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Assessment of galvanic corrosion inside firing device in a torpedo detonator in U864

Marstrand AS

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Objective:

The objective is to assess the galvanic corrosion rates between steel and copper-based alloys inside a torpedo detonator.

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1 EXECUTIVE SUMMARY

DNV has been requested to clarify a corrosion assessment presented in two previous DNV reports issued in 2008, "*Salvage of U864 – Supplementary Studies – Study No. 1: Corrosion," Report No. 23916-1, Rev. 01, dated 2008-07-04"*, and "*Salvage of U864 – Supplementary Studies – Study No. 2: Explosives," Report No. 23916-2, Rev. 01, dated 2008-07-04*". The clarification addresses the following statement made in DNV Report No. 23916-2: "*Without a corrosive agent, galvanic interaction between components in carbon steel and other alloys contained within the shells of the torpedoes is not an issue*."

The concern is the degree of corrosion of the firing pin in the firing device if seawater ingress has occurred. The firing device is understood to most likely consist of components made of carbon steel and copper-based alloys, likely brass.

Galvanic corrosion may occur between carbon steel acting as the anode and a copper-based alloy (e.g. brass) acting as the cathode, which can accelerate the corrosion rate of carbon steel under oxygen-rich seawater conditions, where the reduction of dissolved oxygen is the dominant cathodic reaction.

Under oxygen-depleted conditions, however, the corrosion process is controlled by the reduction of water (hydrogen evolution), which is kinetically slow. As a result, the corrosion of carbon steel becomes cathodically limited by the cathodic reaction occurring on the copper-based alloy. Under such conditions, the corrosion rate of carbon steel is expected to be significantly reduced compared to oxygen-rich conditions, with corrosion rates on the order of approximately 0.001–0.01 mm/year. This is consistent with statements provided by DNV (2008).

Although galvanic coupling between carbon steel and copper-based alloys may result in a corrosion rate acceleration factor of approximately two, the resulting corrosion rates remain relatively low. A similar consideration applies if stainless steel has been used; in this case, the copper-based alloy would act as the anode while corrosion rates (~0.001 mm/year) remain limited by the reduction of water.

It should be noted that the metal surfaces in the firing device might be covered in grease. The presence of grease on the surface may act as a physical barrier, reducing direct exposure to seawater and therefore reduce the corrosion.

2 INTRODUCTION

DNV has been commissioned by FFI to perform a corrosion assessment of a firing device inside a torpedo detonator located in a German submarine U-864 which was torpedoed by the British submarine Venturer on February 9, 1945, and sunk approximately two nautical miles west of the island Fedje in Hordaland. The submarine is located at 150-175 m depth.

The uncertainty is corrosion of the firing pin in the firing device if seawater ingress has occurred into the detonator. The work is a clarification to a corrosion assessment made in two previous DNV reports issued in 2008; 23916-1 /3/ and 23916-2 /4/.

DNV has not evaluated the effect of the corrosion on the functionality of the firing device.

The torpedo detonator comprises of both steel and copper-based alloys. DNV has been informed that the exact chemical compositions cannot be confirmed. Because the available documentation is limited to a single video recording /1/ and drawings /2/, there is significant uncertainty regarding the selected materials and their current condition.

2.1 Scope of work

The scope of work is to

- Familiarize with the two DNV reports No. 23916-1 /3/ and No. 23916-2 /4/.
- Meeting to clarify assumptions, e.g., available inspection data (has any components been retrieved or is the present condition assessment based on ROV videos/pictures) and list of materials used in the torpedo components.
- Re-evaluate if galvanic corrosion is a threat between the relevant metals in the torpedo at Fedje
- Re-assess other relevant corrosion mechanisms.
- Include different exposure scenarios (what if analyse) in the assessments.

3 SYSTEM DESCRIPTION

3.1 Lay-out of torpedo detonator

The following components are the most relevant (indicated by red numbers on the drawing in Figure 3-1):

(1) Firing spring

(2) Firing pin head

(3) Rocker ring

(4) Firing pin release lever locking shaft

(5) The pivot bearing of the pendulum rod

(6) Firing pin lock

According to information from FFI the grade of the materials in the components is unknown, but it is believed that the housing is a copper-based alloy typically brass. The steel is informed to be carbon steel or a low alloy steel, it is less likely that the steel is stainless steel but is also included in the assessment.

For simplifications only a general assessment of corrosion between steel and copper-based alloys is carried out considering an area ratio of 1:1 steel – brass. No specific areas within firing device have been considered.

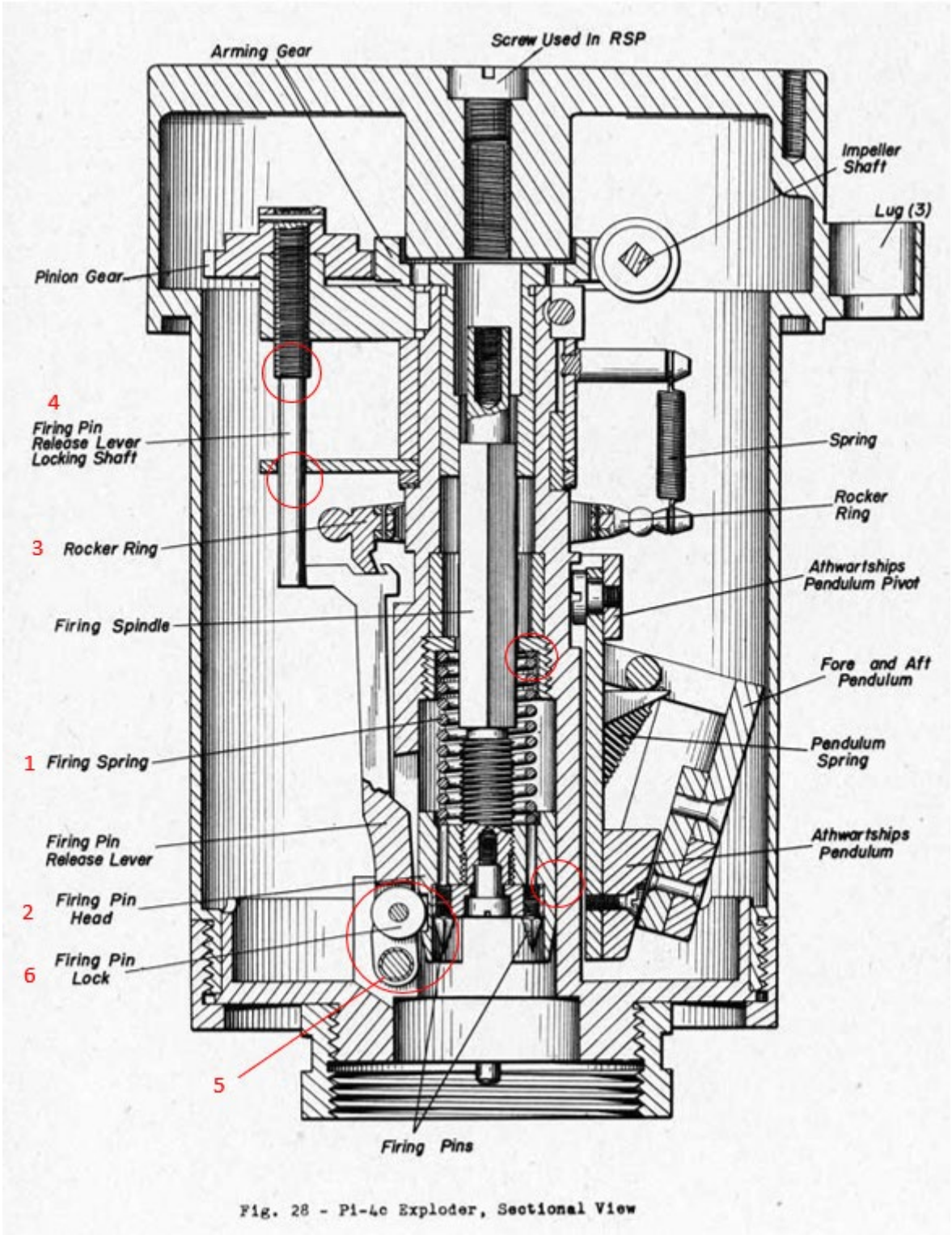

Figure 3-1 Overview picture of the firing device and housing (torpedo detonator)

3.2 Inspection of similar torpedo detonator

Figure 3-2 shows an overview of a comparable torpedo detonator that was recovered from a torpedo inside U 534, which sank on May 5, 1945, and was salvaged on August 23, 1993, in the Kattegat, 20 km northeast of Anholt Island, Denmark. The detonator was fully functional and comprises of a firing device and housing.

The submarine lay on the seabed for nearly 41 years at a 67 meters depth. No information regarding cleaning after recovery is available, however a comment in Ref. /1/ that original grease is still present might indicate that the firing device has not been cleaned. See also Figure 3-3 to Figure 3-5 for details.

The pictures are taken from a video referenced in Ref. /1/ and are used to support the understanding of the system configuration and selected materials.

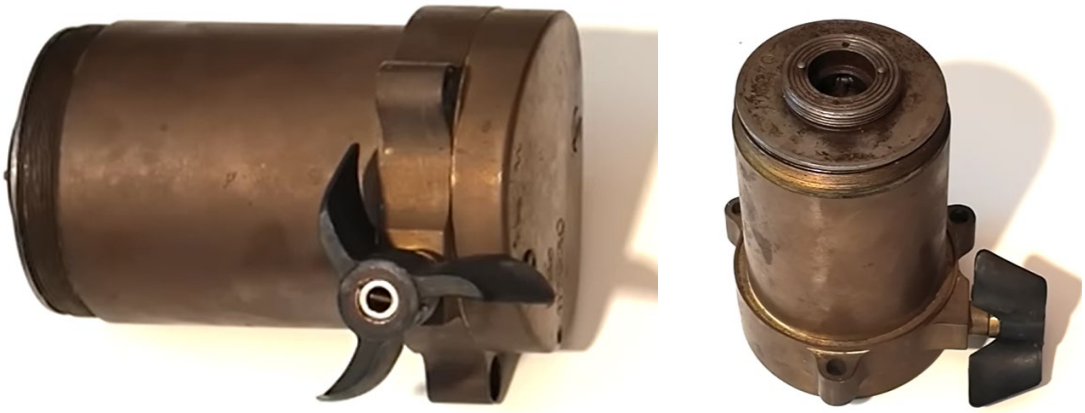

Figure 3-2 Overview pictures of detonator with propeller, firing device and housing

Figure 3-3 Right: Top lock of firing device including firing pin. Left: inside housing with grease firing device in the background

a)

b)

Figure 3-4 a) firing pin release, b) lever locking shaft and c) rocker ring

c)

Figure 3-5 Overview of all components inside the torpedo detonator

4 ASSESSMENT

4.1 Selected Materials

It appears as the parts of the torpedo detonator comprise of an external housing in brass, with the interior consisting of firing device with a mixture of steel and brass.

The firing device (pins, wheels, screws etc.) is assumed to be manufactured from carbon steel or low alloy steel. Carbon steel / low alloy steel is not corrosion resistant towards seawater and under marine atmospheric conditions, flash rusting can occur within hours. Consequently, grease or machine oil is commonly applied not only to reduce friction between moving parts but also to provide corrosion protection. The application of grease is also shown to be used in these components by the inspection video /1/. The observed black surface might indicate magnetite (Fe_3O_4), an iron oxide typically formed in an anoxic (i.e. oxygen depleted) condition. It should be noted that use of stainless steel cannot be ruled out, and for the corrosion assessment this material will also be evaluated. However, stainless steel typically exhibit a lighter grey surface appearance than that observed in the inspection video images.

The copper-based alloys are assumed to be brass with an unknown chemistry. Brasses can be modified by adding certain elements to enhance the corrosion resistance (e.g. tin) or the machineability (e.g. lead). Brasses maintain their resistance to corrosion in water-based solutions as long as the zinc content stays below 15%. When the zinc content exceeds 15%, dezincification may take place in stagnant or slow-moving saline environments. In this process, zinc is selectively removed, resulting in a weakened, porous copper layer. Dezincification is also referred to as dealloying. Brasses are also subjected to stress corrosion cracking. It should be noted that higher zinc content (> 15%) also increases the pitting resistance. DNV has been informed that the spring material is probably a phosphor bronze alloy.

The seal material, if any, is not known. Typical seal materials can be non-metallic material.

The 2008 DNV study assumed that Cu-alloys with limited seawater resistance were used, such as ordinary brass or pure copper, and is aligned with current assumptions and observations.

For the corrosion assessment a ratio of 1:1 steel – brass is assumed.

4.2 Exposure conditions

The firing devices are located inside the submarine, which has been lying on the seabed for approximately 81 years; therefore, the internal environment within the housing is not known.

In Table 4-1 different exposure scenarios inside the housing are assessed. It is assumed that the seals between the steel firing device and brass housing or in the impeller shaft are degraded with time.

Table 4-1 What if exposure scenarios inside the detonator

Exposure condition	Environment	Comments
Closed dry air filled	Insignificant humidity in air	No corrosion in dry air inside the detonator housing
Microscopic leakage and air filled	Significant humidity in air	Atmospheric corrosion
Partly flooded	Significant humidity above water level in air pocket and oxygen depleted within relatively short time	Atmospheric corrosion Water line attack Corrosion in submerged zone
Fully flooded	Oxygen depleted seawater	Corrosion in submerged zone
Fully flooded with circulation	Oxygen saturated seawater	Corrosion in submerged zone

DNV has considered partly flooded (standing seawater with an air saturated headspace) and fully flooded condition with oxygen depleted seawater to be considered as the most relevant exposure cases. Hence these two scenarios are discussed further.

Atmospheric corrosion rates in closed compartments can be difficult to estimate. However, as the temperature is expected to remain stable and low, significant condensation is unlikely, and atmospheric corrosion is therefore assumed to be limited.

Water line attack is considered negligible, as oxygen availability in the small headspace is expected to decrease with time, reducing the driving force for the formation of an oxygen concentration cell at the water line.

4.3 Corrosion assessment

4.3.1 Carbon steel – copper-based alloy

A corrosion process involves both an anodic and cathodic reaction. In aerated water that is slightly alkaline such as seawater, oxygen is the main reduction reaction. If the oxygen in the seawater is depleted (deaerated), reduction of water will take over as the cathodic reaction with hydrogen gas as a by-product. Reduction of water is activation-controlled, meaning the reaction rate depends on how effectively the metal surface can function as a cathode. Reduction of dissolved oxygen is diffusion-controlled, meaning the rate is limited by how rapidly oxygen can reach the metal surface through the bulk seawater or a thin water film under atmospheric conditions. If the detonator contains an oxygen rich headspace, the initial corrosion rate will be higher than in the fully seawater-filled condition. As the oxygen concentration in air is approximately 30 times greater than that of dissolved oxygen in seawater; once the oxygen is consumed, the corrosion rate and resulting metal loss rate will decrease.

When two metals with different corrosion potentials are in electrical contact, the cathodic reduction reaction is transferred to the most noble alloy (i.e. brass), while the anodic dissolution reaction is transferred to the less noble metal (in this case carbon steel). Copper is considered as an effective cathode under aerated conditions, and as dissolved oxygen is consumed by the corrosion process, the cathodic oxygen reduction reaction decreases. This leads to a reduction in galvanic current and corrosion rate. Once oxygen is depleted, the corrosion process is controlled by the reduction of water which is a slow process and the galvanic coupling becomes cathodically limited. The corrosion rate of carbon steel is thus significantly reduced.

The relative surface area ratio affects the galvanic currents. Data published by the Copper Development Association (CDA) /6/ shows that galvanic coupling between naval brass and mild steel can increase the corrosion rate of the steel by a factor of approximately 3 for a steel-to-brass area ratio of 1:1 in flowing, aerated seawater. Here, oxygen reduction is the dominant cathodic reaction. Corresponding data reported by DECHEMA /7/ indicate a lower galvanic acceleration factor of approximately 1.5 – 2 for steel coupled to brass in seawater. No specific data are available for galvanic coupling between carbon steel and brass under oxygen-depleted conditions. In such environments, the cathodic reaction is expected to be significantly less efficient due to the absence of dissolved oxygen, and galvanic acceleration is therefore not expected to be significant /8/. This observation is consistent with statements made in the relevant DNV report/4/.

There is limited information about corrosion rate of carbon steel in an anoxic environment, but one can consider the corrosion rates on the order of ~0.01 mm/year have been reported on steel buried in marine sediments. Using this corrosion rate and an exposure period of 81 years, the resulting one-side uniform metal loss for freely exposed carbon steel is estimated to be approximately 0.8 mm. If the corrosion reaction is affected by the galvanic coupling, a galvanic acceleration factor of e.g. 2 will give 1.6 mm metal loss after 81 years. To DNV's knowledge, corrosion rates in oxygen-free environments can be as low as approximately 0.001 mm/year (1 µm/year). This is further supported by research on carbon steel exposed to oxygen-free groundwater /5/, where initial corrosion rates of about 10 µm/year were reported, before the formation of protective oxide layers reduced the rates to as low as 0.1 µm/year. Using a corrosion rate of 0.001 mm/year, the estimated metal loss is therefore reduced by approximately a factor of ten to 0.08 mm - 0.16 mm (added a galvanic acceleration factor of e.g. 2). It should be noted that the corrosion rate is influenced by several factors, including water

chemistry and the formation, composition, and stability of corrosion products and scale. The interaction of these factors can be complex and introduces uncertainty in long-term corrosion rate estimates.

Waterline attack is a term used to describe pitting due to a differential oxygen cell functioning between the well-aerated surface layer of a liquid and the oxygen-starved layer immediately beneath it. The pitting occurs immediately below the waterline. In this case the carbon steel will protect the brasses.

4.3.2 Stainless steel – copper-based alloy

If the components used are stainless steels, it is assumed that they contain chromium in the order of 12–14 wt%, consistent with low-alloyed ferritic or martensitic stainless-steel grades. It is considered unlikely that the materials used are highly alloyed stainless steels.

The corrosion behaviour of stainless steels can be difficult to predict, as the effective nobility of the material depends on its passivity. The stability of the passive film is governed by the oxide chemistry and environmental factors such as chloride concentration, oxygen availability, and the potential for biofilm formation.

Copper-based alloys are generally less noble than passive stainless steels but more noble than actively corroding carbon steel.

Assuming oxygen-free environment with no seawater exchange and no biofilm development, the stainless steel is expected to remain in a passive state and hence be more noble than the copper-based alloys. Under these conditions, the stainless steel will act as the cathode and the brass as the anode in a galvanic couple. As dissolved oxygen is depleted, the cathodic reaction will be controlled by water reduction on the stainless-steel surface. Since stainless steel is an inefficient cathode for the water reduction reaction, the resulting galvanic current will be low, and the corrosion rate of the brass is therefore expected to be limited. The corrosion rate on brass is expected to be around 0.001 mm/year. Multiplied with an acceleration factor of 2, this rate can be up to 0.002 mm/year.

4.4 Other corrosion mechanisms

Stress corrosion cracking of brass is assumed to be supressed by the low oxygen content and the galvanic coupling with carbon steel.

Microbiologically influenced corrosion (MIC) is considered unlikely in this system due to the lack of bioavailable carbon sources. Grease and oils consist of long-chain, non-polar hydrocarbons that are effectively non-biodegradable, preventing microbial metabolism and thereby inhibiting MIC mechanisms.

Furthermore, the presence of grease on the surface acts as a physical barrier, reducing direct exposure to seawater. This is therefore expected to further decrease the corrosion rate on carbon steel or brass even further.

5 CONCLUSION

DNV have assessed galvanic corrosion between copper-based and steel alloys inside a firing device. Different exposure scenarios inside the housing are assessed. The most relevant are partly flooded (standing seawater with an air saturated headspace) and fully flooded condition with oxygen depleted seawater. The following conclusions can be made:

- The corrosion rate in an oxygen depleted environment becomes cathodically limited by the slow reduction of water, resulting in a significantly reduced corrosion rate compared to oxygen saturated condition.
- The base case considers galvanic corrosion between carbon steel and brass, with an additional case assessing galvanic coupling between stainless steel and brass.
    - The corrosion rate of carbon steel, when galvanically coupled with brass, is estimated to range from 0.01 mm/year to 0.001 mm/year (1 µm/year) in an oxygen depleted environment.
    - The corrosion rate of brass, when galvanically coupled with stainless steel, is estimated to 0.001 mm/year (1 µm/year) in an oxygen depleted environment.
    - Considering the effect of galvanic corrosion, the corrosion rates can be increased with a factor of 2.
- The presence of grease on the surface may act as a physical barrier, reducing direct exposure to seawater and therefore reduce the corrosion.
- The findings are consistent with the conclusion presented in the 2008 DNV report /4/ where galvanic corrosion was considered as limited in an oxygen depleted environment.

The effect of corrosion on the functionality of the firing device has not been assessed.

6 REFERENCES

/1/ Video: German torpedo fuses, how do they work? https://www.youtube.com/watch?v=ei70qsCWAnw

/2/ Notat, Eirik Svinsås, FFI 11. mars 2026, «Innspill til DNV – mulig effekt av korrosjon på tennapparat Pi 4c»

/3/ DNV Report Salvage of U864 - Supplementary studies - Study No. 1: Corrosion report no 23916-1, rev. 01, 2008-07-04

/4/ DNV Report Salvage of U864 - Supplementary studies - Study No. 2: Explosives report no. 23916-2, rev. 01, 2008-07-04

/5/ Anaerobic Corrosion of Carbon Steel and Cast Iron in Artificial Groundwaters: Part 2—Gas Generation, N.R. Smart; D.J. Blackwood; L. Werme, CORROSION (2002) 58 (8): 627–637.

/6/ Copper Development Association (CDA). Tuthill, A.H. – Guidelines for the Use of Copper Alloys in Seawater.

/7/ DECHEMA Corrosion Handbook Volume 11 Corrosive agents and their interaction with materials

/8/ H. Uhlig, The Corrosion Handbook, John Wiley & Sons, 6th Printing, 1958

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