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ENIGMA M4 FROM THE GERMAN MINESWEEPER R15 IN THE UPPER ADRIATIC: HIGH-RESOLUTION MICROCT INVESTIGATION OF THE LAST SETTINGS

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ABSTRACT

This article presents the results of microtomographic analysis of the rotor block of an Enigma machine M4 recovered from the wreck of the German minesweeper R15 in the upper Adriatic Sea (sunk on 16 April 1945). The device (serial number M 15648) was examined using visual inspection and MicroCT. Initial analysis enabled identification of the rotor sequence (Walzenlage) and external wheel positions, while higher-resolution scanning revealed internal rotor settings (Ringstellung). Based on the place and time of the sinking of the R15, it is plausible that the operators of M 15648 used the naval key Hermes within the code network Süd.

Keywords: Second World War, Adriatic, Kriegsmarine, cypher machines, Enigma, micro CT investigation

ENIGMA M4 DEL DRAGAMINE TEDESCO R15 NELL'ALTO ADRIATICO: INDAGINE MICROCT AD ALTA RISOLUZIONE DELLE ULTIME IMPOSTAZIONI

SINTESI

Questo articolo presenta i risultati dell'analisi microtomografica del blocco rotori di una macchina Enigma M4 recuperata dal relitto del dragamine tedesco R15 nell'Alto Adriatico, affondato il 16 aprile 1945. Il dispositivo, recante il numero di serie M 15648, è stato esaminato mediante ispezione visiva e MicroCT. L'analisi iniziale ha consentito di identificare la sequenza dei rotori (Walzenlage) e le posizioni esterne delle ruote, mentre una scansione a risoluzione più elevata ha rivelato le impostazioni interne dei rotori (Ringstellung). In base al luogo e al momento dell'affondamento dell'R15, è plausibile che gli operatori della M 15648 utilizzassero la chiave navale Hermes all'interno della rete di codifica Sud.

Parole chiave: Seconda guerra mondiale, Adriatico, Kriegsmarine, macchine cifranti, Enigma, indagine microCT

INTRODUCTION[1]

Foreword

The renowned German Enigma cipher devices continue to attract significant interest from researchers and the general public, particularly when they originate from their primary contexts of use, such as command posts and other locations in the land theatre of war, as well as from ships and submarines. The still relatively rare examples from marine sites are mostly the result of exploration of sunken shipwrecks and submarines before the significance of such sites as valuable underwater cultural heritage was recognised, so only a few have been studied in full detail. This includes the example presented here: a naval Enigma M4 from the wreck of the German light minesweeper R15 off Umag in the northern Adriatic (Gaspari et al., 2023). The R15 was part of a convoy of three ships and five carriers travelling from Trieste to Pola on the night of 16–17 April 1945. It was detected by the British at around 11 pm and attacked by three torpedo boats of the 28th MTB Flotilla (Reynolds & Cooper, 1999). One of the torpedoes launched by MTB 409 struck its target, and the R15 sank 3 nautical miles northwest of Umag.

The wreck of the R15, lying inverted on the flat sandy seabed at a depth of 23–25 metres, was surveyed several times between 1984 and 1986 by Zvonimir Kralj, curator of the Piran Aquarium. Among the artefacts recovered from the vessel was an Enigma machine in a wooden box, accompanied by a black-printed booklet measuring approximately 30 × 20 cm. As only provisional conservation measures had been taken, the condition of the Enigma machine deteriorated rapidly, while the booklet disintegrated completely. In 2017, Kralj presented the remains of the encryption device to diver and expert Daniel Germek, who recognised its museological significance and research potential. The object was subsequently entrusted to the Military History Park in Pivka, where systematic conservation treatment began in the Conservation Department of the Museum of Modern History of Slovenia (Figure 1).

The conservation and research work, which resulted in an expert treatise on the subject (Gaspari et al., 2023) and a noted museum exhibition in Pivka (Boštjančič & Gaspari, 2023), accompanied by a television documentary, included the investigation of the historical circumstances of the sinking of R15 and the examination of the preserved parts of the Enigma, in particular the rotor block and the remains of a plug-in board, the latter unfortunately with completely degraded and missing cables.

The following lines present the results of recent research on the final settings of the Enigma. Some previously published misconceptions about the final settings and their implications are also clarified and put into perspective.

Initial investigations of the Enigma M4 from the wreck of the minesweeper R 15

The rotor block of the Enigma M4, discovered in the wreck of R 15, has been preserved in a heavily corroded condition, with the upper parts of the zamak alloy wheels and portions of the Bakelite letter rings missing, but it remains fixed in the wheel compartment of the machine chassis (Figure 2). The rotor block was examined in 2020 at the Slovenian National Institute of Civil Engineering using microtomography (microCT), which revealed the arrangement (Walzenlage) and final positions of the rotors as well as their serial numbers and markings (Gaspari et al., 2023). The configuration of the wheel compartment, described from left to right, was identified as: reflector UKW-C, extra wheel Gamma, rotor III, rotor VI and rotor IV. All the wheels bear the serial number M 15648, and the rotor sequence includes a Naval wheel (VI), in accordance with the instructions stipulating that, when operating an M4 machine, one of the rotors had to be a Kriegsmarine rotor (VI–VIII).

Except for the gamma extra rotor (**γ**), which is preserved in its entirety, shorter or longer sequences of letters were preserved in situ on the other three rings (III: B–D, L–O; VI: A–J; IV: K–Q, U–W), sometimes slightly elevated above their original positions due to corrosion of the metal base, but nevertheless allowing the reconstruction of the positions of the missing letters. This circumstance, combined with the arrangement of the rotors within the block and its installation into the partially preserved walls and suspensions of the block compartment, enabled the relatively secure determination of the last external positions of the rotors. These were established based on the

1 We would like to thank Frode Weierud, curator of the cryptocellar.org site, and Paul Reuvers, co-founder of the virtual Crypto Museum, both renowned specialists in the history of cryptology and Enigma cipher machines, for their expert help. We also thank Anton Frank from the Bundesarchiv-Militärarchiv in Freiburg for managing our request and providing a copy of Kenngruppenverfahren Süd. We are indebted to Svetko Kovač, former director of the Military Intelligence Agency [Vojnobezbednosna agencija] of the Republic of Serbia and an expert in the history of cryptography, for his valuable suggestions and contributions of archival material. We extend our gratitude to Robert Derenčin, retired officer of the Croatian Army and a connoisseur of the use of Enigma machines in naval operations. The authors sincerely thank the reviewers and editors of Annales, Series Historia et Sociologia and Cryptographia for their valuable feedback and support in improving this manuscript.

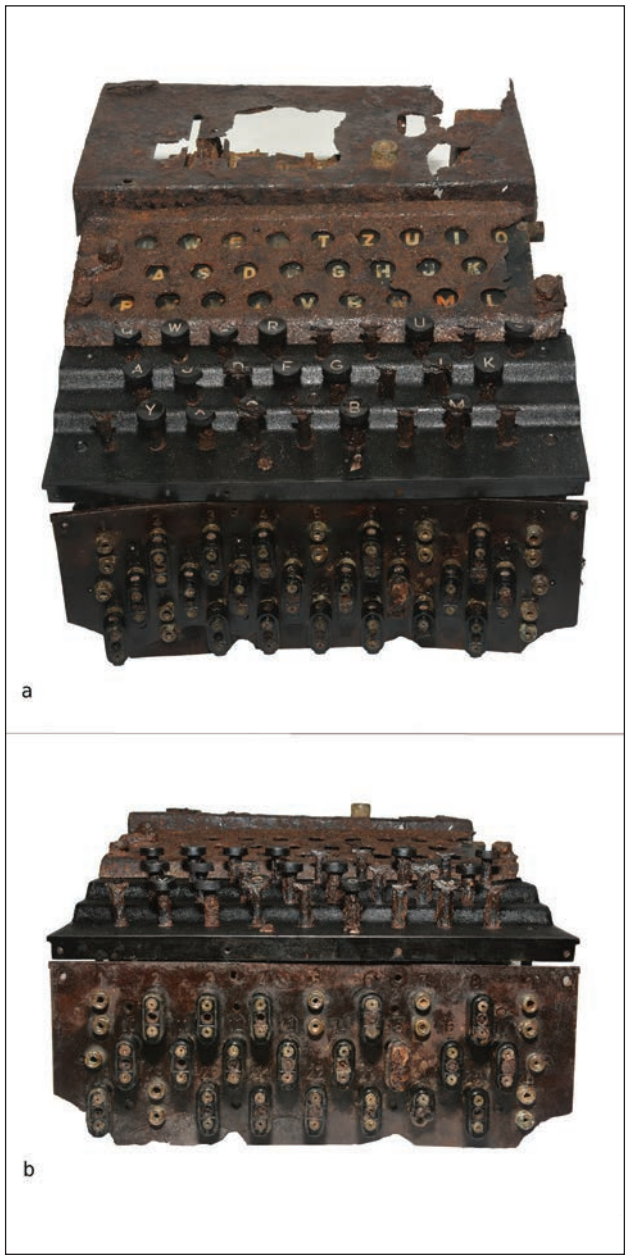


Figure 1: The remains of the Enigma M4 from the minesweeper R 15 after conservation: a – top view; b – front view (Photo: Andrej Gaspari).

fact that the windows on the machine lid plate were canted forward by one position from the top-dead-centre alignment, to make them easier for the operator to read (Marks, 2015, 32).

The plugboard (Steckerbrett) on the front of the machine shows six unused double sockets for the plugs, namely 1 (A), 5 (E), 7 (G), 9 (I), 19 (S), and 26 (Z). The cables connecting the paired plugs were not preserved; only the lower sections of the plugs with their pins remain (Figure 1b).

Figure 2: Enigma M4 from the minesweeper R 15; wheel compartment during conservation (Photo: Andrej Gaspari).

MicroCT ANALYSIS OF THE ROTOR BLOCK (2024)

In 2024, the institute acquired a new, higher-resolution device, enabling the determination of the ring settings of the rotors during their last use and thus the identification of the corresponding key. For the scanned Enigma rotor block, micro-CT was employed to examine the device's internal state. The aim was to confirm the type of each rotor (serial number and marking – Roman numeral) and to identify the ring setting (Ringstellung) without causing any damage or moving the rotors out of position. To achieve this, the EasyTom XL Ultra microCT device from the French manufacturer RX Solutions was used. The Enigma rotor block was placed inside the device on a 3D-printed stand and secured with rubber bands only, to avoid the use of glues or other adhesives (Figure 3). A microfocus Hamamatsu source was used with a 1.7 mm aluminium filter and the following tube settings: 160 kV operating voltage, 160 µA tube current, and 95 µA target anode current. A tungsten filament served as the cathode. A high-speed flat-panel detector captured the radiographs at 1.1 frames per second with a resolution of 2536 × 2024 pixels. A total of 1,984 radiographs were produced for each 360° rotation, and four frames were averaged to acquire each radiograph. To achieve 35 µm spatial resolution across the entire scanned volume, the Enigma rotors were positioned with a source-to-object distance of

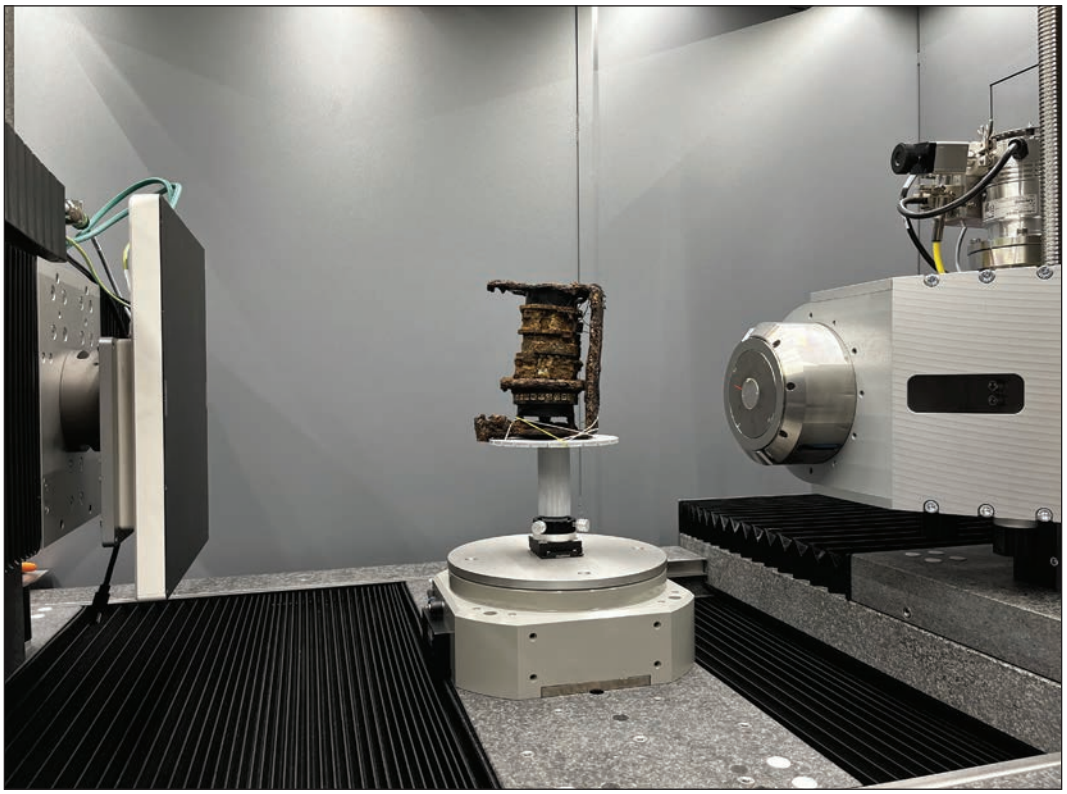


Figure 3: Enigma M4 rotor block on a stand, placed in an EasyTom XL Ultra microCT device (Photo: Miha Hren).

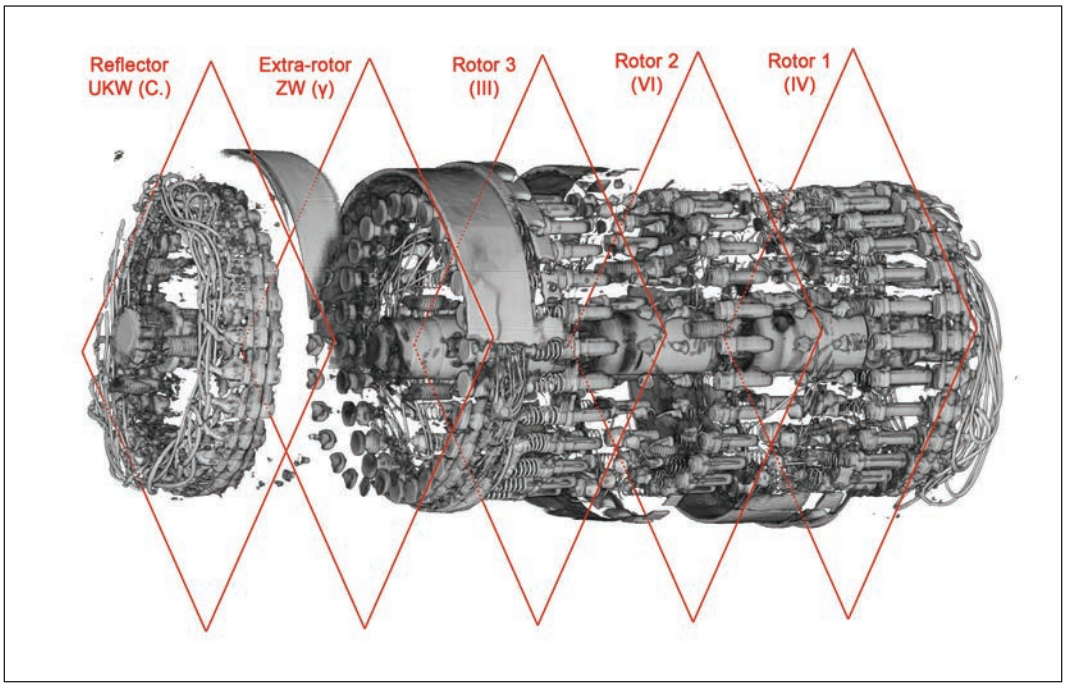


Figure 4: X-ray computed microtomography scan of the wheel block of the Enigma M4 from the minesweeper R 15, acquired with a Zeiss XRadia Micro XTC-400 x-ray microscope (3D render: Lidija Korat & Miha Hren).

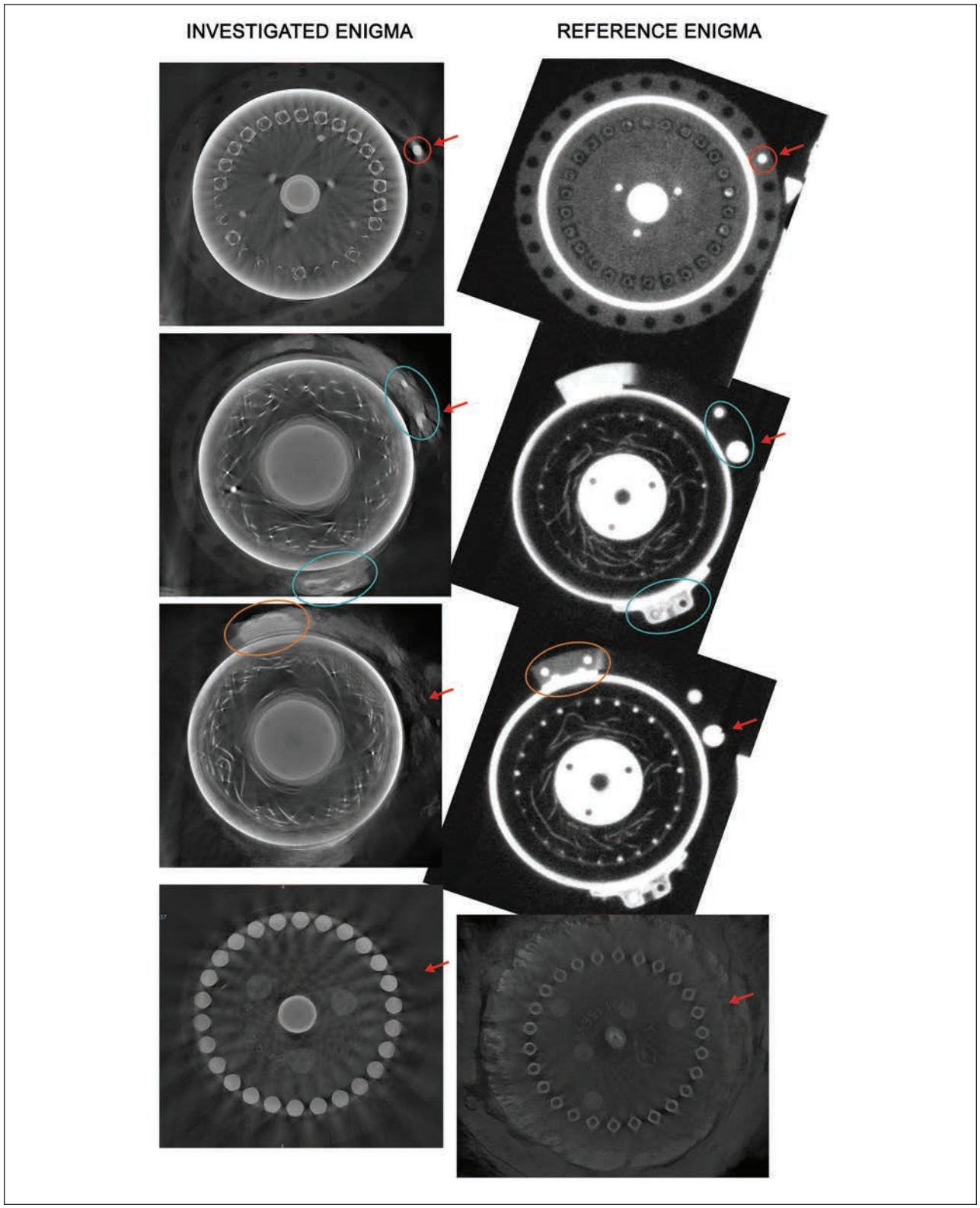


Figure 5: Reconstructed images of the extra-rotor (ZW) gamma in the investigated Enigma (left) and reference Enigma (right). The red, teal, and orange circles indicate the same identifying features (pins, screws, support structure) on both the investigated and reference Enigma. The red arrow points to the location of the gamma sign and the letter A (3D render: Miha Hren).

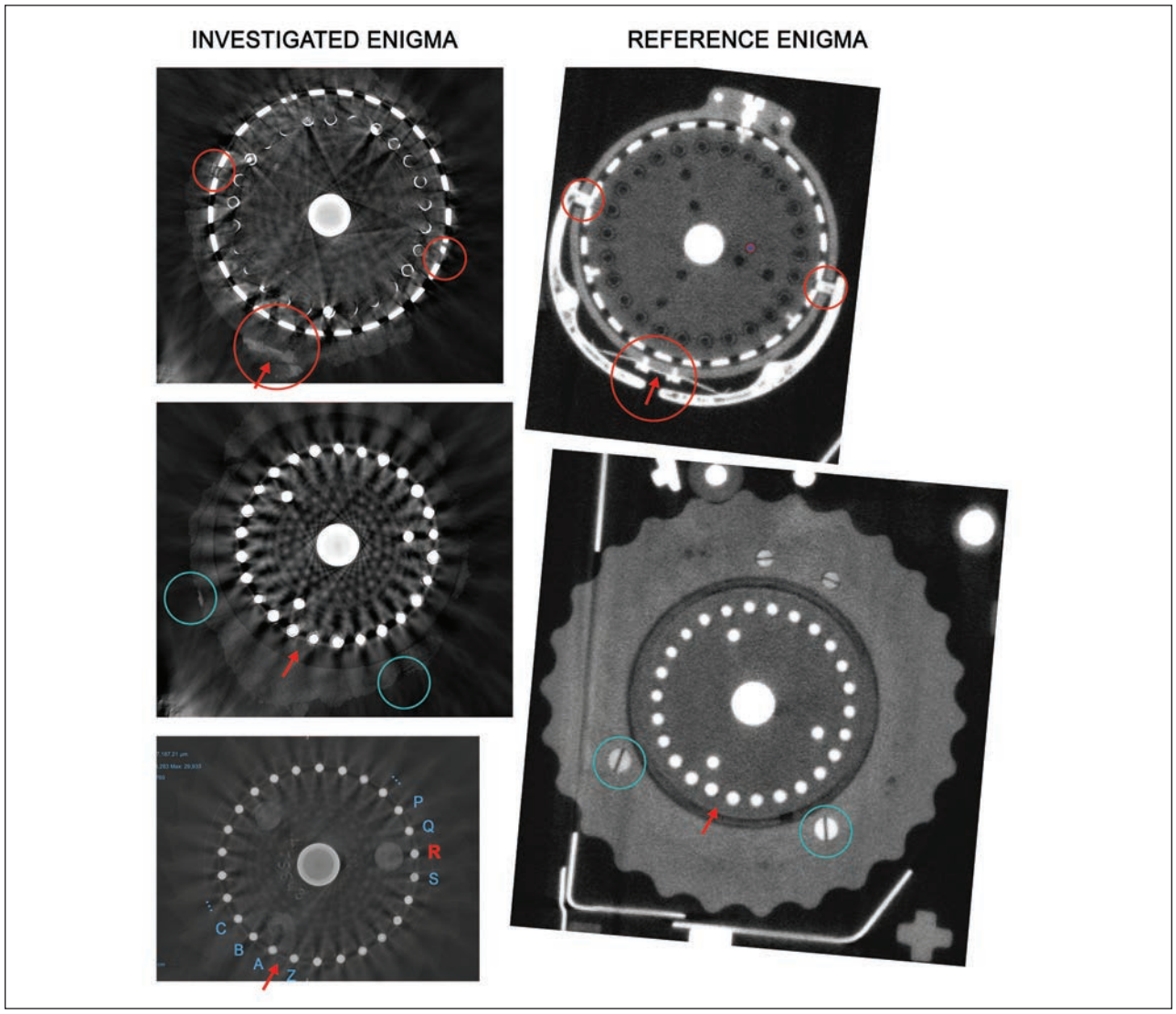


Figure 6: Reconstructed images of Rotor III in the investigated Enigma (left) and reference Enigma (right). The red and teal circles indicate the same identifying features (pins, screws, support structure) on both the investigated and reference Enigma. The red arrow points to the location of the gap between two levers for altering the ring-setting (which is always positioned between letters A and Z). The letter at the III sign (R) is highlighted in red (3D render: Miha Hren).

138 mm and a source-to-detector distance of 491 mm. As the entire rotor construction did not fit within a single radiograph, the helical scanning technique was used. A total of five turns were required to scan the entire volume (Figure 4).

RESULTS

Figures 5 to 10 show the cross-sections of various rotors from the microCT scan of the investigated Enigma and the reference CT of the Enigma M4 (M 7972; circa 1944) from the Deutsches Museum. As the rotor block of the investigated Enigma was severely damaged, the reference Enigma was used to determine the correct positions of identifying features such as pins, screws, support structures, holes, and gaps between the levers of the ring-setting mechanism. These features were used to identify the sequence of the letters on the outer ring and to determine the Ringstellung letters. In all figures, these features are labelled with red, teal, and orange circles on both the investigated and reference Enigmas. Red arrows indicate the location where the letters on the outer ring start: either on the letter A or between letters A and Z. Ringstellung letters are shown in red.

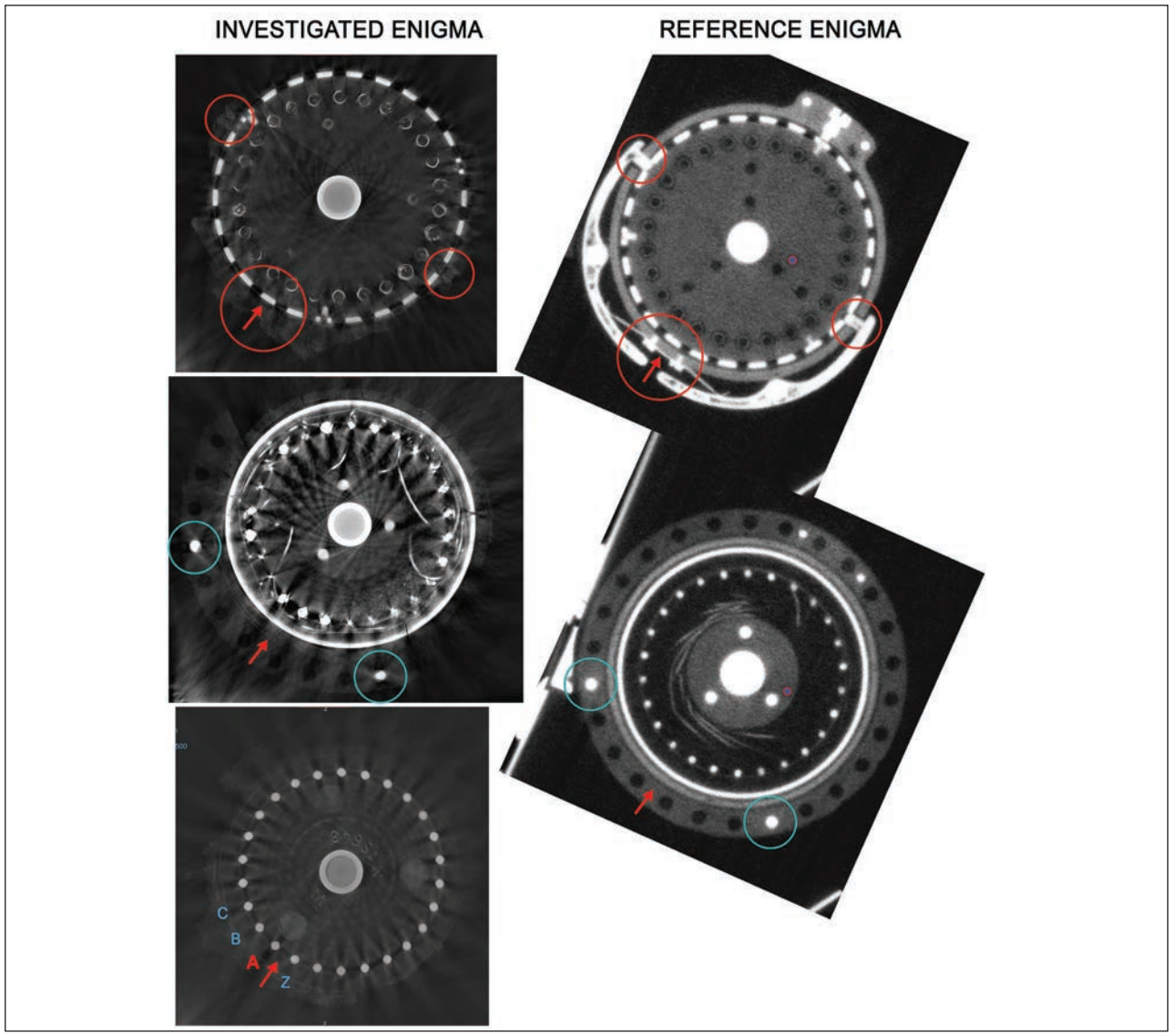


Figure 7: Reconstructed images of Rotor VI in the investigated Enigma (left) and reference Enigma (right). The letter at the VI sign (A) is highlighted in red (3D render: Miha Hren).

DISCUSSION OF THE RESULTS

The recovered internal settings of the M 15648 bring us significantly closer to identifying the cipher network and its daily key during the period when the R15 sank. The settings are as follows: wheel order – UKW-c, Gamma, III, VI, IV; Ringstellung – A, R, A, C; and external wheel positions – P, F, E, Y (Table 1). During the investigation, the question arose as to whether the combination UKW c/ZW γ in M 15648 was compatible with the standard UKW C, used in Enigma I (employed by the Wehrmacht and Luftwaffe) and M3. However, the Germans abandoned the use of UKW C sometime after the end of 1941. The exact date is not known, but the order from 7 September 1944 to rewire all UKW C to UKW B shows that by then, UKW C was no longer in use (Weierud, 2025). It is therefore impossible that UKW C had any connection with the M4 from the Räumboot R15. Furthermore, for thin UKW C and Zusatzwalze Gamma to be compatible with the wiring of standard UKW C, both Gamma's Ringstellung and the setting must be at A.

The possibility that the setting of the Zusatzwalze resulted from operator error or intentional swapping of the rotor in anticipation of capture remains; however, the latter is unlikely due to the night-time and suddenness of the attack and the subsequent sinking of the minesweeper. As is well known, the Kriegsmarine emphasised the importance of security measures (Geheimhaltungsbestimmungen) to keep Naval Enigma

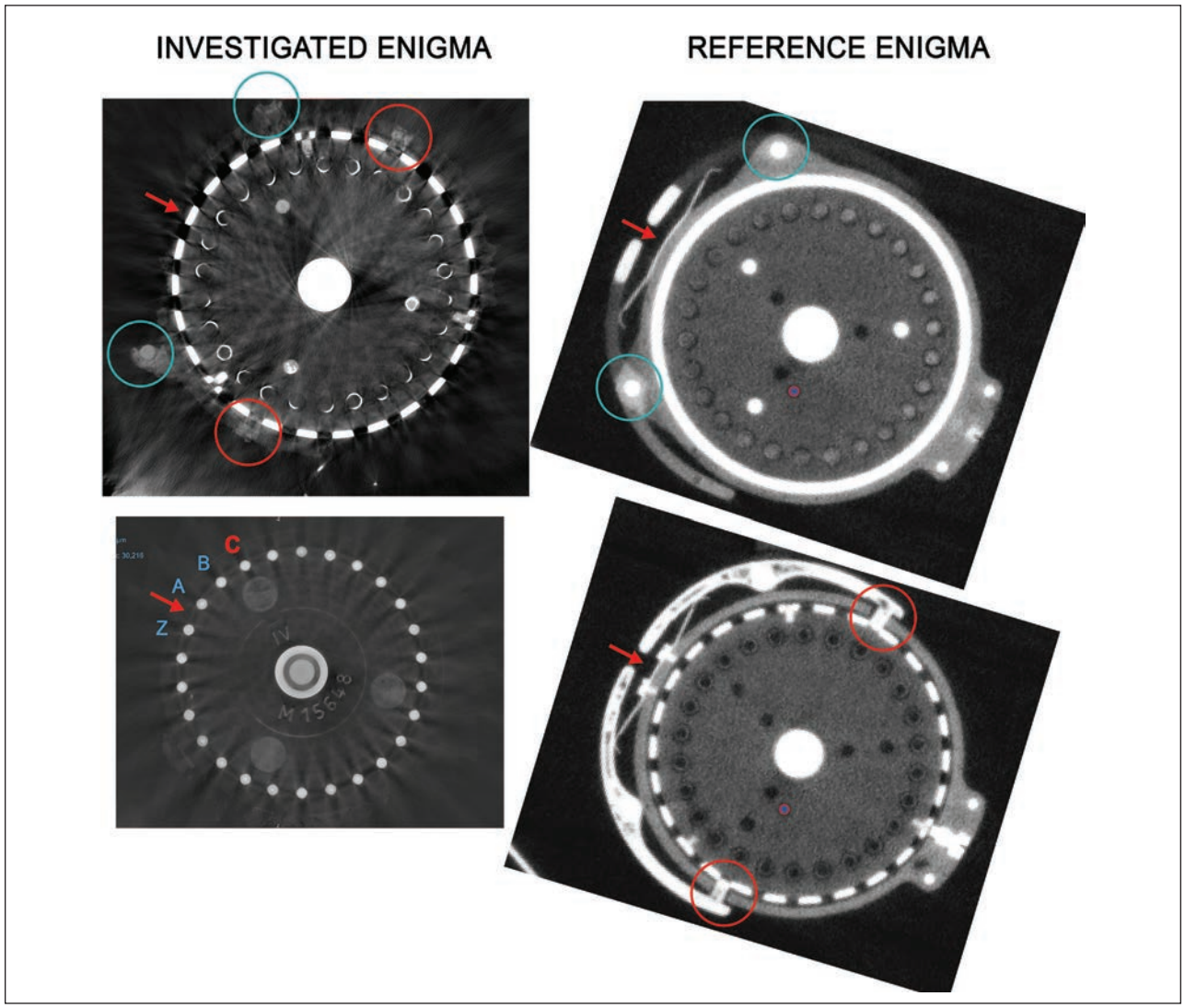


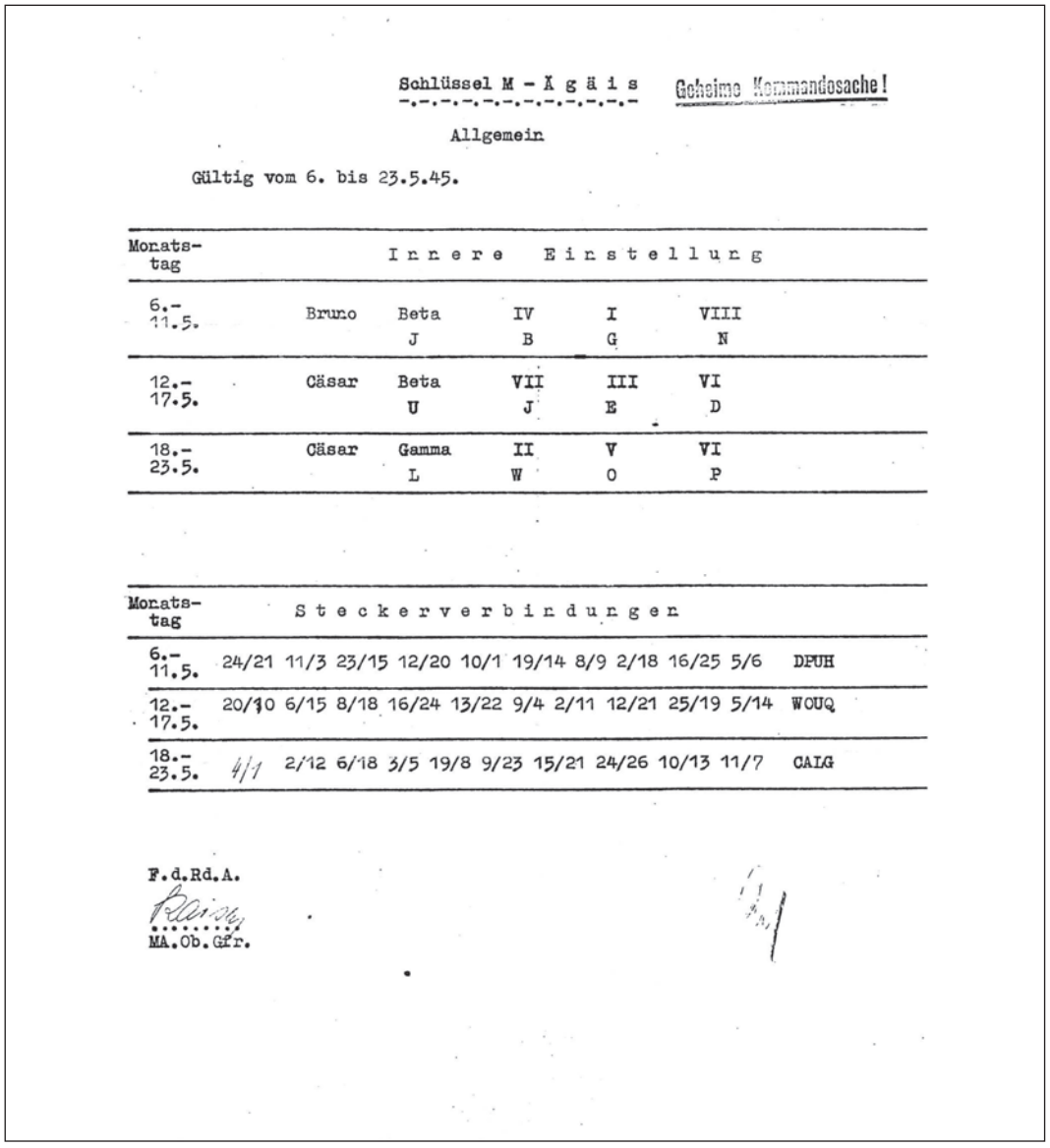
Figure 8: Reconstructed images of Rotor IV in the investigated Enigma (left) and reference Enigma (right). The letter at the IV sign (C) is highlighted in red (3D render: Miha Hren).

Table 1: Configuration and settings of the rotors, from left to right, established from the cumulative X-ray computed microtomography, 2024.

	Reflector / Umkehrwalze	Extra-rotor / Zusatzwalze	Rotor 3	Rotor 2	Rotor 1
Label	**C.**	**γ**	**III**	**VI**	**IV**
Serial number	**M 15648**	**M 15648**	**M 15648**	**M 15648**	**M 15648**
Ring setting	/	**A**	**R**	**A**	**C**
External position	/	**P**	**F**	**E**	**Y**

traffic secret, as evidenced by the detailed instructions for the destruction of the machine and rotors in shallow waters within enemy territory, including preparations for the destruction of code books and radio messages (Der Schlüssel M, 1941, 13–16). Although the minesweeper R 15 most likely served as the convoy's command ship, it is reasonable to assume that ' normal' – rather than officer – messages were used. In the latter case, special instructions applied, including resetting the wheels after each enciphering and deciphering, and removing the Stecker (plugboard) connections after use of the Enigma (Enigma, 1940). The change of keys usually occurred around midnight or at 1 am. The ship would therefore have had the operational Enigma key for 16 April 1945 set up on its Enigma machine at the moment it was attacked and sank. The identification of the actual key

setting sheet for the period when this ship was sunk would be supported by the six unused plugs on the Steckerbrett. These, in combination with the known setting of the gamma wheel (P), which did not move during typing, might enable the identification of the matching daily Grundstellung. The Räumboot R 15 was a small ship and would not have operated on more than one cipher network. Large vessels or naval stations operating across several networks would have had more than one Enigma machine, each set up for a different cipher network. Süd was the Kriegsmarine cipher network for the Black Sea and Mediterranean area, introduced in 1941 and originally a single key, codenamed Porpoise by the Bletchley Park (BP) codebreakers (Erskine, 1996). In October 1943, the code network Süd was split into three keys: Hermes (Porpoise by BP) for the Mediterranean, Poseidon (Grampus) for the Black Sea, and Uranus (Trumpeter) for the Balkans or the Oberkommando der Kriegsmarine (OKM) – Marineoberkommando (MOK) Süd/Südost (from October 1943, deciphered in April 1944). At the end of the war, some of these minor split-up keys again merged with the parent keys, such as key M Wotan (Bloater) for the Mediterranean, created on 1 October 1944, which rejoined Hermes (Porpoise) on 12 January 1945 (German Naval Ciphers, 1944). Two new keys were introduced in February 1945 for the southern Adriatic area (Albanien) and Aegean Islands (Ägäis), which were outside the operational area of R 15.



Schlüssel M – Ä g ä i s Geheime Kommandosache!

Allgemein

Gültig vom 6. bis 23.5.45.

Monats-tag	Innere Einstellung				
6.-11.5.	Bruno	Beta J	IV B	I G	VIII N
12.-17.5.	Cäsar	Beta U	VII J	III E	VI D
18.-23.5.	Cäsar	Gamma L	II W	V O	VI P

Monats-tag	Steckerverbindungen										
6.-11.5.	24/21	11/3	23/15	12/20	10/1	19/14	8/9	2/18	16/25	5/6	DPUH
12.-17.5.	20/10	6/15	8/18	16/24	13/22	9/4	2/11	12/21	25/19	5/14	WOUQ
18.-23.5.	4/1	2/12	6/18	3/5	19/8	9/23	15/21	24/26	10/13	11/7	CAIG

F.d.Rd.A.

MA.Ob.Gfr.

Figure 9: Example of a German naval key from the code network Süd – Schlüssel M »Ägäis«, valid from 6 to 23 May 1945 (Source: courtesy of Frode Weierud, Crypto Cellar Research).

The document Kenngruppenverfahren Süd reveals that Poseidon and Uranus used three-letter message keys (Kenngruppenverfahren Süd, 1944, 9); therefore, the Zusatzwalze was not part of the message key. Only Hermes used a four-letter message key. However, the Kenngruppenverfahren Süd document does not state whether the Grundstellung used four letters or if the daily key (the setting of the wheel order and Ringstellung) also included a fixed setting for the Greek wheel. As the Gamma wheel of the M 15648 is set to P, this may indicate that we are dealing with the Hermes network, which used four-letter message keys. However, we cannot be absolutely certain, as we do not know enough about the key settings for Poseidon and Uranus. If we know that the key settings for the latter always had Ringstellung A and wheel setting A for the Greek wheel, then we can conclude that M 15648 was used with Hermes. In light of all this, the most likely key to have been used on the Räumboote R15 in April 1945 is the Naval key Hermes (Porpoise). The high probability that M 15648 from the R15 was used with the Hermes network before its sinking off the Istrian coast is supported by intercepted communication dated 14 April 1945, originating from the same operational area. This communication reports on the movement of the ship TA 40 of the 9th Torpedo Boat Flotilla (9. Torpedobootflottille) from Pola to Trieste (Birnbaum & Vorsteher, 1987, 310–342), and it is marked with the network indication in double brackets – ((PORPOISE)) (TNA-DEFE 3/685, 34.)

The recovery of operational Enigma key sheets is exceptionally rare, as such classified materials were routinely destroyed after use. Surviving examples are therefore largely limited to April–May 1945, when deteriorating wartime conditions during World War II led German forces to reuse keys, often extending April settings into May with minor modifications. The possible identification of corresponding key sheets within regional military archives is supported by the documented capture of Enigma machine units by Yugoslav Partisans during the retreat of German forces from Romania, Bulgaria, and Greece in 1944–1945. Four preserved machines are currently held in Serbia: one M3 model at the Military Museum in Belgrade and three M4 models exhibited in Pančevo. According to Svetko Kovač (2017), these devices may have originated from German naval units under the command of Marineoberkommando Süd, retreating alongside Army Group E. Following the German surrender in May 1945, large quantities of captured military equipment were consolidated at a central trophy depot in Zagreb. After its dissolution in September 1945, communication equipment – including Enigma machines – was transferred to the Communication Command of the Yugoslav Ministry of National Defence (MNO FNRJ). These machines were subsequently used for cryptographic training between 1951 and 1956, supported by translated German manuals and documentation. Portions of this material are now preserved in the archives of the MNO FNRJ (Kovač, 2017, 45–47, 58–63, 207–211), leaving open the possibility that previously unknown key sheets associated with the Süd network from the final months of the war may yet be identified.

CONCLUSIONS

This study demonstrates the applicability of MicroCT as a non-destructive method for investigating historically significant cryptographic devices. Microtomographic analysis of the rotor block of the Enigma machine M4 (serial number M 15648), recovered from the wreck of the German minesweeper R15 in the Adriatic Sea, enabled identification of the rotor sequence, external wheel positions, and – through higher-resolution scanning – internal rotor settings (Ringstellung), providing insight into the operational configuration of the device at the time of its loss in April 1945.

However, these results do not substantially extend previous historical interpretations. The identified ring settings cannot be unambiguously correlated with known Kriegsmarine key material from April 1945, although the use of the Hermes key within the code network Süd remains plausible. This limitation reflects the broader scarcity of surviving operational key sheets, particularly during the final phase of the Second World War. While captured Enigma machines and associated archival documentation suggest potential for further discoveries, direct correlations remain limited. The study should therefore be regarded primarily as a methodological contribution rather than a definitive cryptographic reconstruction.

More broadly, the results highlight the relevance of MicroCT for the investigation of encryption devices from marine archaeological contexts, where corrosion and mineral encrustation often preclude conventional disassembly. The technique enables non-invasive visualisation of internal assemblies – including rotor stacks, wiring pathways, and mechanical linkages – and supports material differentiation, detection of structural degradation, and reconstruction of internal configurations. Case studies, including the CT analysis of a 1941 Enigma machine at the University of Manchester (2018) and the "3D-Cipher Project" at the Deutsches Museum (2020; Göggerle, 2022), demonstrate its applicability to complex electromechanical systems. Although direct MicroCT investigations of seabed-recovered Enigma machines remain limited, comparable studies – such as the scanning of the seven Enigmas recovered from 2020 onwards by divers in the Baltic Sea at Geltinger Bay near Flensburg (Endres, 2023) – confirm its potential for analysing sealed and highly degraded artefacts.

ENIGMA M4 Z NEMŠKEGA MINOLOVCA R15 IZ SEVERNEGA JADRANA: VISOKOLOČLJIVOSTNA MIKROCT PREISKAVA ZADNJIH NASTAVITEV

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POVZETEK

Prispevek obravnava rentgensko računalniško mikrotomografsko raziskavo (MicroCT) rotorskega sklopa šifrirnega stroja Enigma M4, odkritega v razbitini nemškega lahkega minolovca R15 ob obali Istre v severnem Jadranskem morju, ki je bil potopljen 16. aprila 1945. Naprava s serijsko številko M 15648, danes hranjena v zbirki Parka vojaške zgodovine Pivka, je bila predmet celovite analize, ki je združevala arheološki in zgodovinski kontekst naprave, konservatorske postopke ter napredne ponazoritvene metode visoke ločljivosti. Začetna preiskava z vizualnim pregledom in mikroCT je omogočila določitev zaporedja rotorjev (UKW-C, Gamma, III, VI, IV) in njihovih zunanjih položajev (Walzenlage). Nadaljnje snemanje z visoko ločljivostno MicroXCT napravo je razkrilo tudi notranje nastavitve rotorjev (Ringstellung: A, R, A, C), s čimer se je potrdila izjemna uporabnost metode za pridobivanje sicer nedostopnih podatkov o konfiguracijah korodiranih in poškodovanih kriptografskih naprav iz podvodnih arheoloških kontekstov brez destruktivnih posegov. Primerjava z referenčnimi modeli, izdelanimi z enako tehnologijo (MicroCT), je omogočila natančnejšo interpretacijo zaznanih struktur. Na podlagi kraja in časa potopitve minolovca R 15 ter arhivskih virov je mogoče sklepati, da so operaterji naprave najverjetneje uporabljali pomorski ključ Hermes (Porpoise v terminologiji Bletchley Parka) v okviru kodne mreže Süd. Kljub temu ugotovljenih nastavitev ni mogoče nedvoumno povezati z dostopnimi kodnimi ključi Kriegsmarine iz aprila 1945. Prispevek tako izpostavlja tako analitični potencial kot interpretativne omejitve metode MicroCT pri raziskovanju kriptografskih naprav iz ladijskih razbitin ali morskega dna.

Ključne besede: druga svetovna vojna, Jadran, Kriegsmarine, šifrirne naprave, Enigma, mikrotomografska preiskava

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