine environment. In September 2007 The Norwegian Costal Administration commissioned Det Norske Veritas to further investigate different alternatives to salvage the wreck and remove the mercury from the seabed.

The objective of this supplementary study is to propose a survey method, or combination of methods, that will give the best probability of detecting sub-bottom mercury canisters around the wreck of U-864.

DNV's overall conclusion is: A combination of single caesium vapour magnetometer and pipe tracker, positioned by acoustic LBL technique, is the preferred method to locate sub-bottom canisters. The searching will take at least six days and all surface debris must be cleared from the site prior to operation.

Report No.:	Subject Group:
23916-3	

Report title: Salvage of U-864 – Supplementary Study – Metal detector

Indexing terms

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TECHNICAL REPORT

The German submarine U-864 was torpedoed by the British submarine Venturer on February 9 1945 and sunk approximately two nautical miles west of the island Fedje in Hordaland. U-864 was carrying about 67 metric tonnes of metallic mercury that implies a threat to the marine environment.

In September 2007 The Norwegian Costal Administration commissioned Det Norske Veritas to further investigate different alternatives to salvage the wreck and remove the mercury from the seabed.

1 SUMMARY

This report is *Supplementary Study No. 3: Metal detector*, one of twelve supplementary studies supporting the overall report regarding U-864 (Det Norske Veritas Report No. 23916) prepared by Det Norske Veritas (DNV).DNV' conclusions are:

The objective of this supplementary study is to propose a survey method, or combination of methods, that will give the best probability of detecting sub-bottom mercury canisters around the wreck of U-864.

DNV's overall conclusion is:

A combination of single caesium vapour magnetometer and pipe tracker, positioned by acoustic LBL technique, is the preferred method to locate sub-bottom canisters. The searching will take at least six days and all surface debris must be cleared from the site prior to operation.

DNV's supporting conclusions are:

C1. None of the techniques that have been discussed will be viable to detect sub-bottom canisters, unless surface debris is cleared from the site prior to operation.

C2. A combination of single caesium vapour magnetometer and pipe tracker (metal detector) systems are assessed to be the preferred method to locate mercury canisters below seabed.

C3. It is recommended that survey positioning should be by acoustic LBL technique – more specifically, wideband technology is proposed. This will give decimetric accuracy and high repeatability over a wide area.

C4. Searching for sub-bottom mercury canisters will take at least six days with no weather downtime, and may be performed by one survey-ship with one or two ROVs.

A Gradiometer multi-sensor system deployed from an ROV has the highest probability of any single sensor system of characterising sub-bottom mercury canisters. However, the ROV variation of this sensor does not yet exist, and this technique will carry high risk and development costs.

A combination of single caesium vapour magnetometer and pipe tracker (metal detector) systems (which can both be deployed from ROV) has the second highest probability of characterising sub-bottom mercury canisters. Both systems can be made available after acceptable preparation cost, but survey time will be increased because the site has to be visited by the ROV twice. This is assessed to be preferred methodoly.

Whatever data acquisition techniques are used, it will be good practice to start the survey by testing the techniques in a small area where there is a high probability that canisters are among the sub-bottom debris. Further, it will be good practice to retrieve one or more of the targets to verify the technique.

The suggested systems demand the ROV and survey vessel to fulfil several requirements. These are listed in chapter 6.

DNV's ranking of the described techniques for detection of sub-bottom mercury canisters and ROV-positioning systems are listed in the following table:

Method	Rank	Duration	Advantages	Disadvantages
Detection systems				
Combination of magnetometer and pipe tracker	1	116 hours	Most efficient use of resources to identify targets as mercury canisters	High start-up costs and some technical risk
Caesium vapour magnetometer	2	44 hours	Can cover relatively wide swath during search pattern	Must be towed from ROV, therefore will development costs be incurred. Specialist personnel required
Pipe tracker	3	48 hours	Is deployed on ROV as standard. Possible to identify target as Hg canister	Assumes that target depth is known
Parametric echo sounder	4	N/A	Can be deployed on ROV as standard. High accuracy. Could be used for pre-survey bathymetry.	Cannot classify targets.
Positioning systems				
Acoustic LBL technique for positioning ROV	1		High accuracy and repeatability if many vessels will work in the area	24 hour installation overhead.
Acoustic USBL technique for positioning ROV	2		Most vessels have this system already installed, so low installation overhead.	Poor repeatability and accuracy if many vessels will work in the area

The rest of *Supplementary Study No. 3: Metal detector* details the arguments behind the conclusions.

TECHNICAL REPORT

Den tyske ubåten U-864 ble torpedert av den britiske ubåten Venturer den 9. februar 1945 og sank omtrent to nautiske mil vest for øya Fedje i Hordaland. U-864 var lastet med omtrent 67 tonn med metallisk kvikksølv som utgjør en fare for det marine miljøet.

I September 2007 tildelte Kystverket Det Norske Veritas oppdraget med å nærmere utrede ulike alternativer for heving av vrak og fjerning av kvikksølv fra havbunnen.

2 SAMMENDRAG (NORSK)

Denne rapporten er *Tilleggsutredning nr. 3: Metall detektor*, en av tolv tilleggsutredninger som understøtter hovedrapporten vedrørende U-864 (Det Norske Veritas Report No. 23916) utarbeidet av Det Norske Veritas (DNV).

Formålet med denne tilleggsutredningen er å foreslå en kartleggingsmetode, eller kombinasjon av metoder, som vil gi høyest sannsynlighet for å detektere kvikksølvbeholdere som ligger begravd i bunnsedimentene i området rundt vraket av U-864.

DNV sin overordnede konklusjon er:

En kombinasjon av *singel cesium vapour magnetometer* og *pipe tracker*, posisjonert ved bruk av *acoustic LBL technique*, er vurdert å være den foretrukne metoden for å lokalisere begravde kvikksølvbeholdere. Gjennomføring av søket vil minimum ta seks dager og alle vrakdeler må være fjernet fra området i forkant av søket.

DNV underbygger denne konklusjonen med:

C1. Ingen av metodene som er diskutert er gjennomførbare med mindre vrakdeler allerede er fjernet fra havbunnsoverflaten.

C2. En kombinasjon av *single cesium vapour magnetometer* og *pipe tracker* (metalldetektor) systemer er vurdert å være den foretrukne metoden for å lokalisere begravde kvikksølvbeholdere.

C3. Det anbefales at søket posisjoneres ved bruk av *acoustic LBL technique* – mer spesifikt er wideband-teknologi foreslått. Dette vil gi desimeternøyaktighet med høy repetérbarhet over store områder.

C4. Søk etter nedgravde kvikksølvbeholdere vil ta minimum seks dager uten noe utsettelser pga. været, og kan utføres av et survey-skip med én eller to undervannsfartøy (ROV).

Et *Gradiometer multi-sensor system* tauet etter ROV har høyest forventning blant de enkeltstående sensorsystemene til å karakterisere nedgravde kvikksølvbeholdere. Men ROVvarianten av dette sensorsystemet finnes ikke, derfor innebærer denne teknikken høy risiko og utviklingskostnader.

En kombinasjon av *single cesium vapour magnetometer* og *pipe tracker* (metalldetektor) systemer (som begge kan deployeres fra ROV) har nest høyest sannsynlighet for å kjenne igjen kvikksølvbeholdere begravet i sjøbunnen. Begge systemer kan benyttes med akseptable forberedelseskostnader, men søketiden vil øke siden ROVen må gjennomsøke området to ganger. Dette er vurdert å være den foretrukne metoden.

Uansett valg av sensorsystem, vil god praksis være å starte undersøkelsene med å teste ut metodikken i et mindre område hvor det er høy sannsynlighet for at kvikksølvbeholdere er blant vrakdelene på bunnen. Videre er det anbefalt å hente opp ett eller flere lokaliserte objekter for å verifisere teknikken.

De foreslåtte systemene krever at ROVen og survey-skipet oppfyller flere krav. Disse er kravene er liste i kapittel 6.

DNV sin rangering av de beskrevne teknikker for detektering av kvikksølvbeholdere som er begravet i sjøbunnen og ROV-posisjoneringssystemer er listet opp i tabellen nedenfor:

Metode	Rangering	Varighet	Fordeler	Ulemper
Deteksjonssystemer				
Kombinasjon av *magnetometer* og *pipe tracker*	1	116 timer	Mest effektiv bruk av ressurser for å identifisere objekter som kvikksølv-beholdere.	Høye oppstarts-kostnader og noe teknisk risiko.
Caesium vapour magnetometer	2	44 timer	Kan dekke relativt brede søkefelt under søk.	Må taues etter en ROV, noe som vil medføre utviklings-kostnader. Krever spesialister.
Pipe tracker	3	48 hours	Is deployed on ROV as standard. Possible to identify target as Hg canister	Assumes that target depth is known
Parametric echo sounder	4	N/A	Kan anvendes på en standard ROV. Høy nøyaktighet. Kan bli benyttet til batymetri forundersøkelser.	Kan ikke klassifisere mål.
Positioning systems				
Acoustic LBL technique for possisjonering av ROV	1		Høy nøyaktighet og repeterbarhet dersom flere fartøy opererer i det samme området.	24 timer installasjons-kostnader.
Acoustic USBL technique for possisjonering av ROV	2		De fleste fartøy har allerede dette systemet montert, hvilket gir lave installasjons-kostnader.	Lav repeterbarhet og nøyaktighet dersom flere fartøy opererer i det samme området.

Resten av *Tilleggsutredning nr. 3: Metall detektor* utdyper argumentene bak konklusjonene.

3 INTRODUCTION

3.1 Background

The German submarine U-864 was sunk by the British submarine Venturer on 9 February 1945, approximately 2 nautical miles west of the island Fedje in Hordaland (Figure 3-1). The submarine was on its way from Germany via Norway to Japan with war material and according to historical documents; U-864 was carrying about 67 metric ton of metallic (liquid) mercury, stored in steel canisters in the keel. The U-864, which was broken into two main parts as a result of the torpedo hit, was found at 150-175 m depth by the Royal Norwegian Navy in March 2003. The Norwegian Costal Administration (NCA) has, on behalf of the Ministry of Fisheries and Coastal Affairs, been performing several studies on how the risk that the mercury load constitutes to the environment can be handled. In December 2006 NCA delivered a report to the Ministry where they recommended that the wreck of the submarine should be encapsulated and that the surrounding mercury-contaminated sediments should be capped. In April 2007 the Ministry of Fisheries and Coastal Affairs decided to further investigate the salvaging alternative before a final decision is taken about the mercury load.

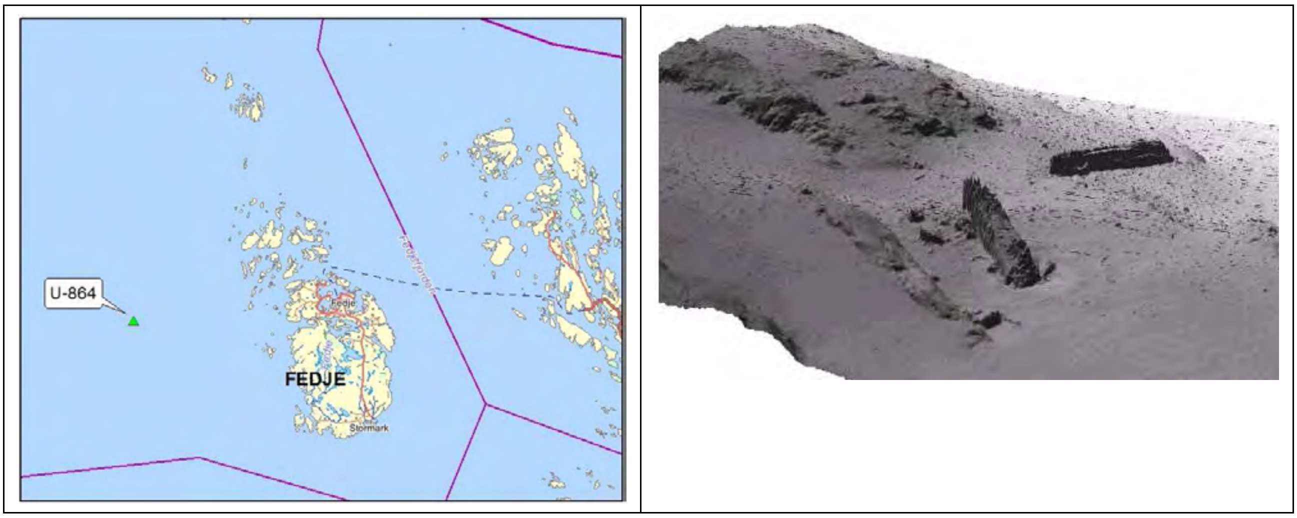


Figure 3-1 Location (left) and a sonar picture of the wreck of U-864 on seabed (right) (from Geoconsult).

3.2 DNV's task

In September 2007 NCA commissioned Det Norske Veritas (DNV) the contract to further investigate the salvaging alternative. The contract includes:

- DNV shall support NCA in announcing a tender competition for innovators which have suggestions for an environmentally safe/acceptable salvage concept or technology. Selected innovators will receive a remuneration to improve and specify their salvage concept or technology.

- DNV shall support NCA in announcing a tender competition for salvage contractors to perform an environmentally justifiable salvage of U-864.
- DNV shall evaluate the suggested salvage methods and identify the preferred salvage method.
- The preferred salvage method shall be compared with the suggested encapsulation/capping method from 2006. (DNV shall give a recommendation of which measure that should be taken and state the reason for this recommendation.)
- DNV shall perform twelve supplementary studies which will serve as a support when the decision is taken about which measure that should be chosen for removing the environmental threat related to U-864. The twelve studies are:

1. *Corrosion*. Probability and scenarios for corrosion on steel canisters and the hull of the submarine.
2. *Explosives.* Probability and consequences of an explosion during salvaging from explosives or compressed air tanks.
3. *Metal detector*. The possibilities and limitations of using metal detectors for finding mercury canisters.
4. *The mid ship section*. Study the possibility that the mid section has drifted away.
5. *Dredging*. Study how the mercury-contaminated seabed can be removed around the wreck with a minimum of spreading and turbidity.
6. *Disposal*. Consequences for the environment and the health and safety of personnel if mercury and mercury-contaminated sediments are taken up and disposed of.
7. *Cargo.* Gather the historical information about the cargo in U-864. Assess the location and content of the cargo.
8. *Relocation and safeguarding.* Analyse which routes that can be used when mercury canisters are relocated to a sheltered location.
9. *Monitoring.* The effects of the measures that are taken have to be documented over time. An initial programme shall be prepared for monitoring the contamination before, during and after salvaging.
10. *Risk related to leakage.* Study the consequences if mercury is unintentionally leaked and spreading during a salvage or relocation of U-864.
11. *Assessment of future spreading of mercury for the capping alternative*. The consequences of spreading of mercury if the area is capped in an eternal perspective.
12. *Use of divers.* Study the risks related to use of divers during the salvage operation in a safety, health and environmental aspect and compare with use of ROV.

3.3 Scope of this report

This report is *Supplementary Study No. 3:Metal detector.* Aquadyne AS was commissioned by Det Norske Veritas to contribute in the work of this supplementary study.

A key requirement was to "Propose a survey method or combination of methods that will give the best probability of detecting mercury canisters". Within this requirement, the scope of work specified was:

- An overall description of available methods for the detection of mercury canisters (volume around 2.5 litres) and other metal parts of the wreck, buried or partly buried in sediments, from seabed level and 0.5m down (acoustic, magnetometer and metal detection).
- Give a technical description of the above methods for detection of mercury canisters.
- Indicate ROV/vessel requirements
- Estimate the duration of the survey using the above methods, survey area being 500m x 500m (excluding waiting on weather)
- Propose a suitable Subsea positioning system relevant for survey and general Subsea construction work.

During 2003 – 2006 a number of surveys had been carried out in this area and produced significant information about seabed topography, sub-surface geology, distribution and description of debris, and distribution of mercury levels. This Report has been made with reference to this information.

The structure of this report:

- Chapter 4: Available methods to locate mercury canisters
- Chapter 5: Subsea positioning systems
- Chapter 6: ROV and vessel requirements
- Chapter 7: Duration of survey
- Chapter 8: References

4 AVAILABLE METHODS TO LOCATE MERCURY CANISTERS

DNV's conclusions are:

C1. None of the techniques that have been discussed will be viable to detect sub-bottom canisters, unless surface debris is cleared from the site prior to operation.

C2. A combination of single caesium vapour magnetometer and pipe tracker (metal detector) systems are assessed to be the preferred method to locate mercury canisters below seabed.

4.1 Overall description of available methods

A commercial Pipe Tracker system is, in effect an ROV-mounted metal detector and can be used to find targets below the seabed. Commercial sub-bottom profilers are well established systems which have been used for ordnance searches on several occasions. There are a number of commercial magnetometers available for subsea use.

4.1.1 The Target

In general, detecting the presence of an object hidden below the seabed depends on measuring the physical characteristics of the object from a remote sensor i.e. without touching the object. No single characteristic will uniquely identify the object, but a combination of characteristics acquired by different techniques may increase the probability of classifying similar objects. The final stage for identifying the object would be to recover typical samples, and determine the 'truth' of the classification ("Ground truthing").

Mercury on this site is believed to be contained in two types of mild steel canisters as follows:

Table 4-1 Mercury canisters

Forged container (flask shaped)	Welded container (cylinder shaped)
Length of cylindrical section: 280 mm Diameter (OD) of cylindrical section: 115 mm*) Thickness of cylindrical section: 5 mm Length of top section: 85 mm Length of plug (above flask connection): 40 mm	Length of cylinder: 250 mm Diameter (OD) of cylinder: 130 mm Thickness of cylinder: estimated 10 mm (+1/-2 mm) Weight empty – 4.2 Kg.
Both of these containers hold 2.5 litres of mercury weighing around 35 Kg.	

Figure 4-1. Original and modern mercury canisters

The relevant physical characteristics of the canisters of mercury could therefore be:

- Weight – heavy with the consequence that the container may sink through the sedimentary layers and will probably not be distributed far away from the wreck.
- Conductivity - both mercury and ferrous material – with the consequence that eddy currents could be induced in the object.
- Density – denser than sea water and sediments – with the consequence that more acoustic energy will be reflected from the dense object than from the surrounding materials.
- Magnetism – only the ferrous material – with the consequence that there will be an anomaly in the earth's magnetic field very close to the object.

4.1.2 Canister burial depth

This report will assume that canisters containing mercury will sink through the sandy sediments and rest on clay at a depth from seabed level to 0.5 metres. A simplified calculation (see Appendix B for calculations) indicates that the welded canisters (cylinder shaped) will achieve a maximum free fall velocity (terminal velocity) of 8 m/s. This will result in a penetration depth of approximately 700mm, with a flask length of 300mm this results in a mean canister depth of 550mm. For the forged canisters (flasked shaped) the maximum free fall velocity (terminal velocity) and furthermore the penetration depth is highly dependent on the orientation of the canisters. The maximum free fall velocity (terminal velocity) varies from 5 to 18 m/s for a canister falling broadside and axially respectively. This will result in a penetration depth varying from 500 mm to 3100mm. This figure is highly sensitive to local soil variations and variations in free fall velocity. The canisters will most likely not achieve terminal velocity, due to directional deviation and missing straight-line stability, which will reduce the expected penetration depth.

4.1.3 Conductivity – metal detection

A commercial Pipe Tracker system is, in effect an ROV-mounted metal detector, and can be used to find targets below the seabed. However, as will be discussed in chapter 4.2.1, the probability of detecting the mercury canisters will be reduced because the target is small. Tests have been carried out on an example of the only commercial Pipe Tracker available to find out what the operating ranges of the system are.

4.1.4 Density – acoustics

Commercial sub-bottom profilers are well established systems which have been used for ordnance searches on several occasions. While typical systems can plot sub-sea targets accurately, the footprint for the acoustic transmission is small, and this type of device will require a tight survey grid. This technique cannot, on its own, be used to characterise the target. This will be discussed further in chapter 4.2.

4.1.5 Magnetism - magnetometer

There are a number of commercial magnetometers available for Subsea use. They fall into two categories; the Caesium Vapour Magnetometer and the Overhauser Magnetometer (as described in Appendix A). In both cases the sensor must be towed near the seabed. In this area, the irregularity of the sea-bed topography and the presence of the two parts of the wreck present challenging obstructions.

4.1.6 Other techniques

There may be other techniques which could be used, but this report focuses on what methods are available and survey techniques which are well established.

4.2 TECHNICAL DESCRIPTION OF METHODS

4.2.1 The Pipe Tracker.

The tested example of a pipe tracker can be used as a search tool for the canisters, provided that the ROV flies at less than 135cms above the target (which could be very close to the seabed), and the adjacent survey lines are not more than 150cms apart.

A 2 metre altitude restriction given by the Norwegian Pollution Authorities may jeopardise the possibility of finding buried canisters by use of the Pipe Tracker.(/17/)

Provided that the depth of burial of the canisters is known when using the Pipe-tracker method (e.g. from parametric echo sounder survey – ref. chapter 4.2.2), the flying height of the ROV is predetermined and the correct Target Scaling Factor is used, targets falling within the 150cm horizontal 'window', and appearing at the correct height, could be characterised as having a similar size and ferrous metal content to the mercury canisters.

It is recommended that prior to a Pipe Tracker survey, a precise Target Scaling Calibration of one of the canisters is carried out at a manufacturer's approved site.

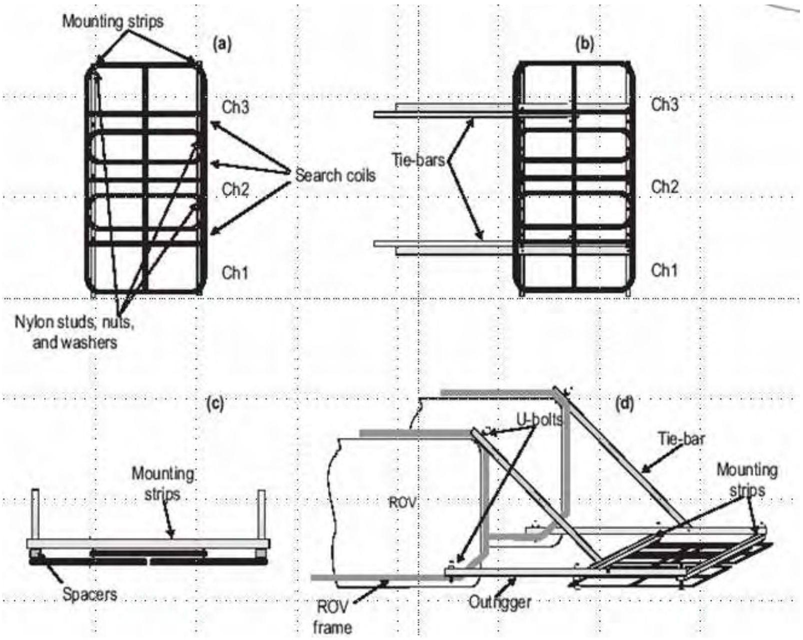
4.2.1.1 Operating Theory – Pulse Induction

See Appendix A.

4.2.1.2 Operating Practice

A typical pipe tracker delivers a VRT (Vertical Range to Target) and the distance of the target to left or right of the centre of the three-coil array (Horizontal Offset). This information, together with the ‘raw’ coil signal strength data can be output to a vessel survey system where it will be tagged with time and position.

The coils are mounted on an ROV using non-metallic components.



4-2. Typical Pipe Tracker Mounting frame details (/1/)

The ROV ‘flies’ at a predetermined height above the seabed and records the VRT and horizontal offset (typically the target is a pipeline). (/1/, /2/)

In a U-864 survey application the ROV would fly on a search pattern. The flying height and the distance between survey lines is dependant on the size of the target. The accuracy of the VRT and horizontal offset measurement will depend on a pre-survey calibration of the system using a sample of the target. The calibration process results in a unique scaling factor for the target at a particular operating height (Target Scaling Factor).

A preliminary calibration of the recovered, now empty canister found at the wreck site was carried out at Asker on December 4 2007. For comparison, the system was calibrated against an empty, modern canister, and a modern canister which was filled with mercury.

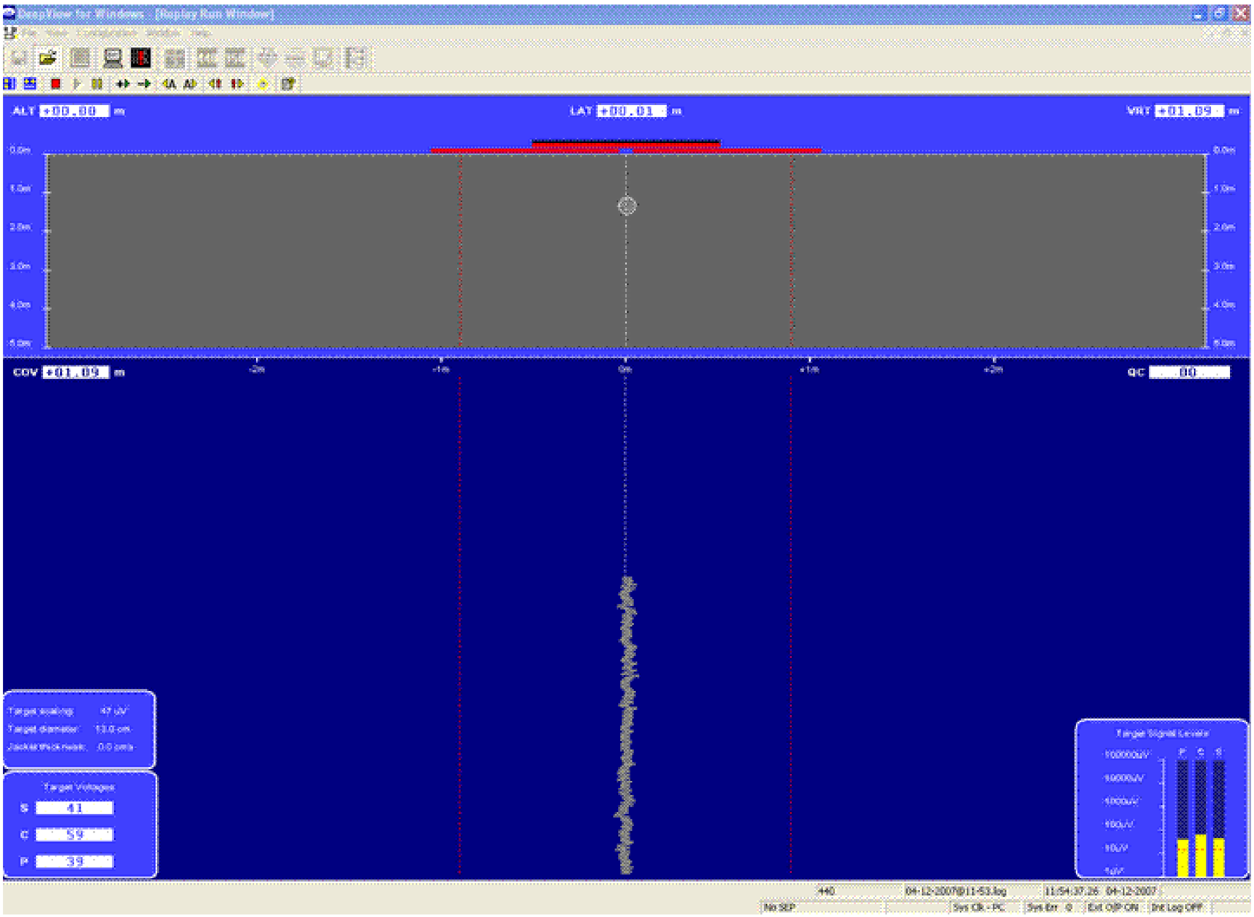


Figure 4-3. Screen dump of canister detected at VRT +01.09 metres below centre of coil.

Figure 4-4. Target Scaling (Calibration) at Asker

This preliminary exercise produced the following information:

- For the recovered canister an accurate VRT could be measured up to a maximum of 135 centimetres above top of target
- At this height, maximum horizontal offset to the canister was 75 cms (either left or right).
- A Target Scaling Factor could be set for the recovered canister, and this did not change significantly either for the empty modern canister, or the full modern canister.
- With two canisters, the system had to be re-calibrated to find a new Target Scaling Factor.

4.2.2 ROV-mounted sub-bottom profiler.

The ROV mounted sub-bottom profiler would probably detect the existence of targets which have settled at the clay surface. However, most of the area is reported as having large numbers of boulders and it is possible that the sub-bottom profiler will not be able to differentiate between boulders and canisters.

The sub-bottom profiler would not be able to classify or characterise the targets. Positioning of such visible targets will be accurate with sub-bottom profiler, depending on ROV flying height.

The sub-bottom profiler will accurately measure the depth of sediment between seabed and clay surface. By using sub-bottom profiler the bathymetry and subsurface data could be acquired from a 5 metre grid, for example and a sub-surface bathymetry map could be produced by normal interpolation processes. The sub-bottom profiler can therefore be used to compliment a pipe tracker survey in positioning application.

4.2.2.1 Operating Theory – Non-linear acoustics

See Appendix A.

4.2.2.2 Operating Practice

For a U-864 sub-bottom survey, a suitable sub-bottom profiler system can be used from an ROV working at around 10m above the seabed. At this range, the footprint will be around 60cm, so positioning of objects relative to the transceiver will be more accurate.

Three of the only commercially available ROV-mounted systems have been supplied to different survey contractors in Norway.

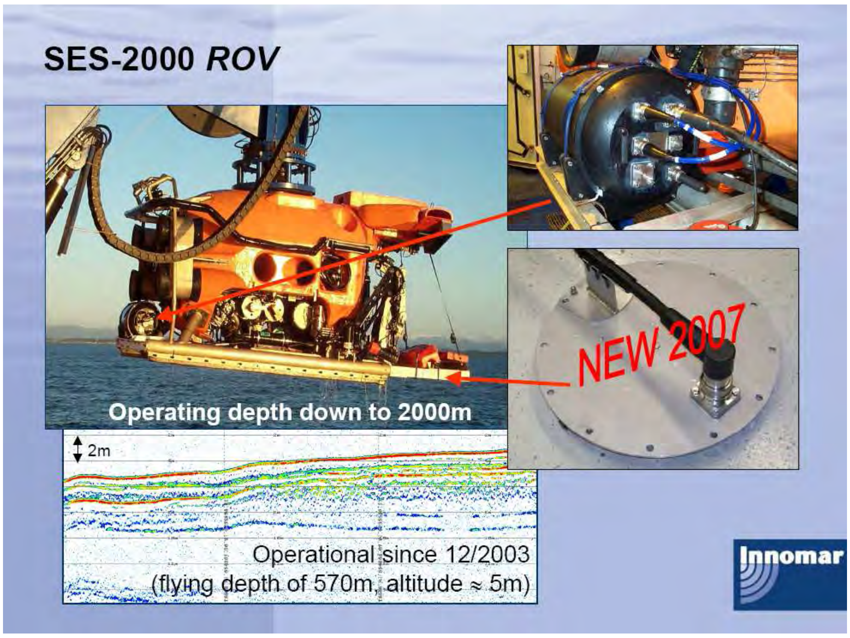


Figure 4-5. Typical ROV-mounted sub-bottom profiler (/5/)

With sub-bottom profiler system, detecting and classifying small objects is still difficult because:

- The low frequency with a long wavelength may ‘overlook’ small objects, such as the mercury canisters.
- The target strength will depend on the angle of incidence of the acoustic energy on the target. More energy will be reflected from the long side of the canister than from the end. It is also possible that the incident energy will refract off the curved surface of the canister and not be returned at all.
- It is not possible yet under real conditions to distinguish mercury containers from other metal objects based on the acoustic return.

On the positive side, the analysis of core samples will help to ‘tune’ the sounder by selecting a secondary frequency to achieve the best delineation of the clay surface beneath the sediment.

Assuming that the targets have settled at the clay surface it will be possible to estimate the height of the seabed above the canisters along each survey line.

Knowing this will help to select the ROV flying height above seabed during a pipe tracker survey line, as discussed in the previous Section.

The flying height for the ROV during a sub-bottom profiling survey will have a relationship to the swath width for the pipe tracker and the magnetometer sensors. For example, to cover a 150cm diameter area (acoustic footprint) the ROV should work at around 20m above the seabed. This has the disadvantage that target positioning accuracy may be compromised.

An operating height of 10m will give a 60cm diameter footprint – and this may mean that on a 150cm grid, some targets may be missed by the acoustics.

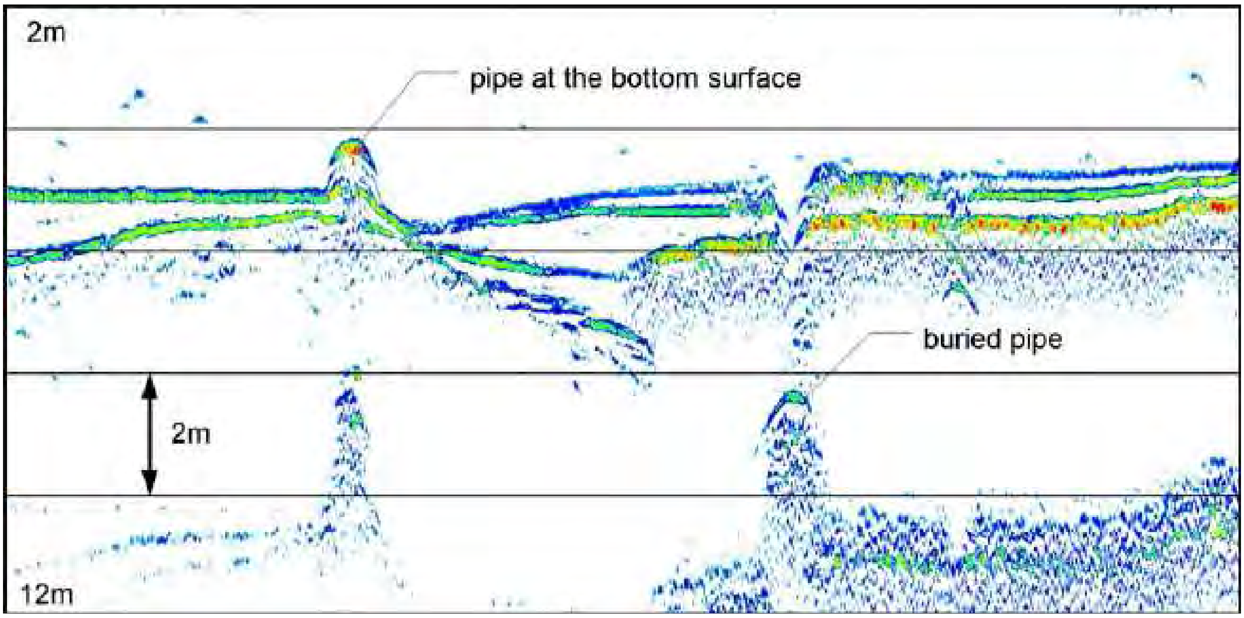


Figure 4-6. Echo print sub-bottom profiler (shallow water pipeline survey; Range 2m - 12m. (/3/)

It should be noted that a German company is running a 2007/2008 development of a parametric acoustics ROV Pipe Tracker system. A requirement for this system is to have a ±150cm (±250cm if possible) swath width at a 3 – 15 metre operating height. However, an ROV version prototype will probably not be ready before Q3 in 2008 (/5/).

4.2.3 Magnetometer / Gradiometer.

The gradiometer sensor is the system which, on its own, could give the best probability for detecting mercury canisters. The caesium vapour magnetometer will probably identify small objects.

Towing any sensor from a vessel near the wreck site will incur significant (and probably unacceptable) risk.

Towing the gradiometer sensor from an ROV near the wreck site will incur significant development costs, but lower costs and risks are associated with use of a single caesium vapour sensor.

Assistance from specialist personnel for survey planning and operation of a magnetometer to maximise its potential for the U-864 survey will be required.

A pipe tracker system could be used to ‘zoom in’ on possible targets to confirm if they are ferrous material or not.

Data from the survey will need to be post-processed by specialist personnel to get final results.

4.2.3.1 Operating Theory – magnetometer

See Appendix A.

4.2.3.2 Operating Practice

The total-field magnetic gradiometer technique is being used successfully for surveys which aim to find small ferro-magnetic objects in areas which are dominated by large magnetic objects or magnetic geological features, and will be the recommended choice of magnetometer for a U-864 sub-bottom survey because:

- Distant large targets are ignored.
- Diurnal variations are irrelevant.
- It is possible to “focus” the direction of maximum sensitivity.
- External noise is automatically filtered when the gradients are calculated.
- With noise filtration the effective sensitivity is increased.
- Preliminary ‘real-time’ results can be produced during the survey.
- It is possible to characterise the target (mercury canisters) by modelling the anomalies expected at different survey altitudes.

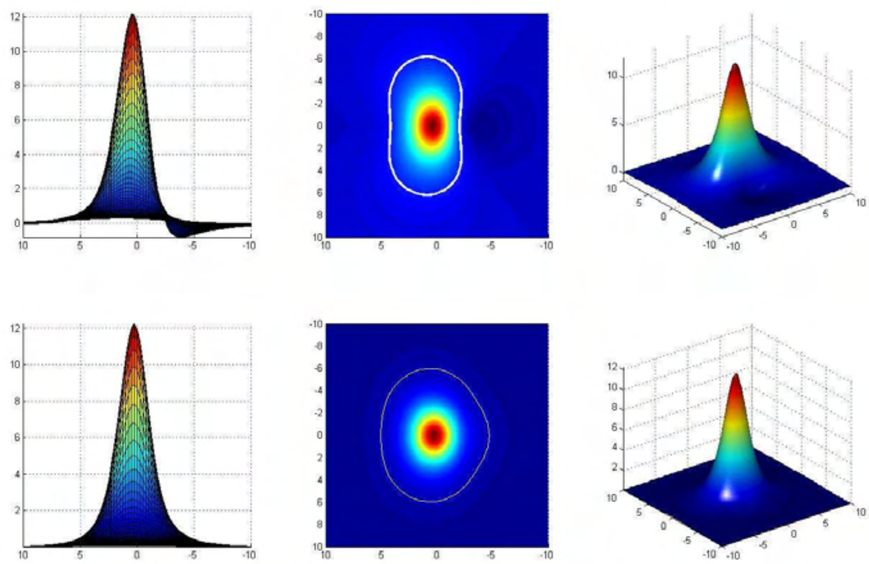


Figure 4-7. Model of anomaly for mercury canister 3m below the gradiometer (/6/)

The top row shows results in total field, and the bottom row shows total magnetic gradient. The first column shows a profile (x-axis=meters, y-axis=nT or nT/m) as it would look if the grad passed right over the target. The next column shows the top-down view of the anomaly (both x and y-axes are in metres) and the final column shows a 3D view of the anomaly, with z-axis being nT or nT/m.

There is only one (Canadian) commercially available gradiometer and it uses three highly accurate Overhauser magnetometers. (A company in Belgium may have a similar product under development).

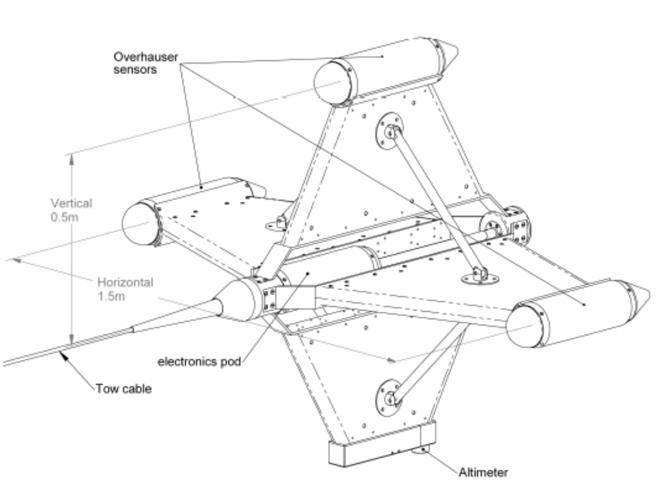


Figure 4-8. The three-axis gradiometer system. (/13/, /8/)

While the Gradiometer technique has significant advantages over acoustics and metal detectors in terms of characterizing the mercury canisters – it also presents significant challenges for deployment of the sensor in the U-864 environment.

It will probably not be practical or safe to carry out a tight grid survey in the vicinity of the wrecks by towing the sensor from a surface vessel. If the sensor could be towed down to 3 meters above seabed (probably around 600m behind the vessel) it could not be sufficiently well positioned or controlled to avoid the risk of fouling the sensor on the wrecks themselves.

However, if the gradiometer would be used to cover a 500m x 500m survey area clear of the wreck site with 5 meter swaths it may be possible with some engineering and operational technique to tow the sensor safely near the seabed. Positioning of the vessel-towed sensor would probably not be accurate enough in this case.

If the gradiometer would be used near the wreck, in the area currently covered by surface debris for example, then the sensor would have to be towed by an ROV. The use of a sensor array such as the one illustrated above with an ROV will present significant deployment challenges.

A similar exercise has been carried out by a Norwegian offshore survey company, but this was with a single element caesium vapour sensor (/13/, /14/).

In this case the caesium vapour sensor was deployed and retrieved from the ROV and towed along the seabed in the hard casing which acted as a ‘sled’. For a U-864 sub-sea survey, the magnetometer would have to be towed above the seabed for a number of reasons, and this would require the ‘sled’ to be redesigned for neutral or slightly positive buoyancy. Developing a variation of a product and process which already exists is less risky and costly than making a completely new product. However, data from the single-sensor magnetometer will be noisy, since it is not able to completely reject the effects of the geological and cultural magnetic anomalies in the area.

If this unit is towed at about 2 meters above the sea-bed for a survey with 5 meter swaths, it is probable that 4.5 Kg canisters will be identifiable as small anomalies within the background noise. Identification will be aided by carrying out an on-shore ‘calibration’ process, similar to that required for the pipe tracker. Some of the ‘targets’ may still be geological anomalies. They could only be identified as ferrous material with the help of the pipe tracker.

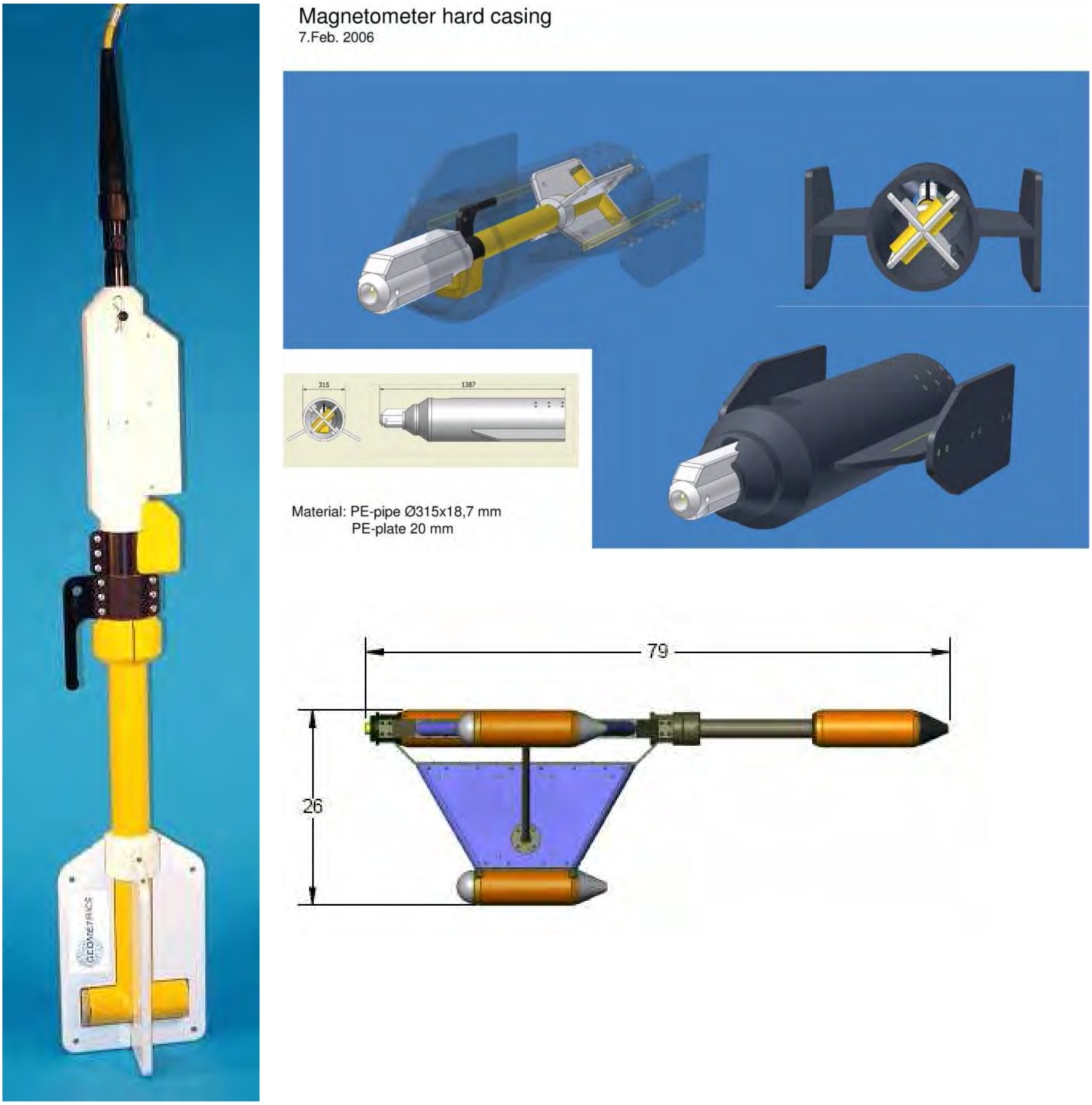


Figure 4-9. Single sensor system (left), hard casing design for towing sensor from ROV, and one variation of a 4-sensor system (/18/, /13/, /10/)

5 SUBSEA POSITIONING SYSTEMS

DNV's conclusion is:

> **C3. It is recommended that survey positioning should be by acoustic LBL technique – more specifically, wideband technology is proposed. This will give decimetric accuracy and high repeatability over a wide area.**

For sub-sea positioning on a U-864 survey, the choice is between two different acoustic positioning systems, Long Baseline (LBL) and Ultra-short Baseline (USBL).

This report makes the assumption that the positioning goal is to achieve 50cm radius repeatability 95% of the time.

Both Ultra-short Baseline (USBL) and Long Baseline (LBL) positioning systems are regularly used by Norwegian survey and construction vessels in the oil industry. The USBL positioning system delivers the required repeatability for single-vessel surveys. The wideband LBL positioning system also delivers the required repeatability, but has a higher overhead.

A wideband LBL positioning system is recommended for a more complex project where more than one survey vessel visits the area.

Both acoustic systems, if properly used will deliver geodetic co-ordinates for a target's position. The choice of system will depend on which system produces the best repeatability for the purpose of this survey.

Repeatability is most important if we assume that, once a canister has been identified, the location will be re-visited for recovery of the item. To minimise ROV time at the location and the amount of sediment to be removed, we could say for the purpose of this study that the recovery ROV should be able to find the buried object within a 50 centimetre radius of its co-ordinates, around 95% of the time.

The established way to achieve repeatability is to make the survey positioning system as accurate as possible. This is achieved by closely controlled calibration and system set-up procedures, so that the survey can proceed with an acceptable degree of confidence that the positions are accurate. If all the vessels involved in a survey follow the same procedures, and therefore achieve the same level of accuracy, then there will be a certain confidence in repeatability.

If there is a possibility that more than one vessel is involved, then the choice of acoustic system will be the one which is least dependant on correct procedures being carried out on the vessel.

5.1 Ultra-Short BaseLine acoustics (USBL)

The 2005 surveys at the site were carried out using a dedicated survey vessel with an ROV positioned by USBL, Hydro Acoustic Inertial Navigation (HAIN) and a Doppler Velocity Log.

The core of the system is an acoustic transceiver head which is deployed through the hull of the survey system, and which communicates acoustically with sea-bed transponders – usually installed on an ROV moving below the vessel. The system measures range and bearing to the ROV transponder.

Accuracy of USBL systems are limited mainly by the signal-to-noise ratio at the vessel of the 'echo' from the ROV's transponder. In the 2005 survey accuracy and reliability may have been enhanced by the use of Hydro Acoustic Inertial Navigation system.

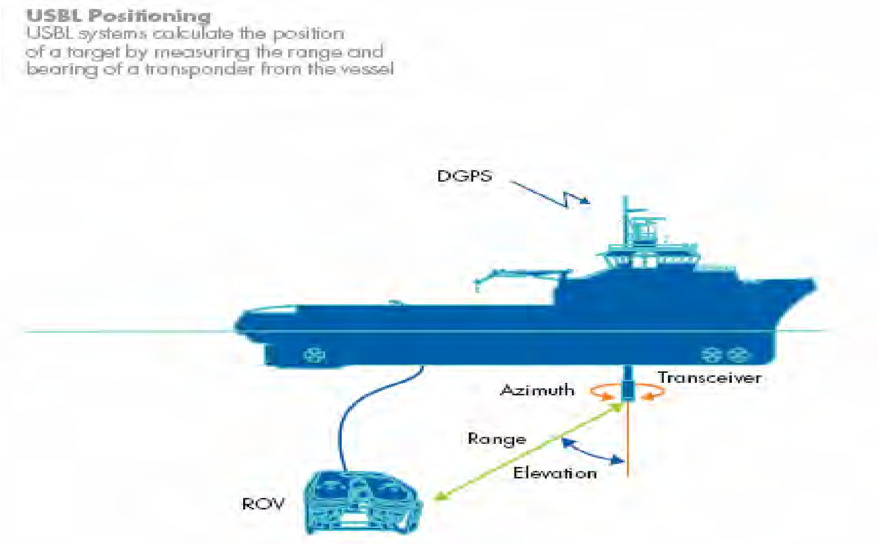


Figure 5-1. USBL Positioning (/12/)

This system, if properly configured can typically achieve 0.25% of slant range between vessel and ROV, most of the time. In 180 m water depth this gives an accuracy of 50 cms. If the ROV was used to find the position of the same target using different sensors, statistically 63% of the target positions will be within 50 cm radius of each other. This would fulfil the proposed repeatability requirement.

With USBL positioning, the absolute accuracy of the system which gives this repeatability is dependent upon:

- the quality of attitude and heading sensors
- beacon source level
- vessel noise
- water depth
- the mechanical rigidity of the transceiver deployment machine and proper calibration of the total system

If a second vessel joins the survey, to achieve the same repeatability, it must closely match the operating characteristics of the first vessel.

5.2 Long BaseLine acoustics (LBL)

To avoid the USBL calibration issues and achieve the same or better repeatability Long Baseline positioning can be used.

This technique has a higher preparation cost, because acoustic transponders must be deployed around the survey area and their positions established to better than 10 cm absolute. In addition, each ROV or sub-sea platform which operates in this network must carry the correct acoustic equipment on board and quickly transmit position information to the surface.

However, once the survey area is 'monumented' with transponder stands, they do not have to be moved until all survey or recovery interest in the area is completed. All users of the acoustic network will achieve repeatability to within less than a 50 cm radius 95% of the time, wherever they are in the network.

Figure 5-2. Ormen Lange Transponder stands in Kristiansund

These techniques have been successfully used in the development of the Ormen Lange gas-field and all of the vessels used during this construction have access to the wideband acoustic LBL equipment which predominated.

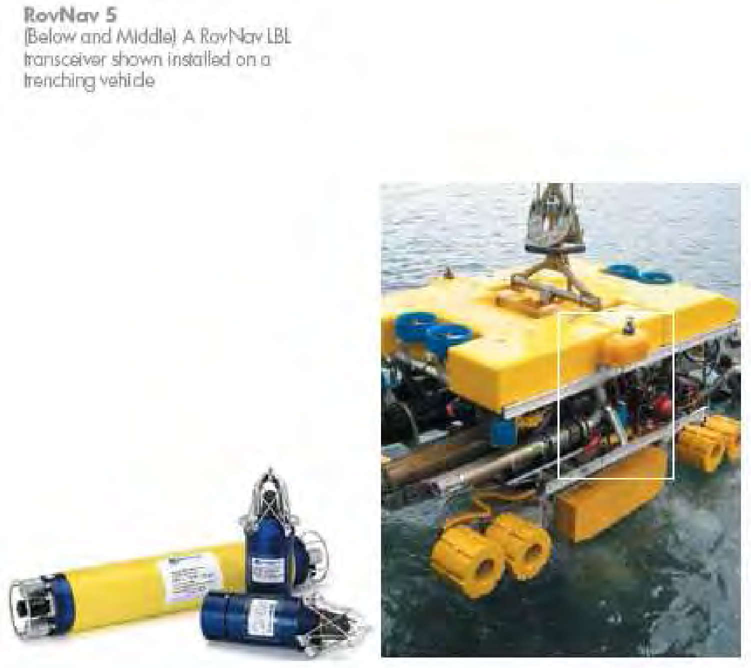


Figure 5-3. Typical ROV mounted equipment for LBL positioning (/12/)

6 ROV AND VESSEL REQUIREMENTS

6.1 ROV

A typical work class ROV is shown below. The vehicle is deployed from its ‘docking station’ near the sea-bed and moves independently within an area constrained by its umbilical. The ROV is able to survey at 2 or 3 knots if required and delivers data in real time to the surface vessel. For long survey lines the surface vessel will ‘follow’ the ROV – steered by the vessel’s Dynamic Positioning system.

Figure 6-1. Work Class ROV (/12/)

ROV’s are usually equipped as standard with gyro, attitude sensor, depth and altitude sensors and cameras. They can be positioned using acoustic USBL or LBL techniques.

In addition, the ROV would be equipped by customer-specified sensor systems, such as pipe tracker, parametric echo sounder, multi-beam echo sounder and others. The number of systems which the ROV can deploy at the same time is constrained by equipment weight, power availability and communications bandwidth to the surface.

ROV's are controlled by operators on the vessel, who guide the ROV along survey lines using joystick control, video, and positioning displays to monitor progress. Modern ROV's, however, have a dynamic positioning system which allows for the flying height, of the ROV, to be set and maintained automatically.

For a U-864 survey, the ROV should feature as a minimum:

- LBL Positioning.
- Dynamic Positioning to maintain authorised height above the sea-bed.
- Standard facility to deploy pipe-tracker (which includes altimeter).
- Standard facility to deploy sub-bottom profiler.
- Custom technology to deploy, tow and recover neutrally buoyant magnetometer.
- Sufficient hydraulic power to drive dredging equipment.

6.2 Survey vessel

A typical survey vessel is shown in Figure 6-2 on the next page. The vessel will be able to deploy one or more ROV's though a moon-pool in the centre of the vessel, or through a door in the side of the vessel. The vessel is positioned on the surface by high accuracy RTK GPS, and the position is offset typically to a USBL transceiver which propagates position to the sub-sea vehicles.

Figure 6-2. DOF Subsea's "Geosund"

Data from sensors on the ROV is transmitted to the Survey Instrument Room where it is time-tagged, annotated with position and saved for post-processing.

Depending on the contract, the vessel will have a skilled survey crew who operate the surface and sub-sea systems on-line, and process the data for analysis and reporting.

For a U-864 survey, the survey vessel should feature:

- All the personnel training, personal protection equipment and decontamination equipment required by Statens forurensningstilsyn (SFT) (/17/).
- Ability to deploy and position LBL transponders on the seabed.
- LBL Positioning on a work class ROV.
- Dynamic Positioning, with 'follow ROV' option.
- Possible second ROV, if required to assist with magnetometer deployment.
- Personnel to fabricate and modify magnetometer deployment hardware.
- Personnel who can process and analyse magnetometer, parametric echo sounder and pipe tracker data.
- EOD personnel (Explosives, Ordnance & Disposal).
- Dredging equipment to uncover some targets for 'ground truthing'.

7 DURATION OF SURVEY

DNV's conclusion is:

> **C4. Searching for sub-bottom mercury canisters will take at least six days with no weather downtime, and may be performed by one survey-ship with one or two ROVs.**

The duration of the survey is ultimately determined by the size of the survey area, the number of survey lines (or swath width) and the speed of the ROV during the survey.

After this, the survey will carry time overheads for position system preparation and calibration, deployment and recovery of ROV(s), on-board mobilisation and demobilisation of different sensor systems, decontamination procedures (in this case) and post-processing of survey data if this is required, to progress the survey.

To estimate the duration of a survey, these processes can only be modelled and some assumptions must be made to develop the model.

7.1 Survey area

The scope of work for this report requires a proposal for a 500m x 500m survey area. Considering the concentration of debris around the wreck parts it is probable that the survey area could be concentrated into a 300m x 300m area centred on the wreck and oriented Northwest to Southeast. The orientation allows longer continuous survey lines.

A small (100m x 100m) trial survey might be conducted on the southeast side of the bow section of the wreck. This area has a high concentration of mercury in the sediments and not too much surface debris.

It is proposed in principle that a survey of the whole area is carried out with a caesium vapour magnetometer towed from an ROV flying at a height of 2 metres, at 1 knot (0.5 metres/second) along lines 5 metres apart (swath width is 5 metres). A worst-case scenario will be where the ROV could only fly in one direction (due for example to adverse currents).

With these figures, and including turnaround time, a 300m x 300m magnetometer survey will take 24 hours. Conventionally, additional time is added for some cross-lines (for example where the survey line is obstructed by the wreck), equipment testing, and ad hoc inspections of significant targets. This is estimated to take 12 hours.

A 500m x 500m survey will take 32 hours – plus the same 12 hours contingency time.

It is further proposed, that when significant targets are identified on the magnetometer records, the vicinity of the target is visited by the ROV carrying the pipe tracker 'metal detector' to check if the targets are indeed ferrous. It has been calculated that with 7m of the keel destroyed, 10% of the mercury cargo may have been lost from the wreck. This model assumes that 100 targets may be visited by the pipe tracker – and that the sites will be tightly distributed. At 30 minutes per target (including transit time), the pipe tracker survey will take 48 hours.

As a comparison, a pipe tracker or acoustic survey with a swath width of 2 metres in the 300m x 300m area would take 48 hours plus 12 hours contingency time.

7.2 Preparation time

- It is estimated that the installation of six LBL positioning transponders in the area will take 24 hours.
- Pre-survey time for 100m x 100m using same ROV survey parameters, plus time for ad hoc investigations, total estimated time: 6 hours.
- Decontamination time, total estimated time: 12 hours.
- Reconfiguring the ROV for pipe tracker is total estimated time: 6 hours.
- For on-site post processing of data within the survey time-line, total estimated time: 6 hours.

7.3 Estimated operation time

Assuming no weather downtime, the information from chapter 7.1 and 7.2 chapters is summarised in the table below:

Activity	Operation time (hours)
Installation of LBL positioning	24
Pre-survey (100m x 100m)	6
Magnetometer Survey (500m x 500m)	32
Cross-lines and contingency	12
Decontamination time	12
Reconfiguring for pipe tracker	6
Investigating viable targets with pipe tracker	48
On-site processing of data	6
Minimum total time on site	**146 hours**

- This figure should be treated as a budget figure for vessel time spent working at the wreck site.

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APPENDIX

A
OPERATING THEORY

A.1. Metal detector

A current flowing through any coil will create a surrounding magnetic field. The strength of that field at any moment will be proportional to the instantaneous magnitude of current. If the current in the coil changes, the strength of the magnetic field will vary in proportion to the change in magnitude of coil current (/1/, /2/).

This variation in magnetic field strength will induce voltages in conductive targets that lie near the coil. The magnitude of eddy currents that flow in the target because of these induced voltages will depend on two factors:

- The electrical characteristics of the target material
- The rate at which the current in the coil changes
- Any eddy currents flowing in the target material will produce magnetic fields of their own and the 'secondary' fields will induce measurable voltage in the coil as they change.

A commercially available pipe tracker system uses this principle to detect the presence of conductive material near the search-coils. The system locates a target by:

- Inducing a pulse of current in the conductive material of the target
- Using three independent coils to detect the magnetic fields associated with the currents induced in the target.
- Calculating the position of the target from the relative strengths of the signals on each channel.

A.2. Acoustic sub-bottom profiler

There are a number of difficulties when a conventional single beam echo sounder is used for detection of embedded objects (/3/, /4/):

- The 'footprint' of a vessel's echo sounder transducer on the seabed is too large to accurately determine an object's position. Typically the footprint of an echo sounder in 150m of water will be more than 6 metres in diameter.
- Low frequencies (e.g. 30kHz), which propagate furthest in sediments, may not detect small objects. In addition, low frequency transmission requires a large transducer.
- High frequencies (e.g. 200kHz), which may detect small objects, will attenuate rapidly within the sediments, so that only the sea-bed echoes will be returned.
- If the transducer is brought closer to the sea-bed (e.g. mounted on an ROV, or in shallow water, reverberation decreases the signal to noise ratio of the echoes and obscures small targets.
- Some of these problems are solved by using non-linear acoustics.
- Non-linear (parametric) echo sounders transmit at least two signals of slightly different high frequencies at high pressures simultaneously. Because of non-linearities in the sound propagation at high pressures, the transmitted signals interact and new frequencies arise.

- The so-called secondary frequency is low enough to penetrate the seafloor. The reflected (echoed) primary frequency signals may be used for exact determination of water depth.
- The high (primary) frequencies require small transducers, and because the directivity of the low difference frequency is similar to the primary frequency, the technique allows transmission of narrow beams at low frequencies.
- The high (primary) frequencies also allow a high bandwidth, and this permits transmission of really short signal pulses. Short pulses help to reduce reverberation in shallow water.
- For parametric systems; low frequencies, short pulses, and narrow beams in shallow water result in high sea-bed penetration depth, less reverberation from the bottom surface and a better signal to noise ratio, especially in areas with weak, sub-surface reflectors.

A.3. Magnetometer and multi-sensor Gradiometer

Magnetometers are passive sensors in that they do not transmit a signal towards a target and then measure the response. Instead, they measure the distortion of the Earth's ambient magnetic field caused by a nearby magnetic target such as the ferrous mercury canisters (mercury itself is not magnetic).

Two types of magnetometers predominate, the Caesium Vapour and the Overhauser.

The **Caesium Vapour magnetometer** (/11/) broadly consists of a photon emitter containing a caesium light emitter or lamp, an absorption chamber containing caesium vapour and a 'buffer' gas through which the emitted photons pass, and a photon detector, arranged in that order.

This 'closed' system functions as the frequency control element in an oscillator circuit. The frequency of the magnetometer's electrical oscillator is known as the Larmor frequency. The Larmor frequency varies with the external ambient magnetic field. These variations are measured and sent to a computer for display and recording.

Where there are ferrous materials the earth's magnetic field distorts and the caesium magnetometer sees this distortion as an increase or decrease in the earth's field intensity. The high sensitivity of this device allows it to detect small targets at quite large distances. For example the sensor could detect a 15Kg object at 10m depending on the background magnetic noise level in the area. A practical range to a 4.5 Kg canister would be around 4 metres (/15/).

The **Overhauser** effect (/11/) takes advantage of a quantum physics effect that applies to the hydrogen atom. This Nuclear Magnetic Response (NMR) effect occurs when a special liquid (containing free, unpaired electrons) is combined with hydrogen atoms and then exposed to secondary polarization from a radio frequency (RF) magnetic field (i.e. generated from a RF source).

The unbound electrons in the special liquid transfer their excited state (i.e. energy) to the hydrogen nuclei (i.e. protons). This transfer of energy alters the spin state populations of the protons and polarizes the liquid. When the RF is removed, the spinning population of protons precesses towards a normal state.

The precession frequency is linearly proportional to the magnetic flux density, independent of temperature and only slightly affected by shielding effects of hydrogen orbital electrons. The constant of proportionality is known to a high degree of accuracy and is identical to the proton precession gyromagnetic constant.

In practical terms, the Overhauser magnetometer produces a ‘clean’ response to magnetic anomalies, making it accurate and consistent. In addition it uses low current and so the sensor can be small and light. Both of these advantages (among others) mean that more than one sensor can be coupled together on a single sub-sea platform to make a **Gradiometer.**

While a magnetometer measures the Earth’s total magnetic field, a gradiometer measures the rate of change of total magnetic field as the sub-sea platform moves through the water. The simplest gradiometer measures magnetic gradient in one dimension by subtracting the difference between two independent magnetometer sensors. Since the Earth’s magnetic field is three-dimensional it is logical to extend the gradiometer concept to measure gradient in three independent directions – requiring three of four sensors on one sub-sea platform (/6/).

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APPENDIX

B

DRIFT OF MERCURY CANISTERS

Tabell B-1 Characteristics of mercury containers

Welded container (cylinder shaped)	Forged container (flask shaped)
	
Length of cylinder: 250 mm Diameter (OD) of cylinder: 130 mm Weight empty 4.2 kg	Length of cylindrical section: 280 mm Diameter (OD) of cylindrical section: 115 mm Thickness of cylindrical section: 5 mm Length of top section: 85 mm Length of plug (above flask connection): 40 mm
Both containers hold 2.5 litres of mercury (Hg) weighing around 35 kg Mass density of seawater is taken as ρ_w = 1025 kg/m^3	
Estimated parameters: Volume: 0.0033 m^3 Buoyancy force (B): 33.4 N Mass of steel: 4.2 kg Total mass: 39.2 kg Weight in air (W): 384.5 N Transversal drag coefficient (C_{Dt}) 0.56 Axial drag coefficient (C_{Da}) 0.85 Projected transversal area (A_{pt}) 0.0325 m^2 Projected axial area (A_{pa}) 0.0133 m^2	Estimated parameters: Volume: 0.0055 m^3 Buoyancy force (B): 55.10 N Mass of steel: 7.5 kg Total mass (M): 42.5 kg Weight in air (W): 417.3 N Transversal drag coefficient (C_{Dt}) 0.56 Axial drag coefficient (C_{Da}) 0.20 Projected transversal area (A_{pt}) 0.0549 m^2 Projected axial area (A_{pa}) 0.0104 m^2

Drift of mercury containers has been calculated by estimating the terminal velocity during free fall in water and assuming the containers will drift horizontally with the same velocity as the ambient current taken to have a low value of U_c = 0.3 m/s and a high value of U_c = 1.6 m/s. Water depth is taken as 150 m.

The terminal velocity is found by assuming equilibrium between weight, buoyancy and drag forces acting on the container during the free fall. The terminal velocity is given by the formula

$$w_t = \sqrt{\frac{2(W - B)}{\rho_w A_p C_D}}$$

where A_p is the projected area and C_D is the drag coefficient.

The containers will fall in an irregular fashion due to hydrodynamic instability and fluctuations in the current velocity. However, it can be assumed that the drift distance will be limited below and above characterized by two basic falling positions, which will maximize and minimize the terminal velocity. A small terminal velocity will be obtained if the container falls broadside and a large velocity will be obtained if the container falls axially. In the first case the projected area and drag coefficient will both be large, while in the second case, both will be small.

Based on the estimated parameters for each of the containers as given in Table 4-1 the following limiting drift off distances are found.

	Welded container (cylinder shaped)		**Forged container (flask shaped)**	
	Broadside	Axially	Broadside	Axially
Terminal velocity	6.14 m/s	7.79 m/s	4.79 m/s	18.44 m/s
Drop time	24.45 s	19.25 s	31.29 s	8.13 s
Drift off (U_c=1.6 m/s)	39 m	31 m	50 m	13 m
Drift off (U_c=0.3 m/s)	7 m	6 m	9 m	2 m

The maximum drift-off distance is 50 m.

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TECHNICAL REPORT

KYSTVERKET NORWEGIAN COASTAL ADMINISTRATION

SALVAGE OF U864 - SUPPLEMENTARY STUDIES - THE MIDSHIP SECTION

REPORT NO. 23916-4

REVISION NO. 01

DET NORSKE VERITAS

DET NORSKE VERITAS

TECHNICAL REPORT

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Client: Kystverket (Norwegian Coastal Administration)	Client ref.: Hans Petter Mortenson

Summary:

The German submarine U-864 was torpedoed by the British submarine Venturer on February 9 1945 and sunk approximately two nautical miles west of the island Fedje in Hordaland. U-864 was carrying about 67 metric tonnes of metallic mercury that implies a threat to the marine environment. In September 2007 The Norwegian Costal Administration commissioned Det Norske Veritas to further investigate different alternatives to salvage the wreck and remove the mercury from the seabed.

The wreck of the German submarine U-864 was located in 2003, on 150 m water depth. The submarine had been split in two, but a section of about 7 meters of the midship was missing. The midship section carried approximately 7 tonnes mercury in the keel.

DNV has been requested by The Norwegian Coastal Administration (NCA) to give an evaluation of the possible drift of the midship section during its descent to the seabed, and possibly give a recommendation for a search area larger than the present area which is 950 x 1000 meters.

DNV's main conclusion is: The midship section is expected to be found among the debris in vicinity of the bow and stern sections. The maximum drift distance is estimated to be approximately 70 m when all possible variations of the current and the geometry of the midship section after the torpedo explosion are accounted for. It is therefore concluded that there is no need to expand the search area.

Report No.: 23916-4	Subject Group:	
Report title: Salvage of U864 - Supplementary studies - The Midship Section		
Work carried out by: Guttorm Grytøyr, Ph.D Arne Nestegård, Ph.D		
Work verified by: Odd Andersen		
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Table of Content ***Page***

The German submarine U-864 was torpedoed by the British submarine Venturer on February 9 1945 and sunk approximately two nautical miles west of the island Fedje in Hordaland. U-864 was carrying about 67 metric tonnes of metallic mercury that implies a threat to the marine environment.

In September 2007 The Norwegian Costal Administration commissioned Det Norske Veritas to further investigate different alternatives to salvage the wreck and remove the mercury from the seabed.

1 SUMMARY

This report is *Supplementary Study No. 4: The Midship Section*, one of twelve supplementary studies supporting the overall report regarding U-864 (Det Norske Veritas Report No. 23916) prepared by Det Norske Veritas (DNV).

The wreck of the German submarine U-864 was located in 2003, on 150 m water depth. The wreck is split in two main sections surrounded by debris. Although, the main sections together lack about 7 meters of the midship section, in which it is likely that approximately 7 tonnes of mercury is stored in the keel.

The objective of this supplementary study is to give an evaluation of the possible drift of the midship section during its descent to the seabed, and possibly give a recommendation to extend the search area, which at present is 950 x 1000 meters, if it is possible that the midsection might be outside this area.

Due to the inherent uncertainties in the problem it was chosen to proceed with hand calculations and physical reasoning instead of time domain computer simulations.

DNV's overall conclusion is:

The midship section is expected to be found among the debris in vicinity of the bow and stern sections. The maximum drift distance is estimated to be approximately 70 m when all possible variations of the current and the geometry of the midship section after the torpedo explosion are accounted for. It is therefore concluded that there is no need to expand the search area.

DNV's supporting conclusions are:

C1. The conning tower is buoyant if it is filled with air and the hatches are closed. But with a net buoyancy of 10.4 metric tonnes was the buoyancy not sufficient to support the entire midship section, which had mercury stored in the keel and was filled with water after the torpedo explosion, buoyant. If the conning tower was separated from the mid ship section after the torpedo explosion it would be buoyant, but it would not contain any mercury as this was stored in the keel.

C2. The maximum drift distance of the mid ship section is estimated to be approximately 70 m and is expected to cover all possible variations of the current

and the geometry of the midship section after the torpedo explosion, and that the conning tower was filled with air and the hatches were closed.

C3. The bottom current is not strong enough to roll the midship section, even when neglecting friction and suction from the seabed.

C4. The bottom topography is not steep enough to allow the midship section to roll under the influence of gravity, even when neglecting friction and suction from the seabed.

C5. The mid ship section is not expected to drift further than the bow and stern sections section on its descent to the seabed. Hence, the midship section is expected to be found in vicinity of the bow and stern sections.

C6. There are no signs of buckling or bending of the hull plates at the fracture. This is an indication that the hull has been torn apart by purely axial loads. If the hull had been torn apart by bending moment, the plates would have shown more signs of bending.

C7. The numerical analysis, and the amount of fragments identified on the seabed, indicates that the midship section most probably has been destroyed by the torpedo explosion, and is found as debris on the in the seabed around the bow and stern sections.

Figure 1-1 graphically presents the main findings in this supplementary study:

- The red cross (solid line) marks the midpoint between the ends of the front and aft section, which is used as an estimate for the position of the vessel mid-ship at the time of the torpedo explosion. The two red circles (solid line) represent the maximum drift distance of the mid section with mean current velocity (radius 14 m), and maximum current velocity (radius 74 m), as predicted by the analysis. The values of 14 m and 74 m are the maximum values from the sensitivity study, and are as such expected to be conservative in the sense that there is little possibility that the section could have drifted any further than 74 meter.

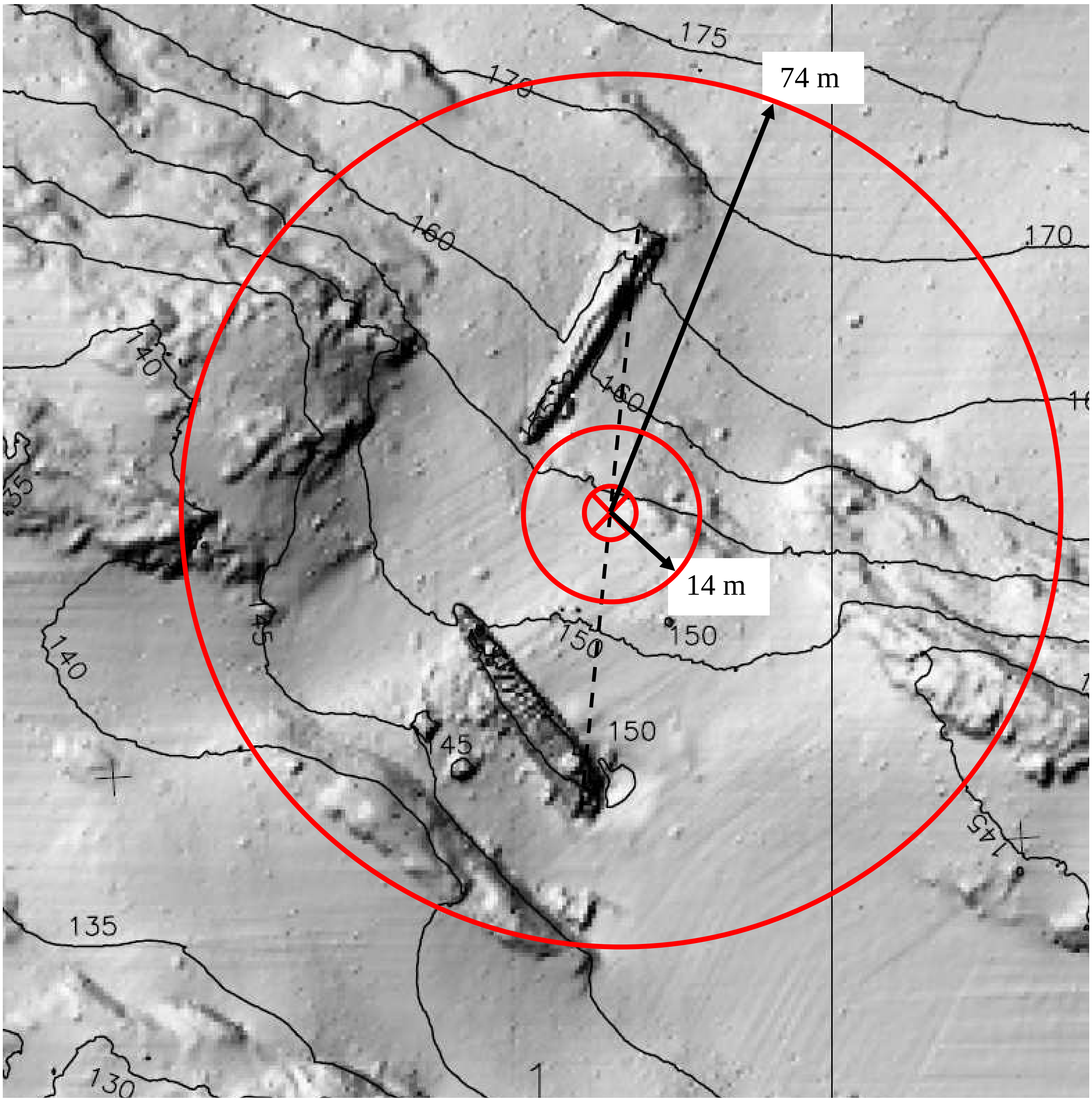

Figure 1-1 Annotated facsimile from ref. /6/.

The rest of *Supplementary Study No. 4: The Midship Section* details the arguments behind the conclusions.

Den tyske ubåten U-864 ble torpedert av den britiske ubåten Venturer den 9. februar 1945 og sank omtrent to nautiske mil vest for øya Fedje i Hordaland. U-864 var lastet med omtrent 67 tonn med metallisk kvikksølv som utgjør en fare for det marine miljøet.

I September 2007 tildelte Kystverket Det Norske Veritas oppdraget med å nærmere utrede ulike alternativer for heving av vrak og fjerning av kvikksølv fra havbunnen.

2 SAMMENDRAG

Denne rapporten er *Tilleggsutredning nr. 4: Midtseksjon*, en av tolv tilleggsutredninger som understøtter hovedrapporten vedrørende U-864 (Det Norske Veritas Report No. 23916) utarbeidet av Det Norske Veritas (DNV).

Vraket av den tyske ubåten U-864 ble lokalisert i 2003 på 150 meters dyp. Vraket er delt i to hoveddeler og omkring ligger det mange vrakrester. Derimot mangler hoveddelene til sammen rundt syv meter av midtseksjonen, hvor det sannsynligvis ligger rundt syv tonn kvikksølv stuet i kjølen.

Formålet med denne tilleggsstudien er å gi en vurdering av mulig drift av midtseksjonen da den sank til sjøbunn, og eventuelt gi en anbefaling om å øke søkeområdet, som måler 950x1000 meter, dersom det er sannsynlig at midtseksjonen kan ligge utenfor dette området.

På grunn av de iboende usikkerhetene i denne oppgaven, ble det besluttet å benytte manuelle kalkulasjoner og fysikalske tolkninger i stedet for datamaskin simuleringer.

DNV sin overordnede konklusjon er:

Midtseksjonen forventes å være blant vrakdelene som ligger ved for- og akterseksjonen. Den maksimale driften er beregnet å være ca. 70 meter når det er tatt hensyn til alle mulige variasjoner av strøm og midtseksjonens geometri etter torpedoeksplosjonen. Det konkluderes derfor med at det ikke er nødvendig å øke søkeområdet.

DNV underbygger denne konklusjonen med:

C1. Kommandotårnet i seg selv ville kunne flyte dersom det var luftfylt og lukene var stengt. Men med netto flyteevne på 10.4 metriske tonn var ikke flyteevnen tilstrekkelig for å kunne holde midtseksjonen, som hadde kvikksølv lagret i kjølen og selv ble vannfylt etter torpedoeksplosjonen, flytende. Dersom kommandotårnet ble separert fra midtseksjonen etter torpedoeksplosjonen kunne dette flyte, men ville da ikke inneholdt noe kvikksølvlast da dette var lagret i kjølen.

C2. Midtseksjonens maksimale driftdistanse fra eksplosjonspunktet er beregnet å være ca. 70 meter og forventes å dekke alle variasjoner av strøm og midtseksjonens geometri etter torpedoeksplosjonen, samt at kommandotårnet var luftfylt og lukene stengt.

C3. Bunnstrømmen er ikke sterk nok til at midtseksjonen kan ha rullet på sjøbunnen, selv når man ser bort fra friksjon og sugekrefter fra sjøbunnen.

C4. Bunntopografien er ikke tilstrekkelig bratt for at midtseksjonen kan ha rullet på grunn av gravitasjonskreftene, selv når man ser bort fra friksjon og sugekrefter fra sjøbunnen.

C5. Midtseksjon er ikke forventet å ha driftet lenger enn baug- og akterseksjon på veg mot sjøbunnen. Herav følger at midtseksjonen er forventet å ligge i nærheten av baug- og akterseksjon.

C6. Det er ikke tegn til buling eller bøying av skrogplatene ved bruddkanten. Dette indikerer at skroget har blitt revet fra hverandre kun av aksielle krefter. Dersom skroget hadde blitt revet fra hverandre av bøyningsmoment ville skrogplatene ha vist flere tegn på bending ved bruddkanten.

C7. De nummeriske analysene, samt mengden vrakdeler som er identifisert på sjøbunnen, indikerer at midtseksjonen mest sannsynlig har blitt ødelagt av torpedoeksplosjonen og er å finne som vrakdeler i området rundt for- og akterseksjon.

Figure 1-1 (side 3) presenterer grafisk hovedfunnene i denne tilleggsutredningen.

- Det røde heltrukne krysset markerer midtpunktet mellom endene av baug- og akterseksjonen, hvilket er brukt som estimat for posisjonen til midtskipet ved torpedoeksplosjonen. De to røde heltrukne sirklene, hhv. med radius 14 og 74 meter, representerer maksimalverdiene fra sensitivitetsstudien av midtseksjonens drift i forbindelse med nedstigningen til havbunnen. Verdiene er forventet å være konservative, det vil si det er lite sannsynlig at midtseksjonen kan ha driftet lenger enn 74 meter.

Resten av *Tilleggsutredning nr. 4: Midtseksjon* utdyper argumentene bak konklusjonene.

3 INTRODUCTION

3.1 Background

The German submarine U-864 was sunk by the British submarine Venturer on 9 February 1945, approximately 2 nautical miles west of the island Fedje in Hordaland (Figure 3-1). The submarine was on its way from Germany via Norway to Japan with war material and according to historical documents; U-864 was carrying about 67 metric ton of metallic (liquid) mercury, stored in steel canisters in the keel. The U-864, which was broken into two main parts as a result of the torpedo hit, was found at 150-175 m depth by the Royal Norwegian Navy in March 2003. The Norwegian Costal Administration (NCA) has, on behalf of the Ministry of Fisheries and Coastal Affairs, been performing several studies on how the risk that the mercury load constitutes to the environment can be handled. In December 2006 NCA delivered a report to the Ministry where they recommended that the wreck of the submarine should be encapsulated and that the surrounding mercury-contaminated sediments should be capped. In April 2007 the Ministry of Fisheries and Coastal Affairs decided to further investigate the salvaging alternative before a final decision is taken about the mercury load.

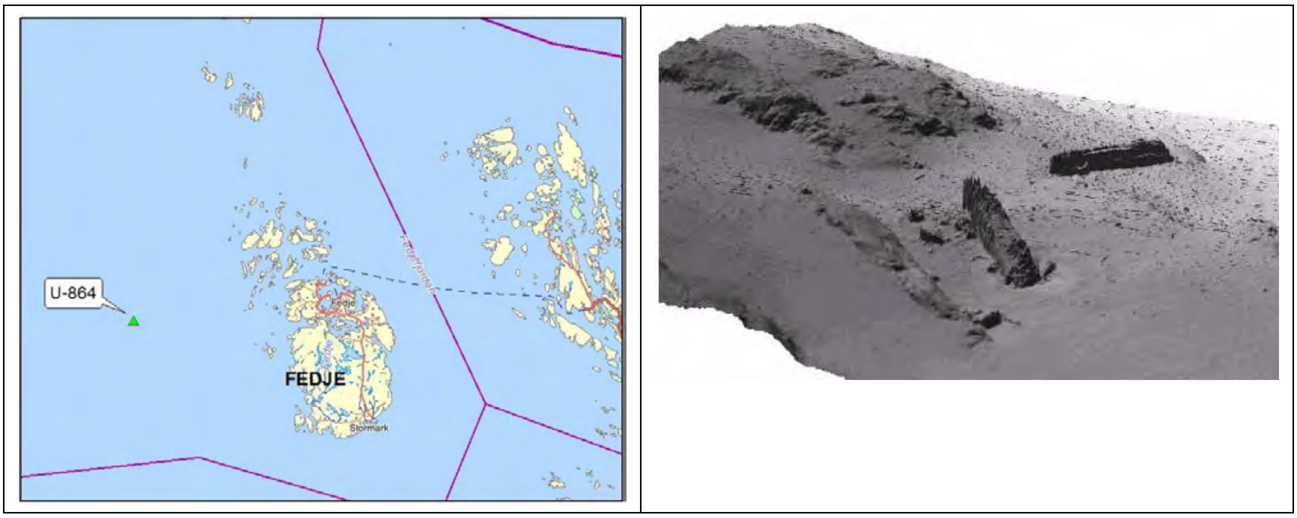

Figure 3-1 Location (left) and a sonar picture of the wreck of U-864 on seabed (right) (from Geoconsult).

3.2 DNV’s task

In September 2007 NCA commissioned Det Norske Veritas (DNV) the contract to further investigate the salvaging alternative. The contract includes:

- DNV shall support NCA in announcing a tender competition for innovators which have suggestions for an environmentally safe/acceptable salvage concept or technology. Selected innovators will receive a remuneration to improve and specify their salvage concept or technology.

- DNV shall support NCA in announcing a tender competition for salvage contractors to perform an environmentally justifiable salvage of U-864.
- DNV shall evaluate the suggested salvage methods and identify the preferred salvage method.
- The preferred salvage method shall be compared with the suggested encapsulation/capping method from 2006. (DNV shall give a recommendation of which measure that should be taken and state the reason for this recommendation.)
- DNV shall perform twelve supplementary studies which will serve as a support when the decision is taken about which measure that should be chosen for removing the environmental threat related to U-864. The twelve studies are:

1. *Corrosion*. Probability and scenarios for corrosion on steel canisters and the hull of the submarine.
2. *Explosives.* Probability and consequences of an explosion during salvaging from explosives or compressed air tanks.
3. *Metal detector*. The possibilities and limitations of using metal detectors for finding mercury canisters.
4. *The midship section*. Study the possibility that the mid section has drifted away.
5. *Dredging*. Study how the mercury-contaminated seabed can be removed around the wreck with a minimum of spreading and turbidity.
6. *Disposal*. Consequences for the environment and the health and safety of personnel if mercury and mercury-contaminated sediments are taken up and disposed of.
7. *Cargo.* Gather the historical information about the cargo in U-864. Assess the location and content of the cargo.
8. *Relocation and safeguarding.* Analyse which routes that can be used when mercury canisters are relocated to a sheltered location.
9. *Monitoring.* The effects of the measures that are taken have to be documented over time. An initial programme shall be prepared for monitoring the contamination before, during and after salvaging.
10. *Risk related to leakage.* Study the consequences if mercury is unintentionally leaked and spreading during a salvage or relocation of U-864.
11. *Assessment of future spreading of mercury for the capping alternative*. The consequences of spreading of mercury if the area is capped in an eternal perspective.
12. Use of divers. *Study the risks related to use of divers during the salvage operation in a safety, health and environmental aspect and compare with use of ROV.*

3.3 Scope of this report

This is *Supplementary Study No. 4: The Midship Section.* The wreck of U-864 had been split in two by the torpedo, but a section of about 7 meters of the midship are missing.

DNV has been requested by The Norwegian Coastal Administration to give an evaluation of the possible drift of the mid section during its descent to the seabed, and possibly give a recommendation for an extended search area[1]. The following tasks and issues are to be treated when doing the analysis:

- Estimate probable current variation with depth at the time of the torpedo attack, based on the current measurements presented in ref /2/.
- Estimate two to three probable geometries and masses of the midship section.
- Consider soil conditions.

Chapter 4 in this report presents the analysis methodology employed. Chapter 5 gives a list of the geometrical and physical parameters that are used, and chapter 6 presents the analysis results.

[1] Geoconcult completed in 2005 a detailed mapping of a 950x1000 m large seabed area around the wreck of U-864. The current at different water depths was measured, and a total of 180 objects on seabed was investigated by video inspection, of which 107 objects was from the U-864. For more information see /21/.

4 ANALYSIS METHODOLOGY

4.1 Introduction

This section presents the methodology used in the analyses presented in this report.

Two cases have been analysed in the following:

1. Estimate of drift distance of mid section. Based on drag forces only.
2. Estimate of drift distance of bow and stern section. Based on drag and lift forces.

In both cases the analysis has been performed as a steady state analysis. This means that the initial phase of the drop, before steady state is achieved, has been neglected. The initial phase is not expected to be significant, since steady state will be reached in a very short time.

The sections have been given an initial condition where they are at rest. The effect of the explosion is not easily verified, but on a general basis one may state that there may be an offset of the sections due to the expanding bubble from the explosion, but the initial velocity when they start to sink will be negligible due to substantial inertia from the structure itself and from the hydrodynamic added mass of the surrounding fluid.

The drift distance of the **mid section** is estimated by assuming that the section is following the ambient current throughout the drop. The time it takes to reach the seabed is found by using the terminal velocity of the section, i.e. the maximum drop velocity. This is found by solving for equilibrium between the submerged weight of the section, and the drag force on the section. This equation is relatively simple, and easily solved.

The drift distance on the **bow and stern section** is estimated in a similar manner as for the mid section. The time it takes to reach the seabed is found by using the terminal velocity of the section, i.e. the maximum drop velocity. This is found by solving for equilibrium between the submerged weight of the section, and the drag force and lift force on the section. This equation is quite complex, and requires an iterative solution scheme. It is assumed that the drift due to the ambient current can be superimposed on the trajectory estimated by the equilibrium equations.

4.2 Mid section

The equilibrium equation for the mid section is given by the following :

$$M_m - B_m = F_D \tag{1}$$

Where M_m-B_m is the submerged weight of the mid section, and F_D is the drag force on the section. The drag force is given in section 5.5.2. This gives an equation for the transverse velocity, *w*, which is the drop velocity of the section.

The time to reach the bottom, t_{DROP}, is given by the ratio of the height of the keel above the seabed, *H*, to the velocity *w* : $t_{DROP} = H/w$

The drift distance is estimated by $S = t_{DROP}\ U_{CURRENT}$.

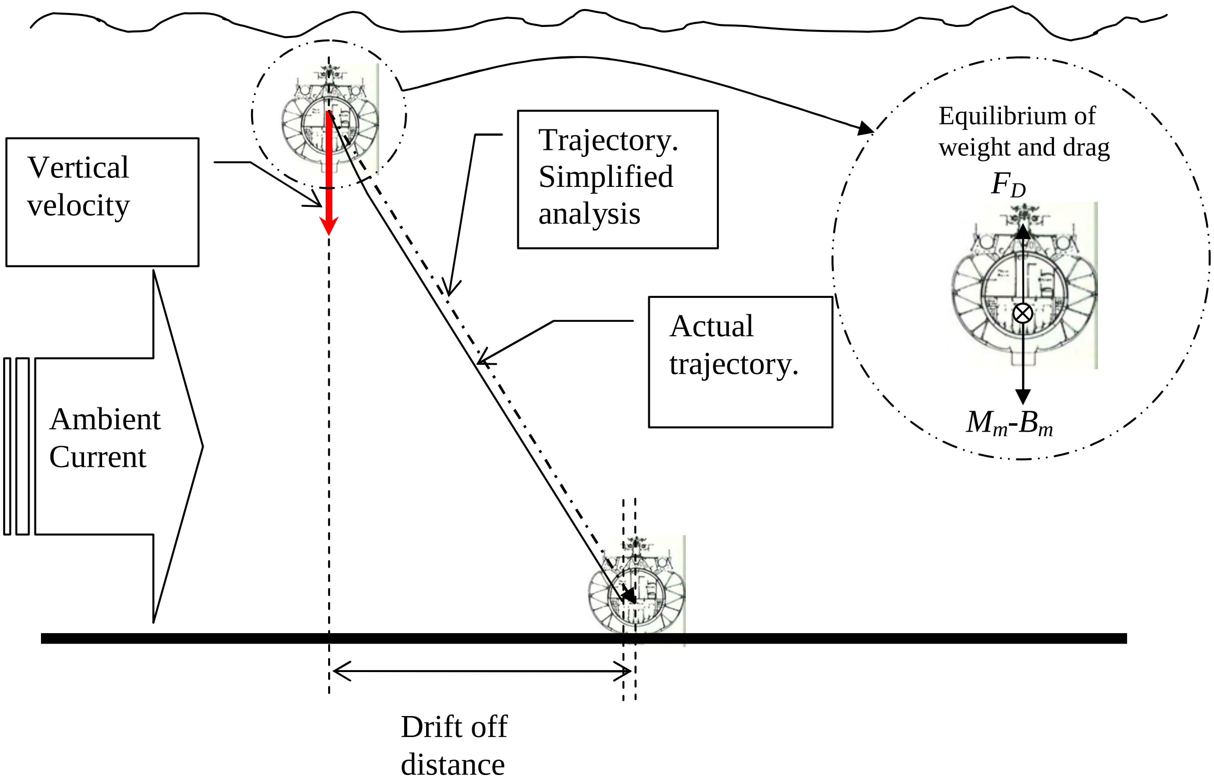

Figure 4-1 Sketch of analysis approach for drop of mid setion. The actual trajectory is expected to be very similar to the simplified analysis due to the large drag coefficient

4.3 Bow section

The equilibrium equations for the bow section is given by the following :

$$\begin{aligned}(M-B)\sin(\theta) &= F_{DL} \\ (M-B)\cos(\theta) &= F_{DT} + F_L \\ B \cdot \Delta &= M_{DT}\end{aligned} \quad \textbf{(2)}$$

Where M is the mass of the section, B is the total buoyancy of the section, $(M\text{-}B)\sin(\theta)$ is the longitudinal component of the submerged weight of the section, $(M\text{-}B)\cos(\theta)$ is the transverse component of the submerged weight of the section, F_{DL} is the longitudinal drag force on the section, F_{DT} is the transverse drag force on the section, F_L is the lift force on the section, θ is the pitch angle of the section during the drop, Δ is the horizontal distance between the Centre of Gravity and the Centre of Buoyancy, and M_{DT} is the moment of the transverse drag load around the Centre of Gravity.

The drag forces are given in section 5.6.2, the lift force in section 5.6.3. This gives a set of equations with three unknowns :

- The longitudinal velocity, U_0
- The transverse velocity, w
- The pitch angle θ.

The velocity components are decomposed into vertical and horizontal velocities, which are used to estimate the drop time and the drift distance. .

The time to reach the bottom, t_{DROP}, is given by the ratio of the height of the keel above the s, H, to the vertical velocity, $U_{VERTICAL}$: $t_{DROP} = H/U_{VERTICAL}$

The drift distance is estimated by $S = t_{DROP}\,(U_{HORIZONTAL} + U_{CURRENT})$.

Where $U_{HORIZONTAL}$ is the horizontal component of the total velocity, $U_{VERTICAL}$ is the vertical component of the total velocity, and $U_{CURRENT}$ is the velocity of the ambient current.

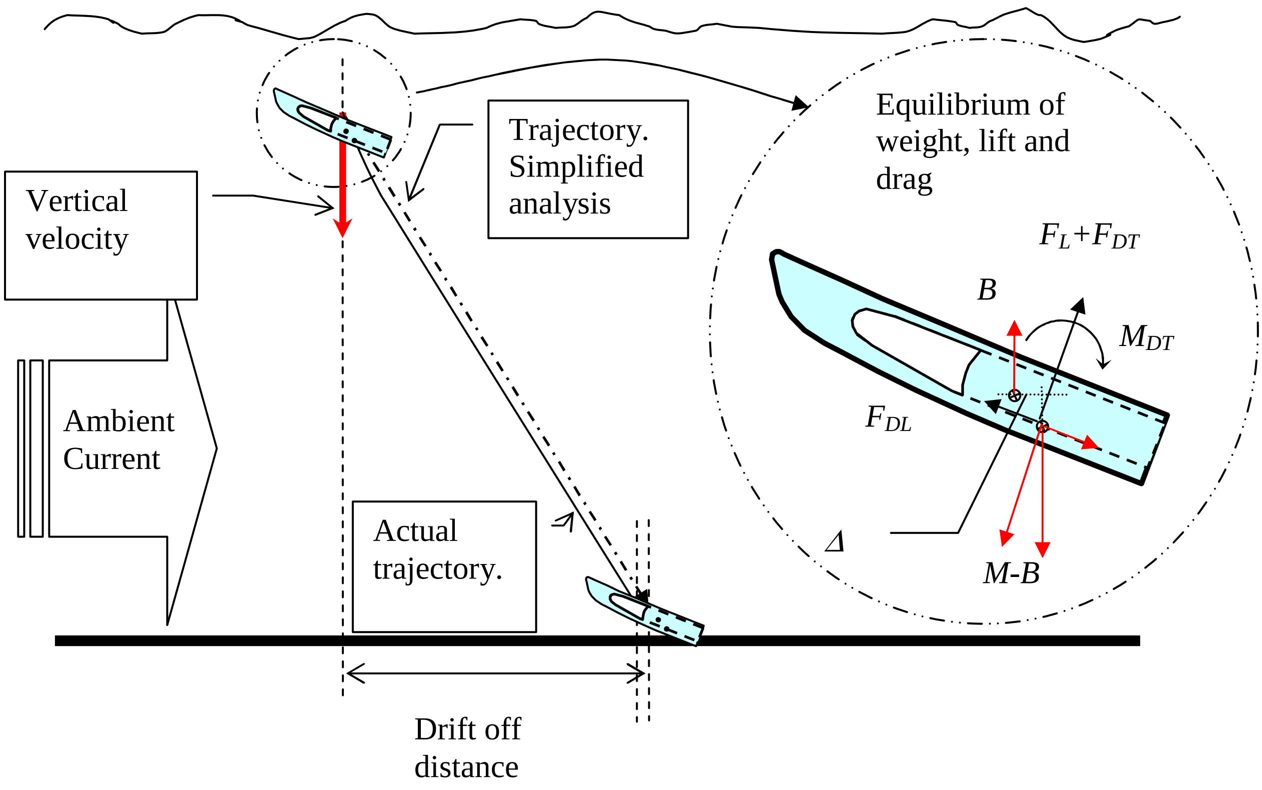

Figure 4-2 Sketch of analysis approach for drop of the submarine. The actual trajectory is expected to be very similar to the simplified analysis due to the large drag coefficient

5 ANALYSIS BASIS

This section presents the data used as basis for the analysis. The data for the intact hull are well documented, whereas the geometry of the sections after the torpedo attack are not well defined, which means that the parameters are inherently uncertain.

The data listed in this section represent what DNV consider to be the best estimates.

5.1 Environmental properties

The U-boat U864 was sunk about 5 km west of Fedje, about 55 km North-North-West of Bergen.

The water depth at the location of the wreck is about 150 m, see e.g. ref. /17/ and /18/.

5.1.1 Current measurements

Geoconsult has reported current measurements from the site, ref. /3/. Their measurements show that the current in the area has a steady direction towards North-West.

The following table summarizes the data presented in ref. /3/ :

Table 5-1 Current measurements from the site.

Elevation above seabed (m)	Mean value (m/s)	Max value (m/s)	Comment
0	0.1	0.87	
40	0.3	1.60	

5.2 Conditions at time of attack

According to the attack log from HMS Venturer, the German U864 was heading South-East on course 135° at the time she was hit, and she was on a depth of approximately 43 ft (13,2 meter) (keel). (See ref. /19/.)

This means that the keel of the vessel was about 135-140 m above seabed when she was hit. This height is used below when estimating the distances the sections may have drifted.

The current velocity and direction at the time of the attack is unknown. HMS Venturer made notes of wind directions, temperatures, etc., in their attack log, but not of the current. Hence, the current measurements made by Geoconsult in ref. /3/ has been used. The measurements show that there is a substantial variation of the current, with a maximum value of up to 0.87 m/s at the seabed, and about 1.6 m/s 40 m above seabed. It is considered unlikely that the current velocity was at maximum during the attack, but this value is used to get a conservative estimate of the maximum drift distance.

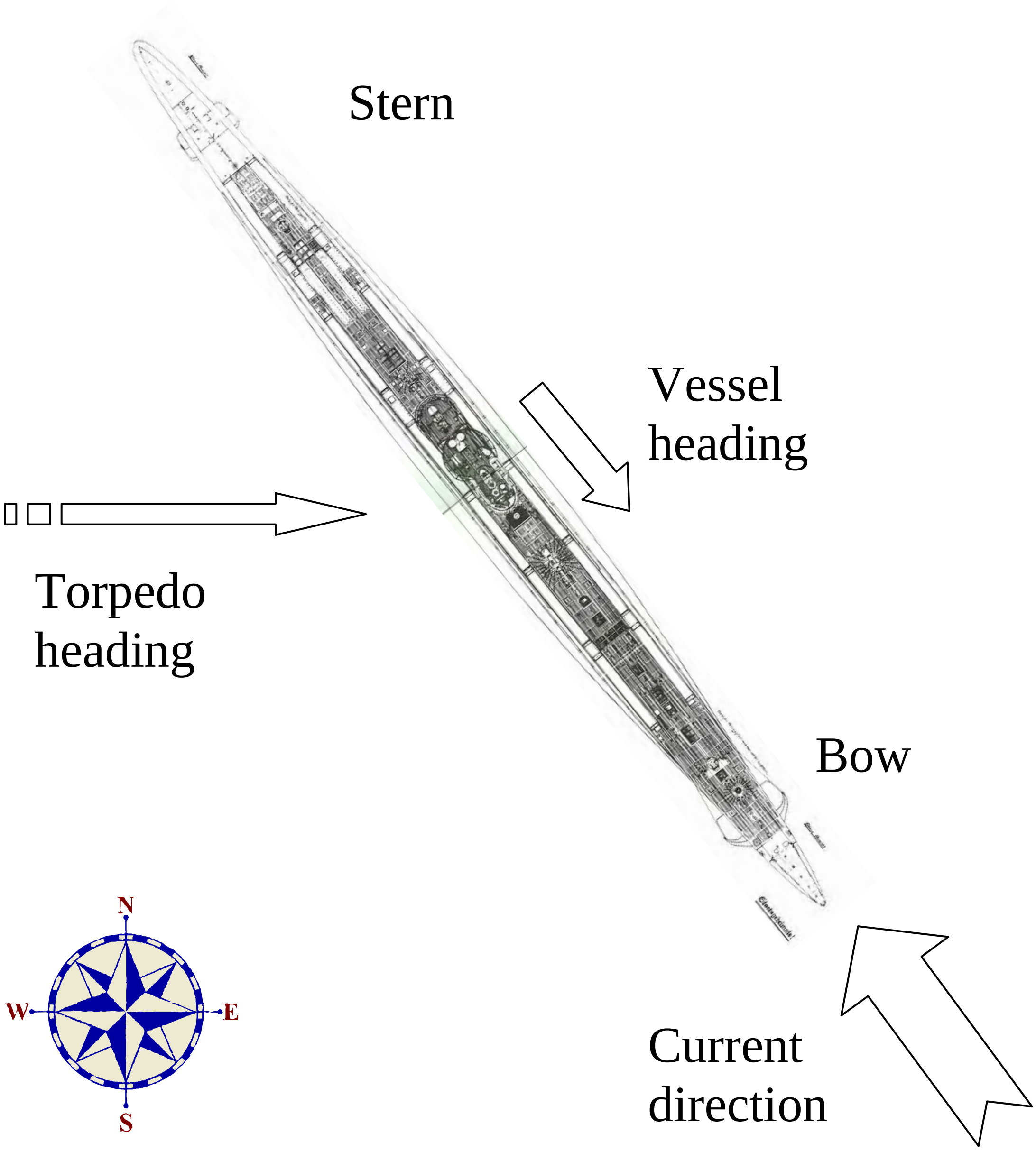

Figure 5-1 Principle sketch of situation at time of attack.

5.3 Physical properties

The following properties have been used for steel and sea water.

Table 5-2 Data for steel and seas water

Property	Value	Unit	Comment
Density of seawater	1025	kg/m^3	Standard value for sea water
Density of steel	7850	kg/m^3	Standard value for carbon steel

5.4 Geometrical properties of submarine

The following geometric properties have been used.

Table 5-3 Data for intact submarine

Property	Value	Unit	Comment
Submerged mass	1804	Metric tonnes	
Length	87.5	m	

5.4.1 Mid section

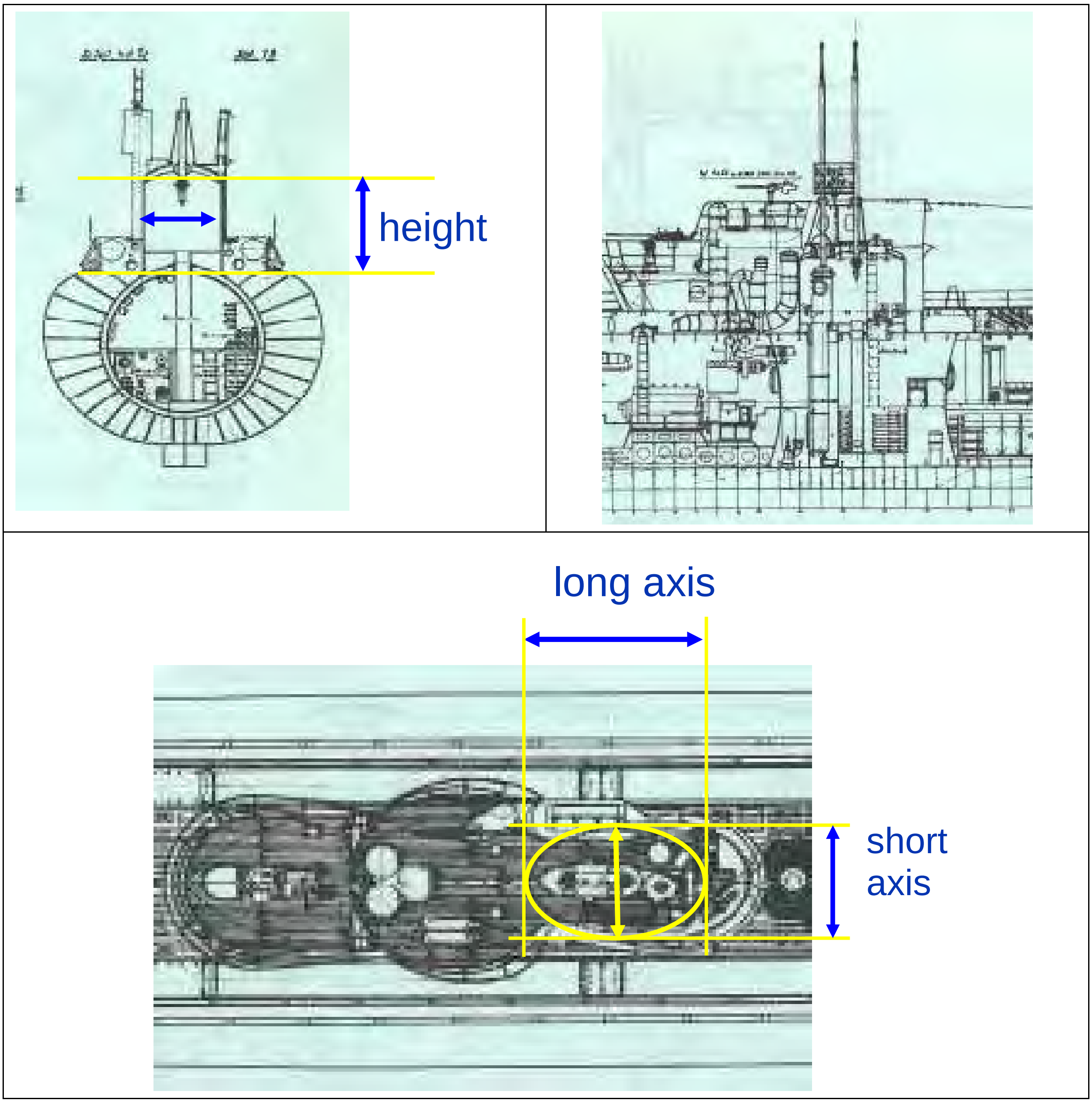

Figure 5-2 Mid section. Front view, plan view and top view. Including ellipse used to approximate conning tower.

Table 5-4 Geometrical and structural properties of mid section

Property	Value	Unit	Comment
Plate thickness of pressure hull	32.0 - 18.5	mm	At midship section. Ref. /1/
Diameter of pressure hull	4.4	m	Ref. /8/ (given as 14.5 ft)
Displacement of hull[1] Surfaced Submerged	 1616 1804	 long ton long ton	 Ref. /8/
Displacement of hull Surfaced Submerged	 1642 1833	 metric tonnes metric tonnes	 Converted from long tons

Table 5-5 Geometrical and structural properties of conning tower

Property	Value	Unit	Comment
Short semi axis, a_t (radius)	1.03	m	Scaled from ref. /4/
Long semi axis, b_t (radius)	1.78	m	Scaled from ref. /4/
Height of tower, h_t	2.63	m	Scaled from ref. /4/
Plate thickness	18.5	mm	At midship section. Ref. /1/

[1] In maritime environments, the term ton is usually referring to long ton, which is slightly heavier than a metric tonne. The difference is only about 2%, so there is no practical difference between the two values in this context.

5.4.2 Bow section

The following figure and tables present the data used on the bow section of the hull, including the ellipse used to approximate it.

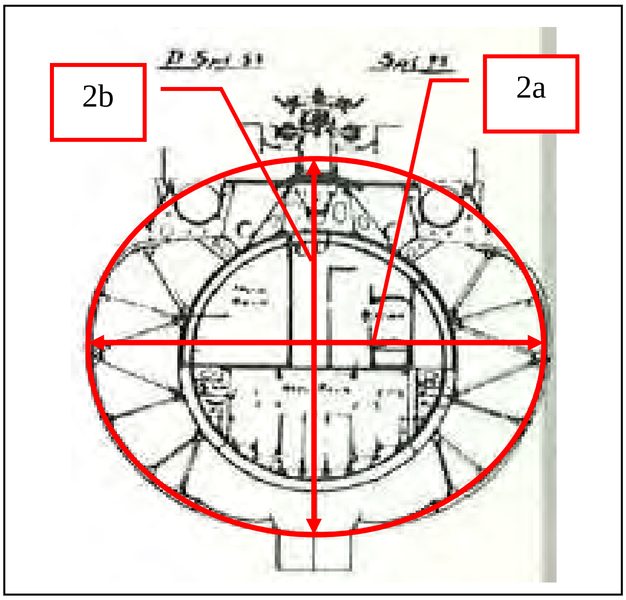

Figure 5-3 Cross section of casing and pressure hull near midship section.

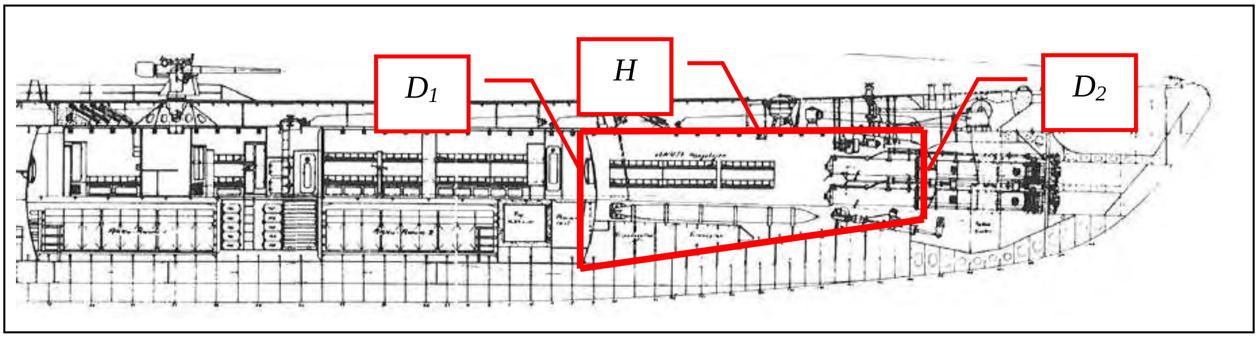

Figure 5-4 Shape of intact part of pressure hull in Bow Section

The volume of the fore torpedo room is estimated as a truncated cone with height, H, base diameter D_1, and top diameter D_2. The volume is then given by the following :

$$V = \frac{\pi}{12}\left(D_1^2 \left(H + \frac{H}{\frac{D_1}{D_2} - 1} \right) - D_2^2 \cdot \frac{H}{\frac{D_1}{D_2} - 1} \right) \qquad \textbf{(3)}$$

Table 5-6 Geometrical and structural properties of bow section after torpedo blast

Property	Value	Unit	Comment
Casing Shape : Elliptical cylinder			
Vertical Semiaxis, *b* (half of casing height)	3.03	m	Excluding keel
Horizontal Semiaxis, *a* (half of casing beam)	3.75	m	Varying linearly to zero at bow
Length of cylinder, *L*	39.60	m	
Pressure hull shape : circular cone, with truncated top			
Base Diameter, D_1	4.4	m	
Top Diameter, D_2	2.9	m	
Length of intact section of pressure hull, *H*	10.4	m	
Volume of intact section of pressure hull, *V*	110.4	m^3	Volume of truncated cone

5.5 Hydrodynamic properties Mid Section

5.5.1 Submerged weight

The submerged weight of the mid section is a very uncertain parameter. It will depend on the mass distribution of the intact hull, and the equipment contained in it.

The mass distribution of the intact hull is unknown. It has not been possible to find any data on this. The best estimate that can be made is to assume that the mass is evenly distributed along the length of the hull. This is probably not correct, but it should give an adequate estimate of the total mass of the section.

The submerged weight of the section after the explosion is an equally uncertain parameter. It has been assumed that the buoyancy of the hull and the equipment is given by the volume of the steel they comprise. It has also been assumed that everything onboard is steel when the volume of the equipment is estimated. This is probably not correct, especially since the weight of the intact vessel includes bunker oil, ballast water, etc. But it is expected to give an adequate estimate of the buoyancy.

The data used in the analysis is summarised in the following table :

Table 5-7 Mass and buoyancy estimates of mid section

Paramter	Value	Unit	Comment
Mass of mid section, M_m	144.3	Metric tonnes	Assuming uniform distribution of mass. Length of section is 7 m
Buoyancy of steel and equipment, B_m	18.8	Metric tonnes	Assuming everything is steel with density 7850 kg/m^3
Estimated submerged weight of mid section	**125.5**	**Metric tonnes**	

5.5.2 Drag coefficient

The shape of the midship section after the torpedo blast is not known. It is expected that it was distorted by the blast, and hence that it may have an irregular shape. This means that it will have a substantial hydrodynamic drag coefficient.

A large drag coefficient will give a conservative estimate of the possible drift distance of the mid section, since it slows down the vertical drop velocity.

From the literature there are few known cases with 2D steady drag coefficients higher than C_D=2.0. A 2D semi-circle with the opening turned towards the current has a drag coefficient of about 2.3, according to ref. /12/.

A base case has been chosen with C_D =2.0. A sensitivity study has been conducted where C_D is varied.

The transverse drag force, F_D, is given by the following formula :

$$F_D = \frac{1}{2} \cdot \rho_w \cdot D \cdot L \cdot C_{DT} \cdot w^2 \qquad \textbf{(4)}$$

Where ρ_w is the density of sea water, D is the cross sectional diameter of the section, L is the length of the section, C_{DT} is the transverse 2 dimensional drag coefficient, and w is the transverse component of the fluid velocity.

5.6 Hydrodynamic properties Bow Section

The basic assumption in the analysis of the Bow and Stern Sections is that the sections will descend with the open ends first. It is expected that the Front and Aft Torpedo Chambers are sealed off and air-filled, thus causing the sections to dip 'nose-down' due to the buoyancy of the air filled part. This is supported by the present position of the sections on the sea bed.

As for the Mid Section, the geometry of the Fore Section is very complicated. The main uncertainty is related to the submerged weight of the section.

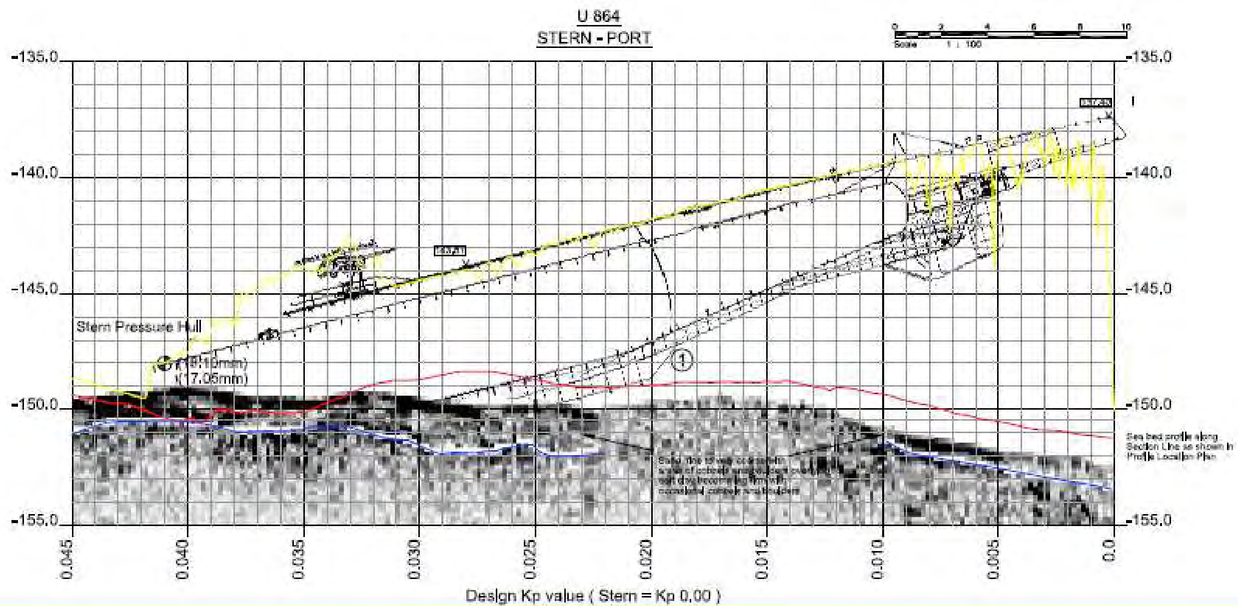

Figure 5-5 Facsimile from ref. /17/

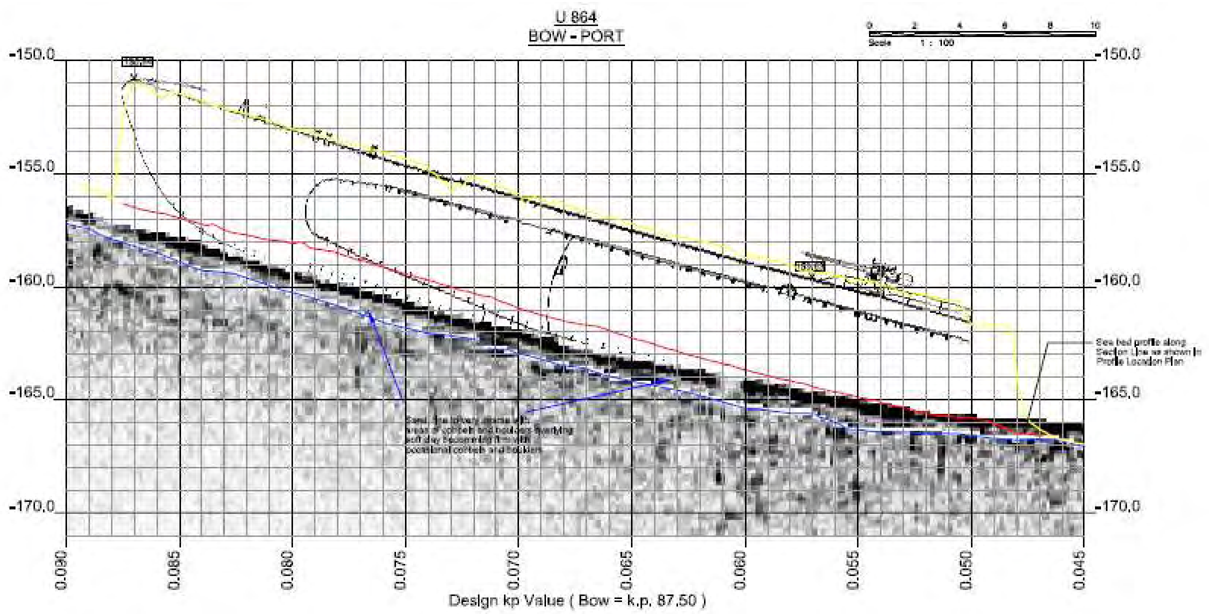

Figure 5-6 Facsimile from ref. /18/

5.6.1 Submerged weight

The submerged weight of the bow and stern sections are very uncertain parameters. The weight will depend on the mass distribution of the intact hull, and also on the amount of water that flows into the section after the torpedo attack.

The mass distribution of the intact hull is unknown. It has not been possible to find any data on this. The best estimate that can be made is to assume that the mass is evenly distributed along the length of the hull. This is probably not correct, but it should give an adequate estimate of the total mass of the sections.

The submerged weight of the sections after the explosion is an equally uncertain parameter. It has been assumed that the torpedo rooms are left intact, and the air pocket is estimated as a truncated cone. It has also been assumed that the buoyancy of the hull and the equipment is given by the volume of the steel they comprise. It has also been assumed that everything onboard is steel when the volume of the equipment is estimated. This is probably not correct, especially since the weight of the intact vessel includes bunker oil, ballast water, etc. But it is expected to give an adequate estimate of the buoyancy.

The data used in the analysis is summarised in the following table :

Table 5-8 Mass and buoyancy estimates of bow section

Parameter	Value	Unit	Comment
Mass of bow section, *M*	816	Metric tonnes	Assuming uniform distribution of mass. Length of section is 39.6 m
Buoyancy of steel and equipment, B_s	107	Metric tonnes	Assuming everything is steel with density 7850 kg/m^3
Buoyancy of intact torpedo room in pressure hull, B_a	113	Metric tonnes	Volume of truncated cone
Estimated submerged weight of bow section	**597**	**Metric tonnes**	

5.6.2 Drag coefficients and drag load

Longitudinal drag coefficient

As mentioned above it is assumed that the section is moving with the open end first. It is thus expected that the drag coefficient will be quite high compared to the intact hull.

A circular cylinder with flat ends, and a length-to-diameter ratio greater than 4, has a drag coefficient in longitudinal current of about 0.8 according to Hoerner, ref. /12/. This value is used in the analysis.

The longitudinal drag force, F_{DL}, is given by the following formula :

$$F_{DL} = \frac{1}{2} \cdot \rho_w \cdot A \cdot C_{DL} \cdot U_0^2 \qquad \textbf{(5)}$$

Where ρ_w is the density of sea water, A is the cross sectional area of the cylinder, C_{DL} is the longitudinal 3 dimensional drag coefficient, and U_0 is the longitudinal component of the fluid velocity.

Transverse drag coefficient

The cross section of the hull is approximately elliptic. At midship the ellipse is close to circular, whereas at the bow and stern it becomes more and more slender, with a vertical long semiaxis. A drag coefficient of 1.0 has been used in the analysis, in accordance with ref. /16/.

The transverse drag force, F_{DT}, is given by the following formula :

$$F_{DT} = \frac{1}{2} \cdot \rho_w \cdot D \cdot L \cdot C_{DT} \cdot w^2 \qquad \textbf{(6)}$$

Where ρ_w is the density of sea water, D is the cross sectional diameter of the cylinder, L is the length of the section, C_{DT} is the transverse 2 dimensional drag coefficient, and w is the transverse component of the fluid velocity.

Moment due to transverse drag

The expression for the transverse drag load is found by integrating the 2-dimensional drag load along the length of the section. The same approach can be used to find the moment of the drag load about a given point along the section. The bending moment about the Centre of Gravity is then given as :

$$M_{DT} = \int_0^L \frac{1}{2} \cdot \rho_w \cdot D(x) \cdot C_{DT} \cdot w^2 (x - L_{CG}) dx = \rho_w \cdot a \cdot C_{DT} \cdot w^2 \left(\frac{1}{3} L^2 - \frac{1}{2} L \cdot L_{CG} \right) \qquad \textbf{(7)}$$

Where $D(x)$ is the width of the section at location x. $D(x)$ has been approximated as a linear variation from zero at the bow to $B=2a$ at the end, i.e. $D(x)=2ax/L$. The position of the longitudinal Centre of Gravity is $x=L_{CG}$ measured from the bow. Section 5.6.4 gives an estimate of L_{CG}.

5.6.3 Lift coefficient and lift load

The lift forces on the bow and stern sections may be significant due to the streamlined shape. This force is very difficult to evaluate, especially since the sections have jagged ends after the explosion, and this may disrupt the flow and hence suppress the lift force.

It has been decided to include lift force in the analysis, and the lift coefficient has been evaluated based on a semi-empirical formula published by NACA, see ref. /15/.

NACA has defined the lift coefficient, C_L, based on the lift force, F_L, as follows :

$$F_L = \frac{1}{2} \cdot \rho_w \cdot L^2 \cdot C_L \cdot U_T^{\ 2} \qquad \textbf{(8)}$$

Where ρ_w is the density of sea water, L is the length of the section, and U_T is the total fluid velocity. Note that the total fluid velocity is related to the longitudinal and transverse velocity components by the formula : $U_T^2 = U_0^2 + w^2$

The expression for the lift coefficient is given in ref. /15/ as follows :

$$C_L = 2(k_z - k_x)\frac{S_b}{A}\alpha + \eta \cdot C_{D_C} \frac{A_\rho}{A}\alpha^2 \qquad \textbf{(9)}$$

Where k_z is the transverse added mass coefficient, k_x is the longitudinal added mass coefficient, S_b is the area of the blunt base, A is the reference area, α is the angle of attack of the flow, η is the ratio of the drag coefficient of a cylinder of finite length to a cylinder of infinite length, C_{DC} is the drag coefficient of a circular cylinder with diameter equal to the beam of the hull, and A_ρ is the planform area.

The various coefficients above are treated in the following :

Table 5-9 Coefficient for lift force on bow section

Coefficient		Value	Unit	Comment
k_z	Transverse added mass coefficient	0.825	-	Using strip theory to find estimate for bow section
k_x	Longitudinal added mass coefficient	0.637	-	Value for hemisphere (=2/π ref. /16/)
S_b	Blunt base area, $S_b = \pi a b$	35.64	m^2	Area of cross section at opening
A	Reference area	1568	m^2	Using L^2
η	Correction factor	0.62	-	From table II in Spencer, p 271, ref. /14/
C_{DC}	Drag coefficient of circle	1.0	-	
A_ρ	Planform area	148.5	m^2	Estimated as triangle, 0.5 L B

The only remaining coefficient is then the angle of attack, α. This has to be solved by use of the equilibrium equations. Since the drag coefficient, C_L, is depending on α it means that the equation system will be non-linear.

5.6.4 Position of Centre of Gravity and Centre of Buoyancy

When calculating the moment equilibrium, as shown in section 4.3 it is important to have good estimates of the longitudinal and vertical positions of the Centre of Gravity and the Centre of Buoyancy.

These are parameters encumbered with uncertainty. They depend on several parameters, all of which are difficult to estimate. The following values represent a best estimate for these parameters.

Table 5-10 Estimating Centre of Gravity of Bow Section

Parameter	Value	Unit	Comment
Intact bow section			
Longitudinal Centre of Gravity	26.4	m	from bow (assuming linear mass distribution from bow to midship)
Vertical Centre of Gravity	2.0	m	above keel (best guess, assuming concentration of mass in keel and engines)
Mass of intact fore section	816	tonn	assuming uniform mass distribution
Water entering bow section			
Longitudinal Centre of Gravity of water	30.1	m	from bow (assuming circular cylinder)
Vertical Centre of Gravity of water	3.5	m	above keel
Mass of water in damaged hull	298	tonn	Assuming a length of 19.1 m of the pressure hull being flooded by the water
Damaged hull			
Longitudinal Centre of Gravity, L_{CG}	27.4	m	from bow
Vertical Centre of Gravity, V_{CG}	2.4	m	above keel

Table 5-11 Estimating Centre of Buoyancy of Bow Section

Parameter	Value	Unit	Comment
Intact bow section			
Longitudinal Centre of Buoyancy	26.4	m	From bow (assuming linear variation of beam)
Vertical Centre of Buoyancy	3.7	m	above keel. Assuming centre of ellipse
Buoyancy of intact fore section	705.6	m^3	Assuming linear variation of beam from midship to bow
Water entering bow section			
Longitudinal Centre of Buoyancy of water	30.1	m	from bow (assuming circular cylinder)
Vertical Centre of Buoyancy of water	3.5	m	above keel
Buoyancy of water in damaged hull	-290.4	m^3	The entering water is reducing the buoyancy
Damaged hull			
Longitudinal Centre of Buoyancy, L_{CB}	23.8	m	from bow
Vertical Centre of Buoyancy, V_{CB}	3.8	m	above keel

Based on the two tables above the estimated distance between the Centre of Gravity and the Centre of Buoyancy is

- Horizontal distance : L_{GB} = -3.5 m (i.e. COB is closer to the bow than COG)
- Vertical distance : V_{GB} = 1.4 m (i.e. COB is higher above the keel than COG)

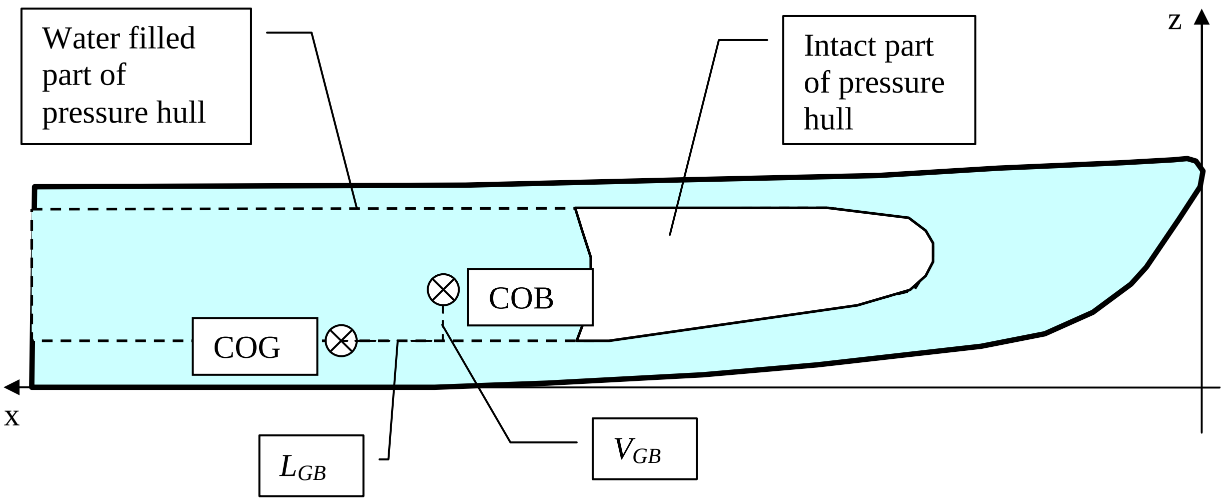

Figure 5-7 Sketch of COG and COB of Bow Section

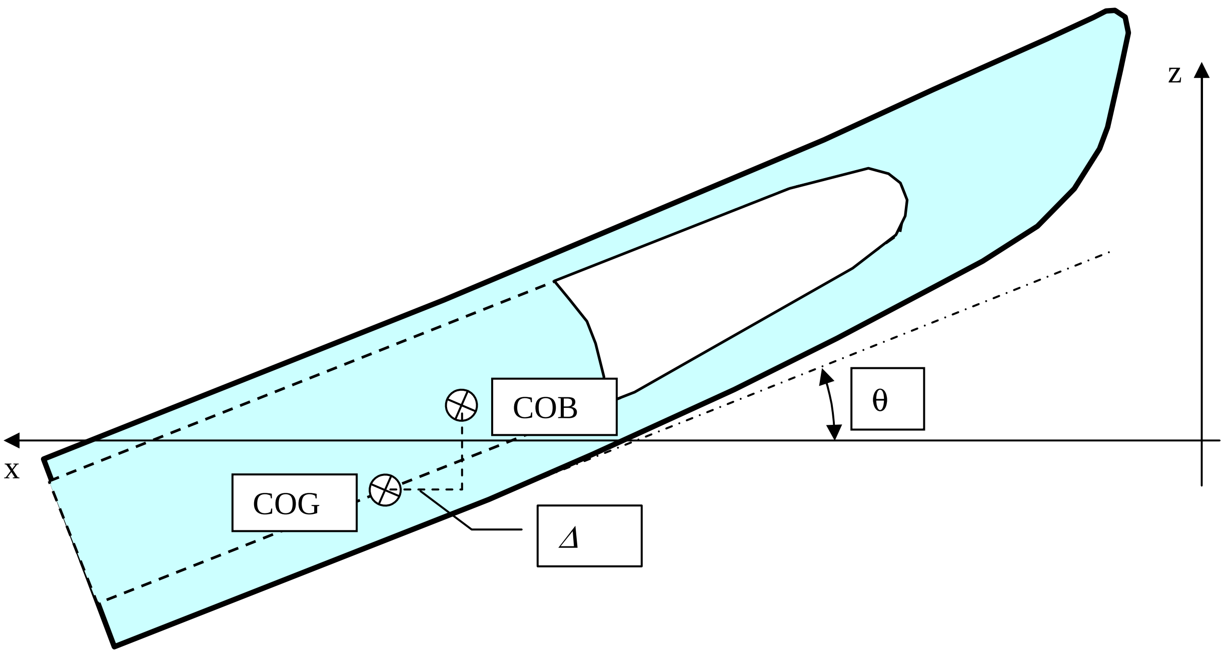

Figure 5-8 Sketch of COG and COB of Bow Section with a pitch angle *θ*. Showing horizontal distance, *Δ*.

6 ANALYSIS RESULTS

This section presents the analysis results of the drift distances of the mid section, bow section, and stern section.

DNV's conclusions are:

C1. The conning tower is buoyant if it is filled with air and the hatches are closed. But with a net buoyancy of 10.4 metric tonnes was the buoyancy not sufficient to support the entire midship section, which had mercury stored in the keel and was filled with water after the torpedo explosion, buoyant. If the conning tower was separated from the mid ship section after the torpedo explosion it would be buoyant, but it would not contain any mercury as this was stored in the keel.

C2. The maximum drift distance of the mid ship section is estimated to be approximately 70 m and is expected to cover all possible variations of the current and the geometry of the midship section after the torpedo explosion, and that the conning tower was

C3. The bottom current is not strong enough to roll the midship section, even when neglecting friction and suction from the seabed.

C4. The bottom topography is not steep enough to allow the midship section to roll under the influence of gravity, even when neglecting friction and suction from the seabed.

C5. The mid ship section is not expected to drift further than the bow and stern sections section on its descent to the seabed. Hence, the midship section is expected to be found in vicinity of the bow and stern sections.

C6. There are no signs of buckling or bending of the hull plates at the fracture. This is an indication that the hull has been torn apart by purely axial loads. If the hull had been torn apart by bending moment, the plates would have shown more signs of bending.

C7. The numerical analysis, and the amount of fragments identified on the seabed, indicates that the midship section most probably has been destroyed by the torpedo explosion, and is found as debris on the in the seabed around the

6.1 Simplified calculations. Drift of Mid Section

By using the equilibrium equation presented in section 4.2, the terminal drop velocity is given as follows :

$$w = \sqrt{\frac{2(M - B)}{\rho_w \cdot D \cdot L \cdot C_D}} \qquad \textbf{(10)}$$

By introducing the estimated submerged weight of 125.5 metric tonnes of the damaged mid-section, and an estimated drag coefficient of 2.0, the following estimates of terminal velocity and drift distance are found :

Table 6-1 Drift distance of mid section. Base case.

Parameter	Value	Unit	Comment
Terminal velocity, *w*	4.8	m/s	Based on drag coefficient of 2.0, and submerged weight of 125.5 metric tonnes
Estimated drop time, t_{DROP}	29.3	sec	Assuming steady state conditions
Estimated drift-off distance[1]	46.8	m	Assuming current velocity of 1.6 m/s (measured maximum current 40 m above seabed)
	8.8	m	Assuming current velocity of 0.3 m/s (measured mean current 40 m above seabed)

Hence, the mid section is not expected to drift more than about 50 m, even if the current velocity is at maximum.

6.1.1 Sensitivity to drag coefficient and submerged weight

A sensitivity study has been performed, in which the submerged weight and the drag coefficient are varied.

- The submerged weight has been varied from 50% to 150% of the base case value of 125.5 metric tonnes, i.e. from 63 to 188 tonnes.
- The drag coefficient has been varied from 1.0 to 2.5, with 2.0 being the value in the base case.

The results of the sensitivity study are presented in the following figures. As expected, the smallest drop velocity, and hence maximum drift distance, is observed for the cases with low submerged weight and large drag coefficient.

The maximum drift distance found is 74 m, based on a submerged weight of 62.7 metric tonnes (50% of base case), and a drag coefficient of 2.5 (50% above base case), based on the maximum measured current velocity of 1.6 m/s. Using the mean current velocity of 0.3 m/s gives a maximum drift distance of 14 m.

This maximum drift distance of 74 m is expected to cover all possible variations of geometry of the mid section after the attack. Hence, it is concluded that there is no need to expand the search area for the mid section. Note that the following section presents a discussion of the submerged weight of the conning tower in the unlikely event that it has been separated in one piece from the main hull.

[1] As mentioned in section 4.1, it is assumed that the section is drifting horizontally with the current.

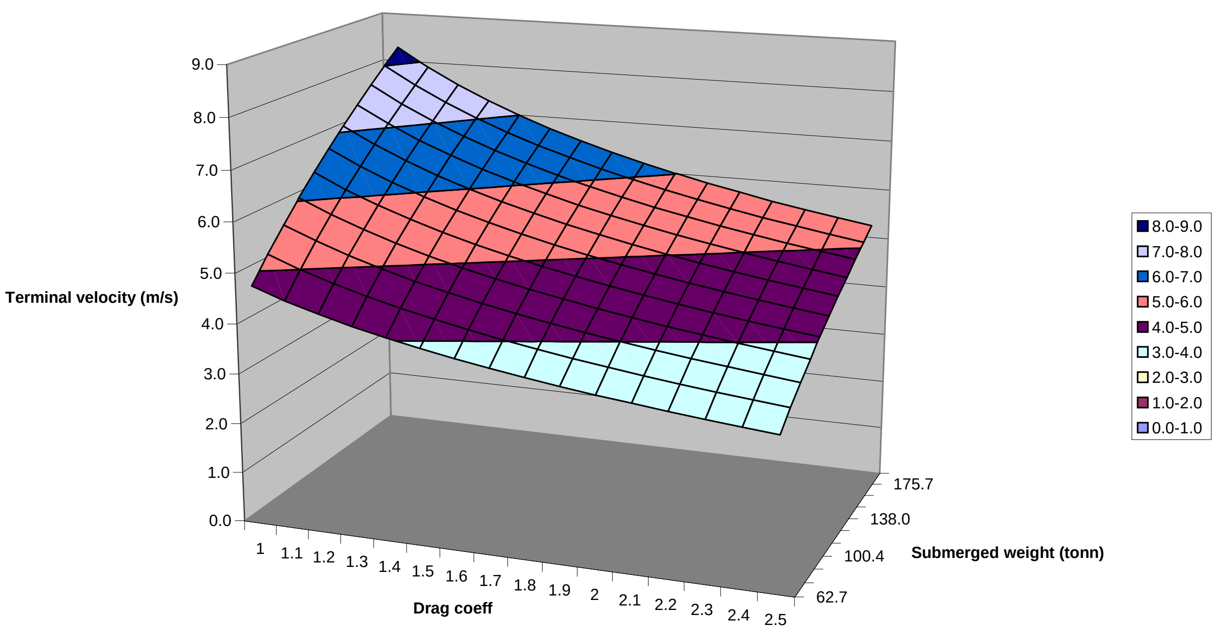

Figure 6-1 Sensitivity of terminal velocity

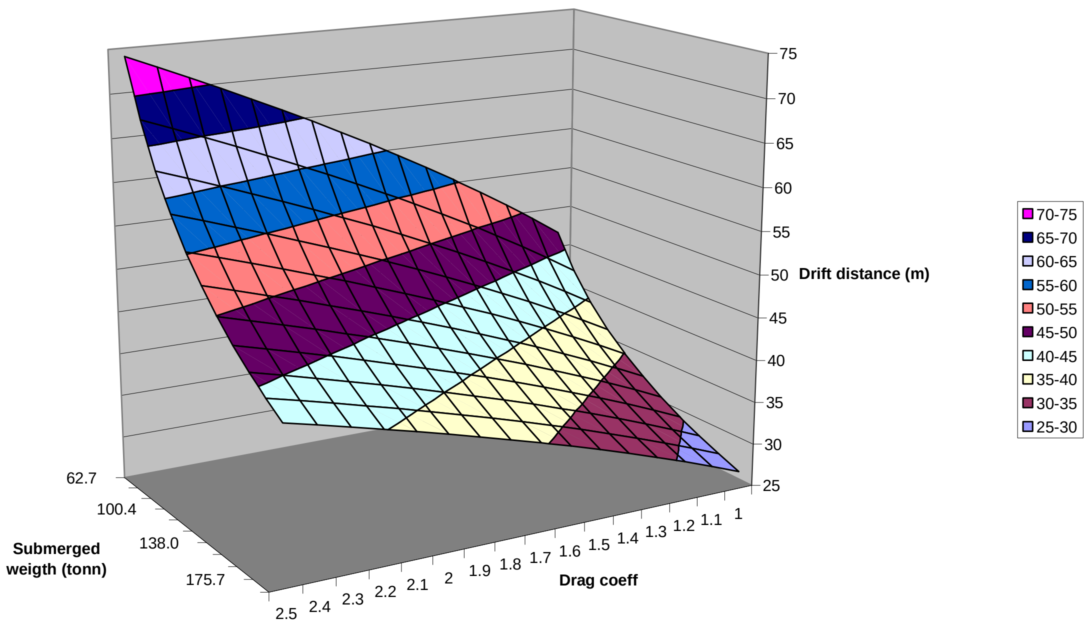

Figure 6-2 Sensitivity of drift distance. Current velocity 1.6 m/s (max value of measured current velocity)

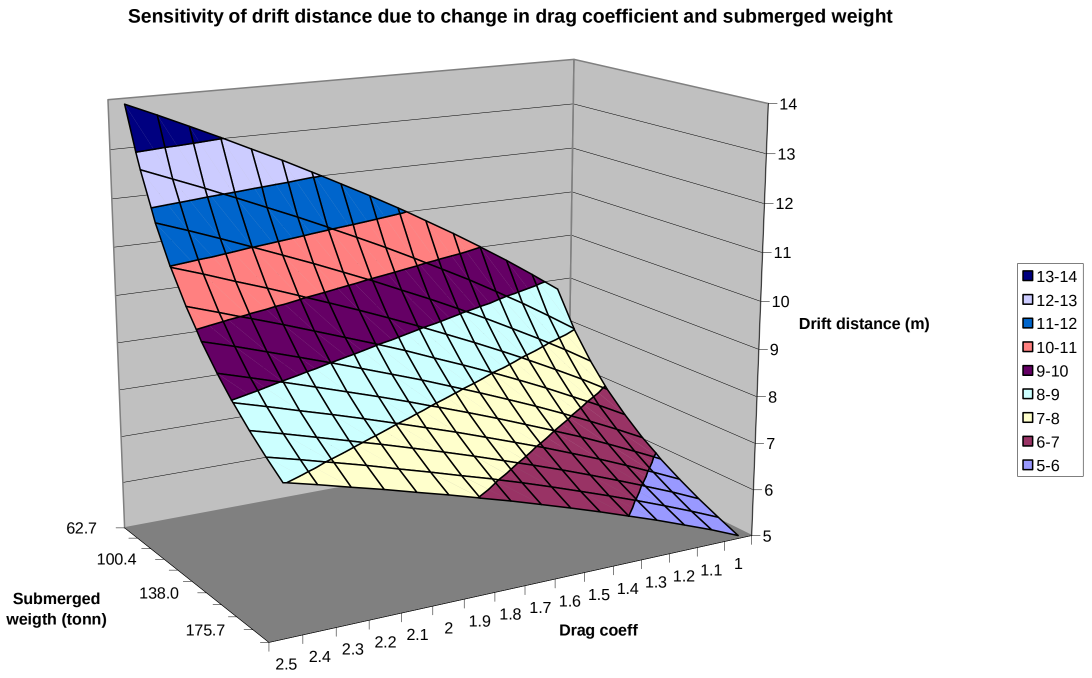

Figure 6-3 Sensitivity of drift distance. Current velocity 0.3 m/s (mean value of measured current velocity)

6.1.2 Estimated submerged weight of tower

Figure 6-4 presents a sketch of the geometry used to estimate the conning tower.

The weight of the steel plating in the tower is estimated as the surface area of the cylinder, including top and bottom, multiplied by the thickness of the steel plates, and the density of steel.

The surface area of the cylinder, excluding top and bottom, is given by the circumference, *C*, of the ellipse multiplied by the height, *h*. A good approximation for the circumference of an ellipse is given by Ramanujan : $C = \pi\left(3(a+b) - \sqrt{(3a+b)\cdot(a+3b)}\right)$

This gives the total surface area of the tower as $A_S = C \cdot h + 2\pi \cdot a \cdot b$. From table Table 5-5, *a=1.03 m*, *b=1.78 m*, and *h=2.63 m*.Using a plate thickness of 18.5 mm, and a steel density of 7850 kg/m^3, this gives an estimated weight of the tower of 5100 kg.

The displaced volume of the cylinder is given by $V_T = \pi \cdot a \cdot b \cdot h$, which yields 15.1 m^3 when inserting the values for *a*, *b*, and *h*. This means that the tower has a theoretical buoyancy of 15500 kg, or 10400 kg net buoyancy when deducting the weight of the steel plates.

Hence, the tower by itself is probably buoyant, i.e. it will float if the hatches are closed. But the net buoyancy of 10.4 metric tonnes is not sufficient to support the entire mid-section, including the Mercury in the keel. Hence, the tower has to be separated from the hull in one piece in order for it to float.

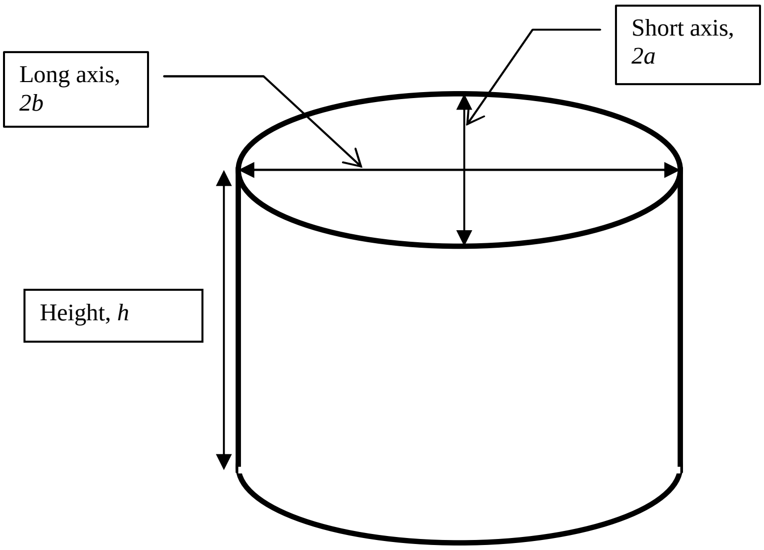

Figure 6-4 Geometry of conning tower.

6.1.3 Discussion of possible rolling of Mid Section on seabed, due to current

In this section, the possibility that the mid section may roll along the seabed driven by current is studied. The following conclusion is made:

> **C3: The bottom current is not strong enough to roll the midship section, even when neglecting friction and suction from the seabed.**

If the mid section should survive the torpedo attack in one relatively intact piece, one could argue that it would be able to roll on the seabed due to its almost circular cross section. This would of course require the conning tower to be removed by the explosion.

This scenario is presented in Figure 6-5. The cross section could theoretically be rolled by the drag force due to current, or due to gradients in the seabed terrain.

A substantial force is required to roll the section due to the low position of the Centre of Gravity (COG) in a submarine. From the figure it is easily seen that the moment of the drag force around the contact point has to be larger than the moment due to the weight.

This gives a simple relation that can be used to find the necessary drag force, and consequently the current velocity that is necessary :

$$F_D = \frac{M \cdot g \cdot \delta}{a} \qquad \textbf{(11)}$$

The drag loads on a cylinder near a wall is about twice as large as on a cylinder in deep water. Hence, we can use a drag coefficient of about 2.0 in this problem. The distance δ from the C.O.G. to the centre of the ellipse is estimated earlier to be about 1.5 m. The long semiaxis, *a*, is half the beam, i.e. 3.75 m. The drag diameter is equal to the beam, i.e. D=7.5 m, and the length of the section is L=7 m.

With a submerged weight of about 125 tonnes, we thus find that the required bottom current is $U_{BOTTOM} = \sqrt{\dfrac{2M \cdot g}{a \cdot \rho \cdot D \cdot L \cdot C_D}} = 2.5\,\text{m/s}$. This value is about 3 times larger than the maximum bottom current measured on the site. Hence, it is concluded that the bottom current is not strong enough to roll the section. This value will increase significantly when adding the suction force and friction from the seabed.

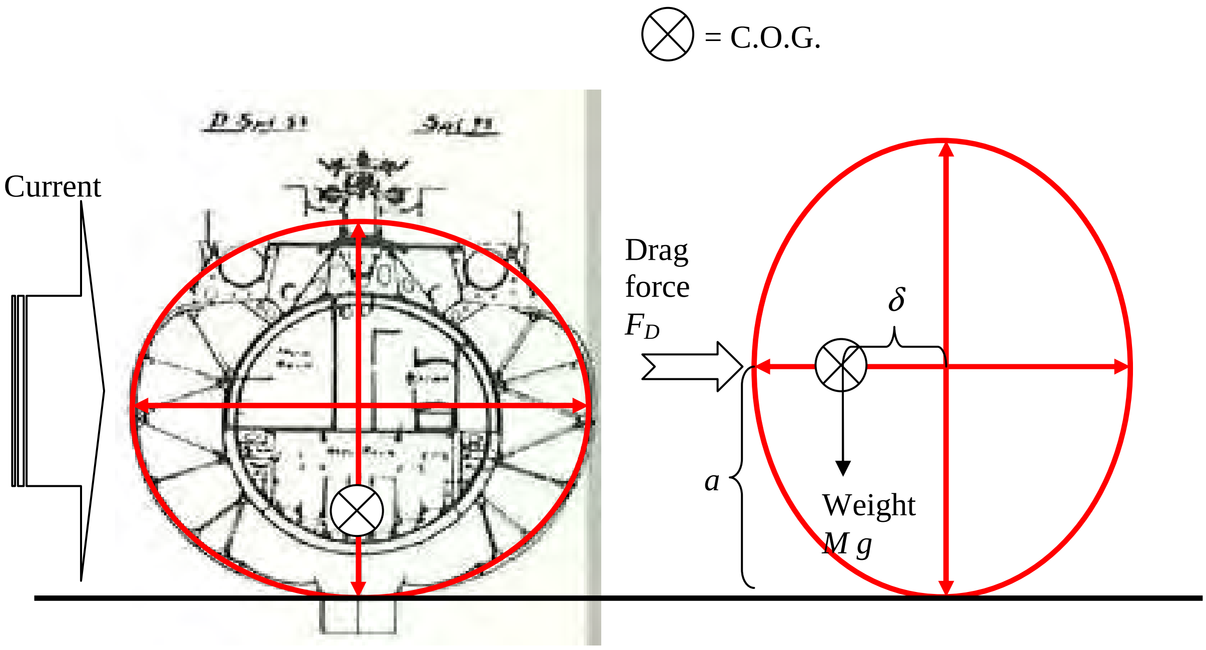

Figure 6-5 Discussion of rolling of Mid Section after drop.

6.1.4 Discussion of possible rolling of Mid Section on seabed, due to seabed slope

In this section, the possibility that the mid section may roll along the seabed driven by steepness of the seabed and gravity is studied. The following conclusion is made:

> **C4: The bottom topography is not steep enough to allow the midship section to roll under the influence of gravity, even when neglecting friction and suction from the seabed.**

The section may have landed on a site with a steep subsea hill, and then rolled down this hill. This situation is shown in Figure 6-6. The figure presents the critical position and angle, which is when the C.O.G. is positioned straight above the contact point with the seabed. From this it is easy to show that the angle that is required for the cylinder to roll is, θ=arcsin(R_1/R_2).

It should be noted that the position of the Centre of Gravity (C.O.G.) is a parameter that is very uncertain. According to ref. /20/ the COG was roughly 0.3-0.4 m below the Centre of Buoyancy (C.O.B.) on the old A-type and B-type submarines, which where built around 1920. These are small submarines with a length of about 40 m, compared to U864, which had a length of 87.5 m.

Hence, the C.O.G. of a Type A submarine is known, but this is for a small submarine, in intact condition, and hence not necessarily valid for the Bow section of the much larger U864 after rupture of the hull. It is expected that the C.O.G. of the Bow section of U864 will be further below the C.O.B., due to all the batteries, equipment, and the keel with the Mercury.

The value of C.O.G. for the bow section has been calculated on basis of four assumptions :

- The mass of the Bow section. Estimated to be 816 metric tonnes
- The C.O.G. of the Bow section. Best guess at approx 1.6 m from the centre of the ellipse used to approximate the outer hull. (Ref. Figure 5-3).
- The mass of the water entering the pressure hull. Estimated to be 298 metric tonnes, assuming the flooded section of the pressure hull is 19 m.
- The C.O.G. of the water entering the pressure hull. Assumed to be at the centre of the pressure hull, i.e. approximately at the centre of the ellipse used to approximate the outer hull.
- The total C.O.G. is then calculated by finding the common centre of gravity of the hull and the water, and is 1.2 m from the centre of the ellipse.

In this case we have $R_1=1.2\ m$, and R_2=3.75m, and hence the required angle is θ=arcsin(0.32) = 18.7°. Note that this does not take into account friction or suction from the seabed. These effects will be significant, but are not easily quantified.

The topography of the seabed near the wreck is shown in Figure 6-7. The equidistance on the map is 5 m, hence if the depth contours are closer than 14.8 m (=5/tan(18.7°)) apart, the slope is steep enough to accommodate rolling of the mid section. This value is expected to be very conservative since friction is neglected. The red dashed ellipse in Figure 6-7 highlights the only area within 100 m of the wreck where the slope is this steep. If the mid section landed here, it could possibly roll down to the flat valley bottom just north of the wreck. The yellow circle that is surrounding the wreck is marking the maximum calculated drift distance for the mid section. Hence, it is considered unlikely that the mid section has been able to reach the steep slope.

If this was the case, such a large structure would show up on the image. It is not possible for such a large structure to sink and disappear into the bottom sediments at this location.

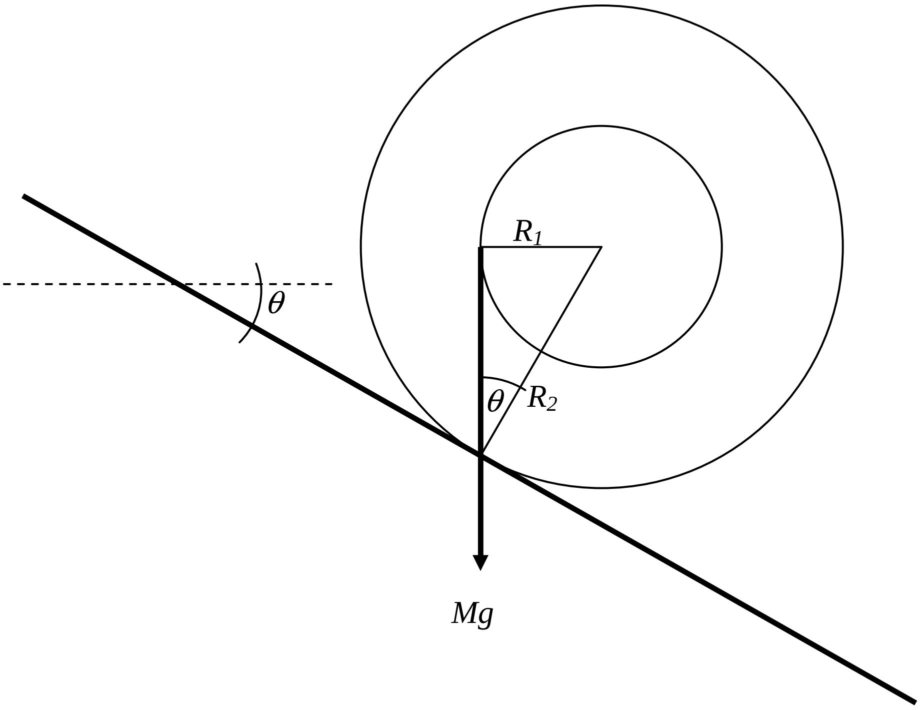

Figure 6-6 Analysis of rolling of mid section (using circle to simplifiy). Definition of critical angle, θ. Circle radius is R_2, C.O.G. is a distance R_1 from centre of circle.

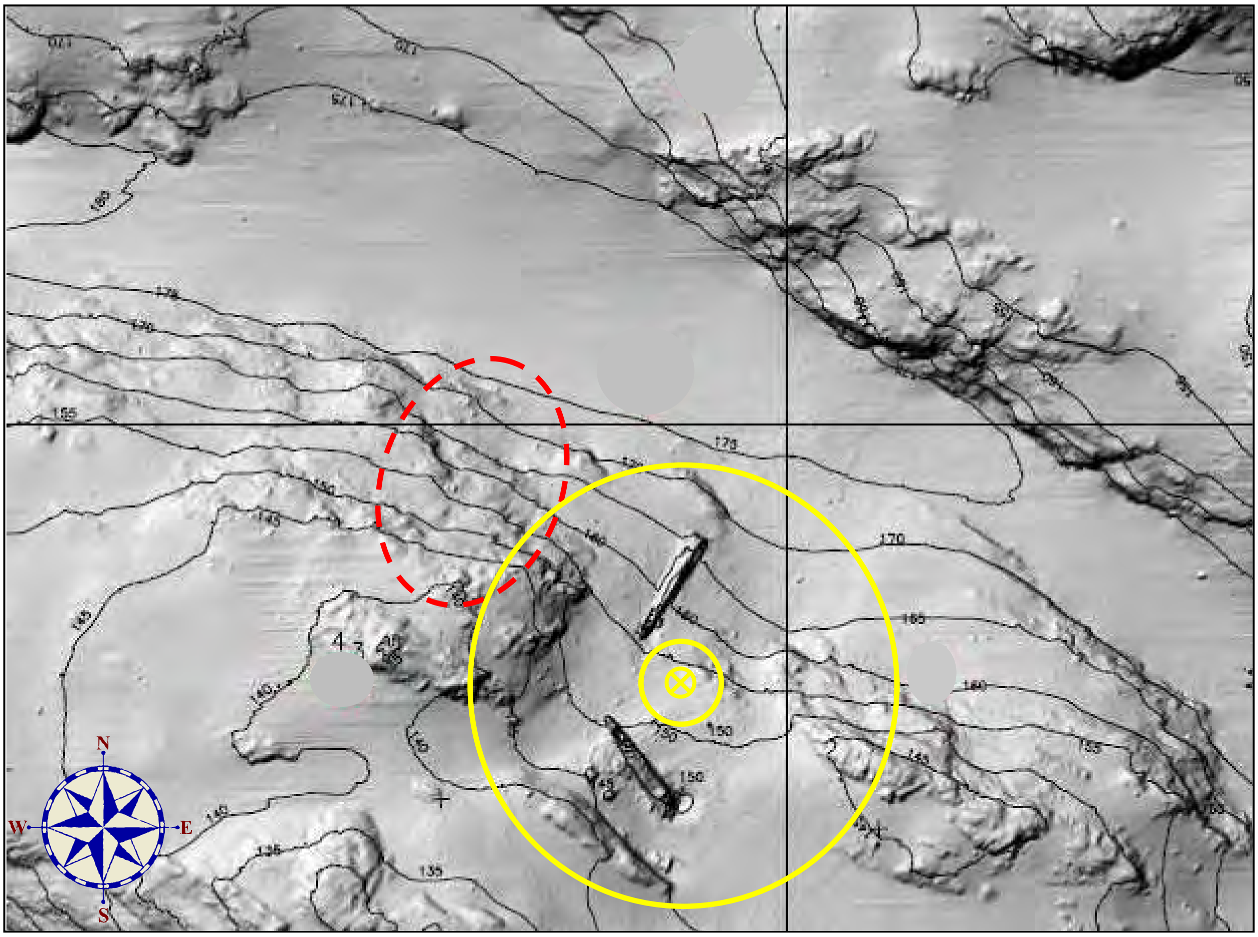

Figure 6-7 Annotated facsimile from ref. /6/.

Showing the gradient of the seabed near the wreck. The red ellipse highlights an area where the slope may be steep enough to accommodate rolling of the mid section. The yellow cross (solid line) marks the midpoint between the ends of the sections, which is used as an estimate for the position of the vessel midship when the torpedo hit. The yellow circles (solid line) represents the maximum drift distances of the mid section based on mean and max current velocities.

6.2 Simplified calculations. Drift of Bow and Stern Sections

The Bow Section is used in the following. It is assumed that the Stern Section will behave similar to the Bow Section. And due to the coarse assumptions that have to be made in this analysis, it is expected that the Stern Section will be covered by the analysis of the Bow Section.

6.2.1 Base Case

By using the equilibrium equations presented in section 4.3, a system of three equations with three unknowns are established.

$$(M-B)\sin(\theta)=\frac{1}{2}\cdot\rho_w\cdot A\cdot C_{DL}\cdot U_0^2$$
$$(M-B)\cos(\theta)=\frac{1}{2}\cdot\rho_w\cdot D\cdot L\cdot C_{DT}\cdot w^2+\frac{1}{2}\cdot\rho_w\cdot L^2\cdot C_L\cdot {U_T}^2$$
$$B\cdot\left(L_{BG}\cos(\theta)-V_{BG}\sin(\theta)\right)=\rho_w\cdot a\cdot C_{DT}\cdot w^2\left(\frac{1}{3}L^2-\frac{1}{2}L\cdot L_{CG}\right) \quad \textbf{(12)}$$

The three unknowns are

- U_0, the longitudinal velocity component
- w, the transverse velocity component
- θ, the pitch angle

In addition, the lift coefficient, C_L, is depending on the angle of attack, α, which is given by α=arctan(w/U_0), and the total fluid velocity over the section, $U_T=\sqrt{U_0^2+w^2}$. This means that the equations have to be solved in an iterative manner.

The base case is represented by the data presented in Table 5-6, and Table 5-8 through Table 5-11, and the equilibrium condition is represented by the following values of the unknown variables :

Table 6-2 Equilibrium condition of Bow Section during drop. Base Case.

Parameter	Value	Unit	Comment
Longitudinal velocity, U_0	18.3	m/s	
Transverse velocity, w	4.7	m/s	
Pitch angle, θ	-56.5	degrees	
Angle of attack, α	14.3	degrees	Given as arctan(w/U_0)
Horizontal drift distance	38.3	m	

The vertical and horizontal velocities in the equilibrium condition is found by a decomposition of the longitudinal and transverse velocity components into global coordinates. The vertical velocity is 17.8 m/s in the base case. This in turn leads to a time to reach bottom of about 6.2 seconds.

The horizontal velocity is 6.2 m/s in the base case, leading to a horizontal drift distance of 38.3 m, not including the effect of current. It is assumed that current can be superimposed independently of the analysis presented here.

Figure 6-8 presents a sketch of the estimated positions of the Bow Section and the Stern Section based on the results from the base case. When comparing this result to the actual position of the sections on the seabed, as shown in Figure 6-9, it is seen that the numerical results are not too far off.

Section 6.2.2 below presents a sensitivity study on several of the main parameters used in the analysis, and as seen in Table 6-3, the horizontal drift distance varies between 15 and 58 metres, depending on the choice of parameters. Hence, the relative positions shown in Figure 6-9 are within the variation of the results in the sensitivity study.

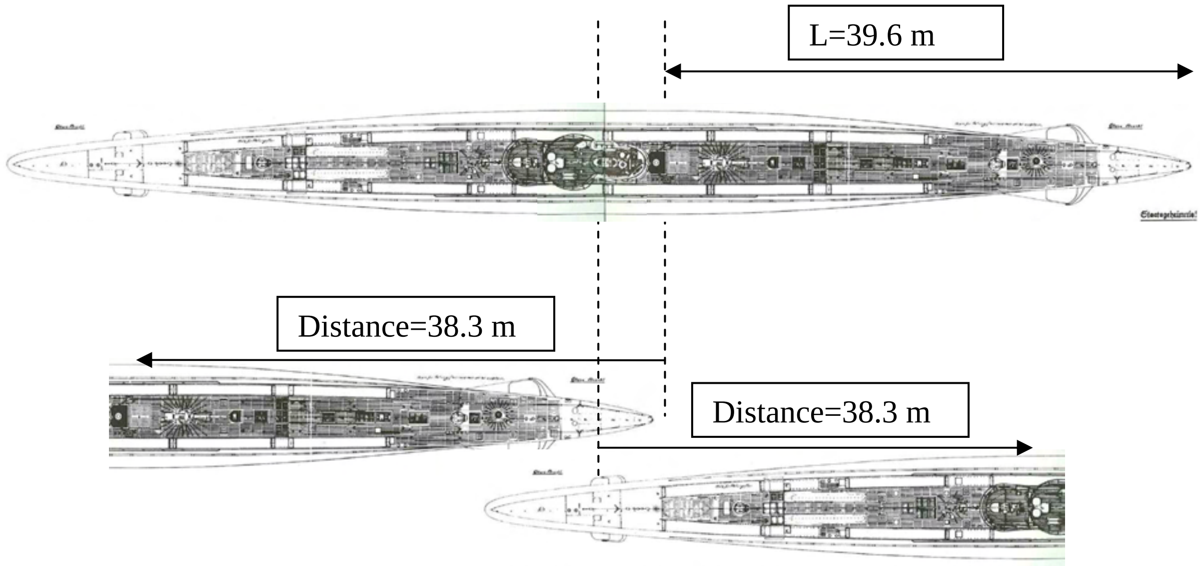

Figure 6-8 Sketch of estimated relative positions on seabed. Base Case.

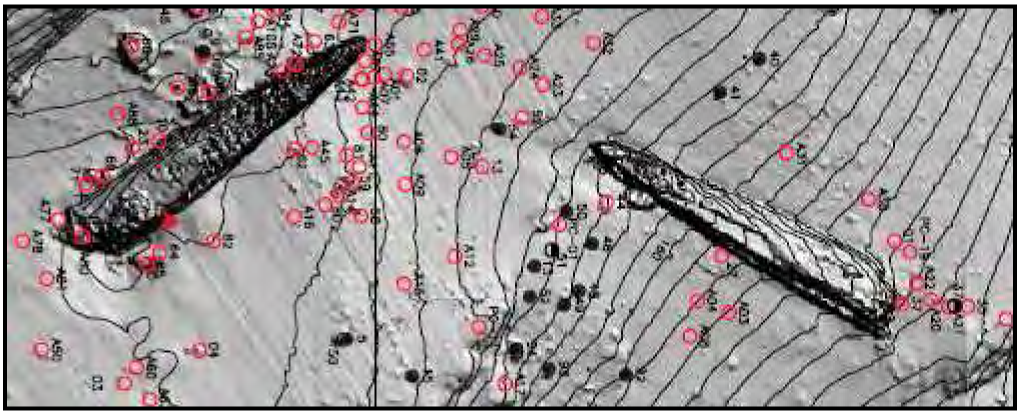

Figure 6-9 Facsimile from ref. /7/. Actual relative position of sections.

As in section 6.1 it is assumed that the sections are drifting with the velocity of the ambient current. Hence, the effect of current is that the bow section, which is moving in the direction of the current, will drift a small distance extra. This distance is equal to the drop time multiplied by the current velocity. In the base case this amounts to

- 9.9 m in 1.6 m/s (maximum current)
- 1.9 m in 0.3 m/s (mean current)

6.2.2 Sensitivity Study

The equilibrium condition is very sensitive to the input parameters, but it seems like the resulting horizontal drift distance does not vary as much.

The following table presents the resulting equilibrium condition and resulting horizontal drift distance due to change in various input parameters. From the table it is seen that the resulting horizontal drift distance (excluding effect of current) is relatively constant. The parameter that influences the drift distance most is the vertical position of the Centre of Gravity of the Bow Section.

Table 6-3 Sensitivity study of horizontal drift distance due to variation of main parameters

Parameter	Base Case	New Value	Longitudinal velocity, U_0	Transverse velocity, w	Pitch, θ	Angle of attack, α	Horizontal drift distance
VCG of intact hull	2.0 m above keel	1.0 m above keel	16.7	5.4	-44.1	18.0	58.0
	2.0 m above keel	3.0 m above keel	19.6	3.2	-72.9	9.4	14.8
LCG of intact hull	26.4m from bow	25.4 m from bow	18.6	4.4	-59.7	13.4	33.4
	26.4m from bow	27.4 m from bow	17.8	5.0	-52.0	15.6	45.3
Lift Coeff. Linear part	Sb=35.6	Sb=0.0	17.8	5.4	-52.4	17.0	41.5
Transverse drag,	C_{DT}=1.0	C_{DT}=0.5	18.7	5.1	-61.0	15.3	26.8
	C_{DT}=1.0	C_{DT}=1.2	18.1	4.5	-55.0	14.0	42.2
Longitudinal drag	C_{DL}=0.8	C_{DL}=0.4	26.1	4.4	-57.9	9.5	45.7
	C_{DL}=0.8	C_{DL}=1.2	14.9	4.8	-55.7	18.0	32.2
Submerged weight of bow section	597 tonn	298 tonn	13.4	2.9	-63.4	12.3	28.0
	597 tonn	895 tonn	20.5	6.7	-44.1	18.1	58.1

6.3 Discussion

6.3.1 Numerical analysis

Based on the analysis and results presented in sections 6.1 and 6.2, it is possible to give estimates of the whereabouts of the Mid Section compared to the position of the Bow Section and Stern Section on the seabed.

- The Mid Section is expected to drift with current toward North-West.
- The Stern Section is expected to drift against the current toward South-East
- The Bow Section is expected to drift in the direction of the current toward North-West

If there was no current, the analysis concludes that the Mid Section should be found between the Bow and Stern Sections.

If there was a slight current, e.g. the mean measured current of 0.3 m/s, the Mid Section is expected to drift 9 m North West, whereas the Stern Section is expected to drift 36.4 m South West, and the Bow Section is expected to drift 40.2 m North-West.

If there was a strong current, e.g. the maximum measured current of 1.6 m/s, the Mid Section is expected to drift 46.8 m North West, whereas the Stern Section is expected to drift 28.4 m South West, and the Bow Section is expected to drift 48.2 m North-West.

In any case the Mid Section is expected to be found in close vicinity of the Bow and Stern Sections.

As shown in section 6.1.2, the Conning Tower can only drift far if the keel and main hull is removed by the explosion. Thus, the Mercury will still be on-site even if the tower has drifted far away.

6.3.2 Effect of explosion

The pictures of the fracture zones on the Bow Section and the Stern Section show that the ends of the steel plates have not been bent significantly. There are no signs of buckling or compression of the hull plates in the fracture zone. It should be noted that part of the hull and fracture zone is hidden in the sediments, but on the bow section one can inspect the better part of the cross section, which builds confidence.

This is an indication that the hull has been torn apart by purely axial loads. If the hull had been torn apart by bending moment, the plates would have shown more signs of bending.

In order to pull the hull apart by axial loads, there has to be a large pressure on the inside of the pressure hull. This can occur only if the torpedo explosion has blown a hole in the outer casing and pressure hull, or if there has been a secondary explosion of the ammunition storage or self-destruct charges in the mid-section, or a combination of the two.

6.3.3 Possible members of mid section

Based on table 3.1 from ref. /2/, a set of targets on the seabed have been identified as possible members of the Mid Section and the Conning Tower. These are listed in Table 6-4. Figure 6-10 through Figure 6-14 present pictures of these targets.

The conclusion from the numerical analysis above, and the target list in Table 6-4, is that the mid section most probably has been destroyed by the torpedo explosion, and is found as debris on the seabed. This is also supported by a statement from the Norwegian Minedykker Kommandoen, in an e-mail dated 19 October 2007. Appendix A includes an excerpt of this e-mail. It is in Norwegian, but the main conclusion is that if the torpedo detonates near the keel, the pressure wave will tear apart the keel and the hull side of the submarine.

Table 6-4 Summary of possible members from the Mid Section, as identified on the seabed

Target	Desription from ref. /2/	Approx size
08	Possible top of Conning Tower	7.8 by 3.9 m
15	Large debris with ribs, pipe, possible part of outer hull, close to torpedo impact	2.6 by 1.9 by 1.4 m
37	Break point on sub (stern section)	1.3 by 3.2 by 1.5
66	Large debris	3 by 2.1 by 2 m
71	Large accumulation of debris, possible part of conning tower, ladder	1 by 1.3 by 0.5 m
78	Large debris, large tube with fin like feature, possible part of conning tower, snorkel	5.5 by 2.4 by 5.5 m

Figure 6-10 Picture of target 08. (Possible top of conning tower)

Figure 6-11 Picture of target 15. (Part of outer hull)

Figure 6-12 Picture of target 37. (Part of outer hull, Saddle Tank)

Figure 6-13 Picture of target 66. (Possible part of conning tower ?)

Figure 6-14 Picture of target 78 (Part of outer hull, with saddle tank?)

7 REFERENCES

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APPENDIX

A
DESCRIPTION OF AN
UNDERWATER DETONATION

By the Norwegian Defence / EOD Command (MDK)

When a torpedo detonates in close proximity of the submarine it will most likely rupture the submarine’s hull. The shockwave will travel in the air filled spaces in the submarine and along the hull of the submarine.

Since the U-864 was hit in relatively shallow water, the shock effect from the bubble itself would have been limited, but the shock wave travelling trough water would affect the submarine. MDK assesses that the shock effect would have a lethal effect on all personnel in the section where the torpedo hit, and in the neighbouring sections. In addition to the rupture of the hull, MDK assesses that the submarine has been thrown sideways and upwards, which could result in further destruction of the submarines hull.

Underwater Explosion Effects

The effects that an underwater explosion will have at a particular place depend on a number of parameters; the energy of the explosion, the depth of the explosion, the depth of the water from the surface to the sea bottom, and the distance from the place to the explosion /1/

Underwater explosions are categorized by the depth of the explosion. Shallow underwater explosions are those where a crater formed at the water's surface is large in comparison with the depth of the explosion. Deep underwater explosions are those where the crater is small in comparison with the depth of the explosion /22/.

The detonation of an explosive charge underwater results in an initial high-velocity shockwave through the water, in movement or displacement of the water itself and in the formation of a high-pressure bubble of high-temperature gas. This bubble expands rapidly until it either vents to the surface or until its internal pressure is exceeded by that of the water surrounding it. (The volumetric expansion of the bubble also leads to a drop in internal temperature in accordance with Charles’ Law.) At this point, as noted above, the over expanded bubble collapses into itself, leading again to a rise in bubble pressure and internal temperature until such time as the bubble pressure exceeds water pressure. The bubble again expands, although to a rather smaller size. A second shockwave is produced by this expansion, although it will be less intense and of rather greater duration than the first. With each cycle, the bubble moves upwards until it eventually vents or dissipates into a mass of smaller bubbles. The number of cycles, while generally low, is difficult to predict; they and the overall effects, depend on explosion depth (and thus water pressure), the size and nature of the explosive charge and the presence, composition and distance of reflecting surfaces such as the seabed, surface, thermoclines, etc. This phenomenon has been extensively used in antiship warhead design since an underwater explosion (particularly one underneath a hull) can produce greater damage than an above-surface one of the same explosive size. Initial damage to a target will be caused by the first shockwave; this damage will be amplified by the subsequent physical movement of water and by the repeated secondary shockwaves or bubble pulse. Additionally, charge detonation away from the target can result in damage over a larger hull area.

Source

/22/ Le Méhauté, Bernard; Wang, Shen (1995). *Water waves generated by underwater explosion*. World Scientific Publishing. ISBN 981-02-2083-9.

APPENDIX

B

EVALUATION OF THE SINKING OF U-864, THE WRECK AND THE DEBRIS FIELD

By Commander s.g. Hans-Chr.Kjelstrup

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ATTACK ON THE U-864 ON 9TH FEBRUARY 1945

BY HMS VENTURER

EVALUATION OF THE SINKING OF U-864, THE WRECK AND THE DEBRIS FIELD

By Commander s.g. Hans-Chr.Kjelstrup

1 GENERAL

In connection with the supplementary studies related to the midship section of the U-864 carried out by the DNV on request by the Norwegian Coastal Administration, it has been proven useful to establish a second opinion as to the sinking of the U-boat an the situation at the debris field as it can be observed and assessed with the current information at hand.

The only source for the attack on the U-864, which led to her sinking, is the
"H.M.S."VENTURER" – REPORT of ELEVENTH WAR PATROL", for the period 2nd February 1945 to 15th February 1945. The commanding officer was Lt. J.S.Launders. This report can today be found in the
Public Record Office, Kew in London, UK.
As for technical information on the U-864, very little documentation as to descriptions and drawings are available today, since most of this was destructed by the Germans after the defeat of Germany in May 1945. The only known drawing is the
Tafel VII: Ubootttyp IX D2-Generalplan". Since the type IX D2 had a known length of 87,6 m, all values for dimensions and lengths related to components, compartments and sections, have been computed from this drawing.
The drawing is an appendix to the book in German: "Geschichte des deutschen Ubootbaus", by Eberhard Rössler, J.F.Lehmanns Verlag, München 1975.

2 ATTACK ON THE U-864

The U-864 was detected by HMS VENTURER on the 9th February 1945 just off Fedje in Hordaland, while both submarines were submerged in the same area.
The initial detection was on the ASDIC (the "sonarsystem" developed by the "Allied Submarine Detection Investigation Committee") by faint sounds coming increasingly stronger. After detection this was supported by sighting the use of the periscopes on the U-864 through the periscope on the VENTURER.
The movements of the U-864 were followed by both using the periscope and the ASDIC. The ASDIC was never used in "active" mode during the attack.
In his report, Lauders states that although the U-boat attacked was zig-zagging at periscope depth, the U-boat was not thought to have been aware of VENTURER's presence. Her radiated noise was very loud and sounded as though Diesels or other heavy equipment was running.
At this point in his report, Lt Launders firmly states that a "schnorkel" was not in use. This item has been contested and discussed amongst submariners in Norway and the Royal Navy, and it

has unanimously been decided that Lt Launders must be wrong on this point. The U-864 would not have been detected on the ASDIC, unless the diesels were running.

Just prior to firing the torpedoes, the U-864 had a calculated speed of 3,5 knots and a course of 140° . The periscopes were observed protruding high above the sea surface, at 0,95 and 2,5 m. By using the above mentioned drawing, the keel would then be at 13,1 m, and top of the casing at 6,6m depth.
Lt Lauders own estimate, taken from the War Patrol report, was keel at 13,6 m depth and top of the casing at 6,3 m.

At 12.12 hrs, four torpedoes were fired by ASDIC readings. The first was fired at the estimated position of the stem and the three following spread in half lengths to <u>one half length astern</u>. The depth of the torpedoes was set at 9,5 to 11,4 m. With the keel at 13,1 m depth, the deepest set torpedoes would have hit the target just above the keel in the lower part of the pressure hull, while the shallower set torpedoes would have hit the target exactly in the middle/on the largest width of the hull.
A loud, sharp explosion came after 2 ½ minutes, followed by breaking up noises. A new fainter, sharp explosion came 2 ½ minutes after the first, followed by two more at 16/17 sec. intervals. In view of the regularity of these three explosions, Lt Launders saw it probable that the first or the last torpedo hit the U-boat.

At 12.46 hrs, VENTURER entered a patch of extensive and spreading oil film which got progressively thicker as it was penetrated until the wavelets looked yellow brown as they lifted against the light. Also a long, steel cylinder with steel brackets and a little bigger than a torpedo, was observed floating with fair buoyancy amidst many odd pieces of wood and dead fish. After sighting this oil patch, Lt Launders says that the position in which the wreckage was found, seems to indicate that the last torpedo was the one that hit.
It is noteworthy that the oil and wreckage patch was observed further to the NW than the assumed position of the U-864 when she was struck by the torpedo.
The position of the oil patch, taken from sketch of attack in the War Patrol Report, was 60° 46'.6N, 04° 36'.9 E.
After this last observation, HMS VENTURER left the area.

3 SINKING OF THE U-864

3.1 Facts and assumptions

In order to establish a theory to the sinking of the U-864, it is necessary to establish all known, relevant facts and from facts and reasoning establish a number of assumptions

What can be established as facts relevant to this theory are:

- The pressure hull of the type IX D2 was made from St 52 a high class steel type with fairly good strength and ductility.
- The pressure hull was divided into 5 pressure tight sections, counting 1 to 5 from aft to forward. In addition there was a pressure tight tower section welded on to the mid section over the control room/section 3.
- Two almost equal long parts of the U-864 were found on the sea bottom at 150 m depth.
    - The forward part containing sections 4 & 5, has an estimated length of 37,6 m and is missing the pressure tight bulkhead between section 3 & 4. Referring to the drawing, approximately 1,5 m is missing from section 4 (bulkhead to bulkhead).
    - The aft part containing section 1 & 2, with an estimated length of 41,9 m and missing the pressure tight bulkhead between section 2 & 3.

    - The mid section/Section 3 would separated from the two parts have had (measuring on the pressure hull) a length of 6,6 m.
- The pressure tight hull edge of both parts indicates that the U-boat was torn apart and not blown apart by the explosion from the torpedo.
- The aft part has a very steep angle to the ocean floor. This indicates that section 1 most likely still is filled with air/ is airtight. Likewise, with the forward part also resting very high on a downward slope and that the part is in an upright position, indicates that also section 5 can be filled with air/ is airtight.
- Observed oil on surface immediately after the sinking must have been engine oil coming from the engine oil tanks inside the pressure hull. Oil tank 1 was under the diesel-generators in section 2, the forward bulkhead of the tank being the same pressure tight bulkhead between section 2 and 3. Oil tanks 2 and 3 were on the sides of battery compartment No. 1 in section 4, the aft bulkhead of the tanks being the same as the pressure tight bulkhead between section 3 and 4. Oil tanks 4 and 5 are still intact on the sides of battery compartment No.2. As far as can be seen from the type IX D2 drawing, the diesel oil tanks are the still intact as part of the saddle tanks of the forward and aft part, well away from the torn zone.
- Only one torpedo hit the U-boat.
- U-864 had a large number of passengers in addition to her regular crew

The following assumptions have been deducted based on the fact that the forward and aft parts of U-864 have been found intact on the sea bottom;

- The U-864 was snorkelling up till she was hit and sunk by a torpedo from HMS VENTURER.
- The passengers and cargo were most likely placed in the aft and forward torpedo rooms, section 1 and 5.
- When snorkelling, the pressure tight hatch between sections 1 and 2 was most likely shut. This is also supported by the positioning of the aft part on the sea bottom today.
- Also the hatch between section 2 (engine room) and section 3 (operation room/"sentrale") was most certainly closed, due to the noise from the running engines.
- The hatch between the control room/section 3 and section 4 was probably closed. This is based on the fact that the mid section/section 3 has been torn away from the aft- and forward parts of the U-boat.
- The hatch between sections 4 and 5 can have been open, but was probably shut after the torpedo from HMS VENTURER hit the U-boat. This is also supported by the upright positioning of the forward part on the sea bottom today.
- It is a fact that the missing mid section/section 3 would have had a length of 6,6 m. Since the bulkheads are missing on the aft part (forward bulkhead section 2) and on the forward part (aft bulkhead section 4), and that these rather significant parts with hatches can not be identified amongst the registered debris on the sea bottom, it is assumed that these two bulkheads are still fixed on to section 3. Also the oval, pressure tight command tower, measuring 2,1m by 3,48m, has not been found on the sea bottom and must presumably still be fixed on to section 3.
- From the torpedo-firing data (depth setting), the snorkel depth of the U-864 at the moment of torpedo impact and the state of the two parts on the sea bottom, it is assumed that the torpedo hit U-864 on Stb side of section 3, and a penetration was made in the pressure hull on the greatest width sideways.
- Only <u>one</u> sharp explosion was heard on the HMS VENTURER. This explosion did not set off the ammunition in the ammunition compartment. Had that happened, there would have been heard one sharp explosion followed immediately by a second, weaker one. This would have been detected on the ASDIC.

- This one explosion was not enough to blow section 3 into smaller parts. This assumption is based on the strength of the steel, the limited energy released from the torpedo warhead detonation and the sheer lack of parts found on the sea bottom.
- Based on the report from Lt Launders, there must have been several inaccuracies related to the attack on U-864. The placing of the oil spillage on the surface in relation to the reported position shows this clearly. The three first torpedoes must have passed ahead of the U-864, while the last one found the target.

3.2 Theory on the sinking of U-864

The following description, is a theory of the events that followed after the U-864 was hit by the last of the torpedoes from HMS VENTURER, based on the above listed observed facts and assumptions.
The torpedo hit U-864 SB side exactly on the greatest width of section 3, and the explosion made a fairly big hole in the pressure hull, thus creating a traumatic, non controllable water inrush. Due to the snorkelling, both hatches in section 3 were closed. The water inrush must have been very fast, creating such a high weight increase in the middle of the U-boat, that it starts splitting up immediately aft of the aft pressure tight bulkhead of section 3 and immediately forward to the fore pressure tight bulkhead of section 3.

It is a fact that the observed oil on the surface immediately after sinking of the U-864 must have been engine oil coming from the engine oil tanks inside the pressure hull, under the diesel generators in section 2 and on both sides of battery compartment No.1 in section 4. Therefore it is assumed that the breaking up of the U-864 took place exactly beneath where the oil was observed, that the separation of section 3 from the aft- and forward parts happened almost simultaneously so that these two parts freely could drift to the sea floor to the area where they were found almost exactly 58 years later. This also places the position of the U-864 when she was hit by the torpedo as to that of the oil patch.

The following figures show how this breaking up into three parts may have occurred.

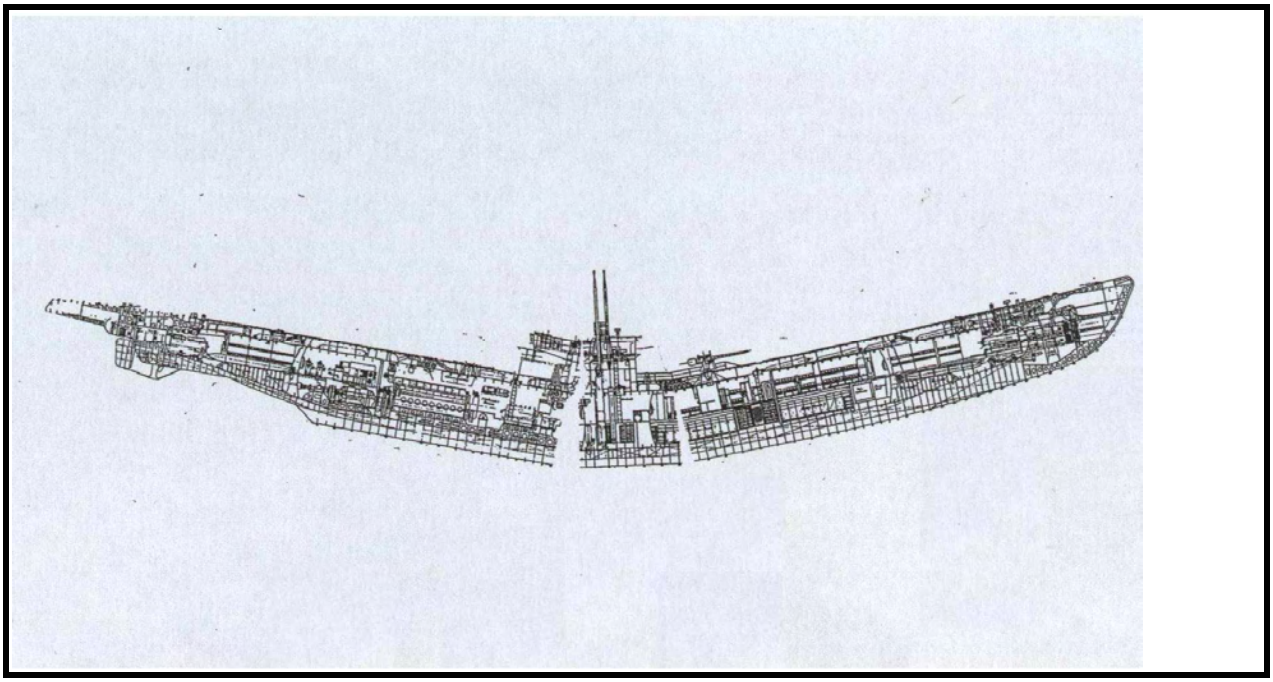

Figure 1. Weight increase causing aft part to crack up first. Oil starts leaking out.

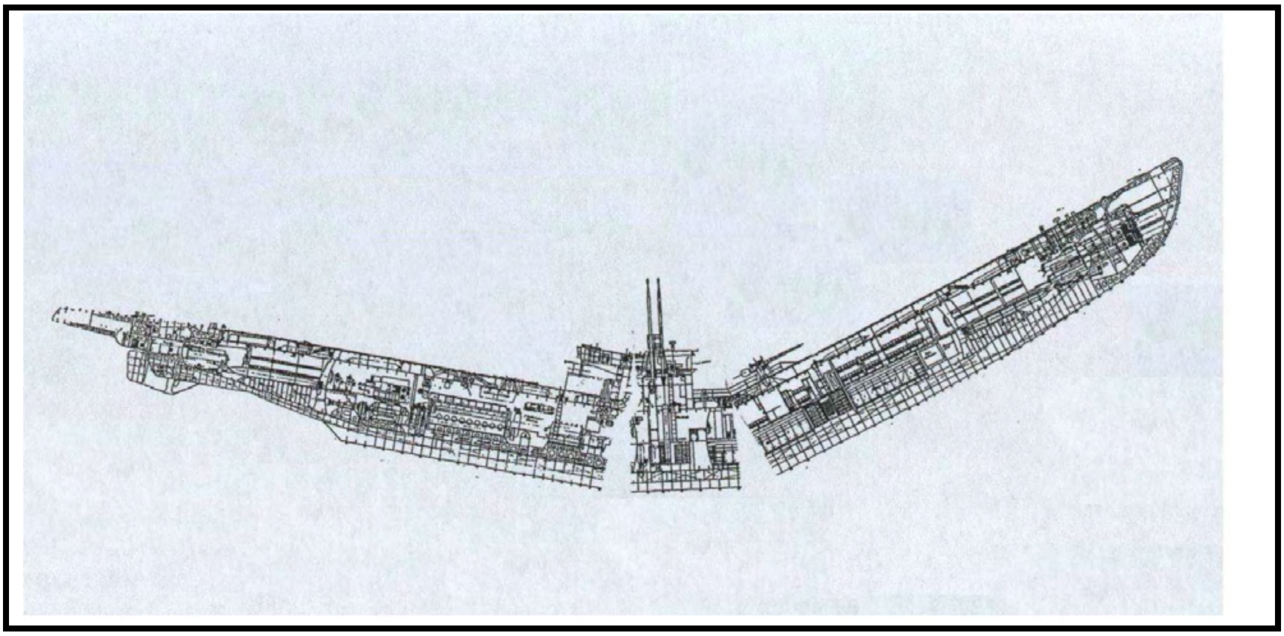

Figure 2. Weight increase also giving full impact on forward part.

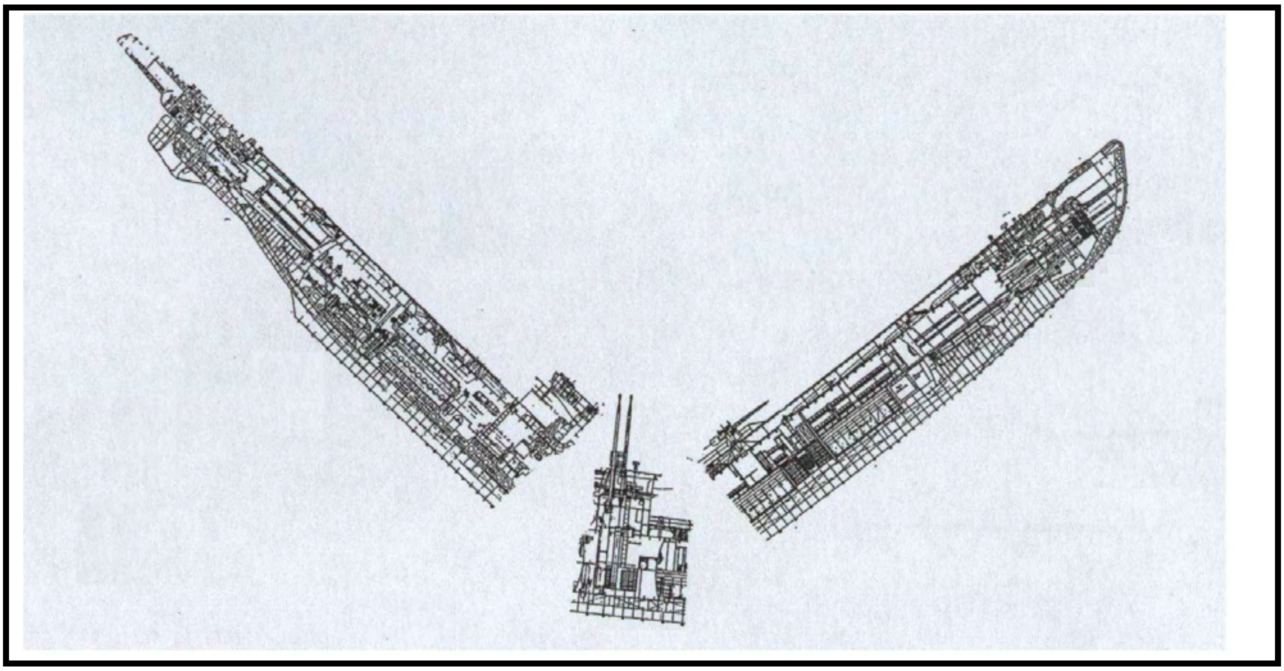

Figure 3. Full separation between aft part, mid section 3 and forward part.

4 EVALUATION OF THE DEBRIS FIELD

After the detection of the aft- and forward part of the U-864 by the Royal Norwegian Navy (RNoN) in February 2003, it was obvious that a major part of the U-boat was missing. Both the RNoN and later the Norwegian Coastal Administration have been looking for the missing section without success.
In 2005 the Norwegian Coastal Administration engaged the Norwegian company "Geoconsult" to map the sea bottom around the two large parts. All detected parts were registered and photographed. At that time I had a more unofficial position in the U-864 project. After the survey I was asked to help Geoconsult in evaluating their find. On the 7th November 2005, half a day was spent at their premises in Bergen going through all video recordings made of the debris on the sea bottom, mainly surrounding the aft part.
None of the significant construction details of section 3 (i.e. pressure tight bulkheads and the oval, pressure tight command tower) were observed.
By this it must be concluded that there is no available evidence supporting the theory that section 3 was blown to pieces when the torpedo exploded into this section.

5 COMPARISON OF REGISTERED PARTS

Figure 5-1 Picture of target 08. (Possible top of conning tower),

This picture is taken from “DNV Technical Report – Salvage of U864 – Supplementary Studies – Midship Section, Report No. 23916-4”, and claims possibly to be “top of conning tower”.
This looks very much like the top “Winter Garten”, the top anti-aircraft gun platform aft of the tower.
The picture below is taken of the same top anti-aircraft gun platform on the U-505, which lies in Chicago, USA. Note that the configuration of the ammunition containers could vary from type to type of U-boat.

Photo by the courtesy of: *Institutional Archives, Museum of Science and Industry, Chicago, USA.*

6 CONCLUSION

The U-864 was snorkelling up till she was hit and sunk by a torpedo from HMS VENTURER. The passengers and cargo were most likely placed in the aft and forward torpedo rooms, section 1 and 5.
The torpedo from HMS VENTURER hit U-864 on Stb side of section 3, and a penetration was made in the pressure hull on the greatest width sideways.
Only one sharp explosion was heard on the HMS VENTURER. This explosion did not set off the ammunition in the ammunition compartment. Had that happened, there would have been heard one sharp explosion followed immediately by a second, weaker one. This would have been detected on the ASDIC.
This one explosion was not enough to blow section 3 into smaller parts. None of the significant construction details of section 3 (i.e. pressure tight bulkheads and the oval, pressure tight command tower) have been observed on the sea bottom.

When the torpedo hit U-864, the explosion made a fairly big hole in the pressure hull, thus creating a traumatic, non controllable water inrush. Due to the snorkelling, both hatches in section 3 were closed. The water inrush was very fast, creating such a high weight increase in the middle of the U-boat, that it started splitting up immediately aft of the aft pressure tight bulkhead of section 3 and immediately forward to the fore pressure tight bulkhead of section 3.

It was the last torpedo fired from HMS VENTURER that hit the U-boat. The observed oil on the surface immediately after sinking of the U-864 was engine oil coming from the engine oil tanks inside the pressure hull, under the diesel generators in section 2 and on both sides of battery compartment No.1 in section 4. The breaking up of the U-864 took place exactly beneath where the oil was observed, the separation of section 3 from the aft- and forward parts happened almost simultaneously so that these two parts freely drifted to the sea floor to the area where they were found almost exactly 58 years later, while section 3 sunk almost downright in this position.
The position of the oil patch was the same as of U-864 when she was hit by the torpedo. This position has been measured in the War Report to be 60^o 46'.6N, 04^o 36'.9E.

For the two identified parts of the U-864, the forward part containing sections 4 & 5, has an estimated length of 37,6 m and is missing the pressure tight bulkhead between section 3 & 4. It is resting very high on a downward slope and the part is in an upright position, which indicates that section 5 can be filled with air/ is airtight. The aft part contains section 1 & 2, has an estimated length of 41,9 m, is missing the pressure tight bulkhead between section 2 & 3 and has a very steep angle to the ocean floor. This indicates that section 1 most likely still is filled with air/ is airtight.

Haakonsvern 10th April 2008

Hans-Chr.Kjelstrup, Commander s.g.

TECHNICAL REPORT

KYSTVERKET NORWEGIAN COASTAL ADMINISTRATION

SALVAGE OF U864 - SUPPLEMENTARY STUDIES - DREDGING

REPORT NO. 47123916-5
REVISION NO. 01

DET NORSKE VERITAS

DET NORSKE VERITAS

TECHNICAL REPORT

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Summary:

The German submarine U-864 was torpedoed by the British submarine Venturer on February 9 1945 and sunk approximately two nautical miles west of the island Fedje in Hordaland. U-864 was carrying about 67 metric tonnes of metallic mercury that implies a threat to the marine environment. In September 2007 The Norwegian Costal Administration commissioned Det Norske Veritas to further investigate different alternatives to salvage the wreck and remove the mercury from the seabed.

The task of the study is to investigate how the seafloor which is contaminated with mercury (about 30 000 m^2) can be removed around the wreck with a minimum of spreading and turbidity. Different methods for an environmentally sound removal are included in the study.

DNV's overall conclusion is: If dredging is chosen as a remediation technology, it is recommended to use an ROV based equipment directly on the seafloor, even though this technique needs further development. For high sediment losses (10 %) during dredging, between 200 to 400 kg of mercury can be lost outside the 1 km2 boundary around the wreck. The dredging capacity has to be increased as the whole dredging operation should ideally not take longer than a month.

Report No.:	Subject Group:	
47123916-5		
Report title: Salvage of U864 - Supplementary studies - Dredging		
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TECHNICAL REPORT

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TECHNICAL REPORT

The German submarine U-864 was torpedoed by the British submarine Venturer on February 9 1945 and sunk approximately two nautical miles west of the island Fedje in Hordaland. U-864 was carrying about 67 metric tonnes of metallic mercury that implies a threat to the marine environment.

In September 2007 The Norwegian Costal Administration commissioned Det Norske Veritas to further investigate different alternatives to salvage the wreck and remove the mercury from the seabed.

1 SUMMARY

This report is *Supplementary Study No. 5: Dredging*, one of twelve supplementary studies supporting the overall report regarding U-864 (Det Norske Veritas Report No. 23916) prepared by Det Norske Veritas (DNV).

The task of the study is to suggest the best dredging technology to use for removing the sediments on the seafloor around U-864, which is contaminated with mercury, with a minimum of spreading and turbidity. Different methods for an environmentally sound removal are included in the study. If all significantly contaminated sediments (>0.6 mg Hg/kg sediment) have to be removed, an area of 30 000m^2 has to be dredged, which is an in situ volume of approximately 15 000 m^3 containing approximately 3 800 kg of mercury.

The working group of this project is not familiar with any similar type of projects that have been done earlier except the dredging that was done with an ROV (remotely operated vehicle) by Geoconsult in September 2006 to reach the keel of U-864.

DNV's overall conclusion is:

If dredging is chosen as a remediation technology, it is recommended to use an ROV based equipment directly on the seafloor, even though this technique needs further development. For high sediment losses (10 %) during dredging, between 200 to 400 kg of mercury can be lost outside the 1 km^2 boundary around the wreck. The dredging capacity has to be increased as the whole dredging operation should ideally not take longer than a month.

DNV's supporting conclusions are:

C1. There are at two main type of dredging technologies for large water depths: 1) Dredging with an independent ROV based equipment directly on the seafloor (including a technology to get the dredged material to a ship), and 2) dredging from a vessel on the water surface.

C2. If dredging is chosen as a remediation technology, it is recommended to use a dredging technology with ROV based equipment directly on the seafloor. The equipment should have the possibility to use both a pump and a grab (which can be closed).

C3. It is necessary to work further on the ROV based dredging techniques. The dredging capacity has to be increased as the whole dredging operation should ideally not take longer than a month due to the unstable weather conditions at the site.

C4. The equipment which is suggested by the contractor(s) should be tested in a nearby (not contaminated) area with the same depth and sediment conditions to verify that the equipment fulfils the necessary requirements.

C5. Modelling of dredging losses indicated that for high sediment losses (10 %), between 200 to 400 kg of mercury can be lost outside the 1 km^2 boundary around the wreck. This is 5 to 10 % of the assumed amount of mercury (3 800 kg) in the dredged material.

C6. Modelling of dredging losses indicates that higher dredging production rates reduce overall clay and mercury losses from the vicinity of the site and is therefore to be preferred

C7. Simulated water column and surface releases at the site show that such releases can be spread outside a 1 km^2 boundary around the wreck. Special measures must be carried out to minimize such releases.

It is assumed that all the dredged sediments are transported to land for further treatment/disposal. It is suggested to stabilise the sediments (cement/gypsum) before disposal. The unit cost for stabilisation and disposal is assumed to be 300 – 600 NOK/metric ton, costs for transportation are not included. The cost also assumes that no dewatering of the sediments is necessary.

The rest of *Supplementary Study No.5: Dredging* details the arguments behind the conclusions.

TECHNICAL REPORT

Den tyske ubåten U-864 ble torpedert av den britiske ubåten Venturer den 9. februar 1945 og sank omtrent to nautiske mil vest for øya Fedje i Hordaland. U-864 var lastet med omtrent 67 tonn med metallisk kvikksølv som utgjør en fare for det marine miljøet.

I september 2007 tildelte Kystverket Det Norske Veritas oppdraget med å nærmere utrede ulike alternativer for heving av vrak og fjerning av kvikksølv fra havbunnen.

2 SAMMENDRAG

Denne rapporten er *Tilleggsutredning nr. 5: Mudring*, en av tolv tilleggsutredninger som understøtter hovedrapporten vedrørende U-864 (Det Norske Veritas Report No. 23916) utarbeidet av Det Norske Veritas (DNV).

Oppgaven for utredningen er å foreslå den mudringsteknologien som best fjerner sedimentene fra sjøbunnen rundt U-864, som er forurenset med kvikksølv, med minimal av spredning og oppvirvling. Ulike metoder for en miljøforsvarlig fjerning er inkludert i utredningen. Dersom alle sedimenter som er vesentlig forurenset (> 0,6 mg Hg/kg sediment) må fjernes, må et område på 30.000 m^2 mudres, hvilket tilsvarer et in situ volum på rundt 15.000 m^3 som inneholder ca. 3800 kg kvikksølv.

Gruppen som har arbeidet med dette prosjektet kjenner ikke til noen lignende type prosjekt som har vært utført tidligere, unntatt mudringen med ROV (fjernstyrt farkost) som ble utført av Geoconsult i september 2006 for å nå kjølen på U-864.

DNV sin overordnede konklusjon er:

Dersom mudring velges som en av opprydningstiltakene anbefales det å benytte ROV-basert utstyr direkte på havbunnen, selv om denne teknologien krever videre utvikling. Ved høyt tap av sedimenter (10%) under mudring, kan mellom 200 og 400 kg kvikksølv forsvinne utenfor 1km^2-området rundt vraket. Mudringskapasiteten må økes fordi mudringsoperasjonen bør ideelt sett ikke ta mer tid enn en måned.

DNV underbygger denne konklusjonen med:

- **C1. Det finnes to hovedteknologier for større havdyp: 1) Mudring med ROV og pumpe plassert på havbunnen (inkludert en teknologi for å føre mudret materiale direkte til et fartøy) og 2) mudring fra et fartøy på havoverflaten.**
- **C2. Hvis en velger mudring som et oppryddingstiltak, anbefales det å bruke en mudringsteknologi med ROV-basert utstyr direkte på havbunnen. Utstyret bør en ha muligheten til å benytte både pumpe og grabb (som kan lukkes).**
- **C3. Det er nødvendig å arbeide videre med utvikling av ROV-baserte mudringsteknologier. Mudringskapasiteten må økes fordi hele mudringsoperasjonen bør ideelt sett ikke ta mer enn en måned på grunn av de ustabile værforholdene i området.**

C4. Utstyret som foreslås av entreprenøren(e) bør testes på et nærliggende (ikke forurenset) område med samme dybde og sedimentforhold for å verifisere at utstyret oppfyller de nødvendige kravene.

C5. Modellering av mudringstap indikerer at ved høyt tap av sedimenter (10%), kan mellom 200 og 400 kg kvikksølv forsvinne utenfor 1km2-området rundt vraket. Dette tilsvarer 5-10% av antatt mengde kvikksølv (3800 kg) i de mudrede sedimentene.

C6. Modellering av spredning under mudring indikerer at høyere mudringshastighet (operasjonen blir ferdig på kortere tid) reduserer den totale spredningen av leire og kvikksølv fra nærområdet rundt vraket og vil derfor være å foretrekke.

C7. Simulerte vannsøyle og overflateutslipp på stedet viser at slike utslipp kan spres utenfor 1 km^2 området rundt vraket. Spesielle tiltak bør iverksettes for å for å minimere slike utslipp.

Det antas at alle mudrete sedimenter transporteres til land for videre håndtering/deponering. Det foreslås at sedimentene stabiliseres (gips/cement) før deponering. Enhetskostnaden for stabilisering og deponering er antatt å ligge på 300 – 600 NOK/tonn, transportkostnad ikke inkludert. Kostnaden forutsetter også at avvanning av sedimentene ikke er nødvendig.

Resten av *Tilleggsutredning nr. 5: Mudring* utdyper argumentene bak konklusjonene.

3 INTRODUCTION

3.1 Background

The German submarine U-864 was sunk by the British submarine Venturer on 9 February 1945, approximately 2 nautical miles west of the island Fedje in Hordaland (Figure 3-1). The submarine was on its way from Germany via Norway to Japan with war material and according to historical documents; U-864 was carrying about 67 metric ton of metallic (liquid) mercury, stored in steel canisters in the keel. The U-864, which was broken into two main parts as a result of the torpedo hit, was found at 150-175 m depth by the Royal Norwegian Navy in March 2003. The Norwegian Costal Administration (NCA) has, on behalf of the Ministry of Fisheries and Coastal Affairs, been performing several studies on how the risk that the mercury load constitutes to the environment can be handled. In December 2006 NCA delivered a report to the Ministry where they recommended that the wreck of the submarine should be encapsulated and that the surrounding mercury-contaminated sediments should be capped. In April 2007 the Ministry of Fisheries and Coastal Affairs decided to further investigate the salvaging alternative before a final decision is taken about the mercury load.

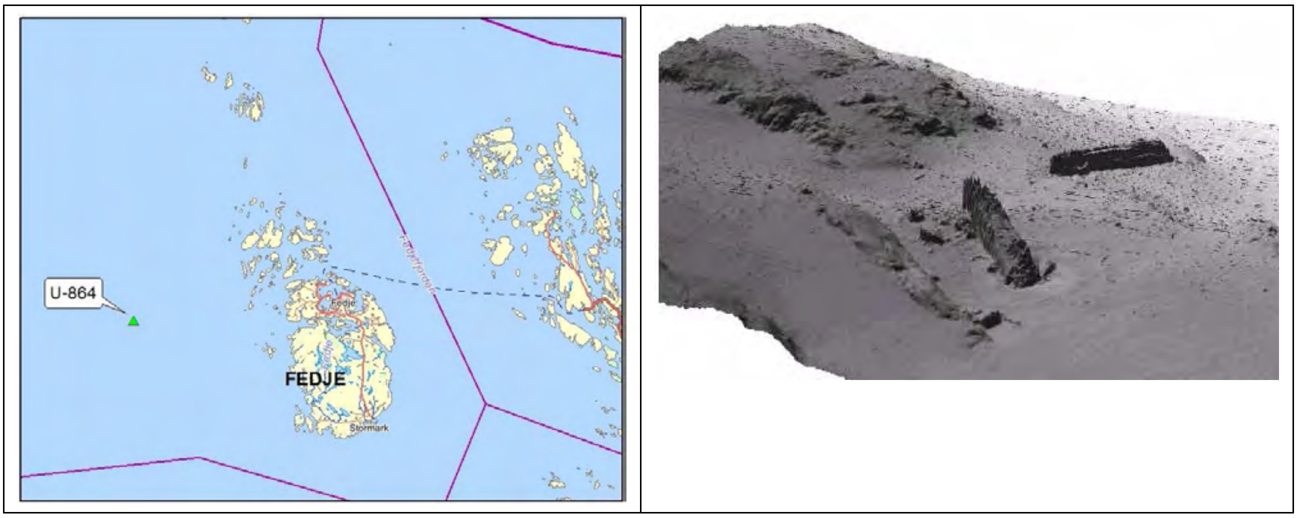


Figure 3-1 Location (left) and a sonar picture of the wreck of U-864 on seabed (right) (from Geoconsult).

3.2 DNV's task

In September 2007 NCA commissioned Det Norske Veritas (DNV) the contract to further investigate the salvaging alternative. The contract includes:

- DNV shall support NCA in announcing a tender competition for innovators which have suggestions for an environmentally safe/acceptable salvage concept or technology. Selected innovators will receive a remuneration to improve and specify their salvage concept or technology.

- DNV shall support NCA in announcing a tender competition for salvage contractors to perform an environmentally justifiable salvage of U-864.
- DNV shall evaluate the suggested salvage methods and identify the preferred salvage method.
- The preferred salvage method shall be compared with the suggested encapsulation/capping method from 2006. (DNV shall give a recommendation of which measure that should be taken and state the reason for this recommendation.)
- DNV shall perform twelve supplementary studies which will serve as a support when the decision is taken about which measure that should be chosen for removing the environmental threat related to U-864. The twelve studies are:

1. *Corrosion*. Probability and scenarios for corrosion on steel canisters and the hull of the submarine.
2. *Explosives.* Probability and consequences of an explosion during salvaging from explosives or compressed air tanks.
3. *Metal detector*. The possibilities and limitations of using metal detectors for finding mercury canisters.
4. *The mid ship section*. Study the possibility that the mid section has drifted away.
5. *Dredging*. Study how the mercury-contaminated seabed can be removed around the wreck with a minimum of spreading and turbidity.
6. *Disposal*. Consequences for the environment and the health and safety of personnel if mercury and mercury-contaminated sediments are taken up and disposed of.
7. *Cargo.* Gather the historical information about the cargo in U-864. Assess the location and content of the cargo.
8. *Relocation and safeguarding.* Analyse which routes that can be used when mercury canisters are relocated to a sheltered location.
9. *Monitoring.* The effects of the measures that are taken have to be documented over time. An initial programme shall be prepared for monitoring the contamination before, during and after salvaging.
10. *Risk related to leakage.* Study the consequences if mercury is unintentionally leaked and spreading during a salvage or relocation of U-864.
11. *Assessment of future spreading of mercury for the capping alternative*. The consequences of spreading of mercury if the area is capped in an eternal perspective.
12. *Use of divers.* Study the risks related to use of divers during the salvage operation in a safety, health and environmental aspect and compare with use of ROV.

3.3 Scope of this report

This report is *Supplementary Study No. 5: Dredging*. The objective of this study is to investigate how the seafloor around the wreck, which is contaminated with mercury (about 30 000 m^2), can be removed with a minimum of spreading and turbidity. Different methods for an environmentally sound removal are included in the study.

Dredging was done with a ROV (remotely operated vehicle) by Geoconsult in September 2006 to reach the keel of U-864. The work had to be stopped when the submarine started to move. The aft end of the submarine tilted 1-2 meters and started cracking. Both when dredging was done with a “closed backhoe” grab and with suction dredging equipment, the amount of particles in the water became relatively high. NIVA concluded that it was difficult to dredge without spreading mercury and recommended therefore that dredging of the sediments should be avoided as far as possible.

This supplementary study looks at which technologies can be used for doing an environmentally safe removal of the mercury contaminated sediments. The 2-3 most promising technologies (BAT = Best Available Technology) are selected, studied in detail and, as far as possible, quantified with respect to spreading potential, consequences of spreading and costs. In addition the amount of masses which have to be disposed of are investigated with respect to location and cost for the disposal. Special attention is given to if it is profitable to separate the most contaminated masses from the rest of the material before disposal. The geotechnical stability is partly bad, thus the geotechnical implications by dredging the sediments is examined for the different dredging technologies.

The structure of this report is:

- Dredging technology for removal of mercury-contaminated sediments from 150 m depth (chapter 4)
- Amount of sediments to dredge and dispose of (chapter 5)
- Modelling of spreading from dredging at 150-175 m depth (chapter 6)

4 DREDGING TECHNOLOGY FOR REMOVAL OF MERCURY-CONTAMINATED SEDIMENTS FROM 150 M DEPTH

DNV's conclusions are:

C1. **There are at two main type of dredging technologies for large water depths: 1) Dredging with an independent ROV based equipment directly on the seafloor (including a technology to get the dredged material to a ship), and 2) dredging from a vessel on the water surface.**

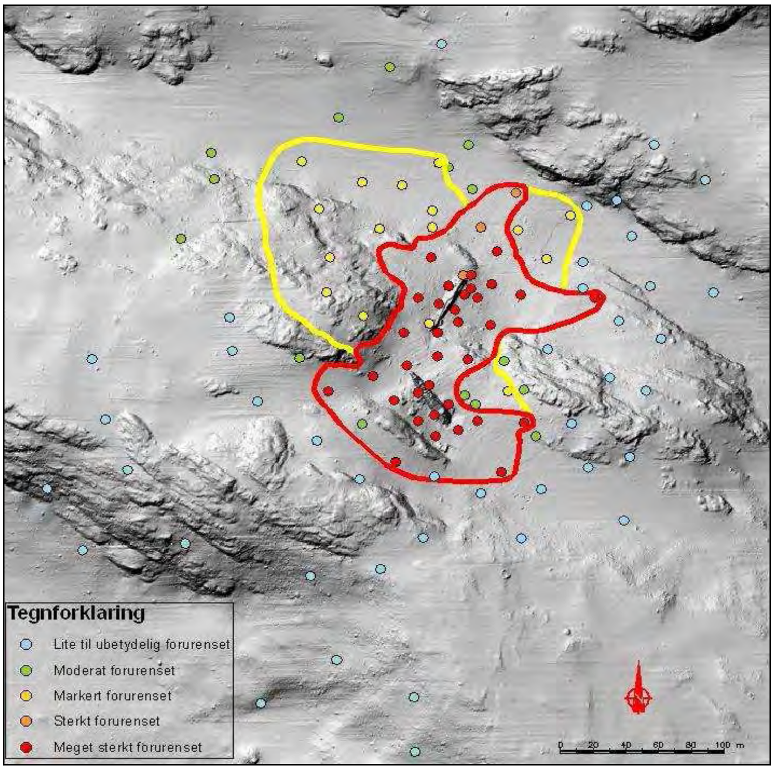
C2. **If dredging is chosen as a remediation technology, it is recommended to use a dredging technology with ROV based equipment directly on the seafloor. The equipment should have the possibility to use both a pump and a grab (which can be closed).**

C3. **It is necessary to work further on the ROV based dredging techniques. The dredging capacity has to be increased as the whole dredging operation should ideally not take longer than a month due to the unstable weather conditions at the site.**

C4. **The equipment which is suggested by the contractor(s) should be tested in a nearby (not contaminated) area with the same depth and sediment conditions to verify that the equipment fulfils the necessary requirements.**

Dredging of mercury-contaminated sediments from 150 m depth involves many challenges, especially with respect to dredging accuracy and the possibilities to avoid turbidity spreading of sediments.

Surveys done in 2005 and 2006 show that approximately 30 000 m^2 seafloor around the wreck is significantly polluted with mercury (see Figure 4-1). Based on core sampling, NIVA estimates that at least 0.5 m thickness of the seafloor is significantly contaminated with mercury. If all the significantly contaminated sediments (>0.6 mg Hg/kg sediment) have to be removed, an in situ volume of approximately 15 000 m^3 has to be dredged.



	I Background	II Moderately polluted	III Significantly polluted	IV Severely polluted	V Extremely polluted
Old guidelines (which the figure is based on)	<0.15 mg/kg	0.15-0.6 mg/kg	0.6-3 mg/kg	3-5 mg/kg	>5 mg/kg
New guidelines (valid from February 2008)	<0.15 mg/kg	0.15-0.63 mg/kg	0.63-0.86 mg/kg	0.86-1.6 mg/kg	>1.6 mg/kg

Figure 4-1 Map showing the area which is severely polluted (>5 mg Hg/kg sediment, red line) and significantly polluted (>0.6 mg Hg/kg sediment, red + yellow line) with mercury around U-864. The map is based on analyses of surface sediment samples (0-2 cm) and the old SFT classification system (SFT, 1997). The map was made by Geoconsult (now DOF Subsea) and NIVA.

The working group of this project is not familiar with any similar type of projects that have been done earlier except the dredging that was done with a ROV by Geoconsult in September 2006 to reach the keel of U-864.

There are at two main types of dredging technologies for large water depths:

1. Dredging with independent ROV based equipment directly on the seafloor (including a technology to get the dredged material to the water surface)
2. Dredging from a vessel on the water surface (using cable bucket or similar)

In the following chapters each of the two main technologies are described, including the advantages and disadvantages.

4.1 Dredging with an independent ROV based equipment directly on the seafloor

With the oil and gas exploration at large water depths, dredging methods which use equipment that is being based directly on the seafloor has been developed. So far this type of dredgers has mainly been developed for excavations and the dredged material has been relocated on the seafloor.

Two types of dredging methods based on the seafloor have been identified as possible methods for dredging the mercury contaminated sediments:

- Dredging with ROV and sea bed pump.
- Dredging with an excavator equipped with a visor bucket.

4.1.1 Dredging with ROV and sea bed pump

The dredging method consists of a ROV (remotely operated vehicle) equipped with a suction hose connected to a pump deployed at seabed (see Figure 4-2). The equipment has a capacity of approximately 100 metric ton/hour (including water) and requires large storage capacity as the pumping efficiency typically gives a mixture of 10 % sediment and 90 % of water.

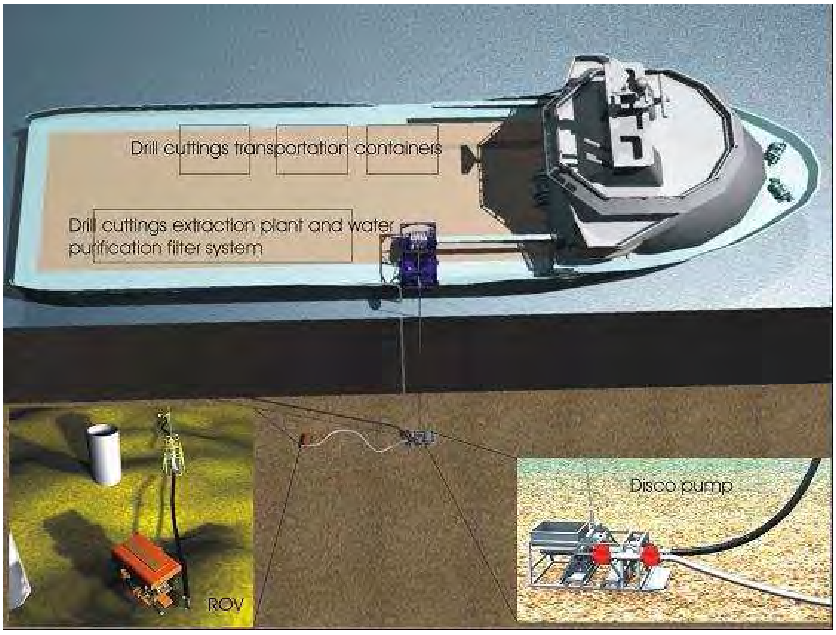


Figure 4-2 ROV with suction hose and sea bed pump (system developed by AGR for dredging drill cuttings)

4.1.2 Dredging with an excavator equipped with a visor bucket

The dredging method consists of an excavator with a visor bucket. The polluted sediments are moved with as little disturbance as possible into a special designed container with the grab

(Figure 4-3). The machine has a dredging unit and a built in documentation system. The capacity is in the same order of size (100 metric ton/hour) as for the ROV with suction hose, maybe even a bit higher under favourable conditions. An advantage of the excavator is that it can remove sediments with low water content. The grab is closed when it moves towards the container. It generates turbidity when emptying the grab into the container, and it may be around 20 % loss of sediments in the process. A possible solution for reducing the loss of sediments would be to have an underpressure in the container, causing the sediments to be sucked into the container.

Figure 4-3 Excavator equipped with a visor bucket (system developed by Scanmudring and used for dredging to reach the keel of U-864 in 2006)

4.2 Dredging from a vessel on the water surface

Dredging at large water depths with a vessel on the water surface requires a very high positioning accuracy and very strong equipment.

Three types of dredging methods have been identified:

- Dredging with trailing suction hopper dredge
- Dredging with Pneuma Pump
- Dredging with closed level cut clamshell

4.2.1 Dredging with trailing suction hopper dredge (TSHD)

A trailing suction hopper dredge (TSHD) is a dredger with a suction head on the end of a moveable arm (see Figure 4-4). There are TSHDs in the market which can dredge down to 165 meter. Reported vertical accuracy is about +/- 25 cm. The THSD can work in wave heights up to approximately 2.5 meters.

The method has a very high capacity and the volume which can be loaded on the hopper dredge is up to 45 000 m^3. Typically the dredged volume contains 75 % water and 25 % solids. The method is robust and not very vulnerable for debris on the seafloor. The TSHD is mainly used for projects which need large production capacity like land reclamation and not very often for contaminated sediments, due to the limited dredging accuracy and turbidity caused by the moveable arm.

Figure 4-4 Trailing suction hopper dredge (TSHD)

Among dredging works for deep water done with a TSHD is the Glory Holes project in Canada, see Figure 4-5 .

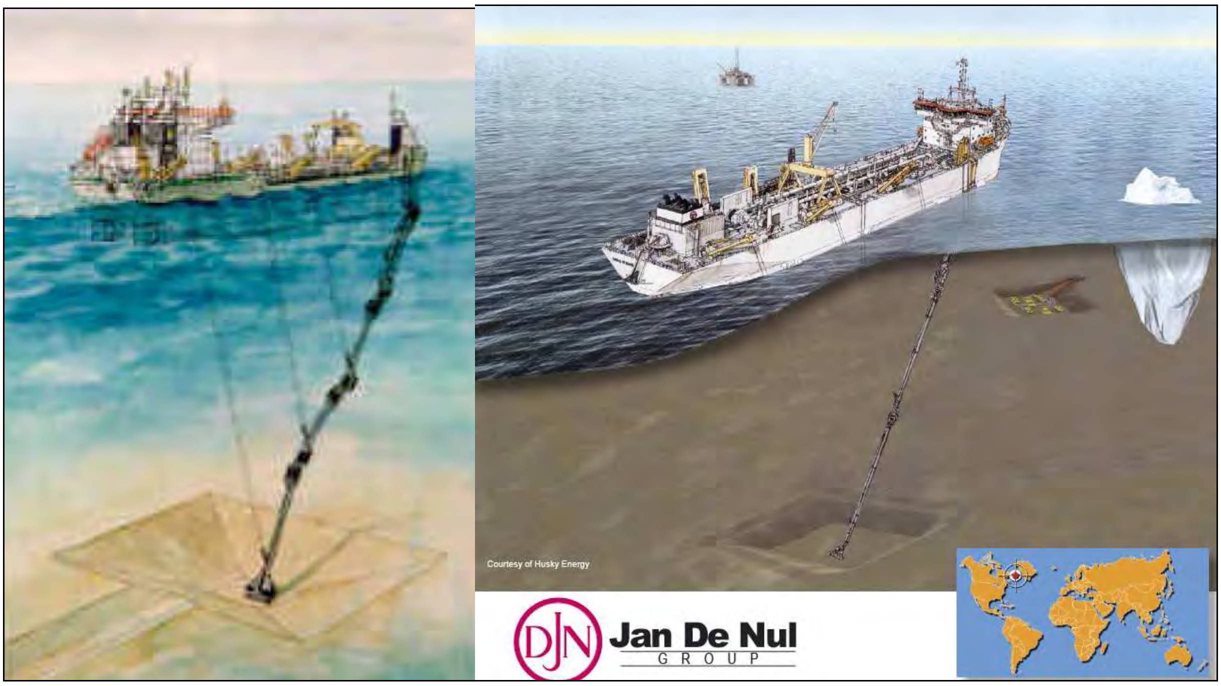


Figure 4-5 Left: Dredging down to 106 m water depth (from Glory Holes project, Canada /3/. Right: Dredging down to 130 m depth (continuation of Glory Holes project, Canada /4/,

4.2.2 Dredging with Pneuma Pump

The Pneuma Pump is a pump operated by compressed air that is designed to dredge sediment at its in situ density, see Figure 4-6. The basic pump consists of three large cylindrical pressure vessels, each with a material intake on the bottom and a compressed air port and material discharge outlet on top. The pump operates on the bottom and uses the difference between ambient water pressure and atmospheric pressure to fill a vessel with bottom material. Once full, material is forced out of the vessel by compressed air and through the discharge line. A study by the Centre for Environmental Risk in the UK was performed in 1999 to evaluate the possibility to use the Pneuma Pump for removal of drill cuttings down to 200 m water depth, no practical trials were however performed /5/. The report however recommended to do field tests because there were great uncertainties about the water uptake of the pump. In more shallow waters the pump can dredge with a high of solid concentration in the dredged mixture (above 50 % and up to 90% according to the company /6/). The pump body can be suspended by a steel cable from the vessel. The Pneuma Pump is vulnerable for debris and this can clog the suction mouth. The Pneuma Pump is suitable for environmental dredging where low turbidity and low spreading of contaminants is important.

A basic version of the Pneuma pump was tested by the Corps of Engineers in 1978 under a variety of typical maintenance dredging conditions /1/. In general, the tests indicated that it could achieve in situ discharge densities in fine-grained estuarine material but not in sand. Power efficiency was low.

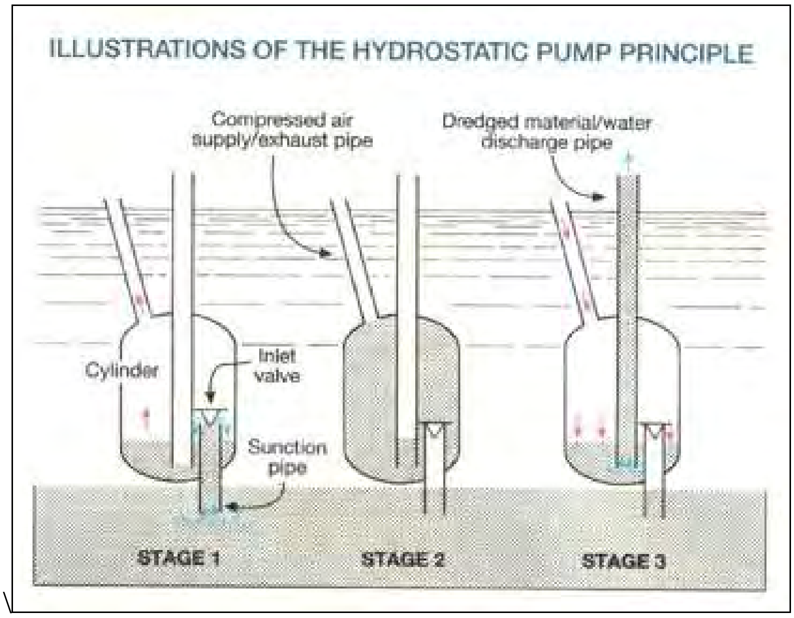


Figure 4-6 The Pneuma Pump, to the left an illustration of the principle and to the right an assembly of Pneuma Pumps (from the homepage of Pneuma Pumps).

There are relatively few field references of the use of the Pneuma Pump /5/.

4.2.3 Dredging with closed level cut clamshell

The closed level cut clamshell can be used for environmental dredging and for large water depths. The accuracy depends on the water depth, for most purposes the vertical accuracy is +/- 30 cm, for the actual water depths (150-175 m) the positioning should be assisted by an ROV. The closed level cut clamshell can dredge material with a water content close to the natural water content (see Figure 4-7). The method is robust and not very vulnerable for debris on the seafloor.

Figure 4-7 Closed level cut clamshell (photo from environmental dredging works in Trondheim harbour, Norway)

4.3 Comparison of the different dredging options

In Table 4-1 on page 15 a quantitative assessment is done on the important issues for a dredging operation where mercury contaminated sediments around U-864 at 150 to 175 m depth are removed. In the assessment the suggested technologies for dredging with an independent ROV based equipment directly on the seafloor and for dredging with a vessel on the water surface, are compared.

Table 4-1 Quantitative assessment of important issues for dredging mercury contaminated sediments around U-864

Type	Dredging with an independent ROV based equipment directly on the seafloor		Dredging from a vessel on the water surface		
	ROV with sea bed pump	Excavator with visor bucket	TSHD	Pneuma pump	Closed level cut clamshell
Accuracy (horizontal/ vertical)	Hor: high Ver: medium-high	Hor: high Ver: high	Hor: low Ver: low (+/- 25 cm)	Hor: low Ver: low *Needs assistance from ROV?*	Hor: low Ver: low (+/- 30 cm) *Needs assistance from ROV?*
Turbidity created during dredging and spreading potential	Low-medium	Medium-high *emptying grab in container causes turbidity*	Medium-high	Low	High
Suitable for actual site offshore	(Yes) *Further develop-ment needed* *Not suitable for boulders*	(Yes) *Further development needed*	? *Waves?* *Accuracy?*	? *Few references* *Not suitable for boulders*	? *Accuracy?*
Adjustable to topography	Yes	? *Can handle steep slopes?*	? *Ship keeps position in strong currents?*	Yes	? *Can handle steep slopes?*
Water content	~90 %	Close to natural water content	75 %	50 %	Close to natural water content
Consequence of spreading Hg to the environment. Exposure through project.	Low	Low-medium	Medium-high *high capacity → more is spread if something goes wrong*	Low	High *clamshell is lifted through the whole water column*
Estimated cost (Day rate)	1 mill NOK/day	1 mill NOK/day	10 mill NOK /day?	1 mill NOK/day	1 mill NOK/day
Completion of dredging (one unit, 16 hour day)	< 2 years	< 1 year	< 1 month	< 1 month	< 2 years
Estimated dredging capacity (theoretical) (practical capacity can be as low as 10 % of theoretical capacity)	100 m^3/hr (160 metric ton/hour)	50 m^3/hr (80 metric ton/hour)	(very high)	900 m^3/hr (1 500 metric ton/hour)	20-30 m^3/hr (30 - 50 metric ton/hour)
Gross volume for finishing the project	150 000 m^3	20 000 m^3	60 000 m^3	30 000 m^3	20 000 m^3
Geotechnical implications*	Low	Low-medium	Low-medium	Low	Low

* Dredging has to start on top and work downwards the slope. Local slide could happen if you place heavy equipment on the seafloor or dredge to deep.

? No or almost no data available and/or or no previous experience on this item.

(Yes) Looks positive but the technology needs further development.

4.4 Recommended dredging technology

No reference projects with the similar conditions as for the dredging of mercury contaminated sediments around U-864 has been identified. A recommendation of dredging technology is therefore based on an assessment of the most important issues for the project as shown in Table 4-1.

A very important factor is that the dredging with ROV based equipment on the seafloor can be done with a high accuracy. It is probably almost impossible to reach a good accuracy when the dredging takes place from a vessel on the water surface. The only solution would be to assist the dredging operation from the water surface with a ROV. It is also important to take into consideration that the area is in open sea with strong winds and high waves.

If dredging is chosen as a remediation technology it is recommended to use a dredging technology with ROV based equipment directly on the seafloor. The equipment should have the possibility to use both a pump and a grab (which can be closed).

It is necessary to work further on the ROV based dredging techniques. The dredging capacity has to be increased, the whole dredging operation should ideally not take longer than a month due to the unstable weather conditions at the site.

The equipment which is suggested by the contractor(s) should be tested in a nearby (not contaminated) area with the same depth and sediment conditions to verify that the equipment fulfils the necessary requirements.

5 AMOUNT OF SEDIMENTS TO DREDGE AND DISPOSE OF

As mentioned in Chapter 4 an in situ volume of approximately 15 000 m^3 mercury contaminated sediments has to dredged if the accept criteria is set to 0.6 mg Hg/kg sediment.

It is assumed that all the dredged sediments are transported to land for further treatment/disposal.

In DNV-report no. 2007-1843 "Salvage of U-864 – Supplementary studies – Disposal" disposal solutions and costs are given for the 15 000 m^3 dredged contaminated sediments outside the wreck. The report suggests a stabilisation (cement/gypsum) prior to disposal. The unit cost for stabilisation and disposal is assumed to be 300 – 600 NOK/metric ton, costs for transportation are not included. The cost also assumes that no dewatering of the sediments is necessary. This is probably correct if the sediments are dredged with a grab, but if a suction dredger is used they have to be dewatered. Dewatering could be done by placing the sediments in a barge with a sand filter with a protective geotextile below.

Companies in Norway which have a permit to receive mercury contaminated waste are NOAH AS and Miljøteknikk Terrateam AS.

If the mercury concentration is above 1 000 mg/kg (0.1 %) in the sediments, it is classified as hazardous waste leading to more severe requirements for disposal. In general it is not assumed that dredged sediments from outside the wreck have such a high mercury concentration. However, a "hot-spot" sediment sample close to the wreck had a mercury concentration of 100 000 mg/kg (10 %). A treatment for such a high mercury concentration could be thermal desorption.

6 MODELLING OF SPREADING FROM DREDGING AT 150-175 M DEPTH

DNV's conclusions are:

C5. **Modelling of dredging losses indicated that for high sediment losses (10 %), between 200 to 400 kg of mercury can be lost outside the 1 km^2 boundary around the wreck. This is 5 to 10 % of the assumed amount of mercury (3 800 kg) in the dredged material.**

C6. **Modelling of dredging losses indicates that higher dredging production rates reduce overall clay and mercury losses from the vicinity of the site and is therefore to be preferred**

C7. **Simulated water column and surface releases at the site show that such releases can be spread outside a 1 km^2 boundary around the wreck. Special measures must be carried out to minimize such releases.**

A full report of the modelling is enclosed in Appendix A. In this Chapter a summary of the most important findings and conclusions from the report is given.

6.1 The model

To be able to predict how much the dredging activity is spreading the sediments (sediment dispersion) modelling has been done with the PC-based numerical model SSFATE. SSFATE was chosen because it has been especially developed to predict sediment dispersion.

The model which has been used is SSFATE, which is a PC-based numerical model to predict sediment dispersion resulting from dredging activities. SSFATE was developed by Applied Science Associates (United States) and the US Army Corps, Engineering Research and Development Centre.

6.2 Input for the modelling

The input for the modelling was set up jointly by the expert group which has been working with this supplementary study during a workshop held at DNV 5 to 7 November 2007. The modelling itself was done by Allen Teeter, member of the expert group coming from Computational Hydraulics and Transport llc in the United States.

In the modelling it was assumed that the wreck and debris was salvaged before dredging. Based on the investigations done by NIVA, the contaminated area was assumed to be 30 000 m^2 and the thickness of the contaminated 0.5 meter resulting in a theoretical dredging volume of 15 000 m^3. The input data of the sea topography was based on the mapping by DOF subsea and covers approximately 1 km x 1 km (1 km^2) with the resolution of 0.5 meters. The mercury contamination was modelled to be 100 % linked to the clay fraction in the polluted sand layer (50 % in the organic fraction and 50 % in the clay, but the organic fraction was modelled as clay).

To be able to describe how much of the mercury that was spread outside the 1 km^2 boundary, a "clay escape probability" (CEP) was defined. The CEP is defined as the fraction of resuspended clay (mercury) that escapes the 1 km^2 boundary without depositing. As stated earlier, the mercury was modelled as bound to the clay, meaning that the "clay escape probability" also can be used as the "mercury escape probability".

6.2.1 Currents

The currents used in the model were taken from measurements done by NIVA /2/ in 2005. Figure 6-1 shows the distribution of the measured currents from 20 to 170 m depth for the 16 %, 50 % ("average") and 84 % percentile. The current is highest near the water surface and drops gradually with water depth. The current speeds in Figure 6-1 were fitted to a log-layer velocity profile by least-squares regression. Results were then used in the model to describe the current field.

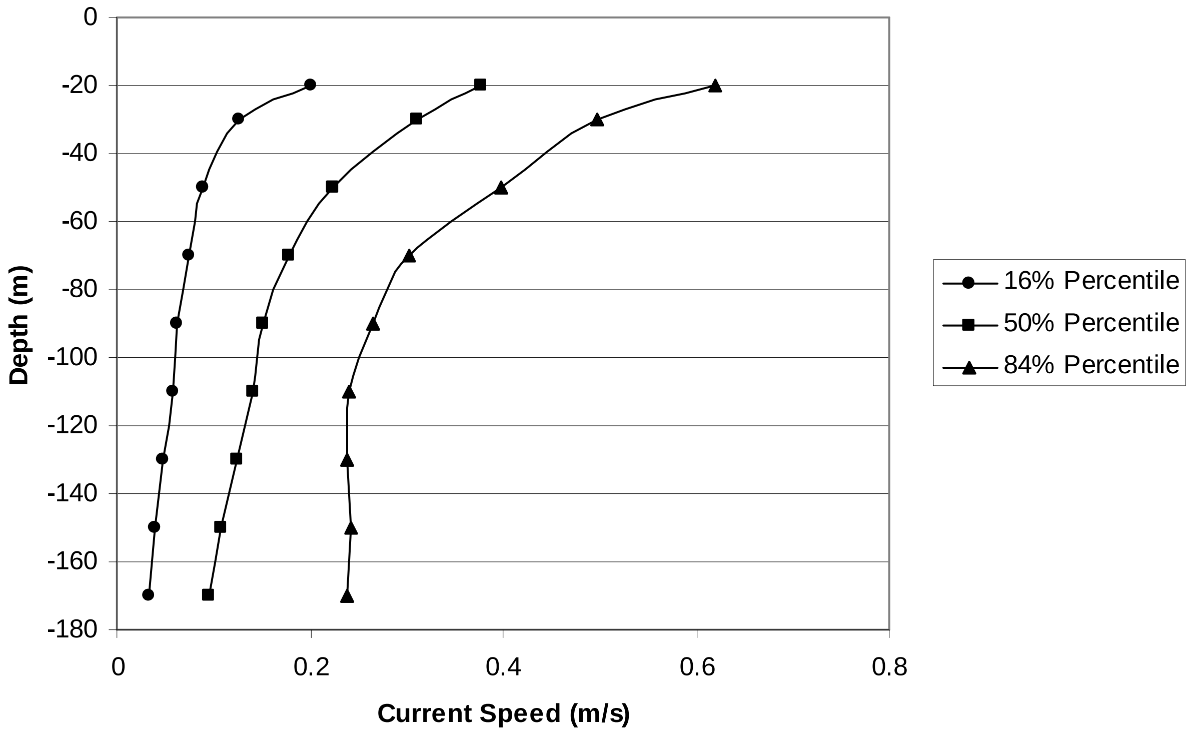


Figure 6-1 Distribution of current speed with water depth for 16, 50, and 84 percentiles of occurrence

The main direction of the current close to the seafloor is about 300 degrees (West to Northwest) and about 340 degrees (Northwest to North) near the water surface.

6.2.2 Sediment characteristics

From the 65 NIVA core samples in the area around U-864, the average fines or mud content (<0.063 mm) was estimated to be 38 % for 0.25 m depth into the bed. This value matched the mean from two Geoconsult samples (Core 101 at 0.5 m depth and Core 106 at 0.6 m depth) which had full grain-size distribution information for the sediments. These representative samples contained on average 15 % clay (<0.002 mm), 10 % fine silt (0.002-0.011 mm), 14 %

coarse silt (0.011 – 0.063 mm), 49 % fine sand (0.063-1 mm) and 12 % coarse sand and gravel (> 1 mm).

6.2.3 Mercury concentration

There is a large variation in the analysed mercury samples in the area around the U-864. The mercury concentrations in the sediments vary from 0.38 to 107 800 mg/kg dry weight. To be able to estimate an estimate of the average mercury concentration, the data set was restricted to values greater than 0.65 mg Hg/kg dry weight and the three highest (extreme) values were considered to be hot-spots. Assuming that the samples were taken quasi randomly over the area, the area-weighted average mercury concentration (50 % Percentile) for the clean up area (30 000 m^2 and 15 000 m^3 sediments) was estimated to be 159 mg Hg/kg dry weight giving a total of 3 800 kg (assuming a sediment dry weight of 1.6 g/cm^3), which is about 6 % of the assumed load of mercury in U-864.

The modelling of losses during dredging was calculated for the 5 % Percentile ("low end"), 50 % Percentile ("average") and the 95 % Percentile ("higher end") of the mercury concentration distribution in the sediments as shown in Table 6-1.

Table 6-1 Mercury concentrations in the 15 000 m^3 of sediments

	Hg concentration	Amount of Hg in the sediments	% of assumed Hg load in U-864 (65 metric ton)
5 % Percentile	37 mg Hg/kg dw	900 kg	1.3 %
50 % Percentile (average area-weighted)	159 mg Hg/kg dw	3 800 kg	6 %
95 % Percentile	824 mg Hg/kg dw	20 000 kg	30 %

6.2.4 Dredging resuspension

In the calculations it has been assumed that the dredging activity can cause the resuspension of between 1 % (low assumption) and 10 % (high assumption) of the material to be dredged.

6.3 Results from the modelling

6.3.1 Near-bed dredging losses

All the dredging options, except the clamshell, have a fully enclosed transport of the dredged material from the sea bottom up to the water surface in a pipe, closed container or similar. For these dredging options it has been assumed that the losses of dredged material will occur only near the sea bed during the dredging.

An estimate of total clay and appurtenant mercury losses (spreading) from near-bed dredging gave clay losses between 22 and 225 metric ton and mercury losses between 24 and 238 kg (between 0.6 % and 6 % of total assumed amount of mercury in the sediments), see Table 6-2.

The calculation is based on average currents and that 1 to 10 % of the sediments will be resuspended.

Table 6-2 Calculation of near-bed dredging losses (escaping the 1 km^2 boundary without depositing) for dredgers with an enclosed transport of the dredged material from the sea bottom to the water surface

Dredging Rate (metric ton/hour)	Fraction resu-spended	Sediment resuspension rate (metric ton/hr)	Clay escape probability[1] (50 % Percentile current) result from model	Total loss or escape of clay[1] (metric ton)	Total loss or escape of mercury[2] (kg)
100	0.01	100*0.01 = 1	0.96	0.01*0.96*3 600 = **34**	0.01*0.96*3 800 = **36**
100	0.1	100*0.1 = 10	0.63	0.1*0.63*3 600 = **225**	0.1*0.63*3 800 = **238**
1 000	0.01	1 000*0.01 = 10	0.63	0.01*0.63*3 600 = **22**	0.01*0.63*3 800 = **24**
1 000	0.1	1 000*0.1 = 100	0.17	0.1*0.17*3 600 = **61**	0.1*0.17*3 800 = **64**

[1] The fraction of resuspended clay (mercury) that escapes the 1 km^2 boundary without depositing

[2] Assuming 3 600 metric ton of clay to be dredged (15 % clay content)

[3] Assuming 3 800 kg mercury to be dredged (50 % Percentile of average area-weighted amount)

Referring the numbers to the different dredging techniques presented in chapter 4; the Pneuma pump would have mercury losses escaping the 1 km^2 boundary without depositing close to the lowest number (approximately 20 kg Hg). The ROV with the sea bed pump would also be relatively close to this number (20 kg Hg). The excavator equipped with a visor bucket, the trailing suction hopper dredge and the dredger with closed level cut clamshell would be closer to the highest number (approximately 250 kg Hg).

6.3.2 Water column releases

For the closed level cut clamshell (dredging rate ~100 metric ton/hr), which is vessel-based and which has to be lifted through the whole water column, there are also expected some water column releases in addition to the near-bed dredging release. The clay escape probability (CEP) for water column releases is almost 1.0 regardless of dredging rate, meaning that all the clay particles released to the water column will be transported out of the 1 km^2 boundary. This is explained by the maximum (sediment) release concentrations which goes up to 126 mg/l based on the model runs (for the sediment release rates tested) which is more than one order of magnitude lower than for the near-bed releases and lack of flocculent settling, see Figure 6-2. The distance for particles to settle before reaching the bed is another factor in this case.

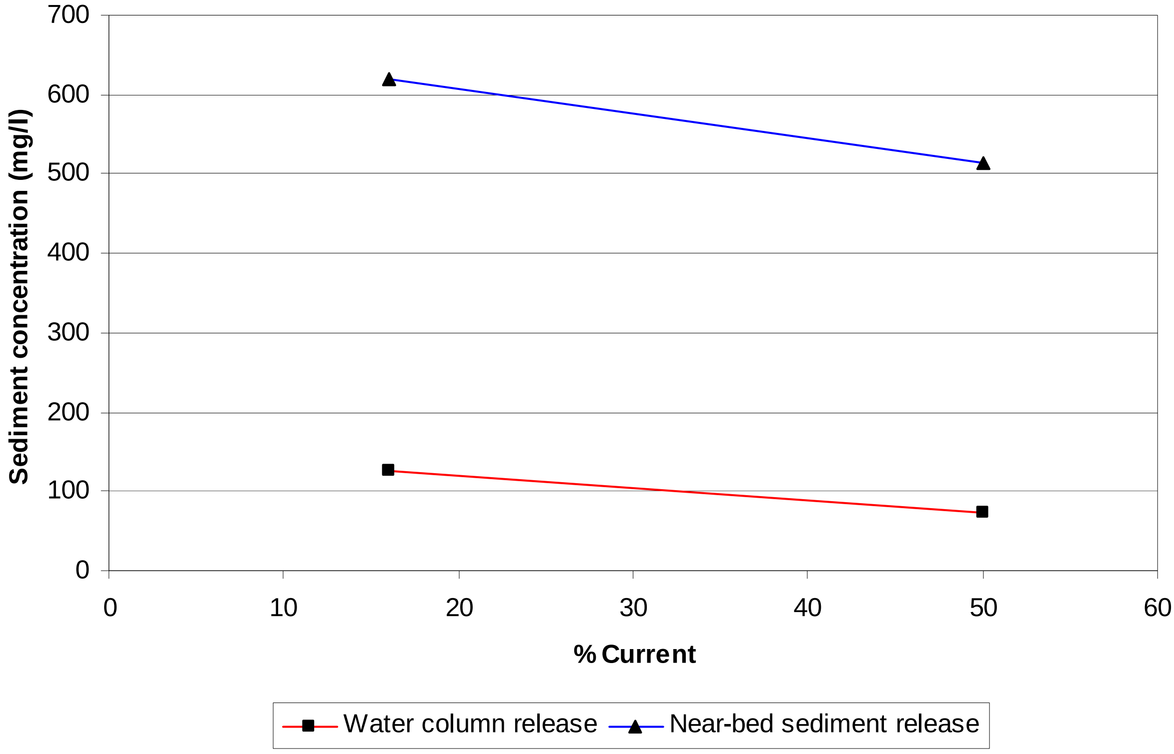


Figure 6-2 The maximum (sediment) release concentrations in the water column and near the seabed for the 16 and 50 percentiles of occurrence of currents for a sediment resuspension rate of 63.7 metric ton/hr

Assuming 3 600 metric tons of clay to dredge and CEP ~ 0.99, total clay loss (near-bed dredging loss + water column release) would be 35 and 353 tons for fractional resuspension rates of 0.01 and 0.1, respectively. Assuming 3 800 kg of mercury to dredge and CEP ~ 0.99, the total mercury loss would be 37 and 374 kg for fractional resuspension rates of 0.01 and 0.1, respectively, see Table 6-3 and Figure 6-3.

Table 6-3 Calculation of losses (escaping the 1 km^2 boundary without depositing) for closed level cut clamshell (near-bed dredging loss + water column release)

Dredging Rate (metric ton/hour)	Fraction resu-spended	Sediment resuspension rate (metric ton/hr)	Clay escape probability[1] (50 % Percentile current) result from model	Total loss or escape of clay[1] (metric ton)	Total loss or escape of mercury[2] (kg)
100	0.01	100*0.01 = 1	0.99	0.01*0.99*3 600 = **35**	0.01*0.99*3 800 = **37**
100	0.1	100*0.1 = 10	0.99	0.1*0.99*3 600 = **353**	0.1*0.99*3 800 = **374**

[1] The fraction of resuspended clay (mercury) that escapes the 1 km^2 boundary without depositing

[2] Assuming 3 600 metric ton of clay to be dredged (15 % clay content)

[3] Assuming 3 800 kg mercury to be dredged (50 % Percentile of average area-weighted amount)

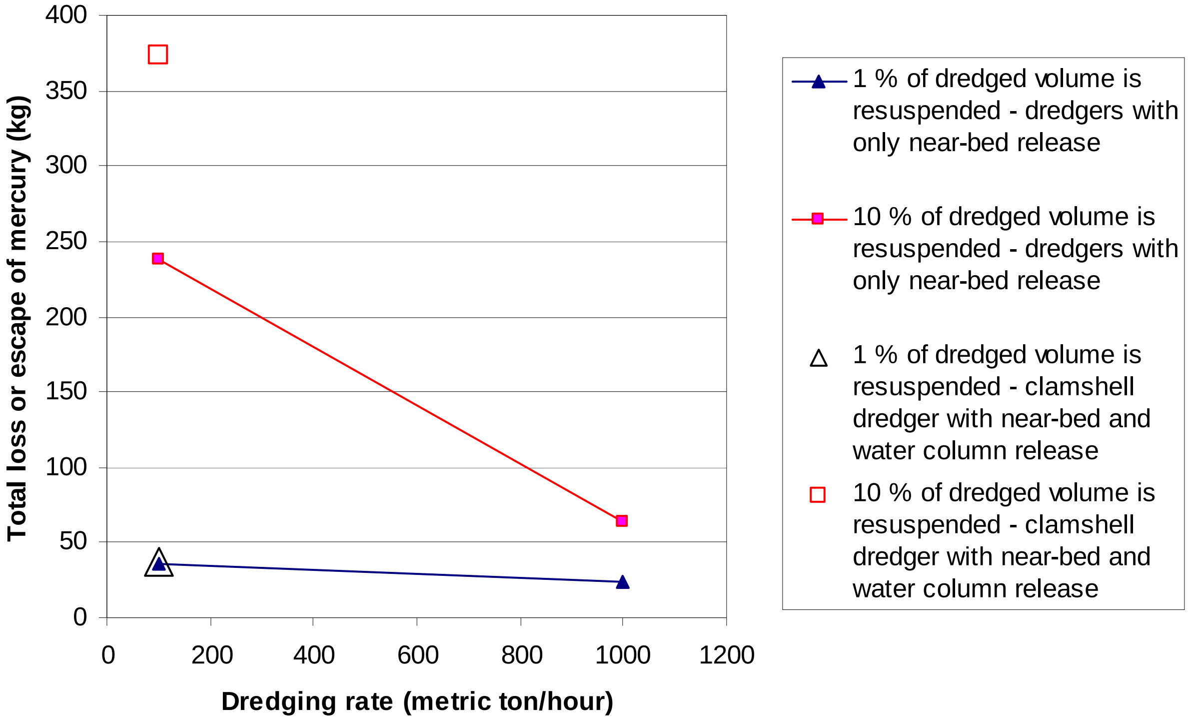


Figure 6-3 Total loss or escape of mercury depending on the dredging rate and the amount of particles which are resuspended from the dredging activity

6.3.3 Surface releases

A release of small quantities of sediment near the water surface was modelled to simulate small spills of sediments during salvage or other operations. Water depths of 175 m (the site of U-864), 50 m and 10 m were simulated. The 50 and 10 m water depth was simulating a surface release during transport of the sediments (after salvage) or when they were unloaded in a harbour.

It was assumed a short release of (0.5 hr) of a small amount of sediments (1.8 m^3 sediments with 0.43 metric ton of clay and 0.5 kg of mercury).

For the 175 m water depth the clay escape probability was 1, indicating that all the clay material released from the surface would be transported out of the 1 km^2 area.

For the 50 m water depth a surface release of sediments indicated a clay escape probability of 0.19 and for 10 m water depth a clay escape probability of 0.02. This was for a distance of 0.76 km from the release point.

6.3.4 Sediment slide release

The dredging activity could induce a sediment slide because the slope on which the wreck is located is only marginally stable. A worst-case with a 55 x 55 m slide with a 2.5 m thickness was modelled, releasing approximately 7 500 m^3 sediments. Of the 7 500 m^3, about 10 % of the cleanup area is included. Calculated mercury losses from such a slide are around 1-2 kg for the average (50 percentile) current. The simulation indicated that the suspended sediments will form a cloud in the water that will drift in the current direction. About 3 hours after the slide the cloud has left the 1 km^2 area around the wreck.

6.4 Conclusions from the modelling

The modelling showed that the major releases of sediments and mercury are during dredging. The main release is near the seabed where the sediments are removed. When dredging with the clamshell an additional release was taken into account for losses to the water column during the transport of the dredged material from the seabed to the water surface. This amount was however relatively limited compared with the near-bed losses. Mercury losses during the dredging were calculated for a low (1 %) and a high rate (10 %) of sediment losses (resuspended fraction).

- Assuming a dredging rate of 100 metric tons/hour the modelling showed that for low sediment losses (1 %) between 20 to 40 kg of mercury was lost outside the 1 km^2 boundary around the wreck. This is 0.5 to 1% of the assumed amount of mercury (3 800 kg) in the dredged material.
- For the same dredging rate, but with high sediment losses (10 %), between 200 to 400 kg of mercury were lost outside the 1 km^2 boundary around the wreck. This is 5 to 10 % of the assumed amount of mercury (3 800 kg) in the dredged material.

In Figure 6-4 the effect can be seen of two different sediment releases (losses). For the higher release rate (637 metric ton/hour) the sediments are spread up to 700 m from the dredging point, causing 20 % of the clay and mercury to be dredged to escape from the vicinity of the site (more than 760 m away).

Results indicate that the escape probability for clay (and therefore the mercury assumed to be associated with clay) tends to decrease with increasing sediment release rate for near bottom releases. This is explained as the influence of concentration-enhanced flocculent settling of the clays, and coupling of clay settling with coarser grain classes. The implication for possible dredging operations is that, for equal fractional resuspension, higher dredging production rates reduce overall clay and mercury losses from the vicinity of the site and are therefore to be preferred. (The fractional resuspension should also be minimized to reduce the residual contamination left at the site after dredging - an issue not directly addressed in this modelling.)

Simulated water column and surface releases at the site resulted in almost complete loss of clay and mercury due to the great depth at the site. It is therefore recommended that special measures be taken to minimize water column and surface releases at the site. Simulation of releases at shallower depths resulted in escape probabilities proportional to depth.

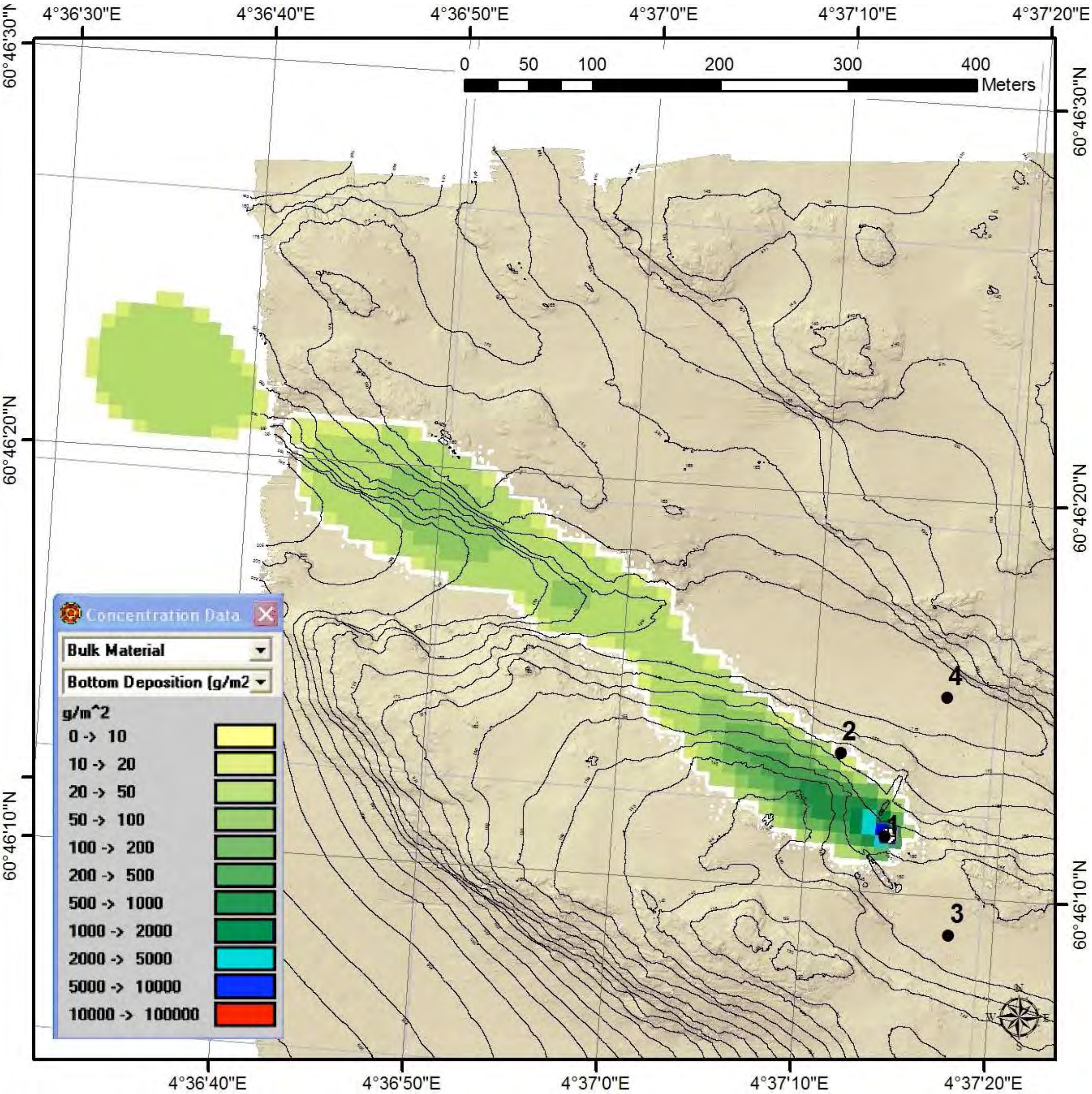


Figure 6-4 (a) Sediment release rate = 127.3 metric ton/hour from point 1

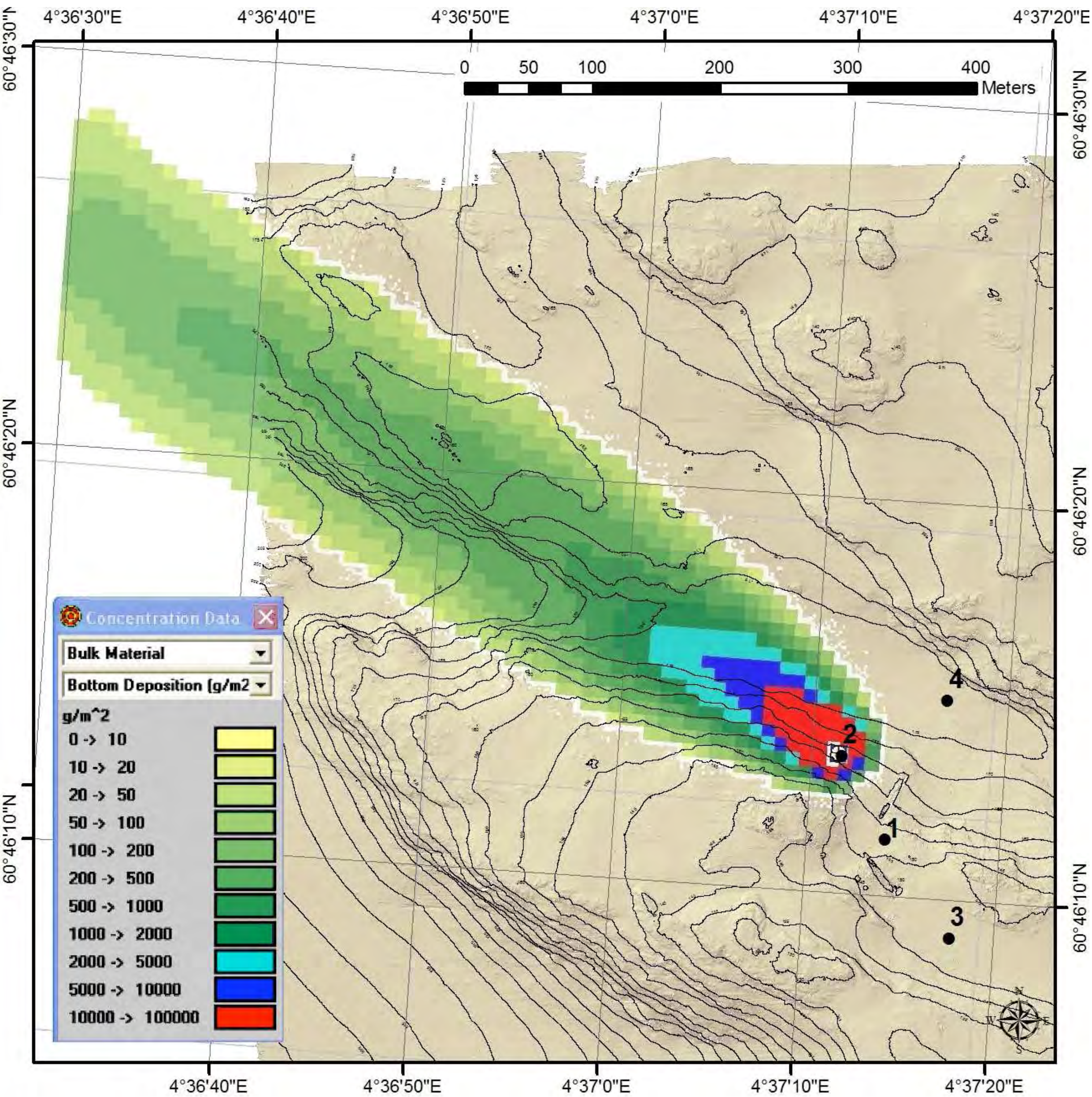


Figure 6-4 (b). Sediment release rate = 637 metric ton/hour from point 2

Figure 6-4 (a,b) Bottom deposit (g/m^2) for sediments spread from dredging (near-bottom release) at hour 12 (after release) for the 50 percentile of the currents. Modelling tests were done to see the effect of the sediment release rate on escape probability.

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APPENDIX

A

DISPERSION OF SEDIMENTS AND MERCURY RESULTING FROM PROPOSED U864 SALVAGE AND CLEANUP DREDGING (ALLEN TEETER, COMPUTATIONAL HYDRAULICS AND TRANSPORT ILC)

- o0o -

Dispersion of Sediments and Mercury Resulting from Proposed U864 Salvage and Cleanup Dredging

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Prepared for: Det Norske Veritas Industry, Hovik, Norway

February 2008

Dispersion of Sediments and Mercury Resulting from Proposed U864 Salvage and Cleanup Dredging

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Introduction

A German submarine sunk in World War II has spilled mercury onto the sea bed near the wreck site. The Norwegian Coastal Administration has asked Det Norske Veritas (DNV) to study a salvage and dredging cleanup scenario involving a 30,000 m^2 area of sediment around the sunken vessel (a radius of about 100 m). DNV is conducting a study of how best to accomplish this scenario and safely remove the mercury contamination with a minimum of spreading into adjacent areas. First the submarine wreckage, human remains, and any mercury canisters would be removed from the area. Then contaminated sediment material would be removed by dredging.

A workshop was held at the offices of DNV from 5 to 9 November 2007 to review previous investigations and scope parts of the study. Jens Laugesen ran the workshop, Thomas Moskeland was deputy, and Helene Ostboll reported for DNV. Ulf Skyllberg, mercury expert, and Allen Teeter, dredged-material dispersion expert, attended the workshop for the week. Other experts made presentations and attended workshop sessions.

Estimates of sediment and mercury dispersion from the vicinity of the wreck site are needed to assess the risks associated with various phases of the cleanup scenario. Since no specific dredging technique or dredge has yet been identified, it was the consensus of those at the workshop that the full range of possible sediment releases should be considered in sediment transport modeling.

Background

The German U-boat U864 sank in 1945 along with 67 tons of elemental mercury (in 1800 steel canisters stored in its keel), all 70 crew, 27 torpedoes, and other explosive war materials on board. A British torpedo struck the submarine near its midsection, blowing the submarine into two pieces. See the image on the title page (courtesy of Eirik Hauger, DOF, formerly Geoconsult). The deck house and an unknown length of keel were almost completely destroyed. The wreckage was discovered in February 2003 in about 150 m water depth 3 km west of Fedje Island (60° 46.2’ N and 4° 37.3’ E) in Norwegian North Sea waters. Sediment testing began in September of that year. Since then, investigations have discovered high mercury contamination, broken canisters, signs of elemental mercury on the sea bed, and unstable geotechnical conditions. Planning for an environmental cleanup began immediately.

The two main wreck parts lay keel-down on a slope of up to 27 degrees on a marginally stable 0.5-m-thick silty sand surface layer. Below the top sediment layer is a normally-consolidated clay-rich layer 2 to 6 m thick. The stern section rests across the upper slope tilted stern-up with the blast breach and almost the entire keel below the sediment surface. Propellers and rudders are above the sediment bed. The bow section rests along the lower, steepest slope butted breached-end against a rock outcrop with the entire keel below the sediment surface. Both wreck sections have been found to contain an appreciable amount of sand and rock inside the blast areas. Just some tens of meters down-slope, a small valley, flanked by very steep rock slopes, runs normal to the slope where the wreck rests. Boulders, some large, and rock outcrops abound in the area and appear to stabilize the sediments along the slope.

Samples collected in 2005 and 2006 with an underwater remotely operated vehicle (ROV) suggest that the contamination is limited to 0.5-m-thick surface layer. Total mercury values of up to 10 percent (by sediment dry weight) have been discovered. Recent attempts to recover mercury canisters by ROV dredging along the keel of the stern section had to be abandoned when the stern section shifted. The ROV used a closed mechanical back hoe to dig and remove sediment. Problems were encountered as clay-layer sediments moved back into the cut. The wreck movement opened a small gap between the hull and the sediments.

A capping alternative has been proposed and is being considered elsewhere by DNV. Geotechnical studies of slope stability and preliminary calculations of the needed counter fill thickness at the bottom of the slope have been completed. Dredging cleanup alternatives, parallel risk studies on wreck salvage, and magnetometer surveying are some ongoing DNV study tasks.

Elemental mercury is slightly soluble as chlorides and hydroxides but tends to adsorb to particulate and organic surfaces. Clay minerals tend to dominate particulate surface area, due to their small size, and present abundant adsorption sites for metal and other ions. Organic carbon and clay content represent relatively small fractions of sediments in the study area. Still, the conservative assumption was made that all the mercury is associated with these two fractions. Since organic compounds tend to coat fine particles, all the mercury is assumed to be associated with the clay sediment fraction for transport calculation purposes (as decided at the DNV Workshop).

The association of mercury (Hg) with organics can be explained as follows: If we have an average 1.5 per mill (ppt) organic carbon and a conservative estimate of 5 mol carboxyl groups per kg organic carbon, one kg of sediment will contain 0.008 mol carboxyl groups. This capacity to bind Hg(II)-ions can be compared with a concentration of 159 ppm Hg as an average in the sediment, corresponding to 0.8 mmol Hg per kg sediment. Thus there are 10 times more carboxyl groups than Hg(II)-ions in the sediment. Carboxyl groups, possibly combined with amino groups, may form bi-dentate complexes with Hg(II) which are strong enough to out-compete most mineral surfaces. The strongest groups are organic thiols, but since the concentration of these are less than 5% of the carboxyls, they will be fully saturated by Hg(II) already at about 40 ppm Hg in the sediment. It may be that some Hg(II) also associates with oxygen functional groups at hydrated, oxidized mineral surfaces like iron oxyhydroxides, but also these types of surfaces likely are associated with clay minerals as coatings (Dr. Ulf Skyllberg, personnel communication).

Objectives and Scope

The objectives are to compute sediment and attached mercury transport out of the vicinity of the cleanup area that might result from various dredging options, including suction, hopper, and mechanical dredge types, as well as from releases associated with leaks occurring during the salvage operation, transport to shore, or a sediment slide at the site. Available current and sediment data were analyzed for use in a fine-scale sediment dispersion SSFATE model developed for the area around the sunken submarine for this purpose. An estimate of mercury droplet sinking rate was made based on published analyses.

Data Analysis

Sediment and current conditions are necessary model input. Results from previous site investigations were analyzed and used for this purpose.

Currents. Currents were measured at eight depths at a location close to the site by the Norwegian Institute for Water Research (NIVA) between 10 September and 10 October 2005. Histograms of current direction and progressive vector displays indicate that currents at the site are relatively steady with respect to direction but that the direction is more northerly near the surface and more westerly near the bottom.

Histograms of discrete current speed occurrence were digitized from figures presented in NIVA report (Uriansrud and Skei, 2005). The histogram current speed interval centers were digitized directly and the number of occurrences in the interval were spread randomly over the interval ranges. Cumulative frequency distributions were created from these data for the eight depths and select percentile current speeds presented in Table 1.

Measurements at the eight depths were used to estimate current velocity profiles. The current speed values for 16th, 50th, and 84th percentiles were fit to a log-layer velocity profile by least-squares regression. The form of the regression equation was $U(z) = U^*/\kappa \ln(z) + C$ where z is distance up from the bed, U^* is the friction velocity, κ is von Karmen's constant, and C is a constant. Two log-layer profiles were required to obtain a reasonable fit. This was probably because the current regime at the site consists of a 75-m thick surface layer which flows in the direction of the offshore depth contours and the shoreline (about 340 degrees) and a bottom layer which follows the direction of local depth features of about 300 degrees.

TABLE 1. Percentile Occurrence of Observed Current Speeds

	Percentile Current Speed, m/sec				
Depth, m	5%	16%	50%	84%	95%
20	0.1034	0.2003	0.3782	0.6188	0.8073
30	0.0699	0.1256	0.3111	0.4976	0.6533
50	0.0475	0.0901	0.2237	0.3975	0.5458
70	0.0407	0.0743	0.1792	0.3029	0.4114
90	0.0329	0.0613	0.1508	0.2649	0.3563
110	0.0319	0.0587	0.1418	0.2401	0.3076
130	0.0246	0.0480	0.1234	0.2378	0.3253
150	0.0208	0.0389	0.1072	0.2435	0.3453
170	0.0167	0.0332	0.0951	0.2383	0.3225

TABLE 2. Results of Log-Layer Fits to the Current Data

Depths, m	U^*/κ, m/sec	C, m/sec	Resid. Std. Err.	R^2	p-value
16th Percentile					
20 to 70	0.2851	-1.2673	0.0327	0.773	0.1207
90 to 170	0.0099	0.0138	0.0056	0.839	0.0288
50th Percentile					
20 to 70	0.4973	-2.1514	0.0278	0.935	0.0332
90 to 170	0.0190	0.0582	0.0104	0.850	0.0259
84th Percentile					
20 to 70	0.7601	-3.2518	0.0401	0.942	0.0297
90 to 170	0.0052	0.2270	0.0113	0.263	0.3766

Sediment characteristics. Sediment characteristics for the site were investigated and presented by NIVA and Geoconsult (Kalsnes 2006). NIVA collected 65 shallow core samples and determined fines content (percent), total organic carbon (ppm by dry-weight), and mercury concentration (ppm by dry weight). Geoconsult collected 23 cores, some of which were sub-sectioned and analyzed for grain-size distribution, moisture (water) content, unit weight, Atterberg limits, undrained shear strength, and sensitivity. These samples were collected using a Vibrocore device.

<u>Fines or mud content.</u> NIVA analyzed 65 samples which were collected by ROV push corer for fines content (%< 63 mm). Mean was 24.8 percent (95% CI = 20.0 to 29.5 percent), median was 16 percent, and geometric mean was 18.4 percent. Over half of the sub-core samples were from the the bed surface while the maximum depth was 42 cm. At the surface, the mean fines content was 15.8 percent (median = 12.0 percent, range 4.0 to 52.0 percent) while at sediment depths in the bed greater than zero, fines were 35.3 percent (median = 43.5 percent, range 5.0 to 67. percent). A statistically significant slope (p-value = 0.) was found between fines content and (mean) sample depth in bed (R^2 = 0.26, residual std. error = 16.6 percent) that suggests that the fines content at 25 cm depth in the bed was 38.4 percent.

<u>Grain size distribution.</u> Geoconsult presents grain size distributions for four sub-core samples at 0.05 to 0.5 m depth plus another sample at 0.6 m depth. They analyzed these samples by a combination of dry sieving for coarse sediments and falling drop method for fine-dominated samples. Particle size distributions were digitized and reproduced in Figure 1. Summary statistics are presented in Table 3.

The fines contents of Core 101 at 0.5-m depth and Core 105 at 0.6-m depth (42 and 36 percent, respectively) are close to the average-depth value for the NIVA samples. The mean of these two distributions was used as the representative grain-size distribution for the sediment. The grain-class content of this distribution is: 15 percent clay (<0.002 mm), 10 percent fine silt (0.002 - 0.011 mm), 14 percent course silt (0.011 - 0.062 mm), 49 percent fine sand (0.062 - 1 mm), and 12 percent course sand and gravel (> 1 mm).

TABLE 3. Grain Size Statistics for the Geoconsult Cores

Core ID	Depth, m	D50, mm	Mean, mm	Sorting	Skewness
101	0.05	0.706	1.011	5.663	0.207
101	0.5	0.105	0.038	17.587	-0.350
105	0.1	0.571	0.568	3.861	-0.004
105	0.6	0.139	0.043	16.957	-0.415
117	0.1	0.356	0.347	2.859	-0.024

Moisture content. Geoconsult lists moisture content for six near-surface samples (those listed in Table 3 plus Core 117 at 0.35 m depth). Moisture content is the water weight of a sample divided by the dry sediment weight. Mean moisture content for those six samples is 26.0 percent (range = 20.3 to 32.4 percent, 95% CI of mean = 21.5 to 30.5 percent). Using 2650 and 1025 kg/m^3 as the densities for sediment particles and water, the volume concentration is 0.598 v/v, concentration by weight is 0.794 w/w, solids content or specific weight is 1585 dry-kg/m^3, and the bulk wet density is 1996.8 kg/m^3.

Mercury concentration. NIVA mercury concentrations vary from 0.38 to 107800 ppm by sediment dry weight (median = 12.5 ppm, 25th percentile = 4.32, 75th percentile = 30.6 ppm). The variance of these data is so large (1.79E8 ppm^2) that the 95% confidence interval for the mean value (1706 ppm) includes zero (-1605 to 5018 ppm). The distribution of the 65 NIVA concentration data is about log-normal (geometric mean = 13.04 ppm) as shown in Figure 2 but deviates from log-normality at the upper and lower extremes of the distribution. There is a trend for surface mercury levels (median = 25.2 ppm) to be higher than those at depth in the sediment (median = 7.8 ppm).

To obtain an estimate of the average concentration value and total mercury mass in the sediment to be dredged, the data set was restricted to values greater than 0.6 ppm (the cleanup cutoff concentration used for planning) and the upper three extreme values were considered to be a separate (log-normal) distribution representing hot spots (see Figure 2). The assumption was made that the samples were taken quasi-randomly over the contaminated area. Then the hot spot samples (geometric mean = 3018 ppm, median = 950 ppm, n = 3) represent 4.8 percent of the area and the remaining area has a geometric mean mercury concentration of 13.1 ppm (median = 14 ppm, n = 59). The area-weighted average mercury concentration for the cleanup area is thus 159 ppm (3780 kg total mercury mass). Combining the low 0.223-probability values for the hot spot and remaining cleanup areas give a combined 0.05-probability area average value of 37.0 ppm mercury (880 kg total mercury mass). The high 0.777-probability values combine to give an area average 0.95-probability value of 824 ppm (19591 kg total mercury mass).

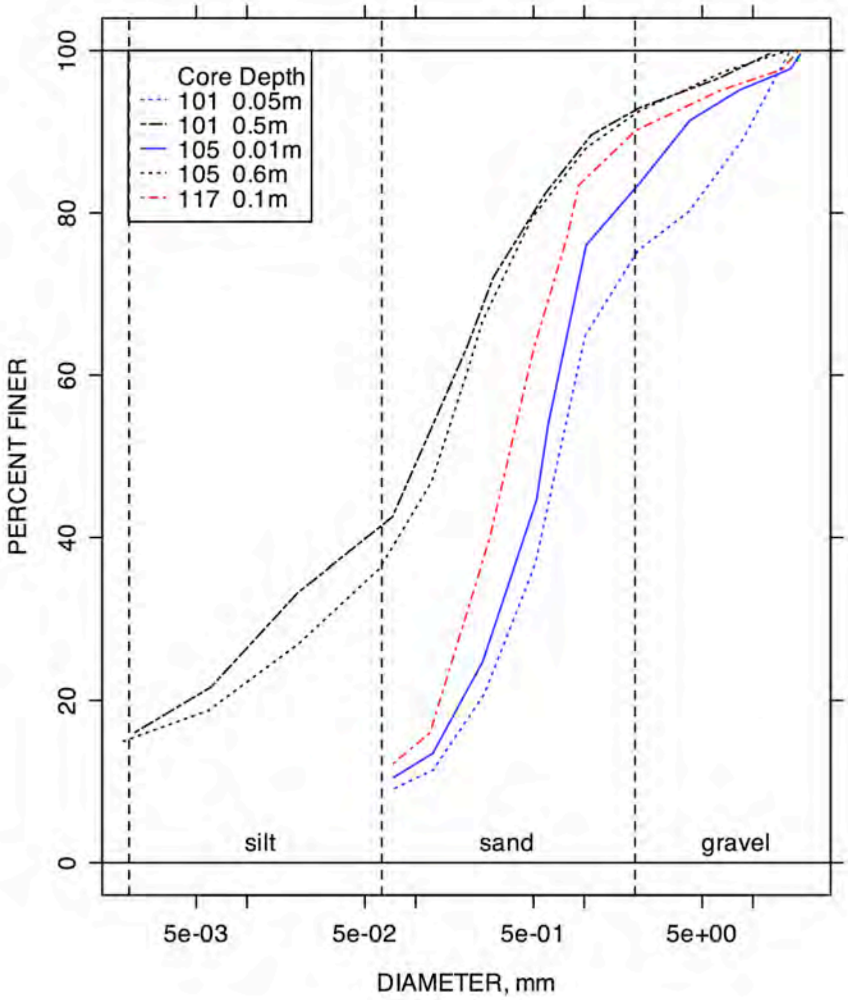


Figure 1. Grain size distributions for Geoconsult core samples

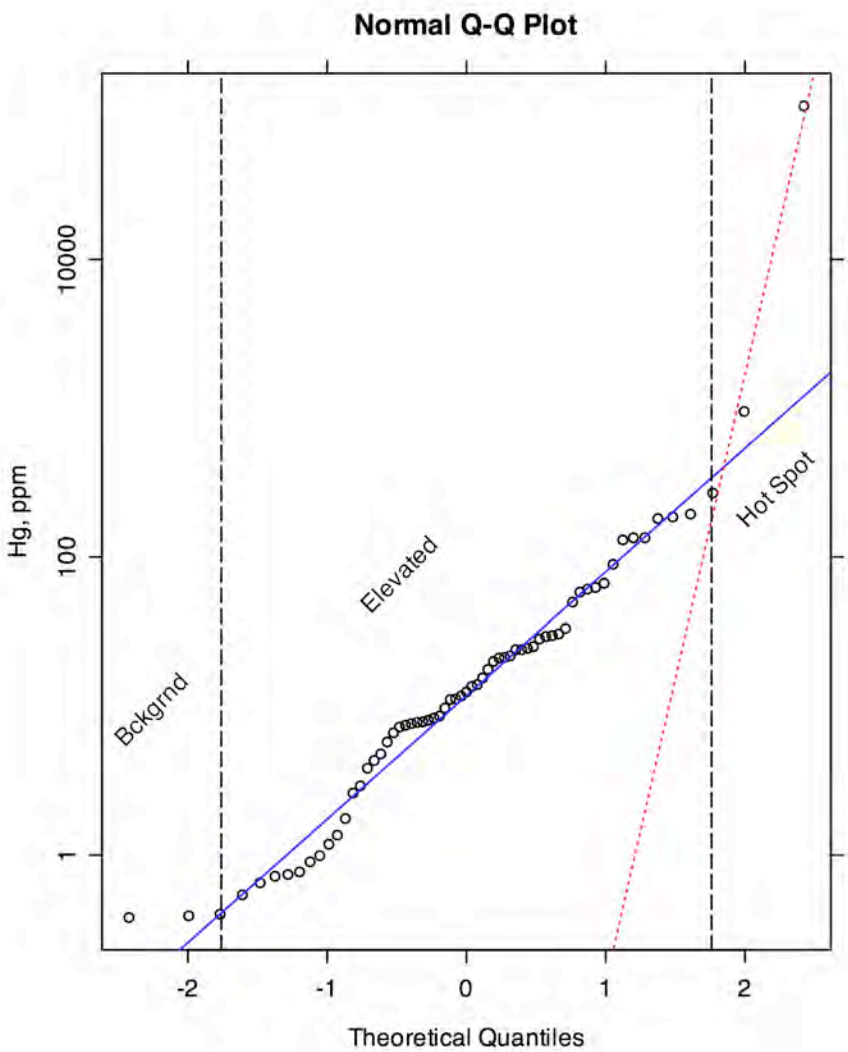


Figure 2. Cumulative probability (on standard-normal quantiles) for mercury concentrations.

Elemental Mercury Droplets

There is a possibility that elemental mercury is present on the submarine wreck and could be released to the environment during a salvage operation. Mercury droplet settling rate is necessary for model input but observed values could not be located in the literature. The following analyses lead to estimates for mercury settling rate.

CRC (2006) lists the following physical properties for mercury. Elemental mercury is a dense fluid (13.55 kg/l at 20 ^oC) with a moderate viscosity (1.526 mPa.sec versus 0.89 mPa.sec for water at 25 ^oC) and high surface tension (488.6 mN/m versus 74.2 mN/m for water at 10 ^oC). Since mercury is immiscible, it forms droplets in water which can become unstable during descent in water. Breakup occurs as the droplet flattens due to drag pressure, becomes toroidal and concave, and ruptures Successive droplet breakups will occur until droplet size falls below a critical value. Tan et al. (2005) presents a good review of droplet breakup.

Studies of droplet breakup in gas flows have generally used a Weber number to express the critical condition of droplet breakup. The dimensionless Weber number (*We*) expresses the ratio of drag force on the droplet to the surface tension. In this case

$$We = \rho_l \, W_s^2 \, D / \sigma_d \quad (1)$$

where ρ_l is the fluid density, W_s is the relative speed between the droplet and the fluid (settling velocity), D is droplet diameter, and σ_d is the droplet surface tension. The theoretical analysis of Duan et al. (2003) indicated that the critical *We* depends inversely on the density ratio between droplet and continuous fluid to an asymptotic of 12.6 (for Kelvin-Helmholtz type instabilities). Experiments have found the critical *We* for mercury droplets to be about 11 (Wierzba 1990 reported by Tan et al. 2005), similar to other fluid combinations with large density differences.

The fall speed for a particle or droplet (the balance of gravity and drag forces) is

$$W_s^2 = \frac{4\,g\,D}{3Cd}\left(\frac{\rho_d - \rho_l}{\rho_l}\right) \quad (2)$$

where g is the acceleration of gravity, Cd is a dimensionless drag coefficient, and ρ_d is the droplet density. The *Cd* for liquid droplets at near-critical *We* has been reported to be 2.5 for Reynolds numbers (*Re*) between 10^3 to 10^5 (Simpkins and Bales 1981 reported by Tan et al. 2005).

Assuming $We_{critical} = 11$, substituting 2.5 for *Cd* in Equation 2 and combining Equations 1 and 2 leads to the following expression for the critical *D* below which breakup is not expected to occur:

$$D = \left(\frac{20.6\,\sigma_d}{g\,(\rho_d - \rho_l)} \right)^{1/2} \tag{3}$$

Equation 3 predicts a droplet *D* of 9.05 mm for mercury in sea water, and Equation 2 predict W_S to be 0.76 m/sec (*Re* = 6800).

Another criteria that might apply was developed for the entrainment of two fluids of dissimilar viscosity (Campbell and Turner 1986). This criteria is a special *Re* based on the viscosity of the material being entrained such that (using the present notation) $W_S\,D / \nu_l > 7$ where ν_l is the kinematic viscosity of water. Using Equation 2 and ASCE (1975), the following expression was developed for the critical *D* after iterating on *Cd* :

$$D = \left(\frac{3\,Cd\,\rho_l}{4\,g\,(\rho_d - \rho_l)} \right)^{1/3} \left(\frac{7\,\upsilon_l}{\rho_l} \right)^{2/3} \tag{4}$$

Equation 4 predicts a mercury droplet *D* of 0.144 mm, and the corresponding W_S from Equation 2 is 0.048 m/sec (*Re* = 7, *Cd* = 10).

Even though Equations 3 and 4 do not agree exactly, they both predict mercury droplet settling rates equivalent to coarse sediment particles (0.35 to 15 mm diameter). Equation 3 is deemed most reliable as it follows conventional droplet breakup analyses. However, droplet breakup is not expected to result in a unique diameter at the critical value. As droplets near the critical diameter breakup, they could produce droplets considerably smaller than the critical value as a result of the dynamics of the breakup process. Assuming a droplet size on the lower end of the range described above is conservative for the purpose of assessing the risk of droplet spreading during salvage or dredging.

Model Description

SSFATE is a PC-based numerical model system designed to predict sediment dispersion resulting from dredging activities. SSFATE was developed by Applied Science Associates, Inc. located in Narragansett, RI and the US Army Corps of Engineers Research Development Center located in Vicksburg, MS in response to a need for tools to assist dredging project managers confronted by requests for environmental windows. Details about SSFATE can be found in The DOER Technical Notes Collection (ERDC TN-DOER-E10). A summary of the modeling system is given below.

SSFATE is a versatile suspended sediment computer modeling system based on the concept of Lagrangian sediment particles. SSFATE contains many features. For example, ambient currents, which are required for operation of the basic computational model, can either be imported from a numerical hydrodynamic model or drawn graphically using interpolation of limited field data. Model output consists of concentration contours in both horizontal and vertical planes, time-series plots of suspended sediment concentrations, and the spatial distribution of sediment deposited on the sea floor. In addition, particle movement can be animated over Geographic Information System (GIS) layers depicting sensitive environmental areas.

SSFATE employs a shell-based approach consisting of a color graphics based, menu-driven user interface, GIS, environmental data management tools, girding software, and interfaces to supply input and display output data from the model. SSFATE runs on a personal computer and makes extensive use of the mouse (point/click) and pull down menus. Data input/output is interactive and mainly graphics based. The system allows a full set of tools to allow the user to import data from standard databases, a wide variety of GIS's, and other specialized plotting/analysis programs. At the heart of the system is a computational model that predicts the transport, dispersion, and settling of suspended dredged material released to the water column as a result of dredging operations. An integral component of the modeling system is the specification of the sediment source strength and vertical distribution.

Model Application and Results

Model bathymetry was created from a recent 1-km by 1-km XYZ survey data supplied by DOF (formerly Geoconsult). The data were trimmed to form a regular grid covering a rectangular area about 0.9 km square with the wreck slightly in the southeast quadrant of the rectangle. The original horizontal XY coordinates (UTM) were converted to the coordinates required by SSFATE (latitude and longitude). The grid resolution scale for transport was 10 m in the horizontal and 1 m in the vertical. The model grid is shown in Figure 3 along with water depths, wreck part locations, and release point locations used in model simulations.

Currents representing 16th, 50th, and 84th percentile observed current profiles were generated for nine locations on the bathymetric grid and 12 vertical layers. The vertical current profiles, including the directional shear described earlier, were interpolated over the current grid from these locations. The sediment characteristics described earlier were used in the model. The default SSFATE settling rates were used for the five grain classes specified. Default values were also used for horizontal and vertical diffusivities. Since the issue of exactly what dredging technique might be employed and how the dredging operation would be configured has not been resolved, the SSFATE model was operated in sensitivity mode.

Dredging operations always generate some amount of resuspension at the point of dredging but the rate of resuspension varies greatly. The rate of resuspension can be expressed as a fraction of the dredging rate. The sediment resuspension rate (SRR, kg/hr or ton/hr) is the volume dredging rate (m^3/hr) times sediment solids content (dry-ton/m^3 or dry-kg/m^3) times the fractional resuspension (v/v). The fractional resuspension is generally between 0.01 and 0.1 (SSFATE default value is 0.03) but can be outside this range. The fractional resuspension depends on sediment conditions (sediment grain size or fines content, sediment bulk density or moisture content, and sediment mineralogy and organic content). The fractional resuspension also depends current conditions and on dredge design and operation.

The model was operated over various SRRs, the three levels of current conditions, and various release locations expected to be typical for dredging-related near-bottom and water column sediment releases. Four release points were used. Three release points covered the center and two locations on the area to be dredged with minimum and maximum distances to the model boundary in the direction of prevailing bottom currents. The fourth site is at the location of a possible submarine sediment slide. See Figure 3 for point locations. Deposition near the site was along a line directed by bottom currents at about 300 degrees from the site. The distance from the central release location (point 1) to the boundary of the grid was 760 m in this direction and is defined here as being the “vicinity” of the site.

The main issue addressed by the model analysis is the escape of mercury from the vicinity of the wreck. As describe earlier, the assumption was made that all the mercury was associated with the clay fraction. The clay escape probability (CEP) is defined as the fraction of resuspended clay that escapes the model domain without depositing - a distance of about 760 m from the release site. Virtually all of the coarsest three sediment classes and the bulk of the fine silt fractions were found to deposit within the model domain for all current conditions.

Example plots of suspended and deposited sediment particles and concentration contours for maximum concentration in the vertical are presented in the Plates at the back of this report. Results are summarized in the following sections.

Near-bottom dredging releases. The SSFATE was operated for various 8-hr simulated dredging operations with 20, 50, 15, 10 , and 5 percent of releases made at 0.25, 0.75, 1.25, 1.75, and 2.25 m above the bed, respectively. This could represent a hydraulic, trailing-suction hopper dredge, or bottom-mounted mechanical dredging operation. The model was operated for a total 12 to 24 hr or 4 to 16 hr following dredging to give sufficient time for deposition or for the currents to sweep suspended material out of the model domain. Results for the three current percentile values and three locations are presented in Figure 4. Currents had a greater influence of CEP than dredging site location.

There was a trend for CEP to decrease with increasing SRR. This occurs because of concentration and class-coupling effects on clay settling. At higher suspended concentrations and/or with faster-settling classes present, clay settling is greatly enhanced. Clay settling rate increases directly as the suspension concentration to a power equal to or greater than 1.0. For example, an order of magnitude or more decrease in clay settling rate is expected as suspended concentration decreases from 1000 to 100 mg/l. The presence of coarser grain fractions can further affect clay settling rates by a factor up to 2 or 3. The SSFATE model default grain class settling dependence on suspension concentration is shown in Figure 5 for an example sediment composed of about 50 clay and 25 percent each of fine- and coarse-silt fractions.

As shown in Figure 6, the model calculated CEP decreases with increasing (maximum) suspension concentrations (related to SRR). However, total clay escape rate (CEP times 0.15 clay w/w times SRR, ton/hr) increased with SRR as can be seen in Figure 7. However, there is a lower concentration limit (50 mg/l by the SSFATE default value) to concentration-enhanced settling rate. The lowest SRR simulated reached this low-concentration limit. A single model run was made at 0.02 ton/hr SRR and had a clay escape probability (CEP) nearly the same as for a SRR of 1 ton/hr, indicating the same settling for these two SRRs.

Total escape or loss of clay (or mercury) depends on CEP and the fraction resuspended by dredging. To estimate the total escape or loss of clay (or mercury), the CEP is multiplied by the fraction resuspended and the total clay (mercury) amount to be dredged. Table 4 gives some example to illustrate the application of model results.

Example model suspension concentration contours and particle fields are shown in Plates 1a and 1b for SRR = 127 tons/hr at release point 1 and 50 % currents. Example model deposit mass per unit area and particle fields are shown in Plates 2a and 2b also for SRR = 127 tons/hr at release point 1 and 50 % currents. Example model suspension and deposit mass-per-unit-area contours are shown in Plates 3 and 4 for SRR = 637 tons/hr at release point 2 and 50 % currents.

TABLE 4. Example Total Clay and Mercury Losses for Hypothetical Dredging Cases

Dredging Rate * Solids Content, tons/hr	Fraction Resuspended, v/v	SRR, ton/hr	CEP (50% current from Fig. 3)	Total Clay Escape or Loss[1], tons	Total Mercury Escape or Loss[2], kg
100	0.01	1	0.96	34 (e.g. 3566*.01*.96)	36 (e.g.3780*.01*.96)
100	0.1	10	0.63	225	238
1000	0.01	10	0.63	22	24
1000	0.1	100	0.17	61	64

[1] Assuming 3566 tons of clay to be dredged.

[2] Assuming 3780 kg of mercury to be dredged.

Water column releases. For the case of a vessel-based mechanical dredging operation, such as a clamshell dredge, some water column releases are expected. Some sediment resuspension might occur as the result of equipment impacting the bed, some sediment might stick to the outside of the equipment and drop off during clamshell ascent, and some sediment might escape as the result of the equipment not being completely closed. The vertical distribution of sediment releases were 5, 10, 15, 30, and 40 percent at 10, 30, 50, 70, and 90 percent depth. (A sensitivity test indicated that the model results were not very sensitive to small changes in the vertical distribution of released material.) Since the depth of cut will only be 0.5 m and will restrict equipment size, the range of SRRs covered by model simulations was more limited than for bottom releases.

Results for 50% and 16% current conditions are shown in Figure 8. The CEPs were so large for these current values that the 84% currents were not simulated but resulting CEPs are expected to be very close to 1. The combined effect of low SRRs and water column dispersion resulted in maximum release concentrations ranging from 7.8 to 126 mg/l for these simulations. The maximum concentrations were therefore more than on order of magnitude lower than for the near-bed release cases (for comparable SRRs) which contributed to low settling and very high CEPs.

An example particle field for suspended sediment after 8 hr of water-colunm releases from dredging is shown in Plate 5. Corresponding deposit for 8 hr dredging releases (16 hours after dredging stopped) in terms of particle field and thickness contours are shown in Plates 6a and 6b. Deposit thickness assumes the deposit to be at *in situ* density (wet density about 2000 kg/m^3).

Assuming 3566 tons of clay to dredge and CEP ~ 0.99, total clay loss would be 35 and 353 tons for fractional resuspension rates of 0.01 and 0.1, respectively. Assuming 3780 kg of mercury to dredge and CEP ~ 0.99, total mercury loss would be 37 and 374 kg for fractional resuspension rates of 0.01 and 0.1, respectively.

Surface releases. Very short releases (0.5 hr) of small quantities of sediment material (1.8 m^3 of material with 0.43 tons clay) were released near the surface to simulate dispersion and transport of small spills that might occur from salvage or other operations. Note that SSFATE does not include density driven vertical transport that might be important in the case of a appreciable spill. For this case SSFATE is conservative in that it would tend to under predict vertical transport rates and over predict escape since only the passive phase of dispersion is simulated.

For these simulations three additional bathymetric grids were developed that had the same horizontal extent as the original grid but with flat bottoms of 175, 50, and 10 m depth. The 16th percentile currents were used for these simulations.

Results for the 175-m deep case indicated that the CEP was 1. Results for the same conditions except with 50 and 10 m grid depths indicated CEPs of 0.19 and 0.02, respectively.

Mercury droplet releases. Elemental mercury could be present in the wreck or in canisters dislodged from the wreck. Salvage or dredging operations might release mercury which would form droplets in water. Simulations were made with a single settling class specified in the model. Values of 0.05 and 0.5 m/sec were used similar to the range estimated in the analysis presented earlier. These simulations used the flat, 175-m deep grid, near-surface release, and 16th percentile currents. The simulated mercury release duration was 0.1 hr, model time step was reduced to 0.1 min and model output was saved every 1 min.

In both cases the model predicted complete deposition of the droplets within the model domain. Deposition patterns for the 0.5 and 0.05 m/sec settling rates are shown in Figures 9 and 10. The deposit pattern for 0.5 m/sec settling rate is nearly circular with a diameter of about 65 m while the pattern for 0.05 m/sec settling rate is elongated in the direction of the current (to about 300 m) and wider (about 102 m average). The patterns reflect the greater effect that vertical diffusivity has on the former (slower-settling droplets) as compared to the latter.

Sediment slide releases. The slope on which the wreck is located is only marginally stable and a salvage or dredging might initiate a sediment slide. Worst case might be a sheet slide 2.5-m thick and 55-m by 55-m horizontal extent that moves down slope and impact the far valley wall and resuspend 10 percent of the sheet-slide sediment mass. A lower value of 1 percent release was also simulated.

The model release was 0.1 hr duration distributed 20 percent in five levels 0.25, 1, 1.75, 2.5, and 3.25 m up from the bottom. The sediment volume was 7562.5 m^3 and the same sediment parameters were used as in the near-bottom release simulations. The results are summarized in Table 5.

TABLE 5. CEP Results for Sediment Slide Conditions			
	CEP		
Slide Release, percent	16% Currents	50% Currents	84% Currents
1	0.178	0.234	0.405
10	0.014	0.056	0.266

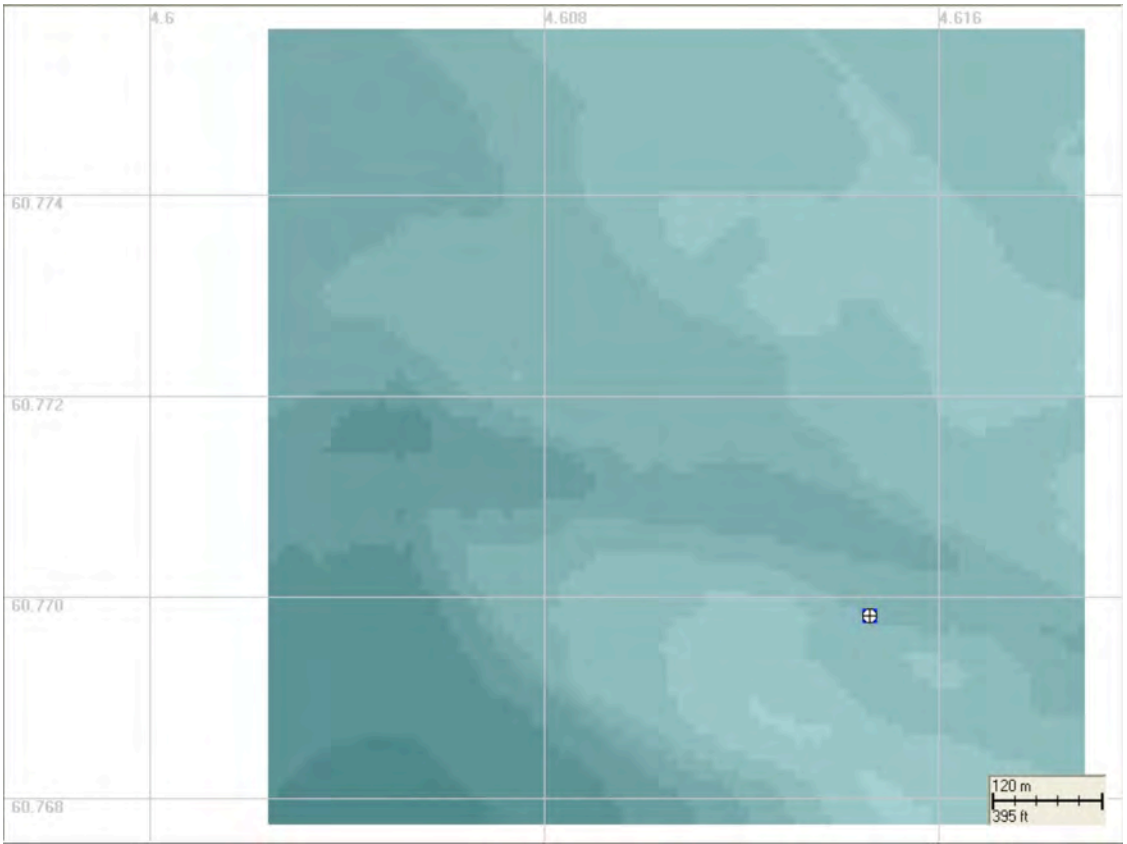
A sequence of suspended sediment cloud contours for 1-3 hours after the slide are shown in Plates 7 to 9. Deposit contour thickness and particle fields are shown in Plates 10a and 10b.

The volume of the hypothetical slide was more than half the volume of the proposed cleanup dredging volume but the surface area was only about 10 percent of the cleanup area. The average mercury concentration in the slide would only be about 20 percent of that in the volume to be dredged due to the assumed slide thickness. However, material at the surface of the slide is the most likely to be resuspended so that the same mercury concentration is likely to be in the resuspended sediment as in the dredged resuspended material. Table 6 presents expected clay and mercury losses.

TABLE 6. Expected Clay and Mercury Losses from a Sediment Slide			
	Clay Escape[1], tons		
Slide Release, percent	16% Currents	50% Currents	84% Currents
1	3.4	4.5	7.7
10	2.7	10.7	50.7
	Mercury Escape[2], kg		
Slide Release, percent	16% Currents	50% Currents	84% Currents
1	0.68	0.89	1.54
10	0.53	2.13	10.1

[1] Assuming clay mass in the slide to be 1906 tons.

[2] Assuming mercury mass available for resuspension to be 381 kg.



a.

b.

Figure 3a. Model bathymetric grid, latitude/longitude coordinates, and release point 1 (a); and an overlay of release point and wreck part locations.

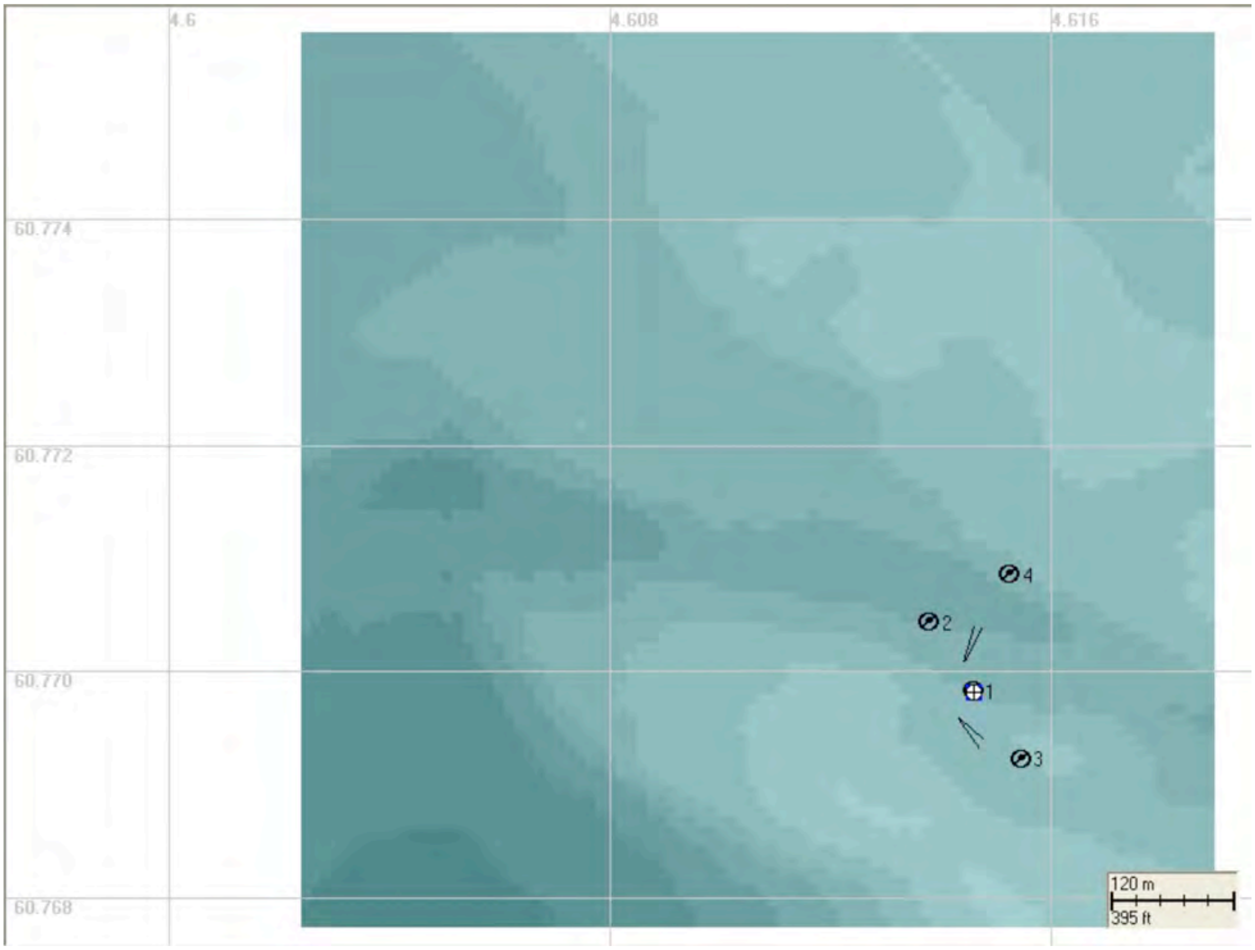


Figure 3b. Model bathymetric grid (light colors are shallow), release points 1-4, and wreck parts.

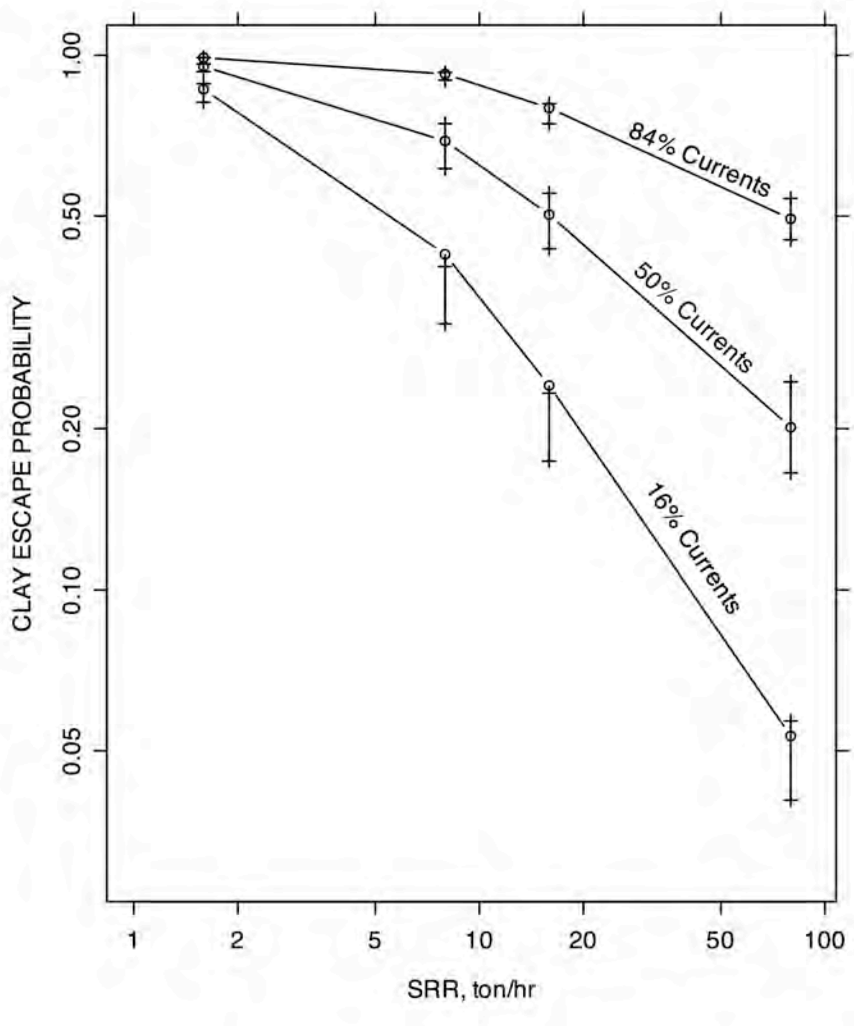


Figure 4. CEP results for near-bed sediment releases at three locations and three current regimes.

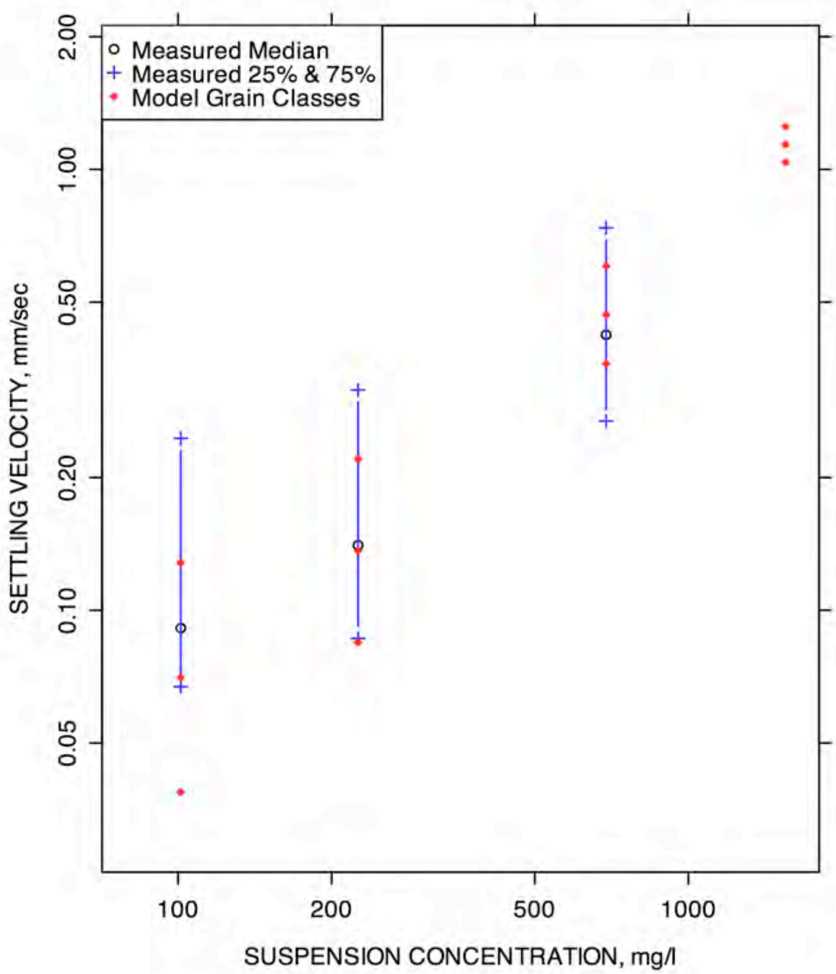


Figure 5. Default SSFATE grain class settling for material composed of 50/25/25 (clay/f. silt/c. silt) compared to laboratory test data on material from the Elizabeth R., Virginia, U.S.A.

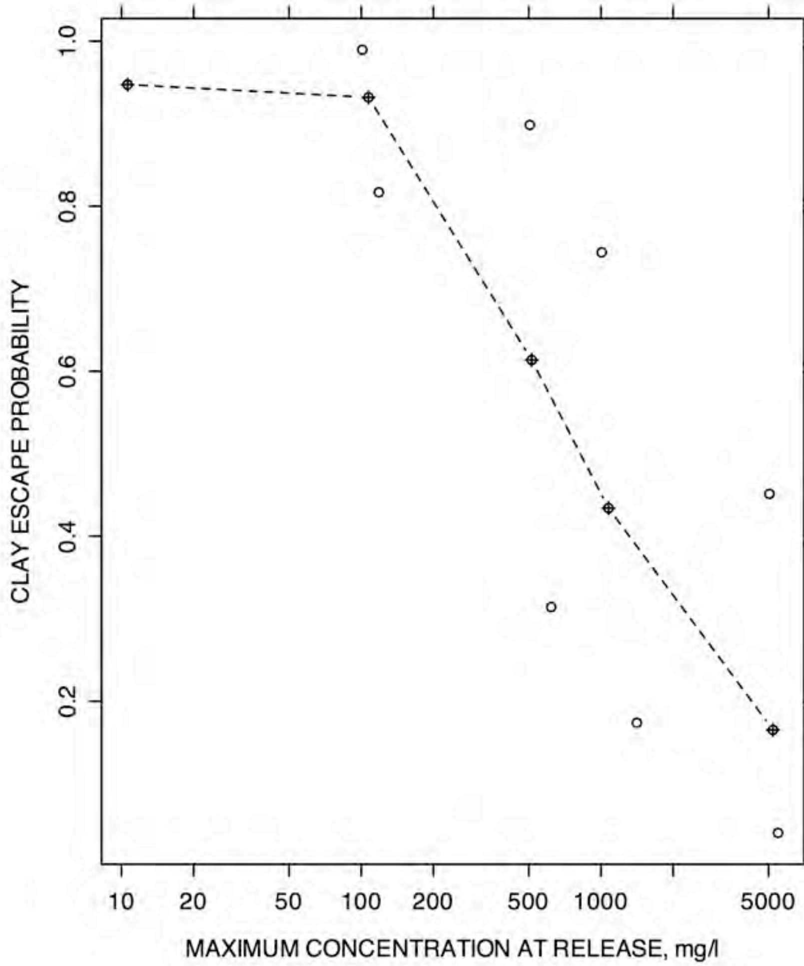


Figure 6. CEP variation with maximum suspended sediment concentration for three current conditions and release point 1.

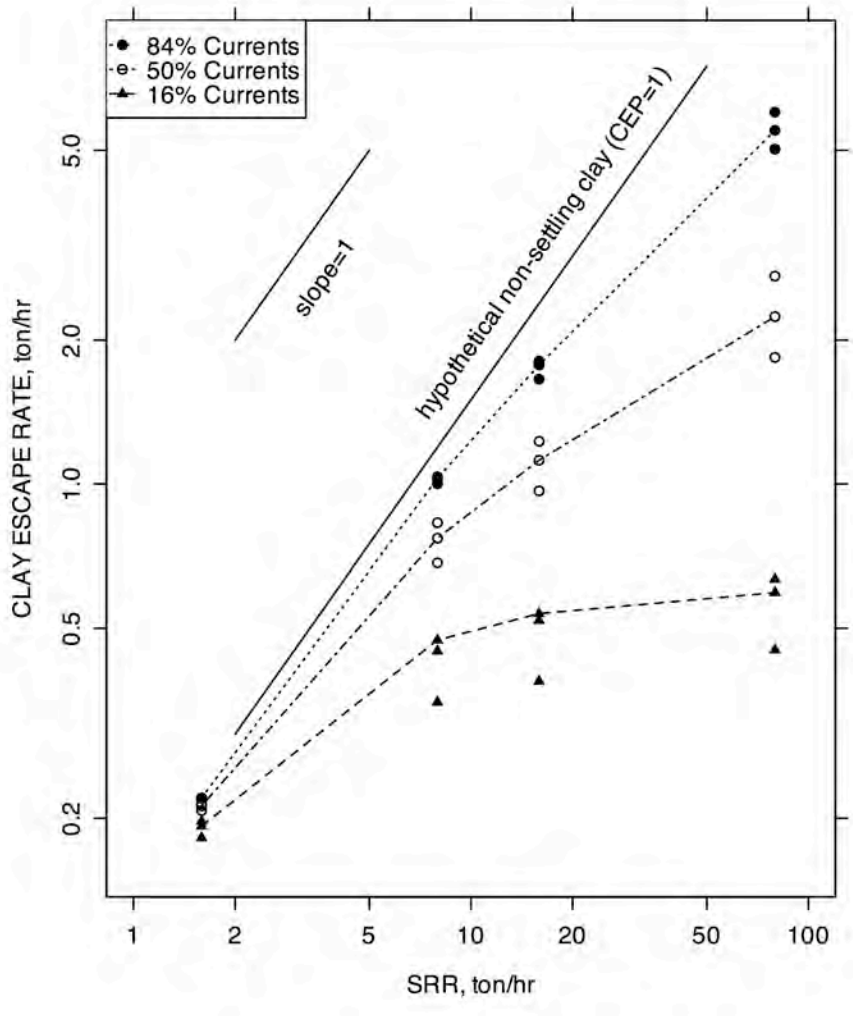


Figure 7. Clay escape rate (CEP * SRR * 0.15) variation with SRR.

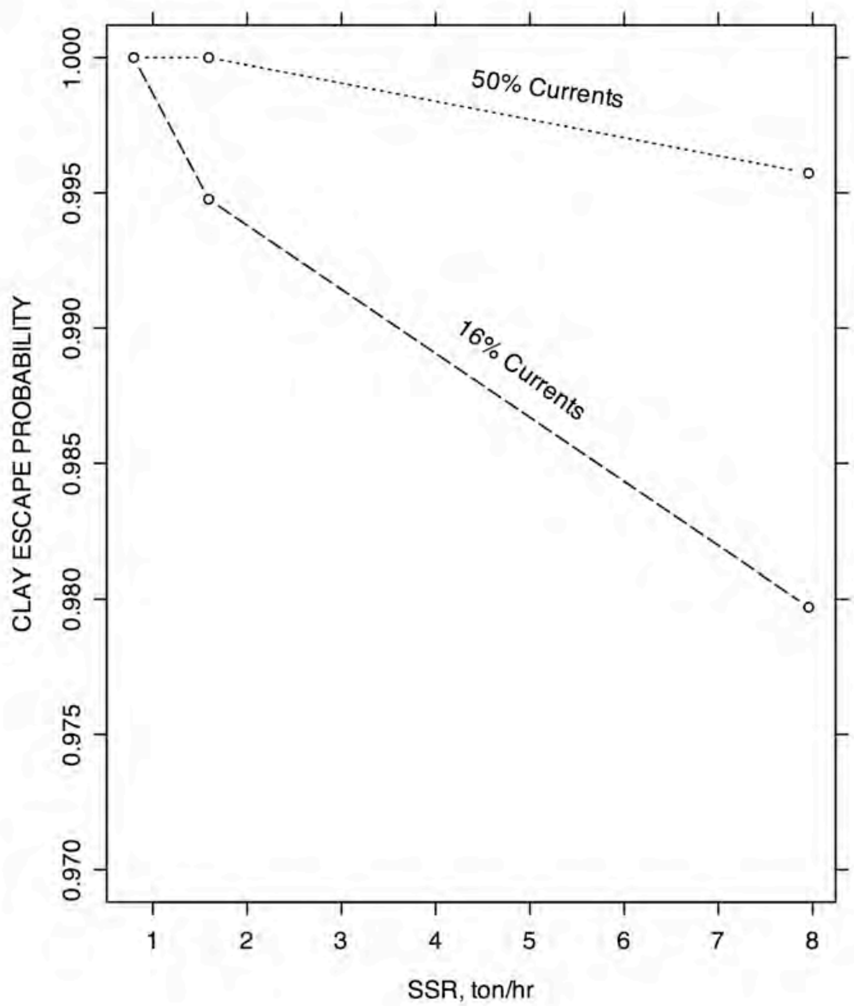


Figure 8. CEP variation with SRR for water column releases.

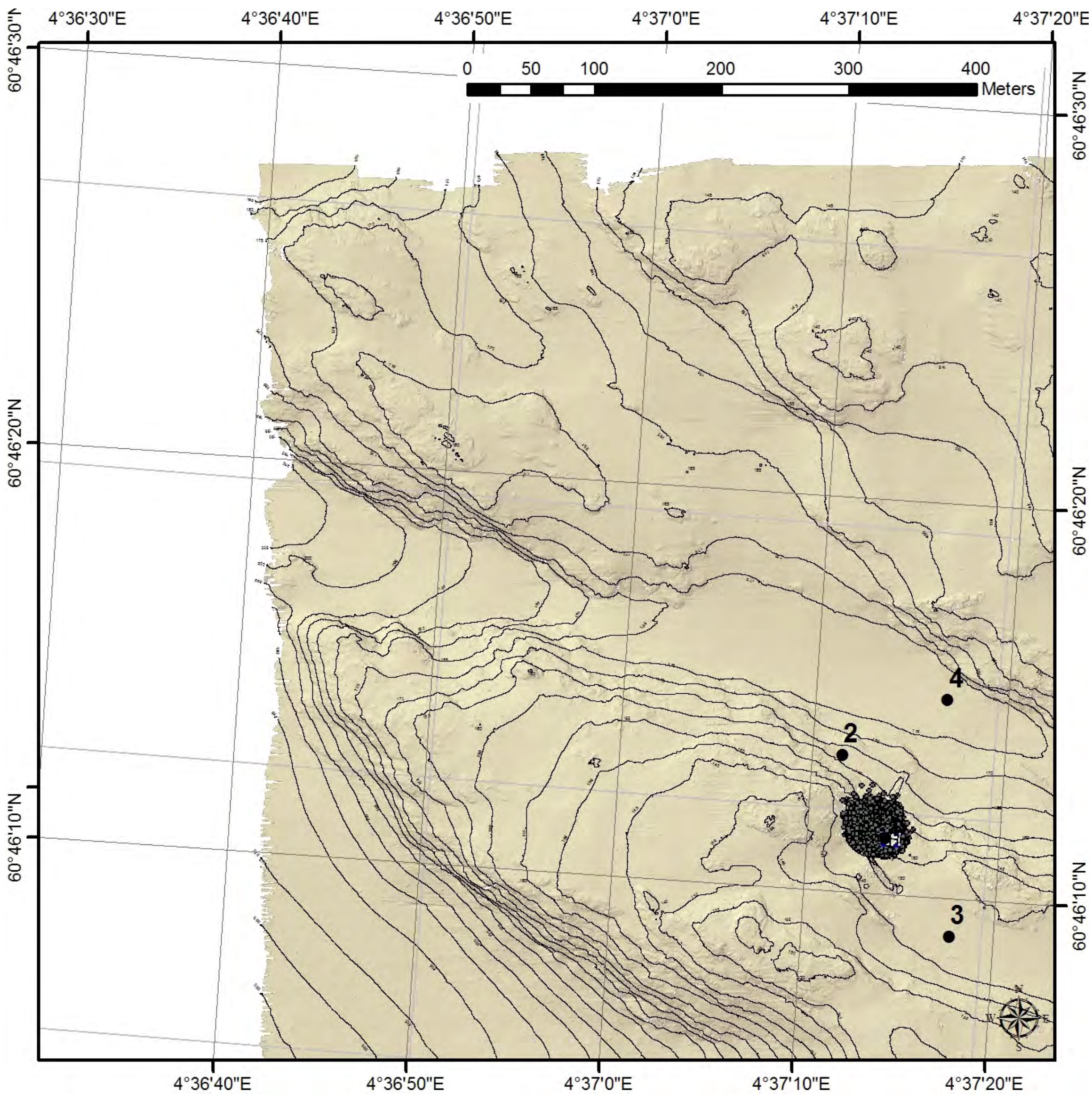


Figure 9. Deposit patch for 0.5-m/sec droplet settling rate with 175 m water depth superimposed onto the submarine wreck site.

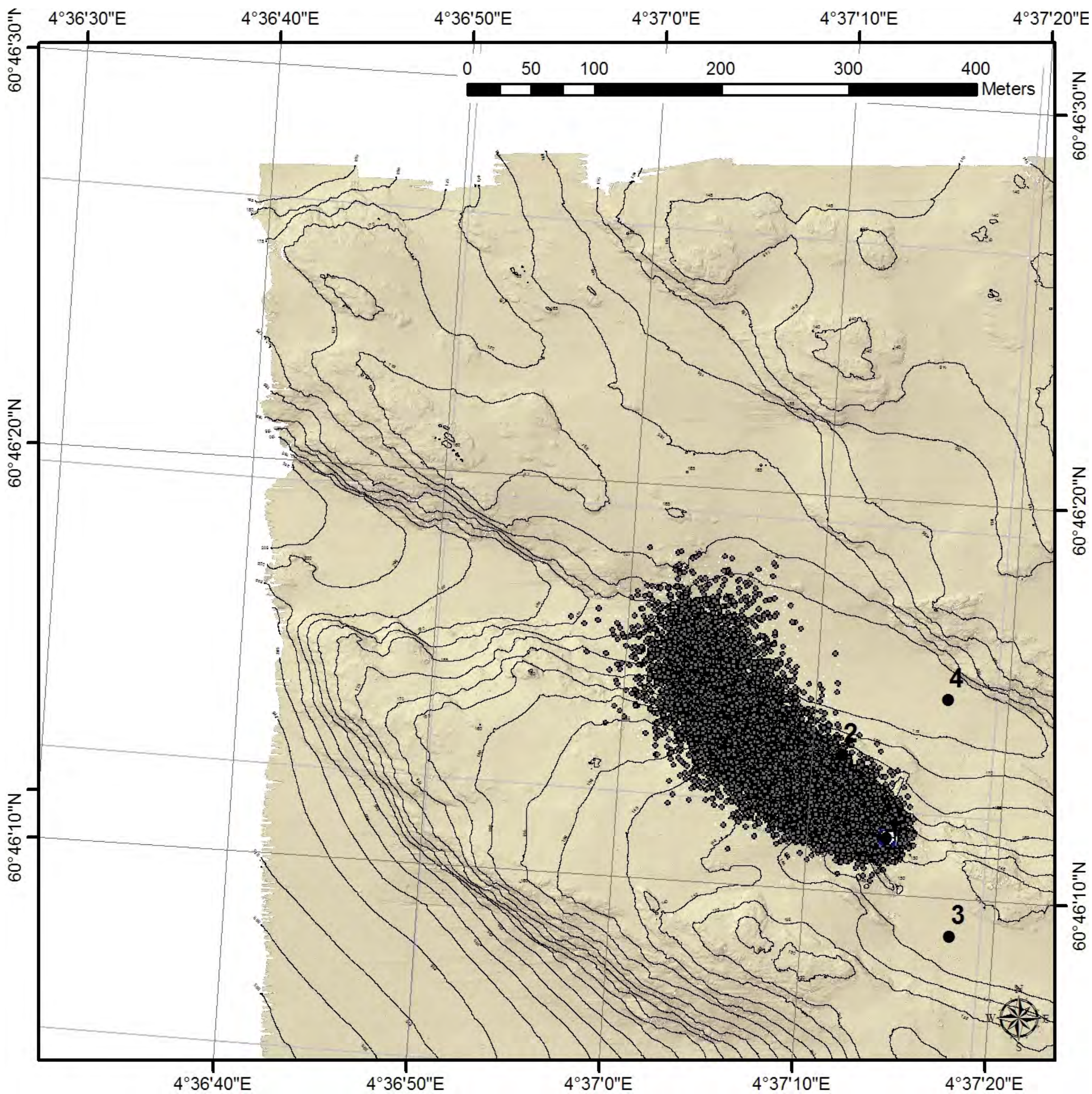


Figure 10. Deposit patch for 0.05-m/sec droplet settling rate with 175 m water depth superimposed onto the submarine wreck site.

Summary and Conclusions

Sediment releases were modeled using SSFATE for the vicinity of the sunken U864 and for some shallower generic cases. The sediment consists of 15000 m^3 of silty sand with clay. Near-bottom, water-column and surface releases were considered that might be associated with salvage and dredging operations. The model was used to assess the escape of material from 760 m of the contaminated site. Virtually all the coarser sediment released deposited near the site.

Results indicate that the escape probability for clay (and therefore the mercury assumed to be associated with clay) tends to decrease with increasing sediment release rate for near bottom releases. This is explained as the influence of concentration-enhanced flocculent settling of the clays, and coupling of clay settling with coarser grain classes. The implication for possible dredging operations is that, for equal fractional resuspension, higher dredging production rates reduce overall clay and mercury losses from the vicinity of the site and are therefore to be preferred. (The fractional resuspension should also be minimized to reduce the residual contamination left at the site after dredging - an issue not directly addressed in this modeling.)

Simulated water column and surface releases at the site resulted in almost complete loss of clay and mercury due to the great depth at the site. It is therefore recommended that special measures be taken to minimize water column and surface releases at the site. Simulation of releases at shallower depths resulted in escape probabilities proportional to depth. Based on simulations of droplet settling, the possibility of elemental mercury escaping the vicinity of the site as suspended droplets appears to be remote.

One of the largest uncertainties in predicting the escape of mercury form the site is the wide confidence interval for the mercury mass in the site sediments. It is believed that 10 to 20 percent of the mercury originally on board might have been lost during the explosion that destroyed the submarine based on the length of keel missing (DNV Workshop). This would amount to 6.7 to 13.4 tons. Yet the mass based on the area-weighted mean concentration was only 4.75 tons. The analysis presented earlier also estimated that the 0.05 and 0.95 probability mercury mass values are 0.88 and 19.6 tons for the site. Extreme high and low clay escape probabilities and fractional resuspension for various dredging alternatives and spill scenarios can be used with those mercury masses to predict mercury escape end-point probabilities (at approximately the 0.01 and 0.99 levels). Results are shown in Figure 11 and described in the following paragraphs.

Near-bed dredging losses. Lowest clay escape probability (CEP) tended to be for higher sediment resuspension rates (SRRs). A dredge operation with 5000 m^3/hr production and 0.01 fractional resuspension would have an SRR of about 80. Model results give an average CEP of 0.2 and result in a low mercury loss of 1.8 kg (0.01*0.2*880). Higher CEP were found for low SRRs. A dredging operation removing 10 m^3/hr with a fractional resuspension of 0.1 would have a SRR value of about 1 and corresponding CEP of 0.93. Thus the high mercury loss estimate for near-bed dredging would be 1822 kg (0.1*0.93*19591).

Water column dredging losses. The CEPs for normal current conditions were all close to 1 for the range of SRRs simulated. Assuming CEP to be 0.99 and fractional resuspension values of 0.01 and 0.1, the low and high mercury release estimates would be 8.7 and 1940 kg (0.01*0.99*880 and 0.1*0.99*19591).

Water column and surface spills. The CEP for both water column and near-surface releases were about 0.99 for small SRR. About 10 m^3 of sediment material is believed to be submarine (DNV Workshop). Since the submarine was heavily contaminated at the time of the explosion, the material inside the submarine can be assumed to be similar to the hot spot found near the wreck. Using the hotspot mercury concentration values for 0.1 and 0.9 probabilities (14.7 and 621727 ppm) and 1 and 10 m^3 spills, the low and high mercury loss estimates are 0.02 and 9760 kg (1*1585*14.7e-6*0.99 and 10*1585*0.622*0.99). The physical possibility of such a high mercury concentration is not known.

Sediment slides. The CEPs for sediment slides was found to vary with currents and fractional resuspension. A sediment slide is a short event which could occur on during current conditions different from normal. Low and high mercury losses were estimated from corresponding mercury mass, fractional resuspension, and currents to be 0.2 and 52 kg (0.01*0.178*88.7 and 0.1*0.266*1975).

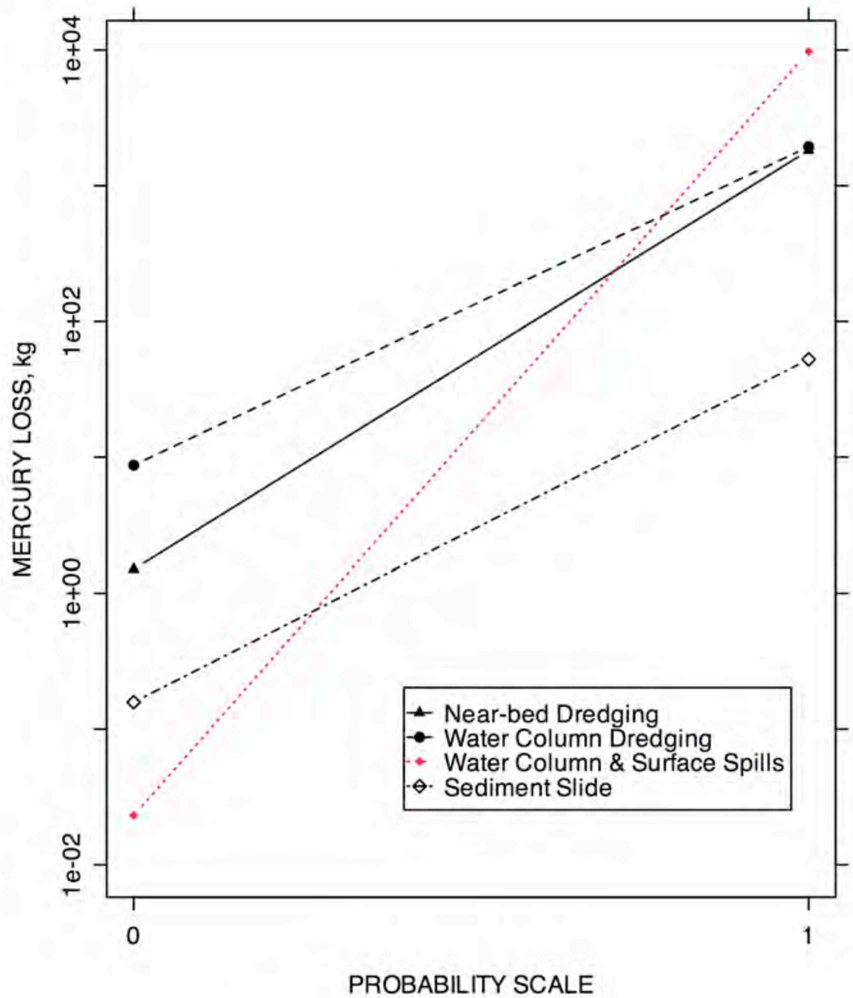


Figure 11. Mercury-loss probability end members for various dispersion sources.

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PLATES

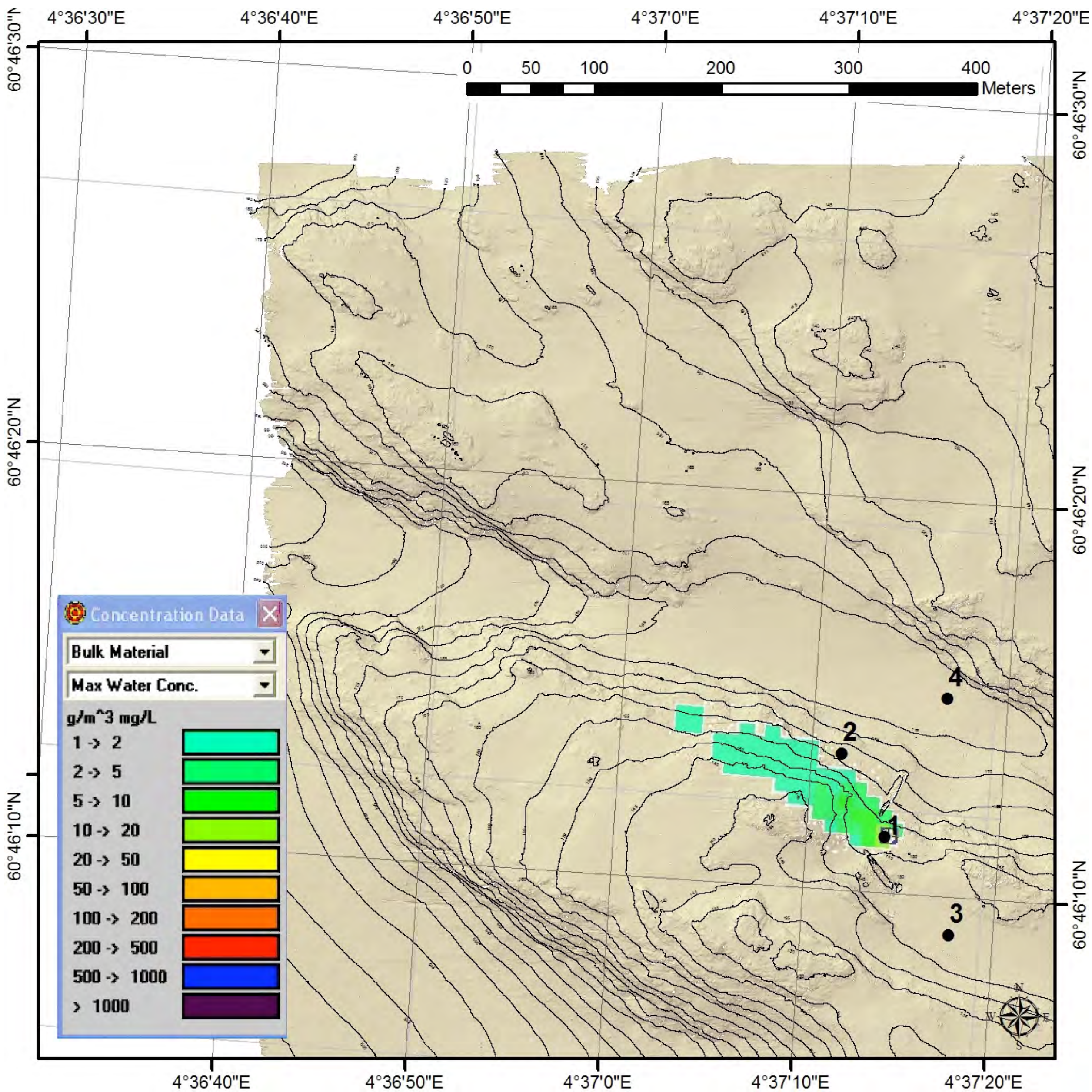

Plate 1a. Maximum water column concentration at hour 8 (after 8 hr of dredging) for a clamshell release at point 1, SRR = 127.3 ton/hr, and 50% currents.

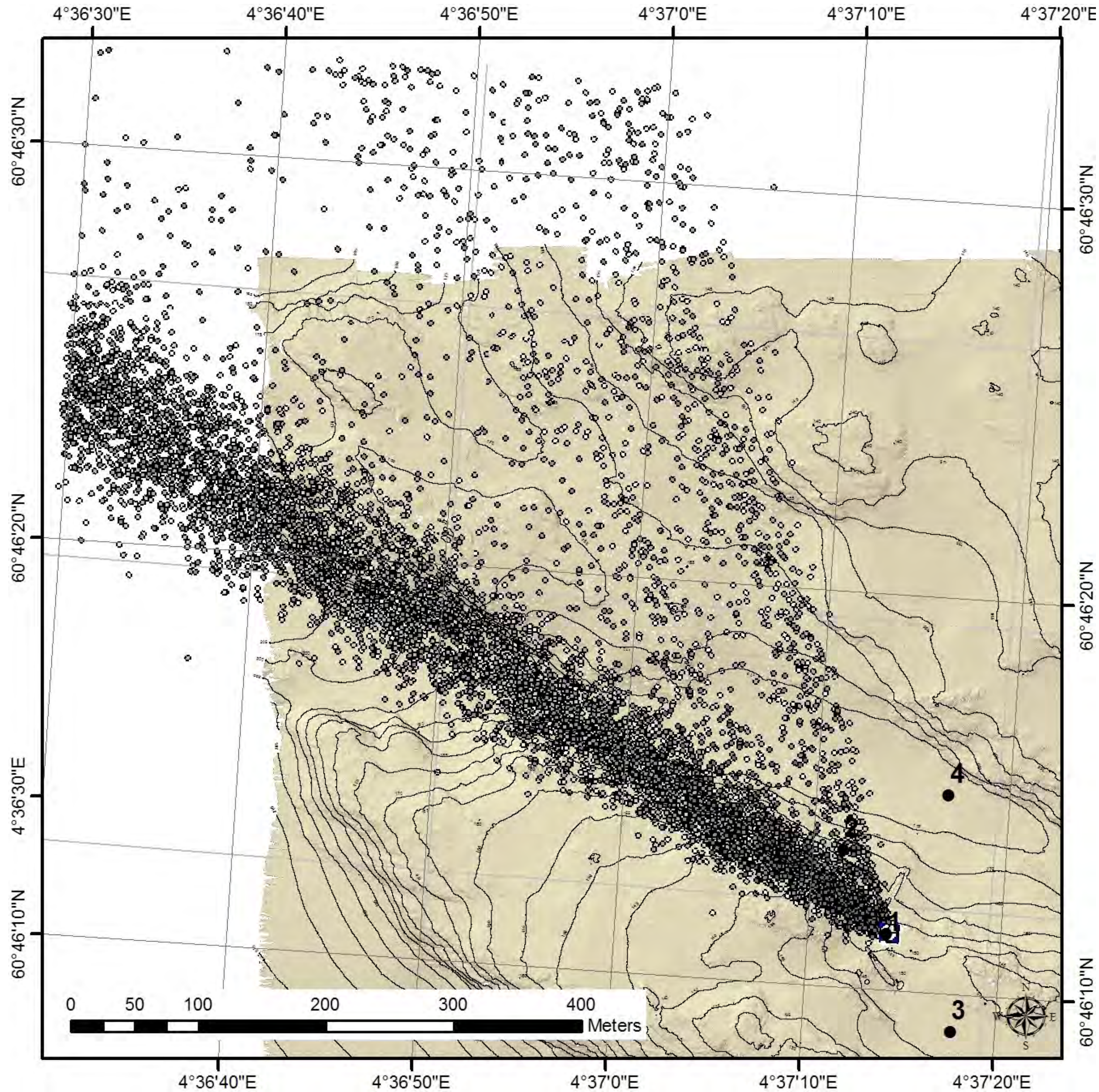

Plate 1b. Suspended particle field at hour 8 for a clamshell release at point 1, SRR = 127.3 ton/hr, and 50% currents (note the effect of current direction shear on near surface particles).

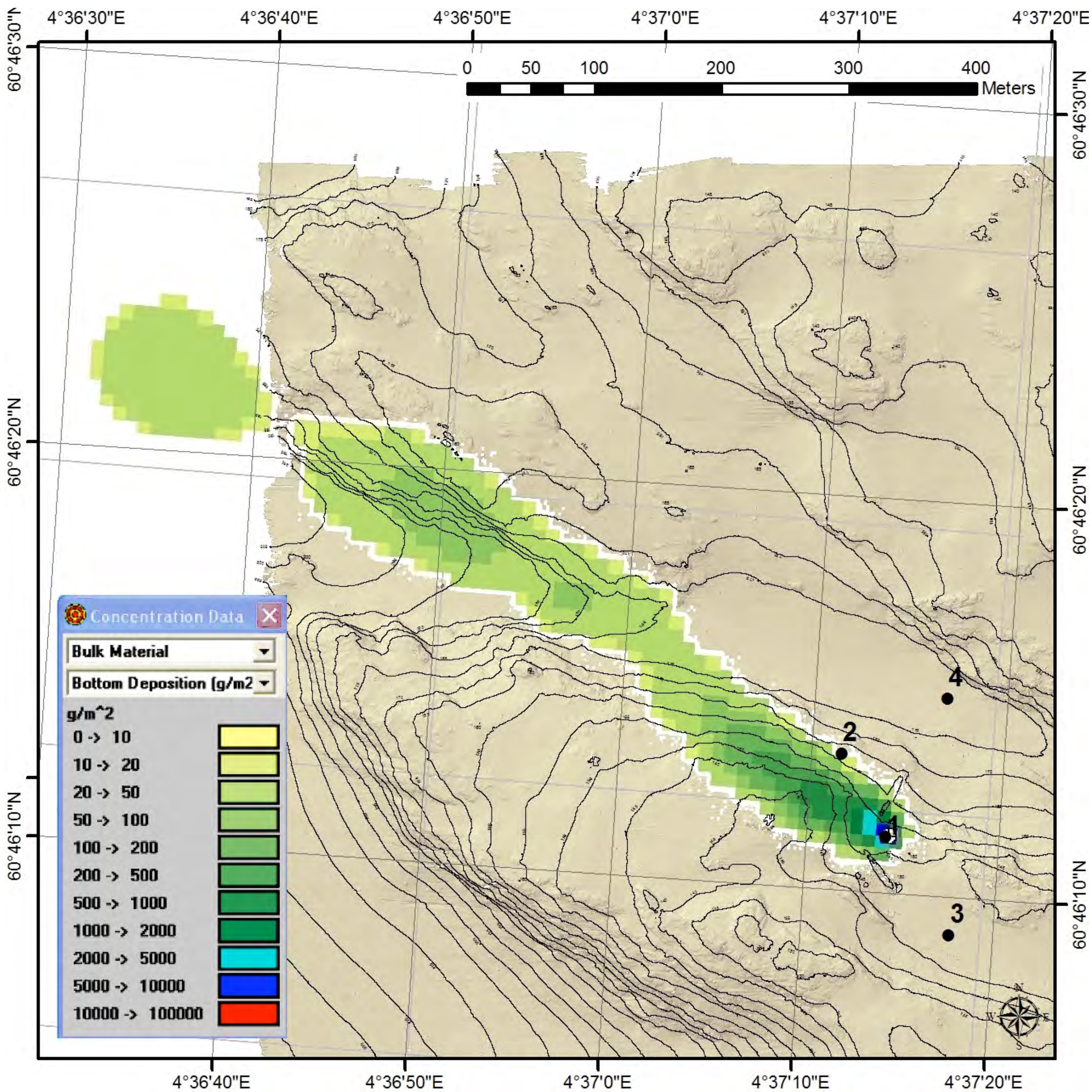

Plate 2a. Bottom deposit at hour 12 for a clamshell release at point 1, SRR = 127.3 ton/hr, and 50% currents.

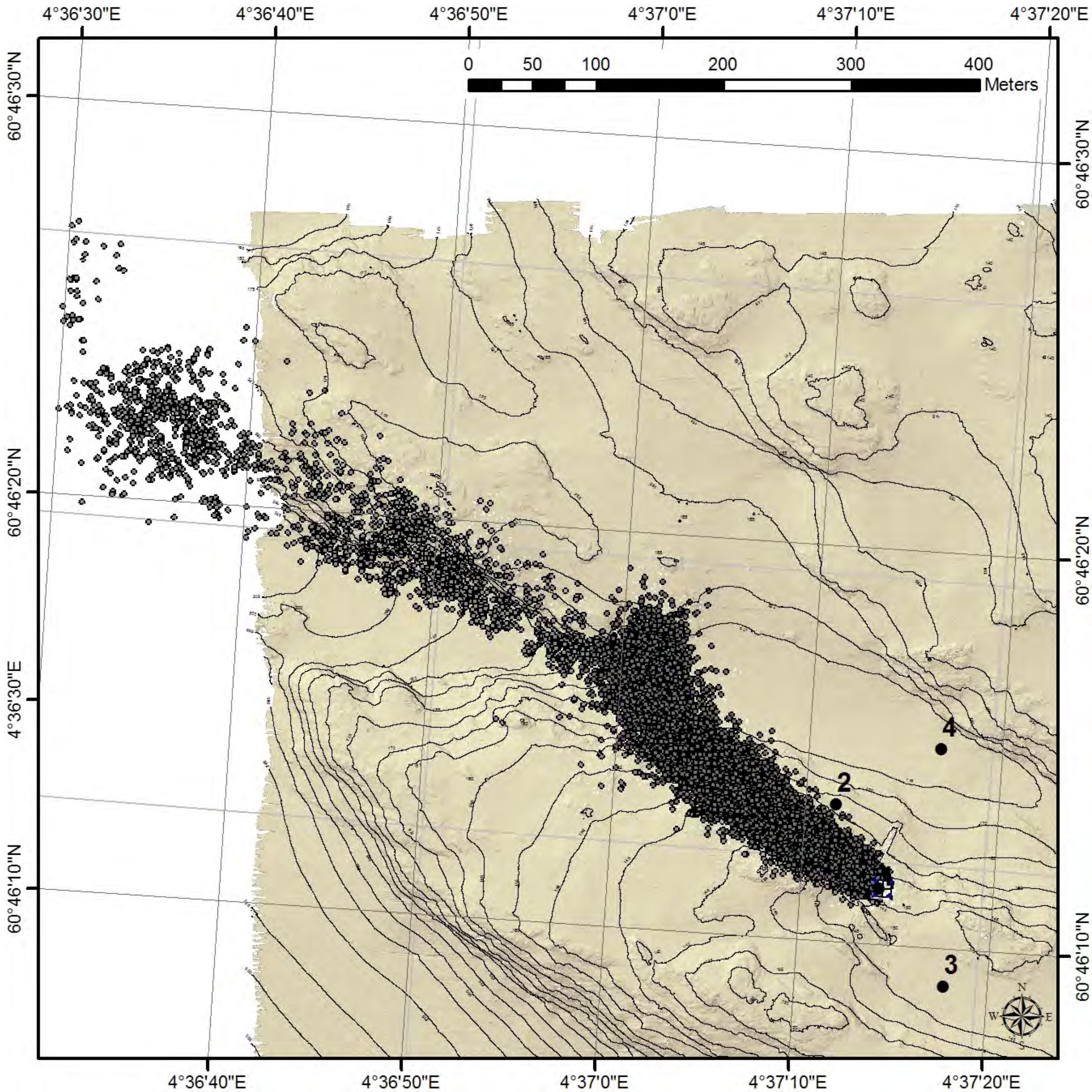

Plate 2b. Particle bottom deposit at hour 12 for a clamshell release at point 1, SRR = 127.3 ton/hr, and 50% currents.

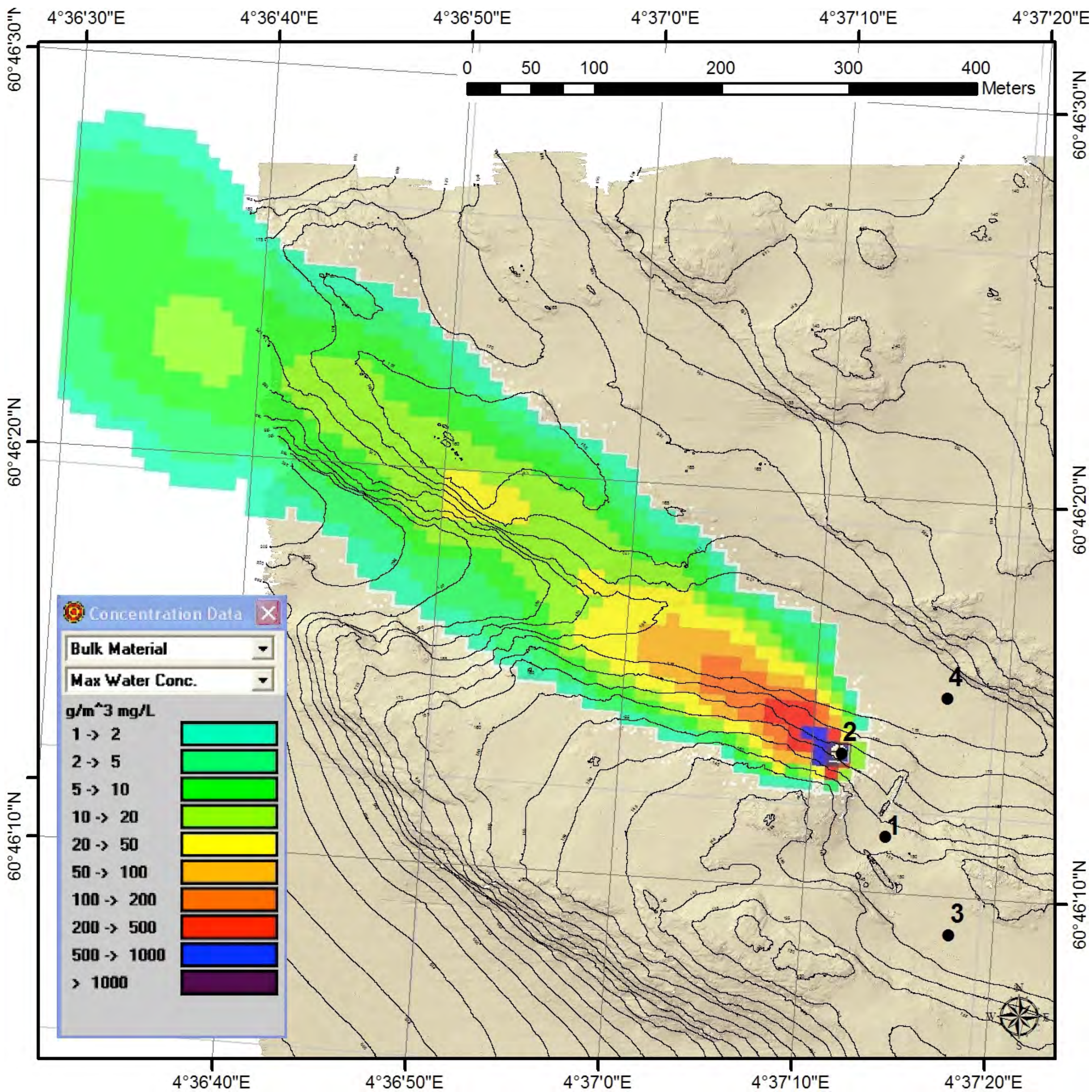

Plate 3. Maximum water column concentration at hour 8 for a near-bottom release at point 2, SRR = 637 ton/hr, and 50% currents.

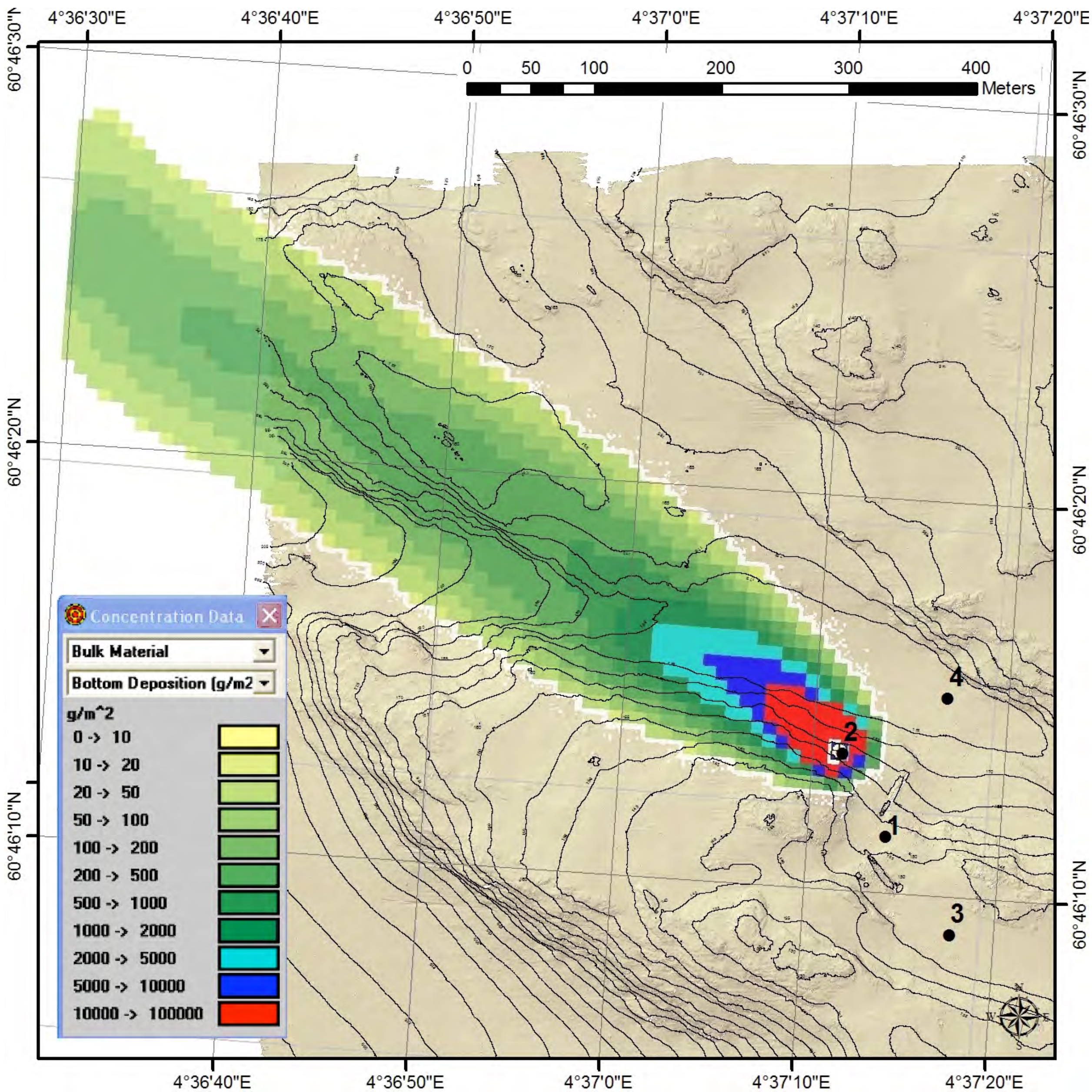

Plate 4. Bottom deposit at hour 12 for a near-bottom release at point 2, SRR = 637 ton/hr, and 50%currents.

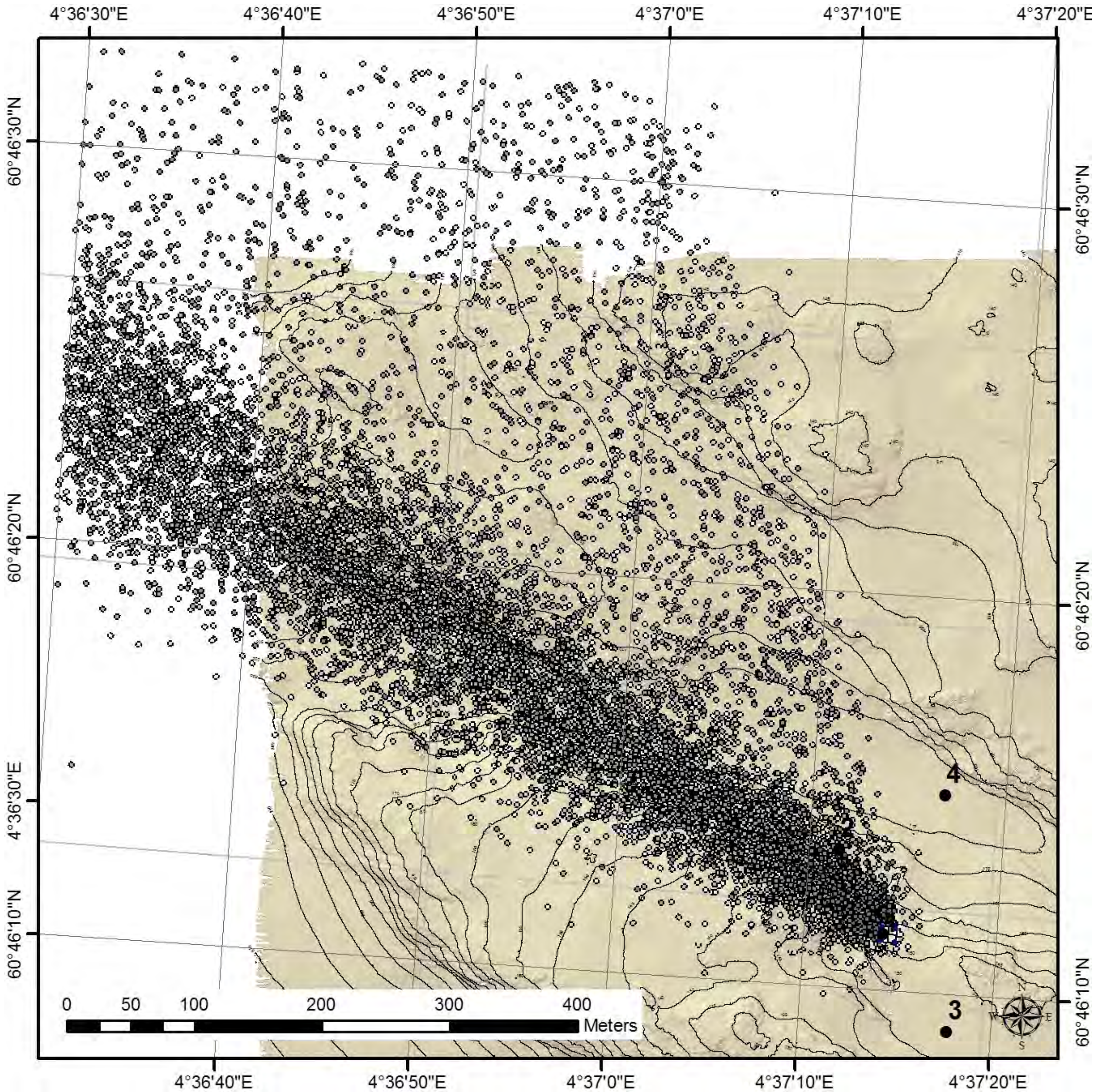

Plate 5. Suspended particles at hour 8 of a water-column release at point 1 for SRR = 64 tons/hr and 16% currents.

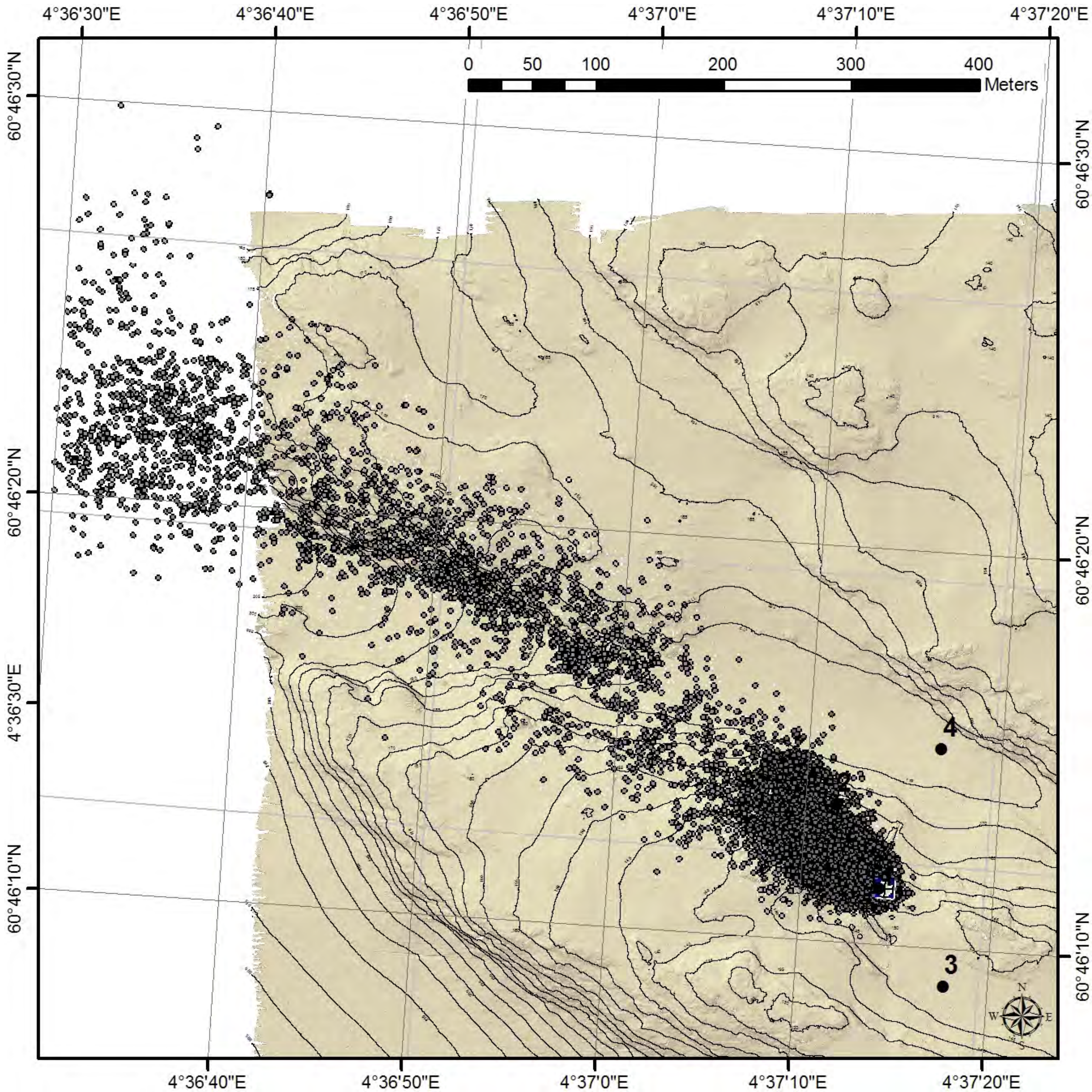

Plate 6a. Deposited particle field at hour 24 for water-column release at point 1 and SRR = 64 tons/hr and 16 % currents.

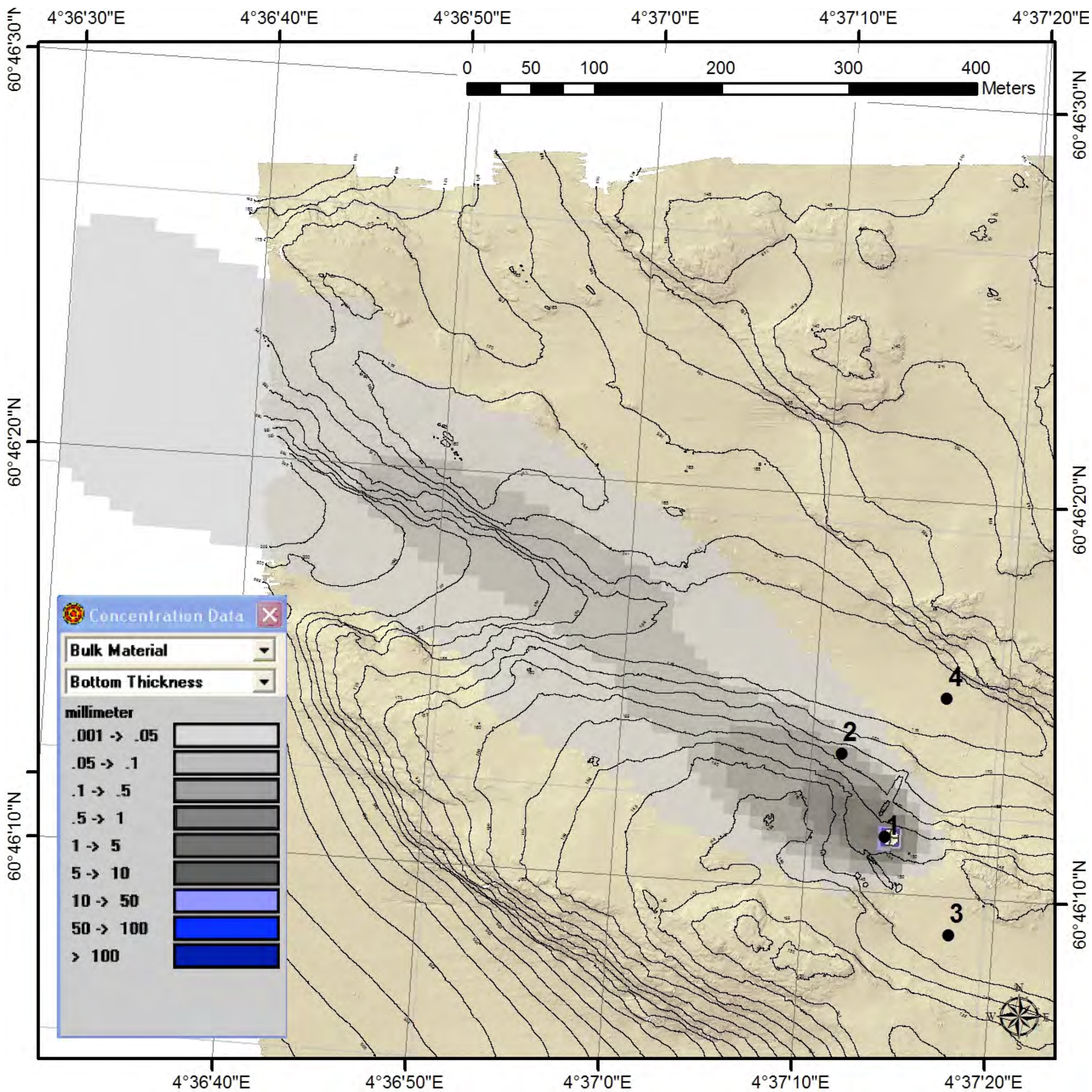

Figure 6b. Deposit thickness at hour 24 for water-column release at point 1 and SRR = 64 tons/hr and 16 % currents.

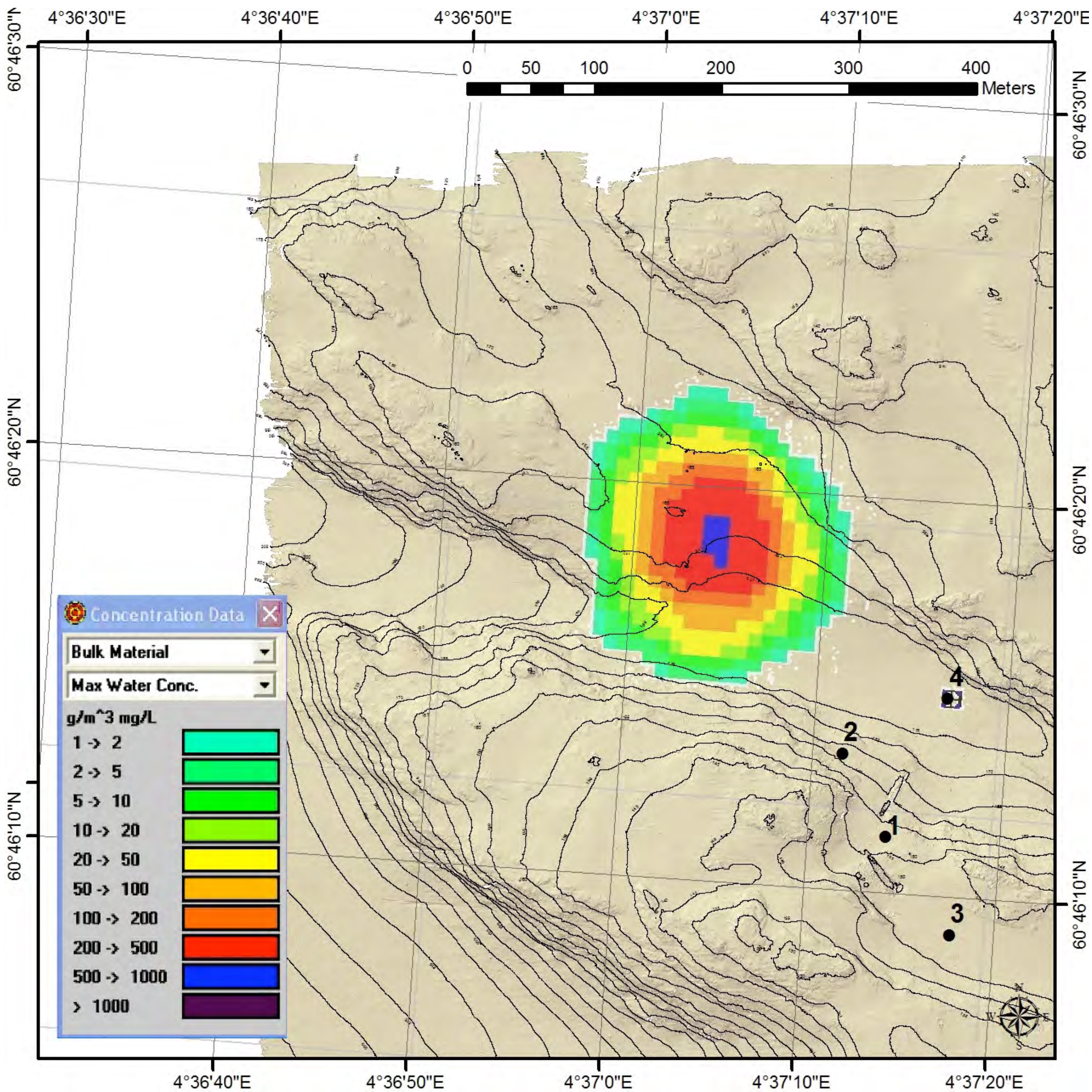

Figure 7. Suspended sediment 1 hr after the beginning of a sediment slide with 0.1 fractional resuspension and 50 % currents (note displacement of cloud from release point 4).

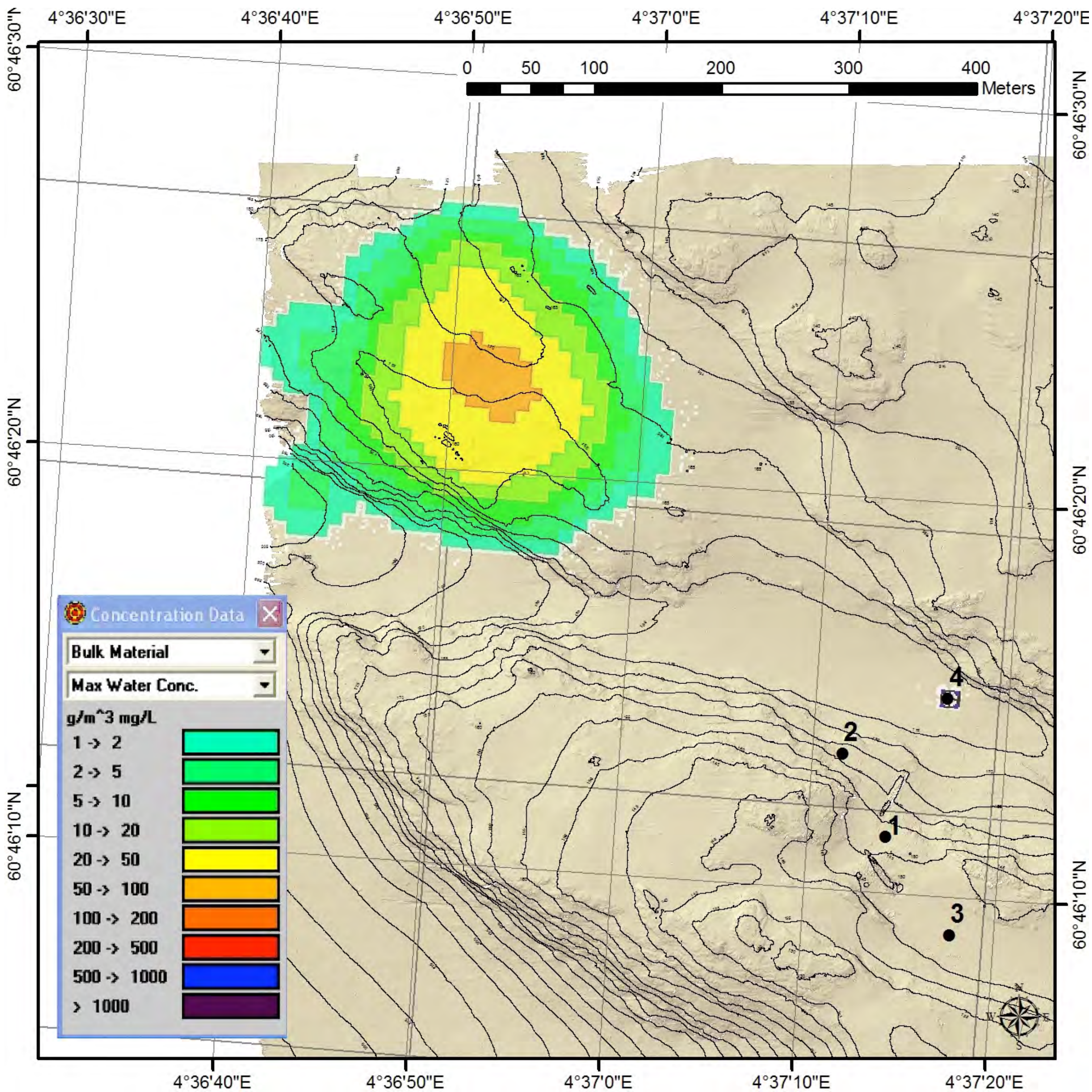

Figure 8. Suspended sediment 2 hr after the beginning of a sediment slide with 0.1 fractional resuspension and 50 % currents (note displacement of cloud from release point 4).

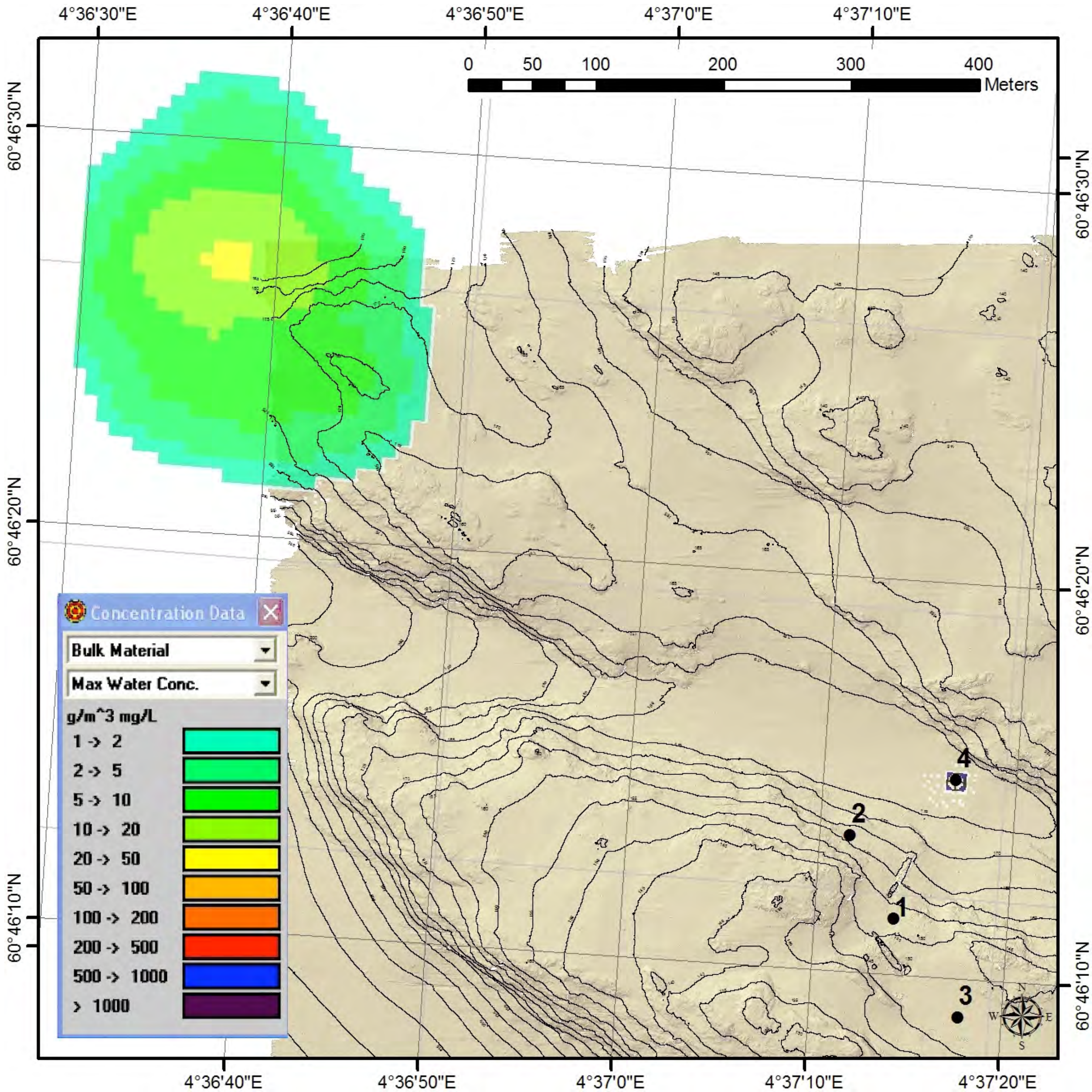

Figure 9. Suspended sediment 3 hr after the beginning of a sediment slide with 0.1 fractional resuspension and 50 % currents (note displacement of cloud from release point 4).

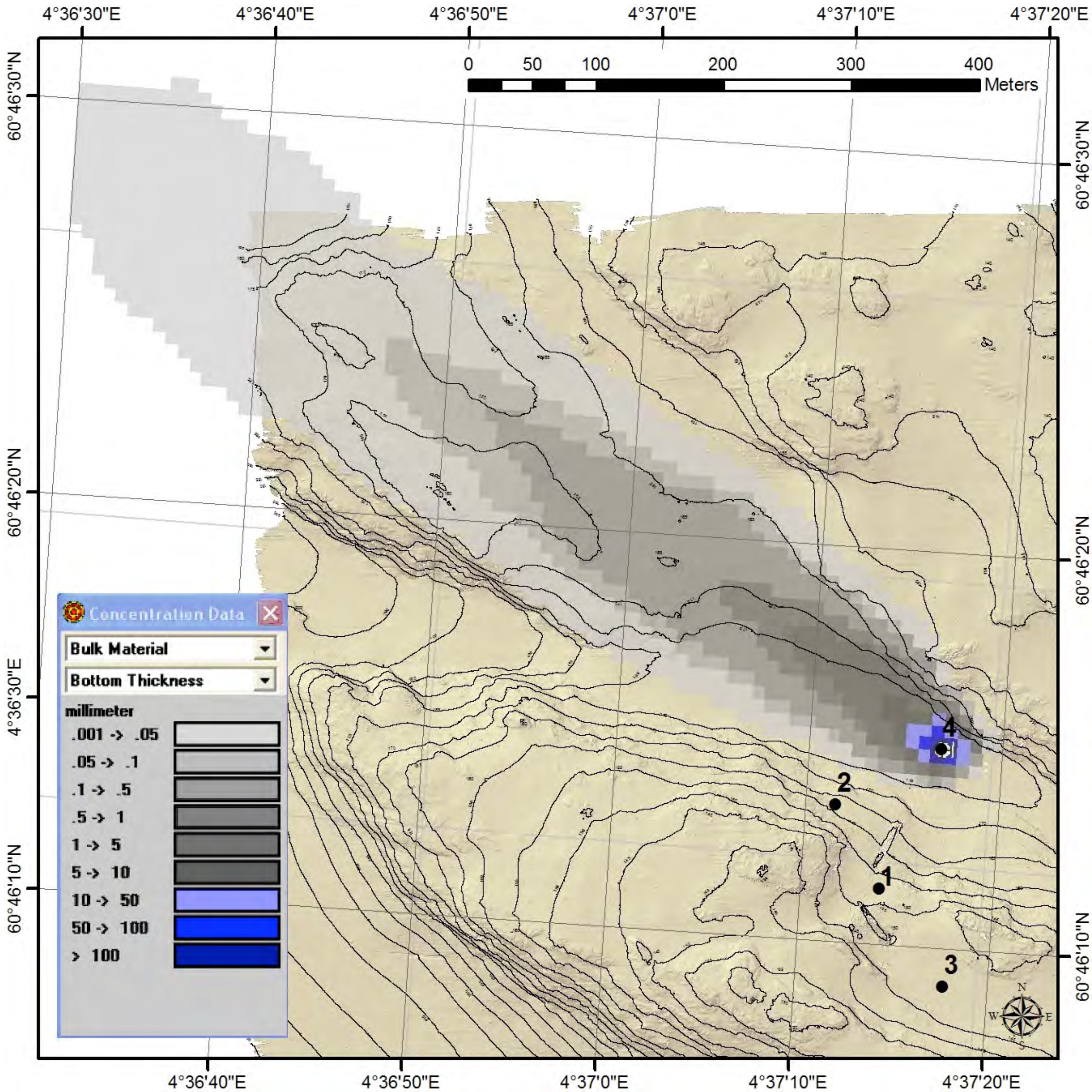

Figure 10a. Deposited sediment thickness 12 hr after the beginning of a sediment slide with 0.1 fractional resuspension and 50 % currents.

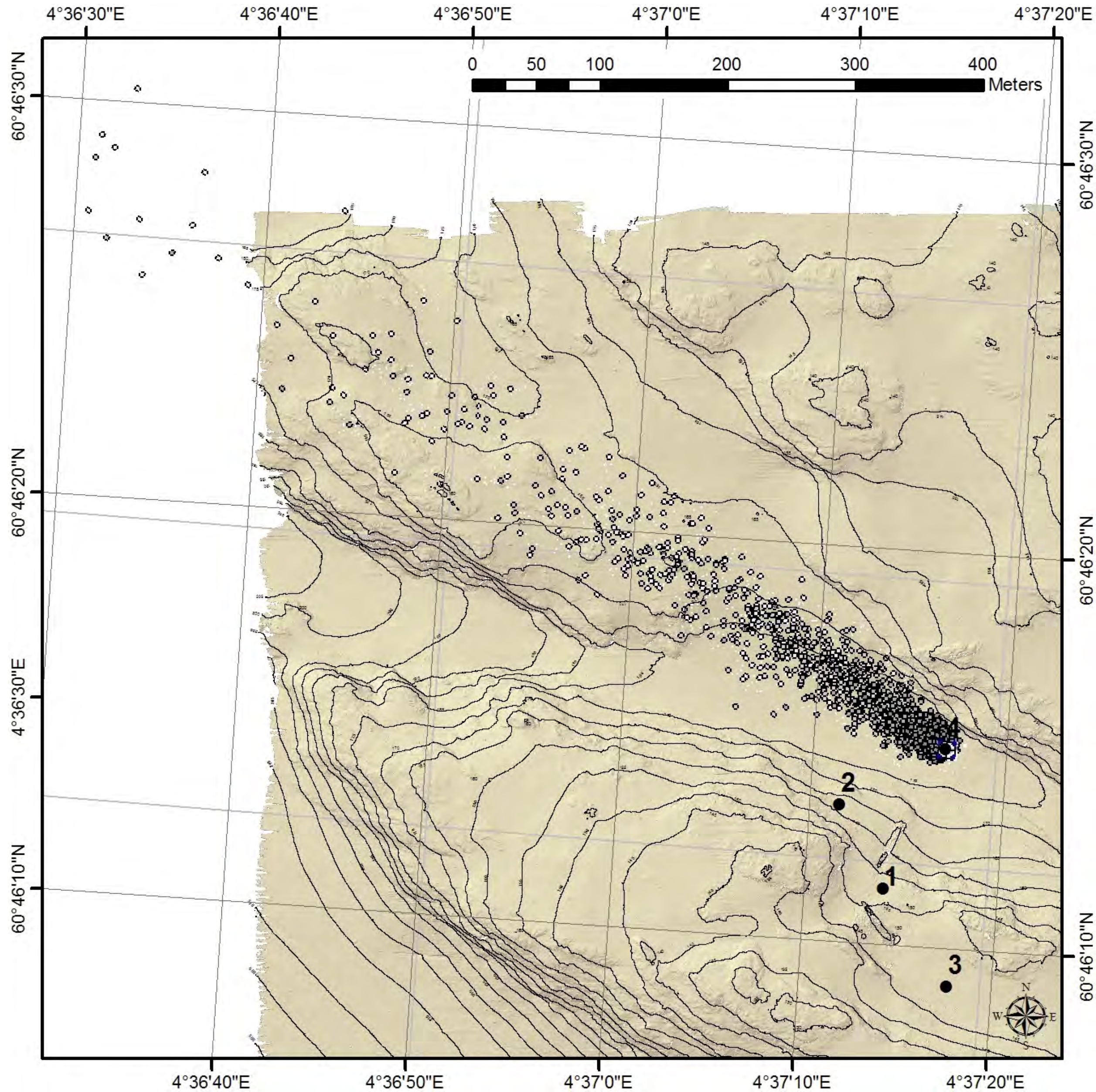

Plate 10b. Bottom deposition particle pattern resulting from a sediment slide (release point 4) with 0.1 fractional resuspension and 50% currents (where lighter particles are finer).

Technical Report

Kystverket Norwegian Coastal Administration

Salvage of U-864 - Supplementary studies - Disposal

Report No. 23916-6

Revision No. 01

Det Norske Veritas

DET NORSKE VERITAS

TECHNICAL REPORT

DET NORSKE VERITAS AS

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Approved by: Carl Erik Høy-Petersen, Senior Consultant	Organisational unit: DNV Industry
Client: Kystverket (Norwegian Coastal Administration)	Client ref.: Hans Petter Mortensholm

Summary:

In September 2007 The Norwegian Costal Administration (NCA) awarded Det Norske Veritas (DNV) the contract to further investigate different alternatives for the salvaging of the mercury, cargo and the wreck of the sunken German WWII submarine U-864. This report deals with supplementary study number 6: “Disposal”.

The task of the study is to investigate the environmental, safety and health consequences from taking up mercury and mercury-contaminated sediments. Further the possible storage locations and costs for the disposal of hazardous waste are included in the study. Finally the study has looked at future demands and legislations and the future market for recycled/disposal of mercury/mercury waste in European Union (EU).

DNV’s main conclusion is: Disposal cost (handling of mercury and other material) is estimated to be in the range of 11-39 MNOK depending on the disposal solution. At the moment it is uncertain how the final disposal of the mercury from U-864 will be due to more restrictive EU and Norwegian legislation for mercury. Other material can be recycled, treated and/or sent to an approved disposal facility

Report No.:	Subject Group:	
Report title: Salvage of U-864 - Supplementary studies - Disposal		
Work carried out by: Jens Laugesen, Ph.D; Thomas Møskeland, Cand.scient; Maria Persson, Cand.scient; Anne Brautaset, Cand.scient; Terje Kirkeng, Cand.scient (NOAH)		
Work verified by: Odd Andersen		
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TECHNICAL REPORT

The German submarine U-864 was torpedoed by the British submarine Venturer on February 9 1945 and sunk approximately two nautical miles west of the island Fedje in Hordaland. U-864 was carrying about 67 metric tonnes of metallic mercury that implies a threat to the marine environment.

In September 2007 The Norwegian Costal Administration commissioned Det Norske Veritas to further investigate different alternatives to salvage the wreck and remove the mercury from the seabed.

1 SUMMARY

This report is *Supplementary Study No. 6: Disposal*, one of twelve supplementary studies supporting the overall report regarding U-864 (Det Norske Veritas Report No. 23916) prepared by Det Norske Veritas (DNV).

The task of the study is to investigate the environmental, safety and health consequences from taking up mercury and mercury-contaminated sediments. Further the possible storage locations and costs for the disposal of hazardous waste are included in the study. Finally the study has looked at future demands and legislations and the future market for recycling/disposal of mercury and mercury waste in European Union (EU).

DNV's overall conclusion is:

Disposal cost (handling of mercury and other material) is estimated to be in the range of 11-39 MNOK depending on the disposal solution. At the moment it is uncertain how the final disposal of the mercury from U-864 will be due to more restrictive EU and Norwegian legislation for mercury. Other material can be recycled, treated and/or sent to an approved disposal facility.

Table 1-1 Summary of the estimated amount mercury (Hg) and other material which most likely has to be disposed of from U-864

Material	Amount (metric tons)	Comment
Mercury (elemental)	67	Based on that U-864 had 1 857 mercury canisters which each contained 36 kg mercury as in the canister that was salvaged.
Hydrocarbons	442	U-864 had a fuel capacity (diesel) of 442 metric tons. It is assumed that it had almost full tank when it was hit. In addition there is lubricants and grease estimated to be a couple of hundred kilos.
Scrap metal	1 800	The submarine (type IX D2) weighed 1 616 metric tons, with some safety margin DNV has estimated the weight to be 900 metric tons for each of the two wreck parts /3/.
Batteries	100 - 140	Based on information that the batteries in submarine type VII weighed 50-70 metric tons. The type IX D2 (U-864) had the double amount of batteries.
Transformers and cables	-	No data has been available to estimate the amount. It is assumed there was insulation and transformers containing PCB and asbestos.

Material	Amount (metric tons)	Comment
Contaminated sediments outside the wreck	22 500	Based on an acceptance criteria of 0.6 mg Hg/kg sediments, NIVA estimates that 15 000 m^3 (22 500 metric tons) has to be removed.
Contaminated sediments inside the wreck	15	Assumed that 10 m^3 (15 metric tons) are inside the wreck parts. These sediments are probably significantly more contaminated than the sediments outside the wreck.
Others	-	Torpedoes with electric batteries or compressed air for propulsion will be demounted by the Norwegian EOD Command (Explosives Ordnance Disposal) and handled by them. The hull was painted; probably the paint contained red lead (Pb_3O_4).

Table 1-2 Summary of the disposal solutions and costs for mercury and other material from U-864 (Transport is not included in the disposal costs)

Material	Disposal Solution	Unit cost	Cost (range)	Comment
Mercury (elemental)	Recycling *or*	32 000 NOK/metric ton	2 - 7 mill. NOK (in best case even a surplus of 2.5 mill. NOK if it is very pure)	Estimated for 30 - 99 % pure mercury, corresponding to an amount between 220 (mercury waste) and 65 metric ton (pure mercury). If the mercury is very pure (99.999 %) it can be sold for 40 NOK/kg.
	Disposal	50 000 - 100 000 NOK/metric ton	3.5 - 20 mill. NOK	Estimated for 30 - 99 % pure mercury, corresponding to an amount between 220 (mercury waste) and 65 metric ton (pure mercury). Cost estimated for stabilising elemental mercury at NOAH (SAKAB method). (Establishment of a disposal in a deep-rock cavern for elemental mercury has in Sweden (2003) been estimated to 210 000 – 550 000 NOK/metric ton).
Hydrocarbons	Incineration	2 000 -3 000 NOK/metric ton	0.9 - 1.3 mill. NOK	Based on that only hydrocarbons are found with low heat value.
Scrap metal	Disposal	500 – 1 500 NOK/metric ton	1 - 3 mill. NOK	The alternative to disposal is pre-treatment such as sandblasting, acid cleaning and recycling (reuse of the steel). Cost in the range of 1 500 – 3 000 NOK/metric ton. Added value for recycling is in the range of 500 - 1 000 NOK/metric ton.
Batteries	Recycling	0 – 500 NOK/metric ton	0 - 0.7 mill. NOK	If the batteries can not be recycled they can be delivered as hazardous waste with a cost in the range of 500 - 1 500 NOK/metric ton.
Transformers and cables	Disposal	1 000 – 2 000 NOK/metric ton	-	No data has been available on amounts.
Contaminated sediments out-side the wreck	Disposal	300 – 600 NOK/metric ton	7 - 14 mill. NOK	Stabilisation prior to disposal. Assuming that dewatering is not necessary.

Material	Disposal Solution	Unit cost	Cost (range)	Comment
Contaminated sediments inside the wreck	Disposal	1 000 - 2 000 NOK/metric ton	<0.1 mill. NOK	Stabilisation prior to disposal is more expensive due to higher mercury content inside the wreck. Average mercury content is assumed to be less than 10 %. If the level of contaminations should be in the range of 10% or more, thermal treatment is probably the only feasible solution (5 000 – 10 000 NOK/metric ton).
Others	-	-	-	Other contaminated waste has to be sent to an approved disposal facility for classification and final treatment/disposal.
		Sum	**11 - 39 MNOK**	

The market for buying and selling mercury will probably be decreasing due to more restrictive EU legislation. The most probable scenario is that both the demand and supply of mercury in the EU will be reduced gradually. The chlor-alkali industry which is the largest consumer and supplier of mercury is gradually phasing out mercury, but this is expected to take many years, probably at least until 2020. However from 2011 they will have to bring the surplus mercury to a safe disposal if the EU proposal comes into force. This will reduce the mercury supply because they can no longer recycle the mercury.

At the moment it does not look as there are any EU directives which will ban an export of the U-864 mercury inside the EU, provided that the Norwegian authorities will allow such an export. In Norway has elemental mercury until very recently been exported for recycling. The amendment to the Norwegian Product Regulation (Produktforskriften) which came into force 1st of January 2008 forbids the export of mercury in products. At the moment it is very uncertain if elemental mercury will be allowed for export from Norway, it depends on if the authorities will regard the elemental mercury as a product or not.

Depending on how EU defines a “deep water formation” as a permanent storage, it could cause problems finding a suitable location for disposal in Norway. The problem consists in that most storage locations in rock are relatively shallow (<100 m) but may still have stable physical and chemical conditions. The waste industry is working on new technologies for treatment (stabilising) mercury which could simplify a final disposal in Norway.

Other material (hydrocarbons, scrap metal, batteries etc.) can be recycled, treated and/or sent to an approved disposal facility

The rest of *Supplementary Study No. 6: Disposal* details the arguments behind the conclusions.

Den tyske ubåten U-864 ble torpedert av den britiske ubåten Venturer den 9. februar 1945 og sank omtrent to nautiske mil vest for øya Fedje i Hordaland. U-864 var lastet med omtrent 67 tonn med metallisk kvikksølv som utgjør en fare for det marine miljøet.

I september 2007 tildelte Kystverket Det Norske Veritas oppdraget med å nærmere utrede ulike alternativer for heving av vrak og fjerning av kvikksølv fra havbunnen.

2 SAMMENDRAG

Denne rapporten er *Tilleggsutredning nr. 6: Avhending*, en av tolv tilleggsutredninger som understøtter hovedrapporten vedrørende U-864 (Det Norske Veritas Report No. 23916) utarbeidet av Det Norske Veritas (DNV).

Oppgaven for utredningen er å undersøke konsekvenser for miljø, sikkerhet og helse ved å ta opp kvikksølv og kvikksølvforurensede sedimenter. Videre inngår mulige lagringssteder og kostnader for deponering av det farlige avfallet i utredningen. Til slutt har utredningen sett på fremtidige krav og lovgivning og det fremtidige markedet for gjenvinning/avhending av kvikksølv og kvikksølvavfall i den Europeiska Union (EU).

DNV sin overordnede konklusjon er:

Avhendingskostnader (håndtering av kvikksølv og andre materialer) er estimert å være i størrelsesorden 11-39 MNOK avhengig av avhendingsløsning. På det nåværende tidspunkt et det usikkert hvordan endelig avhending av kvikksølvet fra U-864 kan skje grunnet mer restriktiv lovgiving i EU og Norge knyttet til kvikksølv. Annet avfall kan gjenvinnes, behandles og/eller sendes til at godkjent deponi.

Tabell 2-1 Oppsummering av estimert mengde av kvikksølv (Hg) og andre materialer som mest sannsynlig må avhendes fra U-864

Materiale	Mengde (tonn)	Kommentar
Kvikksølv (elementær)	67	Basert på at U-864 hadde 1 857 kvikksølvbeholdere og at hver beholder inneholdt 36 kg kvikksølv, slik den beholderen gjorde som ble berget.
Hydrokarboner	442	U-864 hadde til sammen tanker for 442 tonn diesel. Det er antatt at den hadde nesten full tank når den ble truffet. I tillegg er det fett og smøreoljer, estimert til et par hundre kilo.
Metallskrap	1 800	Ubåten (type IX D2) veide 1 616 tonn, med litt sikkerhetsmargin har DNV estimert vekten til 900 tonn for hver av de to vrakdelene /3/.
Batterier	100 - 140	Basert på informasjon at batteriene i en ubåt av type VII veide 50 - 70 tonn. Type IX D2 (U-864) hadde det doble antallet batterier.
Transformatorer og kabler	-	Ingen data er funnet for å kunne estimere mengde. Det antas at det fantes isolasjon og transformatorer som inneholdt PCB og asbest.

Materiale	Mengde (tonn)	Kommentar
Forurensede sedimenter utenfor vraket	22 500	Basert på akseptkriteriet 0.6 mg Hg/kg sediment, estimerer NIVA at 15 000 m^3 (22 500 tonn) må fjernes.
Forurensede sedimenter innenfor vraket	15	Antatt at 10 m^3 (15 tonn) ligger inne i vrakdelene. Disse sedimentene er sannsynligvis betydelig mer forurenset enn sedimentene utenfor.
Annet	-	Torpedoer med batterier eller trykkluft som drivkraft vil bli demontert og håndtert av Forsvarets eksplosivryddingskommando (EOD). Skroget var antagelig malt med farge som inneholdt blymønje (Pb_3O_4)

Tabell 2-2 Oppsummering av avhendingsløsninger og kostnader for kvikksølv og andre materialer fra U-864 (transportkostnader er ikke inkludert i avhendingskostnadene)

Materiale	Avhendings-løsning	Enhets-kostnad	Kostnad (variasjon)	Kommentar
Materiale Kvikksølv (elementær)	Gjenvinning *eller*	32 000 NOK/tonn	2 - 7 mill. NOK (i beste fall et overskudd på 2.5 mill. NOK hvis den er meget ren)	Estimert for kvikksølv med 30 - 99 % renhetsgrad, tilsvarende 220 (avfall med kvikksølv) til 65 tonn (rent kvikksølv). Hvis kvikksølvet er meget rent (99.999 %) kan det selges for 40 NOK/kg.
	Deponering	50 000 - 100 000 NOK/tonn	3.5 - 20 mill. NOK	Estimert for kvikksølv med 30 - 99 % renhetsgrad, tilsvarende 220 (avfall med kvikksølv) til 65 tonn (rent kvikksølv). Kostnaden er estimert for stabilisering av elementært kvikksølv av NOAH (SAKAB-metoden). (Etablering av et deponi for elementært kvikksølv i et dypt bergrom er i Sverige (2003) esti-mert til 210 000 - 550 000 NOK/tonn).
Hydrokarboner	Forbrenning	2 000 - 3 000 NOK/tonn	0.9 - 1.3 mill. NOK	Basert på at en bare finner hydrokarboner med lav brennverdi.
Metallskrap	Deponering	500 – 1 500 NOK/tonn	1 - 3 mill. NOK	Alternativet til deponering er en forbehandling som for eksempel sandblåsing, syrevask og gjenvinning (gjenbruk av stål). Kostnad er i området 1 500 – 3 000 NOK/tonn. Gjenbruksverdien av stål er i størrelsesorden 500 - 1 000 NOK/tonn.
Batterier	Gjenvinning	0 – 500 NOK/tonn	0 - 0.7 mill. NOK	Hvis batteriene ikke kan gjenvinnes kan de leveres som farlig avfall med en kostnad som er i størrelsesorden 500 - 1 500 NOK/tonn.
Transformatorer og kabler	Deponering	1 000 – 2 000 NOK/tonn	-	Ingen data er funnet for å kunne estimere mengde.
Forurensede sedimenter utenfor vraket	Deponering	300 – 600 NOK/tonn	7 - 14 mill. NOK	Stabilisering utføres før deponering. Antatt at avvanning ikke er nødvendig.

Materiale	Avhendings-løsning	Enhets-kostnad	Kostnad (variasjon)	Kommentar
Forurensede sedimenter inne i vraket	Deponering	1 000 - 2 000 NOK/tonn	<0.1 mill. NOK	Stabilisering (nødvendig) i forkant av deponering er mer kostbar på grunn av høyere kvikksølvinnhold inne i vraket. Gjennomsnittlig kvikksølvinnhold er antatt å være mindre enn 10 %. Hvis forurensningsinnholdet er i størrelses-orden 10 % eller mer, er termisk behand-ling sannsynligvis den eneste mulige løsningen (5 000 – 10 000 NOK/tonn).
Annet	-	-	-	Annet forurenset avfall må sendes til godkjent mottak for klassifisering og endelig behandling/deponering.
		Sum	**11 - 39 mill. NOK**	

Markedet for kjøp og salg av kvikksølv vil sannsynligvis minke på grunn av at EUs lovgivning blir mer restriktiv. Det mest sannsynlige scenarioet er at både tilbud og etterspørsel på kvikksølv i EU vil bli gradvis redusert. Kloralkali-industrien som er den største forbrukeren og tilbyderen av kvikksølv er ved å gradvis fase ut kvikksølv, men utfasingen forventes å ta mange år, antagelig i hvert fall minst til 2020. Fra 2011 må de imidlertid levere overskudd av kvikksølv til en sikker lagringsløsning hvis EUs forslag trår i kraft. Dette vil redusere tilbudet av kvikksølv fordi kvikksølv ikke lenger kan gjenvinnes.

For tiden ser det ikke ut til at det vil være noen EU-direktiver som vil forby en eksport av kvikksølvet fra U-864 innenfor EU, såfremt norske myndigheter vil tillate en slik eksport. I Norge har elementært kvikksølv inntil svært nylig blitt eksportert for gjenvinning. Endringen i den norske produktforskriften som trådte i kraft den 1. januar 2008 forbyr eksport av kvikksølv i produkter. For øyeblikket er det meget usikkert om elementært kvikksølv vil bli tillatt eksportert fra Norge, dette er avhengig av om myndighetene ser på elementært kvikksølv som et produkt eller ikke.

Avhengig av hvordan EU definerer en "deep water formation" som en permanent lagring, kan det gi problemer å finne en egnet lokalitet for lagring i Norge. Problemet består i at de fleste lagringssteder i fjell er relativt grunne (<100 m) men kan fortsatt ha stabile fysiske og kjemiske forhold. Avfallsindustrien arbeider med nye teknologier for behandling (stabilisering) av kvikksølv som kan forenkle en endelig lagring i Norge.

Andre materialer (hydrokarboner, skrapmetall, batterier etc.) avfall kan gjenvinnes, behandles og/eller sendes til at godkjent deponi.

Resten av *Tilleggsutredning nr. 6: Avhending* utdyper argumentene bak konklusjonene.

3 INTRODUCTION

3.1 Background

The German submarine U-864 was sunk by the British submarine Venturer on 9 February 1945, approximately 2 nautical miles west of the island Fedje in Hordaland (Figure 3-1). The submarine was on its way from Germany via Norway to Japan with war material and according to historical documents; U-864 was carrying about 67 metric ton of metallic (liquid) mercury, stored in steel canisters in the keel. The U-864, which was broken into two main parts as a result of the torpedo hit, was found at 150-175 m depth by the Royal Norwegian Navy in March 2003. The Norwegian Costal Administration (NCA) has, on behalf of the Ministry of Fisheries and Coastal Affairs, been performing several studies on how the risk that the mercury load constitutes to the environment can be handled. In December 2006 NCA delivered a report to the Ministry where they recommended that the wreck of the submarine should be encapsulated and that the surrounding mercury-contaminated sediments should be capped. In April 2007 the Ministry of Fisheries and Coastal Affairs decided to further investigate the salvaging alternative before a final decision is taken about the mercury load.

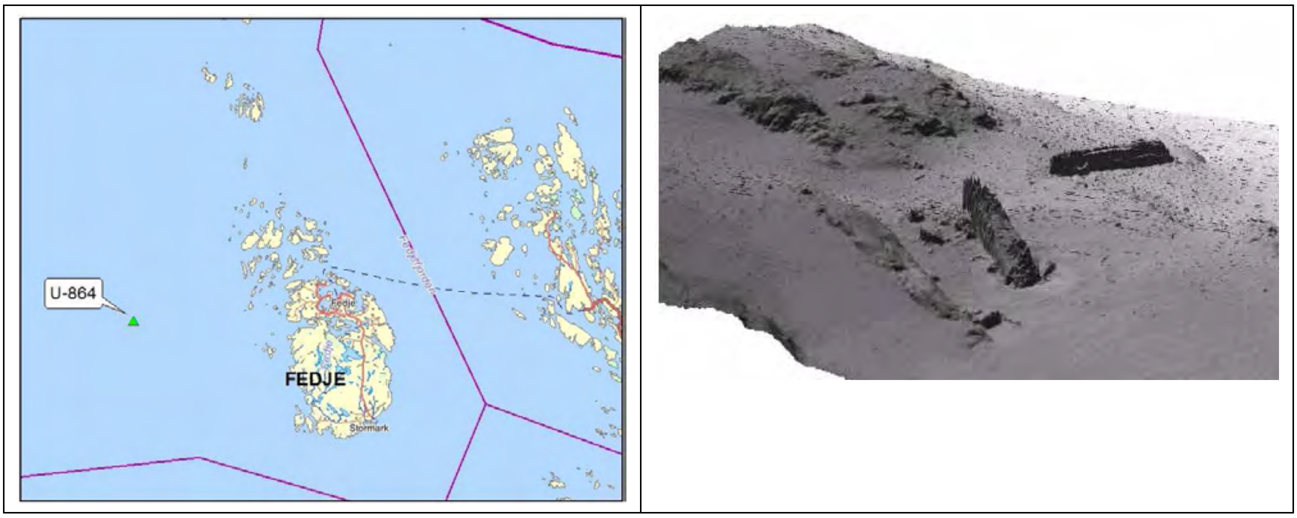

Figure 3-1 Location (left) and a sonar picture of the wreck of U-864 on seabed (right) (from Geoconsult).

3.2 DNV's task

In September 2007 NCA commissioned Det Norske Veritas (DNV) the contract to further investigate the salvaging alternative. The contract includes:

- DNV shall support NCA in announcing a tender competition for innovators which have suggestions for an environmentally safe/acceptable salvage concept or technology. Selected innovators will receive a remuneration to improve and specify their salvage concept or technology.

- DNV shall support NCA in announcing a tender competition for salvage contractors to perform an environmentally justifiable salvage of U-864.
- DNV shall evaluate the suggested salvage methods and identify the preferred salvage method.
- The preferred salvage method shall be compared with the suggested encapsulation/capping method from 2006. (DNV shall give a recommendation of which measure that should be taken and state the reason for this recommendation.)
- DNV shall perform twelve supplementary studies which will serve as a support when the decision is taken about which measure that should be chosen for removing the environmental threat related to U-864. The twelve studies are:

1. *Corrosion*. Probability and scenarios for corrosion on steel canisters and the hull of the submarine.
2. *Explosives.* Probability and consequences of an explosion during salvaging from explosives or compressed air tanks.
3. *Metal detector*. The possibilities and limitations of using metal detectors for finding mercury canisters.
4. *The mid ship section*. Study the possibility that the mid section has drifted away.
5. *Dredging*. Study how the mercury-contaminated seabed can be removed around the wreck with a minimum of spreading and turbidity.
6. *Disposal*. Consequences for the environment and the health and safety of personnel if mercury and mercury-contaminated sediments are taken up and disposed of.
7. *Cargo.* Gather the historical information about the cargo in U-864. Assess the location and content of the cargo.
8. *Relocation and safeguarding.* Analyse which routes that can be used when mercury canisters are relocated to a sheltered location.
9. *Monitoring.* The effects of the measures that are taken have to be documented over time. An initial programme shall be prepared for monitoring the contamination before, during and after salvaging.
10. *Risk related to leakage.* Study the consequences if mercury is unintentionally leaked and spreading during a salvage or relocation of U-864.
11. *Assessment of future spreading of mercury for the capping alternative*. The consequences of spreading of mercury if the area is capped in an eternal perspective.
12. *Use of divers.* Study the risks related to use of divers during the salvage operation in a safety, health and environmental aspect and compare with use of ROV.

3.3 Scope of this report

This is *Supplementary Study No. 6: Disposal.* The task of the study is to investigate the environmental, safety and health consequences from taking up mercury and mercury-contaminated sediments. Further the possible storage locations and costs for the disposal of hazardous waste are included in the study.

So far a total of 25 m^3 of mercury contaminated sediments have been dredged around the stern section of the wreck by use of a Scanmudring machine. Purpose built containers were used for environmental safe recovery of the sediments to the deck onboard the DOF Subsea vessel Geoholm. Only 2 mercury canisters have been recovered and both thoroughly inspected. The mercury content, contaminated consumables from the vessels used in 2005 and 2006 and the containerised sediments have been shipped to a hazardous waste storage facility site at Langøya.

Disposal of contaminated material is dealt with in DNVs risk assessment report from 2006 where disposal of the mercury is assessed to be the largest factor of uncertainty for the salvage alternative. The costs for disposal were assumed to be very uncertain and could be very large.

This report investigates how wreck parts, mercury canisters and contaminated sediments can be disposed of. The costs and benefits by separating the most contaminated material before disposal are studied to evaluate if a separation can give a major cost reduction for the disposal.

The solutions and costs for disposal of the different waste components are calculated and authorized companies which can receive the waste are indicated. In addition the safety, health and environmental consequences are given.

Assessments of the amount of wreck parts and mercury canisters are based on existing estimates and data of the submarine and cargo. Amount of contaminated sediments (volume) is based on existing estimates of the contaminated area and the thickness of the mercury contamination.

In addition, possible new legislation and regulations which are expected to come from the authorities with respect to handling and disposal are evaluated.

The structure of this report is:

- Estimate of amount of material which has to be disposed of (chapter 4)
- Disposal solutions (chapter 5)
- Separation technologies that could give a major cost reduction for the disposal/treatment (chapter 6)
- Future demands (chapter 7)

4 ESTIMATE OF AMOUNT OF MATERIAL WHICH HAS TO BE DISPOSED OF

In this chapter the estimated type and amount (volume/weight) of wreck parts, mercury canisters (and free mercury) and contaminated sediments which have to be disposed of is identified.

4.1 Mercury

Available information reports that there were 1857 canisters filled with mercury on board. The canisters found have been made of steel or cast iron. A canister that was salvaged and opened in 2005 contained 36 kg (2.7 litres) metallic mercury /2/. Assuming all canisters contained the same amount; there was approximately 67 metric tons of mercury on board.

In addition some of the instruments on board like thermometers, barometers etc. most likely contained mercury. The amount of mercury in the instruments has not been investigated; it can be assumed that it was a relatively low amount and less than 1 kg.

4.2 Hydrocarbons

U-864 had a fuel capacity of 442 metric tons. When it was hit by the torpedo it had probable almost full tank since it recently had left Bergen. Some diesel tanks were probably destroyed when it was hit by the torpedo; HMS Venturer reported they saw oil on the water surface after U-864 had sunk.

Lubricants and grease was very likely stored in tanks outside the hull, amounts are not quantified. Estimated amount is in the order of a couple of hundred kilos.

4.3 Scrap metal

The submarine (type IX D2) weighed 1616 metric tons. It is divided in two parts and with some safety margin DNV has estimated the weight to be about 900 metric tons for each of the two wreck parts /3/.

4.4 Batteries

Submarines of the type IX D2 contained 248 lead-acid battery cells type 44 MAL 740 (22 600 Ah) for propulsion under water. All batteries for submarines were produced at AFA Battery Works in Hagen, Germany, the sole manufacturer of special batteries for the submarines of the Kriegsmarine between 1905 and 1945 /4/.

The weight of the batteries on U-864 (for propulsion) is probably in the range of 100-140 metric tons (ref. Fritz Köhl/Axel Niestle – Uboottyp VII; the U-boat type VII had 50 - 70 metric tons of batteries which is half the amount of batteries compared to a type IX D2).

In addition the torpedoes on the IX D2 submarines were equipped with batteries or compressed air for propulsion (http://uboat.net/technical/torpedoes.htm), see also chapter 4.7.

4.5 Transformers and cables

It is assumed that there was insulation and transformers containing PCB and asbestos on U-864. No data has been available for estimating the amount.

4.6 Contaminated sediments

There is 30 000 m^2 seafloor which is contaminated, NIVA estimates that at least 0.5 m has to be removed, equivalent to 15 000 m^3 (approximately 22 500 metric tons) if the acceptance criteria is set to 0.6 mg Hg[1]/kg sediment.

The amount of sediments inside the wreck parts is assumed to be 10 m^3 (approximately 15 metric tons). These sediments are assumed to be significantly more contaminated with mercury than the sediments on the seafloor outside the wreck parts.

4.7 Others

Torpedoes (electric batteries or compressed air for propulsion) will be demounted by the Norwegian EOD Command (Explosives Ordnance Disposal) and handled by them.

The hull was painted; probably the paint contained red lead. In past red lead (lead tetraoxide, Pb_3O_4) was used in combination with linseed oil as a thick, long-protecting anticorrosive paint. Due to its toxicity its use is now being very limited.

[1] Hg = Mercury

5 DISPOSAL SOLUTIONS

In this chapter disposal solutions for the different waste components are presented. When companies which can receive the waste components are known they are presented as well as disposal/treatment costs and information on existing permits. Safety, health and environment (SHE) consequences are discussed and if the solution has any special benefits.

The demolition of the U-864 is not discussed in this chapter. The costs which are indicated in this chapter do not include the transport to the disposal/treatment facilities.

5.1 Mercury

5.1.1 Background information on mercury

Mercury is a silvery metal, which is liquid at or near room temperature and pressure. The melting point of mercury is -38.8 °C and the boiling point is 356.7 °C. The density is 13.5 g/cm^3.

Mercury occurs in deposits throughout the world and it is harmless in an insoluble form, such as mercury sulphide (cinnabar), but it is poisonous in soluble forms such as mercuric chloride or methyl mercury. Mercury is mostly obtained by reduction from the mineral cinnabar.

Mercury has been used widely in many applications (thermometers, barometers etc.), though concerns about the element's toxicity have led to that mercury is being phased out.

Mercury is still used in some chloride-alkali industries (not in Norway), luminous tubes, low energy light bulbs, amalgam in dentistry (being gradually phased-out in favour of other dental filling materials) and in different scientific and research applications.

In 2005, China was the top producer of mercury with almost two-thirds global share followed by Kyrgyzstan. The global demand for mercury is about 3 400 metric tons per year and the European Union (EU) accounted for 440 metric tons of that in 2005. The mercury deposits of Almadén in Spain account for the largest quantity of liquid mercury metal produced in the world. Approximately 250 000 metric tons of mercury has been produced there in the past 2 000 years. In 2000, the mines closed due to the fall of the price of mercury in the international market. However, Almadén still has one of the world's biggest reservoirs of mercury. The state owned company Mayasa owns the Almadén mines and does still export about 1 000 metric tons of mercury per year that it buys from European companies which are turning away from the use of mercury. In October 2007 Mayasa started a 4.2 million Euro project to solve the problem with finding a safe storage of mercury in Europe.

In Europe the EU works towards a phasing-out of mercury. EU has suggested a ban on exports of mercury to countries outside EU from 2011.

5.1.2 Recycling Mercury

There is no known company in the Nordic countries which recycle mercury.

In Germany, Netherlands, United Kingdom and France there are companies which recycle mercury from different wastes and sell the recycled mercury.

The recycling is done by distillation of the mercury containing waste and collection of the pure mercury. Elemental mercury from canisters in U-864 would probably also be going through the distillation procedure to minimise the impurities in the mercury. To obtain a good price for the mercury it is very important that the mercury is as pure as possible.

The companies which have been contacted have policies on mercury export and none of them allows any export of mercury for gold production.

Examples of companies which recycle mercury are:

NQR Nordische Quecksilber Rückgewinnung GmbH, Lübeck, Germany

Homepage: http://www.nqr-online.de

NQR is a part of the international Remondis group (15 000 employees). NQR has a distillation recycling facility for mercury in Lübeck which normally produces about 40 metric tons Hg per year. Less than 10 % of the produced mercury is sold outside EU.

They would be interested to receive the 65-70 metric tons of mercury and they could also be willing to pay for the mercury.

GMR Gesellschaft für Metallrecycling mbH, Leipzig, Germany

Homepage: http://www.quecksilber-gmr.de

GMR was founded in 1991 and has 12 employees. GMR works worldwide and is specialised on recycling of mercury-containing waste. They have a distillation recycling facility for mercury in Leipzig and the facility can treat 500 – 1 000 metric tons of mercury containing waste per year.

GMR would be interested to receive the 65-70 metric tons of mercury, preferably at no cost because of the risk that they maybe need to place some of the mercury in a disposal facility if they can not sell all the mercury (due to possible changes in the laws/regulations for handling mercury).

BMT Begemann Milieutechniek B.V., Dordrecht, Holland

Homepage: http://www.bmt-begemann.nl

BMT was founded in 1991. BMT works worldwide and is specialised in recycling of mercury-containing waste. They have a distillation recycling facility in Delfzijl. The facility has a production capacity of 1 000 metric tons/year (permit up to 5 000 metric tons/year) and a storage capacity of 2500 pallets.

BMT are planning to open a production site in Thailand in 2008. They are ISO 9001 and ISO 14001 certified. Among their customers is Statoil.

Other companies are (not contacted);

Ophram Laboratoire, Saint Fons, France

Homepage: http://www.ophram.com

Mercury Recycling LTD

Homepage: http://www.mercuryrecycling.co.uk

Cost estimate for recycling mercury

Cost estimate for buying mercury in today's market is 10 - 12 EUR/kg for 99.999 % pure and 0.8 EUR/kg for 99 % pure. Delivering pure mercury from U-864 will not likely give more than a maximum income of 5 EUR/kg (40 NOK/kg). Delivering impure mercury will likely generate costs in the order of 4 EUR/kg (32 NOK/kg) mercury waste. Thus, 65 metric ton of mercury (99.999 % pure mercury) could generate a maximum income of approximately 2.5 million NOK. Assumed that impure mercury contains 30 - 99 % pure mercury, which means between 65 - 220 metric ton mercury contaminated waste, there will be a treatment cost of approximately 2 - 7 million NOK.

At this point it is not known what the quality is of the remaining mercury at the site. So far the recovered mercury, one canister, has been of good quality. The main uncertainty is linked to how much mercury is found within intact canisters and how much has leaked out. It is assumed that some of the mercury which has leaked out can be collected and recycled, but this will be at a relatively high cost as shown above.

5.1.3 Disposal of mercury

Disposal of elemental mercury

Today there is no disposal of elemental mercury in the EU due to that it is still much better economy to recycle and sell the mercury. The EU has started to look at the possibilities of disposal of elemental mercury to prepare for a total ban on elemental mercury. As a leading country, Sweden has introduced a ban on export of elemental mercury.

In Norway elemental mercury has until very recently been exported for recycling. The amendment to the Norwegian Product Regulation (Produktforskriften) which came into force January 1 2008 forbids the export of mercury in products /5/. At the moment it is very uncertain if elemental mercury will be allowed for export from Norway, it depends on if the authorities will regard the elemental mercury as a product or not.

Since the EU Commission announced in 2005 that it intended to phase out all mercury exports by 2011 work has been concentrated on providing safe, indefinite storage of liquid (elemental) mercury as part of a strategy against mercury pollution. In the EU, the long-term aim is to develop safe immobilisation technologies. Immobilisation is still at the research level, but in Sweden, SAKAB is working on a promising technology where elemental mercury is mixed with sulphide and over time a stable mercury-sulphide (HgS - cinnabar) is formed. So far this technology is on the labscale, but a pilot plant is planned to develop the technology. SAKAB has discussed with NOAH to establish a pilot plant in Norway, utilising the Langøya facility for safe underground storage. This stabilisation/solidification increases the volume of the material with a factor of 3 but the weight remains almost the same (sulphide is much lighter than mercury).

While immobilisation technologies are developed a temporary storage is recommended. Temporary storage could typically be in salt mines (exists today), rock caverns, e.g., preferably in deep bedrock permanent depositories in order to obtain non-oxidative conditions.

Cost estimate for disposal of elemental mercury

Due that there is no disposal of elemental mercury today, there is no experience with costs for disposal. However, the Swedish Environmental Protection Agency has published an official report (report 81-05, 2003) concerning establishment of a disposal in a deep-rock cavern for elemental mercury. The estimated cost in 2003 was 250 000 - 650 000 SEK/metric ton (210 000 - 550 000 NOK/metric ton).

Establishing a future method for stabilising elemental mercury at NOAH (production of cinnabar) is estimated to cost 50 000 - 100 000 NOK/metric ton.

A temporary solution could be storage of elemental mercury in seamless steel flasks (ref. EU type QC 801) above ground or in rock caverns. The price of such disposal could be relatively low given that the environmental authorities approve the solution. The main uncertainty regarding this option are possible future requirements related to EU regulations. This may again imply high future costs.

Disposal of mercury waste

Hazardous waste containing mercury is disposed of if it is a cheaper and more practical solution than recycling.

Today, disposal of mercury waste with up to 10 % of elemental mercury is possible in Norway. Export of mercury waste from Norway (≤ 10 % Hg) needs permission, but such a permit will almost certainly not be given due to that there are treatment solutions in Norway (ref. Basel Convention). Waste containing > 10 % Hg has probably to be exported for recycling or disposal. If waste containing very high amounts of mercury will be considered to be a product is uncertain, see “Disposal of elemental mercury” on page 16.

In the EU storage (rock caverns, salt mines etc.) or immobilisation would be the two methods for disposal of mercury waste with > 10 % Hg.

In Norway there are at least two facilities which have permits for disposal of mercury waste (≤ 10 % Hg):

NOAH AS, Langøya, Norway

NOAH is Norway’s largest disposal facility for hazardous waste. NOAH has a permit to receive a total of 622 000 metric tons of different types of waste per year, including 322 000 metric tons of inorganic hazardous waste per year. Since the year 2000, NOAH has received approximately 200 000 tons of mercury waste (≤ 10 % Hg). NOAH has developed a stabilisation method in cooperation with the University of Oslo, where mercury is absorbed to gypsum and iron hydroxide. The maximum allowed discharge of mercury to water is 0.0013 kg/day. NOAH is situated on the island Langøya and waste can be transported directly to the island by ship.

Miljøteknikk Terrateam AS, Mo i Rana, Norway

Miljøteknikk Terrateam has a large disposal facility in the rock caverns of the former steel works in Mo i Rana. Miljøteknikk Terrateam has a permit to receive 70 000 metric tons of inorganic hazardous waste per year. The waste has to be stabilised/solidified before placement in the rock cavern. Maximum allowed leaching of waste containing mercury which has been stabilised/ solidified is 0.01 mg Hg/l. The leached amount is determined by using the United States TCLP (Toxicity Characteristic Leaching Procedure) test.

There are also other possible disposal facilities in Norway:

Boliden Odda AS, Odda

Boliden Odda has large rock caverns for disposal of mainly jarosite-bearing sludge from the smelter, but also for mercury sulphide compounds. They have 14 large rock caverns and each is 75 000 m^3 – 220 000 m^3. The waste is placed in plastic drums and is then cast in concrete in the rock caverns.

There has been no inquiry to the company if they are interested to receive Mercury waste from U-864.

BIR (Bergen Interkommunale Renholdsverk), Hordaland

BIR has a disposal facility for hazardous waste in a rock cavern in Stendafjellet. Their permit would probably have to be revised to be able to receive the mercury. This is the disposal facility which is closest to the submarine U-864.

There has been no inquiry to the company if they are interested to receive Mercury waste from U-864.

Cost estimate for disposal of mercury waste

Disposal of mercury waste in Norway (allowed for waste with ≤ 10 % Hg) will need stabilisation prior to disposal. Binders for stabilisation could be gypsum, cement, sulphur and sulphides. The cost will vary dependent on mercury concentration and use of binder. Stabilisation of mercury waste is estimated to vary in cost from 400 - 1 500 NOK/metric ton.

5.1.4 Health, Safety and Environment (HSE)

When working with mercury, special precautions have to be taken. Health, safety and environment measures should include:

- information meetings with personnel at the site.
- disposable coveralls and other personal protection aids such as respiratory protective equipment, gloves and safety glasses.
- establishing a monitoring program, including regular measurement of mercury concentration in the air around different work processes.
- possible measurement of mercury in the urine of employees who have been in intense contact with mercury contaminated waste.
- establishing restricted areas where handling of mercury is ongoing .
- establishing an emergency plan for spills of mercury including first aid.

If possible, work with mercury should be performed at low temperatures (cold seasons) to avoid evaporation of mercury.

5.2 Hydrocarbons

Diesel can probably be reused if it is intact in the fuel tanks. This was the case for the salvage of U-534. If not able to reuse, the diesel can be sent to an approved disposal/recycling facility for incineration.

The cost for incineration is dependent on the diesel quality. Iin Norway the incineration of organic waste costs approximately 2 000 - 3 000 NOK/metric ton (with low heat value). Based on experience, incineration is probably slightly cheaper abroad.

Examples of companies in Norway that may handle the diesel are; Renor, Norsk Spesialolje, Franzefoss Gjenvinning AS, Veolia Miljø AS and NOAH AS (export).

Lubricants and grease were also used on board, no exact figures of the amounts exists. Estimated amount is in the order of a couple of hundred kilos. Costs are in the same range as diesel, and the same companies as above can handle these substances. Special attention has to be shown if there is risk that the diesel and/or organic waste is contaminated with mercury, due to emission of mercury in case of incineration.

5.3 Scrap metal

Steel fractions that are contaminated have to be analysed for impurities and categorised before disposal/recycling.

Possible treatment methods of contaminated steel are:

- Pre-treatment such as sandblasting, acid cleaning and recycling (reuse of the steel). Cost in the range of 1 500 - 3 000 NOK/metric ton. Added value for recycling is in the range of 500 - 1 000 NOK/metric ton.
- Disposal at an approved disposal facility. Cost in the range of 500 - 1 500 NOK/metric ton.

Examples of companies in Norway that may handle the scrap metal are; Stena Jern og Metall, Hellik Teigen Group, NOAH AS, Veolia Miljø Metall AS and Franzefoss Gjenvinning AS.

Sandblasting of contaminated steel should be evaluated especially with respect to Health, Safety and Environment (HSE).

5.4 Batteries

The batteries are old and detailed specifications are missing. Batteries could still be intact, when the submarine U-534 was salvaged in 1993 in Kattegat batteries were reported to still be intact. http://uboat.net/technical/batteries.htm

The possibility for recycling of batteries from U-864 is uncertain. In general, old batteries can be recycled or disposed as hazardous waste.

In Norway, the recycling of batteries is free of charge for private households, but in this case it has to be assumed that a certain cost for delivering the batteries. Companies in Norway which import batteries established in 1993 the company AS Batteriretur to take care of the collection and recycling of batteries containing hazardous waste.

- Examples of companies that can dispose of batteries as hazardous waste are; Miljøteknikk Terrateam AS and NOAH AS. Delivering the batteries as hazardous waste will cost in the range of 500 - 1 500 NOK/metric ton.
- Examples of companies that recycle batteries are Exide (Exide Sønnak in Norway) and Boliden Bergsöe AB (Landskrona, Sweden). NOAH can receive the batteries, remove the lead and send (export) the lead for recycling. The cost for the extra handling has to be deducted from the value of the lead. The cost for handling the batteries is expected to be in the range between 0 (the recycled lead covers the handling) and 500 NOK/metric ton.

5.5 Transformers and cables

Transformers and cables have to be analysed for impurities (especially PCB) and categorised before disposal/recycling. Asbestos is assumed to have been used as insulation.

Possible treatment methods of transformers and cables are:

- If there are no impurities, the transformers and cables can be delivered to an authorized waste dealer. In general, delivery of electronic waste in Norway is free of charge for private households, but in this case it has to be assumed that a certain cost will be involved for delivering the transformers and cables. This cost is expected to be in the range between 0 (the value of the metal covers the handling) and 500 NOK/metric ton.
- If the transformers and cables contain PCB, asbestos or other impurities they have to be delivered to an approved disposal facility. Cost in the range of 1000 - 2000 NOK/metric ton.

Examples of companies in Norway that may handle the transformers and cables are;
Ragn-Sells AS, Veolia Miljø Metall AS, Hellik Teigen Group, Stena Jern og Metall and Franzefoss Gjenvinning.

5.6 Contaminated sediments

Sediments within U-864 could be severely contaminated with several pollutants like mercury, PCB, diesel, heavy metals, etc. These sediments should be treated separately from the sediments outside U-864. Assumed that parts of the mercury canisters, diesel tanks etc. inside the wreck are destroyed, the level of contaminations can be in the range of 10% or more. In this case thermal treatment is probably the only feasible solution. Such facilities are found in the EU region. Thermal treatment is expected to cost in the range between 5 000 - 10 000 NOK/metric ton.

Assumed that the level of contamination is lower than 10%, stabilisation/solidification should be considered. This can be done in Norway by companies like NOAH AS and Miljøteknikk Terrateam AS. Stabilisation/solidification will cost in the range of 1000 - 2000 NOK/metric ton.

Sediments outside U-864 are less contaminated (mostly much less than 1%) and can be treated with stabilisation/solidification but with less binder (cement/gypsum) than sediments inside U-864. This can be done in Norway by companies like NOAH AS and Miljøteknikk Terrateam AS or by establishing a new disposal facility closer to the wreckage site (permit is needed). Stabilisation/solidification of the less contaminated sediments will cost in the range of 300 - 600 NOK/metric ton.

Independent of the contamination level and treatment method the surplus water in the sediments should removed to reduce the amount (and cost) of material for treatment as much as possible.

5.7 Others

Other contaminated waste materials could occur. These have to be collected and sent to an approved disposal facility for classification and final treatment/disposal.

6 SEPARATION TECHNOLOGIES THAT COULD GIVE A MAJOR COST REDUCTION FOR THE DISPOSAL/TREATMENT

In this chapter separation technologies which can give major cost reductions for the disposal/treatment of the (hazardous) waste are described. It is especially volume reduction of the contaminated sediments by dewatering which substantial cost reductions for disposal/treatment.

6.1 Contaminated sediments

If sediments outside the wreck are removed, it will be done with dredging technology. Depending on dredging technology, different amounts of water will follow the sediments. With suction dredging more than 95 % of the dredged material will be water. For such dredging technologies, the separation of water can give a major cost reduction, due that the volume which has to be disposed of can be strongly reduced. One solution could be that the dredged sediments are placed in a barge with a sand filter and a protective geotextile for dewatering. This will demand monitoring of the surplus water which is returned to the sea and accept criteria for the amount of mercury in the water. If the accept criteria are not fulfilled, further water treatment is necessary. A precipitation process using sulphide may be used. An alternative could be to establish a water treatment plant in the nearest safe harbour.

To illustrate the economical advantage of dewatering, the case where the dredged material contains 95 % water can be used. Assuming theoretical dredged volume of 15 000 m^3 would give approximately 300 000 m^3 for disposal at an assumed cost of around 400 NOK/metric ton (500 NOK/m^3) giving a cost of 150 mill. NOK. If it needs to be fully dewatered, the cost would be 7.5 mill. NOK. Dewatering will normally be much less costly than the disposal cost and would therefore be recommended in such a case.

The amount of sediments *inside* the wreck has an assumed volume of 10 m^3 (chapter 4.6). It is assumed that wreck parts will be salvaged together with the sediments that are inside and that mortal remains inside have to removed. Dewatering of these sediments is not assumed to give any major cost reduction.

6.2 Elemental mercury and surplus water

There will probably be a need to collect spilled elemental mercury from both inside and outside the wreck. This could be done with a simplified suction method and result in two main phases, elemental mercury and contaminated sea water. Before delivery to recycle or disposal, it would be cost effective to separate water from elemental mercury. This could be done by decanting and/or filtration. The surplus water can be treated at an approved treatment facility for contaminated water. Due to the high cost of recycling and disposal for elemental mercury, any reduction of surplus water will be cost saving.

7 FUTURE DEMANDS

DNV has been in contact with "The Zero Mercury Working Group" (/6/) to get information about the work with phasing out mercury in the EU area and which legislation that is expected to come in the (near) future. The Zero Mercury Working Group was officially launched on the 7 April 2006, but has been operating since beginning of 2005. It is an international working group of 140 NGOs (non-governmental organisations) based in all 27 EU Member States, and potential EU Member States. The group works in close co-operation with the European Environmental Bureau (EEB). The aim of the group is to reach "Zero emissions, demand and supply of mercury, from all sources we can control, in view of reducing to a minimum, mercury in the environment at EU level and globally."

7.1 Legislation

Norway is presently not a member of the European Union, but it has signed the EEA (European Economic Area) with the union. By this agreement, Norway is in practice following all the EU legislation and treaties.

7.1.1 EU decisions and proposals

- The EU decided in 2001 to phase out priority substances in the Field of Water policy before 2020 (decision 2455/2001/EC). Among "priority one hazardous substances" is mercury included meaning that discharges, emissions and losses of mercury have to cease or be phased out by 2020 (not being used anymore).
- The EU is working on a new proposal (dated October 26th 2006) with a more restrictive policy on mercury. The proposal aims at banning export of metallic mercury and ensuring safe storage of surplus mercury. The proposal is not a law yet, it has first to be approved both by the Council (Ministers of the EU 27 member states) and the European Parliament.[2]
- The EU commission has proposed that export of metallic mercury from the EU shall be prohibited from July 1st 2011.[3]
  - Metallic mercury from the chlor-alkali industry, cleaning of natural gas, non-ferrous mining and smelting operations shall be disposed of according to the Waste directive (safe disposal).

[2] They are at 1st reading stage, which means that the proposal has gone through the Parliament and Council, but since there is no agreement on several points yet, they have to go through 2nd reading, and if no compromise is found it will have to go for Conciliation.

[3] The Commission has proposed July 1st 2011 and the Parliament has proposed December 1st 2010, and the Council supports the Commission's proposal July 1st, 2011.

- The proposal from the Council has an opening for temporary storage (more than one year) or permanent storage of metallic mercury in salt mines and in deep underwater hard rock formations, or temporary storage (not permanent) in above ground facilities. This is not finally decided yet. [4]

- The European Parliament proposes also that mercury compounds containing more that 5% mercury per weight, and mercury-containing products which are already banned in the EU, should be included in the scope of the export ban.[5]
  - No final disposal operation should be permitted until the special requirements and acceptance criteria are adopted.
  - In an amendment to the proposal in June 2007, the European Parliament suggested that the Member States should submit information on movements of metallic mercury, cinnabar ore and mercury compounds entering or leaving their country /7/. (Amendment 10).

The definitions for the requirements of the temporary storage, permanent storage above ground facility have still to be worked out by the EU. Especially the rules for regarding the definition of deep underwater hard rock formation will be important for disposal in Norway. Depending on what is defined by “deep water formation” a permanent storage in Norway could be excluded at many sites.

7.1.2 Norway

Norway introduced an action plan for reduction of mercury emissions in 2005 (Handlingsplan for å redusere utslipp av kvikksølv) /8/.

The following targets have been set:

1) Reducing mercury emissions significantly within 2010 compared to the 1995-levels
2) Emission and use of mercury shall be stopped within 2020.

January 1st 2008 an amendment to the Norwegian Product Regulation (Produktforskriften) came into force which prohibits “*to produce, import, export, sell and use substances preparations that contain mercury or mercury compounds*”. As mentioned earlier, it is unclear if the mercury from U-864 will be considered as a product.

7.1.3 Sweden

Waste containing more than 0.1 % mercury has to be stored in deep rock formation from 2015. Sweden has an export ban on mercury waste containing more than 0.1 %.

[4] The Parliament said that they at the moment only want temporary storage in salt mines or above ground facilities, and has proposed that a fund is created where the industry would put aside money to be used when technologies for final disposal would be available, for example by solidification followed by placement in salt mines or deep bedrock.

[5] The Council is not supporting this position at the moment, it wants only metallic mercury to be banned from export, however many individual member states do support widening the scope.

7.2 The future market for recycling/disposal of mercury

The market for buying and selling mercury will probably be decreasing due to that the EU legislation will be more restrictive. Today there are still approximately 30 chlor-alkali plants in Europe which use mercury in the production and these are the main users of mercury today. The chlor-alkali industry plans to largely phase out the mercury cell process in Western Europe by 2020. Already, some Western European countries have phased out their mercury cell chlor-alkali plants, or have announced plans to phase them out by 2010. However, the largest chlor-alkali plants in France, Germany, Italy, Spain and the UK, expect to have their plants operating after 2010. New chlor-alkali plants will not be using mercury-cell process according to the IPPC (Integrated Pollution Prevention & Control) directive (96/61 EC).

7.2.1 Recycling (export) of mercury from U-864

The most probable scenario is that both the demand and supply of mercury in the EU will be reduced gradually. The chlor-alkali industry, which is the largest consumer and supplier of mercury, is gradually phasing out mercury, but it is expected to take many years probably at least until 2020. However from 2011 they will have to bring the surplus mercury to a safe disposal if the EU proposal comes into force. This will reduce the mercury supply because they can no longer recycle the mercury.

At the moment it does not look as there are any EU directives which will ban an export of the U-864 mercury inside the EU provided that the Norwegian authorities will allow such an export.

7.2.2 Treatment and disposal of mercury from U-864 in Norway

Depending on how EU defines a “deep water formation” as a permanent storage, it could cause problems finding a suitable location for disposal in Norway. The problem consists in that most storage locations in rock are relatively shallow (<100 m) but may still have stable physical and chemical conditions. The waste industry is working on new technologies for treatment (stabilising) mercury which could simplify a final disposal in Norway.

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TECHNICAL REPORT

KYSTVERKET NORWEGIAN COASTAL ADMINISTRATION

SALVAGE OF U864 - SUPPLEMENTARY STUDIES - STUDY NO. 7: CARGO

REPORT NO. 23916-7
REVISION NO. 01

DET NORSKE VERITAS

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TECHNICAL REPORT

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Summary:

The German submarine U-864 was torpedoed by the British submarine Venturer on February 9 1945 and sunk approximately two nautical miles west of the island Fedje in Hordaland. U-864 was carrying about 67 metric tonnes of metallic mercury that implies a threat to the marine environment. In September 2007 The Norwegian Costal Administration commissioned Det Norske Veritas to further investigate different alternatives to salvage the wreck and remove the mercury from the seabed.

According to decrypted and translated intercepts of German naval communications with Japan, the U-864 was on a mission to Japan with military equipment destined for the Japanese military industry, including mercury.

The objective of this supplementary study is to identify what kind of cargo U-864 had onboard when torpedoed, where it was stored and the value of the cargo. This is valuable information because the environmental threat in both short and long perspective for salvage and capping will be assessed, and will be key factors when deciding to salvage or cap U-864.

DNV's overall conclusion is: U-864 had mercury canisters stored in the keel when torpedoed on February 9 1945. Communication with and gathered information from international WWII historians and war veterans concludes that the only remaining record of U-864's cargo list is the one compiled from the Ultra archives in London.

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Report title: Salvage of U864 - Supplementary studies - Study No. 7: Cargo	
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TECHNICAL REPORT

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TECHNICAL REPORT

The German submarine U-864 was torpedoed by the British submarine Venturer on February 9 1945 and sunk approximately two nautical miles west of the island Fedje in Hordaland. U-864 was carrying about 67 metric tonnes of metallic mercury that implies a threat to the marine environment.

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1 SUMMARY

This report is *Supplementary Study No. 7: Cargo*, one of twelve supplementary studies supporting the overall report regarding U-864 (Det Norske Veritas Report No. 23916) prepared by Det Norske Veritas (DNV).

According to decrypted and translated intercepts of German naval communications with Japan, the U-864 was on a mission to Japan with military equipment destined for the Japanese military industry, including mercury.

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DNV's overall conclusion is:

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DNV's supporting conclusions are:

C1. The only known record of U-864's cargo list is compiled from the ULTRA archives in London.

C2. According to the ULTRA archives U-864 had 1857 mercury canisters (approximately 67 tons) stored in the keel when torpedoed on February 9 1945. DNV has found no records indicating otherwise.

C3. There is found no evidence that U-864 had uranium oxide onboard when torpedoed on February 9 1945.

C4. Based on the information presented in Supplementary Study No. 6: Disposal, DNV concludes the that value of the mercury cargo depends on its quality, and its value is assessed to range from a surplus of 2,5 mill. NOK if recycling is possible to a cost of 20 mill. NOK if all mercury must be disposed.

The rest of *Supplementary Study No. 7: Cargo* details the arguments behind the conclusions.

TECHNICAL REPORT

Den tyske ubåten U-864 ble torpedert av den britiske ubåten Venturer den 9. februar 1945 og sank omtrent to nautiske mil vest for øya Fedje i Hordaland. U-864 var lastet med omtrent 67 tonn med metallisk kvikksølv som utgjør en fare for det marine miljøet.

I September 2007 tildelte Kystverket Det Norske Veritas oppdraget med å nærmere utrede ulike alternativer for heving av vrak og fjerning av kvikksølv fra havbunnen.

2 SAMMENDRAG

Denne rapporten er *Tilleggsutredning nr. 7: Last*, en av tolv tilleggsutredning som understøtter hovedrapporten vedrørende U-864 (Det Norske Veritas Report No. 23916) utarbeidet av Det Norske Veritas (DNV).

I følge dekrypterte og oversatte meldinger sendt fra den tyske marinen til Japan, var U-864 på et oppdrag til Japan med militært utstyr ment for den japanske militærindustrien, deriblant kvikksølv.

Målet med denne tilleggsutredningen er å kartlegge hvilken last U-864 hadde ombord da den ble torpedert, hvor dette var lagret og verdi på lasten. Dette er verdifull informasjon fordi miljø-trusselen på både kort og lang sikt vil vurderes, og vil være sentrale faktorer når man skal bestemme om U-864 skal heves eller tildekkes.

DNV sin overordnede konklusjon er:

U-864 hadde flasker med kvikksølv lagret i kjølen da den ble torpedert 9. februar 1945. Kommunikasjon med og innhentet informasjon fra internasjonale historikere og krigsveteraner fra 2. Verdenskrig og konkluderer med at den eneste gjenværende lastelisten til U-864 er den som er sammenstilt fra ULTRA arkivene i London.

DNV underbygger denne konklusjonen med:

C1. **Den eneste kjente lastelisten til U-864 er sammenstilt fra ULTRA arkivene i London.**

C2. **I følge ULTRA-arkivene hadde U-864 1857 flasker med kvikksølv (ca. 67 tonn) lagret i kjølen da den ble torpedert 9. februar 1945. DNV har ikke funnet noe dokumentasjon som indikerer noe annet.**

C3. **Det er ikke funnet noen bevis for at U-864 hadde uraniumoksyd ombord da den ble torpedert 9. februar 1945.**

C4. **Basert på informasjon presentert i tilleggsstudie nr. 6 vedrørende avhending, konkluderer DNV med at verdien på kvikksølvlasten avhenger av dens kvalitet, og er vurdert å ligge mellom et overskudd på 2,5 mill. NOK dersom gjenvinning er mulig til en kostnad på 20 mill. NOK dersom alt kvikksølv må deponeres.**

Resten av *Tilleggsutredning nr.7: Last* utdyper argumentene bak konklusjonene.

3 INTRODUCTION

3.1 Background

The German submarine U-864 was sunk by the British submarine Venturer on 9 February 1945, approximately 2 nautical miles west of the island Fedje in Hordaland (Figure 3-1). The submarine was on its way from Germany via Norway to Japan with war material and according to historical documents; U-864 was carrying about 67 metric ton of metallic (liquid) mercury, stored in steel canisters in the keel. The U-864, which was broken into two main parts as a result of the torpedo hit, was found at 150-175 m depth by the Royal Norwegian Navy in March 2003. The Norwegian Costal Administration (NCA) has, on behalf of the Ministry of Fisheries and Coastal Affairs, been performing several studies on how the risk that the mercury load constitutes to the environment can be handled. In December 2006 NCA delivered a report to the Ministry where they recommended that the wreck of the submarine should be encapsulated and that the surrounding mercury-contaminated sediments should be capped. In April 2007 the Ministry of Fisheries and Coastal Affairs decided to further investigate the salvaging alternative before a final decision is taken about the mercury load.

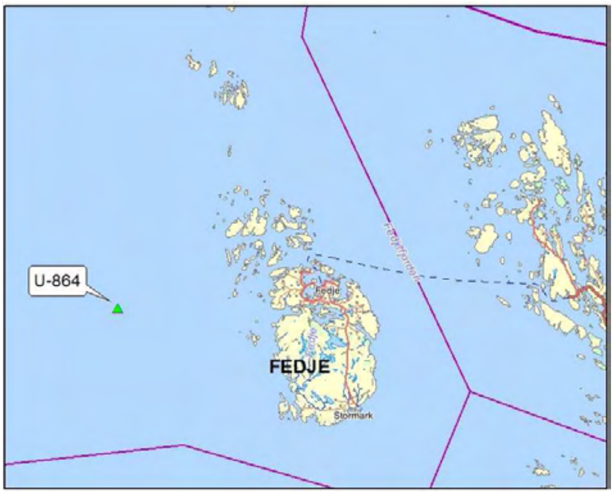

Figure 3-1 Location (left) and a sonar picture of the wreck of U-864 on seabed (right) (from Geoconsult).

3.2 DNV's task

In September 2007 NCA commissioned Det Norske Veritas (DNV) the contract to further investigate the salvaging alternative. The contract includes:

- DNV shall support NCA in announcing a tender competition for innovators which have suggestions for an environmentally safe/acceptable salvage concept or technology. Selected innovators will receive a remuneration to improve and specify their salvage concept or technology.

- DNV shall support NCA in announcing a tender competition for salvage contractors to perform an environmentally justifiable salvage of U-864.
- DNV shall evaluate the suggested salvage methods and identify the preferred salvage method.
- The preferred salvage method shall be compared with the suggested encapsulation/capping method from 2006. (DNV shall give a recommendation of which measure that should be taken and state the reason for this recommendation.)
- DNV shall perform twelve supplementary studies which will serve as a support when the decision is taken about which measure that should be chosen for removing the environmental threat related to U-864. The twelve studies are:

1. *Corrosion*. Probability and scenarios for corrosion on steel canisters and the hull of the submarine.
2. *Explosives.* Probability and consequences of an explosion during salvaging from explosives or compressed air tanks.
3. *Metal detector*. The possibilities and limitations of using metal detectors for finding mercury canisters.
4. *The mid ship section*. Study the possibility that the mid section has drifted away.
5. *Dredging*. Study how the mercury-contaminated seabed can be removed around the wreck with a minimum of spreading and turbidity.
6. *Disposal*. Consequences for the environment and the health and safety of personnel if mercury and mercury-contaminated sediments are taken up and disposed of.
7. *Cargo.* Gather the historical information about the cargo in U-864. Assess the location and content of the cargo.
8. *Relocation and safeguarding.* Analyse which routes that can be used when mercury canisters are relocated to a sheltered location.
9. *Monitoring.* The effects of the measures that are taken have to be documented over time. An initial programme shall be prepared for monitoring the contamination before, during and after salvaging.
10. *Risk related to leakage.* Study the consequences if mercury is unintentionally leaked and spreading during a salvage or relocation of U-864.
11. *Assessment of future spreading of mercury for the capping alternative*. The consequences of spreading of mercury if the area is capped in an eternal perspective.
12. *Use of divers.* Study the risks related to use of divers during the salvage operation in a safety, health and environmental aspect and compare with use of ROV.

3.3 Scope of this report

This report is *Supplementary Study No: 7: Cargo.* According to decrypted and translated intercepts of German naval communications with Japan, the U-864 was on a mission to Japan /4/. Its cargo was various military equipment, drawings and 1857 mercury canisters /3//27/. There has also been speculation on whether U-864 had uranium oxide onboard when leaving Bergen.

The objective of this supplementary study is to

- identify what kind of cargo U-864 had onboard when torpedoed, and where it was stored
- the value of the cargo.

There are mainly three reasons why the cargo on board the U-864 is of interest:

1. The mercury stored onboard is highly toxic. Samples of the seabed around the wreck states that it is severely contaminated by mercury and needs to be cleaned as it posses a severe threat to the marine environment along the Norwegian coast. The amount of mercury and where it is stored will be discussed in chapter 5.2.
2. There has been some speculations on whether U-864 had uranium oxide on board or not, similar to U-234 which was captured by the US Navy in the Atlantic Ocean on May 15 1945. Chapter 5.3 will address this issue.
3. The value of the mercury onboard U-864. Chapter 5.4 will address this issue.

In May 1945 German forces destroyed very much of the documentation about military missions, cargo lists, drawing and other kinds of information /6/. Information about the cargo of U-864 is therefore not easily found. Although historians, as well as private persons, have done a lot of research on German military missions during World War II (WWII), including U-864. The main source of information about the cargo in U-864 is the British ULTRA archive, which contains decrypted intercepts from German forces during the war (for more information about the ULTRA-archives, see chapter 6.1.7).

In addition to the cargo mentioned above, U-864 is expected to have carried torpedoes, grenades, demolition charges and different kinds of anti-air ammunition. All questions about armament are discussed in the *Supplementary Study No. 2: Explosives* and will therefore not be discussed in this report. This report will not deal with questions related to ownership of U-864 and its cargo. Other equipment and personal artefacts on board will not be discussed in this report, as this is not considered relevant information when deciding to salvage or cap the wreck.

The next chapter (4) includes a short historical introduction to German submarine warfare and their agreements with Japan during WWII, and chapter 5 discusses the cargo onboard U-864. Chapter 6 describes DNV's research and main sources of information, and chapter 7 is about the German Type IX submarines.

Appendix B is about U-859, which was sunk on September 23 1944 near Penang in the Straits of Malacca by torpedoes from the British submarine HMS Trenchant (47 dead – 20 survivors). Since U-859 had mercury bottles stored as cargo in her keel, is information about this submarine and how it was salvaged added to this supplementary study.

4 HISTORICAL BACKGROUND /6/

4.1 The tripartite pact

As early as in 1937, the Japanese Naval Attaché in Berlin, Capt. Kojima Hideo recognized the necessity of German aid to Japan in case of war. Due to this he proposed a protocol for the exchange of tactical and technical information and materials between the Japanese and German navies. However, it was not until after the outbreak of WWII on September 1 1939 that Germany saw the necessity of entering into an agreement. Due to the increased weapon production, Germany needed raw materials like rubber, zinc, tungsten and molybdenum, but also opium and quinine. Japan, on the other hand, was interested in new, operational weapon systems like tanks, aircraft, torpedoes and radio location equipment. In addition to this they were eager to obtain drawings, descriptions and details of German technical advances /22/. However, due to Germany's fears that such an exchange would be one-sided, a draft for a cooperative agreement drew out in time. Not until a year later, on September 27 1940, Germany, Italy and Japan signed the "Tripartite Pact". By this, they committed themselves to mutual political, economic and military support in each other's respective spheres of influence and operations /22/.

4.2 Blockade running

With the "Ribbentrop-Molotov" non-attack pact from1939, Russia was kept neutral and the trans-Siberian railroad could be used for the exchange of war materials until the attack on Russia in 1941 /22/.

In addition to this, blockade running merchant vessels started running between Germany and Japan, in the beginning around Cape Horn. After the United States entered the war in December 1941, the route changed to a passage around the Cape of Good Hope. During the first years, many shipments were sent from Germany to Japan and the other way. However, after the Allies got hold of the "Enigma" coding machine and broke the code, they obtained advance information about the movement of merchant vessels. By this the conditions became increasingly worse since the Allies managed to sink many of the blockage runners /22/.

The winter of 1942-43 was the last period surface vessels were used for this purpose, since too many were lost. Out of pure necessity, Adolf Hitler decided in November 1942 that submarines were to be used as blockade runners. In spring 1943 the planning started, initially using Italian and Japanese submarines. Later the same year, the German "Monsun" plan sent a ten-boat group from Germany to Japan which resulted in disaster: the Allies sunk five of the boats in the Atlantic and one in the Indian Ocean, leaving only four boats to arrive in Penang. Later also several of the type IX-D/2 were sent to the Indian Ocean in the transport and combat role, but this also was a failure since most of the boats were lost in the Atlantic. Of 18 boats that departed Penang between 1943 and 1945, six boats returned to Penang and six were sunk. However, of the six that reached Europe, three were lost on their way to Germany /22/.

4.3 Mercury

Approximately 1.500 tons of mercury was purchased by the Japanese in Italy from 1942 to the time of the Italian collapse. This special commodity held the highest priority for shipment to Japan by submarine. Information on shipments during the period of surface blockade running is fragmentary, but successful shipments are believed to have amounted to 141 tons, allied sinking's may have totalled 119 tons.

Approximately 620 tons of mercury was shipped in numerous submarines from Europe since the summer of 1943 with a known loss of approximately 420 tons /7/.

One of the submarines which made a successful round-trip, was the U 861 commanded by Jürgen Oesten. He left Germany in April 20 1944 with 100 tons of mercury filled on steel canisters which were stored in the keel, and reached Penang September 23 the same year. He left Penang in January the following year and arrived safely in Trondheim April 19 1945 /23/.

For the last years of the war, the blockade running submarines operated out of Kiel. The whole operation was classified "Secret", and was supervised by Admiral Hans-Georg von Friedenburg, who was both commanding Admiral of submarines as well as Chief of the "Organisations-abteilung". This organisation was responsible for providing the total personnel and materials support to the German submarines.

U-864 was part of this secheme..

4.4 U-864's last mission

U-864 was launched in Kiel on August 12 1942 /2/. U-864 is a type IX D/2, which is a large submarine designed for higher speed and carrying out longer journeys /1/. (See chapter 7 for more information about the Type IX submarines).

The U-864, commanded by Korvettenkapitän Ralf-Reimar Wolfram, left Kiel with its cargo December 5 1944 to arrive Horten (Norway) four days later /6/.

The tripartite-pact also covered the training of personnel and competence transfer. Therefore several passengers sailed with the U-864 bound for Japan. Four of these have been identified through the ULTRA archive messages (see chapter 6.1.7). These are Rolf von Chlingensperg (Messerschmitt engineer), Riclef Schomerus (Messerschmitt engineer), Tadao Yamoto (Japanese acoustic torpedo expert) and Toshio Nakai (Japanese fuel expert) /7/.

Before leaving Germany, the boat had been refitted with a snorkel mast, thus enabling the submarine to run the diesel generators and charge the batteries while staying submerged (see Figure 4-1). Several messages found in the ULTRA archives shows that there were many problems related to the snorkel mast, which had to be solved before the U-864 set to sea for Japan. Therefore, it was necessary to sail to Bergen to solve these problems /7/.

On transit to Bergen, U-864 run aground and had to stop in Farsund for repairs, and did not reach Bergen until January 5 1945. While in dock No. 3, U-864 received minor damages under the allied bombing of the bunker on January 12. After repairs and adjustments of the snorkel mast (see Figure 4-1), U-864 docked out and started submerged trials and was discovered by HMS Venturer while doing so off Fedje island on February 9 1945. Messages found in the ULTRA

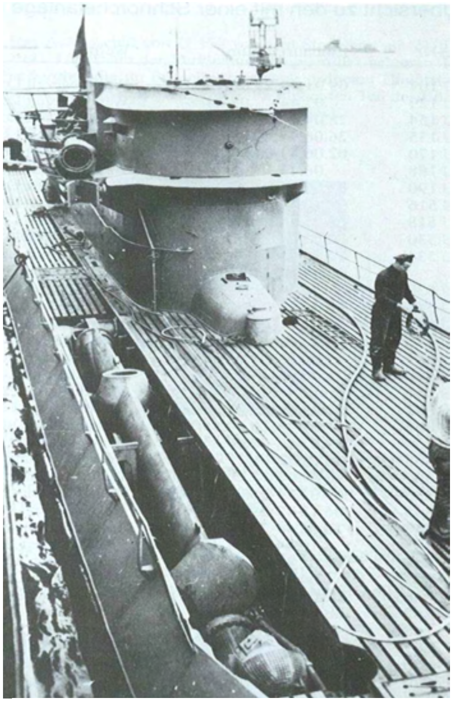

Figure 4-1 U-889's snorkel mast. Type IX C/40 submarine (similar to IX D/2, but approximately 11 metres shorter) /13/

archive shows that the submarine had reported a breakdown and was ordered to return to Bergen /7/.

U-864 set the course for "Fedje Osen". Having discovered the U-864, Lt. Launders, Captain of the HMS Venturer, followed the u-boat working out the target plot and decided to fire his torpedoes resulting in the sinking and breaking up of the U-864 /24/. This is the first and only documented incident where one submarine sinks another submarine while both are submerged /3/.

The Norwegian Submarine Inspection received the first request about U-864 in September 1997. The search for the submarine started spring 2001, but the wreck was not located until February 2003 /25/. In the fall the same year, the NCA started sediment testing of the seabed and discovered high concentrations of mercury around the wreck.

5 THE CARGO ONBOARD U-864

DNV's conclusions are:

C1. The only known record of U-864's cargo list is compiled from the ULTRA archives in London.

C2. According to the ULTRA archives U-864 had 1857 mercury canisters (approximately 67 tons) stored in the keel when torpedoed on February 9 1945. DNV has found no records indicating otherwise.

C3. There is found no evidence that U-864 had uranium oxide onboard when torpedoed on February 9 1945.

C4. Based on the information presented in Supplementary Study No. 6: Disposal, DNV concludes the that value of the mercury cargo depends on its quality, and its value is assessed to range from a surplus of 2,5 mill. NOK if recycling is possible to a cost of 20 mill. NOK if all mercury must be disposed.

5.1 The U-864 cargo list

DNV's conclusion is:

C1. The only known record of U-864's cargo list is compiled from the ULTRA archives in London.

After locating the wreck of U-864, investigations were started by Norwegian and British historians looking for information in archives in Washington, London and Freiburg. Information from Washington led to the discovery of most of the translated intercepts in the ULTRA archive related to the U-864 /4/. The German historian Dr. Niestle located and compiled these intercepts, including the cargo list of the U-864 (attached in Appendix A). Commander s.g. Kjelstrup says that these transcripts are the only information found about U-864's cargo, and refers to Dr. Niestlé /3/, who has been doing research on German submarines for more than 30 years. A reason for this is that the Germans destroyed all archives at the end of the war (for more information, see chapter 6.1.6).

"Kapitän zur See" Hans-Rudolf Rösing – responsible for the 11th U-Flotilla in Bergen, the 33rd U-Flotilla in Flensburg and the 15th U-Flotilla in Kristiansand – was interviewed at his home in Kiel by Commander s.g. Kjelstrup in August 2003. During this interview he confirmed that he had been onboard both the U-864 and U-234 (see chapter 6.1.8) saying goodbye immediately before their departures from Norway. When asked about knowledge of their missions and which cargo they carried, he claimed no knowledge of this. But he knew that these boats were on secret missions, and said that this was fully controlled by Admiral Hans-Georg von Friedenburg. In his view no one in the rest of the German Navy had any knowledge of this. Rösing also said that all information from von Friedenburg's archives was destroyed and burnt in May 1945 after the German capitulation /27/.

5.2 Mercury

DNV's conclusion is:

C2. According to the ULTRA archives U-864 had 1857 mercury canisters (approximately 67 tons) stored in the keel when torpedoed on February 9 1945. DNV has found no records indicating otherwise.

According to the cargo list found in the ULTRA archives, U-864 had 1857 mercury canisters (approximately 67 tons) onboard when leaving Bergen /26/. That the mercury was contained in steel canisters was confirmed when one of the canisters containing mercury was located and brought to the surface during surveys on the wreck in 2005. According to the cargo list, U-864 had equipment and drawings for fighter planes as well as other military equipment destined for the Japanese military forces on board when leaving Bergen /26/.

In an interview with Jürgen Oesten, a former German submarine commanding officer, made by the NRK (the Norwegian Broadcasting Corporation) in 2006, Oesten states that all mercury canisters were stored in the keel (see

Figure 5-1) of the submarine during such operations, replacing the usual lead ballast to secure correct buoyancy and stability /9/. Oesten also confirms this in an e-mail to Commander s.g. Kjelstrup in October 2007 /8/. Based on these references DNV must conclude that the mercury canisters were stored in the keel of U-864 when it was torpedoed February 9 1945. This is also supported in a documentary about U-864 made by Spiegel TV in 2006 /10/.

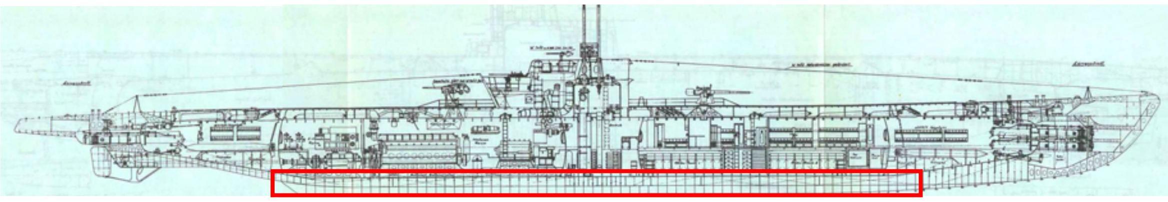

Figure 5-1 Type IX D. The red rectangle shows the keel, in which the mercury canisters were stored according to Oesten /19/.

Figure 5-2 shows the storage room in the keel of the submarine U-534, a type IX C submarine, which were salvaged in 1993 outside Denmark. The storage room in U-864 (Type IX D/2) is similar, but larger as the hull of Type IX D/2 is approximately 11 m longer than the hull of Type IX C /17/. These storage rooms were not pressure tight, but filled with water during operation.

Figure 5-2 The storage room in the keel of U-534 (Type IX C, similar to U-864 but approximately 11 metres shorter)

During investigations on the wreck, two mercury canisters have been found. One of these was a forged canister, while the other was a welded canister (cylinder shaped). A mercury canister was salvaged and opened in 2005 and contained 36 kg (2.7 litres) metallic mercury. Assuming all canisters contained approximately the same amount of mercury, we can estimate that there was approximately 67 metric tons of mercury on board U-864 when torpedoed February 9 1945.

The *Supplementary Study No. 1: Corrosion* discusses the corrosion of the mercury canisters: "*Of the two mercury canisters retrieved and examined, the one fabricated by welding of steel plate material had developed a pinhole leak in a weld, whilst the other type in forged steel had an 80% local reduction in wall thickness (initially 5 mm) that is likely to have developed a pinhole leak within 10-30 years.*" For more information about corrosion on the mercury canisters, see *Supplementary Study No. 1 Corrosion*.

The mercury canisters mentioned above are assumed to have fallen out of the keel as a result of the torpedo explosion or the impact on the seabed. Pictures of the canisters are displayed on the next page.

Figure 5-3 Top section of forged container for mercury

Figure 5-4 Welded mercury canister (diameter 130 mm)

5.3 Uranium oxide

DNV's conclusion is:

C3. There is found no evidence that U-864 had uranium oxide onboard when torpedoed on February 9 1945.

When the loading list of the U-234 (see chapter 6.1.8) became known to the public in the 1980's, the information of 560 kilograms of uranium oxide contained in the cargo started questions and speculations. Combined with the information that the U-234 was a replacement for the U-864, Mr Wolfgang Lauenstein's interest in the matter was started. He wrote several letters to Norwegian Naval- and civilian officials. This again led to the search for the wreck by the Royal Norwegian Navy, resulting in the discovery of the U-864 in February 2003 /6/.

According to Dr. Niestle there are no documentation found which support that U-864 had uranium oxide onboard when leaving Bergen in February 1945 /3/. In addition to this, the cargo list of U-864 found in the ULTRA archives does not contain any information about uranium oxide /26/. During NCA's investigation on the wreck of U-864 in 2005, radiation was measured but no traces of uranium oxide were found.

Based on this information, DNV conclude that the probability that there was uranium oxide onboard U-864 when torpedoed February 9 1945 is remote.

5.4 Value of the mercury

DNV's conclusion is:

> **C4. Based on the information presented in Supplementary Study No. 6: Disposal, DNV concludes the that value of the mercury cargo depends on its quality, and its value is assessed to range from a surplus of 2,5 mill. NOK if recycling is possible to a cost of 20 mill. NOK if all mercury must be disposed.**

If salvaged, the mercury on board U-864 can be sold and recycled if it is of a certain quality, otherwise it must be disposed. Regulations for recycling of mercury, as well as requirements for the mercury's quality, are addressed in *Supplementary Study number 6: Disposal*. Table 5-1 includes the conclusions from this study regarding the surplus or costs if recycling the mercury, as well as the costs if the mercury in U-864 must be disposed. For further information about this topic, see *Supplementary Study number 6: Disposal*.

Table 5-1 Value and disposal cost of the mercury

Material	Disposal Solution	Unit cost	Cost (range)	Comment
Mercury (elemental)	Recycling *or*	32 000 NOK/metric ton	2 - 7 mill. NOK (in best case even a surplus of 2.5 mill. NOK if it is very pure)	Estimated for 30-99 % pure mercury. If the mercury is very pure (99.999 %) it can be sold for 40 NOK/kg.
	Disposal	50 000 - 100 000 NOK/metric ton	3.5 - 20 mill. NOK	Estimated for 30-99 % pure mercury. Cost estimated for stabilising elemental mercury at NOAH (SAKAB method). (Establishment of a disposal in a deep-rock cavern for elemental mercury has in Sweden (2003) been estimated to 210 000 – 550 000 NOK/metric ton).

Based on the information presented in Table 5-1, DNV concludes the that value of the mercury cargo will depend on its quality, and its value is assessed to range from a surplus of 2,5 mill. NOK if recycling is possible to a cost of 20 mill. NOK if all mercury must be disposed.

6 SOURCES OF INFORMATION

When searching for information about the cargo onboard U-864, DNV has focused on using first hand information from ex-servicemen, scientists and official literature. The most important sources of information are presented in chapter 6.1, while the reference list in chapter 8 consists of all references used, either directly or indirectly, when working with this supplementary study.

There are many web pages concerning German submarines, including U-864, due to wide spread interest on the topic. Such information is often less reliable due to lack of references used in the text and professional quality assessments, so DNV has limited the use of such information.

6.1 Main sources of information

The following chapters summarizes the main sources DNV has used to obtain information about the cargo onboard U-864.

6.1.1 Dr. Timothy P. Mulligan, the National Archives and Record Administration, Modern Military records (USA)

Dr Mulligan is a specialist in captured German and related Records. He discovered the codename “CAESAR” in the ULTRA-archives, which led to the discovery of the messages in the ULTRA archive in London related to the U-864 /6/.

6.1.2 Korvettenkapitan Jürgen Oesten

Korvettenkapitän Jürgen Östen, born 24th October 1913, entered the “Reichsmarine” in 1933. He commanded three submarines during his naval career, U-61 (Type II C), U-106 (Type IX B) and U-861 (Type IX D2) /6/. He was the commanding officer on a mission to the Far East /5/ when U-861 in 1944 sailed to Penang with a cargo of approximately 100 tons of mercury /8/.

At the end of the war, on 8 May 1945, he decommissioned U-861 in Trondheim. Oesten and his crew were taken into captivity and the submarine was sunk by the Allies on December 31 1945 during Operation Deadlight.

Korvettenkapitän Oesten is a holder of several decorations /5/.

6.1.3 Dr. Alex Niestlé

Several historians in Germany, the United Kingdom and Norway have been searching for information on the German/Japanese blockade running submarines. The most important and prominent source for investigations related to the U-864, has been the German historian Dr. Alex Niestlé /6/. He has been doing research on German submarine history for about 30 years, including personnel and material exchange between Germany and Japan, and has written books on the subject /3/.

6.1.4 Hans-Rudolf Rösing /6/

"Kapitän zur See" Hans-Rudolf Rösing was responsible for the 11th U-Flotilla in Bergen, the 33rd U-Flotilla in Flensburg and the 15th U-Flotilla in Kristiansand. Rösing entered the "Reichsmarine" in 1924 and trained as a submariner in Finland, Spain and Sweden from 1930 until 1932. From 1932 to 1941 his career varied from the Submarine School in Kiel to Commander of several Submarine Flotillas in Kiel. In the same period he commanded U-11 and U-48. In July 1942 he was appointed "Führer der Unterseeboote West", a position he held until the end of WW2.

After the Allied invasion in Normandy in June 1944, Germany was gradually driven out of occupied France. Because of this, all German submarine bunkers on the French coast had to be abandoned by the German Navy. The bases for submarine operations and Flotillas had to be moved to Norway, and Rösing moved his "Führer der Unterseeboote West" to Bergen in September 1944.

After the war, he returned to the "Bundesmarine" in 1956 and a year later he was promoted to Chief of the "Marine-Abschnittskommando Nordsee". From 1962 he was "Befehlshaber im Wehrbereich 1" and resigned from active service as Rear Admiral in 1965. For his services in the "Bundesmarine" he was awarded the German order "Bundes-Verdienst-Kreuz" in 1966.

Rösing was interviewed at his home in Kiel by Hans-Chr. Kjelstrup in August 2003.

Rösing is a holder of several decorations. He passed away in December 2004.

6.1.5 Commander s.g. Hans-Christian Kjelstrup

Chief of Submarine Systems Section in the Norwegian Defence Systems Management Division. Kjelstrup has been doing research on U-864, and has a personal acquaintance with the persons mentioned above. He entered the Norwegian Submarine Service in 1974, and has since starting up as a chief engineer on the Kobben-class submarines had various posts in the Submarine Service and Materiel Command, ranging from the Submarine School via technical supervisor/submarine maintenance coordinator, then submarine projects to his present position. Commander s.g. Kjelstrup has been a significant contributor in the writing of this report.

6.1.6 Documentation, descriptions & drawings /6/

As for documentation, descriptions and drawings of WWII German submarines and aircraft, very little has survived after the war. According to information from the German archives in Freiburg, a special decree was issued by the Wehrmacht early in 1945, ordering all operative units to destroy all archive documentation in case of surrender to the Allies.

Archives in the UK and Freiburg have been contacted looking for detailed information on the submarine Type IX D/2, without success. The only known drawing ("Generalplan") of this type is taken from the book "Geschichte des deutschen Ubootbaus" /28.

6.1.7 Enigma and the ULTRA archives /6/

"Enigma" was originally a commercial cipher machine patented in 1919, used to encrypt and decrypt secret messages. Development of the military versions in Germany started with the Navy in 1925. Later on the German Army and Air Force introduced the "Wehrmacht Enigma" for their use. Further development of this continued, and by the outbreak of WWII, it was the Navy version which was considered the most advanced model.

The Royal Navy managed in May 1941 to capture two naval Enigma machines with codebooks and manuals, and in June the same year the code breakers at Bletchley Park outside London had broken the code. Several machines were later captured, but since the Wehrmacht constantly changed the parts and codes and developed new versions, code breaking was a constant task throughout the war. The decoded messages were to be known as the "ULTRA" messages, and in the last years of the war, several thousand messages were decrypted each week. The information related to the Enigma messages and the code breaking at Bletchley Park, was not officially released until 1974 /29/. Most of the detailed information related to the movements and cargo of the U-864, have been found in the ULTRA archives in London, now open to the public /6/.

The cargo list of U-864 found in ULTRA archives is attached in Appendix A.

6.1.8 The U-234

The U-234 (Type IX B) was the last blockade runner in WWII to leave Germany with armaments and documentation bound for Japan, a cargo in total of 162 tons. Included in this was 560 kilograms of uranium oxide designated for the Japanese army. Commanded by Johann Heinrich Fehler, U-864 also brought with her several passengers, including two Japanese officers. Sailing via Kristiansand, U-864 left Europe in March 1945. Upon receiving Admiral Dönitz's order May 8 1945 to surrender to an allied port, Captain Fehler had great problems in deciding where to go, due to the special cargo he carried onboard. The Allies had divided the North Atlantic into control grids and assigned each grid to a capitulation port. The U-234's designated port of surrender was Halifax in Canada. Fehler discussed where to go with his passengers and crew, but finally settled for sailing to Portsmouth in the USA. This decision was taken despite that the cargo and U-234 had been paid for and was the property of the Japanese government. For the two Japanese officers, this was a disaster. Since Japan was still at war with the USA, the Japanese officers could not surrender to US officials. Therefore they decided to commit suicide, and were buried with full military honours at sea the May 14 1945 /22.

Upon reaching Portsmouth Navy Yard May 19, the crew was imprisoned and the U-234 emptied of its cargo. During the following interrogations of the crew members, it was stated that the U-234 was sent as a replacement of the U-864. In this phase, also the cargo list of the submarine was discovered /22/.

7 THE TYPE IX SUBMARINE /6/

Design of the Type IX series (from A to D) of submarines started in 1937, being combat submarines a little larger than the Type VII. The increase in size gave these submarines a greater weapon capability and range. All were built with the same pressure-hull diameter and plate thickness, having the same strength by using the same type of steel. An outer casing of saddle-tanks encased the pressure hull, and as the requirements to this type were increased, it was mainly the outer diameter which was increased, keeping the length to a little more than 76 meters. When the requirement arose for using submarines as blockade runners, the Types IX B and C were used as they were. It was clear that a special design would be more suitable for this task. It was decided to use the basic design of the Type IX C, mainly by increasing the length and contents of the engine room and the forward mess- and cabin section, a little over 5 metres in each section. In order to increase the range by adding more fuel tanks, the outer saddle tanks were enlarged to engulf the pressure-hull completely /28/.

Two submarines of Type IX can be studied today, the U-534 in Liverpool in the UK and U-505 in Chicago, USA. Both are of Type IX C, the U-534 being sunk in 1945 and salvaged as a wreck in 1995 in Kattegat. The U-505 was captured by the US Navy in 1944, and is still in a very good condition at the Museum of Science and Industry in Chicago.

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APPENDIX
A
TRANSCODED INTERCEPTS
/26/

The attached document (see the next pages) is a compilation of decoded trancepts regarding U-864 made by Dr. Niestlé. The intercepts were located in the ULTRA archives in London, and the numbers on the left refers to the respective intercept in archive.

Intercept 02216 says: "*Mercury: 1857 flasks*", which is the only information found about the mercury stored in U-864, according to Commander s.g. Kjelstrup.

- o0o -

From: Chief Inspector in Germany #024 1000/28 February 1945
To: Chief, Bureau of Military Preparations

The following was aboard the German submarine (temporarily called CAESAR) which departed for Japan last year. *[handwritten note on page margin: U 864]*

12719:

Plans for ME-163	
ME 1 of 20 to 20 of 20:	20 packages
Plans for ME-262	
MF 1 of 34 to 33 of 34:	33 packages
Supplement to plans for ME-262	
ME-A 1 to 9:	9 packages
Supplement to plans for ME-163	
ME A 1-A to 3-A:	3 packages
Parts for ME-163 and 262:	1 box
Junkers plans and parts	
JU-1 to 6:	6 boxes
Plans for BMW	
BMW-4 1 to 4:	3 rolls, 1 box
Plans for Walter	
WA 1 to 2:	2 drums, 1 box

Informative data for technicians aboard:
EC 1 to 19
ES 21 to 23
ES 24 AB to 35
ES 36 AB to 37 AB
ES 38 to 56
ES 58 to 62
CASPAR 63
Total: 60 packages

02200
Plans for MB 511: 1 set, 1 drum

04044
(3*[second number ?]*)
Caproni Company
1 set of plans for submarines 2 boxes

02201
Bolinder Company
1 set of radio graphs: 1 box

02364C
Zeiss Company
1 set of plans for fire control equipment: 18 packages
Documents on non-magnetic values : 3 packages

02364B
Plans for Kreisel-Geräte Company equipment: 3 packages, 1 box
Same as above, 5 packages and 2 packages of related books ans magazines

12662
Rheinmetall
Plans for MG 151: 2 boxes

12701
Plans for fuel pump: 1 box
1 set of Zaunkoenig measuring device: 3 boxes

12714
Plans for Campini plane: 3 tubes

12702
Plans for Isota Company's gas turbine: 4 tubes

14025
Plans for Isota Company's supercharger: 2 tubes

12699
Plans for Galileo Company's air camera: 8 tubes

12847
Plans for Siemens Company's radar, 1 package
German (Naval Technical Bureau secret?) #058
Plans for Freya and Bisma and explanatory material: 2 packages
German (Naval Technical Bureau secret?) #243
Plans for SATSUKE type submarine: 6 packages
German (Naval Technical Bureau secret?) #273
Plans for manufacturing the same type of switchboards: 7 packages

02216
Mercury: 1857 flasks
(Part of it includes that handled by officials in Italy; we shall report the details later.)
(CZ/[illegible]A#8124-[illegible]I)

GI-A COMMENT: This is probably the manifest of one of the 2 German U/B's believed to have left Europe in August 1944, and to have reached the Far East.
(SU[illegible].151300/ Q March 1945)

Messages related to U-864

LOSS OF U-864 ("SW")

A message from the Japanese Naval Attache in BERLIN to TOKYO on 4th April stated that the German submarine U-864 which sailed from NORWAY for the FAR EAST had been given up as lost. She reported a breakdown shortly after leaving port and was ordered to return, but never arrived. A Japanese engineer and a temporary Japanese Official who was an expert in rocket aircraft were on board her.

Comment: This submarine was given up by the Germans on 8th March.

SJA 1777 (And 794)

U-864	Left February 44 - Sunk February off Bergen	Plans and parts for ME-163, ME-262, Jumo 004, BMW 003, Walter jet unit; experimental reports on new German aircraft. Tomgto - Acoustic torpedo expert. Nakai - Fuel expert for ME-163. Ghlingsnapers - Messerschmitt engineer. Schomerus - Messerschmitt engineer.

24. CARGO OF U-864 ("SW")

The cargo of U-864 ("SW"), sunk by H.M.Submarine off NORWAY in February, is known to have included plans and parts of jet-propelled planes, 64 tons of mercury, and an expert on the German T-5 acoustic torpedo.

APPENDIX

B
THE MERCURY CARGO OF U-859

By Wolfgang Lauenstein

Mr. Lauenstein is working an engineer in ALTSOM (earlier named ABB) and has been engaged in developing engines for submarines. Since 1997 he has also been doing research on the fate of U-864.

PROLOGUE: THE MERCURY CARGO OF U-859

1 COMMON DATA OF U-859 / TYPE IXD2

Technical data:

Displacement:	1616 tons surfaced (sf) 1804 tons submerged (sm)	**Speed** :	9,2 sm surfaced 6,2 sm submerged
Length:	87,60 oa	**Range**: (miles/knots)	23.700/12 sf 7/4 sm
Beam:	7,50 oa 4,40 ph	**Torpedos**:	27
Draught	5,40 m	**Crew**:	55 – 63 men
Hight:	10,20 m	**Max depth**:	ca. 230 m
Power (hp):	4400 sf		

(sf = surfaced / sm = submerged / oa = over all / ph = pressure hull)

U-859 is the first boat of a series of six built at the AG Weser (DESCHIMAG) at Bremen. Its works number is **1065** (The last boat was **U-864** with the works number **1070**). The boat was commissioned on **08.07.1944** under Lieutenant Johann Jebsen.

- From 08.07.1943 to 31.03.1944 it was in training
- From 01.04.1944 to 23.09.1944 it was a front-boat

It was sunk on 23 Sept. 1944 near Penang in the Straits of Malacca by torpedoes from the British submarine HMS TRENCHANT (47 dead – 20 survivors).

Beside mercury and a motor-less helicopter FOCKE-ACHGELIS Fa 330 (Bachstelze) for the Japanese, U-859 had no other cargo on board. It was not a transport submarine.

2 THE MERCURY-CARGO OF U-859 – THE STORY OF ITS SALVAGE

As to the story of the salvage operation of a mercury-cargo from U-859 I have studied several reports published in newspapers and magazines. The operation took place in 1972/73 in the Malacca-Street north-west of Penang, Malaysia.

In addition I visited the U-Boat-Museum in Cuxhaven where I saw one of the salvaged mercury-bottles from U-859. Searching for the divers and the ships crew who had all been members of the salvage-team, I recently found the captain of the JASON, the ship from where the salvage operation was started and monitored.

2.1 The Story:

Lt. Horst Klatt (1WO = First Watch Officer), a former crew-member of U-859 had been responsible for the trimming of the boat. He told in a report, that the boat had first been loaded with 80 tons of mercury but as the boat had become too heavy, he had to remove 20 tons. So the boat sailed for Far East with 60 tons of mercury in its ballast-keel.

In the meantime Lt. Horst Klatt has passed away. Years ago I contacted him and asked him for information on the construction of the ballast-keel, but he didn't remember details. He was never a member of the salvage-team.

Recently the captain of the JASON told me that he had an international crew on board – with about 12 divers. Two of them had been Germans. One of them has passed away in the meantime. I have not been able to determine whether the other diver is still alive.

2.2 About the wreck:

- The depth of the wreck is about 35 meters.
- The British torpedo had hit the middle-part of the boat.
- The wreck consist today of two pieces – a front-part and an aft-part.
- The distance between both parts is about 8-10 meters.
- The control-room had been completely demolished.
- Wreck-parts of the control-room and conning tower are to be found between the wreck parts.

The front-part is still closed by the bulkhead of the control room, but it may be entered through a large hole which had been the result of a big explosion. British divers has opened the boat illegally using explosive charges hoping to find gold, silver and diamonds.

The boat has sunk about 2 meters into the mud. Its position is vertical.

Before being able to dig into the hard seabed on the sides of the wreck, the divers had to use explosive charges to loosen the ground. They dug vertical holes of a depth of about 3 meters and from there they prepared a horizontal tunnel – one at the left, one at the right side – each about 2-3 meters long. In this tunnel they tried to open the ballast keel – working on their knees in a total darkness. First they tried to open the ballast-keel using blowpipes. But because of technical difficulties in their tunnel and the limited sight near the wreck, they decided to loosen the steel plates by using crowbars. After having loosened a plate they removed it by fixing it at an air-lift. This method was not a very efficient one so they started to melt the screw heads using blowpipe. This method worked.

The divers started their operation at the front-part of the wreck. But soon they were surprised by the fact, that all keel-boxes of the front-part were empty. The reason was that British divers had already salvaged the mercury – without the official approval of the German government. The

British divers could be identified in Malaysia where they had stored their prey – **12** tons of mercury filled in steel-bottles. (This corresponds to about **350** bottles)

The German team managed by Mr. Simon of the German BARAKUDA-Company expected that not more than **30** tons of mercury altogether would be on board U-859. That meant that about **18** tons of mercury must still be available in the aft-part.

After having opened the first boxes of the aft-parts ballast-keel they saw that it was untouched. They opened all boxes and salvaged the bottles. Some bottles were already heavily corroded, so that the mercury fell down in droplets to the seabed. Nevertheless – some boxes were empty. No other cargo, i.e. glass or lead was in the boxes.

In a box there had been stowed 5 x 6 = 30 bottles (30 x 34,5kg = 1035kg) in a vertical position. In a report I found that the bottles had been fixed by a special strapping system which was been described.

The captain of the JASON, who had not been a diver before, but who had learnt to dive within a few days – told me that he had given support to the other divers and helped to remove bottles from the boxes. He did not remember if the bottles had been fixed. He said that it was only difficult to remove the first bottle. Then it was easy to remove the others. That means that if a special fixing-system had been used by the Germans it will not be critical for the salvage. The salvaged bottles – always 5 in a steel-box - was then brought to the surface by an air-lift.

A total of **18** tons – about **520** bottles of mercury was salvaged.

The boat had already been plundered before the German team started its official work as mentioned above. Even the boats propellers had been removed and inside the aft-part – where originally a Bachstelze-Helicopter had been stowed – the divers found nothing.

It is unknown whether the ballast-keel of the mid-section is still existing and it is unknown whether it was loaded with mercury-bottles or only steel-blocks for ballast.

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TECHNICAL REPORT

KYSTVERKET
NORWEGIAN COASTAL ADMINISTRATION

SALVAGE OF U864 - SUPPLEMENTARY STUDIES - RELOCATION AND SAFEGUARDING

REPORT NO. 23916-8

REVISION NO. 01

DET NORSKE VERITAS

DET NORSKE VERITAS

TECHNICAL REPORT

Date of first issue: 2008-07-04	Project No.: 47123916
Approved by: Carl Erik Høy-Petersen Senior Consultant	Organisational unit: DNV Consulting
Client: Kystverket (Norwegian Coastal Administration)	Client ref.: Hans Petter Mortensholm

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Summary:

The German submarine U-864 was torpedoed by the British submarine Venturer on February 9 1945 and sunk approximately two nautical miles west of the island Fedje in Hordaland. U-864 was carrying about 67 metric tonnes of metallic mercury that implies a threat to the marine environment. In September 2007 The Norwegian Costal Administration commissioned Det Norske Veritas to further investigate different alternatives to salvage the wreck and remove the mercury from the seabed.

The objective for this supplementary study is to identify feasible locations for disarming and cleaning the wreck of U-864 and the transportation route to these locations. The following factors regarding the environment, operation and safety have been taken into account when choosing and ranking the locations.

DNV's overall conclusion is: Planning of the transport and chosing the final location can not be carried out before the salvage method and type of vessel and equipment to use during operation are chosen, and the operational, navigational and environmental risks and limitations are assessed.

Report No.: 23916-8	Subject Group:	
Report title: Salvage of U864 - Supplementary studies - Relocation and safeguarding		
Work carried out by: Randi Kruuse-Meyer (M.Sc) Sigmund Hertzberg (Master mariner) Alfhild Aspelin (B.Sc) Mads Hell Hansen (B.Eng)		
Work verified by: Odd Andersen		
Date of this revision: 2008-07-04	Rev. No.: 01	Number of pages: 35

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TECHNICAL REPORT

The German submarine U-864 was torpedoed by the British submarine Venturer on February 9 1945 and sunk approximately two nautical miles west of the island Fedje in Hordaland. U-864 was carrying about 67 metric tonnes of metallic mercury that implies a threat to the marine environment.

In September 2007 The Norwegian Costal Administration commissioned Det Norske Veritas to further investigate different alternatives to salvage the wreck and remove the mercury from the seabed.

1 SUMMARY

This report is *Supplementary Study No. 8: Relocation and safeguarding*, one of twelve supplementary studies supporting the overall report regarding U-864 (Det Norske Veritas Report No. 23916) prepared by Det Norske Veritas (DNV).

The objective for this supplementary study is to identify feasible locations for disarming and cleaning the wreck of U-864 and the transportation route to these locations.

Firstly, ten locations was identified based on navigational factors only. These locations was thereafter also assessed according to operational and environmental factors. Subsequently, the three locations assessed most suitable, were inspected on site by the Norwegian Defence EOD-command (Ordnance, Explosives and Disposal) to assess whether they have proper shelter for possible fragments and chock waves if an explosive detonates. During this inspection, an 11th location was suggested and incorporated in this supplementary study. The environmental factors has not been assessed for this location.

As the salvage method and type of vessel and equipment to use during operation has not yet been decided, it is not possible to choose the best location for disarming and cleaning the wreck of U-864. Although, the locations are assessed as either: suitable (2), needs further assessment (1) or as not suitable (8).

DNV's overall conclusion is:

Planning of the transport and chosing the final location can not be carried out before the salvage method and type of vessel and equipment to use during operation are chosen, and the operational, navigational and environmental risks and limitations are assessed.

Table 1-1 on the next page displays which factors that must be considered when choosing location for disarming and cleaning the wreck of U-864 and the transportation route to this location. All locations are displayed in a map in Figure 1-1 on page 3.

Table 1-1 Factors that must be considered (orange shading) for each location respectively when choosing transport route and location (corresponding chapter are included) (green = suitable, yellow = needs further assessment, red = not suitable, black bars = not assessed).

Location number (see Figure 1-1)	Navigational issues (ch. 4.1)	Shelter (ch. 4.2)	Crossing of pipelines (ch. 4.2)	Handling of explosives (ch. 4.3)	Especially environmental sensitive area (ch. 5.1)	Prioritized environmental sensitive area (MOB areas) (ch. 5.2)	Protected and important areas for birds (ch. 5.3)	Shorelines (ch. 5.4)	Fisheries and aquaculture (ch. 5.5)	Outdoor life and culture (ch. 5.6)	Comments
8											Conflict with protected areas and important bird areas. Good weather shelter, but some measures must be taken to make adequate shelter. Road in the vicinity of the location
11											Good shelter for both weather and for handling the explosives. No roads nearby.
5											Conflict with protected areas and important bird areas. Transport route crossing gas pipeline. Close to salmon production areas. Good weather shelter. Close to inhabitants.
1											Poor weather shelter. Conflict with protected areas and important bird areas. Close to spawning area.
2											Conflict with protected areas and important bird areas. Close to spawning area. Poor weather shelter
3											Conflict with protected recreational area/important bird area (MOB A). Transport route crossing gas pipeline.
4											Conflict with protected recreational area/important bird area (MOB A). Transport route crossing gas pipeline.
6											Transport route crossing gas pipeline. Conflict with protected areas and important bird areas. Close to salmon and crustacean production areas.
7											Transport route crossing gas pipeline and poor weather shelter. Conflict with protected areas and important bird areas. Close to salmon and crustacean production areas.
9											Poor weather shelter. Conflict with MOB B area. Close to salmon and crustacean production areas and spawning grounds.
10											Poor weather shelter. Conflict with MOB B area. Close to salmon and crustacean production areas and spawning grounds.

The rest of *Supplementary Study No. 8: Relocation and safeguarding* details the factors that must be considered when choosing the transport route and sheltered location.

TECHNICAL REPORT

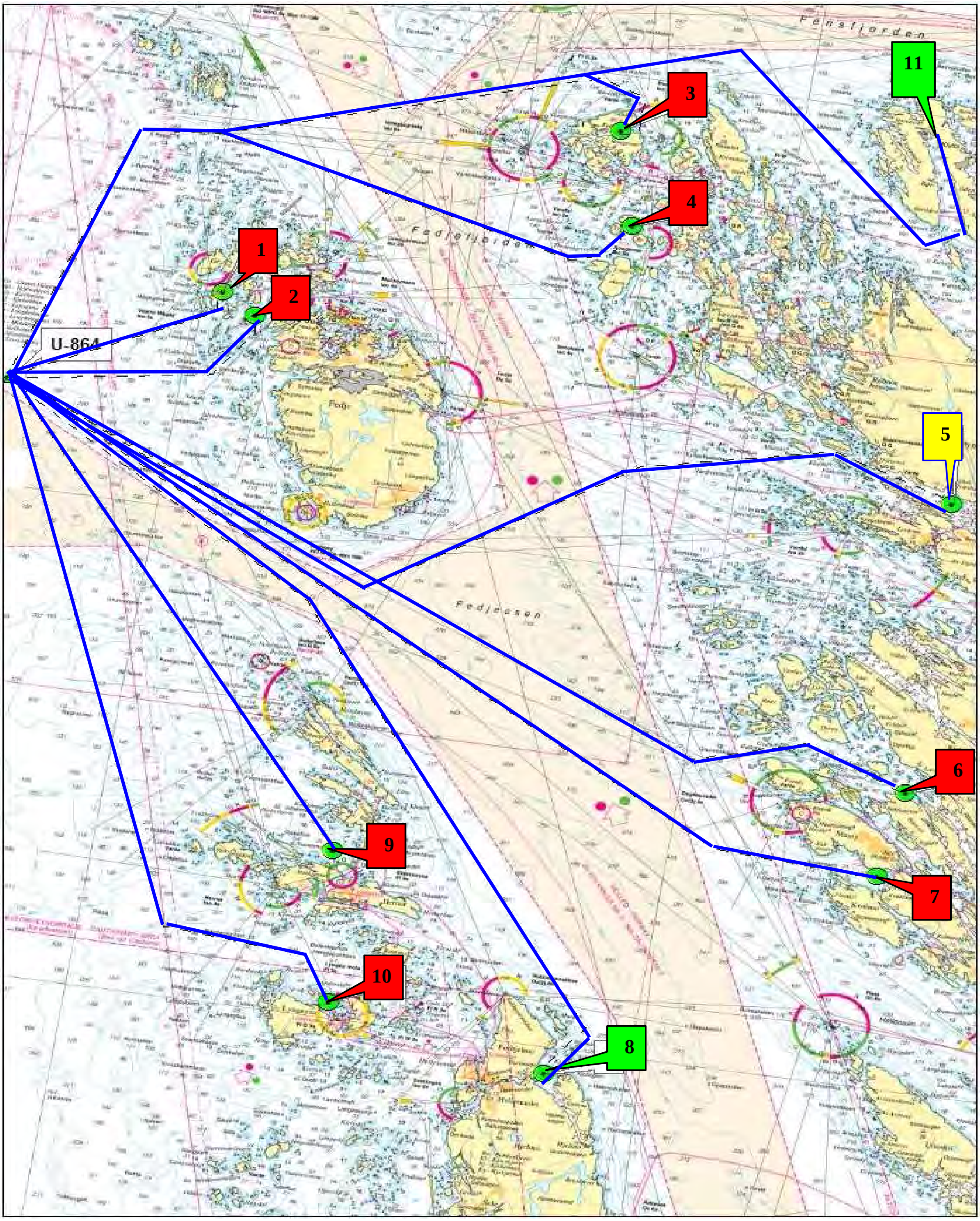


Figure 1-1 Potential transportation routes (blue lines) and sheltered locations (marked with no. 1 to 11) (green = suitable, yellow = needs further assessment, red = not suitable).

TECHNICAL REPORT

Den tyske ubåten U-864 ble torpedert av den britiske ubåten Venturer den 9. februar 1945 og sank omtrent to nautiske mil vest for øya Fedje i Hordaland. U-864 var lastet med omtrent 67 tonn med metallisk kvikksølv som utgjør en fare for det marine miljøet.

I september 2007 tildelte Kystverket Det Norske Veritas oppdraget med å nærmere utrede ulike alternativer for heving av vrak og fjerning av kvikksølv fra havbunnen.

2 SAMMENDRAG

Denne rapporten er *Tilleggsutredning nr. 8: Forflytning og sikring*, en av tolv tilleggsutredninger som understøtter hovedrapporten vedrørende U-864 (Det Norske Veritas Report No. 23916) utarbeidet av Det Norske Veritas (DNV).

Formålet med denne tilleggsstudien er å identifisere mulige lokasjoner der desarmering og rengjøring av vraket av U-864 kan gjøres samt transportrute til disse lokasjonene.

Initielt ble det identifisert ti lokasjoner basert på navigasjonsmessige forhold. Disse lokasjonene ble deretter også ble vurdert med hensyn på operasjonelle og miljømessige forhold. De tre lokasjonene som ble vurdert mest hensiktsmessige, ble fysisk inspisert av Minedykkerkommandoen for å kontrollere om lokasjonene har god dekning for splint og sjokkvirkning dersom et eksplosiv skulle detonere. I forbindelse med denne inspeksjonen, ble en 11. lokasjon foreslått og deretter innarbeidet i denne studien. De miljømessige forholdene for denne lokasjonen er ikke vurdert.

Siden verken hevingsmetode eller type fartøy og utstyr som skal benyttes under operasjonen ikke er bestemt, er det ikke mulig å velge den beste lokasjonen for desarmering og rengjøring av vraket av U-864. Men lokasjonene er vurdert å enten være: egnet (2), krever ytterligere vurderinger (1), eller uegnet (8).

DNV sin overordnede konklusjon er:

Planlegging av transport og valg av endelig lokasjon kan ikke bli utført før det er bestemt hva slags hevingsmetode eller type fartøy og utstyr som skal benyttes under operasjonen, og at operasjonelle, navigasjonsmessige og miljømessige risikoer og begrensninger er vurdert

Tabell 2-1 på neste side inneholder de faktorene som må vurderes når lokasjon for desarmering og rengjøring av vraket av U-864 og transportruten til denne lokasjonen skal velges.

Tabell 2-1 Faktorer som må vurderes (merket med oransje) for hver lokasjon ved valg av transportrute og lokasjon (respektive kapitler er angitt) (grønt = egnet, gult = krever ytterligere vurderinger, rødt = uegnet, grått = ikke vurdert, sorte striper = ikke vudert).

Lokasjonens nummer (ref. Figure 1-1)	Navigasjonsmessige faktorer (kap. 4.1)	Dårlig avskjerming (kap. 4.2)	Krysser rørledning (kap. 4.2)	Håndtering av eksplisiver (kap 4.3	Spesielt miljøfølsomme områder (SMO) (kap. 5.1)	Prioriterte miljøfølsomme områder (MOB) (kap. 5.2)	Verneområder og viktige fugleområder (kap. 5.3)	Strandtyper (kap. 5.4)	Fiskeri og akvakultur (kap. 5.5)	Frilufts- og rekreasjons-områder (kap. 5.6)	Kommentar
8											Konflikt med verneområder og viktige fugleområder. God skjermet for vær, men noen tiltak må gjøres for å gi tilstrekkelig dekning ved håndtering av eksplosiver. Vei i nærheten.
11											Godt skjermet for både vær og håndtering av eksplosiver. Ingen veier i nærheten.
5											Transportruten krysser rørledning. Konflikt med verneområder og viktige fugleområder. Nærhet til havbruksområde (laks).
1											Dårlig skjermet for vær. Konflikt med verneområder og viktige fugleområder. Nærhet til gyteområder.
2											Konflikt med verneområder og viktige fugleområder. Nærhet til gyteområder.
3											Konflikt med vernede friluftsområder og MOB A- område. Transportruten krysser rørledning.
4											Konflikt med vernede friluftsområder og MOB A- område. Transportruten krysser rørledning.
6											Transportruten krysser rørledning. Konflikt med verneområder og viktige fugleområder. Nærhet til havbruksområde (laks og skjell).
7											Transportruten krysser rørledning og er dårlig skjermet. Konflikt med verneområder og viktige fugleområder. Nærhet til havbruksområde (laks og skjell).
9											Dårlig skjermet for vær. Konflikt med MOB B område. Nærhet til havbruks-område (laks og skjell), og gyteområde.
10											Dårlig skjermet for vær. Konflikt med MOB B område. Nærhet til havbruks-område (laks og skjell), og gyteområde.

Resten av *Tilleggsutredning nr. 8: Transport og sikring* utdyper de faktorene som må vurderes når transportrute og lokasjon skal velges.

3 INTRODUCTION

3.1 Background

The German submarine U-864 was sunk by the British submarine Venturer on 9 February 1945, approximately 2 nautical miles west of the island Fedje in Hordaland (Figure 3-1). The submarine was on its way from Germany via Norway to Japan with war material and according to historical documents; U-864 was carrying about 67 metric ton of metallic (liquid) mercury, stored in steel canisters in the keel. The U-864, which was broken into two main parts as a result of the torpedo hit, was found at 150-175 m depth by the Royal Norwegian Navy in March 2003. The Norwegian Costal Administration (NCA) has, on behalf of the Ministry of Fisheries and Coastal Affairs, been performing several studies on how the risk that the mercury load constitutes to the environment can be handled. In December 2006 NCA delivered a report to the Ministry where they recommended that the wreck of the submarine should be encapsulated and that the surrounding mercury-contaminated sediments should be capped. In April 2007 the Ministry of Fisheries and Coastal Affairs decided to further investigate the salvaging alternative before a final decision is taken about the mercury load.

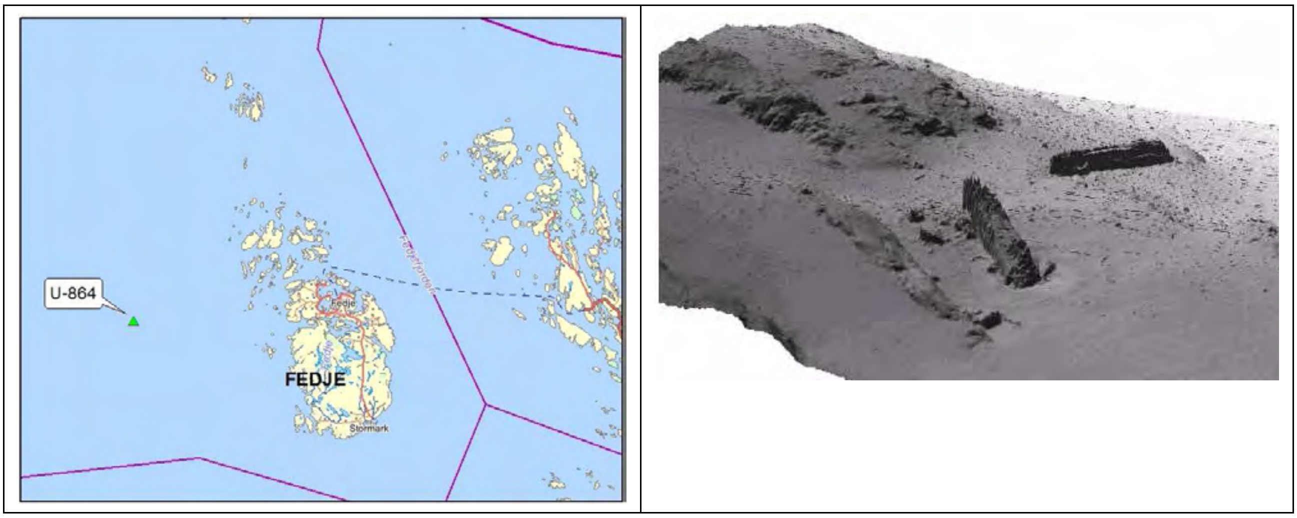


Figure 3-1 Location (left) and a sonar picture of the wreck of U-864 on seabed (right) (from Geoconsult).

3.2 DNV's task

In September 2007 NCA commissioned Det Norske Veritas (DNV) the contract to further investigate the salvaging alternative. The contract includes:

- DNV shall support NCA in announcing a tender competition for innovators which have suggestions for an environmentally safe/acceptable salvage concept or technology. Selected innovators will receive a remuneration to improve and specify their salvage concept or technology.

- DNV shall support NCA in announcing a tender competition for salvage contractors to perform an environmentally justifiable salvage of U-864.
- DNV shall evaluate the suggested salvage methods and identify the preferred salvage method.
- The preferred salvage method shall be compared with the suggested encapsulation/capping method from 2006. (DNV shall give a recommendation of which measure that should be taken and state the reason for this recommendation.)
- DNV shall perform twelve supplementary studies which will serve as a support when the decision is taken about which measure that should be chosen for removing the environmental threat related to U-864. The twelve studies are:

1. *Corrosion*. Probability and scenarios for corrosion on steel canisters and the hull of the submarine.
2. *Explosives.* Probability and consequences of an explosion during salvaging from explosives or compressed air tanks.
3. *Metal detector*. The possibilities and limitations of using metal detectors for finding mercury canisters.
4. *The mid ship section*. Study the possibility that the mid section has drifted away.
5. *Dredging*. Study how the mercury-contaminated seabed can be removed around the wreck with a minimum of spreading and turbidity.
6. *Disposal*. Consequences for the environment and the health and safety of personnel if mercury and mercury-contaminated sediments are taken up and disposed of.
7. *Cargo.* Gather the historical information about the cargo in U-864. Assess the location and content of the cargo.
8. *Relocation and safeguarding.* Analyse which routes that can be used when mercury canisters are relocated to a sheltered location.
9. *Monitoring.* The effects of the measures that are taken have to be documented over time. An initial programme shall be prepared for monitoring the contamination before, during and after salvaging.
10. *Risk related to leakage.* Study the consequences if mercury is unintentionally leaked and spreading during a salvage or relocation of U-864.
11. *Assessment of future spreading of mercury for the capping alternative*. The consequences of spreading of mercury if the area is capped in an eternal perspective.
12. *Use of divers.* Study the risks related to use of divers during the salvage operation in a safety, health and environmental aspect and compare with use of ROV

3.3 Scope of this report

This is *Supplementary Study No. 8: Relocation and safeguarding.* The objective for this supplementary study is to identify feasible locations for disarming and cleaning the wreck of U-864 and the transportation route to these locations. Several factors regarding environmental, operational and safety considerations have been taken into account when choosing and ranking the locations in order to choose the locations disadvantage for the surrounding areas and resources. These factors are listed in Table 3-1.

Table 3-1 The following themes form the basis of the evaluation of which sheltered locations and transportation routes to these locations that will be associated with the least risk.

Chapter	Parameters to be considered
Identified locations and operational issues (chapter 4)	Depth, distance to land, manoeuvrability, crossing of gas pipes and disarming
Vulnerable natural amenities (chapter 5)	
Especially environmental sensitive areas for certain species (SMO-areas) (chapter 5.1	Distance to and type of area (species and vulnerability)
Prioritized environmental sensitive areas (MOB-areas) (chapter 5.2)	Distance to MOB*-areas with high priority (A and B), and information about the areas (species and vulnerability)
Protected areas and other important areas for seabirds (chapter 5.3)	Distance to and type of protected area (species and vulnerability)
Shoreline (chapter 5.4)	The type shorelines ability to self recover
Fisheries and aquaculture (chapter 5.5)	Distance to and type of fisheries and aquaculture
Outdoor life and culture (chapter 5.6)	Distance to and type of recreational area and cultural monuments
Settlements/population densities (Appendix A)	Distance to and type of settlement
Industry (Appendix A)	Distance to and type of activity

In order to establish suitable working/holding areas for the U-864 wreck, the process began with a screening in order find locations to disarm and clean the wreck of U-864. This screening was based on based on navigational conditions only (distance from wreck site and possible transport routes for large vessels). Ten locations was selected for further analysis. The locations are all relatively close to the wreck location in order to minimize transport prior to clean and disarm the wreck of U-864. The identified locations are described in chapter 4.

* MOB = prioritized environmental sensitive areas

In the area of interest there are many natural amenities which could be inflicted by the operation if an accident occurs during transportation. The different kinds of natural amenities in the area of interest are assessed in chapter 0, with detailed information attached in Appendix A.

An 11th location was suggested by the Norwegian Defence OED-command (Ordnance, Explosives and Disposal, named MDK hereafter) after an inspection on site of the three locations assessed most useful. DNV decided to add the 11th location to this supplementary study, but this location has not been assessed according to the vulnerable amenities factors..

4 IDENTIFIED LOCATIONS AND OPERATIONAL ISSUES

Table 4-1 displays which navigational and security factors (concerning handling of explosives) that must be considered for each location respectively when choosing location for disarming and cleaning the wreck of U-864 and the transportation route to this location. All locations are listed in Table 4-2 on page 11 and displayed in Figure 4-1on page 13.

Table 4-1 Factors regarding navigational matters that must be considered (orange shading) for each location respectively when choosing transport route and location (black bars= not assessed) (corresponding chapters are included)

Location	Navigational issues (ch. 4.1)	Shelter (ch. 4.1)	Crossing of pipelines (ch. 4.2)	Handling of explosives (ch. 4.3)	Comments
1					Poor shelter for SW weather.
2					Poor shelter for handling of explosives
3					Crossing a pipeline north of Fedje.
4					Crossing a pipeline north of Fedje.
5					Crossing a Pipeline north of Fedje and a Cable south of Fedje. Good weather shelter. Close to inhabitants.
6					Crossing a Pipeline south of Fedje.
7					Crossing a Pipeline south of Fedje. Poor shelter from NW.
8					Conflict with protected areas and important bird areas. Good weather shelter, but some measures must be taken to make adequate shelter. Road in the vicinity of the location.
9					Very poor weather shelter.
10					Poor shelter from NW.
11					Good shelter for both weather and for handling the explosives. No road nearby.

Regarding the environmental resources, it is especially important to map the resources most vulnerable to pollution. Different interests such as outdoor recreational sites, areas especially important for tourism, and cultural heritage sites should also be emphasized when deciding the sheltered location and transport route. All these issues are discussed in chapter 0.

Industrial and commercial activity (both type and location) in the four different municipalities, in which the ten selected locations are located, have been considered. See Appendix A chapter A.1 to A.4 for information regarding these topics.

4.1 Navigational issues and shelter at location

All locations must be accessible with typical size barge and tugs if surface transportation is chosen. If submerged or partly submerged transport is used, the limited depth may be a problem.

The following criteria have been used when searching for suitable locations:

- Minimum depth along route and depth at final location (approx 10m is suitable for submerged disarming of explosives).
- Ship lane crossing (traffic).
- Special navigational conditions (accessibility, shelter).

Based on the criteria listed above, DNV identified ten locations to clean and disarm the wreck of U-864. An 11th location was suggested by the MDK (no. 11). These are listed in Table 4-2 and displayed in Figure 4-1on page 13.

Table 4-2 Identified locations

Location no.	Position	Min. depth along route	Ship lane crossing	Special navigational conditions
1	N 60° 47.2’ E 004° 40.5’	15m	NIL	Narrow entering. Poor shelter for SW weather
2	N 60° 47.02’ E 004° 40.5’	14m	NIL	Good shelter
3	N 60° 49.5’ E 004° 45.2’	15m	North of Fedje	Ship traffic along Rognværs leia, but only smaller vessels
4	N 60° 48.4’ E 004° 45.25’	14m	North of Fedje	Ship traffic along Rognværs leia, but only smaller vessels
5	N 60° 46.1’ E 004° 53.6’	8m	East of Fedje	Narrow entrance into Purkholmene
6	N 60° 53.9’ E 004° 46.1’	8m	South of Fedje	Good shelter, no crossing traffic
7	N 60° 42.2’ E 004° 53.6’	24m	South of Fedje	Poor shelter from NW
8	N 60° 39.75’ E 004° 48.7’	8m	East of Forhjelmo	Good shelter
9	N 60° 41.72’ E 004° 44.2’	23m	South of Fedje	Very poor shelter from NW
10	N 60° 40.2’ E 004° 44.9’	11m	NIL	Poor shelter from NW
11	N60˚49.3’ E4˚52.3’	Adequate	North of Fedje	Ship traffic along Rognværs leia, but only smaller vessels

Mapping the interests in different areas may ensure that the right considerations are made regarding choice of transportation route and location for handling the cargo. Potential transport routes and locations for bringing the U-864 to land are displayed in Figure 4-1on page 13.

When the transport method and equipment are chosen, a close up survey of the transport routes and sheltered locations needs to be performed in order to verify suitability with regards to needed shelter, disarming of explosives, local navigational aspects, shore side facilities, local communities, local interests etc.

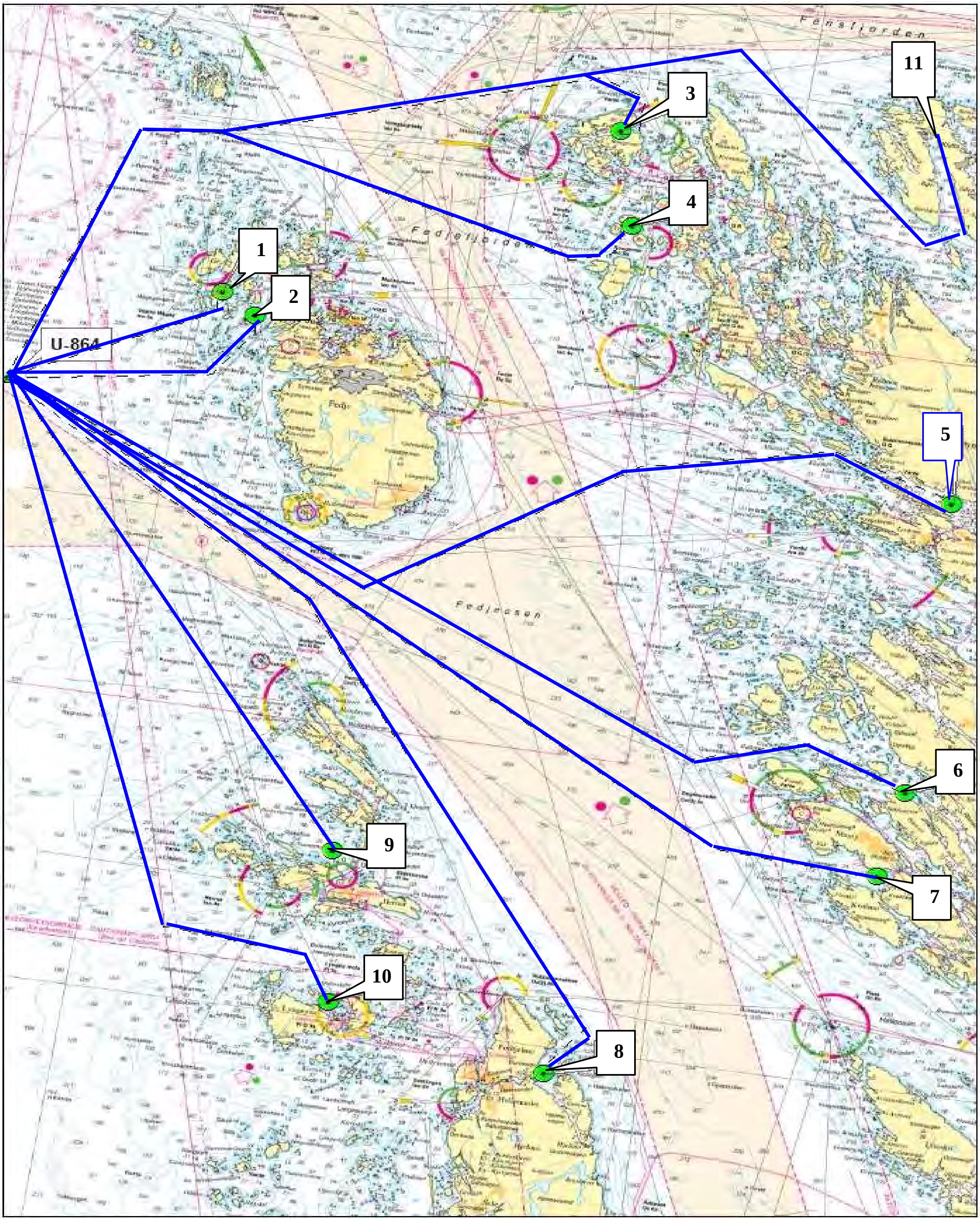
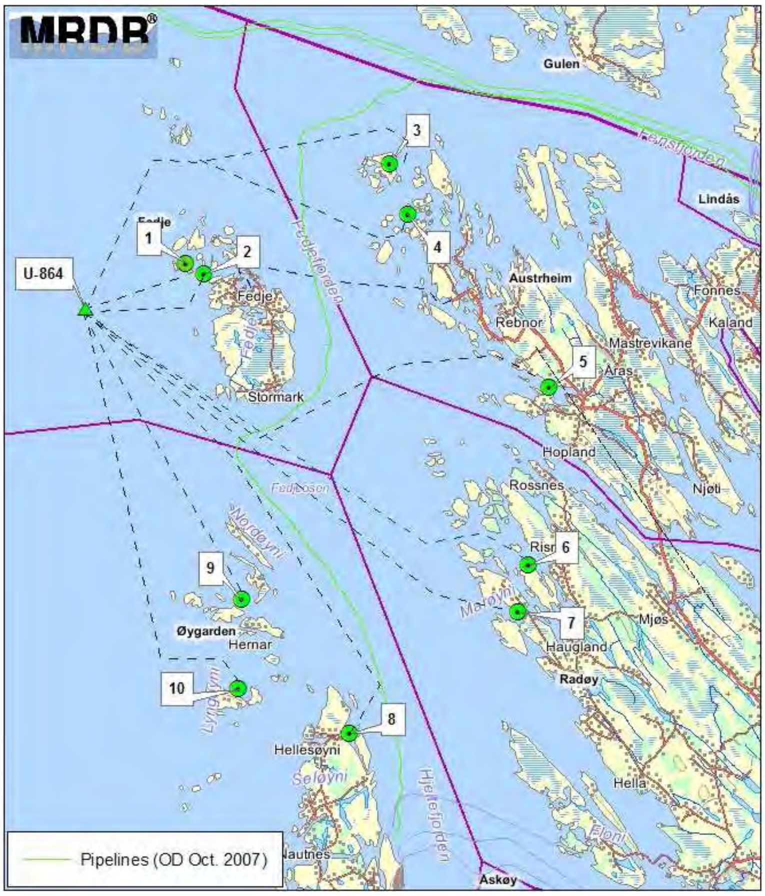


Figure 4-1 Potential transportation routes (blue lines) and sheltered locations (marked with no. 1 to 11)

4.2 Potential conflicts with oil and gas pipelines

From the Troll oil field an oil pipeline runs directly from Troll B to Mongstad, and a gas pipeline runs from Troll A to Kollsnes and then further from Kollsnes to Mongstad (see Figure 4-2) /4/. The gas pipeline between Kollsnes and Mongstad runs from the Kollsnes terminal over land to Osundet east in Øygarden. Here the pipeline dives into the sea, follows the Osundet into Hjeltefjorden along the eastside of Øygarden and Fedje and then turns right into Fensfjorden to Mongstad where the pipeline rises in a tunnel to the refinery area.

In case of choosing a transportation route to locations no. 3-7, the gas pipeline will be crossed. Transportation to location no. 1-2 and 8-10 involve no implications with the pipelines. If a submerged transportation method is chosen, the risk of loosing the wreck when crossing a pipeline must be assessed.



Location no.	Pipeline/cable Crossing
1	NIL
2	NIL
3	Pipeline North of Fedje
4	Pipeline North of Fedje
5	Pipeline 0.7nm South of Fedje, Cable 5.5nm East of Fedje
6	Pipeline 0.5nm South of Fedje
7	Pipeline 1.1nm South of Fedje
8	East of Forhjelmo
9	NIL
10	NIL
11	Pipeline North of Fedje

Figure 4-2 Pipeline (green line) between Kollsnes in Øygarden and Mongstad in Austrheim /1/

4.3 Safe distance when handling explosives

For safety reasons, due to the explosives on board U-864, special considerations have to be made for distance to building and population density. (see *Supplementary Study No. 2: Explosives* for more information on explosives on board U-864).

The three locations assessed most suitable, were inspected on site by the Norwegian Defence OED-command (Ordnance, Explosives and Disposal, named MDK) to assess whether they have proper shelter for possible fragments and chock waves if an explosive detonates. The assessment of location no. 2, 5 and 8 are as follows:

Location no. 2:

This location has no shelter for wind and the waves which are normal on this location. This location is therefore assessed as not useful.

Location no. 5:

Good weather shelter. There are quite many houses in the area which complicates the securing of the location in order to handle explosives in U-864.

Location no. 8:

Good weather shelter. It is easy to position a barge close to a knoll to reduce fragments considerably, including the shipping lane. Some houses are within the secure distance for fragments, but measures on site can be done to make it secure. There are reads in the vicinity of this location.

Location no. 11, proposed by the MDK (N60˚49'30.1" E4˚52'30.0")

Good weather shelter. There are no permanent residences closer than 2,4 km from the location, only some cabins approximately 1 km away. Adequate water depths in the area. This location is assessed as the most suitable of location no. 2, 5, 8 and 11 by the MDK.

5 VULNERABLE NATURAL AMENITIES

Table 5-1 displays factor regarding vulnerable natural amenities that must be considered for each location respectively when choosing location for disarming and cleaning the wreck of U-864 and the transportation route to this location.

Table 5-1 Factors regarding vulnerable natural amenities that must be considered (orange shading) for each location respectively when choosing transport route and location (corresponding chapters are included)

Location	Especially environmental sensitive area (ch. 5.1)	Prioritized environmental sensitive area (ch. 5.2)	Protected and important areas for birds (ch. 5.3)	Shorelines (ch. 5.4)	Fisheries and aquaculture (ch. 5.5)	Outdoor life and culture (ch. 5.6)	Comments
1							Protected areas and important bird areas close to the location. Possible conflicts with aquaculture activity in the area and spawning grounds.
2							Protected areas and important bird areas close to the location. Possible conflicts with aquaculture activity in the area and spawning grounds.
3							Passing close to MOB A area (Innesøyane). Conflict with another MOB A area (Kuøyna), and with protected recreational area.
4							Passing close to MOB A area (Innesøyane). Conflict with another MOB A area (Kuøyna), and with protected recreational area.
5							Conflict with protected areas and important bird areas. Possible conflicts with aquaculture activity.
6							Conflict with protected areas and important bird areas. Possible conflicts with aquaculture activity.
7							Conflict with protected areas and important bird areas. Possible conflicts with aquaculture activity.
8							Conflict with protected and important bird areas.
9							Location close to MOB B area (Kortknappskjær). Possible conflicts with aquaculture activity in the area and spawning grounds.
10							Location is in a MOB B area (Seløy, Alvøy). Possible conflicts with aquaculture activity in the area and spawning grounds.
11							Not assessed

The list below (and Figure 5-1 on page 18) includes are some of the most important factors to consider when assessing the most feasible sheltered location for disarming and cleaning the wreck of U-864 and the transportation route to this location:

- Especially environmental sensitive areas for certain species (SMO-areas) (assessed in chapter 5.1)
- Prioritized environmental sensitive areas (MOB-areas) (assessed in chapter 5.2)
- Protected areas and other important areas for seabirds (assessed in chapter 5.3).
- Shorelines categories (assessed in chapter 5.4)
- Fisheries and aquaculture (assessed in chapter 5.5).
- Outdoor life and culture (assessed in chapter 5.6).

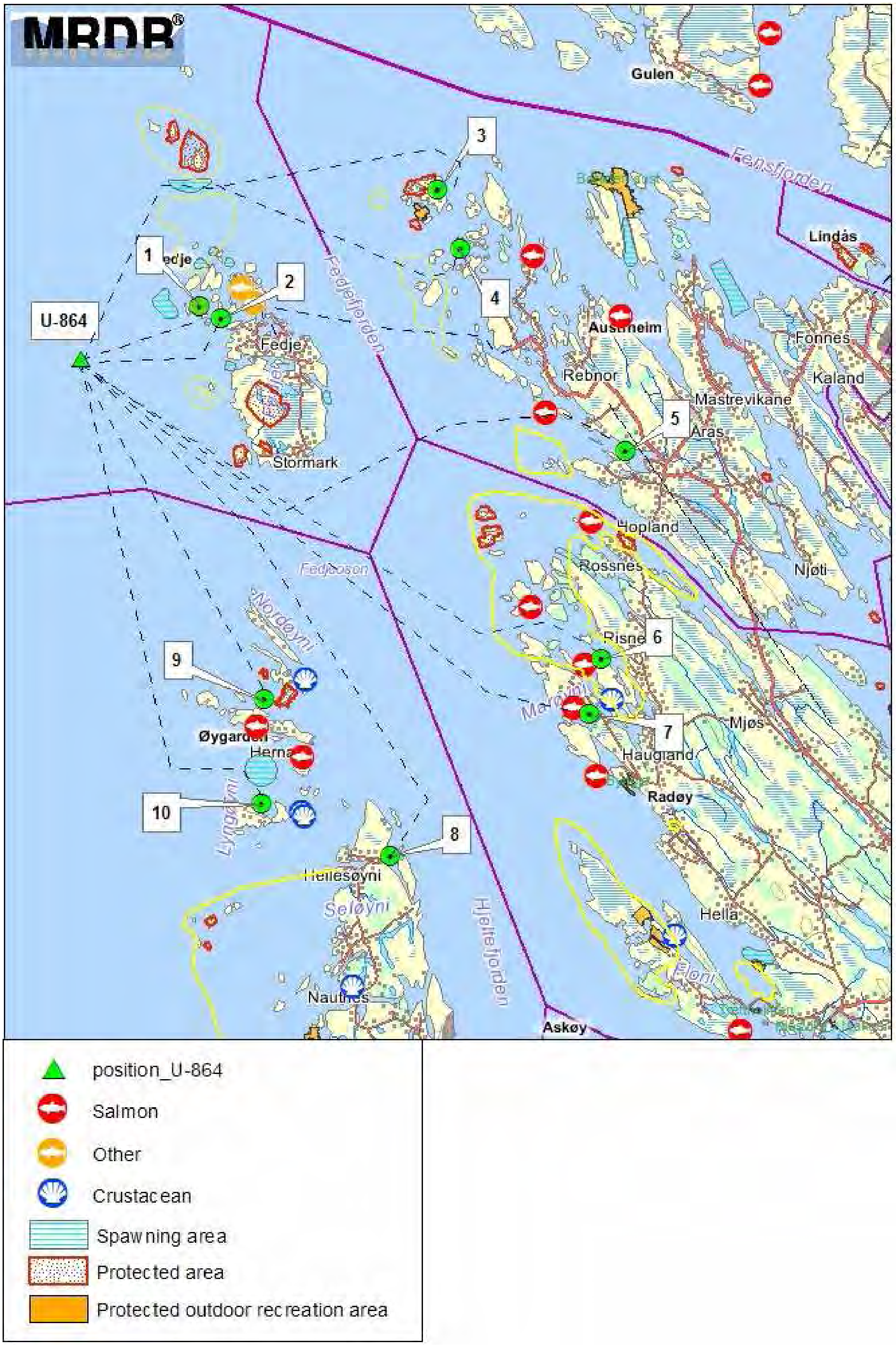


Figure 5-1 Important parameters to consider when evaluating the risk associated with elevation and transportations of U-864.

5.1 Especially environmental sensitive areas for certain species (SMO-areas)

Especially environmental sensitive areas are identified from a set of objective criteria, selected environmental components and their distribution and vulnerability for acute oil pollution. The SMO-concept is build upon the following main elements; Natural resources in Norwegian ocean and coastal areas, Relevant influence factors and their threat to the resource, The resources vulnerability to the relevant threat and the potential damages the threat may cause /15/.

SMO is a geographically restricted area with one or more significant distributions of natural resources vulnerable to a given influence factor. All of the SMOs will suffer greatly from any type of pollution and will require a certain time in order to recover to a natural level after any considerable damage. The SMOs are identified at regional, national or international levels /10/.

SMO for seabirds and marine mammals located close to the area of interest are presented in Figure 5-2. Identified SMOs will not be relevant for choice of sheltered location and transportation route as they are all at a distance from the proposed locations. The most northern locations 1 and 3 are, however, a bit closer to the SMOs than the more southern locations, and should be considered when giving a general evaluation of the environmental risk associated with the operation. There are only regional SMOs in the area. Identified SMOs are for common eider and Red-breasted Merganser in the period August-September, SMOs for Kittiwake in April-August, SMOs for Great Cormorant in October-March and for Shag year round. Harbour Seals are also present in the area year round.

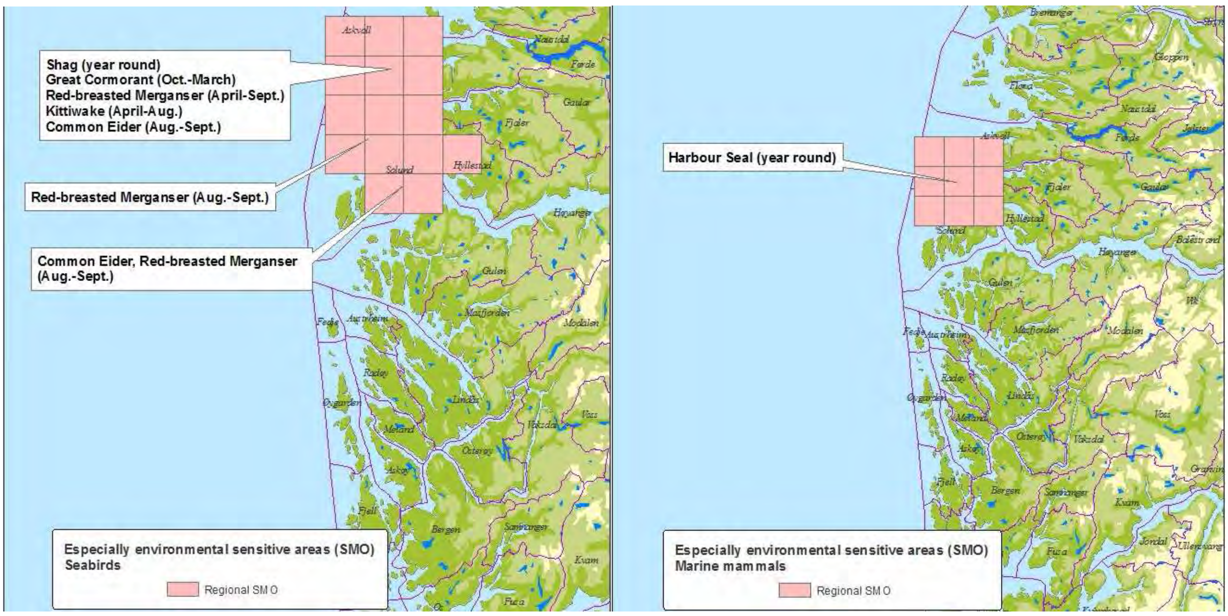


Figure 5-2 Especially environmental sensitive areas for seabirds (left) and marine mammals (right) /13/

5.2 Prioritized environmental sensitive areas (MOB-areas)

MOB is a model for identifying and prioritizing vulnerable environmental resources in case of acute oil spills along the coast. Resources vulnerable to oil pollution will also need extra focus when considering the environmental risk associated with transportation of U-864. The MOB-model is based on four factors:

- Naturalness; is the resource natural?
- Replaceability; can the resource be replaced economically?
- Protective value; what protective value does the resource have?
- Vulnerability; how vulnerable is the resource to oil pollution?

Each factor is given a value, giving the environmental resource a collective priority value which can be arranged by prioritising categories (A-E) where A is the highest priority and E is the lowest priority.

The MOB-areas of priority A and B in the areas of the potential transport routes for U-864 are given in Figure 5-3 on page 21. All the municipalities potentially affected have MOB-areas of priority A or B.

For information about each the MOB-areas in the affected municipalities, see Appendix A chapter A.1 to A.4.

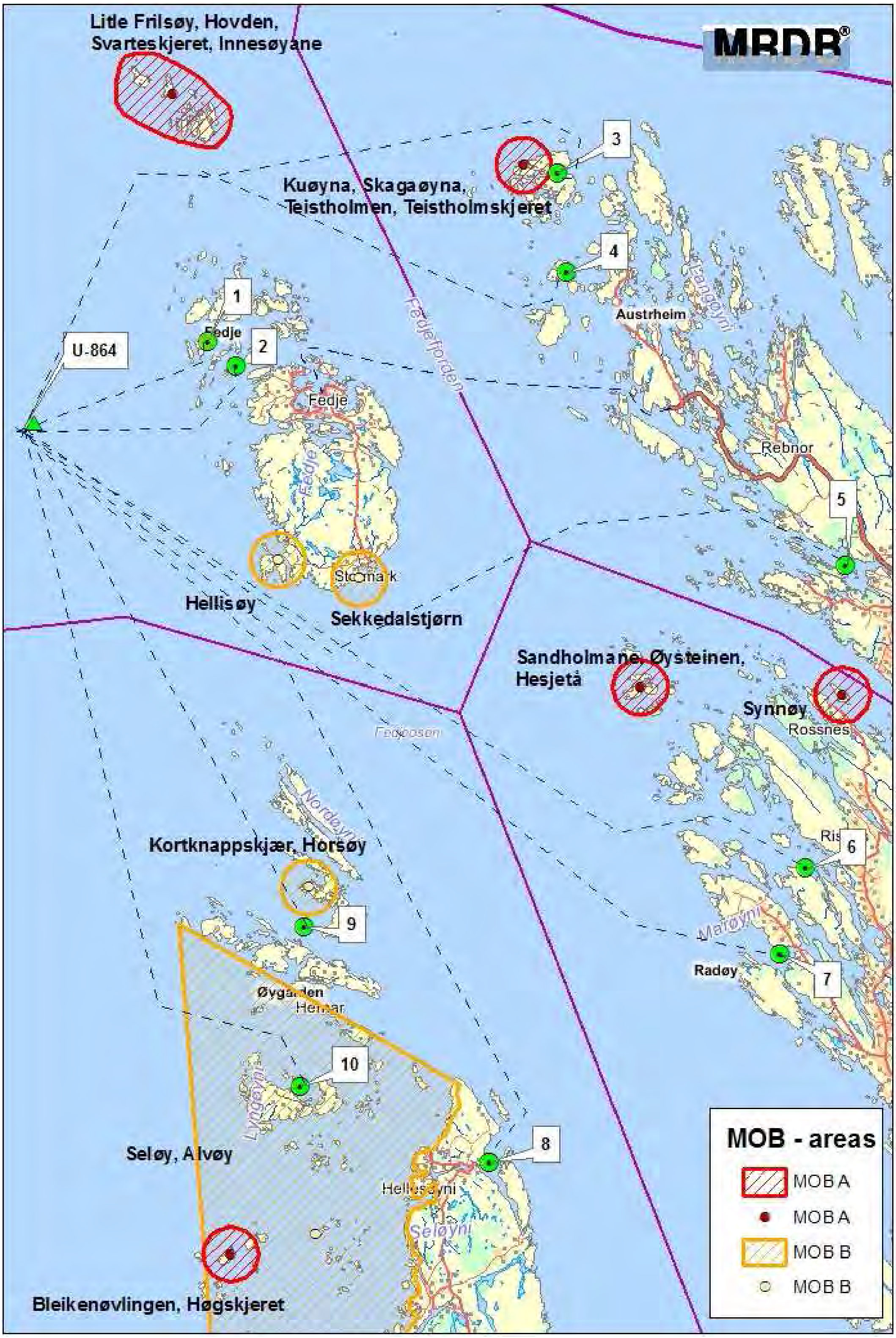


Figure 5-3 MOB-areas in the areas of the alternative transport routes for U-864 /1/

5.3 Protected areas and other important areas for seabirds

5.3.1 Location no. 1 and 2: Fedje municipality

There are two potential transport routes Fedje; to the area east of Sandholmane (no. 1) and to the southern parts of Skarvøya (no. 2).

Marine shallow sea areas are rare in the area and found mainly around the smaller islands north and west in the municipality.

The municipality is situated in the middle of the most important migration route for seabirds along the coast. Fedje is the municipality in Hordaland where the highest diversity of seabird species has been registered (a total of 228). The bird life is of great importance in the municipality. There are several areas in the municipality considered important to seabirds some of which are protected by the state. Three nature reserves were established in Fedje in 1987, due to status as nesting areas for seabirds; Hellisøy, Sekkjedalstjørna, Innesøyane. There is also a large protected area at Fedje island; Fedjemyrane special landscape area (1995). See Appendix A chapter A.1 for more information about these protected areas.

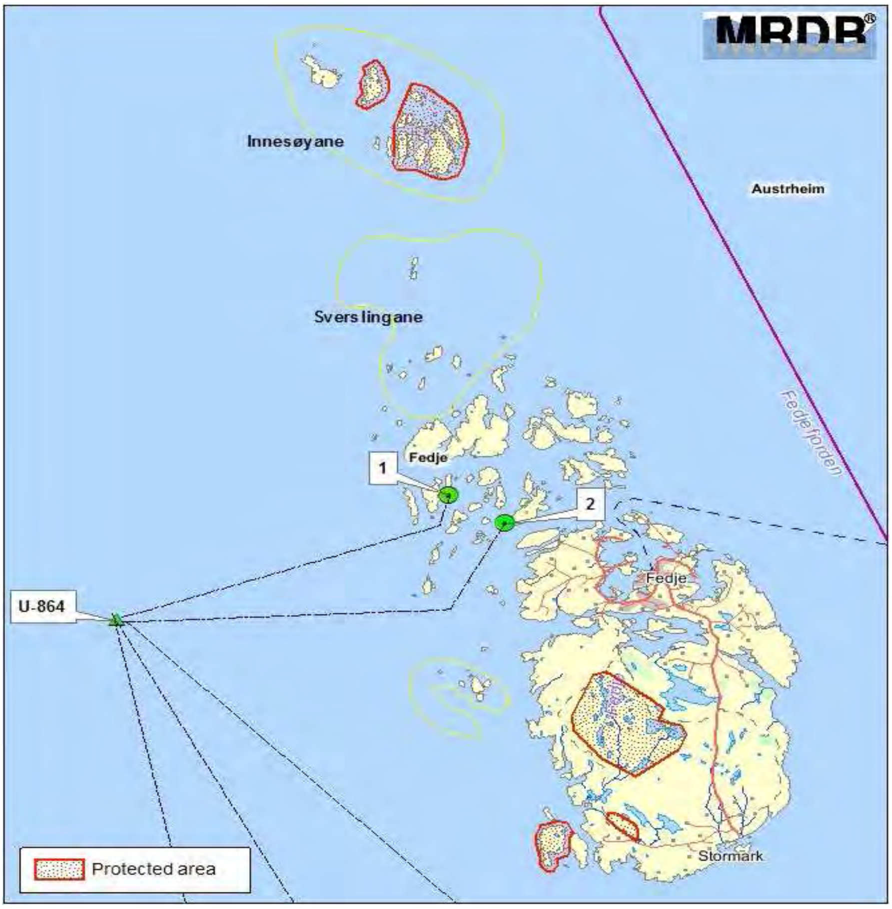


Figure 5-4 Protected areas and areas of special importance to seabirds at Fedje.

5.3.2 Location no. 3, 4 and 5: Austrheim municipality

Austrheim municipality is situated northeast in Hordaland. The municipality is the second smallest in Hordaland. The shoreline is conspicuous and there are several shallow sea areas important for a diversity of species. There are three possible locations for bringing U-864 to sheltered locations in Austrheim (see Figure 5-5).: no. 3 by Rognevær, no. 4 between Eikholmen and Maiskjeret, and no. 5 in Austrheimvågen at Fosnøyna

There are several important areas to consider when looking at the shipping lanes to location no. 3, 4 and 5:

- Location no. 3 is situated very close to Kuøyna, Skagøyna, Teistholmen and Teistholmskjeret Nature reserve.
- Transportation to location no. 4 involves passing between Teistholmen and the area Langskjeret – Senoksen.
- Transportation to location no. 5 means that *Sandholmane, Øyesteinen and Hesjetå Nature reserve* in Radøy municipality will be the closest protected areas (for more information about this nature reserve, see Appendix A chapter A.3 about Radøy municipality)

See Appendix A chapter A.2 for more information about these and other protected areas in Austrheim.

Figure 5-5 Protected areas in Austrheim and Radøy municipality.

5.3.3 Location no. 6 and 7: Radøy municipality

Radøy municipality is situated in the outer part of Nordhordland and is surrounded by fjords and straits in the west and the east. The municipality borders to Austrheim in the north. About 24 % of the total area of the municipality is agricultural areas.

There are several important wildlife areas in the municipality. The following areas will be important to consider in case of choosing transportation routes to location no. 6 or 7:

- Villvangsosen-Syltvågen
- Synnøy Nature reserve
- Uttoska, Toska
- Klubbesøyna
- Kuvågen

See Appendix A chapter A.3 for more information about these protected areas.

Figure 5-6 Protected areas and areas of special importance to seabirds in Radøy municipality.

5.3.4 Location 8, 9 and 10: Øygarden municipality

There are three alternative sheltered locations in Øygarden: no. 8 at Hellesundet, no. 9 in Horsøyosen and no. 10 at Lyngøyna. There are three protected Nature reserves close to these locations, and protected areas at Fedje will be passed during transportation to these locations:

- Horsøy and Kortknappskjer Nature reserve.
- Bleiknøvlingen and Høgskjeret Nature reserve
- Teistholmen Nature reserve

See Appendix A chapter A.4 for more information about the protected areas in Øygarden.

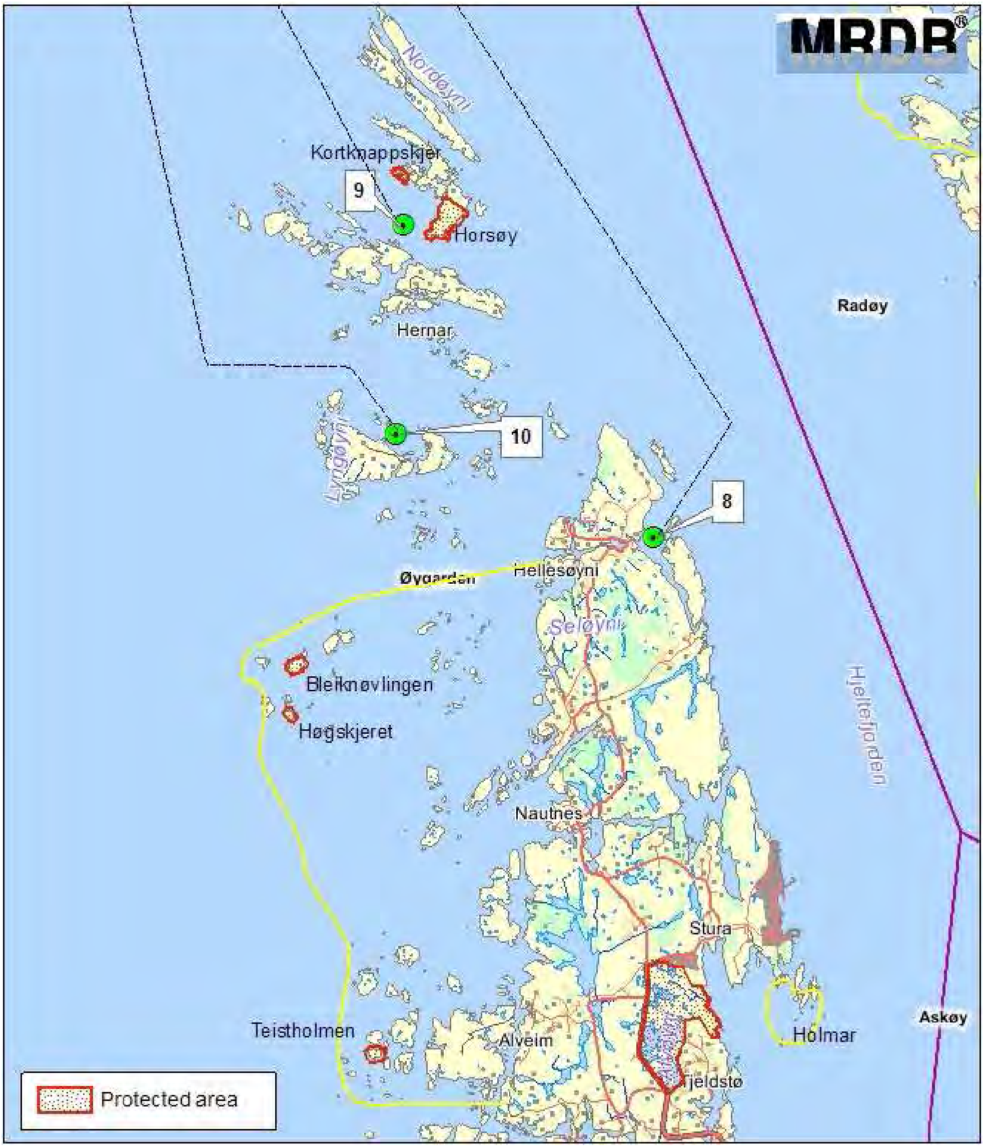


Figure 5-7 Protected areas and areas of special importance to seabirds in Øygarden municipality.

5.4 Shorelines

Different types of shorelines have different vulnerability to pollution, due to variations in exposure and ability to self clean. High exposure leads to less accumulation of pollution, and therefore lesser vulnerability compared to corresponding shorelines in more shielded areas. The ability to self clean is usually better for rocky shores and more exposed locations. Pure soft-bedded shorelines are more difficult to clean than sea cliffs and bare rock-face /14/.

The dominating shoreline category in the area of concern is assumed to be bare rock-face (see Figure 5-8). Some areas of human made structure also occur in the area Stormark (Fedje), Nordøyna/Hernar/Sture (Øygarden) and areas of human made structure and rocky shore/sandy beach occur at Hopland in Austrheim.

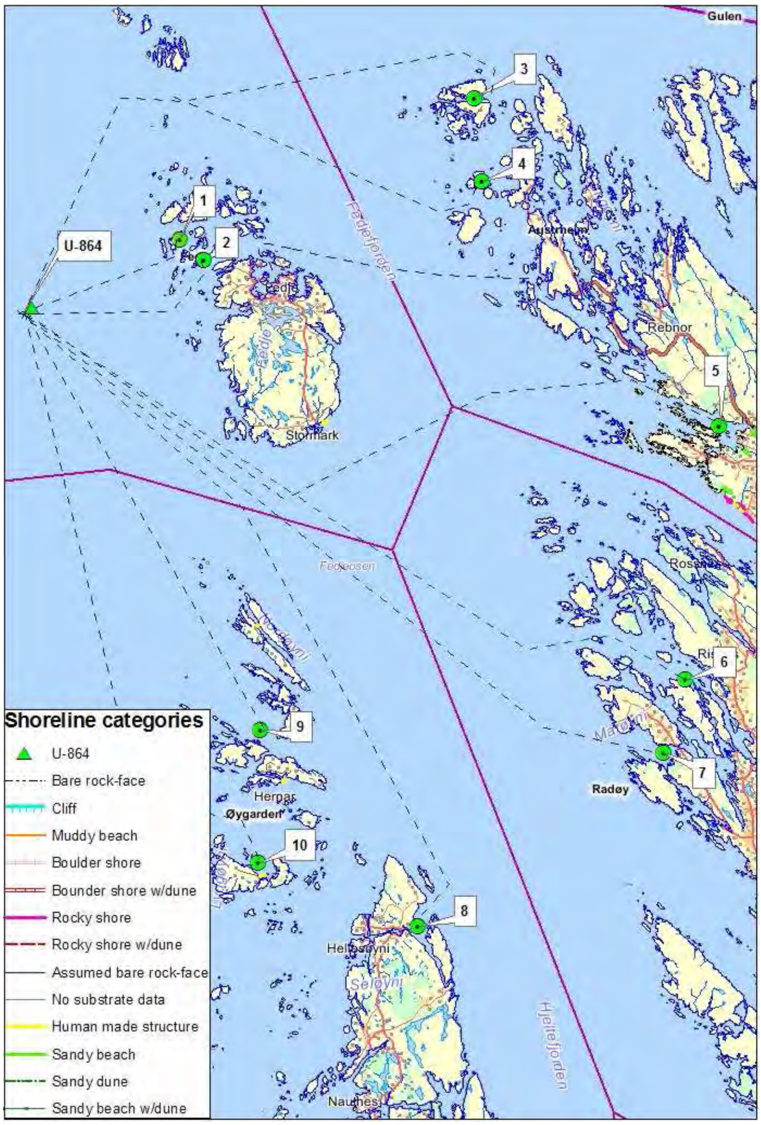


Figure 5-8 Shoreline categories in the areas around the potential sheltered locations for U-864. The figure shows that the dominating shoreline category is assumed bare rock-face (in blue) in the whole area. /15/

5.5 Fisheries and aquaculture

In the areas surrounding Øygarden and Fedje there is a local fishery for shrimps, pollock, mackerel and herring. The western side of these municipalities, the east-western straits in Øygarden and the sea areas surrounding Forhjelmo (at the northern tip of Seløy) and northward are important fishing areas. The activity varies from year to year, but during recent years the fisheries have been reduced in both size and importance.

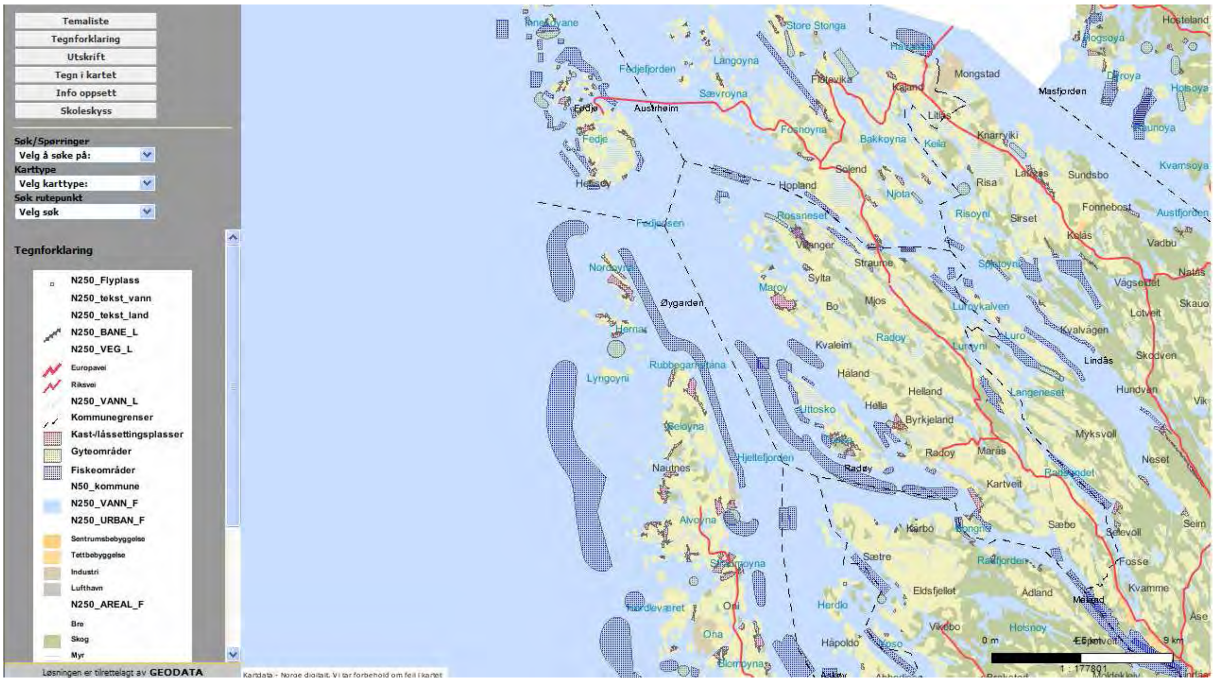


Figure 5-9 Fishing areas, spawning areas, casting sites and netpen sites /16/

Aquaculture involves cultivation of organisms in water, for instance fish, scallops, algae etc. Hordaland is the most important county in Norway when it comes to aquaculture activity.

Figure 5-10 on page 28 shows fish farming locations in the areas close to the identified sheltered locations. The map is based on presently given licenses (September 2007), but the picture may change in short time. Not all the areas are in use today, but may be later on, and new licenses may be allocated.

TECHNICAL REPORT

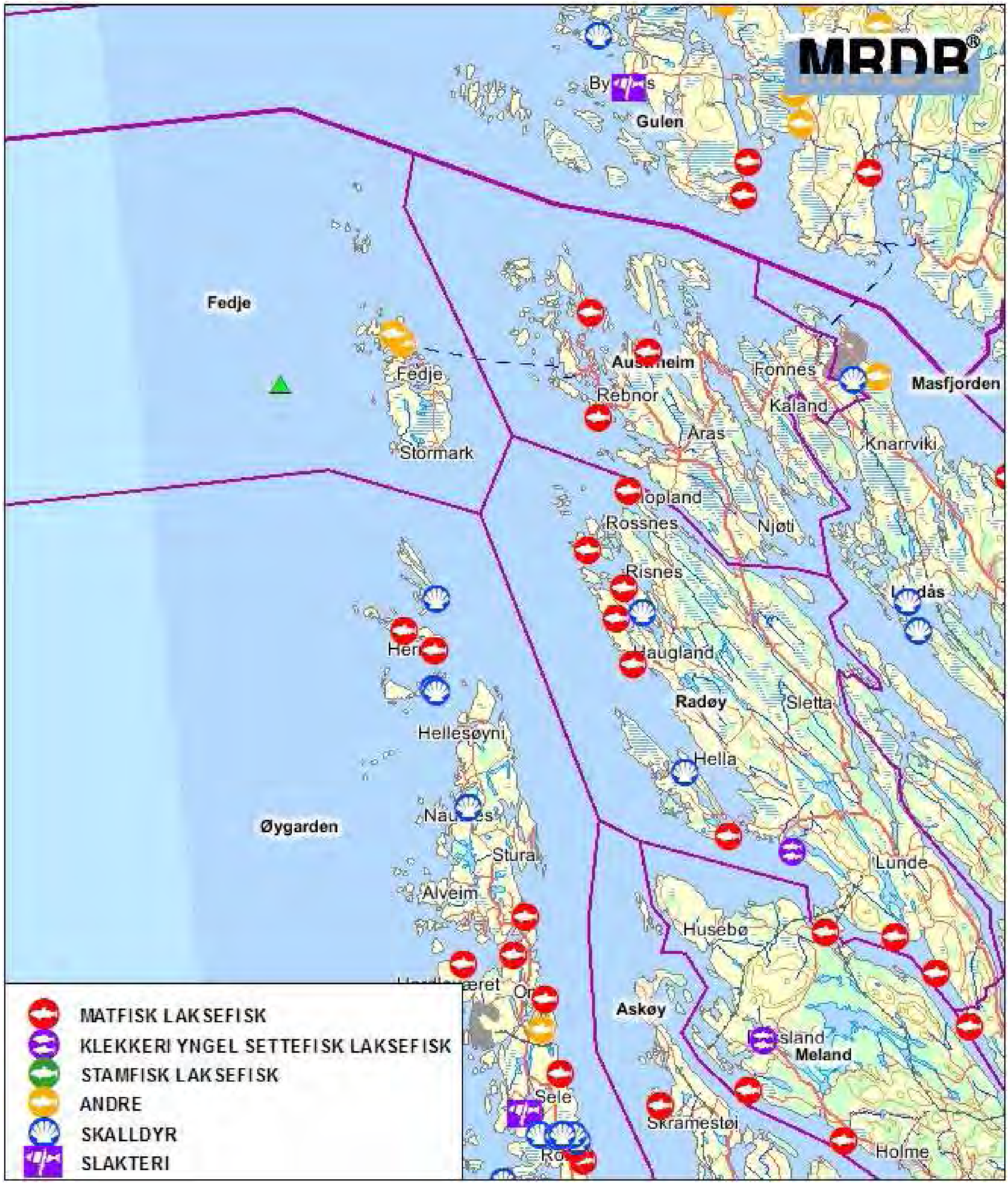


Figure 5-10 Fish farming areas in Øygarden, Fedje, Radøy and Austrheim /18/.

5.6 Outdoor life and culture

Outdoor life

The outdoor life in the relevant region is mainly connected to the use of sea areas and shoreline. Hjeltefjorden (east of Øygarden) has many beaches and popular boat areas, amongst others at Toska, Trettholmen, Skageneste and Byngja in Radøy municipality, and Øksnes and Sauøyna in Austrheim municipality. Several of the areas are protected by the state for recreational purposes. There are also several boat areas of regional value in the relevant areas, especially northwest at Radøy and west in Austrheim. In Øygarden there are also several important boating areas where the northern islands are of most importance /4/. There are several regional outdoor recreation areas in the municipalities potentially affected by the operation. The areas are shown in Figure 5-11, and are given priority *very important* ("svært viktig"), *important* ("viktig") and *registered* ("registrert").

Figure 5-11 Regional outdoor recreation areas /16/

For more detailed information, see Appendix A chapter A.6.

Cultural heritage

Several protected cultural heritage sites are registered on land in both Øygarden and Radøy, and a few in Austrheim. There are also potential for additional findings in the areas. Figure 5-12 shows a variety of historical monuments (marked with "*R*"), protected buildings, museums, libraries and churches.

Hellisøy Fyr situated at Fedje is protected by the law of cultural heritage from 2000. North in Austrheim there is one protected building and one historical monument.

In Øygarden there are three locations with historical monuments in the north/north western parts of Seløyna. There are also two locations with historical monuments at Stura, further southeast in the municipality.

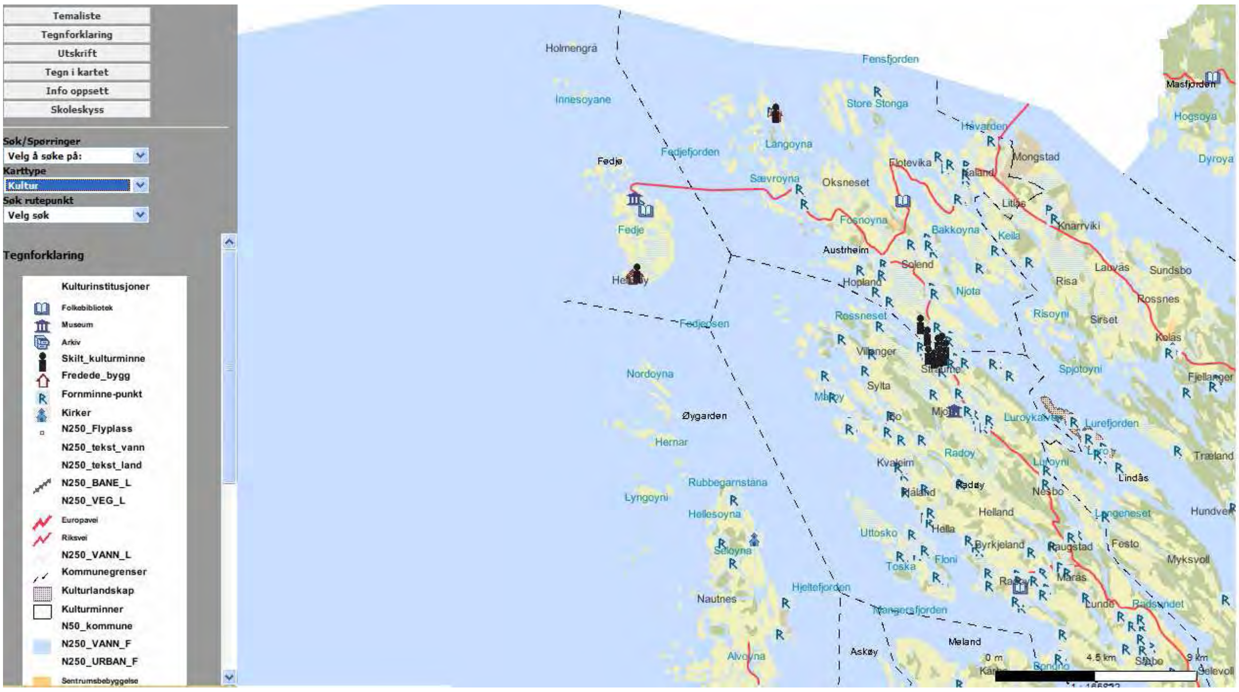


Figure 5-12 Cultural values in the relevant areas /16/

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/17/ Naturbase, http://dnweb12.dirnat.no/nbinnsyn/

/18/ Fiskeridirektoratet, September 2007.

/19/ Fedje kommune: http://www.fedje.kommune.no

/20/ Austrheim kommune: http://www.austrheim.kommune.no

/21/ Radøy kommune: http://www.radoy.kommune.no/

/22/ Øygarden kommune: http://www.oygarden.kommune.no

APPENDIX

A
MUNICIPALITIES POTENTIALLY AFFECTED BY THE OPERATION

A.1. Fedje municipality

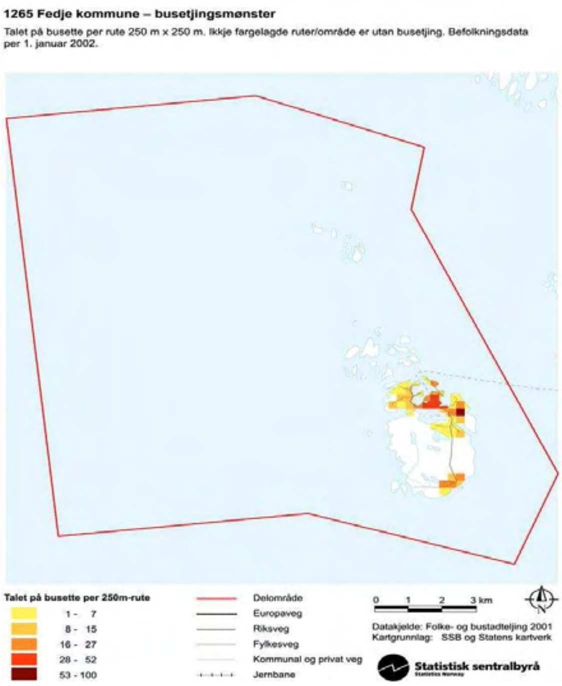

Figure A - 1 Population densities in Fedje. Number of inhabitants pr 250 x 250 m squares. White areas are without settlements (January 2002).

Settlements and population densities

The population of Fedje was in 2006 620 people. The population density is largest in the north-eastern areas of the main island Fedje; Kirkevågen-Rognsvågen and going west towards the community Fedje (see Figure A - 1). Fedje is the only densely populated area (per definition: > 200 inhabitants) in the municipality with 452 inhabitants (SSB, January 2007) There is also a certain population density south-eastern areas of the island (Stormark).

Industry

The total area of Fedje is 9, 4 km^2, of which 0, 3 km^2 is agricultural area. The extension of forest area is very limited (0, 1 km^2).

The industry at Fedje is varied, with production of fish, whale meat, steel constructions and pewter. Fishing, and tourism and the travel industry are becoming more and more important. The pewter production is however moving the business to Nesodden during the winter of 2007/2008. Other businesses at Fedje are the towboat shipping company Buksér og Berging which has an office in Fedje. Fedje has a training centre offering safety courses for fishermen. There are schools, library and health/social services at Fedje.

The industry at Fedje is located in the area around the ports; Kirkevågen and Rognsvågen. /19/

Prioritized environmental sensitive areas (MOB-areas)

In Fedje there is one MOB A area covering the northern archipelago with Litle Frilsøy, Hovden, Svarteskjeret and Innesøyane Nature reserve. The area has national protective value and is considered to be one of the most important nesting areas for seabirds in Hordaland. There are two MOB B areas in the southern parts of Fedje; Hellisøy in the west and Sekkedalstjørn in the east. The areas are further discussed on the next page.

Protected areas and other important areas for seabirds close to the potential transport routes /6/ (see Figure 5-4 on page 22)

The seabird populations in Western Norway have been declining the past decades, and some of the nature reserves have therefore lost their original function. New colonies without protective status have developed, some of which are further elaborated below.

Relevant areas reflecting the potential shipping lanes are displayed in Figure 5-4 on page 22.

Innesøyane: Nature reserve, protected in 1987.

This is a vigorous and growing seabird colony. The archipelago has a good breeding colony of Herring Gull and a few tens of breeding Lesser Black-backed Gull. The breeding population of Greylag Goose is increasing whilst the population of terns have been reduced. The Ruddy Turnstone also breeds at the islands, as well as Common Eider. The Common Eider also has moulting areas in the shallow sea areas in the northwest (July-August). Harbour Seal is observed in the low tide rocky areas from time to time, but only a few individuals. During wintertime several of the smaller islands serve as roosting areas for Cormorant.

Sverslingane

This is an important growth area for several seabirds Common Eider, Great Cormorant and Fulmar, and partly for Black Scoter. It has also recently been established as a moulting area for Common Eider.

Fedjeboen – Islendingane

This is a winter area for seabirds; Black Scoter (up to 300 individuals, mainly in the late winter), Common Eider, Fulmar and partly for Cormorant (Great Cormorant and Shag).

Fedjemyrene

This is a special landscape area with wildlife protection. It is an important breeding area for several types of birds. five species of ducks, among others Mallard, Eurasian Teal and Red-breasted Merganser, four species of waders, among others Snipe, Redshank, Oystercatcher, and six species of gulls, terns and Arctic Skua. It is also a breeding area for Greylag Goose and Red-throated Diver, and some pairs of Common Eider.

Hellisøyane: Nature reserve, protected in 1987

Hellisøyane has the most important breeding colony of Herring Gull at Fedje (> 100 breeding pairs). The colony and has been vigorous since 1980, and is one of the most stabile seabird colonies in Hordaland.

Sekkjedalstjørna, Nature reserve, protected i 1987

The nature reserve was established through a protection plan for seabirds, but there is very little breeding activity in the area today. The largest breeding colony of Black-headed Gull was in the area in the 1980ies. It’s been several years since considerable wildlife activity has been registered in the area. This absence may be temporary; therefore it has kept the protective status.

A.2. Austrheim municipality

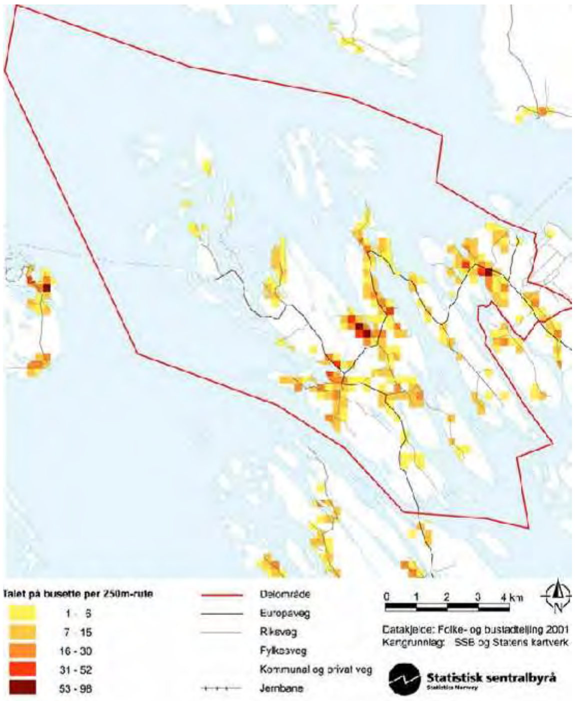

Figure A - 2 Population densities in Austrheim. Number of inhabitants pr 250 x 250 m squares. White areas are without settlements (January 2002).

Settlements and population densities

The population of Austrheim municipality is 2530 people (2007). There are two densely populated ares (per definition: > 200 inhabitants); Kaland with 407 inhabitants and Årås with 560 inhabitants (SSB, January 2007). The population density is largest in the in Åråsvågen (see Figure A - 2). /3/

Industry

The last 25-30 years the industry in Austrheim has gone from mainly being based on agriculture and fishery to becoming more of a industry and oil driven community with the development of the Mongstad refinery, base and harbour partly situated in the north of Austrheim. Potential conflicts with the oil industry are considered in chapter 3. The municipal administration in Austrheim is located in Mastrevik. /20/

Prioritized environmental sensitive areas (MOB-areas)

In Austheim there is one MOB A area: Kuøyni, Skagøyni, Teistholmen and Teistholmskjeret Nature reserve. The area is situated in the north western parts of the municipality, and is further discussed below. It may also be mentioned that there are two MOB B areas further northeast outside the map segment in Figure 5-3 on page 21.

Protected areas and other important areas for seabirds close to the potential transport routes /7/ (see Figure 5-5 on page 23)

Kuøyna, Skagøyna, Teistholmen og Teistholmskjeret Nature Reserve

Kuøyna Nature Reserve was established due to the breeding stock of Herring Gull totalled counted 100 pairs in 1979. The stock is reduced today, but the reserve is increasingly important as it is a breeding area for Greylag Goose. Teistholmen has earlier been a breeding area for Black Guillemot, but little activity has been registered the last few years. The stock of Black Guillemot in Hordaland has in general been low the past decades, but a small increase has been registered during recent years. It is therefore reason to believe that Teistholmen may recover some of its original importance.

Vetegjøgrasskjeret

Vetegjøgrasskjeret is situated west of Kuøyna and Skagøyna. This is not a protected area (marked with a yellow line in Figure A - 3 on page A6), but still considered as an important area for seabirds due to large and concentrated flocks of common eider during the winter season. The area south of Teistholmen (see Figure A - 3 on page A6, marked with a yellow line) is also considered an important wildlife area. The area extends from Langaskjeret in the north to Senoksen in the south, and is a winter area for seabirds, mainly Great Cormorant, Shag and Fulmar, and some Common Eider. There are also several roosting areas for cormorant. Some of the smaller islands are considered to be potential breeding areas for Shag.

Langskjeret – Senoksen

The area Langskjeret – Senoksen is a winter area for seabirds. The most important species in this area are Great Cormorant, at in the islands. Several of the smaller islands are considered to be potential breeding areas for Shag.

Choise of transportation route to Fosnøyna (no. 5) means that *Sandholmane, Øyesteinen and Hesjetå Nature reserve* in Radøy municipality will be the closest protected areas (see Figure A - 3). The nature reserves are enclosed in a large important wildlife area, marked with a yellow line in the figure. The area is further elaborated in Appendix A chapter A.3.

The area Vardholmen – Vardholmskjeret (marked with a yellow line in Figure A - 4 on page A7) does not have protective status, but is considered an important bird area due to occurrences of Great Cormorant and Fulmar during wintertime.

Figure A - 3 Protected areas and areas of special importance to seabirds in Austrheim.

Figure A - 4 Protected areas and areas of special importance to seabirds in Austrheim and Radøy municipality.

TECHNICAL REPORT

Figure A - 5 Protected areas in Austrheim and Radøy municipality.

A.3. Radøy municipality

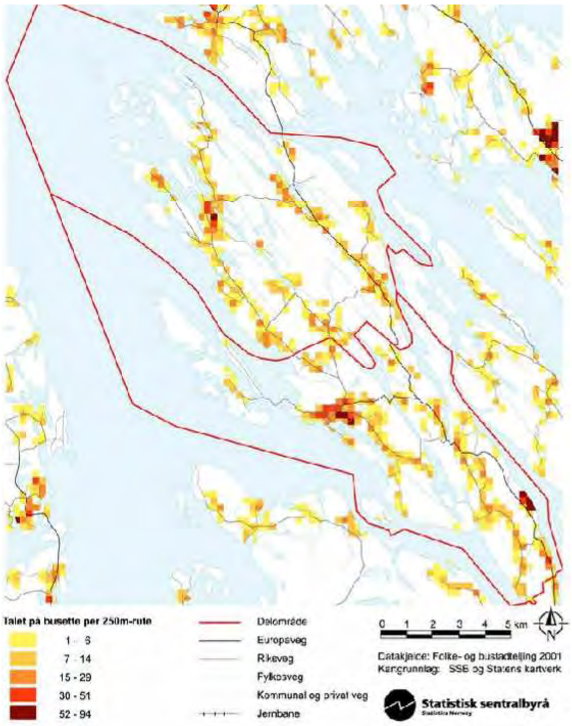

Figure A - 6 Population densities in Øygarden. Number of inhabitants pr 250 x 250 m squares. White areas are without settlements (January 2002).

Settlements and population densities

The population of Øygarden municipality is 4663 people (2007). There are three densely populated areas in Radøy municipality: Austmarka with 392 inhabitants, Manger with 829 inhabitants and Haugland with 429 inhabitants (SSB, January 2007). The population density in general is also largest in the areas surrounding Manger and Haugland (see Figure A - 6). /3/

Industry

The main industries at Radøy are agriculture, fishery products, food industry and wood ware industry.

/21/

Prioritized environmental sensitive areas (MOB-areas)

In Radøy there are two MOB A areas; Sandholmene, Øyesteinen and Hesjetå Nature reserve and Synnøy Nature reserve. The areas are further discussed below.

Protected areas and other important areas for seabirds close to the potential transport routes /8/ (see Figure 5-6 on page 24)

Villvangsosen-Syltvågen

Villvangsosen-Syltvågen is a large archipelago with several islands of different sizes and skerries. One of the important wildlife areas encloses location number 6. The area mainly serves as breeding and foraging area for Common Eider, Gulls and terns, and foraging area for cormorant and ducks. European sea eagle and Eagle Owl is found to breed in the area. The area also encloses *Sandholmane, Øyesteinen and Hesjetå Nature reserve* north in the area. The protective status is based on 20 pairs of breeding Common Gull and a few other pairs of other gull species in 1977. Ruddy Turnstone and Arctic Skua have also been registered breeding in the area. Today the breeding populations are rather limited, but the occurrence of Ruddy Turnstone needs special care. The area is attractive for recreational activities.

Synnøy Nature reserve

Synnøy is situated east in the municipality (se Figure 5-6 on page 24). Important birds in the area are Common Gull, Common Tern, Greylag Goose and Common Eider. The protective status is based on the occurrence of 100 pairs of Common Gull and 20 pairs of Common Tern registered in 1977. There is still a breeding stock of Common Gull in the area, even though it is smaller than in 1977, due to extensive mink predation. Today the stock is larger than it was during the period 1988-1992. The Greylag Goose population is increasing in the area.

Uttoska, Toska

The wildlife area Uttoska is situated south in the municipality (see Figure 5-6 on page 24). The area encloses the north-western part of Toska, Uttoska and some smaller islands. Registered breeding birds in the area are amongst others Common Eider, Red-breasted Merganser, Herring Gull, Great Black-backed Gull, Common Tern, Arctic Skua, Oystercatcher, Eurasian Curlew, Meadow Pipit, Twite and Linnet. During the migration period there are frequent occurrences of Graylag Goose in the area. In the late seventies there was a large mixed colony of all the four species of gulls at Uttoska. The colony does not exist today, but it may reappear. There are still a few gull species breeding in the area.

Klubbesøyna

Klubbesøyna southwest in the area is considered an important area because it is covered with old pine forest which is relatively pristine.

Kuvågen

Kuvågen is a rather shallow inlet with muddy shore which is exposed at low tides. The area probably is a foraging area for waders during the migration period, but no systematic registrations have been done at the location.

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A.4. Øygarden municipality

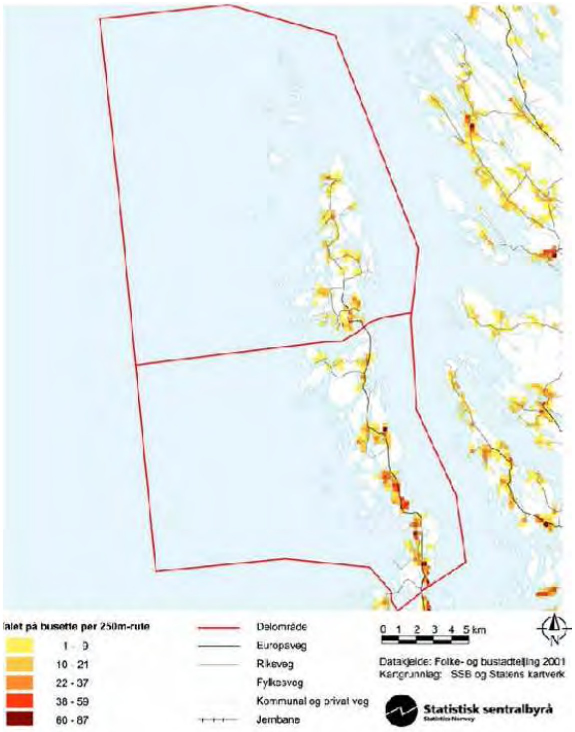

Figure A - 7 Population densities in Øygarden. Number of inhabitants pr 250 x 250 m squares. White areas are without settlements (January 2002).

Settlements and population densities

The population of Øygarden municipality is 4134 people (2007). Øygarden is an archipelago with several islands, most of which are connected with bridges. There are no settlements in Øygarden with more than 200 inhabitants. The largest populated islands from the north to the south are Toftøy, Rongøy, Blomøy Oøy (Oen), Alvøy and Hellesøy. The island Oen is where Kollsnes and the rural areas Breivik and Oen are situated. The largest population density is in the southern part of the municipality (see Figure A - 7). /3/

Industry

The main business activity in Øygarden is fishery and fish processing, along with some other industries. The oil development field, Oseberg, is situated in the North Sea west of Øygarden. Oil produced at Oseberg is brought to land at Alvøy and then brought to the crude oil terminal at Sture. Gass is transported from both the Oseberg oil field and Troll oil field to Blomøy and Kollsnes gas terminal.

The municipal administration in Austrheim is located at Tjeldstø. /22/

Prioritized environmental sensitive areas (MOB-areas)

Bleiknøvlingen and Høgskjeret Nature reserve is situated in Øygarden municipality. The area has MOB priority A. Along the west coast of Alvøyna and Seløy there is a large MOB B area stretching towards Hernar and Storodden in the north and covering Lyngøyna. Kortknappskjær and Horsøy Nature reserve is given MOB priority B.

Protected areas and other important areas for seabirds close to the potential transport routes /4/ (see Figure 5-7 on page 25)

Kortknappskjer Nature reserve

Alternative 9 at Horsøyosen is situated close to Horsøy and Kortknappskjer Nature reserve. Only the southern part of Horsøy is protected. The protective status was established in 1987 to protect breeding seabirds, mainly Herring Gull, Great Black-backed Gull and Lesser Black-backed Gull. Up until 1997 there was no thoroughfare during breeding periods, but the regulations were repealed. Today it seems the reserve has no function as a breeding area, and there is no species requiring protection.

Bleiknøvlingen and Høgskjeret Nature reserve

South of the location there is an important wildlife area. The area encloses three nature reserves of importance to seabirds. In the north Bleiknøvlingen and Høgskjeret Nature reserve are situated. The reserve includes the two small islands furthest out in the mouth of a fjord west of Seløy. Høgskjeret has earlier been a tern colony which now has been depopulated for a long period. It may be discussed if the regulations allowing no thoroughfare at the island should be repealed. Important bird species in the reserve are Great Black-backed Gull, Lesser Black-backed Gull, Herring Gull, Arctic Tern, Black Guillemot and Shag. Bleikholmen is a stable and good breeding area for several gull species and Shag, also well established as a breeding species in the area the past few years. The population of Herring Gull and Great Black-backed Gull seems to have grown in the area, whilst the growth at Høgskjeret seems to be declining. No breeding has been registered at Høgskjeret after the area was protected in 1987.

Teistholmen Nature reserve

Teistholmen Nature reserve is situated south in the municipality, and is a small island surrounded by other small islands west of Hjartøy. Important bird species in the reserve are Arctic Tern and Ruddy Turnstone. During 1988-91 there were practically no birds in the reserve. The terns returned in 1992 and the colony recovered extensively during 1993-95. After that it has been empty, but at the same time a large colony has been established in the industrial site at Tjeldstø. Teistholmen is however unstable as a breeding area for the terns, but important when they do breed in the area.

A.5. Fisheries and aquaculture

In the areas surrounding Øygarden and Fedje there is a local fishery for shrimps, Pollock, mackerel and herring. The western side of these municipalities, the east-western straits in Øygarden and the sea areas surrounding Forhjelmo (at the northern tip of Seløy) and northward are important fishing areas. The activity varies from year to year, and mainly consists of:

- Seining for herring, Pollock and mackerel.
- Fishing with longline/fishline for cusk, common ling, Pollock and haddock.
- Fishing for lobster and crab with using fish pots.
- Troll fishery for mackerel.
- Other fisheries with line for (among others) Pollock, mackerel and Pollack.
- Trammel net and fish traps for (among others) cod.
- Fishing for salmon with keyway and fishing nets.

During recent years the fisheries have been reduced in both size and importance. The plateau from Kvalen to Ådneset is one of the most important fish net areas on the east side of Øygarden. Several species are being fished for and the field is in use year-round. In and at the edge of the deep channel in Hjeltefjorden towards Fensfjorden long-line fishing and fisheries with fish pots takes place. Fedjeosen is a bit more used than other places. At the southern side of Fensfjorden traditional fisheries for cod, haddock, Pollack and cusk with fishing net, long-line, fish trap and fish line take place in the slope towards the seafloor. The fisheries are especially widespread around Fedje, Holmengrå, Rongevær, Børilden and Håvarden. There are also several shrimp trawling areas in Hjeltefjorden, amongst others by Helleosen in Øygarden. These are in use by a smaller number of fishermen. Further, there are several areas for kelp trawling in the area, mainly situated on the north- and west side of the islands of Øygarden and Fedje.

Fishing areas, spawning areas, casting sites and netpen sites are shown in Figure 5-9. There are spawning grounds in the north of Øygarden and Fedje used by cod. On the east side of Fedje there is a spawning ground for haddock. The spawning mainly takes place in January-April and fishing in the same areas takes place simultaneously. There are several local casting sites and netpen sites in this area, amongst others in Hellosen. The casting sites and netpen sites have traditionally been used when fishing for herring, mackerel and pollock, but recent years mainly the two latter species /4/.

Figure 5-10 on page 28 shows fish farming locations in the areas where U-864 potentially may be brought to land. The map is based on presently given licenses (September 2007) and the picture may change in short time. Not all the areas are in use today, but may be later on, and new licenses may be allocated. There are mainly production of salmon and crustacean in the areas and the industry is widespread in Øygarden and Radøy with fewer locations in Austrheim. There are two locations for cod production at Fedje. The areas for aquaculture industry at Fedje are however close to the two potential areas for landing the vessel (no.1 and 2) shows some good areas for scallop based on local knowledge. The areas are marked as circular polygons. In Fedje and Øygarden the potential receiving areas (number 1 and 2 at Fedje and number 9 and 10 in Øygarden) are situated within some of the scallop locations. In Øygarden the scallop location is marked as “active”. There is also one scallop location in Radøy marked as “active” at Flona. Flona is situated south of the potential receiving areas of U-864 in the municipality.

A.6. Outdoor life

At Fedje the areas Måøyni and Hellesøy are very important outdoor recreational areas at the shoreline, whilst Stormarka is a very important outdoor recreation land area. In Øygarden the areas Hernar and Hellesøy-Langøy northwest in the municipality are very important recreation areas at the shoreline, whilst the east side of Alvøyna is an important outdoor recreational land area. There is also one outdoor recreation area protected by the state in the municipality; Langøy (see Figure A - 8 on page A15). In Radøy municipality all of Uttoska and parts of Toska are very important outdoor recreation areas at the shoreline, and there is one protected area on each of the islands (see Figure A - 8). The area Kvolmo-Byngja is classified as a very important outdoor recreational area at the shoreline, and in Byngje there is one outdoor recreation area protected by the state. The areas north in the municipality and further into Austrheim municipality are classified as important outdoor recreational areas. In Austrheim there are two outdoor recreational areas protected by the state; Sauøyna northwest in the municipality and Børilden Aust in the north eastern areas (see Figure A - 8 on the next page).

Figure A - 8 Outdoor recreation areas protected by the state /17

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TECHNICAL REPORT

KYSTVERKET NORWEGIAN COASTAL ADMINISTRATION

SALVAGE OF U-864 - SUPPLEMENTARY STUDIES - MONITORING

REPORT NO. 23916-9

REVISION NO. 01

DET NORSKE VERITAS

DET NORSKE VERITAS

TECHNICAL REPORT

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Client: Kystverket (Norwegian Coastal Administration)	Client ref.: Hans Petter Mortensholm

Summary:

The German submarine U-864 was torpedoed by the British submarine Venturer on February 9 1945 and sunk approximately two nautical miles west of the island Fedje in Hordaland. U-864 was carrying about 67 metric tonnes of metallic mercury that implies a threat to the marine environment. In September 2007 The Norwegian Costal Administration commissioned Det Norske Veritas to further investigate different alternatives to salvage the wreck and remove the mercury from the seabed.

The objective of this study is to suggest a monitoring programme for any remediation alternative which will be chosen regarding U-864. In this way can possible spreading of mercury during and after an operation be monitored in order to make corrective and appropriate actions if needed.

DNV's overall suggestion is:
During and after any operation on the U-864 possible spreading of mercury should be monitored in order to make corrective and appropriate actions if needed. The monitoring should be based on recognized techniques in order to make an environmental acceptable operation, and to monitor the long term effect of the operation.

Report No.: 23916-9		Subject Group: Marin monitoring
Report title: Salvage of U-864 - Supplementary studies - Monitoring		
Work carried out by: Thomas Møskeland, M.Sc (DNV) Espen Eek (NGI)		
Work verified by: Sam Arne Nøland (DNV) Odd Andersen (DNV)		
Date of this revision: 2008-07-04	Rev. No.: 01	Number of pages: 29

Indexing terms

Sediments
Mercury
U-864

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Table of Content *Page*

TECHNICAL REPORT

The German submarine U-864 was torpedoed by the British submarine Venturer on February 9 1945 and sunk approximately two nautical miles west of the island Fedje in Hordaland. U-864 was carrying about 67 metric tonnes of metallic mercury that implies a threat to the marine environment.

In September 2007 The Norwegian Costal Administration commissioned Det Norske Veritas to further investigate different alternatives to salvage the wreck and remove the mercury from the seabed.

1 SUMMARY

This report is *Supplementary Study No. 9: Monitoring*, one of twelve supplementary studies supporting the overall report regarding U-864 (Det Norske Veritas Report No. 23916) prepared by Det Norske Veritas (DNV).

The objective of this study is to suggest a monitoring programme for any remediation alternative which will be chosen regarding U-864. In this way possible spreading of mercury during and after an operation can be monitored in order to make corrective and appropriate actions if needed. Mercury can be introduced to the water column during an initiative or/and in the long term run from:

- the pore water in the sediments (when these are disturbed).
- desorption from particles introduced to the water column.
- leakage from the wreck parts when these are handled.
- stir up of sediments during operation.
- loss from the wreck parts if these are lifted from the sea floor.

DNV suggests the following methods to be used:

Monitoring technique	Before operation	During operation	After operation Long term	Comments (response time)
Turbidity	X	X		Commercial (seconds or few minutes)
ROV equipped with video camera and sonar		X		Commercial, but no detection of dissolved contaminants (< sec.)
Passive samplers	X	X		Experimental for mercury (weeks)
Sediment traps	X	X		Commercial (weeks)
Water sampling		X		Commercial (hours)
Automated water analysis		X		Commercial, but status for deployment offshore is unknown (minutes)
Voltametric mercury determination		X		Pilot (minutes)
Biota			X	
Macro benthic fauna	X		X	
Sediments and pore water			X	

If other suggestions on how to monitor spreading of mercury during and after any operation are suggested, these should be evaluated. This may be to use bio indicators or tracer technology. Both methods are briefly discussed in this supplementary study. The rest of *Supplementary Study No. 9: Monitoring* details the arguments behind the suggested monitoring programme.

TECHNICAL REPORT

Den tyske ubåten U-864 ble torpedert av den britiske ubåten Venturer den 9. februar 1945 og sank omtrent to nautiske mil vest for øya Fedje i Hordaland. U-864 var lastet med omtrent 67 tonn med metallisk kvikksølv som utgjør en fare for det marine miljøet.

I September 2007 tildelte Kystverket Det Norske Veritas oppdraget med å nærmere utrede ulike alternativer for heving av vrak og fjerning av kvikksølv fra havbunnen.

2 SAMMENDRAG

Denne rapporten er *Tilleggsutredning nr. 9: Monitorering*, en av tolv tilleggsutredninger som understøtter hovedrapporten vedrørende U-864 (Det Norske Veritas Report No. 23916) utarbeidet av Det Norske Veritas (DNV).

Formålet for denne tilleggsutredningen er å foreslå et overvåkingsprogram for de ulike tiltaksalternativene tilknyttet U-864. Slik vil mulig spredning av kvikksølv under og etter en operasjon kunne overvåkes slik at korrektive og tilpassede tiltak kan iverksette om nødvendig. Kvikksølv kan bli overført til vannsøylen under en operasjon og/eller på lang sikt i fra:

- porevann i sedimentene (når disse blir rørt opp).
- desorpsjon i fra partikler som blir overført til vannsøylen.
- lekkasje i fra vrakdeler når disse blir håndtert under operasjon.
- oppvirvling av sedimenter under operasjon.
- dersom vrakdeler mistes under heving fra sjøbunn.

DNV foreslår at følgende metoder benyttes:

Overvåkingsteknikk	Før operasjon	Under operasjon	Etter operasjon Lang sikt	Kommentarer (responstid)
Turbidity	X	X		Kommersielt tilgjengelig (sekunder eller få minutter)
ROV equipped with video camera and sonar		X		Kommersielt tilgjengelig, men ikke deteksjon av oppløst forurensning (sekunder)
Passive samplers	X	X		Eksperimentell for kvikksølv (uker)
Sediment traps	X	X		Kommersiell (uker)
Water sampling		X		Kommersiell (timer)
Automated water analysis		X		Kommersiell, men usikker når tilgjengelig for offshore (minutes)
Voltametric mercury determination		X		Pilot (minutes)
Biota			X	
Macro benthic fauna	X		X	
Sediments and pore water			X	

Dersom det blir foreslått andre forslag om hvordan spredning av kvikksølv under og etter en operasjon kan overvåkes, bør disse evalueres. Dette kan være å bruke bioindikatorer eller ”tracer” teknologi. Begge metoder er kort beskrevet i denne tilleggsstudien. Resten av *Tilleggsutredning nr. 2:Monitorering* utdyper argumentene bak konklusjonene.

3 INTRODUCTION

3.1 Background

The German submarine U-864 was sunk by the British submarine Venturer on 9 February 1945, approximately 2 nautical miles west of the island Fedje in Hordaland (Figure 3-1). The submarine was on its way from Germany via Norway to Japan with war material and according to historical documents; U-864 was carrying about 67 metric ton of metallic (liquid) mercury, stored in steel canisters in the keel. The U-864, which was broken into two main parts as a result of the torpedo hit, was found at 150-175 m depth by the Royal Norwegian Navy in March 2003. The Norwegian Costal Administration (NCA) has, on behalf of the Ministry of Fisheries and Coastal Affairs, been performing several studies on how the risk that the mercury load constitutes to the environment can be handled. In December 2006 NCA delivered a report to the Ministry where they recommended that the wreck of the submarine should be encapsulated and that the surrounding mercury-contaminated sediments should be capped. In April 2007 the Ministry of Fisheries and Coastal Affairs decided to further investigate the salvaging alternative before a final decision is taken about the mercury load.

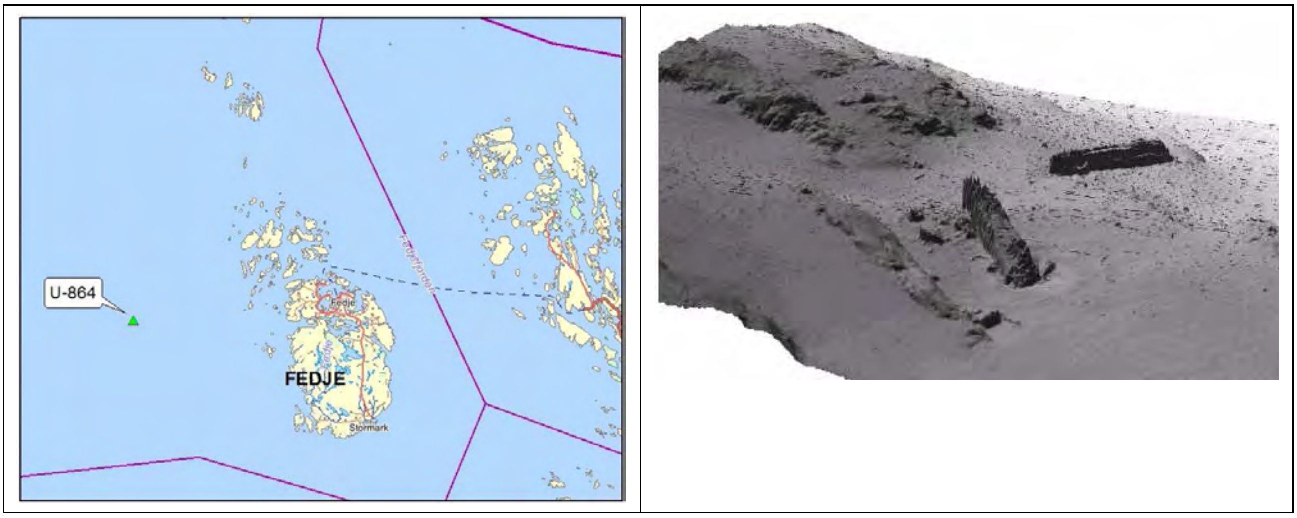

Figure 3-1 Location (left) and a sonar picture of the wreck of U-864 on seabed (right) (from Geoconsult).

3.2 DNV's task

In September 2007 NCA commissioned Det Norske Veritas (DNV) the contract to further investigate the salvaging alternative. The contract includes:

- DNV shall support NCA in announcing a tender competition for innovators which have suggestions for an environmentally safe/acceptable salvage concept or technology. Selected innovators will receive a remuneration to improve and specify their salvage concept or technology.

- DNV shall support NCA in announcing a tender competition for salvage contractors to perform an environmentally justifiable salvage of U-864.
- DNV shall evaluate the suggested salvage methods and identify the preferred salvage method.
- The preferred salvage method shall be compared with the suggested encapsulation/capping method from 2006. (DNV shall give a recommendation of which measure that should be taken and state the reason for this recommendation.)
- DNV shall perform twelve supplementary studies which will serve as a support when the decision is taken about which measure that should be chosen for removing the environmental threat related to U-864. The twelve studies are:

1. *Corrosion*. Probability and scenarios for corrosion on steel canisters and the hull of the submarine.
2. *Explosives.* Probability and consequences of an explosion during salvaging from explosives or compressed air tanks.
3. *Metal detector*. The possibilities and limitations of using metal detectors for finding mercury canisters.
4. *The mid ship section*. Study the possibility that the mid section has drifted away.
5. *Dredging*. Study how the mercury-contaminated seabed can be removed around the wreck with a minimum of spreading and turbidity.
6. *Disposal*. Consequences for the environment and the health and safety of personnel if mercury and mercury-contaminated sediments are taken up and disposed of.
7. *Cargo.* Gather the historical information about the cargo in U-864. Assess the location and content of the cargo.
8. *Relocation and safeguarding.* Analyse which routes that can be used when mercury canisters are relocated to a sheltered location.
9. *Monitoring.* The effects of the measures that are taken have to be documented over time. An initial programme shall be prepared for monitoring the contamination before, during and after salvaging.
10. *Risk related to leakage.* Study the consequences if mercury is unintentionally leaked and spreading during a salvage or relocation of U-864.
11. *Assessment of future spreading of mercury for the capping alternative*. The consequences of spreading of mercury if the area is capped in an eternal perspective.
12. *Use of divers.* Study the risks related to use of divers during the salvage operation in a safety, health and environmental aspect and compare with use of ROV.

3.3 Scope of this report

This report is *Supplementary Study No. 9:Monitoring.* The objective of ambition with this study is to establish a monitoring programme for any remediation alternative which will be chosen regarding U-864 to monitor spreading of mercury during and after an operation in order to make corrective and appropriate actions if needed.

The structure of this supplementary study is:

- Chapter 4: Description of the area and the current situation at wreck site
- Chapter 5: Suggested monitoring program for any remediation alternative which will be chosen regarding U-864

4 DESCRIPTION OF THE AREA AND THE CURRENT SITUATION AT WRECK SITE

4.1 Description of the area

Figure 4-1 shows the location of the wreck. A point by point summary regarding U-864 is given below.

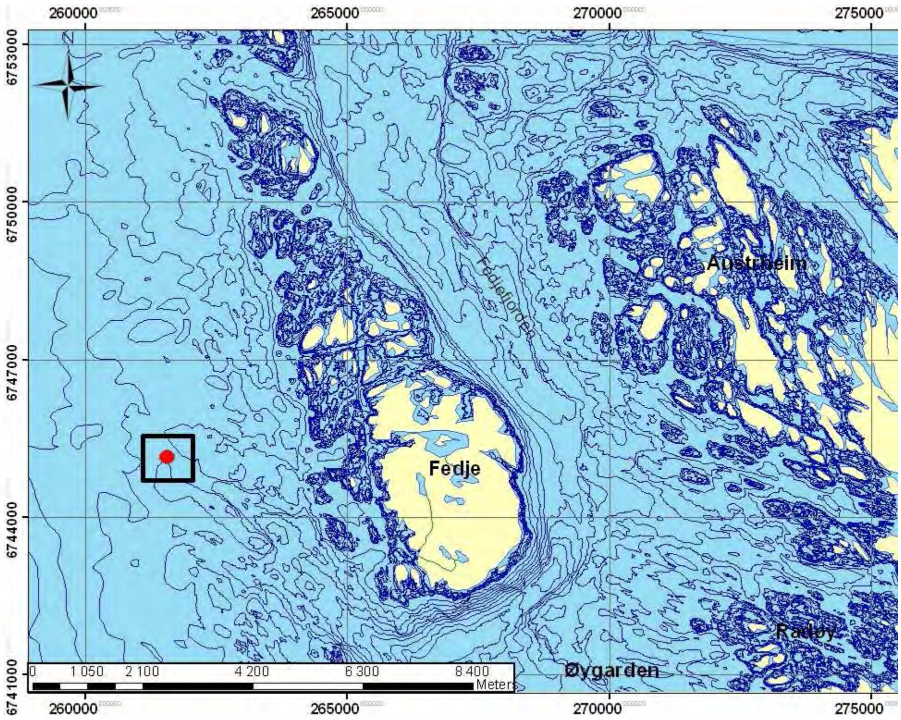

Figure 4-1 Location of U-864 outside Fedje on the west coast of Norway.

4.1.1 Evaluation of the area where the wreck has been localised

- The wreck of U-864 was found on 150 meters depth approximately two nautical miles (3.7 km) west of Fedje in Hordaland County. The area is exposed to rough weather, especially during the winter. Experiences from the surveys show that any measures ought to be carried out in the period from May to August, which has the highest probability for enduring periods of weather that will allow an operation on U-864 to be accomplished
- The area has a rolling bathymetry. Stability calculations of the sediment in the area indicate an imminent danger of slope failure. This is primarily the case for the fore section of the submarine which lies in an unstable slope with an approximately 15 degrees incline.

- Average velocity of the current 3 m above the bottom is about 0.1 m/s. Maximum velocity is measured to 0.87 m/s. Average and maximum velocity, 40 meters above the bottom, is measured to 0.3 m/s and 1.6 m/s respectively.
- The area currents are stable, with a northern main course from the surface down to about 110 m. The current turns westward and follows the bathymetry into the deeper layers.

4.1.2 Environmental factors and pollution in the area around the wreck

- Mercury and methyl mercury are found in the sediment, including pore-water. The sediment samples around the wreck show very high concentrations of mercury around the wreck of U-864. Mercury is also leaking into the water column.
- Mercury has been found in fish from the area. A connection has been established between the pollutant, dispersion of pollution and accumulation in biota.
- Environmental monitoring on the seafloor during operations indicates that such operations will result in resuspension of polluted sediments and therefore be a risk for spreading of mercury.
- It has been suggested to cover the seafloor around the wreck of U-864 in order to limit spreading of mercury in the sediments, either after the wreck has been removed or also including the wreck. The action area for covering of the seafloor is estimated to approximately 30.00 m^2. The action area is restricted to sediments where pollution ranges from 0.6 ppm (parts per million) (class III) to >5 ppm (class V) according to SFT's (State Pollution Authority) classification system.
- The U-864 has a bunker capacity of 441 tonnes, and it was presumably fully loaded when torpedoed. Large quantities of fuel were observed after it was sunk. The remaining quantity is unknown.

4.2 Description of the current situation

The current environmental situation in the area where the wreck is localized is described in the following three documents:

1. Miljøovervåking, strømundersøkelser, sedimentkartlegging og miljørisikovurdering knyttet til fase 1 kartlegging og fjerning av kvikksølvforurensning ved U-864. LNR. 5092-2005

The objective of the survey was to establish a foundation of facts that could be used to define further measures regarding the removal of the contamination hazard related to U-864.

Summary of the report's conclusions:

- Contamination levels are generally low in water samples except some samples close to the bottom (presumably caused by resuspension during sampling).
- Removal of sediments at rear end of the wreck resulted in increased particle abundance and mercury concentrations (resuspension) in the water column.

- The sediments around the wreck are partly very heavily polluted (up to 10 % mercury)
- Based on the analyses of mercury in the sediments, the remediation area is calculated to approximately 30 000 m^2 and a minimum of 15 000 m3.
- Sediment of the area can be characterised as sandy with hard clay beneath. There are also parts with stone and gravel.
- The heading of the current in the upper layers is northerly down to 110 m depth, while below this depth the current deflects to the west and follow the bathymetry. The current has an average velocity at 20 m depth of 0.3 m/s (max 1,6 m/s), and 0.1 m/s (max 0,87 m/s) 3 m above the bottom.

2. NIVA (2005). Utlekking og bioakkumulering av kvikksølv fra sedimenter nær U-864, Fedje i Hordaland. Resultater fra eksperimentelle undersøkelser. LNR. 5089-2005

NIVA has completed leaking and bio accumulation tests for total mercury and methyl mercury on sediments where U-864 is localised.

A short summary of the tests show that:

- mercury bio accumulates in bristleworms (*Nereis*) and gastropods (*Hinia*). There was a high bioaccumulation of total mercury compared to the control sediment (factor 1300 for bristleworms and 450 for gastropods).
- methyl mercury bio accumulates in bristleworms, but to a lesser degree in gastropods (a factor 5 degrees higher than the control sediment, but much lower sediment concentration than for total mercury resulting in a higher bioaccumulation factor for methyl mercury than total mercury).
- analyses of pore water for total mercury and methyl mercury indicate that the mercury is available for sedimentary organisms. Elevated concentrations of mercury in the sediments increases the concentration of mercury in the pore water.
- tests indicate an average leakage rate of total mercury from sediment to water to be 142 kg/km^2/year and 0.8 g/km^2/year for methyl mercury. Tests show that within the suggested remediation area of 0.03 km^2, there is a yearly leakage of 4 kg mercury from the sediments to the water column.

3. NIFES (2004, 2005 og 2006). Kvikksølvinnhald i fisk og sjømat ved søkkt ubåt (U-864) vest av Fedje.

Analyses of total mercury in selected species of fish and crab was performed by NIFES in the years 2004 to 2006. For cod the analysis show the average content of mercury to be the normal level compared to fish caught in the open sea (from The Barents Sea, The Norwegian Sea and the North Sea). The content of mercury in redfish (*Sebastes marinus*) is above normal level but below the limit value adopted by EU of 0.5 mg mercury/kg wet weight (Commission regulative EC 2001/446). In the area there are registered crabs (claw meat) and cusks (*Brosme brosme*) above the limit value adopted by EU. In Figure 4-2 the mercury content in fish and crab for the investigations by NIFES in 2004-2006 are shown.

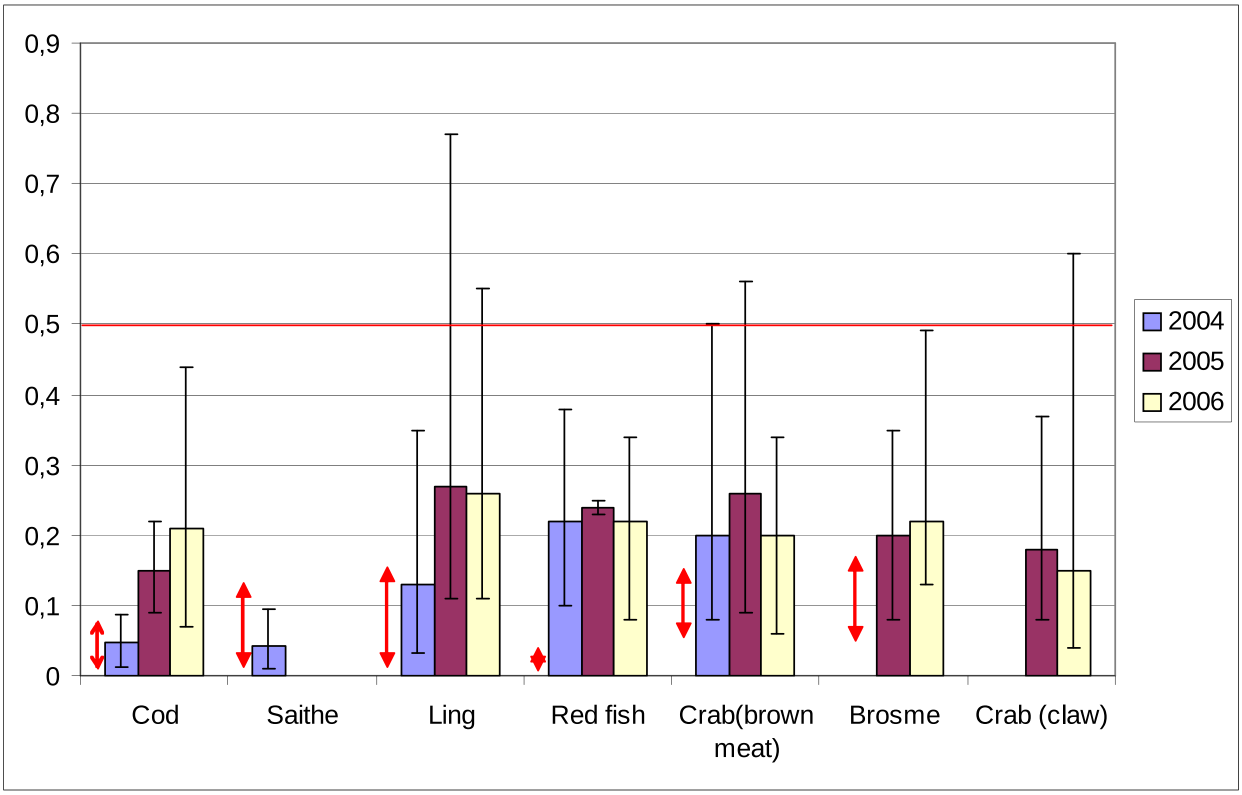

Figure 4-2 Mercury content in fish and crab (mg/kg wet weight) from the sampling performed in 2004-2006 by NIFES. Read arrows indicate normal values (from Norwegian areas unaffected by pollution), columns average values and black bars maximum and minimum values.

See the Coastal Administration internet site (http://www.kystverket.no/) to get access to all reports by NIFES .

5 MONITORING PROGRAM

This chapter describes the suggested monitoring programme for any remediation alternative which will be chosen regarding U-864. Using the suggested program possible spreading of mercury during and after an operation can be monitored in order to make corrective and appropriate actions if needed.

The structure of this chapter is:

- Environmental goal for the area (chapter 5.1)
- The scope for the monitoring activity (chapter 5.2)
- Monitoring methods (chapter 5.3)
- Background values for monitoring parameters – Before operation (chapter 5.4)
- Monitoring during initiative (chapter 5.5)
- Long term monitoring (chapter 5.6)
- Other long term monitoring methods (chapter 5.7)

5.1 Environmental goal for the area

It has been suggested (NIVA 2006) that the concentrations of mercury in the sediments close to the wreck should not exceed 3 mg Mercury/kg (SFT class III). In relation to dredging done around U-864 in 2005 SFT defined sediments with less than 3 mg/kg mercury as unpolluted sediments (/9/). However this environmental goal is not yet formally implemented.

NIVA (2006) has also suggested that: *”the regional environmental goal should be to take measures to prevent that the wreck and its surrounding area will become a source of pollution in the future, as well as prevent that the wreck and the polluted sediments contribute to elevated levels of mercury in seafood (fish and shellfish)”*.

One approach to identify what is an acceptable release of mercury is to make an environmental budget of the expected mercury release before, during and after the operation. The increased release during the operation must be reasonable compared to the reduction in mercury release which can be obtained by the operation. This is illustrated in the example in Figure 5-1, which states that the level of mercury in the water column will increase during operation but outweights the long term benefit of the actual clean up operation compared to no remediation at all (0-alternative). Release of mercury settling to the seabed during the operation can increase the contaminated area. The major consequence of this will be increased costs of dredging or capping a larger area as a part of the final stage of the operation.

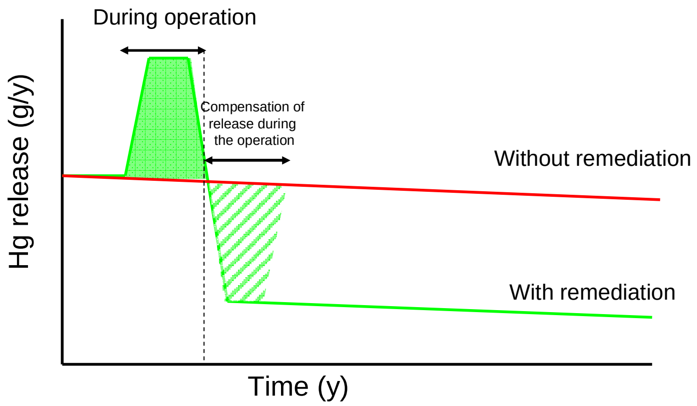

Figure 5-1 Schematic example of a contaminant budget

Another option is to set acceptance criteria's without working out a contaminant budget. This can be done by using background values alone, for example accept some higher turbidity compared to background values during operation, by using some effect limits from relevant literature (for example effect limits from the Guidance to risk evaluation of contaminated sediments, published by the State Pollution Authority) or other relevant effect limits.

5.2 The scope for the monitoring activity

A monitoring program is required to monitor possible release of contaminants during any remediation alternative that may be chosen for U-864. This includes:

- monitoring of preparations at the site to enable salvage of the submarine and the entire salvage operation.
- final transport of the submarine to a storage/disposal facility will also be covered by the program.

Monitoring of the final disposal/destruction of the submarine is not included in this work.

The purpose of the suggested monitoring program is:

- to detect acute contaminant release during the operation in real time in order to implement immediate corrective actions to limit or stop the release.
- to collect time-integrative data on contaminant release during the operation in order to document the environmental impact of the operation.

In general the monitoring should be performed by experienced and preferably accredited personnel. This will secure documentation in accordance with relevant standards of the field work and handling of the samples.

The analysis should also be done in a laboratory with accreditation for analysis of total mercury, and preferably also methyl mercury.

5.3 Monitoring methods

Several methods have been reviewed in this study. Table 5-1 lists the most relevant monitoring methods. In addition more traditional long term monitoring methods like sediment sampling, sampling of biota, soft bottom community analysis and use of tracer are described in chapter 5.6.

Table 5-1 Overview over monitoring methods and evaluation of their applicability for real-time monitoring.

Monitoring technique	Real-time monitoring possible (typical response time)	Development status
Turbidity	Yes (sec. or few min.)	Commercial
ROV equipped with video camera and sonar	Yes (< sec.)	Commercial (no detection of dissolved contaminants)
Passive samplers	No (weeks)	Experimental for mercury
Sediment traps	No (weeks)	Commercial
Water sampling	No (hours)	Commercial
Automated water analysis	Yes (minutes)	Commercial, but status for deployment offshore is unknown
Voltametric mercury determination	Yes (minutes)	Pilot

Turbidity

To measure turbidity is a robust and well tested method to monitor the concentration of particles in the water column. Turbidity sensors can be placed on stationary buoys at several depth intervals or on a ROV to monitor the operation.

Measurement of turbidity is the most reliable method for real-time monitoring of release and dispersion of contaminated particles in the sea. Turbidity is a measure of light dispersion caused by particles suspended in the water column. Contaminants are often strongly associated with particles and turbidity gives an indirect measure of particle concentration in the aqueous phase and therefore some judgments of contaminant transport can be made. Turbidity monitoring is widely used during dredging operations as an indicator of unacceptable spreading of contaminated sediments. The method allows rapid implementation of corrective measures and was used to monitor dredging operations near the U-864 during the field investigations in 2005.

The disadvantage of relying only on monitoring of turbidity measurements is that this parameter is not directly linked to the contaminant of interest, in this case mercury. In the case of uncontrolled release of elemental mercury during salvage, mercury drops will settle rapidly on the seabed and be very hard to detect by turbidity measurements. In order to detect such events it is necessary to follow the operation visually by an ROV equipped with a video camera.

ROV

Video monitoring of the operation will be necessary to detect unwanted events during salvage, and possibly also during transport. The unwanted effects of such events are release of mercury or mercury-contaminated material to the marine environment and contamination of a larger area of the seabed.

Release of dissolved mercury to the marine environment cannot be monitored using an ROV equipped with a video camera, so it should be monitored by direct chemical analysis of water from the site during the whole operation. This would traditionally imply sampling at selected time intervals followed by chemical analysis in an on-site or off-site laboratory facility.

Passive samplers

Passive samplers are devises containing a substance that accumulates the contaminant of interest over time proportionally to the concentration in the aqueous phase. Diffusive Gradients in Thin films (DGT) are passive samplers suitable for monitoring many metals, the method has however not been tested for mercury according to a study by NIVA (2002). Other materials like mercapto modified silicone have been developed to act as a sorbent for mercury in lab-based analytical methods (Merritt and Amirbahman 2007). These methods are presently at an experimental stage, and it seems that many significant obstacles have to be overcome before such materials are suitable for deployment as passive samplers in the marine environment.

Sediment traps

Particles settling in the water column can be collected by sediment traps. Sediment is collected at selected time-intervals and subsequently analysed for the contaminants of interest. This is a well documented method that was deployed to monitor mercury transport during dredging close to U-864 in September 2006 (NIVA 2006). Sediment traps have the advantage over water samples that they collect particles during the whole deployment period (weeks or months) and the results will therefore represent the time-integrated mercury load during the deployment.

Water sampling

The mercury content in discrete water samples can be analysed with several standardized analysis methods offered by commercial laboratories. Water sampling could be combined with a mobile lab in order to get semi-real-time monitoring. Collecting the samples will presumably be the time-limiting factor in this case.

Automated water analysis

Automated systems for analysis of mercury in water, based on continuous flow, exist for analysis of large sample series in the laboratory. Such systems could be modified to generate near real-time data. This requires continuous pumping of water from the monitoring stations at salvage site to the analysing equipment. This method will require some modification of available standard equipment to do this task. Further evaluation and verification is needed to determine if this is a feasible method to use on-site under off-shore conditions.

5.4 Background values for monitoring parameters – Before operation

In order to compare measurements during the operation with the natural situation in the area it is preferable, or most times necessary, to establish reliable background values for all parameters which will be monitored. Baseline monitoring of all parameters that are included in the final program should therefore start as early as possible and at least one month before the operation starts to be able to document natural variation in the parameters of interest.

5.5 Monitoring during initiative

The main purposes of the monitoring during any initiative are:

1) Prevent spreading of particle bound and water borne mercury. This includes measurements which can give real time data so that corrective measures may be taken if unwanted spreading is detected.
2) Documentation of the operation with regards to spreading of particle bound and water bound mercury

Mercury can be introduced to the water column during an initiative from:

- the pore water in the sediments (when these are disturbed).
- desorption from particles introduced to the water column (stir up).
- leakage from the wreck parts when these are handled (e.g. lifted).
- stir up of sediments during operation.
- loss from the wreck parts if these are lifted from the sea floor.

The use of passive samplers is not described further because the method seems not to be available for mercury. But if any future bidders or companies that will perform the monitoring during or after any operation have some suggestions on available technology, it is recommended that monitoring by use of passive samplers are reconsidered.

Also any other methods, for example online measurements of mercury, should be considered if future bidders or companies which will perform the monitoring have some suggestions.

The monitoring programme shall include a possible transport phase (if salvage is chosen).

5.5.1 Monitoring of mercury by water samples

In general water samples need to be analyzed before any conclusions can be made or before any mitigating procedures can be implemented. Below are three suggestions on how water samples may be collected, each with its advantages and disadvantages:

1. Discrete water sampling – analysis in commercial laboratory on land

Considering that this will be an offshore operation and that the operation may take in the order of days to weeks (depending on the weather), it means that if the samples are analyzed on a laboratory on land it may happen that no results are available before the operation is finished. Hence, the water samples will only be input to the documentation on the operation and will not be a tool for implementing corrective actions.

2. Discrete water sampling – analysis onboard during operation

A second solution which may be possible is to establish the necessary analyzing equipment and personnel on the operating ship or separate vessel so the analysis can be done sequential during the operation. If this is possible, water samples could be a tool for implementing corrective actions during operations. Expected turn-around time of such a system, using onboard analytical facilities, is in the order of hours.

3. Automated water analysis – analysis onboard during operation

A third solution is the possibility of deploying onboard automated mercury analyses combined with continuous pumping of water from selected monitoring positions. Continuous flow equipment for mercury is commercial available and bringing this offshore should be feasible. However, to generate near-real-time data, transfer lines should be installed allowing continuous sampling from selected depth. The robustness of the transfer lines under field conditions and the connection to the auto-analyser require further assessment in cooperation with a vendor of the equipment of interest.

Table 5-2 sum up some generalised advantages and disadvantages with the three water sample collecting methods mentioned above:

Table 5-2 Overview over suggested water monitoring methods and evaluation of their applicability

No.	Monitoring technique	Typical response time	Development status
1	Discrete water sampling – analysis in commercial laboratory on land	Days	Commercial and safe
2	Discrete water sampling – analysis onboard during operation	Hours	Commercial, but an analyzing lab have to be established onboard
3	Automated water analysis – analysis onboard during operation	Minutes	Not commercial, needs modification and testing

Acceptance criteria

For very short periods during the operation high peak values of mercury in water can be accepted because the exposure time is limited. For such a shorter period mercury maximum concentration of 0.7 µg/l should be considered. This value is equivalent to category IV (0.14 µg/l) in the state pollution authority classification scheme (/10/) but without the safety factor of 5. The value is based on tests on LC_{50} (Lethal concentration with 50 % mortality) tests on fish, where the fish is exposed to this concentration during 4 days. Short peaks with this concentration should therefore not be mortal to fish in the exposed area.

One may therefore use this value (0.7 µg Hg/l) as an acceptance criteria meaning that corrective actions should be made if water concentrations in any sample is above this concentration.

Sampling strategy

Water samples should be taken in a transect covering the main current direction with increasing distance from the source (meaning the wreck parts).

Considering that huge amounts of water will probably quickly dilute the concentration of mercury in the water column it is suggested that water samples are taken in a transect covering the north, west, east and south direction and in a distance of 100, 200 and 300 m from the wreck parts. This sampling strategy is illustrated in Figure 5-2. The exact distance must be decided based on details in the operation plan and the safety distance any operation demands.

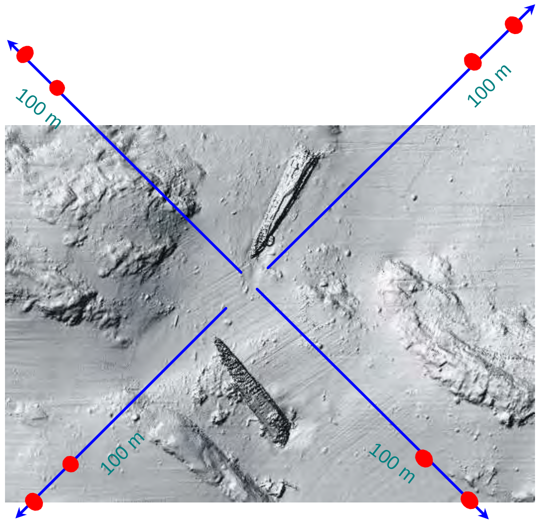

Figure 5-2 Sampling strategy - water samples (distance given not exact, for illustration purpose only).

The water samples should cover several depths in order to reflect the operation, but exact depth should be detailed when it has been decided whether the wreck shall be salvaged or capped. One sample should be taken near the sea floor and three samples higher in the water column, for example 50, 100 and 125 m below sea surface. This will result in a total of 48 samples points.

Handling and analysis of samples

The water samples should be kept cool and dark before they are analyzed. Appropriate sample bottles should be used to avoid loss of mercury by evaporation.

It is suggested that all of the nearest samples (100 m) are analyzed first and if the concentration in these are not above the acceptance criteria the other samples (200 and 300 m) need not to be analyzed. If the concentration of mercury in the nearest samples is above the acceptance criteria the 200 m are analyzed first and if those also exceeds the acceptance criteria the samples from 300 m are analyzed.

5.5.2 Monitoring of particle bound mercury

The monitoring programme should focus on a sampling strategy involving:

- Turbidity measurements
- Sediment traps
- Tracer technology
- ROV

5.5.2.1 Turbidity measurements

Turbidity is a robust and well tested method to indirect monitor the concentration of particles in the water column. Turbidity sensors can be placed stationary on buoys at several depths or mobile on a ROV monitoring the operation.

The main two options when using turbidity measurements are:

1) Online turbidity measurements. In this case there is continuous transfer of data to a PC onboard, either wireless transfer or by wire. In this way the operator have directly access to the measurements. It may also be possible to set up an alarm if measurements are above a predefined level (acceptance criteria), for example direct SMS alerts. The advantage with this method is that the data are instant available and it is not necessary to take the probes out of the water in order to download and analyze the data. The downside may be that it is expensive in the sense that much technology is involved and many probes are needed. Some maintenance of the equipment is also probable.

2) Turbidity measurements without “online view”. In this case the turbidity measurements have to be downloaded manually onboard and analyzed. This is a less complex method in the sense that not so much technology is needed. One may also manage this with only a few turbidity probes, for example by using dedicated personnel to sample predefined sampling stations The downside is that one need to take the equipment out of the water on order to analyze the data and the data is not instant available as it is with online measurements.

Acceptance criteria

The acceptance criteria should be based on background levels in the area which should be measured for a period up to one month before the operation starts. The background levels should be measured as near the start of the operation as possible. The reason for this is mainly because turbidity naturally varies over the year, which means that measurements of background values too long before the actual operation may not be valid.

Acceptance criteria for turbidity should not be based on single peak values but as a time integrated value. A suggestion may be that the acceptance criteria for turbidity should not be higher than five turbidity units (measured as FTU or NTU) higher than the natural background level for more than 20 minutes (which is the same acceptance criteria accepted by the SFT for the remediation project in Oslo harbour).

Alternatively the acceptance criteria should be based on a contamination budget worked out before the operation starts, see chapter 5.1.

Sampling strategy

One of the unwanted effects of an operation is that contaminated sediments are spread to areas outside the boundaries defined as the high risk area (30 000 m^2). In order to detect any spreading outside the area the following strategy is suggested.

Monitoring results from sediment traps during pilot dredging close to U-864 (NIVA 2006) showed that high levels of mercury were found at all stations except “sedimentfelle 1” (OV 1).

This indicates that dredging could cause mercury transport at least over the observed distance. We therefore recommend using the same stations as used during the pilot dredging with the following modifications:

- Station OV 1 is moved 40 m east and is placed in the middle of the valley where U-864 is located.
- An additional station (OV 8) is established 150 – 200 m north-west of U-864. This position is downstream the dominating current direction where mercury was found at both OV 4 and OV5 during the pilot dredging. It is therefore necessary to monitor potential transport further downstream.

An additional reference station is included 500 m south east of U-864. This is upstream the dominating current direction and is assumed to be outside the potential area of influence of the operation.

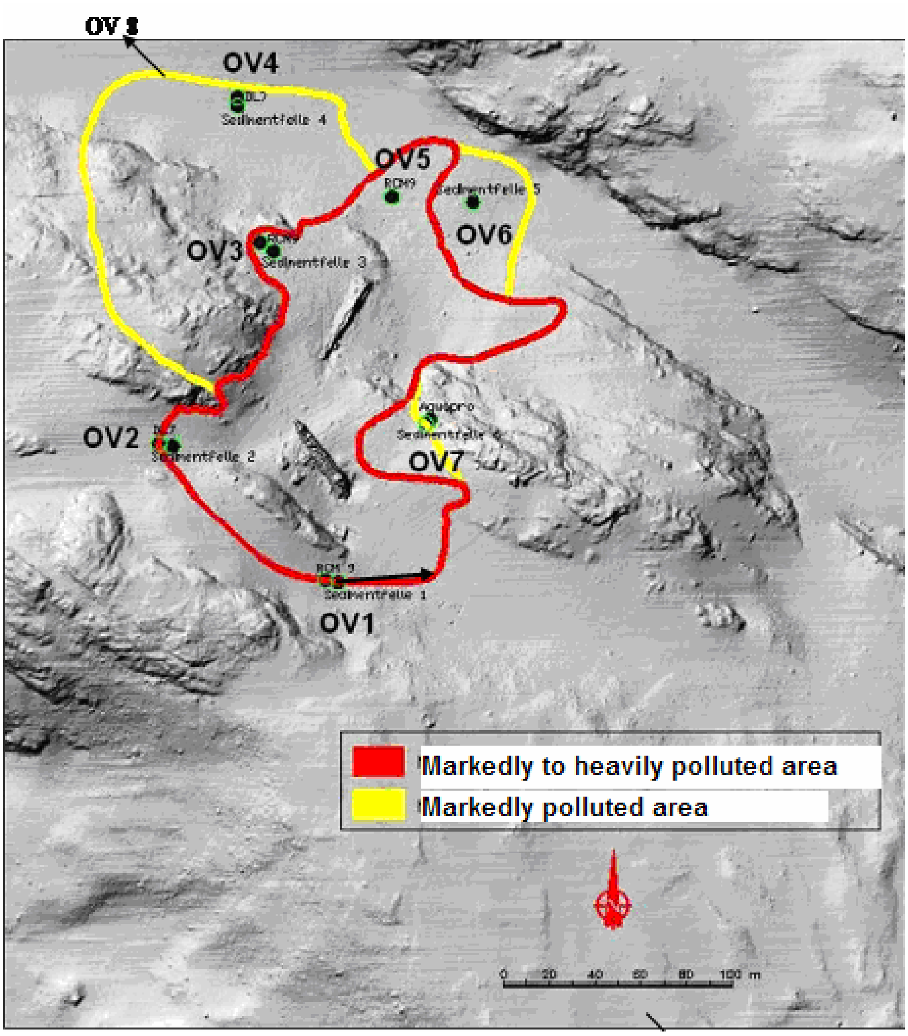

Figure 5-3 Suggested locations for turbidity measurements.

The turbidity sensors should be placed at five depths (5, 50, 100 and 125 m below sea level as well as 3 m above the seabed) at positions OV 1 – 8 and at the reference station (see Figure 5-3).

Turbidity measurements should also be used to monitor during transport of the wreck to a sheltered location. Exactly how this can be done should be worked out when details around the salvage concept is known. In theory, turbidity probes could be mounted on the barge or transport vessel to monitor during transport..

5.5.2.2 Sediment traps

To document the overall impact of the operation, sediment traps located 3 m above the seabed and one higher up in water column are used at positions OV 1 – 8 (see Figure 5-3 above) and at the reference station.

DNV recommend using a trap consisting of four tubes with an inner diameter of about 72 mm in order to collect sufficient amount of material for analyzing. The mooring arrangement is illustrated in the Figure 5-4.

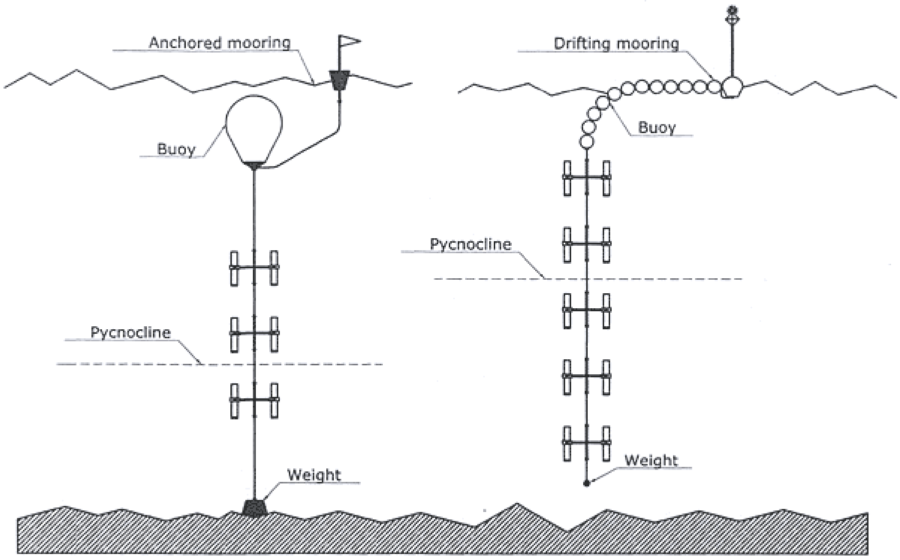

Figure 5-4 Mooring arrangement (for illustration purposes only)

Depending of the duration of the operation, one have to decide if the sediment traps shall be emptied during or after the operation..

In order to acquire background information before the salvage, it is recommended that sampling by use of sediment traps is done over a period for a least a month before the operation starts.

5.5.2.3 Tracer

Tracer technology may be used in order to monitor possible spreading during an operation. The method is only shortly described in this supplementary study, but details may be worked out if this method is considered to give an added value to the overall monitoring program.

The method is not a real-time method, but has the potential to give quantitative results of the sediment spreading from the area. Tracer may be manufactured to mimic the size, density and surface charge of the target species for a wide variety of applications. Another option is to coat a fluorescent signal on to natural sediments (silt, sand) collected from the study site. A number of tracers may for example be added to the sea floor in dissolvable plastic bags, or frozen, in order to prevent any spilling. Tracer collection may be done by sediment sampling or from sediments traps over a given and then the samples can be analyzed for tracers in order to detect spreading and to quantify it.

Tracers are used in a wide range of environment projects around the world, including Norway.

5.5.2.4 Remote Operated Vehicle (ROV)

Visual monitoring of the operation should be done with a ROV equipped with video camera and sonar. This equipment can be operated to give full visual documentation of all stages of the operation. It is highly probable that several ROV’s will be used during the operation and DNVsuggest that one ROV is to be used for the purpose of monitoring spreading of particles and larger objects.

5.6 Long term monitoring

Monitoring after the operation is more resource demanding than during operation. The purpose of this activity is to measure the effect of the remediation over time. The effect of the clean up operation and the long term monitoring have to be measured against situation before the operation (current situation), meaning the investigations described in Chapter 4.2. The long term monitoring can include the following elements:

- Monitoring of mercury in fish and crabs in the remediation area.
- Monitoring of sediment and pore water concentrations of mercury in the remediation area.
- Monitoring of the soft bottom fauna in the remediation area.

5.6.1 Monitoring of mercury in biota

The monitoring program should be based on the sample program as described by NIFES (/4/, in Norwegian).

Relevant species for sampling are cod (*Gadus morhua*), cusk (*Brosme brosme*), Ling (*Molva molva*), redfish (*Sebastes marinus*) and crab (*Cancer pagurus*).

The fish and crabs shall be caught in three defined areas as described by NIFES (/4/):

- Area 0 is defined as the area in the proximity of the wreck
- Area 1 is defined as 1 nautical mile north of the wreck
- Area 2 is defined as 2 nautical mile north of the wreck

In addition it is recommended to measure mercury in an area even further away from the locality, both north and south in the Norwegian Coastal current. This is recommended in order to get data on background values in more near shore areas that will be valuable in order to analyse the results from the locality where U-864 is located. The detail of the location of this area should be discussed further and NIFES, who has performed the monitoring of fish and crab in the area, should be involved.

The fish should be caught alive and the sample should be taken as soon as practical possible after the catch, so that the sample material is as fresh as possible.

It is suggested that an agreement with a local fisherman is done so that the actual fishing can be done by local people well known in the area. Fishing method must be flexible but it is recommended that at least 25 ± 10% individuals of each species are sampled each time.

In earlier investigations (reported by NIFES, /3/ and /4/) analysis were done for each individual (not pooled samples). It is recommended to follow the same sampling strategy in the near future, but if the results show rather low concentrations in biota one may shift to analyze pooled samples. Data gathering (catch of fish and crab) should be done in October, which is the same time of the year the catch in 2005 and 2006 were taken. For each catch the following should be documented:

- Species.
- Weight (kg).
- Type of sample material (liver, filet, claw meat, crab butter).
- Weight of sample material.
- Date of catch.
- Mean depth were catch were taken.
- Catch method (trawling, line, other).
- Length of each fish, width of carapax of crab.
- Area of catch and (coordinates and drawn up on a map).
- Sign of diseases.
- A description of any abnormalities.

In earlier investigations only filets were analyzed. No data exists for liver content of mercury from the area, but it is recommended that liver is included in the monitoring program (this will be discussed further with the Norwegian Food Safety Authority). As previously mentioned the programme may be revised to less extensive sampling and analyzing depending on the results.

5.6.2 Monitoring of sediment and pore water

Sediment and pore water should be monitored. Samples should be taken inside the remediation area and at a reference sites. There should be a relatively high number of sampling stations in order to intercept any hot spots. A suggestion for a sampling grid containing in all 25 sample stations is shown in the figure below. There may be difficulties sampling at the locality due to sandy sediment and areas with hard bottom. It is therefore probable that the exact location of the sampling stations have to be adjusted in the field.

Samples should preferably be taken by a corer, tentatively by grab (van Veen). If it is difficult to sample with conventional equipment from surface, sampling by use of ROV should be considered. Sampling by ROV is considerably more expensive than sampling from the surface (with winch).

The following shall minimum be documented:

- Responsible person for the field work.
- Project id.
- Geographical coordinates for each sampling station (and any deviation).
- Date and time for each sample.
- Water depth.
- Meterological data.
- Lenght of sample.
- Visual description of sample (colour, structure, smell, fragments, other).

In general a reference is made to Norwegian standard, NS9420, regarding requirements for registration for field work.

Three replicate samples from each sediment station can be analyzed as a pooled sample (one analysis pr. station). It is recommended that the top layer (0-2 cm) is analyzed and one deeper layer. The deeper layer could be 2-5 cm or be based on a visual description of the samples, for example where a shift between oxic and anoxic layer can be seen.

It is not considered necessary to analyse all samples for pore water. It is therefore suggested that pore water from 10 sampling locations are analyzed. From these 10 stations one may take pore water from the 3 replica sampled, and then analyze a pooled sample from these. Another option may be to take separate samples for pore water analysis. Pore water may be taken by pressure with inert gas trough a filter with pore size 0.45 µm or by centrifugation.

All samples should be analyzed by an accredited laboratory with sufficient detection limits.

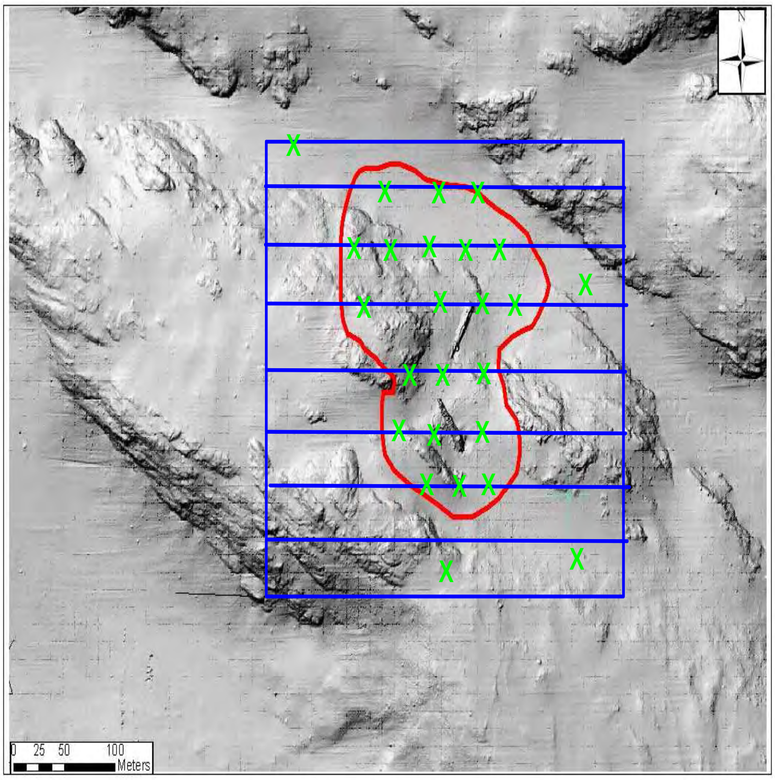

Figure 5-5 Suggested sampling grid for sediment and pore water. Green crosses indicate location of the sampling stations. Red line marks the perimeter of the remediation area.

5.6.3 Monitoring of macro benthic fauna

Macro benthic fauna are traditionally included in environmental monitoring in both offshore and fjord surveys. The reason for this is that the study of benthic communities can give an indication of the effects of pollution, while chemical monitoring of sediments is aimed at assessing the dispersion and concentration levels of pollutants at the locality. The benthic fauna is a suitable biological parameter for monitoring the effects of pollution since most of the species have limited mobility and changes in species composition and densities of individuals can therefore easily be identified. The distribution of the fauna can be related to natural variations in environmental parameters such as depth and type of sediment, but also anthropogenic factors such as river borne pollution or other long transported contaminants.

Normally one has baseline data for an area which is the background data on which future monitoring is measured against. In this case one should have data before any remediation are done and compare these with future monitoring data. These means that background data where U-864 is located should be sampled before any remediation take place. But, even without any background data, monitoring of macro benthic fauna is considered to give valuable input as an effect parameter for the locality.

Monitoring programme

A suggestion for a sampling programme is shown and described below.

A total of nine sampling stations are placed in a cross directed in the main current direction at the sea bottom (North West) and at an angle of 90 degrees of the main current. All stations are located near the wreck of U-864 except one reference station which is located at a place most probable unaffected by the mercury pollution around the wreck of U-864.

The location of the sampling stations in Figure 5-6 are for illustration purposes only and exact location must be decide in field based on sediment type and/or where it is possible to get samples.

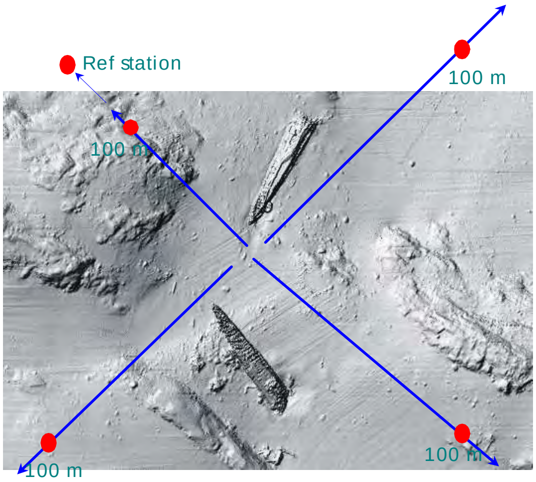

Figure 5-6 Illustration of suggested sampling stations. Red dots illustrate sampling stations (distance given not exact, for illustration purpose only).

For each location five samples should be collected by a van Veen grab with a surface area of 0.1 m^2. All samples should be conserved and marked in field before transport and sorting analysis in the laboratory.

Only animals more than 1 mm (macro benthos) are included in the analysis.

Sorting and species identification

In the laboratory the samples shall be washed on 1 mm sieves with (circular holes) to remove conservation fluid and remaining fine sediment, and then sorted by hand under a magnifying glass. The animals shall be split into the major taxonomic groups; echinodermata, polychaeta, crustacea, mollusca and varia (all other groups) and transferred to 70% ethanol before further species identification.

All animals shall be identified to the lowest possible taxonomic level (i.e. generally to species level) and the number of individuals per taxon in each sample shall be recorded.

Analytical methods

The statistical and mathematical methods utilised to aid interpretation of the benthic fauna data are summarised below.

- Abundance ratio
- Shannon-Wiener's diversity index, H' (Shannon & Weaver 1963)
- Evenness calculated by Pielou's "evenness" J' (Pielou 1969)
- Expected number of species in a sample of 100 individuals (ES100)

Suitable multivariate analysis shall be performed to look at similarity between stations and between different years in order to group stations and assess gradients in the benthic communities.

5.7 Other long term monitoring methods

Monitoring of mercury in blue mussels may be relevant in this case. Caged mussels may be set out in cages around the remediation area and analyzed for mercury or one may look at some biological indicators such as metallothionein. This is only briefly mentioned here since the monitoring methods described elsewhere in this document is regarded as sufficient in order to establish a satisfactory overall monitoring regime with regards to remediation of U-864.

If, future bidders or executers of the monitoring programme related to the U-864 wish to use blue mussels in the monitoring programme, this should be kept open as an option.

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TECHNICAL REPORT

KYSTVERKET NORWEGIAN COASTAL ADMINISTRATION

SALVAGE OF U864 - SUPPLEMENTARY STUDIES - RISK RELATED TO MERCURY LEAKAGE DURING SALVAGE AND RELOCATION

REPORT NO. 23916-10

REVISION NO. 01

DET NORSKE VERITAS

DET NORSKE VERITAS

TECHNICAL REPORT

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Summary:

The German submarine U-864 was torpedoed by the British submarine Venturer on February 9 1945 and sunk approximately two nautical miles west of the island Fedje in Hordaland. U-864 was carrying about 67 metric tonnes of metallic mercury that implies a threat to the marine environment. In September 2007 The Norwegian Costal Administration commissioned Det Norske Veritas to further investigate different alternatives to salvage the wreck and remove the mercury from the seabed.

This report deals with supplementary study number 10; "Risk related to mercury leakage during salvage and relocation".

The task of the study is to investigate the consequences if mercury is unintentionally leaking and spreading during a salvage or relocation of U-864.

DNV's overall conclusion is: The most critical part related to mercury leakage is during the salvage and relocation. If mercury is lost close to the water surface in the assumed deepest area (175 m) it could be spread up to almost 1 km away from the wreck..

Report No.:	Subject Group:
23916-10	

Report title:
Salvage of U864 - Supplementary studies - Risk related to mercury leakage during salvage and relocation

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TECHNICAL REPORT

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TECHNICAL REPORT

The German submarine U-864 was torpedoed by the British submarine Venturer on February 9 1945 and sunk approximately two nautical miles west of the island Fedje in Hordaland. U-864 was carrying about 67 metric tonnes of metallic mercury that implies a threat to the marine environment.

In September 2007 The Norwegian Costal Administration commissioned Det Norske Veritas to further investigate different alternatives to salvage the wreck and remove the mercury from the seabed.

1 SUMMARY

This report is *Supplementary Study No. 2: Risk related to mercury leakage during salvage and relocation*, one of twelve supplementary studies supporting the overall report regarding U-864 (Det Norske Veritas Report No. 23916) prepared by Det Norske Veritas (DNV).

The task of this supplementary study is to investigate the consequences if mercury is unintentionally leaking and spreading during a salvage or relocation of U-864.

Based on a review of a general description of a salvage and relocation operation and an earlier risk assessment done by DNV in 2006, the expert group identified 13 scenarios, out of which six scenarios have a high or a medium probability for an unintentional leakage of mercury:

1. *Sediments slide during operations on seabed*

2. *Parts of the hull and/or part of the keel comes off during the lifting operation*

3. *Free mercury leaks, sediments or canisters fall out during the lifting operation*

4. *Free mercury leaks, sediments or canisters fall out when the wreck breaks the water surface and is placed on a transport vessel*

5. *Spill of mercury, sediments or canisters during the transportation of the wreck on a transport vessel*

6. *Mercury leaks out when the wreck is lifted from the transport vessel to land*

The chosen scenarios were divided into three groups for numerical modelling of mercury leakage:

- **Group A** - Modelling of a sediment slide during operations on the seabed (Scenario no. 1)
- **Group B** - Modelling release of mercury during lifting of the wreck and placement on a vessel (Scenario no. 2, 3 and 4)
- **Group C** - Modelling release of mercury during transport and offloading (Scenario no. 5 and 6)

DNV's overall conclusion is:

The most critical part related to mercury leakage is during the salvage and relocation. If mercury is lost close to the water surface in the assumed deepest area (175 m) it could be spread up to almost 1 km away from the wreck.

DNV's supporting conclusions are:

C1. <u>During operations on seabed:</u> Results from modelling of mercury losses (mercury contamination in the sediments) from sediment slides during operations on the seabed were calculated to be in the order of 1-2 kg for an average (50 % percentile) current. As long as the wreck part is not sliding there is no reason to assume that elemental mercury (from inside the wreck) should be spread.

C2. <u>During lifting:</u> Results from modelling of release of mercury during lifting of the wreck and placement on a vessel show clearly that the size of the mercury droplets is important for how large the depositional area of the mercury will be. Finer droplets give a larger depositional area. The direction in which the droplets are spread from the release point is mainly controlled by the direction of the current. The model results indicate that even for a "worst case" with small mercury droplets released from the water surface above the wreck and a relatively strong current, the droplets will settle within a 1 km^2 area around the wreck.

C3. <u>During transport:</u> As the exact transport route is not chosen, it is only possible to make some major assumptions from the results of modelling of release of mercury during transport and offloading. It is assumed that the water depth should not be substantially more than 175 m along the transport route and the current should not be much larger than measured in the area around the wreck. This means that the results from group B can be used as preliminary "worst case" results.

It should be possible to use some type of a suction dredger for removal of elemental mercury (droplets) from the seafloor. When dredging with a suction dredger, large amounts of water and sediments will follow the mercury droplets. A cleaning/separation of the dredged material has to take place either on the vessel or on land. The suction dredger should be assisted with an ROV (Remote Operated Vehicle) equipped with a camera during the dredging. It is highly recommended that the technology is tested thoroughly before it is taken into use.

The rest of *Supplementary Study No. 2: Risk related to mercury leakage during salvage and relocation* details the arguments behind the conclusions.

Den tyske ubåten U-864 ble torpedert av den britiske ubåten Venturer den 9. februar 1945 og sank omtrent to nautiske mil vest for øya Fedje i Hordaland. U-864 var lastet med omtrent 67 tonn med metallisk kvikksølv som utgjør en fare for det marine miljøet.

I september 2007 tildelte Kystverket Det Norske Veritas oppdraget med å nærmere utrede ulike alternativer for heving av vrak og fjerning av kvikksølv fra havbunnen.

2 SAMMENDRAG

Denne rapporten er *Tilleggsutredning nr. 2: Fare for utlekking av kvikksølv ved heving og forflytning Eksplosiver*, en av tolv tilleggsutredninger som understøtter hovedrapporten vedrørende U-864 (Det Norske Veritas Report No. 23916) utarbeidet av Det Norske Veritas (DNV).

Formålet med denne tilleggsstudien er å undersøke konsekvensene av hvis kvikksølv utilsiktet lekker og spres under heving og forflytning av U-864.

Basert på en generell beskrivelse av en hevings- og forflytningsoperasjon og en tidligere risikovurdering utført av DNV i 2006, har ekspertgruppen identifisert 13 scenarier, hvorav seks scenarier har høy eller middels sannsynlighet for en utilsiktet lekkasje:

1. *Et skred (av sedimenter) utløses under arbeid på sjøbunnen*

2. *Deler av skroget og/eller deler av kjølen faller av under hevingsoperasjonen*

3. *Fritt kvikksølv lekker, sediment og kvikksølvbeholdere faller ut under hevingsoperasjonen*

4. *Fritt kvikksølv lekker, sediment og kvikksølvbeholdere faller ut når vraket bryter vannoverflaten og plasseres på transportfartøyet*

5. *Lekkasje av kvikksølv, sediment og kvikksølvbeholdere under transport av vraket på et fartøy*

6. *Kvikksølv lekker når vraket løftes fra fartøyet over til land*

De valgte scenariene ble delt inn i tre grupper for numerisk modellering av kvikksølvutslipp:

- **Gruppe A** – Modellering av et skred (av sedimenter) som utløses under arbeid på sjøbunnen (Scenario nr. 1)
- **Gruppe B** – Modellering av utslipp av kvikksølv under heving av vraket og plassering på et fartøy (Scenario nr. 2, 3 and 4)
- **Gruppe C** - Modellering av utslipp av kvikksølv under transport og avlasting (Scenario nr. 5 og 6)

DNV sin overordnede konklusjon er:

Den mest kritiske delen knyttet til kvikksølvlekkasje er under heving og transport. Dersom kvikksølv mistes nær havoverflaten over det antatt dypeste området (175 m) kan kvikksølvet spres opp til 1 km vekk fra vraket.

DNV underbygger denne konklusjonen med:

C1. **<u>Under operasjoner på sjøbunn:</u> Resultater fra modellering av tap av kvikksølv (kvikksølvforurensning som finnes i sedimentene) fra skred under operasjoner på havbunnen er beregnet til å være i størrelsesorden 1-2 kg for en gjennomsnittlig strømhastighet i vannet (50 % persentil). Så lenge som vraket ikke sklir ut er det ingen grunn til å anta at elementært kvikksølv (fra innsiden av vraket) skulle spres.**

C2. **<u>Under heving:</u> Resultater fra modellering av utslipp av kvikksølv under heving av vraket og plassering på et fartøy viser tydelig at størrelsen av kvikksølvdråpene er vesentlig for hvor stort avsetningsområdet på bunnen av kvikksølv vil bli. Finere dråper gir større avsetningsområde. I hvilke retning dråpene spres fra utslippspunktet kontrolleres i hovedsak av strømretningen. Modellen indikerer at for et "worst case" med små kvikksølvdråper som slippes fra vannoverflaten rett over vraket og en relativt sterk strøm, så vil dråpene falle til sjøbunnen innenfor et 1 km^2 stort område rundt vraket.**

C3. **<u>Under transportering:</u> Siden transportruten ikke er valgt, er det kun mulig å gjøre noen generelle antagelser fra resultatene av modellering av utslipp av kvikksølv under transport og avlasting. Det antas at vanndybden ikke er vesentlig mer enn 175 m langs transportruten og at strømmen ikke er mye sterkere enn målt i området rundt vraket. Dette betyr at resultater fra gruppe B kan brukes som et preliminært "worst case" resultat.**

Det skulle være mulig å bruke noen type av sugemudringsutstyr for fjerning av elementært kvikksølv (dråper) fra sjøbunnen. Når en mudrer med sugemudringsutstyr vil store mengder vann og sedimenter følge kvikksølvdråpene. En rensing/separasjon av det som mudres må finne sted enten på fartøyet eller på land. Sugemudringsutstyret bør assisteres av en ROV (fjernstyrt undervannsfarkost) utstyrt med kamera under selve mudringen. Det anbefales sterkt at teknologien testes ut grundig før den tas i bruk.

Resten av *Tilleggsutredning nr. 2: Fare for utlekking av kvikksølv ved heving og forflytning* utdyper argumentene bak konklusjonene.

3 INTRODUCTION

3.1 Background

The German submarine U-864 was sunk by the British submarine Venturer on 9 February 1945, approximately 2 nautical miles west of the island Fedje in Hordaland (Figure 3-1). The submarine was on its way from Germany via Norway to Japan with war material and according to historical documents; U-864 was carrying about 67 metric ton of metallic (liquid) mercury, stored in steel canisters in the keel. The U-864, which was broken into two main parts as a result of the torpedo hit, was found at 150-175 m depth by the Royal Norwegian Navy in March 2003. The Norwegian Costal Administration (NCA) has, on behalf of the Ministry of Fisheries and Coastal Affairs, been performing several studies on how the risk that the mercury load constitutes to the environment can be handled. In December 2006 NCA delivered a report to the Ministry where they recommended that the wreck of the submarine should be encapsulated and that the surrounding mercury-contaminated sediments should be capped. In April 2007 the Ministry of Fisheries and Coastal Affairs decided to further investigate the salvaging alternative before a final decision is taken about the mercury load.

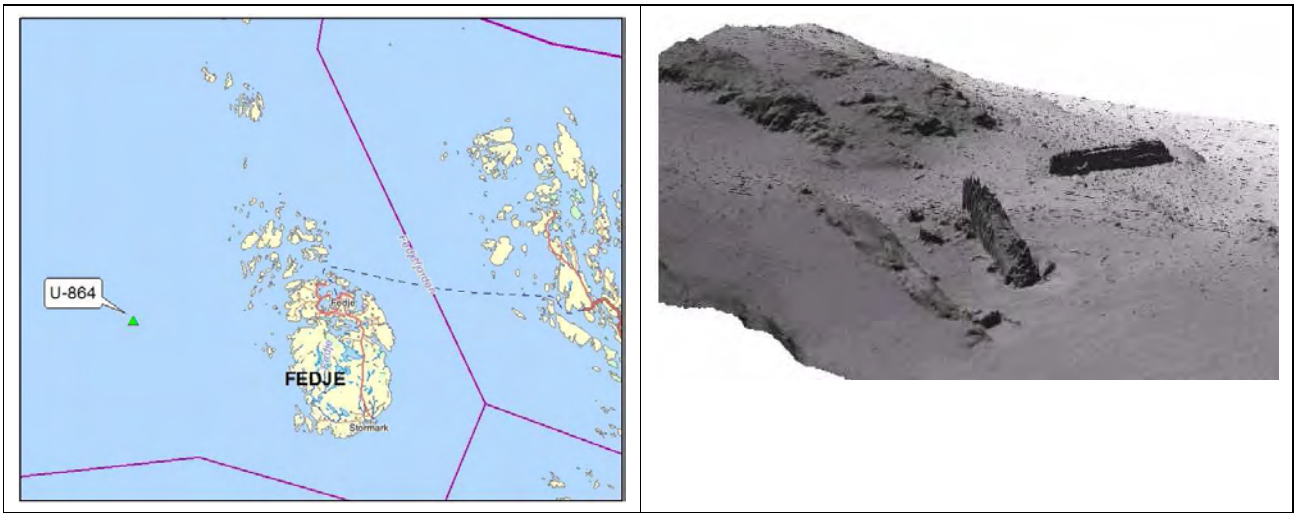

Figure 3-1 Location (left) and a sonar picture of the wreck of U-864 on seabed (right) (from Geoconsult).

3.2 DNVs task

- In September 2007 NCA commissioned Det Norske Veritas (DNV) the contract to further investigate the salvaging alternative. The contract includes:
- DNV shall support NCA in announcing a tender competition for innovators which have suggestions for an environmentally safe/acceptable salvage concept or technology. Selected innovators will receive a remuneration to improve and specify their salvage concept or technology.

- DNV shall support NCA in announcing a tender competition for salvage contractors to perform an environmentally justifiable salvage of U-864.
- DNV shall evaluate the suggested salvage methods and identify the preferred salvage method.
- DNV shall perform twelve supplementary studies which will serve as a support when the decision is taken about which measure that should be chosen for removing the environmental threat related to U-864. The twelve studies are:

1. *Corrosion*. Probability and scenarios for corrosion on steel canisters and the hull of the submarine.
2. *Explosives.* Probability and consequences of an explosion during salvaging from explosives or compressed air tanks.
3. *Metal detector*. The possibilities and limitations of using metal detectors for finding mercury canisters.
4. *The mid ship section*. Study the possibility that the mid section has drifted away.
5. *Dredging*. Study how the mercury-contaminated seabed can be removed around the wreck with a minimum of spreading and turbidity.
6. *Disposal*. Consequences for the environment and the health and safety of personnel if mercury and mercury-contaminated sediments are taken up and disposed of.
7. *Cargo.* Gather the historical information about the cargo in U-864. Assess the location and content of the cargo.
8. *Relocation and safeguarding.* Analyse which routes that can be used when mercury canisters are relocated to a sheltered location.
9. *Monitoring.* The effects of the measures that are taken have to be documented over time. An initial programme shall be prepared for monitoring the contamination before, during and after salvaging.
10. *Risk related to leakage.* Study the consequences if mercury is unintentionally leaked and spreading during a salvage or relocation of U-864.
11. *Assessment of future spreading of mercury for the capping alternative*. The consequences of spreading of mercury if the area is capped in an eternal perspective.
12. *Use of divers.* Study the risks related to use of divers during the salvage operation in a safety, health and environmental aspect and compare with use of ROV.

3.3 This report

This report is *Supplementary Study No. 10: Risk related to mercury leakage during salvage and relocation.* The task of the study is to investigate the consequences if mercury is unintentionally leaking and spreading during a salvage or relocation of U-864.

In this supplementary study the scenarios that can give an unintentional leakage of mercury during salvage or relocation have been identified , among others the scenarios identified in the risk assessment done by DNV in 2006 /1/. For each scenario, the following issues have been addressed:

- What is the probability for spreading mercury?
- What will be the consequences of spreading mercury?
- How easy is it to remediate if an accident (spreading of mercury) happens?

The probability for and the consequences of an unwanted event if spreading of mercury occurs has been assessed by using DNVs risk assessment tool (also used in /1/). Preventive measures for the identified scenarios of spreading are described together with an assessment of the degree of difficulty of (and if needed, also the cost for) the measure.

To be able to assess the consequences of the spreading of mercury it is necessary to know how far the spreading can reach. This has been done by computer modelling of the spreading for the most relevant scenarios. The conditions for the modelling have been established by the expert group (the authors of this report).

Finally, the possibility to remove the mercury with some sort of suction equipment has been evaluated.

The structure of this report is:

- Scenarios which can give an unintentional leakage of mercury during salvage or relocation (chapter 4)
- Modelling of unintentional leakage of mercury during salvage or relocation (chapter 5)
- Technologies for Removal of mercury from the seafloor (chapter 6)

4 SCENARIOS WHICH CAN GIVE AN UNINTENTIONAL LEAKAGE OF MERCURY DURING SALVAGE OR RELOCATION

Salvaging the U-864 will also include the mercury, which is either stored in the keel or as polluted sediments inside the wreck. The salvage of the mercury which is in the surrounding sediments by dredging is described in the DNV report 23916-5 *"Dredging"*.

The salvage of the mercury which is in the wreck parts can result in unintentional leakage both during the lifting of the wreck parts and during the relocation (placement on a vessel and transport to a safe harbour). This supplementary study covers the transport to a safe harbour but not risks related to further handling of the mercury. The DNV report 23916-6 *"Disposal"* describes different disposal solutions for the mercury and Health, Safety and Environment (HSE) measures which should be taken when working with mercury.

4.1 Identified scenarios

Based on a review of the a general description of a salvage and relocation operation and an earlier risk assessment done by DNV in 2006 /1/, the expert group identified 13 different scenarios which can give an unintentional leakage of mercury:

1. Sediments slide during operations on seabed

2. Parts of the hull and/or part of the keel comes off during the lifting operation

3. Free mercury leaks, sediments or canisters fall out during the lifting operation

4. Free mercury leaks, sediments or canisters fall out when the wreck breaks the water surface and is placed on a transport vessel

5. Spill of mercury, sediments or canisters during the transportation of the wreck on a transport vessel

6. Mercury leaks out when the wreck is lifted from the transport vessel to land

7. An explosion occurs during the salvage operation

8. Bursting high pressured air causes spreading of mercury

9. The transport vessel goes down with the entire load during transport

10. Mercury is spread during cleaning and removal of residuals from the transport vessel

11. Mercury leaks out during cleaning and removal of residuals from the wreck

12. The wreck slips out of the lifting or relocation equipment

13. The lifting equipment breaks during the salvage of the sub

4.2 Detailed description and risk assessment of the identified scenarios

The different scenarios are described more in detail (including probability, consequence, mitigating measures) in Table 4-2 (scenarios with high and medium probability) and in Table 4-3 (scenarios with low probability). The scale for probability and consequence is presented in Table 4-1 and the distribution of the 13 different scenarios in a 3x3 risk matrix is shown in Figure 4-1.

Table 4-1 Scale for probability and consequence

	Probability	Consequence
High	The scenario/event will occur more than 3 out of 10 times when such an operation is done.	Can lead to mercury contamination which has long-term negative effects on fish and shellfish and/or the sea. Fishery in the neighbourhood is being influenced
Medium	The scenario/event will occur more than 1 out of 10 times (and less than 3 out of 10) when such an operation is done.	Gives a measurable effect. Can give large contamination on a short term. Can give increased mercury concentration in fish and shellfish. Has no negative consequence on human beings. Fishery in the neighbourhood can be influenced.
Low	The scenario/event will occur less than 1 out of 10 times when such an operation is done.	No measurable effect on fish and shellfish and/or the sea. Fishery in the neighbourhood is not influenced.

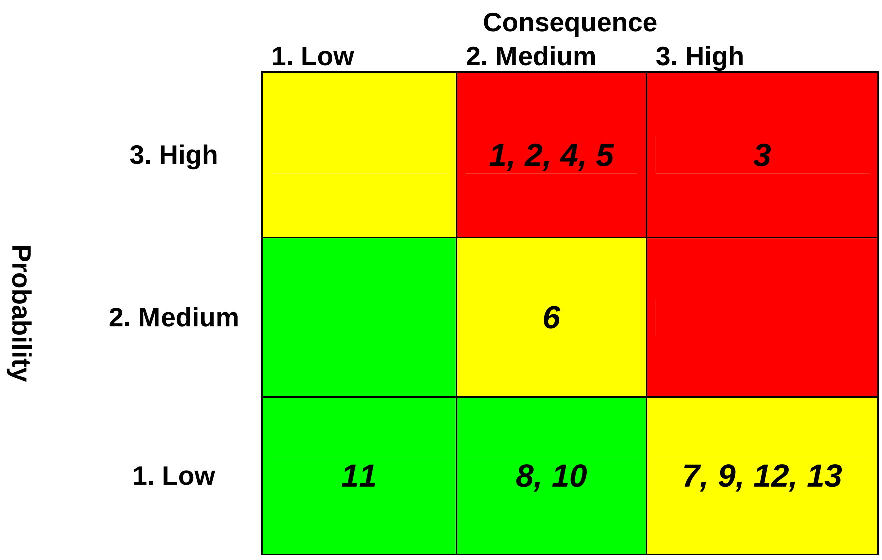

Figure 4-1 Distribution of the 13 different scenarios in a 3x3 risk matrix. (The numbers correspond to the scenarios described in Table 4-2 and Table 4-3). Red = high risk, yellow = medium risk, green = low risk.

Table 4-2 Scenarios with high and medium probability

No	Scenarios	Description	Proba-bility	Consequences	Comments	Mitigating measures
1	Sediments slide during operations on seabed.	Caused by an excessive load on the seabed. There is low sediment stability around the front part of wreck (in the steep slope).	High	Medium-Low. The wreck and sediments are sliding; causing massive turbidity and spreading of a limited amount of mercury outside the contaminated area.	The worst case slide has been estimated to be 55x55 m and 2.5 m deep, invol-ving 7 500 m^3 of sediments and the loss of mercury is expected to be 1-2 kg (Appendix A). Steep and unstable terrain makes the probability for a slide at the front higher than at the stern part.	1. Stabilise the slope with a counterfill on the bottom (possible but expensive). 2. Place the heavy equipment on hard bottom (possible if hard bottom is around). 10-15 kPa is assumed maximum load on seafloor. 3. Secure the wreck and heavy equipment with wires, anchors. etc. (possible but expensive). 4. Avoid contact with the seafloor for heavy equipment (depends on approach).
2	Parts of the hull and/or part of the keel comes off during the lifting operation.	Caused by underestimated suction between wreck and sediment. Damage to keel or hull when positioning lifting equipment. The wreck parts are filled with sediments near the opening towards the midsection.	High-Medium	Medium. Loss of contaminated sediments, canisters, oil and mortal remains, and this causes spreading of mercury locally.	The operation has to start all over again to recover the keel or other wreck parts.	1. Dredge around to get better access to the hull and reduce the suction forces to the hull. 2. Look at the possibilities to use softer materials for the lifting equipment without sharp edges. 3. Distribute the lifting load better. 4. Look at the possibility to remove the sediments, oil and diesel inside the wreck before the lifting starts. 5. Use ROV to pick up as much as possible of lost canisters
3	Free mercury leaks, sediments or canisters fall out during the lifting operation.	The mercury canisters leak due to corrosion or damage caused by original hit by torpedo in 1945. The hull is not sufficient secured against leakage.	High	High-Medium. Depending on the amount of free mercury, number of canisters and amount of sediments released into the water column. Height above seabed will have impact on the consequence.	This has to be prepared for. It has to be assumed that there will be loss of material of some amount and form.	1. Remove sediments, canisters and free mercury before lifting the wreck. 2. Seal the hull breach. 3. Look at the possibility to encapsulate the whole wreck before lifting. 4. Use a collection device beneath the wreck. 5. Monitor balance of the wreck 6. Slow and careful lifting because much water will come out (look at the possibility of performing a hydraulic laboratory test beforehand).

No	Scenarios	Description	Proba-bility	Consequences	Comments	Mitigating measures
4	Free mercury leaks, sediments or canisters fall out when the wreck breaks the water surface and is placed on a transport vessel.	Mercury, water and suspended sediments comes out during this phase of the operation.	High	Medium. Less mercury is lost due to better control compared to the initial lifting phase at the bottom where the wreck is tilted.	The potential for spreading of sediments far away is highest from the surface. The challenge with using a drainage collector is that it will be filled with water. This will cause losses of sediments, canisters or any free mercury in the drainage collector.	1. Remove sediments, canisters and free mercury before lifting the wreck 2. Seal the hull breach 3. Look at the possibility to encapsulate the whole wreck. 4. Use some (drainage) collection device beneath the wreck during lifting.
5	Spill of mercury, sediments or canisters during the transportation of the wreck on a transport vessel.	Mercury, water and suspended sediments is released during this phase of the operation.	High	Medium-Low	Minor losses of sediments are seen as low consequences. Spill of free mercury is seen as medium consequences. Depends on the probability of methylation.	1. Plan for the most safe transport route. 2. Secure and seal the wreck and the load during transportation.
6	Mercury leaks out when the wreck is lifted from the transport vessel to land.	When lifting the wreck, canisters, sediment etc are spread to the environment.	Medium	Medium-Low	Focus should be on health problems for humans working with the lifting. The consequences are expected to be less severe because the operation are in shallow water close to land or on land.	1. Find a location where the probability and consequences are low. 2. Have controlled and limited access to the decontamination area. 3. Lift with a "tub" (drainage collector) below the wreck. 4. Take into account extra weight when lifting, due to remaining water and sediments in the hull.

Table 4-3 Scenarios with low probability

No	Scenarios	Description	Proba-bility	Consequences	Comments	Mitigating measures
7	An explosion occurs during the salvage operation.	Explosives are exposed to excessive force during lifting (elevation or preparation for transport). Torpedoes, grenades/ ammunition can still detonate.	(Very) Low	High. Massive destruction to submarine, massive spreading, loss of canisters, damage to canister, massive sediment transport. Damaged equipment.	The risk for an explosion is considered very low (theoretical). The Norwegian Defence Authorities do not have any records of such incidents occurring in prior operations of this type.	1. Involve experts on explosives. (For more details it is referred to the DNV-report no. 23916-2, Salvage of U864 – Supplementary studies – Explosives).
8	Bursting high pressured air causes spreading of mercury.	High pressure air containers burst during operation due to exposure to excessive force or reduction of ambient pressure.	(Very) Low	Low-medium. Less severe (explosive force) than explosives. Pressured air was not in the area where mercury was stored.	The risk has been assessed to be insignificant.	1. Involve experts on compressed air in submarines. (For more details it is referred to the DNV-report no. 23916-2, Salvage of U864 – Supplementary studies – Explosives).
9	The transport vessel goes down with the entire load during transport.	Due to an accident, collision or other reason the transport vessel goes down.	Low	High		1. Not allowing other ships in the area during transport. 2. Plan for the safest transport route. 3. Use a pilot boat or a pilot on board the transport vessel.
10	Mercury is spread during cleaning and removal of residuals from the transport vessel.	The transport vessel has to be cleaned before it is cleared for other operations.	Low	Low-Medium	Residuals have to be taken care of, this means that a final cleaning has to be done to the vessel after unloading.	1. Establish a water treatment plant. 2. Contain the cleaning area in the harbour (silt curtain, oil boom, hazardous waste procedures).

No	Scenarios	Description	Proba-bility	Consequences	Comments	Mitigating measures
11	Mercury leaks out during cleaning and removal of residuals from the wreck.	The wreck has to be cleaned before it is scrapped.	Low	Low	If the decontamination site has sealed ground and water run off is collected, the consequence is low.	1. Establish a water treatment plant. 2. People working in the area should have protection against mercury vapour (inhalation protection).
12	The sub slips out of the lifting or relocation equipment.	Miscalculated distribution forces can cause unbalance and loss of wreck during lifting.	Low	High	Could cause major spreading of elemental mercury, sediments, canisters and the wreck may be so damaged so it can't be lifted any more.	1. Work in periods with good weather conditions. 2. Monitor the load distribution. 3. Remove sediments in the hull before lifting.
13	The lifting equipment breaks during the salvage of the sub.	Miscalculated weight of the wreck or the wire is hit by other equipment.	Low	High	Could cause major spreading of elemental mercury, sediments, canisters and the wreck may be so damaged so it can't be lifted any more.	1. Work in periods with good weather conditions. 2. Keep distance from other working equipment in the water. 3. Monitor the load distribution.

5 MODELLING OF UNINTENTIONAL LEAKAGE OF MERCURY DURING SALVAGE OR RELOCATION

DNV's conclusions are:

C1. During operations on seabed: Results from modelling of mercury losses (mercury contamination in the sediments) from sediment slides during operations on the seabed were calculated to be in the order of 1-2 kg for an average (50 % percentile) current. As long as the wreck part is not sliding there is no reason to assume that elemental mercury (from inside the wreck) should be spread.

C2. During lifting: Results from modelling of release of mercury during lifting of the wreck and placement on a vessel show clearly that the size of the mercury droplets is important for how large the depositional area of the mercury will be. Finer droplets give a larger depositional area. The direction in which the droplets are spread from the release point is mainly controlled by the direction of the current. The model results indicate that even for a "worst case" with small mercury droplets released from the water surface above the wreck and a relatively strong current, the droplets will settle within a 1 km^2 area around the wreck.

C3. During transport: As the exact transport route is not chosen, it is only possible to make some major assumptions from the results of modelling of release of mercury during transport and offloading. It is assumed that the water depth should not be substantially more than 175 m along the transport route and the current should not be much larger than measured in the area around the wreck. This means that the results from group B can be used as preliminary "worst case" results.

To be able to predict how far the mercury can be spread for the most relevant leakage scenarios modelling has been done with the PC-based numerical model SSFATE. SSFATE was chosen because it has been especially developed to predict sediment dispersion.

A full report of the modelling is enclosed in Appendix A. In this chapter a summary of the most important findings and conclusions from the modelling is given.

5.1 The model

The model which has been used is SSFATE which is a PC-based numerical model to predict sediment dispersion resulting from dredging activities. SSFATE was developed by Applied Science Associates (United States) and the US Army Corps of Research Development Center.

5.2 Input for the modelling

The input for the modelling was set up jointly by the expert group which has been working with this report during a workshop held at DNV 8 to 9 November 2007. The modelling itself was done by Allen Teeter, member of the expert group coming from Computational Hydraulics and Transport Ilc in the United States.

In the modelling it was assumed that the wreck and debris will be salvaged before dredging (or capping) of the contaminated sediments on the seafloor takes place. Based on the investigations done by NIVA the contaminated area was assumed to be 30 000 m^2 and the thickness of the contaminated layer to be 0.5 meter, resulting in a theoretical dredging volume of 15 000 m^3. The input data of the sea bed topography was based on the mapping by DOF Subsea and covers approximately 1 km x 1 km with the resolution of 0.5 meters.

5.2.1 Currents

The currents used in the model were taken from measurements done by NIVA in 2005 /2/. Figure 5-1 shows the distribution of the measured currents from 20 to 170 m depth for the 16 %, 50 % ("average") and 84 % percentile. The current is highest near the water surface and drops the gradually with water depth.

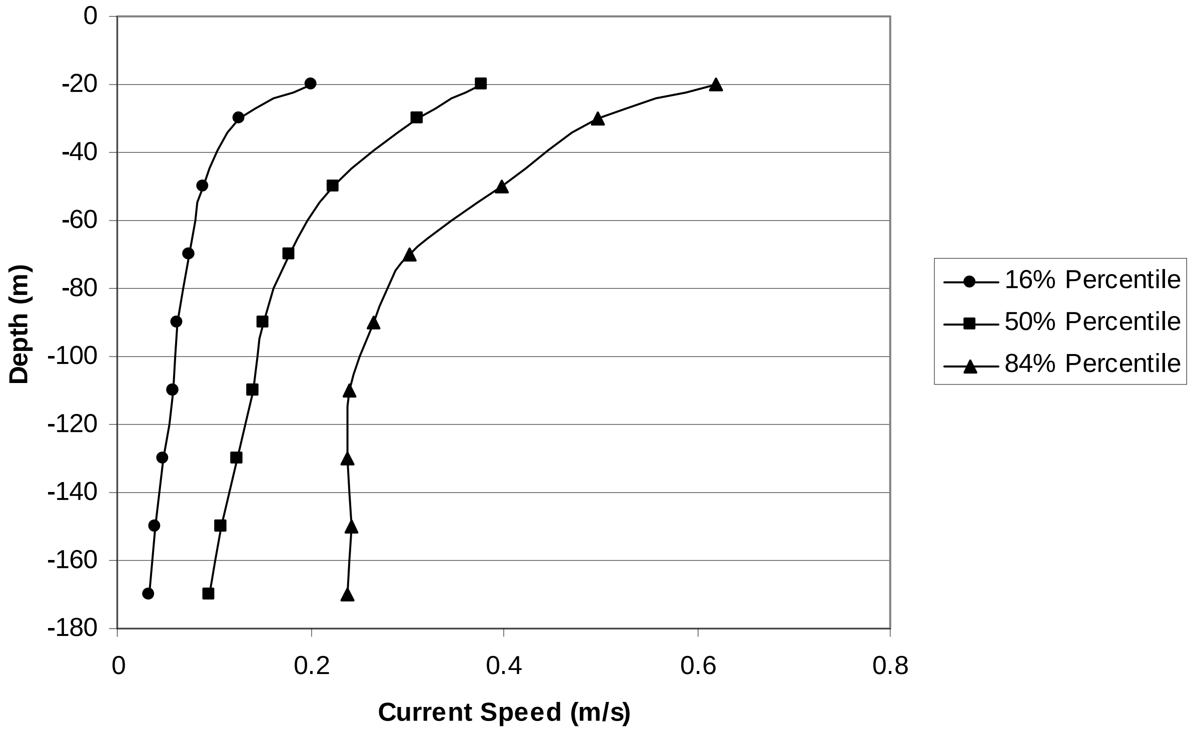

Figure 5-1 Distribution of current speed with water depth for different percentiles of occurrence

The main direction of the current close to the seafloor is about 300 degrees (West to Northwest) and about 340 degrees (Northwest to North) near the water surface.

5.2.2 Mercury

It is assumed that the unintentional leakage of mercury during salvage or relocation, consists of "pure" elemental mercury (density 13.5 g/cm^3). Since mercury is immiscible (does not mix with water) it forms droplets in the water which become unstable during descent in water. This leads to that the mercury droplets will break up during descent in water until the droplet reaches a critical value. The critical droplet size has been calculated with two different equations; one equation predicting a critical droplet diameter for mercury in sea water of 9.1 mm and the other a critical droplet diameter of 0.144 mm. It was concluded that the droplets represented a possible range; the 9.1 mm droplet representing a size close to an upper limit and the 0.144 mm droplet a size close to a lower limit for the critical droplet size. The 9.1 mm droplet has a calculated settling rate of 0.76 m/s and the 0.144 mm has a settling rate of 0.05 m/s.

5.3 The scenarios which were modelled and the results

In the previous chapter the consequences of the different scenarios which can cause unintentional leakage of mercury during salvage or relocation were evaluated. The expert group decided that it would be most relevant to model the scenarios which have medium or high probability for an unintentional leakage. This meant that scenarios 1 to 6 were chosen for numerical modelling (see Table 4-2 and Figure 4-1).

The chosen scenarios have been divided into three groups:

- **Group A** - Modelling of a sediment slide during operations on the seabed (Scenario no. 1)
- **Group B** - Modelling release of mercury during lifting of the wreck and placement on a vessel (Scenario no. 2, 3 and 4)
- **Group C** - Modelling release of mercury during transport and offloading (Scenario no. 5 and 6)

5.3.1 Group A - Modelling of a sediment slide during operations on the seabed (Scenario 1)

Scenario 1: Sediments slide during operations on seabed

The assumed slide is shown in Figure 5-2, and it is basically the same slide as the geotechnical experts assume is the worst case scenario (NGI).

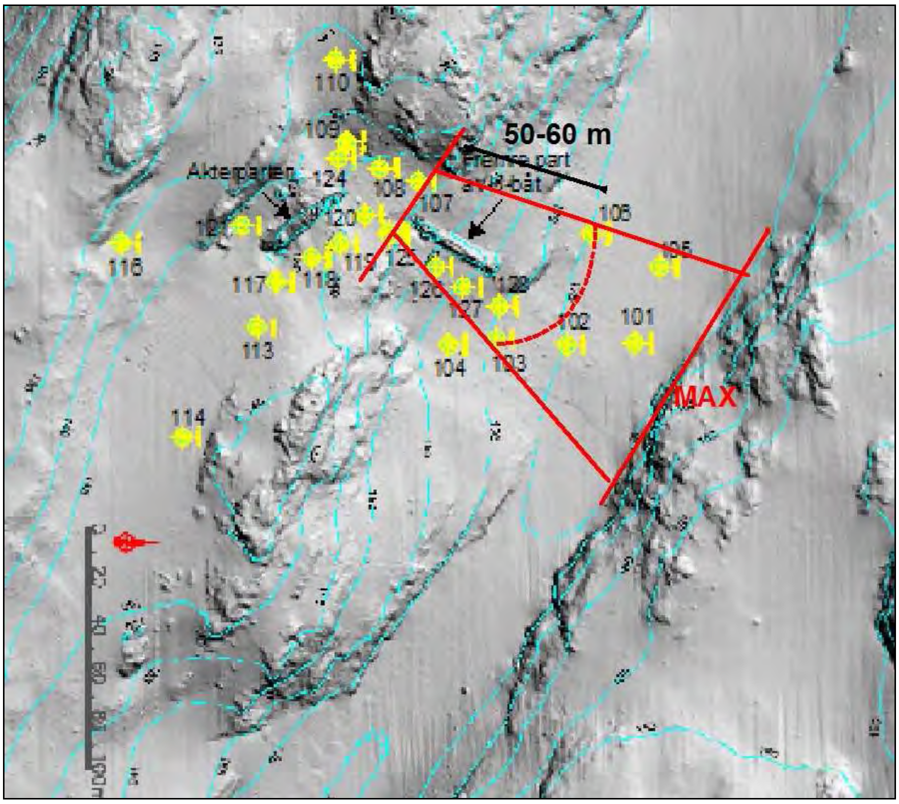

Figure 5-2 Assumed "worst case" slide

This worst case scenario assumes a 55 x 55 m slide with a 2.5 m thickness, releasing approximately 7 500 m^3 sediments including about 10 % of the cleanup area. This is the same as was assumed could be triggered by dredging activities (see DNV report 23916-6 *"Dredging").* Mercury losses (mercury contamination in the sediments) from such a slide were calculated to be in the order of 1-2 kg for an average (50 % Percentile) current. The simulation indicated that the suspended sediments (and the mercury in the sediments) will form a cloud in the water that will drift in the current direction. About 3 hours after the slide the cloud has left the 1 km^2 area around the wreck.

As long as the wreck part is not sliding there is no reason to assume that elemental mercury (from inside the wreck) should be spread.

5.3.2 Group B - Modelling release of mercury during lifting of the wreck (Scenario 2, 3, and 4)

Scenario 2: Parts of the hull and/or part of the keel comes off during the lifting operation

Scenario 3: Free mercury leaks, sediments or canisters fall out during the lifting operation

Scenario 4: Free mercury leaks, sediments or canisters fall out when the wreck breaks the water surface and is placed on a transport vessel

This group involves release of mercury during lifting operations and placement on the vessel. In general the area over which a release of mercury is spread will increase with the height above the seafloor that the release occurs. The model assumes that a large amount of mercury droplets are accidentally released at the water surface 175 m above the seafloor during 0.1 hour (6 minutes). Figure 5-3and Figure 5-4 show results for two different droplet sizes from such a release for a 16% percentile current.

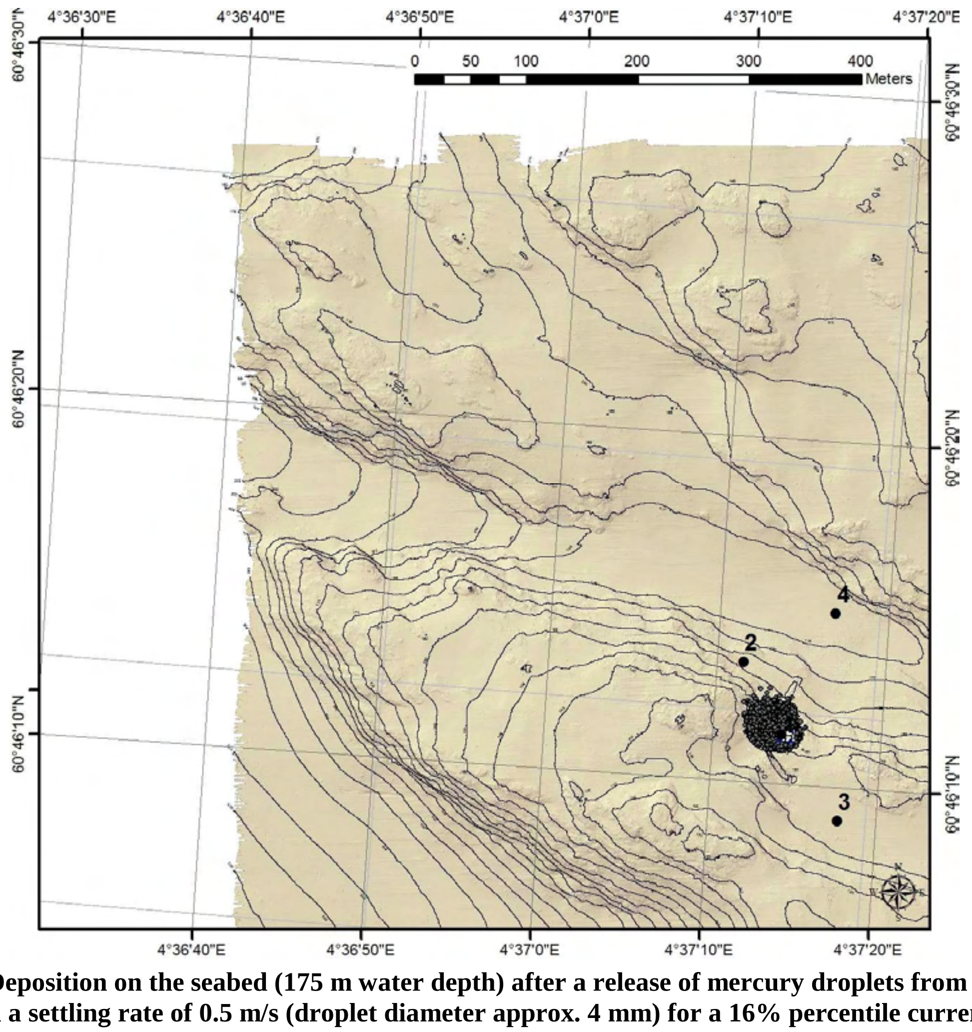

Figure 5-3 Deposition on the seabed (175 m water depth) after a release of mercury droplets from the water surface with a settling rate of 0.5 m/s (droplet diameter approx. 4 mm) for a 16% percentile current.

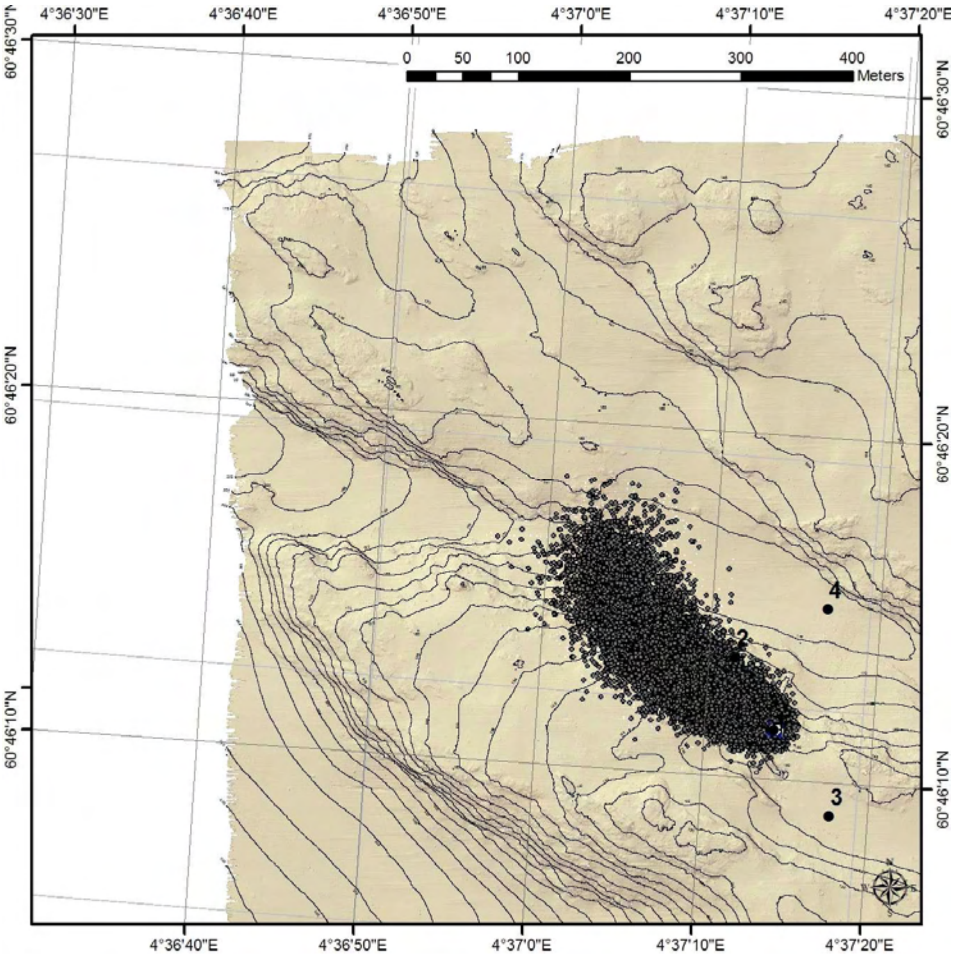

Figure 5-4 Deposition on the seabed (175 m water depth) after a release of mercury droplets from the water surface with a settling rate of 0.05 m/s (droplet diameter approx. 0.15 mm) for a 16% percentile current.

The results show clearly that the size of the droplets is important for how large the depositional area of the mercury will be. The larger 4 mm mercury droplets settled within a 65 m diameter circular area (Figure 5-3) around the release point (above the wreck). The smaller 0.15 mm mercury droplets settled within a fan-shaped area reaching about 300 m away from the release point (above the wreck) in the current direction (Figure 5-4). The results show that the direction in which the droplets are spread from the release point is mainly controlled by the direction of the current.

The strength of the current will decide how far the mercury droplets will be spread. Table 5-5 shows the distance the 0.15 mm and the 4 mm droplets stay within in case of a release on the water surface for a 16% percentile current (as shown in Figure 5-3 and 5-4) compared to a 84% percentile current.

Table 5-1 Distance that mercury droplets stay within on the seafloor after a release from the water surface above the wreck

Current (from Figure 5-1)	Current speed at 170 m water depth (from Figure 5-1)	Droplet size	Settling rate of mercury droplets	Distance that the mercury droplets stay within on the seafloor when spread from the release point (above the wreck)
16% percentile	0.03 m/s	0.15 mm	0.05 m/s	300 m
16% percentile	0.03 m/s	4 mm	0.5 m/s	65 m
84% percentile	0.24 m/s	0.15 mm	0.05 m/s	750 m
84% percentile	0.24 m/s	4 mm	0.5 m/s	120 m

The results indicate that even for a "worst case" with small mercury droplets released from the water surface above the wreck and a 84% percentile current, the droplets will settle within the 1 km^2 area around the wreck.

5.3.3 Group C - Modelling release of mercury during transport and offloading (Scenario 5 and 6)

Scenario 5: Spill of mercury, sediments or canisters during the transportation of the wreck on a transport vessel

Scenario 6: Mercury leaks out when the wreck is lifted from the transport vessel to land

For group C there is only possible to make some major assumptions as long as the exact transport route is not chosen. It is assumed that the water depth should not be substantially more than 175 m along the transport route and the current should not be much larger than measured in the area around the wreck. This means that the results from group B can be used as preliminary "worst case" results (fine mercury droplets, Figure 5-4). When the water gets shallower the deposition area will be reduced.

6 TECHNOLOGIES FOR REMOVAL OF MERCURY FROM THE SEAFLOOR

There are no examples in the literature of removal of elemental mercury from deep water. In more shallow waters tests have however been done with dredging of mercury hotspots originating from goldmining activities. In the South Fork of the American River (California, US) a test was done with a small 4 inch (10 cm) suction dredge to remove mercury. It was possible to remove sediments containing mercury droplets with the equipment, further information can be found on /3/.

It should be possible to use the same technology, but with a suction dredger with larger capacity for removal of elemental mercury (droplets) from the seafloor. When dredging with a suction dredger, large amounts of water and sediments will follow the mercury droplets. A cleaning/ separation of the dredged material has to take place either on the vessel or on land.

The suction dredger should be assisted by an ROV (Remote Operated Vehicle). It is highly recommended that the technology is tested thoroughly before it is taken into use.

7 REFERENCES

/1/ DNV 2006, Rapport risikovurdering av alternative miljøtiltak U-864: Rapport til Kystdirektoratet, Beredskapsavdelingen, Rapport no.: 2006-1964, Rev.1, 24 november 2006 (the whole report is in Norwegian)

/2/ Uriansrud and Skei, 2005. Miljøovervåkning, strømundersøkelser, sedimentkartlegging og miljørisikovurdering til Fase 1 kartlegging og fjerning av kvikksølvforurensing ved U864. NIVA Rapport lnr. 5092-2005 (in Norwegian).

/3/ http://www.swrcb.ca.gov/general/publications/docs/mercurystaffreport2005.pdf

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APPENDIX

A

DISPERSION OF SEDIMENTS AND MERCURY RESULTING FROM PROPOSED U864 SALVAGE AND CLEANUP DREDGING (ALLEN TEETER, COMPUTATIONAL HYDRAULICS AND TRANSPORT ILC)

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TECHNICAL REPORT

KYSTVERKET NORWEGIAN COASTAL ADMINISTRATION

SALVAGE OF U864 - SUPPLEMENTARY STUDIES - USE OF DIVERS

REPORT NO. 23916-12

REVISION NO. 01

DET NORSKE VERITAS

TECHNICAL REPORT

Date of first issue:	Project No.:
2008-07-04	23916
Approved by: Carl Erik Høy-Petersen, Senior Consultant	Organisational unit: DNV Consulting
Client: Kystverket (Norwegian Coastal Administration)	Client ref.: Hans Petter Mortensholm

Summary:

The German submarine U-864 was torpedoed by the British submarine Venturer on February 9 1945 and sunk approximately two nautical miles west of the island Fedje in Hordaland. U-864 was carrying about 67 metric tonnes of metallic mercury that implies a threat to the marine environment.

In September 2007 The Norwegian Costal Administration commissioned Det Norske Veritas to further investigate different alternatives to salvage the wreck and remove the mercury from the seabed.

This report is *Study No. 12: Use of divers,* one of twelve supplementary studies supporting the overall report regarding U-864 (Det Norske Veritas Report No. 23916) prepared by Det Norske Veritas (DNV).

This supplementary study has assessed the opportunities for and the risk by using divers to salvage mercury canisters and debris from seabed, and assistance during salvage of U-864. Special attention is on safety, health and environmental issues regarding use of divers compared to use of remotely operated vehicles (ROVs).

DNV’s main conclusion is that diving to the depth of U-864 (150 m) is done routinely and no special attention must be given to compression and decompression procedures for the divers according to NORSOK U-100. The risks related to diving can not be assessed before the salvage method is chosen.

Report No.:	Subject Group:
23916-12	
Report title: Salvage of U864 - Supplementary studies - Use of divers	

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TECHNICAL REPORT

The German submarine U-864 was torpedoed by the British submarine Venturer on February 9 1945 and sunk approximately two nautical miles west of the island Fedje in Hordaland. U-864 was carrying about 67 metric tonnes of metallic mercury that implies a threat to the marine environment.

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1 SUMMARY

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This supplementary study has assessed the opportunities for and the risk by using divers to salvage mercury canisters and debris from seabed, and assistance during salvage of U-864. Special attention is on safety, health and environmental issues regarding use of divers compared to use of remotely operated vehicles (ROVs).

DNV's overall conclusion is:

Diving to the depth of U-864 (150 m) is done routinely and no special attention must be given to compression and decompression procedures for the divers according to NORSOK U-100. The risks related to diving can not be assessed before the salvage method is chosen.

DNV's supporting conclusions are:

C1. Diving to 150 meters, which is the depth of the U-864, is within normal diving depths on the Norwegian shelf. No special attention must be given to compression and decompression procedures for the divers according to NORSOK U-100.

C2. At the depth of U-864 using divers can be considered as a complementary intervention method to ROV-operations.

C3. Compared to ROVs, the use of divers during the salvage process' phases Preliminary Study, Elevation and Pollution abatement on seabed is expected to be beneficial as divers can get better access to the wreck, obtain more information about the situation and stir up less polluted sediments than an ROV.

C4: The criticality (probability and consequence) for each risk related to using divers during salvage of U-864 can not be assessed before the salvage methodology is chosen.

The rest of *Supplementary Study No. 12: Use of divers* details the arguments behind the conclusions.

Den tyske ubåten U-864 ble torpedert av den britiske ubåten Venturer den 9. februar 1945 og sank omtrent to nautiske mil vest for øya Fedje i Hordaland. U-864 var lastet med omtrent 67 tonn med metallisk kvikksølv som utgjør en fare for det marine miljøet.

I September 2007 tildelte Kystverket Det Norske Veritas oppdraget med å nærmere utrede ulike alternativer for heving av vrak og fjerning av kvikksølv fra havbunnen.

2 SAMMENDRAG

Denne rapporten er *Tilleggsutredning nr. 12: Bruk av dykkere*, en av tolv tilleggsutredninger som understøtter hovedrapporten vedrørende U-864 (Det Norske Veritas Report No. 23916) utarbeidet av Det Norske Veritas (DNV).

Denne tilleggsutredningen har vurdert muligheter for og risikoen ved bruk av dykkere til å heve kvikksølvbeholdere og vrakdeler fra havbunnen, og assistanse under en hevingen av U-864. Aspekter tilknyttet helse, miljø og sikkerhet er vurdert spesielt ved når bruk av dykkere er sammenlignet med bruk av fjernstyrt undervannsfartøy (ROV).

DNV sin overordnede konklusjon er:

Dykking ned til U-864 sin dybde (150) gjøres rutinemessig og det kreves ikke særskilte tiltak i forbindelse med kompresjons- og dekompresjonsprosedyrer for dykkerne iht NORSKO U-100. Dykkerrelaterte risikoer kan ikke vurderes før metode for heving er valgt.

DNV underbygger denne konklusjonen med:

C1: Dykking til 150 meter, som er dybden til U-864, er innenfor normale dykkedybder på norsk sokkel. Det kreves ikke særskilte tiltak i forbindelse med kompresjons- og dekompresjonsprosedyrer for dykkerne iht NORSKO U-100

C2: På dybden til U-864 regnes bruk av dykkere som komplementær intervensjonsmetode til bruk av ROV

C3: Sammenlignet med ROV, er det forventet at bruk av dykkere under hevingsprosessene Forberedelser, Heving og Fjerning av forurensning fra sjøbunn være fordelaktig fordi de lettere får tilgang til vraket, kan innhente mer informasjon om situasjonen og de virvler opp mindre forurensede sedimenter enn en ROV.

C4: Kritikaliteten (sannsynlighet og konsekvens) for dykkerrelaterte risikoer under heving av U-864 kan ikke vurderes før metode for heving er valgt.

Resten av *Studie nr. 12: Bruk av dykkere* utdyper argumentene bak konklusjonene.

3 INTRODUCTION

3.1 Background

The German submarine U-864 was sunk by the British submarine Venturer on 9 February 1945, approximately 2 nautical miles west of the island Fedje in Hordaland (Figure 2-1). The submarine was on its way from Germany via Norway to Japan with war material and according to historical documents; U-864 was carrying about 67 metric ton of metallic (liquid) mercury, stored in steel canisters in the keel. The U-864, which was broken into two main parts as a result of the torpedo hit, was found at 150-175 m depth by the Royal Norwegian Navy in March 2003. The Norwegian Costal Administration (NCA) has, on behalf of the Ministry of Fisheries and Coastal Affairs, been performing several studies on how the risk that the mercury load constitutes to the environment can be handled. In December 2006 NCA delivered a report to the Ministry where they recommended that the wreck of the submarine should be encapsulated and that the surrounding mercury-contaminated sediments should be capped. In April 2007 the Ministry of Fisheries and Coastal Affairs decided to further investigate the salvaging alternative before a final decision is taken about the mercury load.

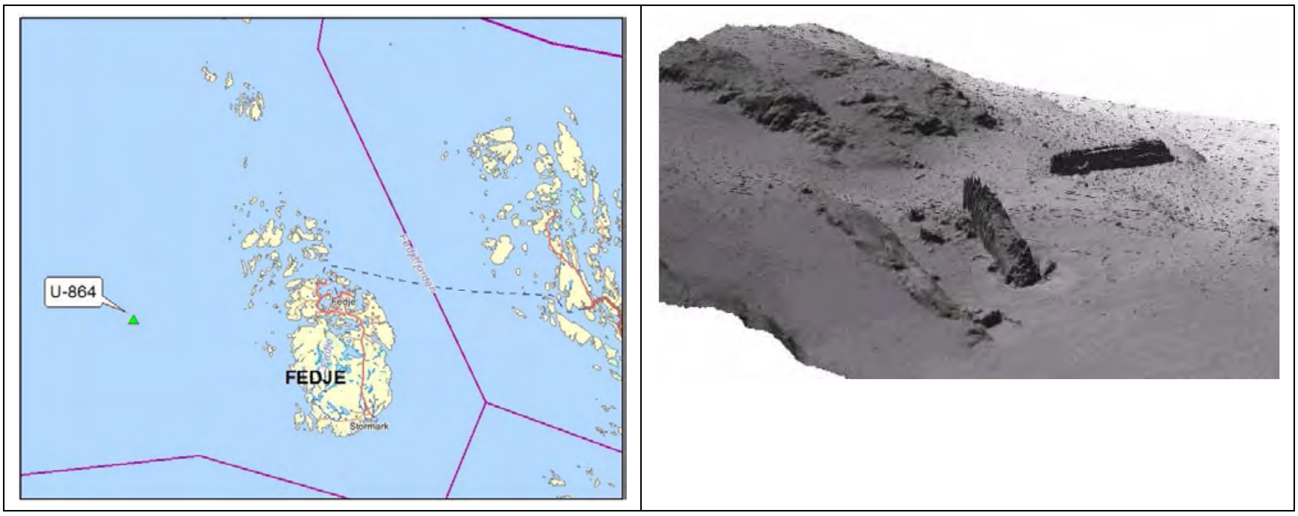


Figure 2-1 Location (left) and a sonar picture of the wreck of U-864 on seabed (right) (from Geoconsult).

3.2 DNV's task

In September 2007 NCA commissioned Det Norske Veritas (DNV) the contract to further investigate the salvaging alternative. The contract includes:

- DNV shall support NCA in announcing a tender competition for innovators which have suggestions for an environmentally safe/acceptable salvage concept or technology. Selected innovators will receive a remuneration to improve and specify their salvage concept or technology.

- DNV shall support NCA in announcing a tender competition for salvage contractors to perform an environmentally justifiable salvage of U-864.
- DNV shall evaluate the suggested salvage methods and identify the preferred salvage method.
- The preferred salvage method shall be compared with the suggested encapsulation/capping method from 2006. (DNV shall give a recommendation of which measure that should be taken and state the reason for this recommendation.)
- DNV shall perform twelve supplementary studies which will serve as a support when the decision is taken about which measure that should be chosen for removing the environmental threat related to U-864. The twelve studies are:

1. *Corrosion*. Probability and scenarios for corrosion on steel canisters and the hull of the submarine.
2. *Explosives.* Probability and consequences of an explosion during salvaging from explosives or compressed air tanks.
3. *Metal detector*. The possibilities and limitations of using metal detectors for finding mercury canisters.
4. *The mid ship section*. Study the possibility that the mid section has drifted away.
5. *Dredging*. Study how the mercury-contaminated seabed can be removed around the wreck with a minimum of spreading and turbidity.
6. *Disposal*. Consequences for the environment and the health and safety of personnel if mercury and mercury-contaminated sediments are taken up and disposed of.
7. *Cargo.* Gather the historical information about the cargo in U-864. Assess the location and content of the cargo.
8. *Relocation and safeguarding.* Analyse which routes that can be used when mercury canisters are relocated to a sheltered location.
9. *Monitoring.* The effects of the measures that are taken have to be documented over time. An initial programme shall be prepared for monitoring the contamination before, during and after salvaging.
10. *Risk related to leakage.* Study the consequences if mercury is unintentionally leaked and spreading during a salvage or relocation of U-864.
11. *Assessment of future spreading of mercury for the capping alternative*. The consequences of spreading of mercury if the area is capped in an eternal perspective.
12. *Use of divers.* Study the risks related to use of divers during the salvage operation in a safety, health and environmental aspect and compare with use of ROV.

3.3 Scope of this report

This report is *Supplementary Study No. 12: "Use of divers"*. The main objectives for this study are to:

- decide whether diving to the depth of U-864 is within the relevant regulations or not
- assess which salvage phases use of divers might be relevant and the related risks

Use of divers will be evaluated in relation to use of remotely operated vehicles (ROV), with a special attention on safety, health and environmental issues.

Norwegian Underwater Intervention AS (NUI) has been involved with this supplementary study, as they possess valuable competence on the topic, and has been the primary source for information when discussing diving history and regulations.

- Chapter 4 discusses the possibility of diving to the depth of u-864
- Chapter 5 assesses benefits and risks by using divers in salvaging u-864

4 DIVING TO THE DEPTH OF U-864

DNV's conclusion is:

C1: Diving to 150 meters, which is the depth of the U-864, is within normal diving depths on the Norwegian shelf. No special attention must be given to compression and decompression procedures according to NORSOK U-100.

Diving operations similar to those suggested in chapter 5.2 is normally referred to as *Manned Underwater Intervention*, and is considered an alternative method to other intervention methods, like the use of ROV.

In 1991 the Norwegian authorities introduced a distinction between *normal diving* and *deep water diving* operations. The term deep water diving is used in relation to diving operations to depths below 180 meters. The wreck of U-864 is situated on a depth of 150 meters and is therefore considered well within the zone of normal diving operations. This report focuses on normal diving operations to depths less than 180 meters.

Saturation diving is the relevant method for diving operations when diving to the depths of the U-864 wreck (150 metres). Appendix A briefly describes a generic saturation diving operation and some relevant studies on the risks related to saturation diving are presented.

4.1 Regulations

Petroleum related diving on the Norwegian shelf is strictly regulated under the provisions of i.a. the Petroleum act. For detailed provisions, it is mostly referred to the NORSOK-standard U-100 "Manned Underwater operations". The supervisory body is the Petroleum Authority, which does not directly control the diving companies, but has contact with each operator (oil company).

Inshore diving in Norway is given in "the Diving regulations" stipulated by the Working Environment Act. It has very limited references to saturation and bell diving.

Since diving at Fedje will for most practical issues be more similar to offshore than inshore diving, DNV and NUI finds it most sensible to base the requirement on offshore practise. All relevant requirements of NORSOK U-100 should be applied. The formal version of this standard is from 1999, but it has lately been through a revision (2nd edition) which was on public enquiry in 2007. The edition is expected to be public early in 2008. NORSOK U-100 states that only diving to depth deeper than 180 m needs special attention to compression and decompression procedures. As U-864 is situated on a depth of 150 meters, no such special considerations are needed.

5 BENEFITS AND RISKS BY USING DIVERS IN SALVAGING U-864

DNV's conclusion is:

C2. At the depth of U-864 using divers can be considered as a complementary intervention method to ROV-operations.

C3. Use of divers during the salvage process' phases Preliminary Study, Elevation and Pollution abatement on seabed is expected to be beneficial as they can get better access to the wreck, obtain more information about the situation and stir up less polluted sediments than an ROV.

C4: The criticality (probability and consequence) for risks related to using divers during salvage of U-864 can not be assessed before the salvage methodology is chosen.

Chapter 5.1 presents some general information about the present practice related to saturation diving, and advantages and disadvantages by using saturation divers in general. Chapter 5.2 assesses when saturation divers could be useful during a salvage of U-864, and chapter 5.3 assesses the associated risks.

5.1 The present best practice related to intervention

C2. At the depth of U-864 using divers can be considered as a complementary intervention method to ROV-operations.

Apart from the possible mercury contamination, explosives and pressurised gas cylinders (localisation, contact with, inspection, handling etc), the challenges should be similar to what experienced offshore dive teams are used to handle.

Remote intervention has been the dominant underwater (UW) intervention method used by the oil companies operating in Norwegian sector during the period starting in the 1990's and a few years into 2000. During the last two to three years this has changed towards considering diving- and remote-intervention as complementary UW intervention methods, for depth less than 180 meters. Before deciding which method to use, the following factors must be considered:

- Need for flexibility
- Available time and vessel
- Total operational costs
- Safety, health and environmental issues (SHE)

Often a combined solution is chosen because both methods have their strong sides.

The main advantages related to the use of saturation divers are the great flexibility of the diver with his manual dexterity directly integrated with vision and sensitivity. In a possible salvage operation of U-864, the divers' ability to work carefully to avoid further breakage to already weakened mercury cylinders is thought to be of great benefit compared to use of ROV. Also operating close to bottom where sediments are contaminated by mercury, divers are expected to have a better ability to minimise stir up and spreading of contaminants than an ROV. In general any necessary task where fine tactility and visual control is needed, the diver will be of great value. In addition to situations where vision is limited.

The main disadvantages of using divers in the salvage of U-864 are the inherent risks related to putting humans under water and subjecting them to high pressure. A result of the high pressure is the disadvantage of long decompression times required. Divers may need about one week decompression time after being subjected to the pressure of 150 meters water depth.

Appendix B presents previous experiences where divers have been used during salvage operations.

5.2 Use of divers during salvage of U-864

DNV's conclusion is:

C3. Compared to ROVs, the use of divers during the salvage process' phases Preliminary Study, Elevation and Pollution abatement on seabed is expected to be beneficial as divers can get better access to the wreck, obtain more information about the situation and stir up less polluted sediments than an ROV.

This chapter gives a description of how divers can be utilized to support the process when salvaging U-864. As a basis for discussion, DNV has used the high-level generic salvage process description illustrated in Figure 5-1.

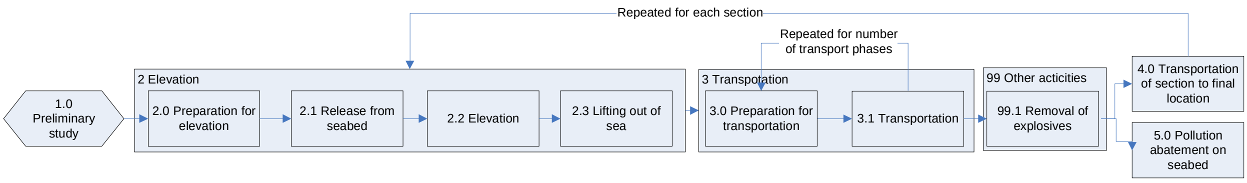


Figure 5-1 General description of a salvage process

Given the operation procedures and regulations related to diving, DNV has identified the following general salvage phases as the most relevant phases for using divers:

Phase 1.0 Preliminary study

DNV and NUI expect that the use of divers during a Preliminary study phase can be beneficial.

Relevant tasks are:

- Get an overview and assess the situation on the seabed.
- Evaluate where and how to position lifting equipment.

- Evaluate what kind of equipment should be used during the salvage.
- Locate and remove mercury canisters on the surface of the seabed.
- Assist in the identification of obstacles that may influence the salvage.

In all operations minimal disturbance of the polluted sediments on the seabed is crucial. Utilizing the divers' flexibility and ability to effectively monitor the operations can be very valuable in this respect.

Divers are suited to effectively get an overview and assess the situation on the seabed. This may prove valuable when planning the salvage operation in detail.

It is crucial that lifting equipment is properly designed and take into account the state of the wreck and how it is positioned on seabed. Divers may be used to verify that the suggested equipment is well suited, and may suggest alterations where necessary.

During the surveys that have been performed, two mercury canisters have been brought to the surface. Both canisters were located in proximity of the wreck. Unidentified mercury canisters on or near the surface of the seabed can be damaged during a salvage operation. A detailed scan of the seabed in the area around the wreck may identify other mercury canisters and reduce the risk of further mercury pollution. Divers are suited to effectively remove this kind of debris.

As a result of the torpedo hit, the mid section of the submarine is destroyed and a large amount of debris is spread out on the seabed around the wreck. Some of this debris may obstruct the positioning of lifting equipment or influence other parts of the salvage process. Divers can assess what debris needs to be removed and the equipment needed for removal.

Phase 2 Elevation

As illustrated in the process description in Figure 5-1, the elevation phase comprises several sub processes. DNV and NUI assess that divers would be most useful in the initial stages of the elevation phase; Preparation for elevation (2.0) and Release from seabed (2.1)

Relevant tasks are:

- Clearing the way for lifting equipment, assist in the removal of debris.
- Checking the positioning of lifting equipment.
- Monitoring of release from seabed.

Divers can be very useful in the removal of debris in order to clear the area around the wreck, e.g. for positioning of lifting equipment. This can be manually moving the small objects to a lifting cradle or assisting positioning of lifting equipment on heavier items.

Once the area around the wreck is sufficiently cleaned of obstructing objects, the divers can assist in the positioning of the lifting equipment to the hull of U-864. The divers can also assist in controlling that the lifting equipment is properly secured and are in the intended position. The assistance needed will vary depending on the chosen salvage method.

For safety reasons the divers should leave the area before the elevation commences. The salvor could consider having divers remaining in the diving bell at a safe distance during the release from seabed phase to assist if the wreck needs to be replaced on the seabed for adjustments before being elevated to the surface, e.g. if the positioning of the lifting equipment is not optimal or the hull shifts position.

When the wreck is ready for elevation to the surface, divers can return to pressure chamber on the diving vessel. Based on the process described above DNV does not consider the use of divers to be relevant in other parts of the elevation phase. This may change depending on the method proposed by the salvors.

Phase 5.0 Pollution abatement on seabed

The salvage operation includes pollution abatement on the seabed. The salvors may use several methods in order to remove the environmental risk related to the polluted seabed. Depending on the chosen method, divers may assist in this operation.

Relevant tasks are:

- Locate mercury canisters within the target area.
- Collect debris and mercury canisters.
- Prepare and attach lifting equipment on debris when clearing seabed (preparation for search with metal detector).
- Assist in removal of polluted sediments in hot spot areas.

The polluted target area on the seabed is approximately 30 000 square meters. In order to minimize the risk of future spreading of mercury it may be relevant to search the target area especially for locating mercury canisters. Several methods for scanning the seabed have been proposed e.g. using metal detector (see *Supplementary Study No. 3:Metal detector* for more information).

As noted above, divers can be an effective tool for both location and removal of objects on the seabed, either separately, or in combination with other methods.

As stated above, divers are particularly effective if used in the removal of smaller objects on the seabed, and may be valuable in preparing and attaching lifting equipment to larger debris for elevation to the surface.

Divers may also assist in the removal of polluted sediments, e.g. increased precision when dredging in areas with particularly high sediment concentration of mercury.

Other activities where use of divers may be relevant

The NCA has previously attempted to gain access to the keel in order to determine the location of mercury canisters. Removing the entire mercury cargo without salvaging the wreck has been suggested.

The attempt to reach the keel by ROV in 2005 was abandoned. Geoconsult reported that the aft section of the submarine shifted position as a result of dredging around the keel in order to gain access to the storage rooms where mercury is expected to be stored. Later survey revealed a gap that had appeared between the hull and the surrounding sediments as a result of the hull shifting position. This indicates the instability of the wreck in its current position.

Given proper safety precautions, it is assumed that divers could gain access to the keel without removing as much sediments as an ROV needs when performing a similar operation. Divers can assist in obtaining information about the status of the mercury cargo. Either prior to lifting the wreck from the seabed, or to assess the tools needed to remove the mercury without salvaging the wreck. This way divers can contribute to reducing the risk of mercury spreading when lifting the wreck from seabed, or when maneuvering in order to gain access to the keel.

The use of divers in relation to the removal of explosives is considered in *Supplementary Study No. 2: Explosives*, and is therefore not considered in detail here. If explosives or ordnance is located, the location should be marked without affecting the object, and further investigated and evaluated by the Norwegian Defense before action is being taken. Moving of explosives should only be done by using ROV under supervision of experts from the Norwegian Defense.

5.3 Risks related to use of divers when salvaging u-864

DNV’s conclusion is:

> **C4: The criticality (probability and consequence) for risks related to using divers during salvage of U-864 can not be assessed before the salvage methodology is chosen.**

5.3.1 Top risks related to relevant process steps

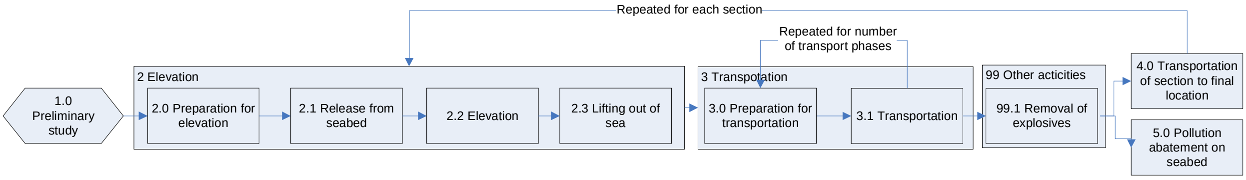


Figure 5-2 General description of a salvage process (same as Figure 5-1)

DNV has assessed the most relevant risks present related to use of divers when salvaging U-864, using a general description of a salvage process (Figure 5-2). General divers’ risks related to diving are not considered, for this DNV refers to studies described in Appendix A. The risks are presented in Table 5-1 on page 12.

Table 5-1 Most relevant risks related to use of divers when salvaging U-864

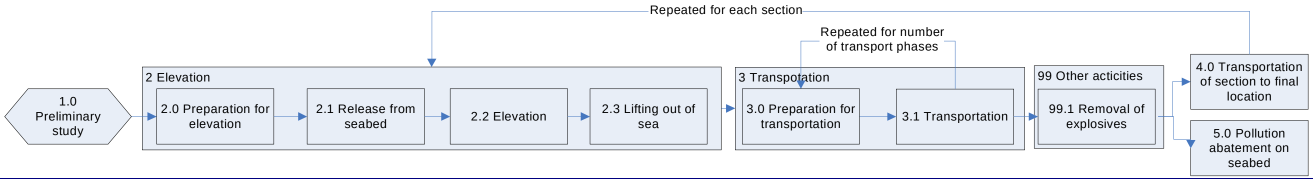
Risk	Name	Description
Phase 1.0 Preliminary study (general risks)		
R1	The wreck slide or shifts position as a result of influence from divers or equipment	**Front section:** • The front section is positioned in a slope of up to 15 degree angle. • There is uncertainty about the stability of the front section of the submarine. • Based on their evaluation of the sediments, Norwegian Geotechnical Institute (NGI) does not expect the structure of the top sediments to affect the stability of the submarine. **Aft section:** During the 2006 survey of U-864, Geoconsult attempted to gain access to the keel by dredging around the aft section of the wreck. This resulted in a significant shift in the position of the wreck and gives an indication of the instability of the aft section.
R2	Sediment slide caused by imposed pressure from divers or equipment	Calculations show a vulnerability to slope failure around the front section of the submarine if it is exposed to pressure e.g. from objects placed on the seabed. Geotechnical calculations shows that the weight of a diver alone is not expected to be large enough to set off a sediment slide. Placement of heavier objects on the seabed however may set off a sediment slide if placed in the wrong area. The nature of a slope failure is uncertain. A slug failure is expected to have limited effect, but if there is a canyon effect, the effect is larger and the risk of spreading contaminated masses to new areas is large. It may also cause shifting of the front section and, in worst case, significant movement.
R3	Ordnance are set off as a result of impact from divers or their equipment	Ordnance (ammunition, grenades) may be spread in the area around the submarine. There is a theoretical possibility that these can be set of as a result of change in ambient conditions (pressure/weight). This may be caused either by the divers themselves or by the placement of objects on the seabed where the ordnance is located. Experience from the salvage of U-534, another World War Two (WWII) German submarine, indicates that the ordnance are relatively stable when handled appropriately. Caution must be taken and ordnance should be clearly marked when located. For more information about ordnance, see *Supplementary Study No. 2: Explosives.*
R4	Mercury contamination of divers due to exposure to contaminated water and sediments cause negative health effects	During the operations on the seabed around the U-864, the divers will be exposed to hazardous contaminants. Specialized personnel protective equipment (PPE) is necessary. Mercury is highly toxic. Divers bringing mercury or mercury contaminated sediments into the diving bell may result in negative health effects.

Phase 2.0 Preparation for elevation		
R5	Injury due to malfunction or wrong handling of lifting equipment for the wreck	Heavy equipment is needed to lift the submarine hull from the seabed and elevate it to the surface. If divers are to assist in the placement of this lifting equipment, they will be exposed to risk related to malfunctions or wrong handling of this equipment. Mistakes may be fatal for the divers.
R6	Hull collapse while divers are in proximity of the wreck causing injury of fatality	The condition of the wreck is unknown. A hull collapse may occur when heavy equipment is mounted in order to lift the wreck. If divers are in the proximity of the wreck when heavy equipment is placed on the wreck they may be caught and squeezed under parts of the wreck if it collapses.
Phase 2.1 Release from seabed		
	N/A	DNV expects that regulations for diving operations will require that the diving vessel is relocated away from the area during lifting.
Phase 2.2 – 4.0		
	N/A	DNV evaluates that using divers in these phases is not feasible due to operational risks (phase 2.2 and 2.3) or not relevant (phase 3.0, 99 and 4.0).
Phase 5.0 Pollution abatement on seabed		
R7	Injury due to malfunction or wrong handling of lifting equipment for debris	Divers may assist if parts of the seabed need to be cleaned of debris. Movement of large debris during handling constitutes a risk for the divers if they are closely involved in the operation. If divers are in the proximity of the moving large debris, either assisting the movement, or as a result of wrong handling of the lifting equipment, they may sustain injuries e.g. get caught under debris or between the debris and outcrops of bedrock.

5.3.2 Risk analysis of the salvage phases

A salvage method has not yet been chosen and risks associated with diving depend on the nature of the chosen method. The identified risks presented in Table 5-2 are therefore not assessed.

Table 5-2 Risk related to saturation diving (including Figure 5-1)



Risk	Name	Relevance								
R1	The wreck slide out or shifts position as a result of influence from divers or their equipment	Relevant	Relevant	Relevant						
R2	Sediment slide caused by imposed pressure from divers or their equipment	Relevant	Relevant	Relevant						Relevant
R3	Ordnance are set off as a result of impact from divers or their equipment	Relevant	Relevant	Relevant						Relevant
R4	Mercury contamination of divers due to exposure to contaminated water and sediments cause health effects	Relevant	Relevant	Relevant						Relevant
R5	Injury due to malfunction or wrong handling of lifting equipment for the wreck		Relevant	Relevant						
R6	Hull collapse while divers are in proximity of the wreck causing injury of fatality	Relevant	Relevant	Relevant						
R7	Injury due to malfunction or wrong handling of lifting equipment for debris									Relevant

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APPENDIX

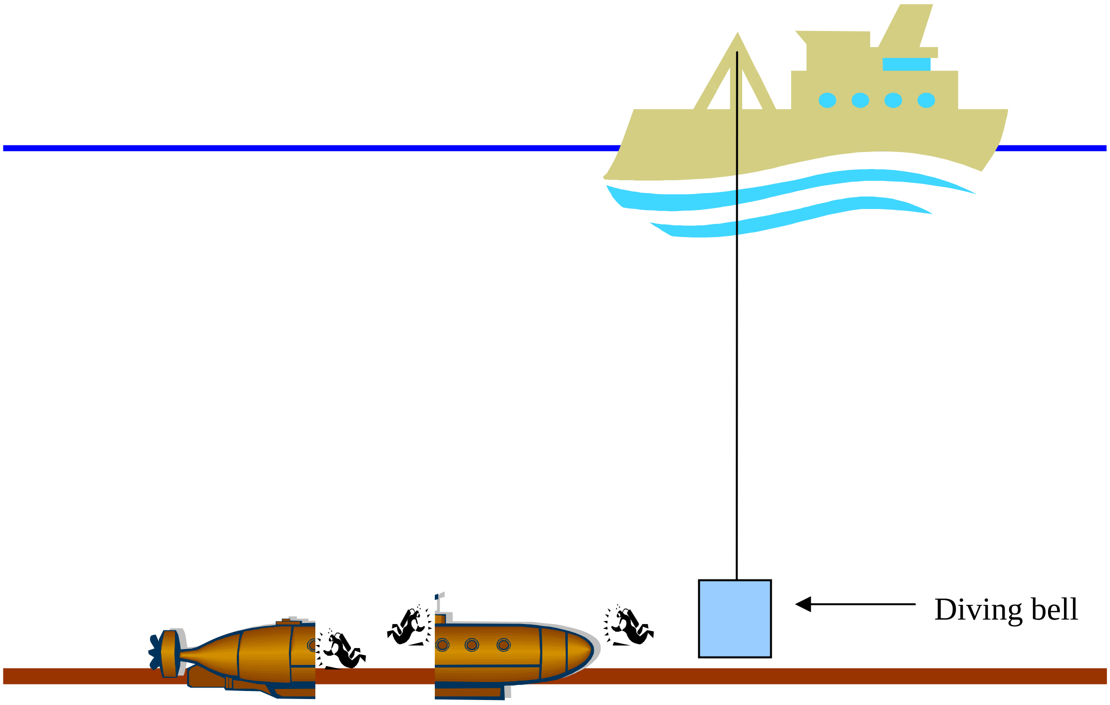
A
GENERAL DESCRIPTION OF DIVING OPERATIONS

A1. Normal diving operations - Diving between 50-180 m

Professional diving to more than 50 m performed with a diving bell is called *saturation diving*. In these operations helium-oxygen mixes (heliox) are used as breathing gas. The divers stay at a constant pressure corresponding to the relevant working depth all the time. Sleep and rest is done in pressure chambers on a surface vessel. A diving bell is used to move to and from the depth where the operations are performed.

A typical operation can be as follows:

- The divers enter the diving bell directly while it is connected to the diving complex on the surface vessel.
- The bell is then disconnected from the chambers and is lowered to the bottom or working depth.
- On the work depth, the door can be opened since the pressure inside the bell is kept at the corresponding pressure with the outside.
- One or two divers enter the water while at least one stays in the bell as a standby diver.
- While they are working in the water they are connected to the bell and further to the surface through umbilicals. The operations are monitored by people on surface using ROV.
- When the work or lockout period is through, the divers re-enters the diving bell and the bell is then hoisted back to the vessel and connected to the chamber system.
- The dive team who have finished their shift will then return to their living chamber. Usually another fresh team will be ready to enter the bell and go down to continue the work while the first team will be resting.



A2. Evolvement of saturation diving as a work method

Diving bells with open bottom (resembling a church bell) have been used for practical diving for several hundred years. But a bell that can be closed for so called ”Transfer Under Pressure” (TUP) was not made before after World War I. It was also done some scattered trials with saturation diving, but there was no significant evolvement of this diving method until after 1960. US Navy has been leading in the following development, with contributions from France and UK. The evolvement of diving operations has mainly been motivated by the need for assisting submarines in emergency situations.

The first commercial saturation system was made and used for dam construction work in USA in 1965. This system was used in petroleum related work in Gulf of Mexico in 1966. After this, there came a substantial growth in saturation diving worldwide.

In the Norwegian sector of the North Sea the first saturation dive was to 145 m, done in 1974. By 1978 dives to 200m were carried out. Since then a lot of research and development (R&D) has been done to enable safer and deeper diving operations.

In later years saturation diving is carried out routinely to more than 300 m water depth, e.g. in Brazil. In the North Sea the deepest operational diving depth have been 246 m, but since 1989 no operational diving to more than 180 m has been performed on the Norwegian shelf.

A3. Investigations into the health risks related to saturation diving

The health implications of deep water diving has been debated by professionals throughout the world for a long time. One particular problem with saturation diving has been the High Pressure Neurological Syndrome (HPNS) caused by compressions to more than 180 m /6/. In the case of U-864, the maximum relevant diving depth is approximately 150 meters. By diving to 150 m this syndrome is practically non-existing /4/, even if some divers show changes on the EEG (electroencephalogram) /5/.

In the following sections we present some results from studies that have been performed on the health risks related to commercial diving operations. They offer information about which health issues saturation diving can induce.

Norwegian Government Commission - Study on diving on the North Sea pioneer period, 2001

The Norwegian offshore diving has been heavily debated in the media and political forum. Interest groups of so-called “pioneer divers” (usually meaning a diver who has dived in petroleum related activity before 1990) have raised the issue about whether offshore diving have led to fatal accidents, suicides and long-term health problems. In 2001 the Norwegian government appointed an independent Commission of Enquiry to investigate all circumstances related to diving in the North Sea in the pioneer period (1965 to 1990). This Commission state i.a. (NOU 2003:5):

“After an average of about 14 years in the North Sea, the majority are in a satisfactory state of health based on the information they have supplied. However, a relatively high proportion have acquired appreciable health problems, illustrated by the fact that almost one-fifth are disabled, and that a number of divers complain of concentration, memory and hearing impairments. The same symptoms are documented in Norwegian and foreign investigations alike. It seems probable that the extreme stress to which many North Sea divers have been exposed at work has been a significant factor behind the disorders that a number of them have developed.”

But they also say in their conclusion:

“The (fortunately) steep decline in serious accidents in the 1980s on both sides of the North Sea can to some extent be ascribed to improved rules and oversight of compliance with the rules. Another important reason was the switch to saturation diving which considerably reduced time pressure on the seafloor.”

ELTHI (Examination of Long Term Health Impact of diving)

A British study /8/ investigated a much larger group of divers, including still active divers and concluded that the health-related quality of life was similar for divers as for offshore workers and within normal values. But more divers than offshore divers complained about “forgetfulness and loss of concentration”. There have been some conferences on the issue of long-term-health-effects of diving. In the last one in Bergen /9/, there were still rather large discrepancies on whether it has been proved that “normal diving” will lead to health effects that are important to the diver’s quality of life.

Scanpower – study on risk for fatality and serious diseases for divers, 2005

Scandpower was given the task to present objective description of the risk for fatality and serious disease for divers involved in the current activities in the Norwegian sector. In their report /10/ they estimate a Fatal Accident rate (FAR) for diving in the UK and Norwegian sector from 1990-2003.

The study registered 27 fatalities per 100 million saturation man-hours. This result corresponds to an individual risk per annum (IRPA) of around 0.0006.

This should put this type of diving in the group of acceptable activities, although any means should be taken to reduce risk. The Scandpower states that it was a much bigger challenge to handle the question of long-term health effects. This is partly because the existing studies differ with regards to whether the observed changes are reducing quality of life. They also assume that the diving as it is done today will result in less risk of long-term health effects, since frequencies of decompression illness and life-threatening incidents have been significantly reduced after 1990.

Petroleum Safety Authority Norway - Diving on the Norwegian shelf

The Petroleum Safety Authority Norway (PTIL) has a Safety forum consisting of representatives from the authorities', workers' and employers' organisations. In later years, there have been great discussions in Norwegian media about the safety level of today's diving. The discussions are based on claims against the Norwegian State from Norwegian pioneer divers with health problems, thought to be related to diving around 20 years ago. As a result of this the Safety forum made an evaluation resulting in the report "Dykking norsk sokkel" /1/.

PTIL collects statistics on the diving operations on the Norwegian shelf and HSE incidents related to this activity. Figure 6-1 gives an overview of the evolvement of activity and HSE related incidents in the past two decades. As the graph shows, the level of activity dropped significantly on in the beginning of the 1990's but has picked up in the last few years. The graph also shows that the number of personal injuries is on a significantly lower level compared to the late 1980's. Some experts attribute the somewhat increased number of near misses to a generation change in saturation diving, resulting in a reduction in the experience level of the divers. DNV has not found studies to confirm this.

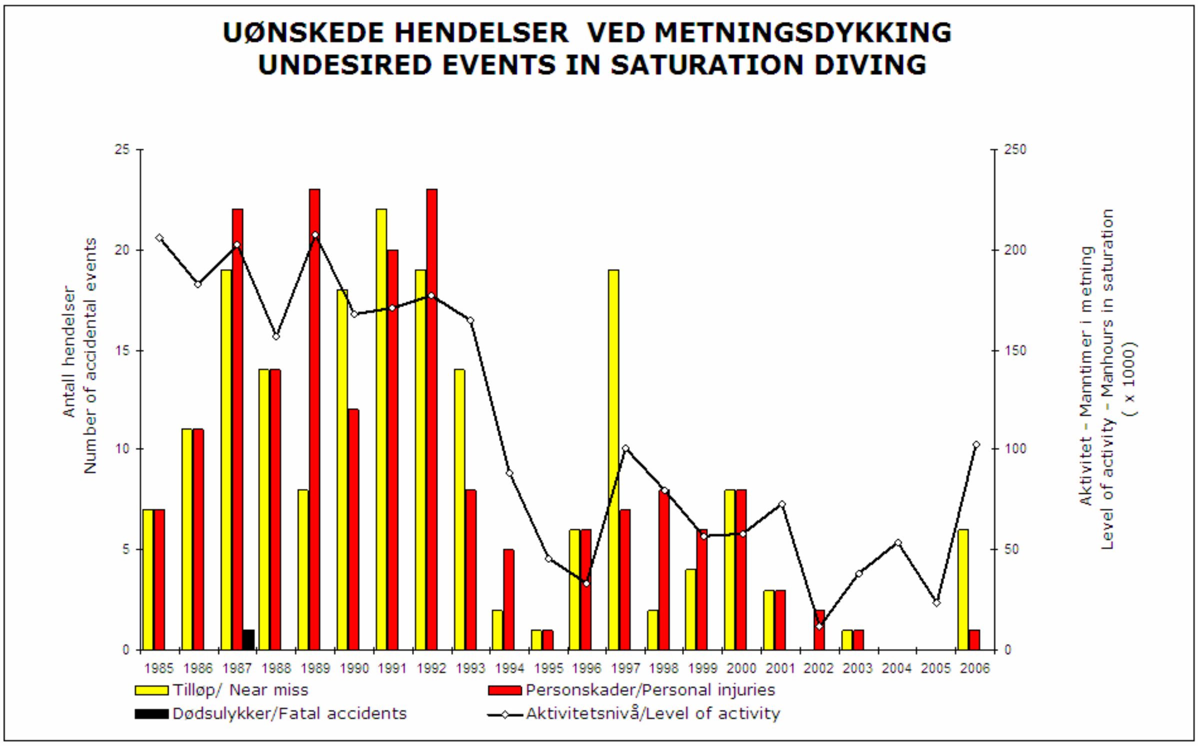


Figure 6-1 Undesired events in saturation diving, PTIL database /2/

Main findings in the reports presented:

In the Scandpower report it is stated that most of the diving in the Norwegian sector has been done in the depth range 70 – 160 m. And after 1990 no operational dives to more than 180 m have been done. In the UK sector there has been a significant amount of diving to 200m on the Magnus field. Diving to 160 m, which is the Statfjord depth, is done routinely, and frequently.

The PTIL study conclude that diving on the Norwegian shelf today is within the frame conditions set in the regulations and in accordance with accept criteria for SHE risk. But they, in line with Scandpower, recommend further evaluations of the existing regulations, i.e. with regard to long term health surveillance and post diving career plans.

Based on the results from the studies DNV must conclude that given compliance with the rules an regulations for saturation diving, diving to a depth of 150 m, which constitutes the depth of U-864, can be considered within the acceptance zone for safe diving operations.

A4. Diving in contaminated water

The studies above indicate that diving operations in it self present risks for the divers, all though assessed acceptable. These risks are compounded by the presence of hazardous materials in either the water or the sediments on the seabed.

The US Navy published the report Guidance for Diving in Contaminated Waters (Direction of Commander Naval Sea Systems Commando 15 January 2008). This report looks on both evaluation criteria and guidelines for diving operations and equipment.

In this report, they define the following categories and definitions of contaminated water:

Contaminated Water Categories	Definitions
Cat 1	a. Grossly contaminated b. Extreme Risk of Injury (or even death) (Note 1) c. Fully encapsulated Diver (inc. Surface Exhaust) (Note 2)
Cat 2	a. Heavily contaminated b. High Risk of Injury (Note 3) c. Fully encapsulated Diver (in water exhaust)(Note 2)(Note 4)
Cat 3	a. Moderately contaminated b. Some risk of Injury (especially if ingested) c. Full face mask (skin covered as necessary)(Note 5)
Cat 4	a. Baseline contamination (EU Bathing Water 'Sufficient' or better) b. Low risk of Injury(Note 6) c. Standard diving dress

Figure 6-1 US Navy - Contaminated water categories

During the operations on the seabed around the U-864, the divers will be exposed to mercury contaminated water and sediments. Given the results from previous surveys /3/, the water contamination will be at Cat 2 or Cat 3. Specialized personnel protective equipment (PPE) is necessary.

Precautions against exposure to mercury also need to be taken during the decontamination of the divers, which should take place as soon as possible after they leave the contaminated area and preferably before entering the diving bell.

Offshore diving operations in Norway related to the oil and gas sector may involve contact with polluted elements like oil and sludge. The divers may then use an extra protective suit outside the diving suit, which can be removed before entering the diving bell, leaving most of the pollution outside, and minimising the need for decontamination inside the diving bell. This should be considered used if diving is performed in the contaminated area near the U-864.

APPENDIX
B
PREVIOUS EXPERIENCES WITH DIVING IN SALVAGE OPERATIONS

Throughout history salvage has been one of the most important tasks for divers. The capability to rescue crew from sunken submarines has been of special importance in the evolvement of diving operations. Diving support in the salvage of cargo and vessels has also been of great interest. Examples are:

- In 1981 the gold cargo of HMS Edinburgh was taken up from 245 m depth in the Barents Sea.
- In 1993 the wreck of the German submarine U-534 was recovered from 60 meters water depth outside Denmark with the assistance of divers.
- In 1994 the German WWII vessel Blücher were to be emptied of oil in Drøbaksundet, in the Norwegian Oslo Fjord. This was planned as an intervention without use of divers, but the unmanned intervention was unsuccessful. Saturation divers were mobilized and carried out the task efficiently at 70 meters depth.
- Saturation divers from the North Sea were mobilized in the attempt to assist the crew in the Russian submarine Kursk that sunk in the Barents Sea in 2001. Unfortunately they were too late, but it was demonstrated how useful divers can be in unforeseen tasks of this kind. In the later phase, when Kursk was salvaged, divers were again useful and did excellent work at 110 meters depth.

Divers can normally be mobilized quickly to assist in various operations. Vessels and crews are in practically continuous operation, primarily with petroleum related work. The diving activity is not necessarily continuous in the Norwegian sector, but a handful of diving support vessels (DSV) are to a large extent in continuous operation on missions either in Norway or UK, regularly crossing the border between the Norwegian and British sector.

In the mid 1990's management in Statoil and Hydro declared the goal to become independent of divers by year 2000. This turned out to be unrealistic. A group initiated by Statoil, reported /11/ hat it is necessary to strengthen the dive support capacity as diving services will be necessary in the near future. The report gives a number of necessary actions. Among these are building of new DSVs and education of all categories of dive competence. Therefore, education of bell/saturation divers is planned to start in Bergen in 2008.

Worldwide there are at the moment 23 DSVs being built. Of these, four will be owned by Norwegian companies and these will all be finished before end of 2009.

Presently three companies are actively running offshore diving operation in Norway: Acergy, Subsea7 and Technip. Technip runs a diving contingency service administered by StatoilHydro, primarily to be able to repair pipelines on the sea bottom. The activity level on the Norwegian shelf has varied around 50-100 000 man-saturation hours in the later years, but activity has increased since 2005, probably because of renewed faith in diving operations similar to those of Statoil Hydro.