Analysis of the US Navy Cryptanalytic Bombe Schematics and Simulation of Selected Circuits

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Abstract

This paper analyses several sheets of schematic circuit diagrams and drawings of the US Navy Cryptanalytic Bombe which was used as part of the process of deciphering German Enigma encrypted messages.

The functionality of selected circuits is verified through simulation and some circuits are analysed in-depth.

1 Background

In 1942, with the help of Bletchley Park, the US Navy signals intelligence and cryptanalysis group *OP-20-G* started working on a new Turing Bombe design. The result was a machine with both similarities and differences compared to its British counterpart (Ekhall and Hallenberg, 2018).

The work was led by Joseph Desch who was managing an electronics lab at the National Cash Register Company in Dayton, Ohio (Turing and Andrew, 2020). Desch researched the use of fast thyratron electron tubes for use in NCR products.

There is an original US Navy Bombe still in existence at the National Cryptologic Museum in Fort Meade, MD, USA. The Bombe on display is not in working order and the exact way it was operated is not fully known.

The US Navy Bombe was based on the same principles as its British version but had a different appearance and thus a different way of operation. The Bombes were used to search through a part of the Enigma key space, looking for a possible Enigma rotor core starting position which would not contradict a given enciphered message and its plaintext (Carter, 2008).

A number of pages of schematic circuit diagrams covering the US Navy Cryptanalytic Bombe has been retrieved from the US National Archives by researcher Dr. Glen Miranker. This paper describes what has been concluded so far from studying the schematic documents.

2 Overview

The purpose of the Bombe is to iterate through all Enigma rotor starting positions of a certain rotor order and, given a part of an Enigma enciphered message as well as a supposed crib, test each position. The Bombe uses a number of rotor banks to do this test. Each rotor bank corresponds to the rotors and reflector of an Enigma machine. The rotor banks are interconnected according to the message and crib that are to be investigated, and via a so called diagonal board which utilises the fact that if letter X is connected to letter Y on the plug board of an Enigma machine, then it means that letter Y is connected to letter X.

When the Bombe is running, for most of the time the test voltage injected into one terminal on one of the rotor banks will reach, via the interconnected rotor banks and diagonal board, all 26 terminals of the rotor. This indicates that the current position is not correct.

If the test voltage fails to reach all 26 terminals a rotor starting position has been found which could be the one used to encipher the whole message. Apart from the actual starting position it is also possible to deduce a number of Enigma plug board settings from a Bombe stop. This is the "output" of the Bombe and needs to be processed further in order to get the actual Enigma message key.

Depending on the enciphered Enigma message and crib used there will be several stops that do not correspond to the actual Enigma message key setting. Some of these will be ruled out automatically by the US Navy Bombe.

With a four rotor Enigma any given rotor order has $26^4 = 456976$ different starting positions.

The US Navy Bombe operates at great speed: About 780 positions are tested each second. When the Bombe detects a position that does not consti-

Document ID	Description	Date
GM-7 1D-107a	Abridged schematics of the entire N-530 Bombe	4/5/44
SD-5150	Earlier version of GM7 1D-107a	7/20/43
GM-3 1C-152a	‘Amplifier chassis’, Generates stop signal on a Bombe ‘hit’	8/8/44
GM-3 1C-110	‘Relay chassis’, performs tests on a ‘hit’Note: these schematics are for the N-800 Bombe	4/27/44
GM-3 1C-120a	‘Amplifier chassis’, variant of GM-3 IC-152a	5/9/44
GM-3 1C-117	‘Thyratron chassis’, retains the hit rotor position	5/5/44
GM-3 1C-113a	‘Resistor board chassis’, injects test current into diagonal board	5/2/44
GM-3 1C-119	‘Motor control chassis’, Controls forward and rewind motors, clutch and break	5/8/44
GM-3 1C-121	‘Main frame’, Power supply, motor connections, switches	5/9/44
B-3575g	‘Commutator’, mechanical drawing of a Bombe commutator	2/24/43

Table 1: The documents currently available to the authors. If not noted otherwise, the document covers the model N-530 Bombe.

tute a contradiction, a so called “hit” or “stop”, it will stop and rewind to the position in question, after which a test will be carried out. The results of the test is printed and the Bombe continues the search.

The detection, testing and printing of a potential solution is done by the Bombe itself, without operator involvement. Figure 1 shows an overview of what happens when a hit is handled: Assuming the Bombe is running, the diagonal board is monitored by a hit detector circuit (1). The hit detector will signal both the thyratron chassis, which will remember the rotor position where the stop occurred, and the motor control chassis which will break the rotors and start the rewind motor (2). When rewinding, the thyratron chassis will signal the motor control chassis when the correct stop position has been reached again (3). The rewind motor will be turned off and a signal is sent to the relay chassis (4) telling it to perform a test on the position in question. The test is done on the diagonal board (5). If the test is positive, the printer control chassis is signalled from the relay chassis, and prints the state of the diagonal board (6). When this is done the relay chassis signals the motor control chassis to resume the search.

3 Observations

Table 1 shows the documents currently available to the authors, of those documents the most interesting one is 1D-107a which is a high level schematic of the electrical circuit of the full N-530 Bombe on one sheet. To make it possible to fit all this on one sheet some parts that occur in multitude, typically 26 times, have been reduced to occurring just a few times in the schematics. For example, the diagonal board which is normally 26 x 26 connections has been limited to 5 x 5, four printer connections are present instead of the actual 20 and so on. On the whole, this sheet provides an excellent overview of the complete Bombe.

Most of the other documents are detailed schematics of different sections of the Bombe. 1C-110 is from an N-800 Bombe, nicknamed “Granddad”, a later and enhanced model with 32 rotor banks instead of 16 (Smith, 2011).

B-3575g is a mechanical drawing; interesting in its own but does not give much information on the function of the Bombe.

The main sections in 1D-107a will be referred to using the letters in Figure 2. Many of the sections are also visible in the photo of the N-530 Bombe shown in Figure 3.

3.1 Bank Switches

A Turing Bombe uses a number of Enigma equivalents where each Enigma equivalent has the same function as the rotors and reflector of an Enigma machine (Wilcox, 2006). On the US Navy Bombe

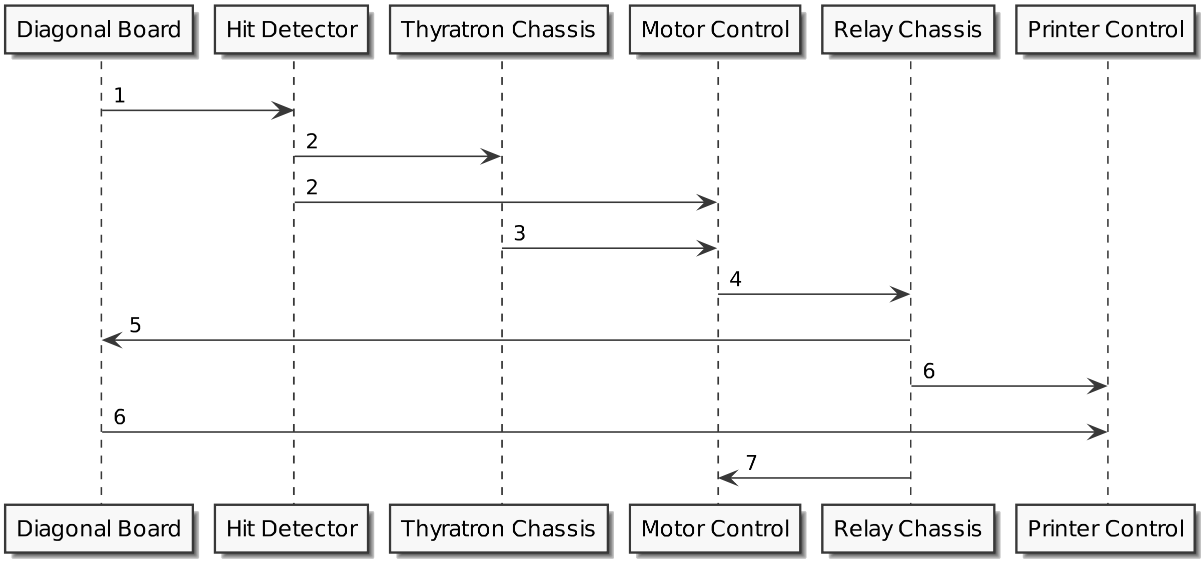

Figure 1: Overview of how a hit is handled by the US Navy Bombe.

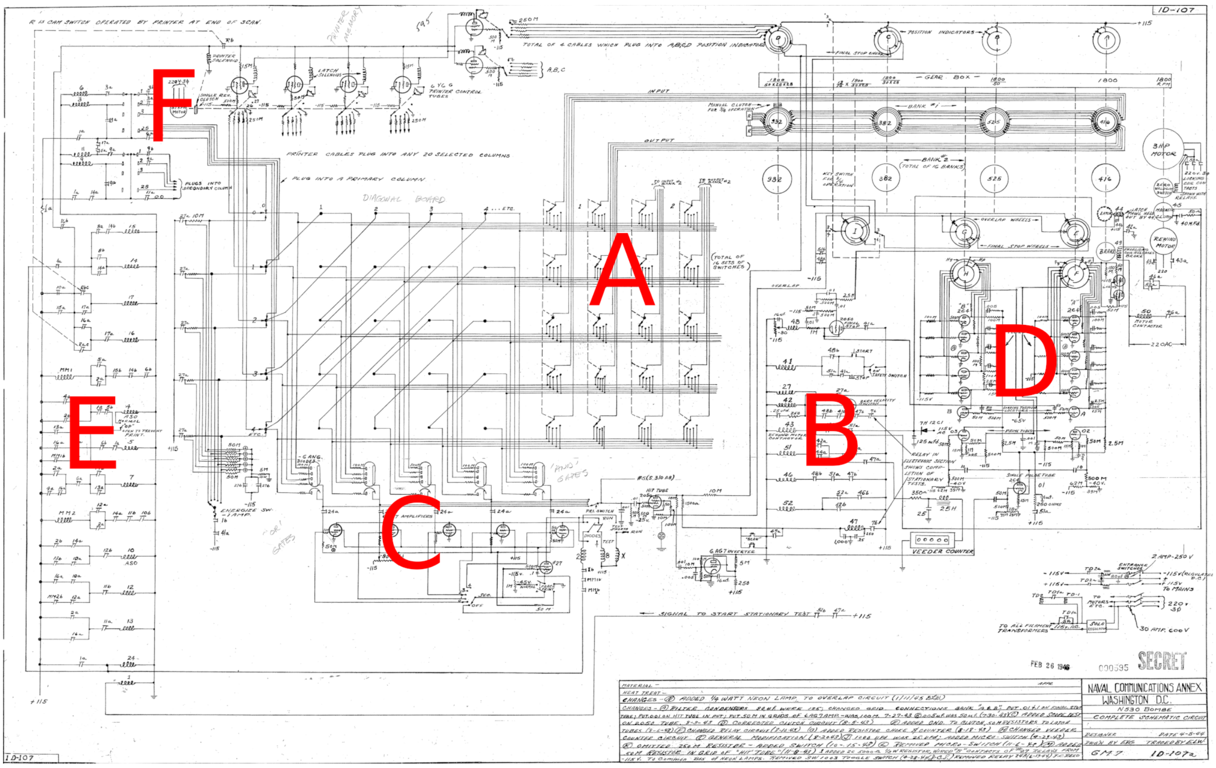

Figure 2: The full N-530 circuit with added labels. Document GM-7 1D-107a.

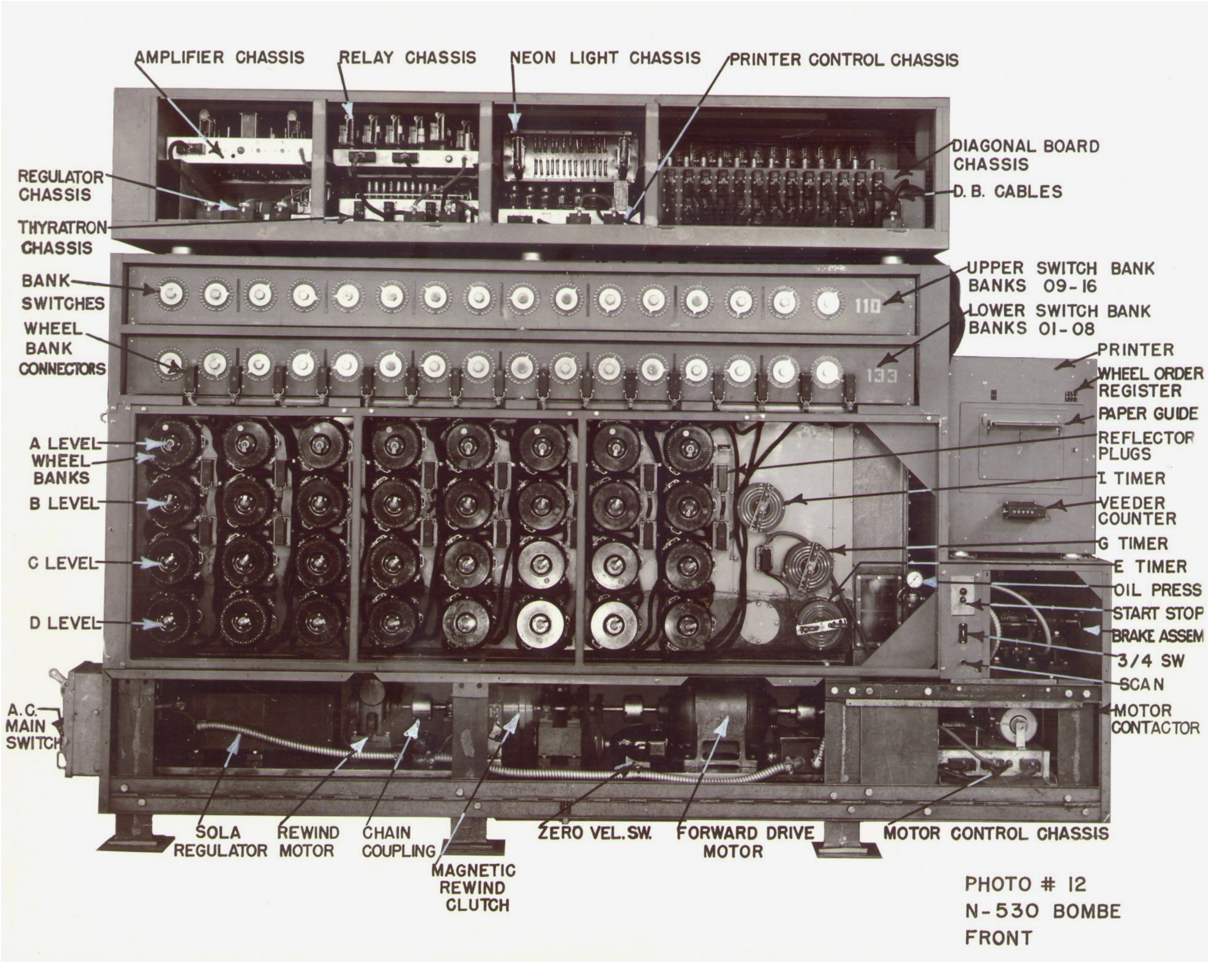

Figure 3: Photo of N-530 with parts labelled. Source: NSA.

such a unit is called a "rotor bank" of which there are 16 on the N-530 model, eight on the front and eight on the back of the machine.

Section **A** shows two of the bank switches. Each bank switch consists of an output selector and an input selector. These control at what column on the diagonal board the input and output of each of the 16 wheel banks are connected. According to Desch (1942): "Each switch will be a 26 plate pole, 27 position device (one position is dead so [the] machine can be disconnected) probably of the Centralab wafer type switch, or perhaps a special drum switch."

By comparison, the British Turing Bombe's 36 rotor banks are connected to the diagonal board by means of plugging 26-way cables into jacks on the back of the Bombe. This would have been much more time consuming and error prone compared to setting the bank switches on the US Navy Bombe where the same thing is accomplished by turning the bank switches for each bank to the right position. The drawback of the bank switches of the US Navy Bombe is that it uses more wire internally. Turing (1942) writes on the subject of the rotor bank design used in the US Navy Bombe: "This method sounds as if it would use up an awful lot of wire, but on second thoughts it does not seem quite so bad. I should say it would use up about six times as much wire as we have in the Jones plugs for a Bombe. It eliminates the need for an independent diagonal board and for commons, and should speed up the plugging-up time very greatly."

3.2 Motor Control

The N-530 Bombe has a three horse power electric main motor, a rewind motor, a motor break assembly, a magnetic clutch and a zero velocity switch. All these parts are controlled by and interacts with the relays in section **B**. The relays are connected to form a Boolean network similar to digital logic gates. The function of the motor control relays has been deduced using a computer simulation.

Apart from starting and stopping the mechanical components of the Bombe, this part of the circuit also has some inputs: The start and stop buttons are connected here, the "hit" signal which stops the Bombe if a possible solution has been found and the "final stop" signal which is activated when the Bombe has finished its run.

Each relay consists of a coil and a number of switches that can either close or open when the relay is energised. In the schematics, each coil is marked with a number and the corresponding switches are marked with the same number followed by a letter. The letter *a* denotes a switch closing when the coil is energised, at the same time the switch marked with the letter *b* opens. *B* switches remain closed while the relay coil is not energised (Electric, 1961).

This forms the basis of the logic circuits used by the US Navy Bombe. For example an AND gate can be built by connecting two switches in series, both switches need to be closed for a signal to pass the switches. Conversely, if two switches are connected in parallel an OR gate is formed.

3.3 Amplifier Chassis

Section **C** is responsible for detecting a possible solution and generating a stop signal to the motor control logic and thyratron chassis. The "primary" and "secondary" rotary switches on the front of the Bombe are connected here. The amplifier chassis implements the hit detector mentioned in section 2.

The primary switch selects on which column of the diagonal board to look for a stop condition. The actual check is implemented with a number of quadruple diode vacuum tubes of model 6AN6. In the schematics these diodes are depicted as a vacuum tube with four plates and a common cathode. This is likely to be the purpose-built four-in-one tube which is mentioned in Burke (2002).

In the schematics one whole and one fourth of a quadruple diode tube are used per diagonal board column since the abridged diagonal board is of size 5 x 5 instead of 26 x 26. In the Bombe there would have been $\lceil 26/4 \rceil = 7$ such tubes per column, giving a total of 182 tubes for all 26 columns. Table 3 has a comprehensive list of the various tubes used in the US Navy Bombe.

During normal operation all diode tubes will have a negative potential of -115 V on all plates. When a stop condition occurs, one or more plates are not reached by the negative potential. This causes the stop signal to be triggered. Desch describes this as a "Rossi circuit"(Desch, 1942). A Rossi circuit can be seen as a rudimentary AND-gate, and each column of the diagonal board is connected to its own Rossi circuit.

This function that the diode circuit is carrying out is called the *cold point test* by Desch (1942). When a test current failed to reach all 26 points of the selected primary column of the diagonal board, the Rossi circuit would generate an output signal, a "stop signal".

3.4 Thyratron Chassis

Section **D**, called the thyratron chassis, serves as an electronic memory. When a "hit" occurs the stop signal is received from the amplifier chassis and the position of the fastest and second fastest wheels are stored with the help of the fast switching action of model 2C4 thyratrons. The motor control circuit will then stop and rewind the Bombe, after which the energised thyratrons are used to find the position where the hit was found. Desch has filed several patents with similar circuits, where a number of thyratrons are used together as an electronic memory in for example an impulse counter scenario (Desch and Mumma, 1951).

In the Bombe schematics there are a number of devices denoted "timers". These are circular commutators similar to those used with the rotor banks, but instead of a Enigma rotor there is an arm which interconnects part of the commutator as it rotates. This is used to generate electrical pulses to various electrical circuits in the Bombe. Since the timers are driven by the same motor and gearbox as for the rotor banks, the electrical signals will automatically be synchronised even if the motor speed would vary.

The thyratron memory is made up of two sets of 26 2C4 thyratrons each where each set can store one digit between 1 and 26 (one letter of the alphabet). When the Bombe is running the two sets of 26 thyratrons will be connected to timers denoted "H" and "F" which indicate at what position the fastest and second fastest rotor is at. When the stop signal arrives from the amplifier chassis the two thyratrons that happen to be connected to the timers at that moment are activated and thus the current position is stored.

The circuit that achieves this requires another five 2C4 thyratrons and other supporting passive circuitry.

3.5 Relay Chassis

Section **E** is the relay logic circuit responsible for checking a "hit" when the Bombe has been stopped. A signal from section **B** and **D** starts the so called *stationary test*. The logic circuit operates two electromechanical stepping switches called *MM1* and *MM2* in the schematics, where MM is short for *Motor Magnet*, to perform the necessary tests. The stepping switches iterate the checking circuit through the 26 nodes each of two columns of the diagonal board, denoted primary and secondary column (Desch, 1942).

When the check is completed, the motor control logic in section **B** is signalled and the Bombe resumes its run.

3.6 Printer Control

If the checking logic finds a hit that passes the tests, the Bombe automatically prints relevant information. The printer is connected with up to 20 26-way cables to the diagonal board. The checking logic, upon a successful test result, activates the printer control circuit which then steps through all 26 leads and prints the state of the diagonal board.

There is a 57 RPM motor and a single revolution clutch which allows for 20 rotary switches to automatically do the above mentioned sequence. The printer logic will activate the single revolution clutch for each row in the stepping sequence.

Four mechanical position indicators are connected to the printer in order to provide information on where in the Bombe run the current stop occurred. The position indicators are located on the back of the Bombe.

When the printout is completed a cam switch triggers a signal which will cause the Bombe to continue.

This part of the schematics is marked **F** in Figure 2.

3.7 Printer Logic

The printer logic is responsible for making the printer output the correct data in the case where a stop condition has occurred and the stationary tests have passed.

If the diagonal board has suitable voltage in a printer cable connected to one of the columns of the diagonal board a latch tube is activated. There are 20 printer connectors which are connected to 20 tubes, and each of these can make the printer produce a mark on the paper on a specific column. There are also four latch tubes which are dedicated to be connected to the position indicators, these tubes will produce a mark on four additional columns on the paper indicating at what rotor position the stop occurred.

The printer logic will activate the single revolution clutch which in turn causes the printer to read all the latch tubes and print a row of numbers. It will then feed the paper strip forward one step. After all 26 rows are scanned a cam switch is triggered which causes the relay logic to stop the print scan.

Desch notes that: "Operator identifies columns on paper tape of printer according to menu letters chosen." (Desch, 1942). This probably means that the operator would simply make a note on the top of the paper with the letters of the connected printer cables.

Below follows an example of what the printer output could have looked like. The letters shown would be added by the operator, the printer could only print numbers.

In this example the machine has stopped at position 26, 26, 1 and 13 and found the following potential steckers: `BF EA KK OO TT XL`.

```
A  B  E  F  K  L  O  T  X

5  6  1  2  11 24 15 20 12   26 26 1 13

E  F  A  B  K  X  O  T  L
```

3.8 Simulation of Basic Operation

The motor control chassis and the relay chassis contains logic implemented with relay circuits as noted in sections 3.2 and 3.5. A computer simulation of the logic has been made with a custom made simulator written in the Python programming language. The connection between the relay coils, relay contacts and external devices such as motors are statically defined in the simulator. The initial state of each relay coil in the simulation is set up to mimic the situation of a stationary Bombe. The simulator iterates through all the relay coils and changes the relay switches corresponding to changes in relay coil state. This iteration is repeated until there are no more changes happening. At this point the simulator is given a stimuli corresponding to an external event of some kind. The stimuli given to the simulator are:

- Operator presses start button
- Zero velocity switch active
- Operator releases start button
- Hit tube activated
- Hit tube inactivated
- Zero velocity switch inactive
- Thyratron chassis signal rewind complete

This simulates what the logic does from the starting of a Bombe, when reaching a stop condition and how a stop is being handled. From the simulation output a sequence of events can be noted.

In Table 2 the sequence of events during basic operation is listed, in the order in which they occur. There are three different event types. "Operator events" are external events generated by the operator. "Relay" events are signals generated within the different relay logic circuits. "Internal signals" are signals from tubes or mechanical switches. "Conditional signals" are dependent on the current test setup.

4 Components

There are a number of components in the schematics that can be identified and sometime the manufacturer and/or model can be identified.

4.1 Connectors

On the detailed schematic drawings there are connectors with varying number of leads. These are blade type connectors of the "Jones" type, still available today.

The connectors labelled with a P or S followed by three digits and possibly something after this. P denotes a plug and S a socket. The digits tells how the leads are organised.

For example, "P-327 AB #51" is a plug of the 300-series with 27 leads and has the number 51 on the Bombe. "AB" means that the plug has an angle bracket mounting.

The following Jones connector models have been identified in the documents: S-310-AB, P-318-CCT, S-318-AB, P-321-AB, P-321-CCT, S-321-AB, P-327-AB, S-327-AB, S-327-CCT, S-333-AB, P-412-AB and S-412-CCT.

There are at least three different power connector models from Hubbell: 7577, 7556 and 7468.

4.2 Relays and Other Electro-Mechanical Components

At least two different types or models of relays are used in the Bombe. These are described as AQA (sometimes HD AQA) and ASO. HD AQA is a "Heavy Duty Quick Acting relay of type A" and ASO is a "Slow Operating relay of type A". A "slow operating" relay has a copper collar added to the coil core. This delays the operation of the relay as well as the release.(Electric, 1961) This is useful in order to ensure synchronisation in a circuit where multiple relays might operate at the same time, such as in the relay logic circuit of the US Navy Bombe.

One relay manufacturer is mentioned: "Automatic Electric", at the time a company based in Chicago, Illinois manufacturing telephony equipment. According to (Electric, 1955), during the second world war "The Company was called on further to cooperate with both Army and Navy authorities in the development and manufacture of many special types of apparatus in the fields of communication and electrical control." It is unclear if Automatic Electric knew about the construction of the US Navy Bombes.

The two stepping switches used in the relay chassis are most likely from Automatic Electric as well.

There are different switches on the front of the Bombe, and some have been identified: The start-stop push button switch is an Allen-Bradley N-1020 two button station. The "Scan" switch is a Mallory model 2001. For switching between four- and three-rotor mode an Automatic Electric key switch model DG-33 is used.

Two different electromechanical counters are present in the schematics: A counter from the Veeder company, and a magnetic counter from Dunco model EC21A.

4.3 Transformers and Regulators

There is an input power regulator from Sola, model 3005.

In order to supply the filament voltage to all the electron tubes a number of transformers were used. Three different models of filament transformers have been identified: Stancor P-6390, Utah 2466 and Thordarson T-74F24.

Event Type	**Description**
Operator	The Bombe is powered on
Relay	The diagonal board is connected to +115 Volts
Relay	The latch pawl holding the rotor banks in place is disengaged
Operator	The “start” button is pressed
Relay	The thyratrons in the thyratron chassis are powered up
Relay	The main motor is started
Relay	The break is released
Internal signal	Zero velocity switch indicates that rotors are spinning
Conditional signal	The Rossi detector finds a stop condition which leads to the “hit tube” generating a stop signal
Relay	Power from the main motor is disconnected
Relay	The break is engaged
Internal signal	The zero velocity switch detects that the rotors have come to a halt
Relay	The diagonal board is connected to -115 Volts
Relay	The clutch is activated, disconnecting the main motor from the motor shaft
Relay	The rewind motor is started
Relay	The break is released, rotors are now rewinding towards the position where the stop condition was found
Internal signal	Thyratrons signal that the correct position has been reached
Relay	The latch pawl is engaged, locking the rotors in place
Relay	The thyratrons in the thyratron chassis are powered off
Relay	The stationary test is started
Relay	Tubes in the amplifier chassis are powered on
Relay	The rewind motor is powered off
Relay	The stepping switch for the primary column is activated
Relay	Stepping switch motor magnets are energised, stepping through rows of the primary and secondary column to carry out the test
Relay	The stationary test is concluded
Conditional signal	If tests passed the printer scan is started
Relay	Tubes in the amplifier chassis are powered off
Relay	The diagonal board is connected to +115 Volts
Relay	The latch pawl is disengaged
Relay	Main motor is started
Relay	The rewind break is disengaged

Table 2: Typical sequence of events in the US Navy Bombe.

4.4 Other Components

There is one semiconductor identified in the whole of the Bombe circuit. It is a selenium rectifier of model 7H12C1 and it is used as a half wave rectifier.

Neon bulbs are used as indicators on the front of the Bombe. They are all from General Electric, 1/4W and are either with or without internal resistor.

4.5 Electron Tubes

There are about 300 identifiable electron tubes in the Bombe as described in the electrical schematics available. See Table 3 for a list of tube model, number and their function in the Bombe.

4.6 Passive Components

Naturally, there are a large number of passive components in the various circuits. It is worth pointing out that the prefix used to denote 1000s of Ohms is M (for mille) instead of k (for kilo) which is practice today. So a resistor of 15000 Ohms is marked as being 15M in the schematics.

Resistors used in the Bombe schematics have the following power rating: 1/4W, 1/2W, 10W, 25W and 50W.

A number of potentiometers are used internally in the Bombe, only one has been identified: Mallory model M5MP.

Not many capacitors have their type written in the schematics. The only one positively identified is a Cornell Dubilier metal-cased Dykanol paper capacitor.

5 Conclusions

It has previously been known what different parts of the US Navy Bombe that existed and what their general function are. By analysing the schematics the authors have been able to verify the functionality and show in more detail how that functionality was implemented.

Partly this was done by reading the schematics, and partly by computer simulations of the Boolean network implemented by the relays.

Currently, the authors do not have the archive reference for the schematic circuit diagrams. This information will hopefully be retrieved in June 2022 and we encourage anyone interested to contact us for this information.

On the whole the US Navy Turing Bombe can be seen as a largely digital machine, and is a fascinating mix of digital and analogue electronics using both relays and tubes, electro-mechanics and pure mechanical components.

During the review process the authors were given access, through one of the reviewers, to a document which is a technical and theoretical report of the N-530 Bombe (Chief of Naval Operations, September 1946). This document details the functionality of the Bombe and by studying this document we can conclude that our analysis of the schematics has been successful. One noteworthy detail that differed is regarding the rotors in the rotor bank. They are numbered 0 to 25 and the digits represent the letters of the alphabet. Our assumption was that 0 represented A, 1 represented B and so on. In reality, 0 represented Z, 1 represented A and so on. This was done for reasons of security. This document is a great source for further research.

A natural next step would be to closely investigate the surviving Bombe and also perhaps reconstruct part of the circuit from the schematics to further understand the operation.

Acknowledgements

The authors would like to thank the reviewers in general for providing suggestions for improvements, and specifically the reviewer who supplied us with further detailed technical documentation on the US Navy Bombe. This material will most likely make further research possible.

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References

Colin B. Burke. 2002. *It Wasn't All Magic: The Early Struggle to Automate Cryptanalysis, 1930s - 1960s*. Center for Cryptologic History, National Security Agency. https://media.defense.gov/2021/Jun/29/2002751411/-1/-1/0/MAGIC.PDF.

Frank Carter. 2008. *The Turing Bombe*. Report No. 4. Bletchley Park Trust, new edition. ISBN: 978-1-906723-03-3.

Model	Type	Description
6Y6G	Beam power tube	There are 24 of these tubes are used for controlling the printer.
2C4	Low power miniature thyratron	There are 57 of these used in the thyratron chassis to remember the rotor position when a stop condition occurs.
2050	Gas tetrode	Two used in total: one to generate the final stop signal when the Bombe has completed the search, and one to relay the stop signal to the thyratron chassis.
6AG7	Pentode	There are 30 pentodes are used in total. 26 of them are used in the amplifier chassis, one is used as an inverter and two are used to control an electro-mechanical latch.
6AN6	Quadruple diode tube	Each tube consists of four diodes with a common cathode. 186 tubes of this model are used in the amplifier chassis.
6X5	Twin diode rectifier	One tube of this model is used as a rectifier.
VR75-30	Voltage regulator Tube	One tube used as a voltage regulator

Table 3: Type and number of electron tubes in the US Navy Bombe.

US Naval Communications Chief of Naval Operations. September 1946. Communications Intelligence Technical Paper 88: Technical and Theoretical Report of N-530 Bombe. [Library of the National Cryptologic Museum, Ft. Meade, Maryland, USA, Archive reference VF042-001.].

Joseph R. Desch and Robert E. Mumma. 1951. Electronic impulse-counting and data-storing circuits. U.S. Patent 2 556 614, June 12 1951.

Joseph R. Desch. 1942. Memo of Present Plans for an Electro-Mechanical Analytical Machine. `http://cryptocellar.org/USBombe/desch.pdf`. [Published online by Frode Weierud in 2000, accessed 16-September-2016].

Magnus Ekhall and Fredrik Hallenberg. 2018. US Navy Cryptanalytic Bombe - A Theory of Operation and Computer Simulation. In *Proceedings of the 1st International Conference on Historical Cryptology HistoCrypt 2018*, pages 103–108. Linköping University Electronic Press, Linköpings universitet.

Automatic Electric. 1955. Pioneers in Communication Techniques. Brochure.

Automatic Electric. 1961. Relays Class B and C Technical Bulletin 961-537. Brochure.

Michael Smith. 2011. *The Bletchley Park Codebreakers*. Biteback Publishing. ISBN: 978-1-849546-23-2.

Dermot Turing and Christopher Andrew. 2020. *The Codebreakers of Bletchley Park: The Secret Intelligence Station that Helped Defeat the Nazis*. Arcturus Publishing.

Alan M. Turing. 1942. Visit to NCR. `http://cryptocellar.org/USBombe/turncr.pdf`. [Published online by Frode Weierud in 2000, accessed 16-September-2016].

Jennifer Wilcox. 2006. *Solving the Enigma: History of the Cryptoanalytic Bombe*. Center for Cryptologic History, NSA.