University of Dundee

HMS Royal Oak 80 Survey (2018-2019)

Turton, Emily; Fitzsimmons, Clare ; Rowland, Chris; Crofts, David ; Kay, Simon ; Hyttinen, Kari

DOI:

[10.20933/100001184](https://doi.org/10.20933/100001184)

Publication date:

2021

Document Version

Publisher's PDF, also known as Version of record

[Link to publication in Discovery Research Portal](#)

Citation for published version (APA):

Turton, E., Fitzsimmons, C., Rowland, C., Crofts, D., Kay, S., Hyttinen, K., Tynkkynen, M., & Wade, B. (2021). *HMS Royal Oak 80 Survey (2018-2019)*. University of Dundee. <https://doi.org/10.20933/100001184>

General rights

Copyright and moral rights for the publications made accessible in Discovery Research Portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from Discovery Research Portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain.
- You may freely distribute the URL identifying the publication in the public portal.

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

REVENGE CLASS BATTLESHIP

HMS ROYAL OAK

80 Years Underwater 1939-2019

HMS ROYAL OAK 80 SURVEY 2018 – 2019 REPORT

Emily Turton, Dr Clare Fitzsimmons,
Professor Chris Rowland, David
Crofts, Simon Kay, Professor Kari
Hytinen, Marjo Tynkkynen, Ben
Wade

ISBN: 1-899837 84 1

DOI: 10.20933/100001184

Copyright Statement

This report and its content were produced under licence from the UK Ministry of Defence. All materials are copyright of the authors except where otherwise acknowledged. All rights reserved.

Any redistribution or reproduction of the content of this report in part or in full, and in any form is prohibited other than the following:

- i. Printing or downloading to a local hard disk for your personal and non-commercial use only, acknowledging this report as the source of the material.
- ii. Copying to other individual third parties for their personal use, acknowledging this report as the source of the material.

This report and its contents may not, except with the express written permission of the copyright holders, be distributed or commercially exploited, nor may it be transmitted or stored in any other website or other form of electronic retrieval system except as described in (i) above.

First published in 2020

© Emily Turton, Ben Wade, Dr Clare Fitzsimmons, David Crofts, Simon Kay, Professor Chris Rowland: 2020

Report to be cited as: Turton *et al* (2020) HMS Royal Oak 80 Survey 2018-2019, Report 2020

1. Executive Summary

In the early hours of 14th October 1939 HMS ROYAL OAK was struck by four torpedoes fired from the U49 whilst at anchor in Scapa Flow. The ship sank within minutes, 835 men and boys were lost. The HMS ROYAL OAK 80 Survey took place between October 2018 and November 2019 under special licence from the Secretary of State for Defence. The survey was self-funded and conducted by professional divers volunteering their time in collaboration with the Royal Navy Northern Diving Group and the Royal Oak Association and academic partners at the University of Dundee and Newcastle University. The purpose of the survey was to document this protected war grave at 80 years underwater, to shed new light on the damage that caused the ship to sink and to raise the profile of the loss of the ship and the sacrifice made by her crew.

HMS ROYAL OAK was a WWI battleship of the dreadnought era. She was built at Devonport Dockyard in Plymouth and commissioned on 1st May 1916 into the First Battle Squadron. She saw her first action at the Battle of Jutland on 31st May 1916 but survived to see service again in WW2. Between the wars she was modified with the addition of torpedo blisters to port and starboard, new bridge structures and modified secondary guns. Post sinking, the four propellers were removed and repurposed by the Admiralty along with anchor chain and anchors. No other commercial salvage has taken place.

In the late 1950s the Orkney County Council (as named then) was approached by the Admiralty to gauge local opinion at their plans to sell the wreck for salvage. Local opposition ultimately protected the wreck. Anecdotal evidence tells us that some small-scale removal of artefacts occurred during the early years of recreational diving. Significant work has also subsequently been conducted by the Ministry of Defence (MOD) to monitor and remove fuel oil from the ship.

In the 1980s the Royal Navy began a programme of ceremonial diving to change a White Ensign, which continues to this day. Recreational diving was limited by the local harbour authority at a similar time, and in 2002 she became a controlled site under the Protection of Military Remains Act. Diving can now only take place under special licence from the Ministry of Defence, which has ensured the relative integrity of the site. She is the most complete example of a dreadnought battleship existing underwater and was sunk in full fighting condition.

The ROYAL OAK 80 survey focussed on in-water survey techniques to gather high resolution video, still photographs and 3D photogrammetry data in a bid to record the site as it is today, digitally preserving the ship in its current state. Remote survey techniques were used to provide a bathymetrically accurate model of the wreck and identify the location and extent of outlying debris or objects likely to be from the ship.

The site is unique. A near intact dreadnought battleship, she lies in approximately 30m of water, upside down. A 45° angle allows access to the portside deck. The survey describes the site in four main sections: Port/Deck side, Hull, Starboard side, and Outlying targets. Further subdivision was utilised to better manage survey activity, data recording and cataloguing.

Specialists in explosive effects and historic weaponry contributed analyses of the torpedo damage, exposed munitions and firepower present on the ship. A major new finding of this survey being the proximity of torpedo damage to her magazines. The pristine site that is ROYAL OAK today was only inches away from catastrophic explosion, similar to that suffered by her WW1 contemporary VANGUARD. Significant artefacts and architectural features were also discovered, described, and documented. Marine life was recorded to capture the natural heritage of the site.

Evidence of salvage was present but at only a small scale. Structurally, her collapse has not been as pronounced as anticipated by earlier surveys. The notable change from the 2006 survey is found at the bow. Hull plating that was observed in the multibeam data to be hanging over the starboard side of the first torpedo impact is now missing, and is presumed to be amongst the debris on the seabed below.

Given this relatively pristine state, HMS ROYAL OAK should continue to be treated as a site of huge historical importance. Notwithstanding her war grave status, she also has substantial relevance to current maritime conservation efforts relating to the removal of oil from shipwrecks. She is a time capsule into WWI naval architecture and an underwater monument to the sacrifice made by her crew.

Methods used by the ROYAL OAK 80 survey team have been developed from earlier survey work and represent a significant achievement in shipwreck visualisation and the teamwork required to succeed. The survey team also made significant contributions to the 80th anniversary commemorations, displaying outputs at community events across Orkney. Survey and outreach methods were highly effective and would benefit future wreck site surveys and wreck management.

2. Table of Contents

1.	Executive Summary	3
2.	Table of Contents	5
3.	Table of Figures	7
1.	Introduction	18
1.1	The Vessel	18
1.1.1	Anatomy of HMS ROYAL OAK	19
1.1.2	Service History	23
1.1.3	Sinking	24
1.2	Post Sinking: HMS ROYAL OAK the Shipwreck	25
1.2.1	Salvage, Diving and Surveys	26
1.2.2	HMS ROYAL OAK Community	31
1.3	Rationale for project	31
1.4	The Project	32
2.	Survey Methods	32
2.1	Overview	32
2.2	Multibeam Sonar	33
2.3	Sidescan Sonar Surveys	34
2.4	Diving Methods	35
2.5	Visualisation Methods	35
2.5.1	Stills Photography	36
2.5.2	Underwater Artist	36
2.5.3	Videography	38
2.5.4	3D Visualisation	39
2.5.5	Marine Ecology	41
3.	Results and Discussion	41
3.1	Site Description - Overview	41
3.1.1	Deck/Portside Section	43
3.1.2	Starboard Side	116
3.1.3	Top of the Hull	128
3.1.4	Gunnery and Fire Control	133
3.1.5	Exposed Munitions	164
3.1.6	Torpedo Damage	169
3.1.7	Outlying Targets	180

3.1.8	ROYAL OAK's Pinnaces.....	184
3.1.9	Marine life.....	191
4.	Discussion	201
5.	Conclusions.....	203
5.1	Outputs.....	205
6.	Recommendations for Future Work	206
7.	Sources & Bibliography	207
8.	Annex	208
8.1	Scuttle Arrangement.....	208
8.1.1	Port Side Scuttle Arrangement	208
8.1.2	Starboard Side Scuttle Arrangement.....	212
8.2	Outlying Acoustic Target Contact Report	216
8.3	Survey Report 1950	217
8.4	ADUS Survey Report 2006	219

3. Table of Figures

Figure 1: HMS ROYAL OAK in 1916, © Orkney Library & Archive (OLA).....	18
Figure 2: HMS ROYAL OAK in 1937, © OLA.....	19
Figure 3: ROYAL OAK Ship's Profile	20
Figure 4: Cross section of ship's plans detailing deck levels.....	20
Figure 5: Ship's plan detailing fuel oil storage.....	21
Figure 6: Ship's Plan detailing A & B-Turrets and associated systems.....	22
Figure 7: Archive images of A & B-Turrets and X & Y-Turrets, © IWM Q 017919 & Q 018117	22
Figure 8: The torpedo tubes were mounted on the Upper Deck	23
Figure 9: U-47's route into Scapa Flow and the attack on HMS ROYAL OAK	24
Figure 10: Gunter Prien	25
Figure 11: U-47	25
Figure 12: Extract taken from archive document ADM116-5790, The loss of HMS ROYAL OAK and the defences of Scapa	26
Figure 13: Recovered upper side rudder from one of the torpedoes that struck HMS ROYAL OAK	26
Figure 14: Herbert Bullen on the left and Sandy Robertson on the right.....	26
Figure 15: Extract from the Nation Archive - ADM116-5790 Main Fleet Base Scapa Flow, inception, development and history	27
Figure 16: Extract from a WWII navigation chart showing the radar station in place on the wreck and a diagram of the caisson construction	27
Figure 17: Archive images showing salvage caissons in their original purpose, as air locks. © OLA	28
Figure 18: 1950 Survey diagram showing torpedo damage to the starboard side.....	28
Figure 19: Left: Extract from the Norther Wing, Tuesday 3rd December 1957.....	29
Figure 20: The remains of one of the torpedoes that hit HMS ROYAL OAK.....	29
Figure 21: 2006 Multibeam sonar image showing a wide view of the port side of the wreck.	33
Figure 22: Wrecksight image: screen capture.....	34
Figure 23: Printed multibeam wreck image with annotations, on board MV Huskylan.....	34
Figure 24: HMS ROYAL OAK - a painting by Caroline Appleyard.....	37
Figure 25: From left to right: Underwater artist Caroline Appleyard, Royal Oak Association member Andy Smith and Royal Oak Association Chair Gareth Derbyshire aboard Dive Vessel Huskylan at the ROYAL OAK buoy. The underwater paintings show the stern of the wreck flying the 79th anniversary White Ensign and the portside steam pinnace which rests on the seabed just aft of the bridge.....	37
Figure 26: Caroline painting a ship's paravane on the left and the portside pinnace on the right.....	38
Figure 27: Caroline returning from a dive on the left, and with Royal Oak Association chair Gareth Derbyshire on the right with paintings of a scuttle in the Admiral's Sleeping Cabin, a bedframe is inside, and a shoe sole lying on the seabed.....	38
Figure 28: Divers capturing video for photogrammetry.....	39
Figure 29: Wide view of combined Multibeam and photogrammetry integrated data	40
Figure 30: A-Turret photogrammetry integrated with multibeam sonar data	41
Figure 31: Multibeam image of the stern on HMS ROYAL OAK	42
Figure 32: Multibeam visualisations of the Deck/Portside, Starboard side and Top of Hull sections that structure this report	42
Figure 33: Subdivision of Deck/Port Side	43
Figure 34: Forward Section	43
Figure 35: Multibeam image of the bow showing the starboard edge clear of the seabed	44

Figure 36: The upturned bow showing jackstaff and chain	44
Figure 37: The anchor chain runs out from the bow	45
Figure 38: Ship's plan detailing cable holder and anchors.	46
Figure 39: Foredeck showing anchoring equipment. This archive image also shows the ship's crew exercising, note the wave break in the bottom of the image which deflected wave water from the bow away from structures further aft.....	46
Figure 40: Anchor chain hanging from the deck.....	47
Figure 41: Blake Bottle Screw Slip, used to secure the anchor at the Hawsepipe.....	47
Figure 42: Under the deck the chain drapes to the seabed secured from a Blake slip. Teak decking is visible and in the background the Sheet Cable Holder is illuminated.....	48
Figure 43: Sheet Cable Holder and Chain.....	48
Figure 44: Ship's plans extract detailing wave break, hawser reels and ventilation.....	49
Figure 45: Multibeam image of the bow section with 3D Photogrammetry overlay of A-turret	50
Figure 46: 3D Photogrammetry Image of A-turret	50
Figure 47: A-turret, front view with both apertures visible and the fallen barrels buried in the seabed below	51
Figure 48: A-turret gun breeches and rammers	51
Figure 49: A-turret open breech door on left-hand gun and view of both breeches clearly showing the rammers protruding	52
Figure 50: Turret Periscope.....	52
Figure 51: The smaller of two paravanes on the starboard side with the heel of the lifting derrick in the foreground	53
Figure 52: Ship's plan profile showing paravane stowage	53
Figure 53: Aft section of the portside paravane lies on the seabed adjacent B-turret.	54
Figure 54: Video screen grabs of the forward section of the portside paravane and the heel of the portside paravane lifting derrick.....	54
Figure 55: B-turret gun breeches. The right- hand gun rammer is in the left-hand side of the image and access to the officer's cabinet is in the top of the image.....	55
Figure 56: B-turret Officer's Cabinet	55
Figure 57: Aerial plan image of the aft part of the gun turret	56
Figure 58: Cross section plan image of the officer's cabinet	56
Figure 59: Archive image of the crew of HMS ROYAL OAK with a Carly raft in the foreground. ©IWM Q 18082	57
Figure 60: The remains of a Carly raft lie alongside the forward barrel of B-turret	57
Figure 61: Spoons from the Petty Officers Pantry	58
Figure 62: Archive image showing the experimental double torpedo tube door on HMS ROYAL OAK	58
Figure 63: Video screen grab of the portside torpedo doors.....	58
Figure 64: Profile view of the Deck/Port Side Midships section	59
Figure 65: Multibeam image of the Deck/Port Side Section	60
Figure 66: Plan image detailing visible open deck space at Shelter Deck level.....	60
Figure 67: Bulkhead/Wardroom lantern. In addition to the carrying handle these half hexagonal lamps would have a flat back fitted with a flat faced hook for attached to a wall fitting	61
Figure 68: Lamps have fallen to the seabed from the Lamp Room	61
Figure 69: Looking up into the Lamp Room	62
Figure 70: A pair of leather boots	62
Figure 71: WWI sailor aboard HMS ROYAL OAK wearing a similar pair of leather boots. In the background are	

two Carly rafts and the sailor also wears a gas mask. ©IWM Q 17937.....	63
Figure 72: Plan showing location of Lamp Room, Boatswain's Ready Use Store and Skylight.....	63
Figure 73: Scuttles and Armoured Shutters.....	64
Figure 74: The three visible levels of the armoured conning tower.....	64
Figure 75: The 3-pdr gun in the foreground with a diver illuminating the 0.50 quad machine gun in the background.....	65
Figure 76: Quad 0.50 Vickers MkIII Machine Gun.....	65
Figure 77: 2001 image of the Quad 0.50 Vickers MkIII Machine Gun by Peter Rowlands.....	66
Figure 78: Archive image of the Quad 0.50 Vickers MkIII Machine Gun. ©IWM A 1249.....	66
Figure 79: Ship's Badge mounted on Rope Drums.....	67
Figure 80: Labelled multibeam image of the mast and bridge structures.....	67
Figure 81: Plan image of the Foremast.....	68
Figure 82: 3D Photogrammetry image of the Spotting Top. The severed port side mast strut is labelled.....	69
Figure 83: A Navigation Lamp lies in the wreckage of the Bridge.....	69
Figure 84: Auxiliary Compass on HMS ROYAL OAK and an example aboard HMS PRINCE OF WALES in WWII. ©IWM A 3901.....	70
Figure 85: A Kelvin Ball lies in the wreckage at the foremast of HMS ROYAL OAK and archive example aboard HMS ROEBUCK in Scapa Flow during WWII. The brass compass hood in the archive image is similar to the one seen on the seabed ©IWM A 18037.....	71
Figure 86: The Spotting Top and HACS Director.....	71
Figure 87: 3D Photogrammetry image of the Spotting Top.....	72
Figure 88: Aerial image of the Spotting Top looking aft. The port side yard arm is in place top centre. In the right of the image is the remains of the 6-inch port side director and platform.....	72
Figure 89: View of the Spotting Top looking forwards with windows illuminated.....	73
Figure 90: Looking into the port wing of the Spotting Top.....	73
Figure 91: The HACS Director sits on top of the Spotting Top and was one of the interwar modifications. It formed part of the.....	74
Figure 92: The forward part of the Spotting Top rests on the seabed. The canopy (roof) has decayed and is mostly absent offering access to the equipment inside.....	74
Figure 93: The gun ready panel in the Spotting Top. This device has a light for each barrel of the four turrets and provided information to the Spotting Top as to when enough guns were ready to fire.....	75
Figure 94: Spotting Top Fire Control Instruments. Headphones remain visible in the silt.....	76
Figure 95: An "Aid to Spotter" is lying partially buried in the forward spotting top.....	77
Figure 96: Looking into the port side 6-inch Director. The roof has detached from the main structure. The door into the director is on the upper side and is locked with a padlock.....	78
Figure 97: Images of the Spotting Top and HACS Director from 1999.....	79
Figure 98: 2019 image of the Spotting Top and HACS Director.....	79
Figure 99: Glass Insulating Rods made by Pyrex.....	80
Figure 100: Glass insulating rods on the bridge of HMS RESOLUTION in 1933. ©IWM Q 65629.....	80
Figure 101: A smoking pipe lies on the seabed.....	81
Figure 102: Overhead 3D image of the bow section and boiler of the pinnacle.....	82
Figure 103: Pinnacle looking aft from the bow. The cowl and gun mount are visible.....	82
Figure 104: Two images of the pinnacle bow taken 20 years apart.....	83
Figure 105: The rudder from the pinnacle is buried in the seabed surrounded by associated support brackets.....	83
Figure 106: Caisson sections 2 & 3.....	84

Figure 107: Main Mast HACS range finder and pinnacle window	84
Figure 108: Annotated 3D Photogrammetry overview of the port side midships section.....	85
Figure 109: Stern aspect of the port side midships section	86
Figure 110: Items from unidentified wreckage including an alloy cabinet and electrical items.....	86
Figure 111: Profile image showing funnel, Pom Pom Gun and Searchlights.....	87
Figure 112: Octuple Pom Pom Gun and Ammunition Boxes	88
Figure 113: A Gas Mask.....	88
Figure 114: Plan image of the aft Shelter Deck.....	89
Figure 115: The Aft Shelter Deck of HMS ROYAL OAK.....	90
Figure 116: The transom of the twin-screw motorboat. Both rudders stand upright but the propellers.....	90
Figure 117: The spare anchor lies on the seabed.....	91
Figure 118: Boat Cradle. The cable hanging through the frame has a light fitting on the other end.....	91
Figure 119: A light fitting hangs on the boat cradle. How it got there is a mystery	92
Figure 120: A Ready Ammunition Box.....	92
Figure 121: A Pan Yan Pickle jar is buried in the seabed, just the lid is visible.....	93
Figure 122: Plates and glassware have fallen to the seabed.....	94
Figure 123: Looking up into the Wardroom Pantry.....	95
Figure 124: Plan showing the location of the Wardroom and Gunroom Pantries.....	95
Figure 125: Shaving Soap Bottles.....	96
Figure 126: Used Small Arms Ammunition.....	96
Figure 127: Access to the aft bulkhead of the Wardroom is between the Sea Crane base and X-Turret.....	97
Figure 128: A 4-inch shell lies under the ship	97
Figure 129: The remains of a double bass and bow lie on the seabed fallen from the Wardroom	98
Figure 130: The Shelter Deck, Forecastle Deck and Upper Deck.....	98
Figure 131: The two port side anti-aircraft guns	99
Figure 132: Divers filming the wreck of HMS ROYAL OAK. The companionway is visible with decayed holes in the bulkhead	99
Figure 133: An oval scuttle in the companionway.....	100
Figure 134: A huge dough mixer in the bakery.....	100
Figure 135: A Belfast style sink in the Bakery.....	101
Figure 136: External light fittings in the Companionway	101
Figure 137: The Warrant Officer's Pantry. The scuttle has decayed and fallen into the space	102
Figure 138: The second port side paravane.....	102
Figure 139: The companionway anchor shown alongside an archive image of HMS RESOLUTION. ©IWM Q 65630.....	103
Figure 140: Casemate Number 1	104
Figure 141: Casemate Number 2	104
Figure 142: Casemate Number 3	105
Figure 143: Casemate Number 4	105
Figure 144: Casemate Number 5	106
Figure 145: Casemate Number 6.....	106
Figure 146: Stern Section	107
Figure 147: Multibeam image of the stern	107
Figure 148: The stern of HMS ROYAL OAK	108
Figure 149: Stern Scuttles – Port side.....	108
Figure 150: Port Side Stern Accommodation Ladder	109

Figure 151: Archive images showing port side stern accommodation ladder	109
Figure 152: Archive image of 15- inch shell handling detailing oil lamp and electric cage light. ©IWM Q 17903	109
Figure 153: Oil Lamp base at Y-Turret	110
Figure 154: Oil Lamp at X-Turret.....	110
Figure 155: Electric light in the Officer's Cabinet of the turret, missing its brass cage	110
Figure 156: 3D Photogrammetry image of Y-turret. The barrel of the right-hand gun is clearly visible protruding from the.....	111
Figure 157: Firing Trigger	112
Figure 158: The breech of the left-hand gun at Y-Turret	112
Figure 159: A 6-Pdr Sub Calibre Gun lies on the gun house roof of Y-Turret.....	113
Figure 160: Breech end view of the 6-Pdr sub calibre gun at Y-Turret. The 15-inch gun is visible in the background	113
Figure 161: Catapult at X-Turret	114
Figure 162: X-Turret Range Finder atop the Catapult	114
Figure 163: X-Turret Range Finder.....	115
Figure 164: Two Divers Illuminate X-Turret	115
Figure 165: Breech Operating Lever. It opens and closes the breech of the gun via the hydraulic power mechanism.....	116
Figure 166: The Starboard Side.....	116
Figure 167: The forefoot of HMS ROYAL OAK rests on the seabed with paravane skeg visible.....	117
Figure 168: 3D Multibeam sonar overlaid with photogrammetry.....	117
Figure 169: Scuttles for Chief Petty Officer's Toilet Cubicles.	118
Figure 170: Engine Room Artificer's Pantry	119
Figure 171: A cup and glass bottle lie on the seabed. The Royal Navy Crown emblem is visible of the cup and the deck.....	119
Figure 172: Royal Navy messware, glassware and a tile have fallen from the ERA's Pantry.....	120
Figure 173: A glass fruit bowl lies on the seabed at the bow.....	120
Figure 174: Plan image of the Sick Bay.....	121
Figure 175: Medicine bottles from the Sick Bay	122
Figure 176: The Isolation Ward Porthole/Scuttle	123
Figure 177: Video screen grab detailing seabed scouring.....	124
Figure 178: A closed scuttle on the Middle Deck at the stern. This space was the Warrant Supply Officer's Office.	124
Figure 179: View of the Admiral's bedframe from scuttle No 5	125
Figure 180: View of the Admiral's Sleeping Cabin from scuttle No 6	125
Figure 181: A telephone is visible in Cabin No 5 designated for the Medical Officer. The right-hand image shows what is.....	126
Figure 182: The Admiral of HMS QUEEN ELIZABETH in his cabin in 1942.	126
Figure 183: Admiral of HMS BELFAST in his cabin in Scapa Flow 1943. Examples of a curtain pole and ink blotter are present. The object behind his right shoulder is a rack containing smoking pipes. ©IWM A 21758	127
Figure 184: A Chinese soup spoon lies on the seabed	127
Figure 185: The remains of the head of a banjo with tuning pegs visible.....	128
Figure 186: Decorative brass ventilation fitting.....	128
Figure 187 Multibeam image of the hull of HMS ROYAL OAK, viewed from astern	129

Figure 188: The Rudder	130
Figure 189: Outer Portside A-Frame Bucket	130
Figure 190: The recovery of the 79th Anniversary Ensign on the left and the stowing of the 80th Anniversary Ensign	131
Figure 191: Plan image detailing torpedo bulges in blue and new bilge keel in red	131
Figure 192: Multibeam image detailing torpedo bulges and bilge keels.....	132
Figure 193: A hot tap valve on the hull of HMS ROYAL OAK	132
Figure 194: 3D Photogrammetry overlay of the four 15-inch gun turrets.....	133
Figure 195: HMS ROYAL OAK as modernised in 1939	134
Figure 196: HMS ROYAL OAK as she would have looked on 14th October 1939. ©IWM FL 12252.....	135
Figure 197: Control Top and HACS Director.....	135
Figure 198: 15-inch and port 6-inch Directors under the Control Top.....	136
Figure 199: Gun director on tripod mounting.....	136
Figure 200: Diagram of an Aloft Director	137
Figure 201: Diagram of an Armoured Director Tower.....	137
Figure 202: View of the inside of the Port 6-inch Director.....	138
Figure 203: ROYAL SOVEREIGN (in 1917) showing: D 15" directors, 2d P&S 6" directors (later moved to foremast on ROYAL OAK),	138
Figure 204: Dreyer Fire Control Table	139
Figure 205: Dumaresq Mark VIII from BR 1535 Handbook on Minor Fire Control Instruments 1946	141
Figure 206: Dumaresq from HMS VANGUARD housed at Stromness Museum.....	141
Figure 207: Control Top HMS REVENGE. ©IWM A 1510	142
Figure 208: Forward end of the Control (Spotting) Top.....	143
Figure 209: Bearing Indicator with Periscope and drawing of bearing indicator (courtesy dreadnoughtproject.org).....	144
Figure 210: Bearing Indicator and drawing of bearing indicator (courtesy dreadnoughtproject.org)	144
Figure 211: A Gun Ready Board in the Spotting Top	145
Figure 212: Spotting Top Fire Control Instruments	146
Figure 213: Training Receiver on the left and Training Receiver Mechanism, the red cylinders are the receiver motors	146
Figure 214: Minor fire control instruments for relaying observations data between positions.....	147
Figure 215: A-Turret 15-inch Gun Breeches.....	148
Figure 216: A-turret right-hand elevating mass (gun barrel, slide, cradle, loading rammer and recoil system)	149
Figure 217: The gun loading cage carries ammunition from working chamber to gun.....	149
Figure 218: 15-inch Mk1 Gun Mounting (Longitudinal Section).....	150
Figure 219: Gun house plan view	151
Figure 220: Officer's Cabinet at rear of gun house with range finder on roof.....	151
Figure 221: Central sight position Y-turret. Right-hand gun is in its correct position, left-hand gun has fallen to the seabed.....	152
Figure 222: Diagram of an Elevation Receiver on the left and Gun Layers Position (front right of gun house) on the right	152
Figure 223: Officer's Cabinet.....	153
Figure 224: Kilroy's model turret training indicator	153
Figure 225: Sub calibre 6-pdr gun.....	154
Figure 226: Drawing of sub calibre gun.....	154

Figure 227: Sub calibre 6-pdr stowage.....	155
Figure 228: Loading a 6-inch gun. ©IWM Q 18005	155
Figure 229: 6-inch Pedestal Mk IX Mounting	156
Figure 230: 6-inch casemate gun.....	156
Figure 231: HACS on spotting top - HMS REVENGE. ©IWM A 1513	157
Figure 232: Spotting top HACS director	157
Figure 233: Remains of HACS director on Main Mast	158
Figure 234: Main Mast HACS director and range finder	158
Figure 235: Twin 4-inch anti-aircraft gun with fuze setter labelled.....	159
Figure 236: Octuple 2pdr (40mm) pom pom	159
Figure 237: Pom Pom mount	160
Figure 238: Pom Pom Barrels.....	160
Figure 239: Quad .50 Vickers machine gun. ©IWM A 1249	161
Figure 240: Quad .50 Vickers machine gun on HMS ROYAL OAK	161
Figure 241: 3-pdr gun.....	162
Figure 242: The bow of HMS ROYAL OAK in drydock - her paravane skag and chains clearly visible.....	162
Figure 243: Example of a paravane and towing arrangement.....	163
Figure 244: Exposed 4-inch ammunition stored on the Shelter Deck	164
Figure 245: Deck house containing 4-inch ammunition and location of the 4-inch anti-aircraft guns	165
Figure 246: Exposed 4-inch ammunition magazine exposed in the 2nd torpedo damage hole.....	166
Figure 247: Location of the G7e/T2 torpedo	167
Figure 248: Images of the G7e/T2 Torpedo war head, battery bank and remains of the tail with queen scallop dredge	167
Figure 249: 3D Photogrammetry of the G7e/T2 Torpedo. It shows the warhead, battery bank and tail and the remains of the queen scallop dredge	168
Figure 250: Small Arms Ammunition	168
Figure 251: U-47's plot of the attack.....	171
Figure 252: Hold Deck plan showing the 4-inch HA QF Magazine and Cold Room at frame 27, breached by torpedo hit #2, and the aviation fuel tank destroyed by the torpedo hit #1 at frame 10. The 4" HA QF magazine is adjacent to the 15" Shell Room and Magazine on the deck above. This view clearly illustrates how close the torpedo hit #2 came to causing a catastrophic magazine explosion.....	172
Figure 253: Torpedo Damage & Flooding, torpedo hits number 1 & 2.....	173
Figure 254: Cross sections of HMS ROYAL OAK's plans at frames 144 and 180, close to the locations of the third and fourth torpedo hits. These views of the ships layout clearly show the torpedo protection compartments, fuel bunkers, longitudinal bulkheads and electric hydraulic power companionway through the boiler room.....	174
Figure 255: Torpedo Damage and Flooding, torpedo hits number 3 & 4	176
Figure 256: Example Tripod	181
Figure 257: Mooring Buoy.....	181
Figure 258: Discarded port inner A-frame bracket.....	182
Figure 259: 3D model and image of the severed end of the possible mast strut.....	182
Figure 260: Side Scan image of targets 4 & 5.....	183
Figure 261: 3D Photogrammetry of target 5 and image of voice pipes	183
Figure 262: Brass Railings.....	183
Figure 263: A Royal Navy Steam Pinnace	184
Figure 264: One of ROYAL OAK's Two Steam Pinnaces	184

Figure 265: a) Royal Navy Pinnace b) Side scan sonar image overlain with outline of a pinnace (Shiptime 2017)	186
Figure 266: Photogrammetric image of ROYAL OAK's midships section, showing pinnace location (left), and close up of pinnace within the imagery (right)	187
Figure 267: A-C Photographs of ROYAL OAK pinnace at midships section, showing bow and funnel; D Propeller	188
Figure 268: Pinnace from starboard side	188
Figure 269: Pinnace from port side highlighting stern damage	188
Figure 270: Pinnace from starboard side highlighting boiler, engine and damaged stern	188
Figure 271: Pinnace Bow, looking aft	188
Figure 272: Photographs of ROYAL OAK pinnace WSW of main wreck, showing (top to bottom) bow, helm, compass and propeller	189
Figure 273: Photographs of ROYAL OAK pinnace WSW of main wreck, showing (top to bottom) bow with cleat and distinctive lattice structure, and hatch with internal lattice structure; engine room gauges; remains of the transom and stern latticework and a decorative dolphin	190
Figure 275: Summary of residual (magenta) and tidal (red) currents (note different scales), from Edwards 2017 SSF ECE Scapa Flow Estimates for SEPA (https://www.sepa.org.uk/media/320796/1157275_ece_estimates.pdf)	191
Figure 276: Complex community on top of ROYAL OAK in summer. From <i>Ulva sp.</i> , <i>Saccarina sp.</i> , <i>Asparagopsis sp.</i> , to <i>Aplysia sp.</i> and some <i>Metridium sp.</i> where space allows	193
Figure 277: Moving down the hull of ROYAL OAK from ~8-18m species of red algae dominate. Plumose anemones are common, starfish, tunicates and dead man's fingers are present	194
Figure 278: Under the hull and down the teak decking from ~18m to the seabed, faunal turfs and filter feeders cover the structure. Starfish, urchins, crustacea and fish are found	195
Figure 279: On structures near the seabed rich faunal turfs are observed and individual animals are more easily observed. From top left to bottom right: urchins and starfish; cod, featherstars, velvet swimming crab; tunicates and Devonshire cup coral; hydroids, sponges, coralline algae; edible crab, sunstar, hydroids; barnacles and bryzoans; and much more in every picture	196
Figure 280: ROYAL OAK within Scapa bay, illustrating scour patterns with both tidal and drift directions indicated	196
Figure 281: Finer sediment and examples of individuals colonising the smallest of available hard substrate, further	197
Figure 282: Courser sediment and examples of mussel/brittlestar communitites formed below the shelter of the bow	197
Figure 283: Shelter is provided in softer sediment by artefacts from the wreck. Whelk eggs are laid on a wooden davit, barnacles encrust a gas lamp as crab shelter under a gun barrel, anemones and barnacles cover a bottle, and even rope, more likely from salvage, has become home to some	198
Figure 284: Top to bottom: sea lemon and eggs; scallops and whelk eggs; ballan wrasse and blenny (smaller non-commercial species); cod and ling (commercial species); and larger visitors orca and spider crab	199
Figure 285: Top to bottom: Laying the ensign in remembrance and after two weeks; Ensign the following year; Plumose anemone and velvet swimming crab in their new homes	200
Figure 286: Fallen Oak Documentary	205
Figure 287: VR experience	206

Acknowledgements

Our thanks go to everyone who supported this project, to those who gave their time and expertise freely we are forever in your debt. Together we have helped to raise the profile of HMS ROYAL OAK so that she will continue to be remembered now, and into the future.

We would like to offer our specific thanks to:

Remote Survey: Kevin Heath of Sula Diving for sidescan sonar data and ADUS for Multibeam sonar data

Dive Team: Emily Turton, Ben Wade, Marjo Tynkkynen, Clare Fitzsimmons, Kari Hyttinen, Chris Rowland, Kieran Hatton, Jen Smith (JS), Bob Anderson, Immi Wallin, David Crofts, Simon Kay, Paul Toomer, Paul Haynes, Greg Booth, Gary Petrie, Rod Macdonald, Duncan McGregor, Nick Butcher (NB), Dennis Vessey, Rob Wetherall, Diane Stanning, Brian Burnett, Dave Gration, James Spence, Alex Warszinsky, Tim Nottage and Caroline Appleyard

Surface and Drone Imagery: Alice Watterson, Kieran Baxter and Chris Housley

Photography: Marjo Tynkkynen (MT), Bob Anderson (BA/RPA), Kieran Hatton (KJH), Simon Kay (SK). All images contain photographer's initials for identification

Underwater Videography: Immi Wallin (IW), Tim Nottage (TN), Kari Hyttinen (KH)

Photogrammetry: Professor Kari Hyttinen (KH) and Professor Chris Rowland (CR), University of Dundee, Dr Clare Fitzsimmons (CF), Newcastle University, Brian Burnett, Dave Gration and Ben Wade (BW)

Underwater Artist: Caroline Appleyard

Subject Matter Experts: Simon Kay (Gun Systems), Clare Fitzsimmons (Marine Biology) and David Crofts (Munitions & Explosives)

Archive & Wreck Research: Kevin Heath

Academic Partners: University of Dundee and Newcastle University

Our specific thanks also go to: Gareth Derbyshire and the HMS Royal Oak Association, Lt Cdr Lee Vessey, the Ministry of Defence, The Royal Navy, Orkney Marine Services, the Royal Navy Northern Diving Group, BAE Systems and the National Maritime Museum, Naismi Flett

Dedication: Our special gratitude must go to the late Johnnie Meil – thank you for the stories

Image Copyright

All underwater photographs, 3D photogrammetry images, video screen grabs and sidescan sonar images are copyright HMS ROYAL OAK 80 Survey and the individual image taker. No images may be reproduced without permission. Permission can be sought by contacting the licence holders E. Turton or B. Wade.

The ship's plans and gun plans are re-produced with kind permission from:
The National Maritime Museum, Greenwich, London
BAE Systems, Barrow in Furness

Purpose of Report

The purpose of this report is to disseminate the information gathered by the HMS ROYAL OAK 80 Survey. This survey is the most comprehensive conducted to date on HMS ROYAL OAK and the imagery gathered brings the ship to the surface for non-divers and future generations. The report describes HMS ROYAL OAK, her construction, service history and loss. A detailed description of the survey design and methodology are included. A complete and illustrated description of the wreck site is provided, complemented by description and photography of the marine life legacy of this relatively undisturbed wreck site. Munitions experts were part of the survey team and have provided a forensic explanation of the torpedo damage which caused the loss of the ship.

1. Introduction

In the early hours of 14th October 1939 HMS ROYAL OAK, a dreadnought battleship of the Royal Navy anchored in Scapa Flow, Orkney, sank. Of the 1259 sailors aboard only 424 survived. The ship was hit by four torpedoes fired from U-47 and sank in approximately 10 minutes. 835 sailors perished.

The HMS ROYAL OAK 80 Survey was conducted between October 2018 and November 2019 under special licence from the Secretary of State for Defence. The survey used innovative visualisation techniques combining multibeam sonar and 3D photogrammetry to create bathymetrically accurate high-definition 3D imagery of the site. Sidescan sonar survey identified outlying targets for subsequent diving. Extensive stills photography captured both large scale architectural features of the ship and the smaller scale artefacts relating to life aboard and the ship's crew. Working closely with the Royal Navy Northern Diving Group, the 79th and 80th anniversary changing of the White Ensign on the ship were documented as part of the project. The survey also gathered underwater video footage of the ship, and surface footage of the team throughout the survey process. Key figures and personalities in the ROYAL OAK community were interviewed and the contributions of this project to 80th anniversary commemorations documented.

The survey was self-funded and conducted by volunteer professional divers. The purpose of the survey was to document this protected war grave at 80 years underwater, to shed new light on the damage that caused the ship to sink and to raise the profile of the loss of the ship and the sacrifice made by her crew. The purpose of this report is to disseminate the information gathered by the HMS ROYAL OAK 80 Survey for the historical record, non-divers, and future generations, in memory of those lost in the sinking of this great ship.

1.1 The Vessel

HMS ROYAL OAK was a World War 1 (WWI) Revenge-class battleship of the dreadnought era. Commissioned into service in 1916 she survived WWI and was heavily modified between the wars. She was the eighth Royal Navy vessel to bear the name ROYAL OAK, replacing a pre-dreadnought scrapped in 1914, and was named after the oak tree in which Charles II hid, following his defeat at the 1651 Battle of Worcester.

Figure 1: HMS ROYAL OAK in 1916, © Orkney Library & Archive (OLA)

Figure 2: HMS ROYAL OAK in 1937, © OLA

1.1.1 Anatomy of HMS ROYAL OAK

HMS ROYAL OAK was built between 1914 and 1916 at the Devonport dockyard in Plymouth. Launched a decade after HMS DREADNOUGHT, she belonged to a new super-dreadnought era. Ships of the Queen Elizabeth and Revenge classes sacrificed the midships turret of their predecessors, freeing weight and volume for larger, oil-fired boilers. They introduced a further step-change in armament, speed and protection; although armour focussed on lateral strikes, making them vulnerable to vertical attack and lack of underwater protection, was an acknowledged weakness of pre-WWI designs that originated before widespread use of torpedoes.

After surviving WW1, the ship underwent a series of modifications between 1922 and 1936. The most extensive of these was the addition of large torpedo blisters and new bilge keels to port and starboard. These increased the ship's beam by 4 metres and, due to increased buoyancy, reduced her draught to 9 metres. The ancillary guns aboard the ship were upgraded to reflect the increased threat from the air as were her anti-aircraft defences with the addition of High Angle Control Systems (HACS) to both masts. The ship's four original 21" submerged torpedo tubes (two forward and two aft) were also removed during this time and replaced with four experimental torpedo tubes mounted in two pairs above the water line forward of A-Turret. The ships plans were redrawn in 1936 to reflect HMS ROYAL OAK as she is today. Both the original 1916 plans and the redrawn 1936 plans are housed at the Ship's Plans Archive at the National Maritime Museum.

Figure 3: ROYAL OAK Ship's Profile

At the beginning of WWII HMS ROYAL OAK was 189 metres long with a draught of 9 metres and a beam of 31 metres. She displaced over 30,000 tons and could only achieve a top speed of approximately 21 knots.

The main structure of HMS ROYAL OAK comprised eight decks within the hull and superstructure, from the Hold at the bottom of the hull, to the Shelter Deck at the top of the superstructure. Atop the Shelter Deck were the Bridge structures, funnels, and masts.

Figure 4: Cross section of ship's plans detailing deck levels

HMS ROYAL OAK was a steam powered ship. Eighteen oil-fired Yarrow boilers were arranged in 3 boiler rooms, with six boilers per room. The 18 boilers powered two sets of steam turbines, which in turn powered four propellers. The ship carried over 3,400 tons of fuel oil stored in tanks longitudinally along the port and starboard side of the ship.

Figure 5: Ship's plan detailing fuel oil storage

3.1.1.1 Armaments

The ship's primary and secondary armaments remain as fitted at the time of construction in 1916. The ancillary guns were modernised to defend against air attack.

- Primary Armament: 4 x 15 inch 42/Mk I turrets
- Secondary Armament: 12 x 6 inch 45/BL Mk XII casemate guns
- Ancillary Guns
 - 4 x Twin 4 inch 45/QF Mk XIV anti-aircraft guns
 - 2 x 2-pdr (40mm/39cal) QF Mk VI Octuple Pom Pom
 - 2 x Quad 0.50 Vickers MkIII machine gun mounts
 - 4 x 3-pdr guns
 - 4 x 21-inch torpedo tubes

The primary armament consisted of 4 twin-barrelled 15-inch gun turrets. All four turrets are mounted on the centre line of the ship, two forward of the bridge (A & B turrets) and two aft of the main mast (X & Y turrets). A-turret is mounted on the Forecastle Deck whilst B-turret is mounted one deck higher on the Shelter Deck allowing it to superfire A-turret. Y-turret is mounted on the Upper Deck and X-turret is mounted on the Forecastle Deck to allow it to superfire Y-turret. The ship carried approximately 100 rounds per gun.

The armoured gun houses sit above decks, but the turret system descends through all of the ship's decks to the Hold. Adjacent to the lower levels of this system are the shell rooms located on the Hold Deck, and cordite magazines located on the Platform Deck.

The turret system and ammunition were protected from enemy gunfire by armour comprising of large, thick, and hard steel plates attached to the ship's deck, hull sides, turrets and barbette. The barbette was the round structure within the hull that surrounded the turret system.

Figure 6: Ship's Plan detailing A & B-Turrets and associated systems

Figure 7: Archive images of A & B-Turrets and X & Y-Turrets, © IWM Q 017919 & Q 018117

Twelve 6-inch casemate guns made up the secondary armament, all mounted on the Upper Deck; six to port and six to starboard. They had an arc of fire of approximately 116°, although this figure varies slightly from port to starboard and from the forward guns to the aft guns on each side. Four of the six casemates on each side were forward-facing with gun 6 and 7 facing aft.

The ancillary guns fitted at the time of sinking are interwar modifications and formed part of the improved anti-aircraft defences. Four twin-barrelled, 4-inch anti-aircraft guns were mounted on the Shelter Deck, two to port and two to starboard. The 2 x Quad 0.50 Vickers MkIII machine guns and the 4 x 3-pdr guns were mounted slightly higher and forwards on the Conning Tower Platform. A designated Pom Pom Platform mounted aft of the funnel supported the 2 x 8 barrelled Pom Pom guns. A full description of the gunnery and fire control aboard HMS ROYAL OAK is included in section 3.1.4.

The ship was originally fitted with submerged torpedo tubes. During the ship's modifications these were removed and fitted above the waterline. Four x 21-inch tubes were mounted in pairs, sharing a common external aperture fitted with two watertight doors. The doors are marked in red in Figure 6.

Figure 8: The torpedo tubes were mounted on the Upper Deck

1.1.2 Service History

In May 1916 HMS ROYAL OAK was commissioned to the Third Division of the Fourth Battle Squadron of the Grand Fleet. Both she and her sister ship HMS REVENGE saw action at the Battle of Jutland. She scored successful hits against the German light cruiser WEISBADEN and the battlecruisers SMS DERFFLINGER and SEYDLITZ. She returned from the battle undamaged. Following the battle, the ship was reassigned to the First Battle Squadron. The ROYAL OAK was anchored in Scapa Flow on 9th July 1917 with the theatre ship GOURKA tied alongside. Entertainments that night were provided for the Officers from HMS VANGUARD, which ultimately saved their lives. HMS VANGUARD suffered a series of catastrophic internal explosion with the loss of 843 of the 845 men still aboard.

On 21st November 1918, HMS ROYAL OAK took part in Operation ZZ and the subsequent internment of the German Fleet in Scapa Flow, as part of the armistice agreement at the end of WWI. The ship was also present seven months later on 21st June 1919, when the German Fleet was scuttled in Scapa Flow. Fifty of the 74 German war ships anchored in Scapa Flow were successfully sunk. The ROYAL OAK took some of the German sailors aboard before their transfer to a prisoner of war camp in England.

Peacetime reorganisation saw her assigned to the 2nd Battle Squadron of the Atlantic Fleet. The ship underwent a series of modernisations between 1922 and 1936, before being tasked with conducting non-intervention patrols around the Iberian Peninsula during the Spanish Civil War. In 1938 she returned to the

Home Fleet and was made flag ship of the 2nd Battle Squadron based in Portsmouth. In November of the same year the ship returned the body of Queen Maud to Norway.

In June 1939, and ahead of the impending hostilities, HMS ROYAL OAK returned to Scapa Flow. By this time she was a 23 year old vessel, and although her gunnery was modernised and well equipped to defend against air attack, she was ill equipped to keep up with the newer warships of WWII. In October 1939 she joined the search for the German warship GENEISENAU but, due to her comparatively slow speed (~20 knots) she did not join the rest of the Fleet in the North Sea and was instead tasked to the west of Shetland with a destroyer escort. The vessel encountered heavy seas, lost contact with the destroyers, and returned to Scapa Flow. It was reported that she lost many Carly rafts overboard. By 12th October HMS ROYAL OAK was at anchor in Scapa Bay to provide anti-aircraft cover for Scapa Flow and the Radar station at Netherbutton.

1.1.3 Sinking

Figure 9: U-47's route into Scapa Flow and the attack on HMS ROYAL OAK

On 8th October 1939 German submarine U-47 under the command of Gunter Prien departed Kiel, Germany, to carry out 'Special Operation P,' targeting the Royal Navy's Home Fleet's main base in Scapa Flow. It was believed to be a one-way mission. Six days later, U-47 navigated her way past the blockships in the poorly defended Kirk Sound. Most of the Home Fleet had been ordered to sea, leaving only a small number of ships in Scapa Flow. A battleship at anchor was located to the north. The ship was HMS ROYAL OAK.

At 00:58am on 14th October, U-47 fired a salvo of three torpedoes. Two missed their target, but one struck the bow of HMS ROYAL OAK. The muffled explosions awoke the sailors onboard at 01:04am, but not for an instant did they believe they were under attack; after all, they were in the safety of the home anchorage. Magazines were checked but many sailors returned to their hammocks, unaware U-47 was repositioning for a further attack. Prien attempted a shot via the stern tube but missed. After reloading his bow tubes he turned towards HMS ROYAL OAK once again and fired a further salvo of three torpedoes. All three found their target.

At 01:16am explosions blew three additional large holes in the starboard side of the ship, the aft two opening fuel bunkers and spilling oil into the sea. The battleship quickly listed to starboard and the open scuttles (portholes) were submerged below the waterline, causing a rapid intake of water. HMS ROYAL OAK rolled further over, remaining there for several minutes before watertight hatches, left open due to the fine weather, rapidly flooded the ship. Some crew who had made it on deck escaped into the water, others climbed over the port side to a waiting drifter, Daisy II. Some made it aboard one of the two steam pinnaces. Daisy II and one pinnacle escaped the sinking ship. The bravery of the crew of the Daisy II saved hundreds of lives. Those aboard the pinnacle were not so fortunate. Survivors report over 100 men aboard the ship's boat as she made her way west. Overloaded by at least 50% she capsized and sank, most of the men aboard died.

At 01:29am, just 13 minutes after Prien's second attack HMS ROYAL OAK was gone. Of the 1259 men aboard 835 perished with the ship, including over 134 Boy Seamen, not yet 18 years old.

Figure 10: Gunter Prien

Figure 11: U-47

1.2 Post Sinking: HMS ROYAL OAK the Shipwreck

Today the wreck of HMS ROYAL OAK is unique. She remains the most intact dreadnought style battleship in an accessible depth underwater, and as a relatively untouched site she is of extreme archaeological and historic importance. She is the grave of 835 sailors. Attitudes towards our underwater heritage and

gravesites have changed considerably over the last 80 years. The wreck of HMS ROYAL OAK has been considered a war grave (in the official sense) since the 1980s and designated a 'Controlled Site' since 2002, which means no diving is permitted without Ministry of Defence (MOD) authorisation.

1.2.1 Salvage, Diving and Surveys

In the days after the sinking, commercial divers from the salvage company Metal Industries dived the wreck in an attempt to ascertain the cause of her rapid loss. Herbert Bullen and Sandy Robertson were amongst the divers. They reported the orientation of the wreck on the seabed and the presence of 4 large blast holes in the starboard side. Also recovered was the upper side rudder of a German G7e/T2 torpedo confirming the submarine attack.

(2) Counter measures taken that night failed to reveal the cause of the explosions, about which there was considerable speculation at the time. This, however, was resolved by the broadcast reports from Germany that a submarine had successfully penetrated the defences of the Flow, and by the discovery by Metal Industries' Divers of parts of German Torpedoes in the wreck of the "ROYAL OAK".

Figure 12: Extract taken from archive document ADM116-5790, The loss of HMS ROYAL OAK and the defences of Scapa

Figure 13: Recovered upper side rudder from one of the torpedoes that struck HMS ROYAL OAK

Figure 14: Herbert Bullen on the left and Sandy Robertson on the right

In 1942 a Radar ranging platform was fitted on the upturned hull of the wreck. The work was conducted by salvage company Metal Industries and involved fixing a tower to the underwater hull, secured by supporting wires. A platform was fixed to the top and a rotet was added in 1944. The process involved converting and erecting a salvage caisson such as those used in the salvage of the WWI German Fleet in Scapa Flow, and was technology well known by the salvage company.

maintained in four out of five of these sounds. Diving and other operations were carried out daily. A Radar Ranging Mark was constructed, utilising Airlock Sections, and erected on the upturned hull of "Royal Oak" during May, 1943. A Rotet was added in July, 1944.

Figure 15: Extract from the Nation Archive - ADM116-5790 Main Fleet Base Scapa Flow, inception, development and history

Figure 16: Extract from a WWII navigation chart showing the radar station in place on the wreck and a diagram of the caisson construction

The caisson stayed in place during the 1940's until the supporting wires rotted through. The caisson collapsed into the sea at the end of the decade. According to local resident Johnnie Meil, the caisson was in place one day and gone the next.

Figure 17: Archive images showing salvage caissons in their original purpose, as air locks. © OLA

In 1950 a survey was conducted under the supervision of Boom Defence and Salvage Officer Mr J. Alexander and Captain W.R Fell, R.N (Ret'd) from Royal Fleet Auxiliary (RFA) salvage vessel Salvictor. Some salvage work was also conducted during this time. All four propellers were removed during the work, along with some chain. It was found during the survey that the anchors had already been removed and the end of the cables cut. During the war, Metal Industries removed 146 anchors in Scapa Flow for the Admiralty. They would be repurposed and would have been of high value. It is possible that the anchors from HMS ROYAL OAK were recovered as part of that work. One purpose of the survey was to ascertain the feasibility of raising the ship for salvage.

Figure 18: 1950 Survey diagram showing torpedo damage to the starboard side

In 1957 tenders were invited by the Admiralty for scrapping the ship. This was met by fierce opposition from survivors and the relatives of those lost and the people of Orkney. The idea was abandoned by early 1958.

Figure 19: Left: Extract from the Northern Wing, Tuesday 3rd December 1957
Right: Halifax Evening Courier, Thursday 23rd January 1958

Recreational divers began to visit the wreck in the 1970s. Local divers recovered the remains of German torpedoes during this time and one can be seen in Stromness Museum.

Other artefacts were also removed by visiting divers during this period, including the large brass letters of the ship's name during an expedition in 1975. The diver later returned the name to Orkney and it is housed at the Scapa Flow Visitor Centre. In 1979 a large scale BSAC expedition took place and some of the first video footage and underwater images of the wreck were taken. This expedition located the ship's bell, which was later recovered by the Royal Navy and now hangs in St Magnus Cathedral in Kirkwall.

Figure 20: The remains of one of the torpedoes that hit HMS ROYAL OAK

Diving was banned later in the 1970s when concern was raised with the MOD about amateur divers visiting the wreck. The ban was policed locally by the Orkney Harbour Authority. The ship then became a controlled site in 2002. Permission must be granted by both the MOD and the Orkney Harbour Authority to visit the wreck today. Underwater photographers and videographers have documented the wreck in the intervening

years with MOD and Royal Navy permission, primarily Lawson Wood, Peter Rowlands and Simon Brown.

3.1.1.2 *Naval Protection*

The Royal Navy has commissioned significant work over the years to support their custodianship. HMS ROYAL OAK was an oil powered ship. Much oil was spilt into the sea during the sinking, but most remained in the ship's bunkers. The ship has always leaked a small amount of oil, but environmental concerns were raised over the possibility of a large pollution event as the ship deteriorated underwater. Oil recovery trials began in 1994, first with a canopy erected above the ship to capture the escaping oil, and later with absorbent material secured on the surface to soak up the oil. Finally, it was decided that the direct removal of oil from the ship's hull was the only secure option. In 2003, work commenced under the direction of the MOD Salvage and Marine Operations team (SALMO). This resulted in the installation of a series of diver operated "hot tap" valves to the top of the hull to enable oil removal from deeper within the ship.

In support of ongoing monitoring a confidential survey for the MOD was conducted in 2004 by a commercial surveying company called SRD, but this has not been made public. In 2006, MOD commissioned a multibeam sonar survey of the wreck and surrounding area. This was completed by ADUS, the University of St Andrews and the University of Dundee. This survey report was confidential at the time but is now included in Annex 8.4. High-definition imagery of the ship was produced. More information about this data is included in section 2.2.

The Royal Navy has officially paid its respects to the ship and her lost crew since the early 1980s, and continue to do so. Their ceremonial work is of the upmost importance to the ROYAL OAK and Orkney communities. Each year a White Ensign is raised on the wreck as a tribute to the ship and her lost crew. The ensign is then carefully folded and stored on the site for a year. The stored Ensign is recovered the following year and presented to a chosen person as part of the Orkney commemorations. This annual pilgrimage by the Royal Navy continues to this day and, at the time of our survey, is conducted by the Northern Diving Group based at Faslane.

3.1.1.3 *Other surveys*

Regular remote surveys have been conducted on ROYAL OAK, and civilian visitors have dived the site with permission. In 2010 the ROYAL OAK was also captured in a remote survey of Scapa Flow conducted by Fathoms. While, during a seabed survey for the Orkney Harbour Authority in 2015 a target was identified to the east of the main wreck using side scan sonar. The survey was conducted by Sula Diving. Their archive research coupled with the imagery gathered revealed that this was likely to be one of the ship's steam pinnaces which got away from the ship after the torpedo attack but sank some distance off.

In 2017, the Shiptime Project included some work on the ROYAL OAK as part of a wider collaborative multidisciplinary remote sensing survey of historic sites in Orkney. Conducted by ORCA Marine and Sula Diving, one focus was to further investigate the target to the east. This was dived and confirmed as being the missing ROYAL OAK pinnacle. A wider survey of the seabed surrounding the ship was conducted and, due to the shallow nature of the wreck, the work was undertaken by Triscom and Sula Diving from a smaller vessel and not from the main survey vessel Scotia. During the search a target was located 27 metres from the steam pinnacle, along with a series of additional targets worthy of further investigation. As part of the collaborative nature of the project this data was shared with the ROYAL OAK 80 Survey Team and the targets

dived during this project. Details are discussed in section 3.1.7. Also in 2017, a multibeam survey of many of Scapa's wrecks, including HMS ROYAL OAK was completed by the Sea War Museum Jutland in conjunction with Bournemouth University.

1.2.2 HMS ROYAL OAK Community

The loss of HMS ROYAL OAK at the beginning of WWII was a huge blow to the Royal Navy, and had a profound impact on the people of Orkney. It altered irreparably the lives of the 429 men who survived and the lives of the families of the 835 men and boys who perished. The HMS Royal Oak Association was formed in the 1960s by survivors and those closely involved. The first remembrance service was held in 1967 at the war memorial on Southsea Common.¹ It was held there for a number of years and the services were followed by a gathering at the Armed Forces Club in Lake Road, Southsea. Some time later the Association secured the use of St Barbara's Church at HMS Excellent on Whale Island, Portsmouth, where they have met every year in October, with the exception of 2020. The 2019 80th anniversary service involved coaches from HMS Excellent to St Ann's Church at HM Naval Base Portsmouth, where the Princess Royal unveiled a new stone memorial. The Princess Royal has attended several anniversaries, both in Portsmouth and in Orkney.

Orkney has a dedicated memorial and garden to HMS ROYAL OAK at Scapa Beach in Orkney which looks out over the wreck site. The ship's bell and book of remembrance is on display in St Magnus Cathedral, Kirkwall. The graves of the sailors whose bodies were recovered rest in the naval cemetery at Lyness on the island of Hoy, and artefacts from the ship are housed at both Stromness Museum and the Scapa Flow Visitor Centre. The late Charlie Miller dedicated over 40 years to helping people visit the wreck site and pay their respects.

The Orkney based annual commemoration is organised and hosted each year by the Royal Oak Association and the Royal British Legion in Kirkwall, and supported by the Orkney Harbour Authority. A service is held at the Scapa memorial followed by an on-water service above the wreck. The Orkney commemoration also incorporates the Royal Navy's annual visit to change the White Ensign.

In addition to the memorials in Portsmouth and at Scapa, there is a stone plaque in memory of the ship and her crew at the National Memorial Arboretum in Staffordshire.

1.3 Rationale for project

The underwater archaeology of Scapa Flow and beyond has long been of interest to divers. HMS ROYAL OAK holds a special place in the hearts of the Orkney community and is of specific interest to naval historians, divers and people interested in historic warships.

Modern underwater stills and video cameras, together with associated software now allow us, as divers, to document wrecks in ways and at a level of detail not possible until very recently. Technology is allowing us to spend increased time underwater, meaning more survey time and more data to relay back. The results of HMS ROYAL OAK 80 Survey will paint the fullest picture yet in terms of data gathered, pictures taken and 3D visualisation accessible to those unable to dive on the wreck herself.

¹ The late Taffy Davies, a Royal Marine Corporal and survivor of the sinking confirmed the date of the first service.

No survivors of the sinking are alive today. Working closely with the Royal Oak Association it is our responsibility to help ensure the loss of the ship and the sacrifice made by the crew is not forgotten.

1.4 The Project

The aim of the HMS ROYAL OAK 80 Survey was to tell the story of the ship at 80 years underwater, to shed new light on the damage that caused the ship to sink, and to raise the profile of the loss of the ship and the sacrifice made by her crew. The dive team was assembled with the requisite skills to document the ship using photography, videography and 3D photogrammetry, and to conduct a full survey of the site.

The project team then aimed to maximise the impact of the technical outputs by:

- Robustly documenting the wreck and publishing detailed records of current condition.
- Sharing imagery from the ship with the wider public, bringing the wreck of HMS ROYAL OAK to the surface for future generations and supporting the Royal Oak Community as they continue their work to remember the ship and the sacrifice made by her crew.
- Contributing to the commemoration event for the 80th anniversary of the loss of the ship.
- Developing closer connections with the Royal Navy and the Orkney community.
- Collaborating with the Royal Navy Northern Diving Group (NDG) to document their ceremonial dives and White Ensign changes on the ship in October 2018 and October 2019 and to raise the profile of the ceremonial work of the NDG.

2. Survey Methods

2.1 Overview

The ROYAL OAK 80 Survey utilised both in-water and remote survey techniques. Remote survey data from previous and separate projects was shared with the survey team. This data was invaluable, and we offer our thanks and gratitude for the use of the data. Sidescan sonar data provided an overview of the wider site, identifying important targets for investigation and documentation including the missing second ship's pinnace. Multibeam data from the 2006 ADUS survey provided a bathymetrically accurate model of the ship on which the visualisation of the survey was based. The visualisation of HMS ROYAL OAK was of paramount importance. The in-water diver survey allowed detailed architectural features and artefacts to be located and documented. A dedicated 3D photogrammetry team have undertaken the most accurate and ambitious in-water shipwreck data collection project to date, and our underwater videography team have worked to document both the ship and the project for distribution via film media. One focus was to conduct an explosive effects survey of the torpedo damage to HMS ROYAL OAK today, and to gain insight into the extent of the damage that caused the loss of the ship. HD and 4K video were used for broad scale documentation of the site, whilst underwater stills photography and 3D photogrammetry were employed for recording the site and her features.

The survey took place under special licence from the Secretary of State for Defence. The licence holders were Emily Turton and Benjamin Wade of Huskyn Charters, Stromness, Orkney. The licence period for the survey ran from October 2018 – November 2019. All diving took place from the dive charter vessel MV HUSKYAN owned and operated by the licence holders. Twenty-eight volunteer divers conducted over 1,000

survey hours on the ship. The survey was self-funded.

2.2 Multibeam Sonar

Multibeam sonar data was used during the survey as a tool for advanced dive planning and to locate features identified on the wreck site as the survey progressed. The multibeam data was collected prior to the 80th anniversary survey. The key advantage of multibeam sonar is its accuracy, producing data that reliably represents the general architecture of the shipwreck. Its main disadvantage is that the process does not capture colour or texture. The grey scale tone in the multibeam images is added in post-production.

In 2006, Advanced Underwater Surveys (ADUS) was commissioned by the UK MOD through SALMO, to conduct a multibeam sonar survey of the wreck of HMS ROYAL OAK. ADUS consisted of Martin Dean and Mark Lawrence (University of St Andrews) and Chris Rowland (University of Dundee). The survey was undertaken with a Reason SeaBat multibeam sonar system mounted on ADUS's Independent Sonar Head Attitude and Positioning System (ISHAPS). The survey was focussed on the hull, masts, overhanging features and seabed debris. Multibeam sonar technology was chosen for its positional accuracy and bathymetric data. Side-scan sonar can produce excellent images, but lacks positional accuracy and is not bathymetric, i.e. precise depth measurements cannot be ascertained.

The outcomes from the survey were high resolution 3D images showing details of the wreck and the main architecture of the hull. These were presented as stills and animated sequences alongside the report. The 3D data was compared to an earlier survey carried out by SRD in 2004 and findings concluded that minor deterioration was detectable on the wreck between the two surveys.

Figure 21: 2006 Multibeam sonar image showing a wide view of the port side of the wreck.

In addition, a detailed topographical survey of the surrounding seabed extending to 800m x 800m centred on the wreck was carried out. The resolution of the data allowed identification and positioning of scattered debris and other seabed features. These included the possible remains of anti-torpedo defences extending to the North, East and West of the wreck and a small wreck approximately 300m South West of HMS ROYAL OAK. Martin Dean surmised that the small wreck was likely to be from HMS ROYAL OAK. See Annex 8.4: 2006

Survey Report: section 7.4, page 17.

The 80th anniversary survey team used the 2006 3D multibeam data via the interactive viewing software “Wrecksight” to plan the survey dives during on-board briefings. The interactive data allows the wreck to be viewed from any perspective.

Figure 22: Wrecksight image: screen capture

Large format prints of the port and starboard views of the wreck were used as a base map to add annotations and sketches during debriefing sessions after each dive and to mark progress of the survey. These informed diving plans for the following days activity.

Figure 23: Printed multibeam wreck image with annotations, on board MV Huskylan

2.3 Sidescan Sonar Surveys

Separate remote surveys of the seabed surrounding the wreck were conducted by Kevin Heath of Sula Diving as part of work commissioned by the Orkney Harbour Authority, and as part of the Shiptime project. This

data was consulted prior to any diving activity to identify outlying targets (see Annex 8.2). A digital scanning unit called a towfish is towed behind a boat in the water column above the seabed. The sidescan looks to both sides of the towfish over the seabed, producing easily interpreted images of the seabed and objects on it. This survey technique allows large areas of the seabed to be covered quickly. The sidescan used was a C-Max CM2 EDF and all sidescan data was post processed using Sonarwiz 6 software, allowing 'mosaics' and 'Contact Reports' to be generated.

2.4 Diving Methods

The in-water diver surveys were conducted by a team of technical divers using closed-circuit rebreathers wherever possible to reduce the impact on the ship from divers' exhaled gases. The team consisted of professional underwater image makers, technical wreck divers, marine biologists and experts in munitions, weaponry, and explosive effects. Survey techniques gathered high resolution video, stills photographs and 3D photogrammetry data in a bid to record the site as it is today, digitally preserving the ship in its current state.

The ship lies in approximately 30 metres of water with the least depth of water over her keel of 4.5 metres at low water. Most dives were conducted with a 100–120 minute run-time allowing decompression to be conducted on the upturned hull. The use of technical diving equipment was key to enabling relatively long bottom-times, thus allowing extended periods of underwater data capture.

As ROYAL OAK is famously a completely intact dreadnought, the main objective was to thoroughly capture the detail of the wreck as she existed, at 80 years underwater. To ensure a systematic approach by the team the wreck site was divided for cataloguing artefacts. The survey report describes the site in three main sections: Deck/Portside (3), Starboard side (3.1.2) and Top of the Hull (3.1.3). Outlying targets (3.1.7) and Pinnaces (3.1.8) were covered separately. Further subdivision was utilised to better manage survey activity, data recording and cataloguing.

Preliminary broadscale surveys were undertaken by the dive team, and targets for specialist survey and image capture identified. Dive schedules were then developed to task the appropriate specialist teams with data collection.

2.5 Visualisation Methods

3D photogrammetry, underwater stills photography and videography were used primarily to document the wreck. The survey team included three professional stills photographers, skilled videographers and a dedicated 3D photogrammetry videography team. The survey also included an underwater artist. In addition, all survey divers carried small underwater video cameras to capture details during exploratory dives. This information was collated after each dive enabling specific areas to be identified which were then documented by the professional image takers. This multi-method approach allowed the team to document the survey process and provide reliable data to communicate the condition of the wreck to both scientific and non-specialist audiences.

2.5.1 Stills Photography

Stills Photography was used extensively throughout the survey. The primary image taker was Marjo Tynkkynen with substantial contributions made by Kieran Hatton and Bob Anderson. Additional imagery by gun systems expert Simon Kay can be found in section 3.1.4.

The photographers were chosen specifically for their different technical and artistic approaches to image taking in order to best capture the essence and detail of HMS ROYAL OAK at 80 years underwater. They each worked to capture documentary images for artefacts and feature identification and larger scale images where the viewer's eye was guided to points of interest by independent lighting, carried or placed by divers. Further details of their individual methods can be found in the HMS VANGUARD survey report (Turton *et al*, 2018). It was important to gather large wide-angle images, giving scale to the vast naval architecture of a near intact dreadnought battleship and which speak to a non-diving audience. Equally important was the documentation of small artefacts and specific details in the wreckage which help tell the story of life aboard. Other images were gathered to form the basis for reinterpretation of the explosive effects of the loss and capture a snapshot in time to the condition of parts of the ship.

2.5.2 Underwater Artist

Caroline Appleyard is a professional artist who combines her passion for the underwater world with her joy of painting. She brings a unique perspective of the ship to the visualisation team. During the survey Caroline had two objectives.

- To use the collective knowledge and imagery gathered to create a painting of the entire site for the 80th Anniversary.
- To create a collection of underwater paintings of HMS ROYAL OAK.

In addition to traditional surface painting techniques, such as those employed to create the painting below, Caroline also paints whilst underwater using oil pastels. She has painted the WWI German shipwrecks of Scapa Flow extensively, and offered the ROYAL OAK Survey a very special opportunity. During the license period a series of six scenes were captured and displayed in an exhibition for the 80th Anniversary.

Figure 24: HMS ROYAL OAK - a painting by Caroline Appleyard

Figure 25: From left to right: Underwater artist Caroline Appleyard, Royal Oak Association member Andy Smith and Royal Oak Association Chair Gareth Derbyshire aboard Dive Vessel Huskyn at the ROYAL OAK buoy. The underwater paintings show the stern of the wreck flying the 79th anniversary White Ensign and the portside steam pinnacle which rests on the seabed just aft of the bridge.

Figure 26: Caroline painting a ship's paravane on the left and the portside pinnace on the right.

Figure 27: Caroline returning from a dive on the left, and with Royal Oak Association chair Gareth Derbyshire on the right with paintings of a scuttle in the Admiral's Sleeping Cabin, a bedframe is inside, and a shoe sole lying on the seabed.

2.5.3 Videography

The project licence offered a unique opportunity to access an important protected war-time shipwreck, and it was decided that as much of the process should be recorded as possible. Videography was used to record interviews with the survey participants as they returned from survey dives, as well as during day-to-day activities such as setting up equipment and discussing dive plans. At the start of the project, the intention to produce some form of documentary was agreed and team members were allocated tasks to ensure that video footage was gathered at every opportunity. The documentary film, "Fallen Oak" was produced using this footage.

Videography was also used as an underwater data capture method for documentary purposes to record survey divers at work, their findings, and as a data source for 3D photogrammetry (Structure from Motion). Each of these require a specific approach to video capture. Documenting divers at work requires wider camera angles to capture the diver and the ship's features they are focussed on. With often limited visibility (<5m) and shorter daylight hours this proved a particular challenge during the winter months of the project. On many occasions multiple divers were allocated lighting tasks to illuminate the subject of the video.

Capturing video for photogrammetry typically involved pairs of divers, one with a high-resolution camera recording 4K video and lighting rig, supported by a buddy with additional lights. The challenge was to illuminate the subject as evenly as possible whilst maintaining a depth of focus that revealed details of the wreck's features. The photogrammetry process requires sharp, in-focus image sequences to calculate the 3D

data, therefore the divers moved as slowly as possible over the target features to eliminate motion blur.

Using 4K video allowed the teams to capture overlapping image sequences which were later subsampled in post-production. Typically, 2 frames per second were sampled from a video sequence recorded at 25 frames per second. This method allows for greater areas to be covered in a single dive. The only disadvantage with this method is that each image had a maximum resolution of 4k (3840 x 2160 pixels), whereas photography can be captured at much higher resolutions per frame.

Figure 28: Divers capturing video for photogrammetry

High-resolution photography sequences were also used to provide data for photogrammetry. Where features on the wreck were complex and detailed, divers followed up the 4K video capture with photography sequences of overlapping images. The higher resolution provided by DSLRs allowed smaller details to be more visible in the visualisation. This process takes longer to capture than video, since the diver must reposition the camera at fixed overlapping intervals to capture each frame. The disadvantages to this method is the extended time required to capture the images and the subsequently higher resolution images take much longer to process in post-production.

2.5.4 3D Visualisation

Visualisation of the 3D data captured during the survey was principally carried out by the photogrammetry teams. The initial process required the photogrammetry data to be processed using the following methodology:

1. Data capture: video and photography.
2. Initial processing: Low quality photogrammetry tests were carried overnight to check that the data aligned correctly. This was usually achieved using laptops.
3. If the test was not successful, the target would be revisited to capture additional data.
4. If the test was successful, the data would be re-processed at a higher quality level at a later date on more powerful computers.

The adopted methodology was to record data at the highest resolution available at the time, and reduce the

image sequence size when necessary to speed up the photogrammetry processing. The high-resolution data could be re-processed at a later date when more powerful computers became available or photogrammetry algorithms became more efficient. For this and data security reasons, three copies of the video and photography were archived in three separate locations in case of any data being corrupted or compromised.

Photogrammetry data was processed using off-the-shelf software (Agisoft and Reality Capture) and edited using open-source software (Cloud Compare). Additional editing and rendering occurred in Autodesk Maya using custom point cloud plugins developed at the 3DVisLab (University of Dundee).

2.5.1.1 *Integration of Multibeam and Photogrammetry*

Multibeam data from the 2006 ADUS survey provides a bathymetrically accurate 3D model of the whole wreck and surrounding seabed. This data shows the general architecture of the shipwreck, but resolution does not reveal fine details. However, the photogrammetry data captured during the survey provides high resolution data of the features and details of the wreck. Integrating both data types provides the best of both worlds, resulting in a unique visualisation of the wreck. Comparing the resolution of each data type, the multibeam model of the whole wreck and seabed consists of 1.2 million points whereas the photogrammetry model of A Turret alone contains 22.2 million points.

Figure 29: Wide view of combined Multibeam and photogrammetry integrated data

Figure 30: A-Turret photogrammetry integrated with multibeam sonar data

2.5.5 Marine Ecology

Marine life encountered during the dives was described *in-situ* and recorded using video- and photographic techniques. Data captured for photogrammetry and in stills photography were used, in addition to dedicated ecological survey dives, to build up a picture of the significance of the site within the environment. The project aimed to generate a qualitative understanding of the natural heritage of the site to complement its cultural value. Previous projects, such as VANGUARD 2018, had emphasised the importance to relatives of a narrative that describes the transition back to nature of their loved one's final resting place.

Photogrammetric data captured provides a detailed record of the species inhabiting the site, and further detailed surveys, including species identification, counts and sub-cm measurement, can be conducted in virtual reality in the future.

3. Results and Discussion

3.1 Site Description - Overview

The wreck of HMS ROYAL OAK lies in approximately 30 metres of water in the mouth of Scapa Bay in Scapa Flow, Orkney. She lies with her bow pointing east and the least depth over the upturned hull is 4.5m at low water. Examination of the site reveals an intact dreadnought battleship, with a small number of discrete outlying items also identifiable in the acoustic images.

The ship lies upside down propped up at an angle of approximately 45 degrees allowing access underneath her deck from the portside of the ship. The seabed is composed of a mixture of fine silt and extended patches of broken shell.

Figure 31: Multibeam image of the stern on HMS ROYAL OAK

The description of the ship is divided into the following sections: Deck/Portside (3), Starboard side (3.1.2) and Top of the Hull (3.1.3), which are further sub-divided aid navigation.

Figure 32: Multibeam visualisations of the Deck/Portside, Starboard side and Top of Hull sections that structure this report

3.1.1 Deck/Portside Section

The deck/port side description of the site includes the structure and artefacts located on and around the port side of the ship and on the seabed under the exposed deck. To aid site description, this section is further subdivided into three; forward, midships, and aft.

Figure 33: Subdivision of Deck/Port Side

3.1.1.1 Deck/Port Side - Forward

The forward section extends from the stem to the aft end of B-turret on the portside of the ship. The bow section is dominated by A and B turrets, cable holders (commonly known as anchor capstans) and capstans and associated deck side chain. The anchors and the majority of the post hawse chain was salvaged. The bow is held off the seabed by the superstructure and the forward gun turrets. The starboard edge is clear of the seabed as far aft as frame 37 just forward of A-turret. The bow is intact except for the forefoot which has been detached as a result of the first torpedo strike, and lies on the seabed to starboard. The remains of the jackstaff, a short pole mast erected at the bow of the ship on which the national flag is hoisted when at anchor, is intact at the bow. Anchor chain drapes to the seabed and runs out in the direction of the now salvaged anchors.

©National Maritime Museum, Greenwich, London

Figure 34: Forward Section

Figure 35: Multibeam image of the bow showing the starboard edge clear of the seabed

Figure 36: The upturned bow showing jackstaff and chain

Figure 37: The anchor chain runs out from the bow

Moving aft from the bow, the deck is lined in teak which remains in good condition. The anchor chain drapes in loops from the deck fixed only by the cable holders and Blake slips. The ship's plans describe three cable holders, one for each anchor, and one capstan. A Royal Navy ship of this design would be equipped with two bower anchors, one to port and one to starboard. These are main ship's anchors used in normal anchoring procedures. A third sheet anchor abaft the starboard bower anchor is fitted for redundancy and emergency use.

Figure 38: Ship's plan detailing cable holder and anchors.

Figure 39: Foredeck showing anchoring equipment. This archive image also shows the ship's crew exercising, note the wave break in the bottom of the image which deflected wave water from the bow away from structures further aft.

©IWM Q 17974

Figure 40: Anchor chain hanging from the deck

Figure 41: Blake Bottle Screw Slip, used to secure the anchor at the Hawsepipe

Figure 42: Under the deck the chain drapes to the seabed secured from a Blake slip. Teak decking is visible and in the background the Sheet Cable Holder is illuminated

Figure 43: Sheet Cable Holder and Chain

Aft of the anchoring equipment on the deck a large wave break protects structures further aft. This remains intact along with a variety of ventilation cowlings. Several hawser reels were also located on the deck but have now fallen to the seabed.

Figure 44: Ship's plans extract detailing wave break, hawser reels and ventilation

A-turret and B-turret sit on the centre line of the ship. The armoured gun house of A-turret sits on the Forecastle Deck whereas the gun house of B-turret, which superimposes A-turret, sits aft and one deck higher on the Shelter Deck, allowing it to train over the top of A-turret. Each twin barrellled gun has an arch of fire of 150° on each side allowing each turret to rotate from 60° abaft the beam on the starboard side around to 60° abaft the beam on the port side. As the ship rests on the seabed today, the barrels of all four gun turrets lie at 90° to the centre line pointing directly to starboard. This means the ends of the gun barrels are buried in the seabed underneath the ship, exposing the aft side of each gun house on the port side of the wreck. The weight of the ship resting predominantly on these gun barrels have forced the barrel mountings to fail and prized open the gun house roof of each turret. Gun house equipment and all 8 gun breeches are exposed, offering a unique insight into the inner workings of this dreadnought's primary guns.

Figure 45: Multibeam image of the bow section with 3D Photogrammetry overlay of A-turret

Figure 46: 3D Photogrammetry Image of A-turret

A-turret offers clear access to the inner working of the gun house. Both barrels have broken their mounts, fallen to the seabed and lie clear of the main gun house structure. The left-hand gun, as it would be in her firing position, and foremost on the wreck has an open breach door. The right-hand gun breech is closed.

Both rammers, the mechanism used to push the shells and propellant into the barrels are in situ and sit directly behind each breech. On the seabed the gun house roof is clearly visible, and part of the gun house roof of B-turret overlaps this (see figure 48). Protruding from the gun house roof is a periscope. There were two of these per turret, one for range finding and one for general observation. The range finder can still be seen underneath the turret roof.

Figure 47: A-turret, front view with both apertures visible and the fallen barrels buried in the seabed below

Figure 48: A-turret gun breeches and rammers

Figure 49: A-turret open breech door on left-hand gun and view of both breeches clearly showing the rammers protruding from the rear of the barrels

Figure 50: Turret Periscope

B-turret and the Shelter Deck structure is supporting most of the weight of the bow section. Access to the starboard side of the Shelter deck is open by swimming between the two forward turrets. On the seabed underneath the ship and alongside the starboard superstructure lies the smaller of the two paravanes originally mounted on the side of the Forecastle superstructure. The heel of the paravane lifting derrick can also be seen although the wooden derrick itself has rotted away.

Figure 51: The smaller of two paravanes on the starboard side with the heel of the lifting derrick in the foreground

Figure 52: Ship's plan profile showing paravane stowage

The corresponding portside paravane is broken in two. The forward half rest on top of B-turret's upturned gun house. The aft part of the paravane lies directly below on the seabed.

Figure 53: Aft section of the portside paravane lies on the seabed adjacent B-turret.

Figure 54: Video screen grabs of the forward section of the portside paravane and the heel of the portside paravane lifting derrick.

For more information about paravanes please see section 3.1.4.11.

The current exposed layout of B-turret mimics closely the layout of A-turret. However, the opening into the turret is more compact as she is mounted higher on the ship and correspondingly rests closer to the seabed in the wreck's upturned state. Both barrels have also broken their mountings but remain approximately in-situ due to their proximity to the seabed. Both breech doors are closed. The aft portion of the gun house roof has been displaced forwards and rests with A-turret roof. The forward roof structure remains with B-turret.

Figure 55: B-turret gun breeches. The right- hand gun rammer is in the left-hand side of the image and access to the officer's cabinet is in the top of the image

The officer's cabinet was a self-contained space within the turret providing a centralised control station for the turret.

Figure 56: B-turret Officer's Cabinet

Figure 57: Aerial plan image of the aft part of the gun turret

Figure 58: Cross section plan image of the officer's cabinet

Carly rafts were mounted on the forward face of B-turret. The remains of these have fallen to the seabed and rest alongside the left-hand gun. Carly rafts were emergency life rafts and consisted of a buoyant ring comprised of copper and cork, netting, and a wooden platform in the bottom. Sailors would be immersed in water within the raft.

Figure 59: Archive image of the crew of HMS ROYAL OAK with a Carly raft in the foreground. ©IWM Q 18082

Figure 60: The remains of a Carly raft lie alongside the forward barrel of B-turret

The accommodation across the Upper and Main Decks in the bow of the ship can be viewed in snippets through the open scuttles. The accommodation spaces on the portside comprised of seamen's heads (toilets) in the bow, the Boys Mess, Petty Officers (PO) Mess, Artisans Mess and Shipwrights Mess. This area also housed the four forward torpedo tubes which are visible through a rotted hole in the ship's side adjacent to the Boys Mess. Little recognisable material is present, and due to the angle of the wreck many artefacts would have fallen away from the scuttles towards the centre of the ship. However, a collection of spoons from the Petty Officers Pantry are visible.

Figure 61: Spoons from the Petty Officers Pantry

The large and experimental watertight torpedo tube doors dominate this side of the hull situated in the Upper Deck (see Figure 62). The two rectangular doors are housed in a single large wedge-shaped indentation into the hull. The rack gearing is clearly visible on each door and make up one half of the rack and pinion mechanism for opening the doors.

Figure 62: Archive image showing the experimental double torpedo tube door on HMS ROYAL OAK

Figure 63: Video screen grab of the portside torpedo doors

3.1.1.2 Deck/Port Side Midships

The Deck/Portside Midships section of the wreck spans four complete deck levels from the Upper Deck to the Conning Tower Platform. Both the main mast and forward mast and some of their associated platforms are also present. This section contains all secondary and ancillary guns still visible on the wreck and the largest collection of ship's artefacts and items pertaining to life aboard and the ship's crew observed across the entire site. In addition, and at seabed level, there is access under the deck of the ship at both Shelter Deck and Forecastle Deck levels. As such, this section is the most complex to describe. For clarity, the description will concentrate at seabed level first from forward to aft encompassing the areas under the ship, parts of the Shelter Deck and Conning Tower Platform, the Masts and associated platforms, and other wreckage and artefacts located on the port side seabed. Moving up the side of the ship the Forecastle Deck will then be described before completing this section at the Upper Deck level.

Figure 64: Profile view of the Deck/Port Side Midships section

The space between B-turret and armoured conning tower is large enough to swim between, giving access at seabed level under the deck to the starboard side. The deck above the diver's head at this point is the Shelter Deck and was used to store Carly rafts. There are large skylights in the deck. The remains of the rafts are visible on both port and starboard sides. Decay in the Shelter Deck above has led to deck structure and artefacts from internal spaces falling to the seabed. Five lamps have fallen from the lamp store above. The decay in the deck reveals several more lamps still in-situ in the room and the wooden shelving for lamp storage.

Figure 65: Multibeam image of the Deck/Port Side Section

Figure 66: Plan image detailing visible open deck space at Shelter Deck level

Figure 67: Bulkhead/Wardroom lantern. In addition to the carrying handle these half hexagonal lamps would have a flat back fitted with a flat faced hook for attached to a wall fitting

Figure 68: Lamps have fallen to the seabed from the Lamp Room

Figure 69: Looking up into the Lamp Room

Tucked in a corner in this area is a pair of leather knee-high boots. These are lying in an upright position on the remains of a skylight cover (see figure 72). Given their location it is assumed that these have fallen from the ship as the skylight cover has collapsed to the seabed. A rope reel can be seen through the skylight above located in the boatswain store.

Figure 70: A pair of leather boots

Figure 71: WWI sailor aboard HMS ROYAL OAK wearing a similar pair of leather boots. In the background are two Carly rafts and the sailor also wears a gas mask. ©IWM Q 17937

Figure 72: Plan showing location of Lamp Room, Boatswain's Ready Use Store and Skylight

The aft bulkhead in this space is the forward face of the armoured conning tower. Two forward facing scuttles can clearly be seen with armoured shutters. One shutter is open.

Figure 73: Scuttles and Armoured Shutters

Moving out from underneath the wreck, the armoured roof of the forward section of the conning tower can be seen protruding from the seabed with the armoured director tower half buried. The director tower is partially separated from the main conning tower structure exposing the turning gear. The aft side of the conning tower is accessible under the deck and its main opening is visible.

Figure 74: The three visible levels of the armoured conning tower

Mounted adjacent to the conning tower is the portside quad 0.50 Vickers MkIII machine gun. Approximately 3 metres aft of this is a 3-pdr gun, the only one of four mounted on the ship visible today.

Figure 75: The 3-pdr gun in the foreground with a diver illuminating the 0.50 quad machine gun in the background

Figure 76: Quad 0.50 Vickers MkIII Machine Gun

The machine gun is still attached to the deck. However, most of the fixings for the mount have failed and the gun hangs precariously. Little is left securing it in place but no change in its position was observed during the survey between October 2018 and November 2019. However, in 2001 the gun was photographed by Peter Rowlands. The image clearly shows the mount still intact.

Figure 77: 2001 image of the Quad 0.50 Vickers MkIII Machine Gun by Peter Rowlands

Figure 78: Archive image of the Quad 0.50 Vickers MkIII Machine Gun. ©IWM A 1249

Two rope drums are mounted on the external portside bulkhead of the Shelter Deck. Today these are situated just above and aft of the 3-pdr gun and would have originally been used in conjunction with the

lifting derricks mounted on the same bulkhead. Decorative plaques bearing the ship's badge (crest) are mounted on both rope drums. In the last days of the survey, ship's badges were also observed on the two aft rope drums located on the Wardroom and Gunroom external bulkheads on the Forecastle Deck and on the forward sheet cable holders (capstans) at the bow.

Figure 79: Ship's Badge mounted on Rope Drums

HMS ROYAL OAK was fitted with a tripod foremast consisting of a central mast mounted on the centre line with two angled supporting struts running aft to port and starboard. The remains of the external bases of the port strut and centre mast are visible in the wreckage closet to the seabed, and directly below the rope drums. The mast would have snapped and been displaced to port as the ship rolled over and sank. On the seabed to port rests the spotting top with High Angle Control System (HACS) director, the 15-inch gun director, the 6-inch gun directors and the top of the tripod. The lower part of the mast and associated platforms appears to be missing.

Figure 80: Labelled multibeam image of the mast and bridge structures

Figure 81: Plan image of the Foremast

The lower levels of the mast structures, including the Lower Bridge, Upper Bridge and Torpedo Lookout were not observed during the survey, instead there is a pronounced gap between the upper mast structures and the ship's side. It is within the realms of possibility that some of this structure is crushed underneath the ship, however some evidence of damaged searchlights from the platform below the missing material is visible amongst the wreckage at seabed level. Artefacts from the missing structures were observed including a navigation lamp and a small 8-inch compass mounted in a gimble. Also observed was a kelvin ball with associated bracket, a compass buried in the seabed and a hood for a compass binnacle. Located to the north of the wreck are two small lumps of wreckage located in the remote survey. One of these is a length of mast strut bent at 90° at one end. It measures approximately 5 – 8 metres long. A bundle of wire projects from the end of the mast. This would suggest that if this is from HMS ROYAL OAK it is part of the port mast strut, as wires were observed in the severed end of the port strut at the 6-inch Director. No wires were observed in the mast or starboard strut.

Figure 82: 3D Photogrammetry image of the Spotting Top. The severed port side mast strut is labelled.

The second contact is a large piece of wreckage several metres high. The only identifiable features are three voice pipes, a section of steel deck or platform, a large collection of heavy electrical cabling and a section of brass railings. The possibility exists that this wreckage is part of the missing bridge structures. For more detail about the outlying targets see section 3.1.7.

Figure 83: A Navigation Lamp lies in the wreckage of the Bridge

Figure 84: Auxiliary Compass on HMS ROYAL OAK and an example aboard HMS PRINCE OF WALES in WWII. ©IWM A 3901

Figure 85: A Kelvin Ball lies in the wreckage at the foremast of HMS ROYAL OAK and archive example aboard HMS ROEBUCK in Scapa Flow during WWII. The brass compass hood in the archive image is similar to the one seen on the seabed ©IWM A 18037

This section will describe the spotting top, as it lies today, but a detailed explanation of the function and purpose of the Spotting Top and Directors can be found in section 3.1.4.2. The structure is in very good condition despite spending 80 years underwater. The majority of the equipment is still in place, offering a unique insight into dreadnought gunnery control.

Figure 86: The Spotting Top and HACS Director

Figure 87: 3D Photogrammetry image of the Spotting Top

Figure 88: Aerial image of the Spotting Top looking aft. The port side yard arm is in place top centre. In the right of the image is the remains of the 6-inch port side director and platform

Figure 89: View of the Spotting Top looking forwards with windows illuminated

Figure 90: Looking into the port wing of the Spotting Top

Figure 91: The HACS Director sits on top of the Spotting Top and was one of the interwar modifications. It formed part of the ship's anti-aircraft defence

Figure 92: The forward part of the Spotting Top rests on the seabed. The canopy (roof) has decayed and is mostly absent offering access to the equipment inside

Figure 93: The gun ready panel in the Spotting Top. This device has a light for each barrel of the four turrets and provided information to the Spotting Top as to when enough guns were ready to fire

Figure 94: Spotting Top Fire Control Instruments. Headphones remain visible in the silt

Figure 95: An "Aid to Spotter" is lying partially buried in the forward spotting top. This is a pair of binoculars combined with periscope extensions for improved vision.

Figure 96: Looking into the port side 6-inch Director. The roof has detached from the main structure. The door into the director is on the upper side and is locked with a padlock.

Overall, there has been relatively little structural change in this area of the wreck in 25 years.² However, comparison with the 50th anniversary film (1989) by Peter Rowlands shows that the forward Spotting Top roof was still intact. It has decayed and fallen off at some point between that footage being taken and 1996. The Spotting Top was also photographed around the time of the 60th anniversary and clearly shows deterioration in the HACS Director.

² Anecdotal evidence from a team member who was part of the initial oil recovery research work.

Figure 97: Images of the Spotting Top and HACS Director from 1999

The HACS Director was attached through the spotting top via a cylindrical mount. In 1999 the mount had parted from the spotting top floor but the exterior of the HACS was intact. During our survey the rangefinder remains in the upright position while the exterior of the HACS platform has corroded extensively. The cylindrical mount has also parted at the top forcing the HACS to drop towards the seabed.

Figure 98: 2019 image of the Spotting Top and HACS Director

Scattered on the seabed around the Spotting Top and between the two masts are glass rods made by Pyrex. The letters are embossed on the rods and they measure 33cm long. These are insulating rods and would have originally had metal end cap fixings to secure the radio aerial wires to the masts.

Figure 99: Glass Insulating Rods made by Pyrex

Figure 100: Glass insulating rods on the bridge of HMS RESOLUTION in 1933. ©IWM Q 65629

Also lying on the seabed just aft of the Spotting Top is a smoking pipe. Pipe smoking was very popular at this point in history and officers even had special pipe racks in their cabins (see figure 185 in section 3.1.2).

Figure 101: A smoking pipe lies on the seabed

HMS ROYAL OAK had two 50-foot steam pinnaces, their fate is fully discussed in section 3.1.8, but the first to sink now lies on the seabed just aft of the spotting top at approximately midships. The forward part of the pinnacle is structurally recognisable, albeit decayed. A forward air cowl is in place, as is the gun mount. The double diagonal wooden construction of the hull is clear. The small pinnacle boiler is in situ but displaced almost 90° to the line of the boat. In the 1979 survey, imagery suggests that this part of the boat was intact with roof and handrail present. The external structure was absent by 1999. The main recognisable structure of the pinnacle ends at the boiler, but moving aft several details can be identified partly buried in the seabed. These include one of the lifting eyes mounted in the keel of the boat and used to lift the boat on and off the ship. Fragments of the double diagonal planking are scattered in this area of seabed. Also present is a single rectangular window from the aft superstructure, the propellor and stern cleats. The rudder was not observed. The pinnacle debris extends aft over an area of seabed consistent with the size and shape of the original boat.

It is noteworthy that the boiler is displaced by almost 90° to the line of the boat and the small steam engine used on these boats was not located. Underwater, the seaplane crane from the aft superstructure appears to be the only other structure that may have come into contact with the boat and caused structural damage, but survivors described it sinking before OAK, due to falling superstructure. This account is presented in 3.1.8. Our work can neither clearly corroborate nor refute this assertion.

Figure 102: Overhead 3D image of the bow section and boiler of the pinnace

Figure 103: Pinnace looking aft from the bow. The cowl and gun mount are visible

Figure 104: Two images of the pinnacle bow taken 20 years apart.
The left-hand image was taken in 1999 and the right-hand image was taken in 2019.

Figure 105: The rudder from the pinnacle is buried in the seabed surrounded by associated support brackets

Lying between the pinnacle and the main wreck is the first of three sections of steel caisson. The second and third sections lie further aft.

- 1 6 metres x 1.24 metres
- 2 9 metres x 1.24 metres
- 3 3 metres x 1.55 metres

A platform was identified mounted to the first section measuring 3.5 x 3.5 metres.

Figure 106: Caisson sections 2 & 3

These are the remains of the Radar ranging platform constructed during WWII and discussed in section 1.2.1. The steel cables supporting the structure decayed and failed in the late 1940s, causing the structure to collapse into the sea, witnessed by local resident Johnnie Meil. The 1950 survey report indicates that the base for the caisson was cut flush with the highest part of the wreck during their work. The base was not located during the survey.

Lying alongside the 2nd length of caisson is a range finder from the main mast HACS director and resting up against it is the window from the steam pinnacle.

Figure 107: Main Mast HACS range finder and pinnacle window

Figure 108: Annotated 3D Photogrammetry overview of the port side midships section

Figure 109: Stern aspect of the port side midships section

The Main Mast and supporting struts lie alongside the ship in a forward direction. The mast is detached at the ship and extends as far as the Upper Platform where all three legs converge. The Main Mast and port strut sections are complete, but it is unclear if parts of the starboard strut are missing or buried. The Upper Platform was not attached or observed in this location. It is possible that it is buried at this point but the 1st section of caisson and associated radar ranging platform have fallen on top of this area. The Main Mast HACS Director which was mounted halfway up the Main Mast remains in situ but broken. The range finder for this lies to the south alongside the 2nd section of caisson (see figures 109, 111 & 236). Further to the south is a collection of unidentified wreckage. It contains aluminium (or similar alloy) cabinets, the remains of electrical equipment and more Pyrex glass insulator rods. It could be wreckage from the Upper Platform of the Main Mast which contained the Direction Finding Office.

Figure 110: Items from unidentified wreckage including an alloy cabinet and electrical items

There is a large mass of wreckage inside the 1st caisson, consisting of material from the midships section of the Shelter Deck, the Pom Pom Platform, and the Searchlight Platforms. A large volume would have originally been occupied by the funnel. Funnel material tends to decay quickly, and it is unlikely to be recognisable or

even present after 80 years underwater.

The portside 2-pdr Quick Firing Mk VI Octuple Pom Pom gun is visible in the wreckage. Upside down, the ammunition boxes stick out. All eight barrels are visible, and ammunition is present in the boxes. The two port side 36-inch searchlights are buried underneath. Resting in the wreckage forwards of the Pom Pom gun is the remains of a solitary gas mask. It was the only mask identified during the survey which is, perhaps, unusual given the number of crew.

Figure 111: Profile image showing funnel, Pom Pom Gun and Searchlights

Figure 112: Octuple Pom Pom Gun and Ammunition Boxes

Figure 113: A Gas Mask

Moving aft from the Pom Pom gun and underneath the deck behind the Main Mast structure is an open space containing deck equipment from the Shelter Deck, including boat cradles, deck lighting, ready ammunition boxes, and a spare anchor. Crushed underneath the mast is a twin-screw motorboat. Both rudders are present but the small propellers have been removed.

Figure 114: Plan image of the aft Shelter Deck

Aft of the funnel, the Shelter Deck was used to store the ship's boats, including the two 50-foot Steam Pinnaces. The main derrick was mounted on the main Mast and would be used to lift the boats in and out of the water. Stored in between the pinnaces on the centre is a large spare ship's anchor. This has fallen to the seabed and, as the pinnaces were in the water at the time of sinking, their empty cradles are above on the upturned hull. The main derrick was not observed but ready ammunition boxes are present.

Figure 115: The Aft Shelter Deck of HMS ROYAL OAK

Figure 116: The transom of the twin-screw motorboat. Both rudders stand upright but the propellers are missing from the P-brackets.

Figure 117: The spare anchor lies on the seabed

Figure 118: Boat Cradle. The cable hanging through the frame has a light fitting on the other end

Figure 119: A light fitting hangs on the boat cradle. How it got there is a mystery

Figure 120: A Ready Ammunition Box

Moving aft under the ship is a collection of crockery, glass and jars on the seabed. These have fallen from a decayed hole in the deck above. The hole looks into the Wardroom Pantry where plates and other crockery remain in their racks.

Figure 121: A Pan Yan Pickle jar is buried in the seabed, just the lid is visible

Figure 122: Plates and glassware have fallen to the seabed

Figure 123: Looking up into the Wardroom Pantry

Figure 124: Plan showing the location of the Wardroom and Gunroom Pantries

Moving aft you encounter a collection of shaving soap bottles. Their original location in the ship remains unclear, but they presumably fell from one of the skylights to the Wardroom. Also present is a collection of used small arms cartridges, most probably from the 0.50 Vickers Machine Gun. These cartridges would be

gathered up post firing and kept for recycling.

Figure 125: Shaving Soap Bottles

Figure 126: Used Small Arms Ammunition

Figure 127: Access to the aft bulkhead of the Wardroom is between the Sea Crane base and X-Turret

Moving out from under the Shelter Deck and around the base of the Sea Plane Crane is access under the ship at Forecastle deck level between the Sea Plane Crane base and X-turret. The aft bulkhead of the Wardroom and Gunroom is accessible all the way round to the starboard side door into the Wardroom Lobby (see Figure 124). On the starboard side a solitary 4-inch shell lies partially buried next to a Wardroom Lobby scuttle. Part of this aft bulkhead has rotted through allowing items to fall from inside. Lying in the debris is a double bass scroll and bow. The scroll is the decorative end where the tuning pegs are housed.

Figure 128: A 4-inch shell lies under the ship

Figure 129: The remains of a double bass and bow lie on the seabed fallen from the Wardroom

Figure 130: The Shelter Deck, Forecastle Deck and Upper Deck

Mounted on the port extremity of the Shelter Deck are two twin-barrelled 45/QF Mk XIV anti-aircraft guns, one forwards and one aft. The guns are both in place and hang from the Shelter Deck. Their gun shields have decayed and fallen to the seabed. It is noted that the gun shields were in place during the filming of the 50th anniversary documentary. The frame of the aft gun shield rest on top of caisson 2 (see Figure 108).

Figure 131: The two port side anti-aircraft guns

A companionway is visible above the anti-aircraft guns on the Forecastle Deck. This external passageway gives covered access to midships accommodation and workspaces. On the port side of the ship these spaces include the Bakery, Warrant Officer's Mess and Pantry, and the Gunroom. The companionway is lit with external lights. Some access doors are open. The spaces are also fitted with a combination of round and oval scuttles. Decay in the external bulkhead also offers visual access to internal spaces.

Figure 132: Divers filming the wreck of HMS ROYAL OAK. The companionway is visible with decayed holes in the bulkhead

Figure 133: An oval scuttle in the companionway

Figure 134: A huge dough mixer in the bakery

Figure 135: A Belfast style sink in the Bakery

Figure 136: External light fittings in the Companionway

Figure 137: The Warrant Officer's Pantry. The scuttle has decayed and fallen into the space

Half way along the companionway and secured to the outside of the ship is a large anchor. Similar examples can also be found on HMS ROYAL OAK's sister ships. The second portside paravane is located at the forward end of the companiway. It rests on the upturned deckhead and is displaced a short distance aft from its original mounted position. It remains intact and is adjacent to a large watertight door into the Forecastle Deck.

Figure 138: The second port side paravane

Figure 139: The companionway anchor shown alongside an archive image of HMS RESOLUTION. ©IWM Q 65630

Above the companionway is the Upper Deck. The midships section houses the six 6-inch casemate guns. At a depth of approximately 20 metres they are all in situ and intact. During the sinking, some guns have swung to port to varying degrees. The guns are numbered 1 – 6 from bow to stern.

Figure 140: Casemate Number 1

Figure 141: Casemate Number 2

Figure 142: Casemate Number 3

Figure 143: Casemate Number 4

MT

Figure 144: Casemate Number 5

BA

Figure 145: Casemate Number 6

3.1.1.3 Deck/Portside Aft Section

Figure 146: Stern Section

The stern section extends from the forward edge of X-turret to the stern post on the portside of the ship. The stern section is dominated by X and Y-turrets, a large range finder at X-turret, and the ship's seaplane catapult also at X-turret. Like the bow, the stern is held off the seabed supported by the gun turrets. The starboard edge is clear of the seabed as far forward as frame 241, and approximately in line with the skeg. The stern is intact but largely free of any intricate architectural features. The remains of the base of the Ensign Staff is still in place. Two sets of fairleads are visible along the port and starboard rail, as are stern bollards. Some parts of the stern railings remain but these are limited to stanchions and the occasional rail. The stern deck is covered in teak which is in very good condition and punctuated with skylights and access hatches to the Admiral and Officer's accommodation.

Figure 147: Multibeam image of the stern

Figure 148: The stern of HMS ROYAL OAK

Two rows of scuttles line the aft port hull opening to the Main and Middle Decks. There are seven openings into the Middle Deck which housed the Victualling Office and Captain's Office in the stern and the remaining scuttles give access to Officers' Cabins. On the Main Deck, 26 round scuttles and two square ports offer glimpses into accommodation spaces from the Admiral's Cabins at the stern, which extends to eight round and two square ports and take up approximately one third of this space to the Marine Mess, just forward of X-turret. A large proportion of the scuttles at the stern remain closed with deadlights in place.

Figure 149: Stern Scuttles – Port side

The seabed underneath the stern is mostly free from artefacts or ship's structure. The largest artefact aft of the stern turrets is the portside accommodation ladder. The structure remains recognisable but shows the expected signs of decay associated with being underwater for 80 years.

Figure 150: Port Side Stern Accommodation Ladder

Figure 151: Archive images showing port side stern accommodation ladder

Examples of both oil and electric lighting are present throughout the site including the gun houses of the turrets. The archive image below is a staged shot handling a 15-inch projectile within the armoured gun house. In the top of the image, we can see both an oil lamp and an electric cage lamp.

Figure 152: Archive image of 15- inch shell handling detailing oil lamp and electric cage light. ©IWM Q 17903

At Y-turret an oil lamp base sits in between the exposed gun barrels and a second broken oil lamp base lies on the seabed just aft of the turret. An intact oil lamp is located at X-turret.

Figure 153: Oil Lamp base at Y-Turret

Figure 154: Oil Lamp at X-Turret

Figure 155: Electric light in the Officer's Cabinet of the turret, missing its brass cage

The gun house rooves of both stern turrets (X & Y) are also detached, and rest on the bottom. As with the forward turrets (A & B) the barrels have broken their mounts and forced the rooves to the seabed. The remains of the internal structures of both stern turrets closely resemble the forward turrets with some distinct differences. At Y-turret the right-hand gun, which is the aft most gun, has not fallen from its mounts and remains in its original position. The gun barrel is buried in the seabed at a steep angle. The forward (left-hand) gun has fallen from its mounts and lies on the seabed. This arrangement offers a unique insight into the material between the two barrels. Both breech doors are closed, and the rammers are present. Close to the seabed on the left-hand gun rests the auxiliary firing trigger which resembles the pistol grip of a small hand gun. While gunfire was generally controlled centrally from the 15-inch Director Tower at the Bridge each gun could be fired independently using such a trigger.

Figure 156: 3D Photogrammetry image of Y-turret. The barrel of the right-hand gun is clearly visible protruding from the front of the turret while the breech end of the left-hand gun is visible on the seabed.

Figure 157: Firing Trigger

Figure 158: The breech of the left-hand gun at Y-Turret

Lying on the seabed alongside the forward edge of Y-turret is the 6-Pdr sub calibre gun which should be stowed inside the gun house. This has broken its mounting and fallen to the seabed (see section 3.1.4.6 for more information).

Figure 159: A 6-Pdr Sub Calibre Gun lies on the gun house roof of Y-Turret

Figure 160: Breech end view of the 6-Pdr sub calibre gun at Y-Turret. The 15-inch gun is visible in the background

The external structure of X-turret is the same as her three counterparts except she had a catapult for launching a seaplane mounted longitudinally on the turret roof. This now rests at the aft edge of X-turret. The catapult strut protrudes out to the side of the ship and is partly covered by the range finder mounted on the gun house roof. The armoured gun house roof also partially rests on the catapult and range finder and so is raised off the seabed on the aft edge. The seaplane was absent from the ship at the time of sinking.

Figure 161: Catapult at X-Turret

Figure 162: X-Turret Range Finder atop the Catapult

Figure 163: X-Turret Range Finder

Figure 164: Two Divers Illuminate X-Turret

Figure 165: Breech Operating Lever. It opens and closes the breech of the gun via the hydraulic power mechanism. If power failed the wheel below is used.

3.1.2 Starboard Side

The starboard side description includes the structure and artefacts located on and around that side of the ship. The entire section is dominated by the four torpedo holes and as the ship rests at a 45° angle allowing access under the deck from the port side there is no access under the starboard side. Consequently, the starboard casemates and centre section of the upper decks are all buried in the seabed or displaced to port. Visual access to internal accommodation spaces is via open scuttles only and some artefacts and material have fallen from these openings onto the seabed due to the angle of the ship and flow of water through the structure.

Figure 166: The Starboard Side.

3.1.2.1 Torpedo Damage

The torpedo damage is the defining characteristic of this side. The ship was struck on her starboard side by four torpedoes (see 1.1.3). The first torpedo hit the bow of the ship and is labelled box 1 in Figure 168. This was a single strike from the first salvo fired. A subsequent salvo containing three torpedoes all found their target in quick succession and are labelled 2,3 & 4 in the diagram above. Technical analysis of the torpedo

damage is included in section 3.1.6.

All four holes in the starboard side of the ship are extreme. The first hit created a large area of blast damage just back from the forefoot of the ship. The bow damage is the widest and cuts almost through to the port side as the ship is very narrow at this point. The wreckage of the forefoot rests on the seabed under the bow and just to the starboard side. Clearly visible on the wreckage is the paravane skeg (also see 3.1.4.11). HMS ROYAL OAK was one of the first ships to be fitted with a paravane skeg; these were new technology in 1916.

Figure 167: The forefoot of HMS ROYAL OAK rests on the seabed with paravane skeg visible

At the time of the sinking the forefoot was still attached to the bow of the ship as observed in a 1950s diver survey of the site (see Figure 18). The 2006 ADUS multibeam survey of the wreck observed the forefoot on the seabed. This has fallen at some point between the two surveys. The result of the forefoot detaching from the bow is the appearance that the initial torpedo damage is larger than it would have been.

Holes two, three and four are similar sizes, ~8 metres wide by 5 metres high. Hole two penetrates the ship below the forward accommodation and exposes the 4-inch magazine in this part of the ship.

Figure 168: 3D Multibeam sonar overlaid with photogrammetry

Holes three and four are further aft and extremely close together. They have penetrated the torpedo blister and ruptured internal longitudinal bulkheads. The bilge keel has been damaged in the explosion. The aft

section now hangs down in between holes three and four. The aft end touches the seabed.

3.1.2.2 *Starboard Side Accommodation*

Visible above the along the starboard side of HMS ROYAL OAK are all the scuttles of the Upper Deck and Main Deck at the bow and Main Deck and Middle Deck at the stern. During the survey, 58% of these were observed to be open. Scuttle status and contents are detailed in Annex 8.1.

Forward, two rows of scuttles are visible, 30 in Upper and 17 in Main Deck. The first four back from the bow in both decks are barred to protect from overside working of anchors and other equipment. The spaces across these decks are divided between equipment stores such as the Paint Store and Boatswain's Store, as well machinery spaces such as the torpedo rooms and accommodation spaces for lower ranking sailors, including mess rooms, bathroom, toilets, and the ship's prison cells.

Figure 169: Scuttles for Chief Petty Officer's Toilet Cubicles.

Figure 170: Engine Room Artificer's Pantry

Crockery and glassware are visible in the open ports for the Engine Room Artificer's (ERA) Pantry (Figure 172) and Mess on the Main Deck, and for the Electrical Artificer and Ordnance Artificer's Pantry and Mess on the Upper Deck. Some items have fallen from these ports to the seabed.

Figure 171: A cup and glass bottle lie on the seabed. The Royal Navy Crown emblem is visible of the cup and the deck edge of the ship can be seen in the background.

Figure 172: Royal Navy messware, glassware and a tile have fallen from the ERA's Pantry

Figure 173: A glass fruit bowl lies on the seabed at the bow.

The sick bay aboard HMS ROYAL OAK was located on the Upper Deck and occupies the entire space between A and B-turrets on the starboard side of the ship.

©National Maritime Museum, Greenwich, London

Figure 174: Plan image of the Sick Bay

The sick bay would be equipped with adult sized swing cot beds to ensure the patient did not fall with excess movement in rough seas. The remains of cots are visible in the sickbay through a large rotted opening the ship's hull. On the seabed lie a collection of medicine bottles.

Figure 175: Medicine bottles from the Sick Bay

The last scuttle on the Upper Deck was that of the Isolation Ward and is labelled in red on Figure 174. Some days after the loss of the ship, the relatives of George Charles Pollard received a letter posted before the loss on 10th October 1939. George was a 2nd Class Stoker aboard HMS ROYAL OAK, but at the time of writing he was in the Isolation Ward with suspected measles. It is unknown if he escaped the ward during the sinking or indeed if he was still there, but it is likely that to look at the porthole to the Isolation Ward is to look directly at the grave of George Charles Pollard.

Figure 176: The Isolation Ward Porthole/Scuttle

A greater number of the scuttles at the stern are closer to the seabed than at the bow. As such, the seabed has been subjected to significant scouring through the action of tidal flow and water surge. Relatively, the wreck of HMS ROYAL OAK is not subjected to significant tidal flow. However, it was observed throughout the survey period that the tidal flow that does exist travels predominantly across the wreck from port to starboard. Due to the size of the ship and the depth of water in which she lies, coupled with her position on the seabed and the small clearance of water above her upturned hull, the wreck is subject to water surge during rough weather. This is exacerbated with winds from the south and south-west.

The ship presents a 20-metre high barrier to both tidal flow and water surge. The combined effect appears to funnel the water through the wreck from port to starboard, forcing a large volume of water through the small open ports on the starboard side. During the survey a scalloped effect on the seabed adjacent to every open port at seabed level was observed. Small artefacts have been washed from the scuttles and now lie on the seabed. It was also observed that these small items moved small distances during the survey period consistent with the water flow.

Figure 177: Video screen grab detailing seabed scouring

Seven scuttles exist on the Middle Deck at the stern of the ship offering light and ventilation to office space and lower ranking officers' cabins. All seven are closed. The upper row of scuttles situated in the Main Deck comprise of 28 round and 1 square ports. All are given to higher ranking officers except the last 4, which offer an insight into the Marines Mess. It is noteworthy that not all accommodation spaces have scuttles or skylights, so did not have access to direct fresh air or sunlight, including Ordinary Seamen, Stokers, Ship's Cook and catering staff.

Figure 178: A closed scuttle on the Middle Deck at the stern. This space was the Warrant Supply Officer's Office.
The closed deadlight is visible through the glass.

The Admiral's accommodation spans the breadth of the ship at the stern. On the port side of the ship this extends to 10 round scuttles and 1 square port. Scuttles 5 and 6 (from the stern) look into the Admiral's Sleeping Cabin. Both scuttles are open, enabling the space to be lit from one and photographed from the

other. Visible inside are the remains of the Admiral's bed frame, a drawer handle and a curtain pole. The doorway through to the Admiral's bathroom is also visible in the space, although the scuttle to the bathroom remains closed.

Figure 179: View of the Admiral's bedframe from scuttle No 5

Figure 180: View of the Admiral's Sleeping Cabin from scuttle No 6

Figure 181: A telephone is visible in Cabin No 5 designated for the Medical Officer. The right-hand image shows what is believed to be an ink blotter

Figure 182: The Admiral of HMS QUEEN ELIZABETH in his cabin in 1942.
An example of a telephone and drawer handles are labelled. ©IWM A 7967

Figure 183: Admiral of HMS BELFAST in his cabin in Scapa Flow 1943. Examples of a curtain pole and ink blotter are present. The object behind his right shoulder is a rack containing smoking pipes. ©IWM A 21758

A small number of artefacts were observed on the seabed adjacent to the open scuttles. These included three Chinese soup spoons, the head of a four stringed banjo with tuning pegs visible, and what we believe to be a decorative brass ventilation fitting mounted on a wooden board. It is likely this would have provided through ventilation to a bathroom or possibly a wardrobe, but at the time of writing we have not been able to discover its specific purpose.

Figure 184: A Chinese soup spoon lies on the seabed

Figure 185: The remains of the head of a banjo with tuning pegs visible

Figure 186: Decorative brass ventilation fitting

3.1.3 Top of the Hull

When describing the top of the hull we are referring to the upturned hull which is now the shallowest part of the site and therefore the “top” of the wreck. The stern section of the hull is dominated by the remains for the four propellor shafts and A-brackets and the large single rudder.

All four propellers were salvaged during a survey of the ship conducted in 1950. The survey report is included in Annex 8.3. The survey was conducted under the supervision of Boom Defence and Salvage Officer Mr J. Alexander and Captain W.R Fell, R.N (Ret'd) from Royal Fleet Auxiliary (RFA) salvage vessel Salvictor.

Figure 187 Multibeam image of the hull of HMS ROYAL OAK, viewed from astern

The Port inboard propeller was salvaged first by cutting the A-frame and prop shaft and then lifting the propeller and A-frame as a composite unit. Unfortunately, the propeller slipped from the A-frame during the lift and landed back on the hull adjacent to the rudder and was subsequently salvaged. The A-frame was located on the seabed some 30 metres off the starboard side and has been dropped here during the salvage operations. The other three propellers were salvaged by severing the prop shaft just aft of the A-frame brackets which proved to be far more successful and less labour intensive. The rudder is intact and lies just aft of the shafts.

Figure 188: The Rudder

Figure 189: Outer Portside A-Frame Bucket

Traditionally the Royal Navy White Ensign flown from the wreck each year to mark the anniversary is secured to the outer port propellor shaft.

Figure 190: The recovery of the 79th Anniversary Ensign on the left and the stowing of the 80th Anniversary Ensign on the right by members of the RN Northern Diving Group

The remainder of the hull is a vast expanse spanning some 30 metres, and reveals both original build architecture and the additional structures added to the ship during her lifetime. Upon completion the ship was fitted with two bilge keels running from the aft end of A-turret to the forward edge of X-turret. The addition of the torpedo bulges during the interwar period has mostly covered the original bilge keels. On the hull today we see the forward and aft ends only. The torpedo bulges extend from very close to the bow at frame 6 to frame 240 in line with the outside A-frame brackets. New bilge keels were fitted to the outside of the torpedo bulges and extended from the aft end of B-turret to the forward end of X-turret.

Figure 191: Plan image detailing torpedo bulges in blue and new bilge keel in red

Figure 192: Multibeam image detailing torpedo bulges and bilge keels

The forward section of the top of the hull encompasses the damage from torpedo strike number one, described in sections 3.1.2 and 3.1.6.

HMS ROYAL OAK was an oil-fired ship sunk in fighting condition. Since the loss the ship has leaked oil, this is exacerbated by the gradual decay of the hull. In the 1990s it was deemed necessary to reduce the loss of oil and reduce the risk of a serious environmental pollution event. Several methods were tested, included devices to capture leaking oil. This period culminated in the decision to remove oil directly from the hull. In 2003 work commenced under the direction of the MOD SALMO. This resulted in the installation of a series of diver operated "hot tap" valves to the top of the hull to enable oil removal from deeper within the ship. This method proved highly successful with the removal of over 1,600 tons of heavy fuel oil. The valves remain in place on the hull and are monitored by SALMO. They will enable future oil removal as and when necessary.

Figure 193: A hot tap valve on the hull of HMS ROYAL OAK

3.1.4 Gunnery and Fire Control

"The first object in all cases of gunnery against a moving target is to fire a projectile in a direction and at a time to cause the projectile and the target to reach a certain point simultaneously"

RN Gunnery Manual BR1898(9)

3.1.4.1 State of preservation

ROYAL OAK is unique in having most of her fire control equipment present and accessible. The control top is complete with the roof missing from the forward part, the directors are present and the officers cabinets in the gun houses are open, the gun house rooves having fallen off. The only inaccessible part of the fire control system is the transmitting station deep inside the ship.

Apart from the addition of four twin 4-inch anti-aircraft guns and their associated High Angle Control System (HACS) the ship was not significantly modernised between WW1 and WW2 so the fire control equipment is as it was at the end of the WW1.

When she sank the guns were pointing to starboard, possibly covering the entrance to Scapa Flow, or they may have rotated to point 'downhill' as the ship rolled. The end result is that the weight of the ship rests on the barrels. This caused the trunnion caps to fail and the guns to fall out of their mountings, in turn dislodging the gun house roof. In the forward turrets the elevating mass (gun barrel, recoil slide, recoil buffers and loading system) of all four guns are lying exposed on the seabed. In the aft turrets the guns have not fallen so far from their original position.

From bow to stern the four 15 inch turrets are designated A, B ,X and Y

Figure 194: 3D Photogrammetry overlay of the four 15-inch gun turrets

3.1.4.2 Fire Control

The gunnery process was controlled from the control top. High on the foremast this had a good view of the target and was clear of gun and funnel smoke. Rather than each turret aiming and firing independently, they were all controlled by a single director; a dummy gun turret placed high on the foremast just below the control top. All corrections for range and deflection are applied to its sights while the operator tracks the target. The guns are all slaved to, and fired from, the director.

Behind B-turret is an armoured conning tower from which the ship could be controlled in battle, although the poor view through narrow slits in the armour meant the command team usually stayed on the open bridge. An armoured gunnery control position with a large rotating armoured tower above it is located behind the conning tower. The tower contains a second director and a range finder as backup, in case the control top and aloft director were shot away. Each 15-inch turret also has a range finder and a set of sights that would allow it to engage the enemy in local control if the central control system failed. X-turret could also take over as the director for the other turrets.

The range finder is a long tube with a mirror at each end, an optical arrangement allows the operator to see an image of the target from each mirror through a single eyepiece. By adjusting the angle of one of the mirrors the two images could be overlaid on each other and the range calculated from the mirror angle. The longer the range finder tube the more accurate it was (in reality the mechanics of the range finder are rather more complex involving prisms and multiple lenses.) One arm of the HACS range finder stands clear of the wreckage of the director on the control top and various parts of the turret rangefinders can be seen around A and X-turrets.

Figure 195: HMS ROYAL OAK as modernised in 1939

Figure 196: HMS ROYAL OAK as she would have looked on 14th October 1939. ©IWM FL 12252

Figure 197: Control Top and HACS Director

Figure 198: 15-inch and port 6-inch Directors under the Control Top

Figure 199: Gun director on tripod mounting

Figure 200: Diagram of an Aloft Director

Figure 201: Diagram of an Armoured Director Tower

Figure 202: View of the inside of the Port 6-inch Director

Figure 203: ROYAL SOVEREIGN (in 1917) showing: D 15" directors, 2d P&S 6" directors (later moved to foremast on ROYAL OAK), Δ X turret backup director

3.1.4.3 Target Engagement Sequence

Once equipped, you then can fire. The first task is to identify which ship in the enemy fleet to engage and ensure that everyone is looking at the same target. The captain and gunnery officer achieve this by transmitting the target bearing from a bearing indicator on the bridge or gunnery control tower to the control top. Once the gunnery team in the control top are tracking the target, they send the bearing electrically to the transmitting station deep inside the ship, from there it is distributed to the turrets and directors. Once the transmitting station starts to receive ranges from the range finders (or estimates from the spotting top) they are combined with target bearing data on the 'Dryer fire control table' (Figure 204) to form a plot of the target movement relative to own ship.

Figure 204: Dreyer Fire Control Table

To provide accurate bearing and elevation data to the guns when they are ready to fire, it is necessary to continuously calculate the range and bearing to the target at the point in the future when the projectile will land. To do this it is necessary to know:

- Range to target.
- Rate at which the range is changing.
- Bearing to target.
- Rate at which the bearing is changing.

Knowing these rates allows the system to account for how far the target moves whilst the shell is in the air. At a range of 20,000yds (18km) the time of flight is 35 seconds. A König class battleship could steam at 20 knots (10.3 m/s), so in 35 seconds it would have moved 360 meters. As a König is 175 meters long the shot would miss unless calculations compensate for the target's speed.

All this assumes that gun knows exactly where the target is when it fires, however in the days before radar and laser rangefinders this was far from certain. What is the relative position of own ship and the target now, a number of minutes since the last reliable fix? In the unlikely event that the two ships were sailing directly away from, or towards each other at 20 knots (a total range rate of 40 knots) then even if the first shot was a direct hit, without allowing for the relative movement of the two ships, a second shot 34 seconds later would miss by 700m.

Whilst keeping a track of the target bearing is relatively easy, by keeping a sight pointing at it, range data of dubious quality was received infrequently from range finders in the turrets and the armoured director tower which would be struggling with poor visibility, smoke, shell splashes and vibration of a ship running at near

full speed. In order to provide continuous range data, the estimated range is set on a mechanical 'range clock' which then runs at a speed set by the estimated range rate to provide a continuous read out of range to target.

A Dumaresq (invented by Lt John Dumaresq in 1902) is used to calculate range rate and speed across. The Dumaresq is a mechanical calculator rather like a complicated slide rule that subtracts own ship's course and speed from the target's course and speed to give the relative motion along the line of sight to the target (range rate) and across the line of sight (speed across). The system can work in either direction, estimated enemy course and speed being used to calculate rates or observed rates used to calculate enemy course and speed, this allows constant checking of the results and best use of data.

The range rate used to set the range clock is estimated by the Dreyer fire control table. The table consists of two plots (rolls of paper moving at a constant speed), one showing estimated range, observed range and fall of shot, the other showing estimated and observed deflection. By laying a grid over the plot an estimate could be made of how fast the range or deflection was changing and this rate then applied to the range clock.

Own ship's course and speed are applied to the Dumaresq automatically which in theory allowed the system to keep working even when the ship was manoeuvring. In practice the gyrocompass and speed log were not really up to the job and the plot usually had to be restarted after a turn. The table operators provide their best estimate of range and range rate to the gunnery officer in the control top who has final say on what rate to use.

A simpler form of Dumaresq is fitted in the control top (Figure 205) to provide a sanity check on the solution provided by the transmitting station. This instrument is bolted down in line with the ship's keel. The operator rotates its base until a simple open sight points at the enemy. Own ship speed and estimates of enemy course and speed are set on the appropriate scales and the resulting target range rate and speed across read from the main scale. A deflection drum scaled for the ship's guns displayed the deflection to be applied to the gun sights based on range and calculated rates.

Once firing commences the observers in the control top report the fall of shot (over, short or straddle) and call for corrections to the range, deflection and range rate. These reports were relayed electrically to the transmitting station by an array of instruments mounted on the spotting top bulkhead.

Figure 205: Dumaresq Mark VIII from BR 1535 Handbook on Minor Fire Control Instruments 1946

Figure 206: Dumaresq from HMS VANGUARD housed at Stromness Museum

Figure 207: Control Top HMS REVENGE. ©IWM A 1510

Figure 208: Forward end of the Control (Spotting) Top

Figure 209: Bearing Indicator with Periscope and drawing of bearing indicator (courtesy dreadnoughtproject.org)

Figure 210: Bearing Indicator and drawing of bearing indicator (courtesy dreadnoughtproject.org)

The 'aid to spotter' placed two periscopes in front of a pair of binoculars. These periscopes moved the image seen by the operator's eyes further apart, improving his stereoscopic vision at long-range making it easier to estimate how far over or under the target the shots were falling.

A 'gun ready board' with four pairs of lamps, one for each gun, indicates when the gun loading cycle is

complete and a gun ready to fire, this lets the spotters know how many splashes they are looking for. A similar board in the director is used to determine when enough guns are ready to fire a salvo.

Figure 211: A Gun Ready Board in the Spotting Top

3.1.4.4 *Follow the Pointer*

At the time ROYAL OAK was built and through into the 1940s the technology did not exist to remotely control the motion of machinery. The best that could be achieved was to move a lightweight pointer by electrical signals. This led to 'follow the pointer' control. A transmitter fitted to a pointing device such as a director or bearing indicator sent an electrical signal to receivers around the ship, frequently through an arrangement of change over switches which allowed the receiving device to take its input from different sources. The receiving device such as a training receiver (Figure 213) or elevation receiver (Figure 222) has a motor to drive a red pointer, a second black pointer on the same dial is driven by a mechanical input shaft connected to the machinery to be controlled, for example a 15-inch gun turret or pair of binoculars. The operator sits in front of the receiver and drives the machinery through hand wheels or levers to align the two pointers. In the control top a training receiver takes training data from either the gunnery control tower or director and through a series of shafts and flexible drives rotates the various optical devices to track the target, this ensured that everyone was looking at the same target and provided a quality check on the firing solution.

Figure 212: Spotting Top Fire Control Instruments

Figure 213: Training Receiver on the left and Training Receiver Mechanism, the red cylinders are the receiver motors

Figure 214: Minor fire control instruments for relaying observations data between positions

The whole process of tracking the target and generating a fire control solution was cumbersome and required a large number of people to operate as a team. Each control required an operator which led to a very crowded working environment. Without regular practice it was difficult for the process to run smoothly in benign conditions, never mind under the stress of battle.

The system relied heavily on getting regular accurate ranges. Operating the range finder in battle with less than perfect visibility, the ship moving at high-speed causing everything to vibrate, the view obscured by funnel and gun smoke and shell splashes was extremely difficult. At Jutland very few of the Grand Fleet ships got good range readings. Frequently, the whole elaborate process was ignored and the gunnery officer controlled firing by simply observing fall of shot and calling for corrections. This worked so long as the enemy was on a broadly parallel course and range and bearings were changing slowly.

3.1.4.5 15-inch Guns

Some of the largest calibre naval guns ever built, ROYAL OAK's 15-inch guns remain impressive even today. The barrels themselves are imposing atop the deck, but the gun workings are built deep into the fabric of the ship. Gun mountings are colossal rotating structures reaching down to the ship's keel through all the intermediate decks. The visible portion, the gun house containing the two guns, sits on a turntable which in turn rests on a roller path supported by a ring bulkhead which transfers the weight to the ship's structure. A working chamber suspended below the turntable takes shells and propelling charges from a central hoist and transfers them to the loading cages which are hoisted up to behind the gun breech where a rammer pushes the ammunition into the gun. This portion of the mounting above the main deck is protected by a ring of heavy armour or 'barbette'. The hoist projects down from the working chamber to the shell room at the bottom of the ship where a bogie runs around the base of the hoist to transfer shells from the ship to the rotating hoist. The deck above the shell room houses the propellant magazine. Flash doors are positioned throughout the loading path to stop fire spreading down to the magazine.

In normal operation the guns are aimed by a remote director with the gun crew driving the turret in elevation and training to 'follow the pointer' on elevation and training receivers. It is possible to operate the guns in local control, in this case an officer situated in the cabinet at the rear of the gun house controls the operation. There are three sets of sights in the front of the gun house; one between the two guns and one at either side each, with a periscope looking out through a hood in the roof. It took six men to lay the guns, two each for elevation of the left and right gun, and two to control training. A sight setter applies the desired elevation and deflection to the sight, a layer looks through the sight and drives the gun to keep the sight on the target. To provide backup any of the three positions could control training and the central position could control elevation of both guns.

Figure 215: A-Turret 15-inch Gun Breeches

Figure 216: A-turret right-hand elevating mass (gun barrel, slide, cradle, loading rammer and recoil system)

Figure 217: The gun loading cage carries ammunition from working chamber to gun

Figure 218: 15-inch Mk1 Gun Mounting (Longitudinal Section)

151

Figure 221: Central sight position Y-turret. Right-hand gun is in its correct position, left-hand gun has fallen to the seabed

Figure 222: Diagram of an Elevation Receiver on the left and Gun Layers Position (front right of gun house) on the right

With the guns in local control there was a possibility that the guns of A and B-turrets could hit each other or that a shell fired by B could hit one of A's guns (the same applies to X and Y). To protect against this, Willie Dickson Kilroy, an inventor and officer in the Royal Navy Volunteer Reserve, developed a 'turret danger

signal' and a 'model turret training indicator.' Both systems are fitted to HMS ROYAL OAK, the turret training indicator is in the Officer's Cabinet and shows the position of the two turrets. The danger signal sounds a horn and flashes a light when a clash is possible.

Figure 223: Officer's Cabinet

Figure 224: Kilroy's model turret training indicator

3.1.4.6 Training & Practice

Controlling the guns either with the full fire control organisation or in local control was a complex process that required continuous practice if it were not to fall apart under the stress of battle. Regularly firing the guns was not feasible since guns had a life of only a few hundred rounds even when fired with reduced propelling charge, and the 15-inch ammunition was extremely expensive. To overcome this a small 'sub

calibre' gun using cheap 6-pdr ammunition was placed inside the 15-inch gun and locked in place. The sights would then be set for the 6-pdr ballistics, and the whole gun laying process including firing at real targets could be practiced. There was also the advantage that this exercise could be done in confined waters without annoying the neighbours.

MT

Figure 225: Sub calibre 6-pdr gun

Figure 226: Drawing of sub calibre gun

3.1.4.7 6-inch secondary battery

A black and white photograph showing the interior of a ship's engine room. Several crew members, wearing dark uniforms and white head coverings, are working with large machinery and pipes. One person in the foreground is holding a large cylindrical object, possibly a fuel tank or engine component. The room is filled with various mechanical parts, pipes, and a large cylindrical tank on the floor. The lighting is dim, and the overall atmosphere is one of busy, manual labor.

155

Figure 229: 6-inch Pedestal Mk IX Mounting

Figure 230: 6-inch casemate gun

3.1.4.8 4-inch Anti-Aircraft Defences

In 1936, ROYAL OAK was fitted with four twin 4-inch anti-aircraft guns and their associated fire control system the High Angle Control System (HACS). The system is made up of two directors, one above the

Spotting Top and one on the Main Mast, four gun mounts with fuze setters to set the time delay fuze and a fire control table inside the ship to translate the data from the director into gun aiming and fuze setting orders.

Figure 231: HACS on spotting top - HMS REVENGE. ©IIWM A 1513

Figure 232: Spotting top HACS director

The director tracks the target aircraft providing range, bearing and elevation to the table where they are plotted, and an estimate of the target speed and course made. This is then translated into gun orders and fuze delay transmitted electrically to the guns. The system worked reasonably well against targets flying

straight and level at high altitude, since the rate of change in range and deflection was low. The delays inherent in calculating the target rate and setting the fuze before firing meant it could not cope with dive bombers or torpedo bombers flying directly at the ship. The best that could be done was to set the fuzes so that a barrage of exploding shells is set up at a fixed point in the sky on the predicted path of the aircraft. As many ships found to their cost, this didn't work very well.

Figure 233: Remains of HACS director on Main Mast

Figure 234: Main Mast HACS director and range finder

Figure 235: Twin 4-inch anti-aircraft gun with fuze setter labelled

Each mounting has two fuze setters, one for each gun. Examples of the twin 4-inch mount and fuze setter can be seen aboard HMS BELFAST in London.

3.1.4.9 2pdr (40mm) Vickers Mark VIII on Mark VI octuple mount (pom pom)

The Vickers 2 pounder octuple mounting or pom pom, is a 40mm anti-aircraft gun with a rate of fire of 115 rounds per minute per barrel. The mount is powered, HMS ROYAL OAK has the low velocity version of the gun without the conical flash hider that was added to the end of the barrel later. There are two mounts one either side of the funnel. The ammunition boxes are fully loaded.

Figure 236: Octuple 2pdr (40mm) pom pom

Figure 237: Pom Pom mount

Figure 238: Pom Pom Barrels

3.1.4.10 *Minor weapons*

HMS ROYAL OAK has two quad 0.50-inch anti-aircraft machine gun mounts, one on each side of the conning tower along with 4 small 3-pdr guns originally intended for countering small boats, but probably most useful

as saluting or signalling guns.

Figure 239: Quad .50 Vickers machine gun. ©IWM A 1249

Figure 240: Quad .50 Vickers machine gun on HMS ROYAL OAK

Figure 241: 3-pdr gun

3.1.4.11 Countermeasures

HMS ROYAL OAK was equipped with four Shark-Shaped paravanes to protect her from seabed moored sea-mines. The paravanes were simple and inexpensive buoyant torpedo shaped bodies of welded steel, fitted with horizontal rudders to keep them at the required depth. They were stored on the side of HMS ROYAL OAK's forward superstructure and deployed one to port and one to starboard when the ship sailed in seas thought to be mined. They were streamed out at an angle of 50 degrees from the bow forefoot at the end of cables which cut through or deflected the mine mooring cables, so protecting the ship's sides.

Figure 242: The bow of HMS ROYAL OAK in drydock - her paravane skew and chains clearly visible

Paravanes were invented during WWI amid much secrecy by Commander Sir Charles Burney RN at HMS VERNON, and HMS ROYAL OAK was one of the first capital ships designed for them, with towing eyes (the paravane skeg) for the cables fitted to her bow forefoot. The forefoot eyes and three of the paravanes are still visible on the wreck of HMS ROYAL OAK.

Institution of Mechanical Engineers

Figure 243: Example of a paravane and towing arrangement

3.1.5 Exposed Munitions

Considerable quantities of exposed munitions are observed on ROYAL OAK, and she would have been fully loaded when she sank. The survey team included a munitions expert, who reviewed the exposed munitions present on the site and assessed the damage and explosive effects of the four torpedo strikes that caused the ship to sink. This section reviews munitions by type and provides an assessment of the significance of each.

3.1.5.1 4-inch High Angle (anti-aircraft) Quick-Fire (QF) ammunition

This is fixed ammunition whereby the projectile (steel casing containing high explosive, and fuze) and brass cartridge case (containing propellant) are assembled together. Ammunition of this nature has been observed in two locations.

On the Port/Deck side of the ship approximately twenty rounds of ammunition are located in a deck house store atop the aft part of the Shelter Deck. One empty cartridge case has fallen to the seabed adjacent to the entrance to the Wardroom nearby. This location is not marked as a designated munitions store on the ship's plans but is close to the four twin barrel 4-inch anti-aircraft gun-mounts located on the ship's Shelter Deck, therefore this was probably "ready ammunition", fuzes are visible fitted to the nose of the projectiles.

Figure 244: Exposed 4-inch ammunition stored on the Shelter Deck

©National Maritime Museum, Greenwich, London

Figure 245: Deck house containing 4-inch ammunition and location of the 4-inch anti-aircraft guns

On the Starboard side, multiple brass ammunition boxes each containing four rounds, are visible in the Hold Deck magazine forward of A-turret barbette. The contents of the magazine have been exposed by the blast damage caused by the torpedo strike near frame 27. The longitudinal armoured bulkhead has been breached around frame 27 and the ammunition boxes close-by have sustained blast damage; they have been deformed around the ammunition and the box lids have been displaced. However, the boxes have evidently done their job of protecting the ammunition; no damaged ammunition was observed or exposed cordite propellant, nor is there any evidence of an ammunition explosion or fire. Only the cartridge cases are visible, so it is uncertain whether fuzes are fitted to the projectiles.

Figure 246: Exposed 4-inch ammunition magazine exposed in the 2nd torpedo damage hole

3.1.5.2 2lb Multi Pom-Pom ammunition

The two 8-barrel multi-pom-pom gun-mounts were originally mounted on platforms above the Shelter Deck each side of HMS ROYAL OAK's funnel. The starboard gun-mount is not visible, buried in the seabed beneath the shipwreck. The port mount can be accessed beneath the angled shelter deck. The loading racks are approximately half full of fixed ammunition, significantly in excess of a hundred rounds are visible (see Figure 112: Octuple Pom Pom Gun and Ammunition Boxes

3.1.5.3 G7e/T2 Torpedo

Lying flat on the seabed approximately 60m from the bow of HMS ROYAL OAK are the remains of a German G7e/T2 torpedo including the warhead and firing pistol. This torpedo can be positively identified because the steel casing has corroded away to reveal the large battery and guidance control steering mechanism. The aft casing containing the propulsion motor remains intact, being made of stainless steel, however the hydroplanes and propellers have corroded away. The torpedo has a small scallop dredge net snagged on it. The absence of the steel casing, hydroplanes and propellers is probably due to either physical damage by fishing gear or seawater corrosion over the intervening years, accelerated by leaking battery acid.

This is a torpedo of the same type fired at HMS ROYAL OAK by U-47 and is most probably one of the three fired by U-47 that did not strike the ship. Its heading (~305 degrees) and position (~60m & ~350 degrees NNW of HMS ROYAL OAK's bow) suggest it missed the bow of the ship by approximately 42m. The brass cased warhead and firing pistol remain intact without significant damage, including the impact trigger vanes

at the front³. The G7e/T2 torpedo was fitted with a 280kg brass cased high explosive warhead, and a firing pistol that could be triggered by impact with the target or magnetic influence. The warhead and fuze on the seabed are consistent in size and type with this.

Figure 247: Location of the G7e/T2 torpedo

Figure 248: Images of the G7e/T2 Torpedo war head, battery bank and remains of the tail with queen scallop dredge

³ The torpedo warhead was moved away from the site of HMS Royal Oak by specialist divers from the Royal Navy Northern Diving Group and destroyed in a controlled explosion in December 2019.

Figure 249: 3D Photogrammetry of the G7e/T2 Torpedo. It shows the warhead, battery bank and tail and the remains of the queen scallop dredge

3.1.5.4 *Small Arms Ammunition.*

A small quantity of small arms (rifle) ammunition has been found on the seabed adjacent to the remains of one of the ship's steam pinnace launches close to the main wreck.

Figure 250: Small Arms Ammunition

3.1.5.5 *Summary of exposed munitions*

Three of these findings are of particular historical significance.

Firstly, the damage to the 4-inch HA QF magazine around frame 27 suggests that the first of the final three torpedo hits came very close to causing a catastrophic explosion of one of ROYAL OAK's magazines. Had this occurred, the explosion could have propagated to other magazines nearby and caused a catastrophic explosion similar to that which destroyed BARHAM in 1941 following a U-boat torpedo attack, and would have caused even greater loss of life amongst ROYAL OAK's crew.

Secondly, the presence of ammunition in the 2lb Multi Pom-Pom mounting, and 4-inch HA QF ready-ammunition in the deck-house on the Shelter Deck, confirms the high state of readiness of the ship to defend against air attack.

Finally, the close presence of an almost intact German G7e/T2 torpedo and its apparent heading suggest it is probably the one fired from the stern tube of U-47, missing the bow by just ~42m. There is no significant evidence of impact damage to the torpedo, so it is unlikely that it struck its target. U-47's log suggests this torpedo was fired ~3,000m from ROYAL OAK, which is at the limit of range for the G7e/T2 if the batteries were not preheated. The flat resting position and intact condition are consistent with it having sunk at the end of its run, rather than having crashed into the seabed or the ship at speed.

3.1.6 Torpedo Damage

The torpedoes that found their target tell a very different story. At 01:29 on 14th October 1939, having been hit by four G7 torpedoes fired by U-47, OAK sank (Weaver 1980). The submarine fired a total of seven torpedoes in three salvos, three missed their target. All were G7e/T2 torpedoes, chosen for their silent running and lack of an exhaust wake, except one of the final salvo which was a G7a/T1 (Konstam 2015).

3.1.6.1 *The G7a/T1 Torpedo*

The G7a/T1 torpedoes were 53cm diameter and 7.16m long, driven by a reciprocating piston engine powered by compressed air and steam superheated by burning Dacaline, an analog of Naphthalene. Consequently, they could reach a high speed of up to 44 knots and a long range of up to 12 km. They were, however, noisy and left an exhaust trail of bubbles. Their track from the submarine could be seen and heard, exposing the launch submarine to counterattack. Therefore, they were not preferred for use in daylight, or for the attack of warships and escorted ships. The G7a/T1 torpedo, like the G7e/T2, was fitted with a 280kg warhead and firing pistol working on impact or magnetic influence. The G7a/T1 torpedo was considered more dependable and capable than the electrically driven G7e/T2 and remained in service, with improvements, throughout and after the Second World War.

3.1.6.2 *The G7e/T2 Torpedo*

The G7e torpedoes were the same size but electrically driven; they were nearly silent and did not emit exhaust bubbles that could indicate their course. They had 280kg warheads and were equipped with magnetic (proximity) and impact firing pistols. The torpedoes that hit HMS ROYAL OAK were fired at shallow depth to strike the side of the ship and activate the more reliable impact mechanism in the firing pistol

(Weaver 1980, Haversham 2004). These torpedoes were stealthy and powerful; designed, built, and used to sink enemy warships.

However, they were unreliable and a number of attacks on British warships were unsuccessful as a result; most notably the famous aircraft carrier ARK ROYAL and the fleet flagship NELSON in September and October 1939. The main problems were that they ran approximately 2m too deep, and that the magnetic pistols, designed to detonate beneath the target ship, often failed. Consequently, U-boat commanders were instructed to fire at a depth of just 3.5m to ensure an impact on the side of the target ship at a depth of approximately 5.5m (Haversham 2004), which is consistent with the damage to ROYAL OAK. These faults were remedied on later versions of the G7e torpedo.

	G7a/T1 Torpedo	G7e/T2 Torpedo
Weight	1538kg in air	1603kg in air, 271kg in water.
Length	7.16m	7.16m
Diameter	53cm	53cm
Propulsion	110/255/350hp 4-cylinder steam engine driving a pair of six blade contra-rotating propellers	100hp electric motor driving a pair of two blade contra-rotating propellers
Power	Compressed air and Decaline fuel	124v Lead Acid Battery
Warhead	280kg, Hexanite explosive, Brass casing	280kg, Hexanite explosive, Brass casing
Firing Pistol	P1, Magnetic or Impact	Magnetic or Impact
Speed	Variable 30 / 40 / 44 knots	30 knots with pre-heat (@ 30degC), 28knots without preheat
Range	12000 / 7500 / 5000m depending on speed	5000m with preheat, 3000m without preheat
Endurance	13 minutes / 6 min 5 seconds / 3 min 41 seconds depending on speed	5 min 25 seconds with preheat, 3 min 28 seconds without pre-heat
Guidance	Gyroscope & inertial pendulum for heading and depth	Gyroscope & inertial pendulum for heading and depth

3.1.6.3 U-47's Firing Log

U-47 fired seven torpedoes at ROYAL OAK in three salvos, scoring a single hit from three G7e/T2 torpedoes in the first salvo and three hits from three torpedoes (G7e/T2 and one G7a/T1) in the third salvo. The single G7e/T2 torpedo in the second salvo, from the stern tube, did not score a hit.

According to the U-47's logbook (Weaver 1980) the first salvo was fired at a range of 3,000m and time 00:58 (amended from 01:16) with a run-time to the warhead detonation of "...a good 3½ minutes ..." consistent with a range of 3,000m. The second salvo was fired at a time of 01:02 (amended from 01:21) and, given the time taken to turn the submarine, was probably from a similar range. The third salvo struck HMS ROYAL OAK approximately ten minutes after the first, apparently with a shorter run-time recorded in U-47's logbook (Konstam 2015) of "... three tense minutes..." before the explosion of the first torpedo, maybe because of reduced range, or the use of the faster G7a/T1 torpedo.

Figure 251: U-47's plot of the attack

3.1.6.4 *First Salvo - a forewarning*

The first torpedo hit at 01:04 (Weaver 1980) came from the first salvo of three. It struck the battleship at frame 10 on the starboard side approximately 10 metres back from the bow below the second anchor at a water depth of approximately 5m. At this point the ship's hull is no more than 4 metres wide, so the explosion caused extensive damage across the full width of the ship. It destroyed the fuel tanks for the ship's aircraft, and opened to the sea the flammable store containing volatile substances. The blast opened a massive hole through the ship's bow below the waterline, along a length of approximately 16 metres from the ship's bow post and forefoot to the watertight bulkhead at frame 15, and approximately 5 metres in height from the keel up to the armoured Lower Deck. Such was the damage that the massive structures of the ship's keel, bow post and forefoot have, since the sinking, broken away and fallen to the seabed.

3.1.6.5 *Second Salvo - a near miss*

U-47s second salvo was a single torpedo fired from her stern tube, this torpedo did not explode against ROYAL OAK and there is no record of the sound of an impact either from the ship's survivors or U-47s log. The ostensibly intact G7e/T2 torpedo found on the seabed close to the bow might well be this torpedo, its heading and position are consistent with the likely track of this torpedo having been fired at ROYAL OAK from a more easterly firing position, and its course would have taken it past the bow of the battleship missing by approximately 42m.

3.1.6.6 *The Third Salvo - that sank the battleship*

The second, third and fourth hits were the three torpedoes fired by U-47 in her third salvo. They struck further aft on the starboard side in quick succession (Weaver 1980). Of this second group of three torpedo strikes, the first struck furthest forward at frame 27 approximately 31m from the bow, below and slightly aft of the starboard above water torpedo tubes, below the Electrical Artificer and Ordnance Artificer's Mess on the Upper Deck forward of A-turret barbette, and at ~5 metres water depth. The blast tore a massive hole in the side of the ship measuring approximately 8 metres wide and 5 metres high. The armour belt above the torpedo strike on the ship's side remained intact but did not protect the ship, nor did the ship's anti-torpedo protection comprising the (i) watertight compartments inside the hull, and (ii) the watertight bulge fitted outside the hull, which were ripped open by the explosion. The inner longitudinal bulkhead, made of 38mm armour, was bent inwards and cracked, opening to the sea the 4-inch anti-aircraft magazine and the refrigeration store on the Hold & Platform Deck levels. Blast and flash (fireball) from the detonation of the torpedo warhead would have entered the ship's nearby compartments and companionways causing injury to crewmembers and damage to equipment before flooding took place. Some of the boxes of ammunition in the magazine sustained blast damage, but the ship's ammunition did not explode and an even greater disaster was narrowly averted.

Figure 252: Hold Deck plan showing the 4-inch HA QF Magazine and Cold Room at frame 27, breached by torpedo hit #2, and the aviation fuel tank destroyed by the torpedo hit #1 at frame 10. The 4" HA QF magazine is adjacent to the 15" Shell Room and Magazine on the deck above. This view clearly illustrates how close the torpedo hit #2 came to causing a catastrophic magazine explosion.

Torpedo Damage and Flooding

Torpedo Hits #1 and #2

Figure 253: Torpedo Damage & Flooding, torpedo hits number 1 & 2

The second and third torpedo strikes of the third salvo were much further aft at frames 142 and 176, approximately 100 metres and 111 metres from the bow, beneath the aft 4-inch HA QF gun mount and the aft 6-inch casemate gun respectively at a water depth of ~5 metres. The thick 152mm armour belt above the torpedo strikes remain intact but did not protect the ship, nor did the ship's torpedo protection, comprising watertight bulges fitted to the outside of the main hull, and watertight compartments & oil-fuel bunkers between the inside of the hull side, and the boiler room & engine room (Sarkar 2012).

Figure 254: Cross sections of HMS ROYAL OAK's plans at frames 144 and 180, close to the locations of the third and fourth torpedo hits. These views of the ships layout clearly show the torpedo protection compartments, fuel bunkers, longitudinal bulkheads and electric hydraulic power companionway through the boiler room.

Both torpedo blasts breached the torpedo protection bulge and the hull side, the hole in each exceeding 8 metres long and 5 metres high, almost coalesce into a single hole. The aft end of the bilge keel has detached from the torpedo protection bulge and now bends down to rest on the seabed. Both torpedo blasts breached and opened to the sea the watertight compartments and fuel oil bunkers inside the hull causing the immediate leakage of up to 500 tons of oil. ROYAL OAK's fuel bunkers were almost full at the time of her sinking, up to 3,400 tons were on-board.

Both blasts caused considerable bending and cracking of the 38mm armoured inner longitudinal bulkhead, opening Boiler Room No 3 and the Starboard Wing Engine Room to the sea. In both cases, the joint failed between the top of the armoured longitudinal bulkhead and the underside of the armoured middle deck. At frame 142 (Boiler Room 3) the gap between longitudinal bulkhead and middle deck measures 12m long and 0.3m wide, and the bulkhead has a vertical split measuring 4m long and 0.2m wide close to frame 142 at the point at which its deflection into the ship is greatest. At frame 176 (Engine Room) the gap between longitudinal bulkhead and Middle Deck is 4m long and 0.8m wide.

The compartments between the hull side and the longitudinal bulkhead contained fuel oil. This oil would have been ignited by the explosion of the torpedo warheads and forced into the ship by the blast. Consequently, blast and flash (fireball) would have entered the Boiler Room, Engine Room and adjacent compartments, fuelled by vaporised burning oil. The adjacent compartments would have included:

- The Stokers Washplace on the Middle Deck and the Stokers and Marines Mess on the Main Deck above the torpedo explosions. This would explain eye-witness reports of flash (fireball) occurring in this location causing many fatalities and injuries to crew members (Weaver 1980, Sarkar 2012).
- The fuel-oil handling compartments directly above the fuel bunkers and torpedo protection compartments, and adjacent to the Stokers Washplace on the Middle Deck.
- The starboard longitudinal services passage for electric cables and hydraulic pipes running through the starboard side of the boiler rooms from the turbo-generator, hydraulic machinery & dynamo compartments, frames 187-221. This would explain the loss of power throughout the ship (Weaver 1980, Sarkar 2012).
- The ventilator fan trunking from the Boiler Rooms to cowlings on the Shelter Deck, and smoke uptakes from the boilers to the funnel, all passing through large apertures in the Middle and Main Decks. This would explain eye-witness accounts of flash (fireball) appearing around the funnel (Weaver 1980, Sarkar 2012).

The damage to the hull of the battleship from the two aft-most torpedo strikes at frames 142 & 176 merge into one because of their proximity and can only be described as brutal. They opened large compartments to the sea resulting in rapid flooding that led to the capsizing of the ship, they caused blast and flash to enter the mess decks directly injuring and killing many crew members, and they caused power failure that prevented the ship's emergency equipment such as pumps, lights, radios and winches to operate. It was these last two torpedo hits that led directly to the loss of ROYAL OAK and the majority of her crew.

Figure 255: Torpedo Damage and Flooding, torpedo hits number 3 & 4

3.1.6.7 *Flooding and Sinking of HMS ROYAL OAK*

The four torpedo hits caused extensive damage and flooding such that ROYAL OAK capsized and sank in just 13 minutes following the impact of the third salvo. The following table is a simple analysis of the flooding and sinking of the ship, informed by the results from the HMS ROYAL OAK 80 Survey; it makes simplifications and assumptions including:

- Primary flooding was limited to the compartments directly opened to the sea by torpedo hits.
 - We know water-tightness and readiness of the ship was poor, so it was likely that additional flooding took place.
 - Water entered the ship through scuttles as she listed to Starboard.
- The ship settled on an even keel.
 - We know that the ship listed to Starboard before capsizing.

Simple analysis of the flooding and sinking of HMS ROYAL OAK							
Torpedo hit		Flooded Compartments	Approx. Primary Flood Volume m³	Hole Size (m²)	Water Flow rate (m/s)	Flooding Rate (m³/s)	Time to flood (seconds)
1	Frame 10	Hold, Platform & Lower Decks, (frames 1 to 15)	227	40 Hull	4.4	176	1.3
2	Frame 27	Hold, Platform & Lower Decks, (frames 22 to 42)	1365	6 Longi bulkhead	4.4 (1m water depth)	26	52
		Watertight compartments and anti-torpedo bulge (frames 22 to 42)	278	40 Hull	7 (5m water depth)	280	1.0
3	Frame 142	Boiler Room #3 (frames 131 to 150)	1910	4.4 Longi bulkhead	4.4 (1m water depth)	19	98
		Watertight compartments, fuel-oil bunkers and anti-torpedo bulges (frames 120 to 150)	893	40 Hull	7 (5m water depth)	280	3.2
4	Frame 176	Starboard wing engine room (frames 152 to 187)	783	3.2 Longi bulkhead	4.4 (1m water depth)	14	56
		Watertight compartments, fuel-oil bunkers and anti-torpedo bulges (frames 150 to 187)	669	40 Hull	7 (5m water depth)	280	2.4
Volume of water in flooded compartment (m³)			6125				
Water density tons/m³			1.014				
Weight of water in primary flooded compartments (tons)			6211				
ROYAL OAK Displacement (tons) (deep load)			33,240				
ROYAL OAK draught (m)			8.7				
Increase in average draught due to flooding (m)			1.6				

This analysis shows us that the primary flooding of the compartments that were opened to the sea by the torpedo hits probably happened within two minutes, and would have caused a significant list to starboard but the loss of buoyancy alone was not sufficient to sink HMS ROYAL OAK. Indeed, she took a further 11 minutes to capsize and sink. This suggests that additional factors contributed to her loss such as:

- The general water-tightness of the ship was considered to be poor (Weaver 1980), which would have led to flooding of adjacent compartments through doors, hatches and other apertures, for example from Boiler Room 3 to Boiler Rooms 2 and 1, and from the starboard wing engine rooms to the

centre and port Engine Room.

- The boiler rooms were not fitted with longitudinal bulkheads, so floodwater was free to move laterally across the ship, adding to her instability as she listed.
- Ventilators to improve the ventilation of crew living spaced during blackout replaced many scuttles (Weaver 1980). This would have allowed seawater to enter the ship as she listed to starboard (Weaver 1980, Sarkar 2012).
- The ship's power failed denying the crew the use of equipment such as pumps, radio, lights and winches (Weaver 1980). This power failure was probably caused by torpedo strike #3, which caused damage to the companionway carrying hydraulic and electrical power forward through boiler room #3.
- The crew was at a low state of readiness, the ship being in a friendly harbour and no call to an elevated state of readiness had been ordered.

3.1.6.8 *Magazine Explosion*

The accounts of survivors and records from the official enquiry both refer to flash (fireball) in the Stokers & Marines mess-decks caused by a magazine explosion (Weaver 1980). The closest magazines were:

- 1) X-turret 15-inch cordite magazine at frame 187, approximately 8m away from the torpedo explosion at frame 176 and protected from it by two watertight bulkheads. This magazine contained approximately 35 tons of cordite in silk bags. A cordite fire in this compartment would probably have caused a catastrophic explosion similar to that which destroyed BARHAM in 1941 following a U-boat torpedo attack.
- 2) the aft 4-inch HA QF magazine at frame 199, approximately 8m away from the torpedo explosion at frame 176 and protected from it by two watertight bulkheads. The same type of ammunition was exposed directly to the torpedo explosion at frame 27 and did not itself explode.

No evidence of a magazine explosion was observed on the wreck during the ROYAL OAK 80 Survey. The Survey only examined the outside of the shipwreck and no observations were made of the interior. The torpedo strike at Frame 27 breached the forward 4-inch HA QF magazine and caused damage to the ammunition boxes therein but there was no evidence there of a magazine fire or explosion. A catastrophic explosion was narrowly averted by the robust construction of the ammunition and boxes. The most likely explanation of the flash (fireball) observed by survivors in the Stokers and Marines mess deck appears to be flash from the detonations of the torpedo warheads fuelled by burning oil spray ignited and propelled into the ship by the blast.

3.1.6.9 *Summary of damage*

The four torpedo holes in the wreck and the torpedo lying on the seabed nearby provide a remarkable historical record of the design and effectiveness of the weapons that armed the German U-boats at the beginning of WWII. The fact that three of the seven torpedoes failed to find their target, which was anchored and stationary in calm and sheltered sea conditions, illustrates the difficulties in operation and the unreliability of the torpedoes that the U-boat crews experienced.

The damage to ROYAL OAK is extensive, the torpedoes overwhelmed the anti-torpedo protection designed and built into the battleship and the bulges added after her construction. She was an old ship designed during WWI at a time when the damage caused by underwater explosions was not well understood, and the threat from such weapons was less apparent. Her hull construction differed little from that of the original DREADNOUGHT (1906) despite other developments such as the size of battleships, increase in calibre of their guns, use of fuel-oil in lieu of coal, and the introduction of director gunnery control. Later battleship designs such as HOOD, NELSON, KING GEORGE V and VANGUARD (1944) incorporated more sophisticated underwater protection.

During the 1920s ROYAL OAK underwent modifications to her construction including the fitting of bulges to the sides of her hull to increase buoyancy, improve sea keeping and provide additional underwater protection, and additional deck armour to protect against long range gunnery and aircraft bombs. The bulges provided additional watertight compartments outside the main hull to mitigate the blast and shock wave effects of an underwater explosion on the ship's structure. They could also be flooded to correct the trim of the ship should a loss of buoyancy occur somewhere. Air, oil and water filled compartments within the hull provided additional protection to preserve the integrity of the inner longitudinal armoured bulkhead shielding the Engine Rooms and Boiler Rooms. Unfortunately, these improvements did not keep pace with the evolution of the threat from underwater weapons and left the ship vulnerable to the modern torpedoes used by the U-boats.

The torpedo strike at frame 27 nearly caused a catastrophic explosion of one of the ship's magazines, which would probably have propagated and caused a mass explosion of the ship's ammunition as happened to BARHAM in 1941; an even greater catastrophe was narrowly averted. But the three torpedo explosions in the third salvo were all close to parts of the ship occupied by the crew. Blast and flash (fireball) would have entered these crew-spaces and caused many injuries, fatalities and much confusion. However, it was the torpedo strikes furthest aft at frames 142 and 176 that ultimately caused her to sink, flooding Boiler Room 3 and the Starboard Wing Engine Room, with resulting loss of power that lead directly to her capsize. The torpedo explosions breached the ship's torpedo protection and inner longitudinal armoured bulkhead causing blast and flash to enter the ship's compartments and companionways, fuelled by burning oil spray & vapour.

3.1.7 Outlying Targets

ROYAL OAK sank rapidly at anchor and remains near intact, so there is little debris in the surrounding area. However, a series of outlying targets worthy of investigation were discovered by both remote sensing and diver searches (Shiptime 2017).

3.1.7.1 *Acoustic targets*

A series of targets were identified during the sidescan sonar survey of the seabed around the wreck site during the Shiptime Project. This data was shared for further investigation by the ROYAL OAK 80 survey team. The contact report is included in Annex 8.2.

1. Six tripods with a height of 2.5 metres were located around the wreck site, 3 each side (1 at the bow, 1 midships, 1 stern) and lying approximately 30-40 metres away from the wreck. MOD SALMO confirmed that they are standard positioning tripods, which would have had a Long Baseline (LBL)

transponder attached to the top. LBL transponders are used for high precision survey work and can track underwater vehicles and divers. They are generally deployed around the perimeter of a work site, hence their location around the wreck of HMS ROYAL OAK. It is unknown when the tripods were placed on the site, but it is believed to be related to earlier survey work conducted on the wreck. The tripods were not seen on the 2006 multibeam data. It is therefore possible that these have been deployed since 2006.

Figure 256: Example Tripod

2. A target located to the south which also shows up in the 2006 data from the ADUS survey was identified as being a large and modern mooring buoy and most likely unrelated to the wreck unless it was lost as part of more recent commercial survey work.

Figure 257: Mooring Buoy

3. A target lying on the seabed on the starboard side of the wreck approximately 25 – 30 metres out from the rudder was identified as the port side inner A-frame bracket. This was discarded during the salvage of the propellers during the 1950s. For more information see section 3.1.3.

Figure 258: Discarded port inner A-frame bracket

4. A section of metal tubing most likely to be a section of a mast strut was located 318 metres north of the main wreck. The structure above the seabed measures approximately 8 metres long and is bent in the middle at approximately 90°. The exposed end has a series of electrical cable jutting out and severed. The opposing end disappears into the seabed and continues partially buried for some distance.

Figure 259: 3D model and image of the severed end of the possible mast strut

5. A large mass of wreckage is located a short distance away from target 4. It measures approximately 3 metres high and 3 metres wide. The wreckage consists of metal plating, a large bundle of heavy electrical cabling and three voice pipes consistent with those found on the wreck of HMS ROYAL OAK. The largest piece of steel plating resembles a section of platform or deck, the voice pipes are mounted to the plate. Lying on the seabed a couple of metres off to one side is a section of brass railings. To the other side lies a short length of ladder.

Figure 260: Side Scan image of targets 4 & 5

Figure 261: 3D Photogrammetry of target 5 and image of voice pipes

Figure 262: Brass Railings

3.1.7.2 Diver Located Targets

During a peripheral seabed search of the wreck, a single intact German torpedo was located lying approximately 60 metres north of the bow. Identified as a G7e German torpedo of the type fired by U-47. It was noted that a queen scallop dredge had been caught and subsequently abandoned in the propellor end of the 7 metre long torpedo. As discussed in section 3.1.5.3.

3.1.8 ROYAL OAK's Pinnaces

Steam Pinnaces were central to the Royal Navy's ship-to-ship and -shore transport. Used as guard boats and for offensive use in shallow waters, they were built in small shipyards countrywide. The Navy List of 1914 showed 634 such vessels in service. Most were armed with a 3-pdr gun, a Maxim gun and rifles, plus 14" diameter torpedoes and were capable of 12 knots. Pinnaces were often used as picket boats patrolling capital ship anchorages, due to their ability to move and fire at moderate speeds (<http://www.ww1britainssurvivingvessels.org.uk/vessels/steam-pinnace-199>).

As with most Capital ships, ROYAL OAK carried two 50' steam pinnaces (numbers 749 and 752). Their wooden carvel constructed hulls were both ordered towards the end of WWI in June 1918, and built by JS White in Cowes (749) and Rowhedge Ironworks in Essex (749). Hull 749 was then fitted with a pinnacle boiler and compound engine by Mumford's of Colchester, before being delivered to Portsmouth in September 1918, where she sat out the end of the war. She joined QUEEN ELIZABETH (then Flagship of the Atlantic Fleet) in July 1920 prior to service aboard ROYAL SOVERIGN and BARHAM, making her last transfer to ROYAL OAK in July 1939 as the Fleet prepared for the start of WWII. Fewer records exist for 752, which was likely also fitted by Mumford's, before sitting at Chatham Dockyard until joining ROYAL OAK in 1924, a post she occupied to the last. Both were lost with the ship.

Figure 263: A Royal Navy Steam Pinnace

Figure 264: One of ROYAL OAK's Two Steam Pinnaces

©IWM Q 18000

Eye witness reports from the night of the sinking describe both pinnaces being in the water alongside ROYAL OAK before the torpedos struck. It is not clear which of the following narratives refers to 749 or 752, but a description of the fate of each pinnacle follows.

Survivor Arthur Smith probably had a narrow escape from the first pinnacle sinking: "When I went into the sea, the ship's launch, a large boat, was still tied up to the starboard boom, so I climbed aboard with quite a

few others. By this time though, ROYAL OAK had listed at an angle preventing us from releasing the launch from the boom, as the painter was like an iron ball. I came to the conclusion that things were becoming rather dangerous, so, once again, I took to the sea.” (Sarkar 2013).

“As ROYAL OAK heeled farther over, her spotting top came adrift, hurtled down on the launch on the starboard side and sank it.” ‘Taffy’ Davies (Weaver 2008, p51). She can be seen near this position on the seabed today (Figure 102 and Figure 266).

Then OAK sank. Three vessels remained in the vicinity.

- Civilian drifter Daisy II chartered to support the fleet in harbour had been moored on OAK’s port side prior to her sinking and was saved by crewman Johnie Duthie’s quick action to cut her adrift, she was free to pick up survivors from the water.
- a covered Admiral’s gig that had floated off the quarter deck to which survivors clung with varying degrees of success.
- the remaining pinnace (or picket boat).

Subsequent references to the demise of the latter are harrowing.

“In the crowded picket boat – she had a life saving capacity of 59 but had more than 100 on her deck, in her cabin and forepeak – sailors three deep were hanging on, some to old motor tyres hanging over her side; others were using ripped up floor boards to paddle her away. Some were using their hands. One man clinging to the side was pleading to get aboard. His leg was broken. He could not swim. But by now the boat was beginning to rock, backwards and forwards, heeling from one side to the other, the freeboard getting lower and lower, whipping water on the lower side.” (Snyder 1976)

“With more than a hundred men on board, double the number it was designed to take, the picket boat turned turtle, trapping some of ROYAL OAK’s crew inside it. Those thrown into the water tried to clamber back onto the upturned hull, which eventually sank under their weight and was not seen again.” (Weaver 2008, p52).

3.1.8.1 *Discovery*

Surveys of ROYAL OAK have been required regularly by the Salvage and Marine Operations section of the Ministry of Defence to support monitoring of any structural deterioration, management of oil leakage from the upturned hull, and occasional civilian dive teams have been licenced to dive the wreck. Notably for the pinnaces, Peter Rowlands produced a video of the wreck in 2002, ADUS conducted a multibeam survey in 2006, and the Shiptime project with Sula Diving conducted multibeam, sidescan and diver surveys in 2017 (Shiptime 2017).

Rowlands (2002) first provided some corroborating evidence for the spotting top sinking the first pinnace, as visible near the platforms on the seabed are the remains of a ship’s boat. The bow section is shown on film (Rowlands 2002) and described as the remains of a 50’ pinnace. These are also seen in the ADUS 2006 multibeam.

The second pinnace was sunk off the main wreck site, and its location was not known. ADUS 2006 identify an ‘off site feature’ in the multibeam data (p27). Target 58 is described as a Wreck 275m south west by west of RO, of a “10.8m boat with a transom stern. Bows to east, heeled over 300 to the south, with debris astern.

Possibly a 35' launch from the ROYAL OAK.” Recommendations for future work suggested this be investigated in future. The same ‘lump’ shows up in a subsequent 2010 Fathoms survey, but it was not interrogated or commented on at that point. It was not until 2015 that further and separate investigation was made possible. Sula Diving identified the object in sidescan imagery (in a survey for Orkney Harbour Authority) as a wreck, the sidescan’s additional detail allowed them to hypothesise that it was a damaged 50' pinnace (Sula 2015).

Figure 265: a) Royal Navy Pinnace b) Side scan sonar image overlain with outline of a pinnace (Shiptime 2017)

It was finally formally identified two years later when a visual survey by the dive team from Sula Diving as part of the Shiptime project confirmed the object was a 50' admiralty pinnace. New sidescans also found the missing stern section 27 metres from the rest of the pinnace. The pinnace itself being confirmed as 237 metres from the stern of the wreck, and is now known to be the resting place of up to 100 of ROYAL OAK's sailors.

3.1.8.2 Documentation

Knowing the location of both pinnaces, the role of this survey was to document them in situ. Both photographic and photogrammetry teams actively recorded both small wrecksites as part of the surveys in 2018 and 2019. Basic surveys of both areas were undertaken, and key measurements recorded. Scaled photogrammetric maps of the sites were also produced.

Survey Results

Pinnace 1: Midships Divers found the bow of the pinnace as described amongst the wreckage amidships. The boiler is visible, but the majority of the stern of this small wreck appears to be beneath collapsed parts of the superstructure as sinking reports suggest.

Figure 266: Photogrammetric image of ROYAL OAK's midships section, showing pinnacle location (left), and close up of pinnacle within the imagery (right)

Figure 267: A-C Photographs of ROYAL OAK pinnacle at midships section, showing bow and funnel; D Propeller

Pinnacle 2: ~275m south west by west of RO A shotline was positioned near the bow of the second pinnacle to allow divers to optimise their time on the wreck in 32-34m of water. The vessel came to rest in her original configuration on a near even keel with a slight list to starboard on a sand and mud bottom. Broken sections of hull reveal the latticed wood characteristic of the admiralty pinnacle double hull design, diagonal inner sheets combined with fore and aft outer sheets (ORCA 2013). From the bow to the engine, the pinnacle remains nearly intact, although the funnel beautifully preserved on the other pinnacle is absent here. Aft of the engine, the wreck has clearly been significantly damaged most likely by fishing gear or an anchor dragging through the site. The propeller, as well as the helm and a well preserved compass, can be seen aft of the engine but the stern section itself is missing. Sula Diving sidescans (Shiptime 2017) found a probable location for the missing stern section 27m from the rest of the pinnacle. This project was able to visually confirm Sula's prediction when Royal Oak 80 divers located and recorded evidence of parts of the transom and additional fragments of hull in 2018 (Figure 273).

Figure 268: Pinnacle from starboard side

Figure 269: Pinnacle from port side highlighting stern damage

Figure 270: Pinnacle from starboard side highlighting boiler, engine and damaged stern

Figure 271: Pinnacle Bow, looking aft

The bow to the central section is the most intact with helm and bridge fittings (including compass) still approximately insitu. Moving forward, the steel engine and boiler remain in position within the hull. Details like pressure and sight gauges are still intact and in their original positions. Pipes and valves still connect to

the engine aft of the boiler. The hull is clearly in a fragile condition, and is breaking up in several places (Figure 268 to Figure 271). Significant artefacts, such as the helm, compass and propellers remain (Figure 272), but evidence of any surviving decorative features are absent (Figure 273).

Figure 272: Photographs of ROYAL OAK pinnacle WSW of main wreck, showing (top to bottom) bow, helm, compass and propeller

Figure 273: Photographs of ROYAL OAK pinnacle WSW of main wreck, showing (top to bottom) bow with cleat and distinctive lattice structure, and hatch with internal lattice structure; engine room gauges; remains of the transom and stern latticework and a decorative dolphin

Water movement in the area is limited, and both the state of fragile elements of wreck and growth of marine life (limited coverage of short animal turf) are also indicative of a low energy site. Debris are scattered around the main area of wreckage the site, and as the stern section has been dragged some way off the total footprint covers an area larger than the original vessel dimensions. Although the remains are broken in two, significant sections remain intact. Multiple artefacts were exposed but makers plates or boiler numbers could be found, so no positive identification of which of the two pinnaces this is can yet be made.

3.1.9 Marine life

Within the sheltered environment of Scapa Flow, ROYAL OAK sits where she was sunk at anchor in the early hours of 14th October 1939 at the entrance to Scapa Bay. A glacially scoured basin with an area of approximately 130 square kilometres surrounded by islands, Scapa Flow was chosen as a protected anchorage for the fleet. At the time of OAK's sinking, channels remained between the islands to the east, allowing Prien and U-47 to gain entry on tides that no longer exist. In response to OAK's sinking, Churchill began to barricade entrances to the Flow, permanently changing water movement, the sedimentary regime, and marine life in the area. Since then, Scapa Bay has been well sheltered from prevailing current, as well as enemy ingress.

Scapa Flow is a now semi-enclosed with entrances only via Switha and Hoxa Sounds to the South and Hoy Sound to the West. The main basin is relatively steep sided with an approximately level bottom averaging 25-35m, but 'deeps' down to ~70m (www.orkneyharbours.com/port_environment.html).

The seabed is characterised by mud, sand and gravel sediments. Water movements around the Flow are now greatly reduced and a generally anti-clockwise water circulation occurs with a turnover of approximately ten days, as well as the rise and fall of the tides approximately perpendicular to the shores (https://www.sepa.org.uk/media/320796/1157275_ece_estimates.pdf).

Figure 274: Summary of residual (magenta) and tidal (red) currents (note different scales), from Edwards 2017 SSF ECE Scapa Flow Estimates for SEPA (https://www.sepa.org.uk/media/320796/1157275_ece_estimates.pdf)

Scapa Bay is sheltered from the main circulation, and limited tidal flow means that fine sediments are deposited. It is likely that the Churchill Barriers have altered the tidal regime and are causing these fine silty, muddy sediments to build up in the northeast of Scapa Flow over time (http://www.dynamiccoast.com/files/Ramsay_Brampton_Cell_10.pdf). This is reflected by observations around ROYAL OAK's current resting place. She sits on a bed of sandy mud, and is not subject to any strong currents. ADUS (2006) measured a gentle scour around the wreck, and a 240m wide ~2m deep channel in

the natural seabed running west, with more subtle scour (average 1m deep) running south from the wreck. The wreck today is not subject to harsh tidal conditions or visibly high levels of sedimentation; her shallow depth and adequate water movement provide ideal conditions for a wide variety of marine life.

On this seabed comprising mainly of silt and sand, ROYAL OAK has become a rich artificial reef. A thriving ecosystem spanning multiple zones across her 4-34m depth range, she supports diverse faunal and algal communities. Starfish and urchins are common, the wreck provides shelter to crab and lobster and habitat for multiple life stages of many fish species, as well as a playground for curious seals.

3.1.9.1 *Vertical distribution*

The upper sections of wreck lie in only 4-5m of water so, rarely for a Scapa wreck, in summer ROYAL OAK hosts a vibrant community of green, brown, red and calcareous algae upon its shallow upturned hull. Many species of anemones form part of this community, and other invertebrates such as starfish, small crustacea, gastropods and juvenile fish frequent this zone. Green and brown algae die away in the winter months.

Figure 275: Complex community on top of ROYAL OAK in summer. From *Ulva sp.*, *Saccarina sp.*, *Asparagopsis sp.*, to *Aplysia sp.* and some *Metridium sp.* where space allows

Moving slightly deeper down the sides of the upturned hull from about 8m to 18m, greens and browns give way to red algae and filter feeders begin to have more space to colonise less crowded surfaces. Plumose anemones and tunicates become common, and soft and hard coral species such as dead man's fingers and Devonshire cup corals are seen. Although the current flow is relatively limited, parts of the structure that are subject to greater water movement become obvious, as more, larger *Metridium* and *Alcyonium* individuals appear.

Figure 276: Moving down the hull of ROYAL OAK from ~8-18m species of red algae dominate. Plumose anemones are common, starfish, tunicates and dead man's fingers are present

As the hull gives way to decking the life again changes markedly. Flora becomes rarer as the space under the deck is shaded and photosynthetic organisms do not thrive. Filter feeders *Alcyonium* sp. and *Metridium* sp. are abundant and diverse anemone species are encountered. The teak decking in particular is host to a stunning array of species. A thick white fur here is comprised of Moon jellyfish polyps, prior to release into the water column when they mature.

Figure 277: Under the hull and down the teak decking from ~18m to the seabed, faunal turfs and filter feeders cover the structure. Starfish, urchins, crustacea and fish are found

Proceeding to deeper parts of the wreck faunal turfs cover any exposed surfaces. More sediment influences horizontal spaces, and individuals stand out more clearly in these environments.

Figure 278: On structures near the seabed rich faunal turfs are observed and individual animals are more easily observed. From top left to bottom right: urchins and starfish; cod, featherstars, velvet swimming crab; tunicates and Devonshire cup coral; hydroids, sponges, coralline algae; edible crab, sunstar, hydroids; barnacles and bryzoans; and much more in every picture

3.1.9.2 Horizontal distributions: seabed habitats

ROYAL OAK rests predominantly on the fine silty, muddy sediments building up in the northeast of Scapa Flow. But the influence she has had on the seabed is clear. In close proximity to the wreck this has resulted in several distinct benthic habitat types.

Figure 279: ROYAL OAK within Scapa bay, illustrating scour patterns with both tidal and drift directions indicated. (Fitzsimmons C, using GEBCO bathymetry 2020)

To the deck side, the bottom is predominantly silty mud and life colonises this, while the hard substrate introduced by the former deck and ship structures that have fallen to the sea bed provide settlement areas for different communities. Towards the hull, the seabed is covered by much coarser sand and shell. Behind the wreck and at either end as the water is slowed by her presence, larger items of shell and debris overlay the silt, and provide complex but dynamic surfaces that foster different communities again. Live mussels and

the large shells that remain are covered by brittlestars, shelter small fish and crustacean species and are colonised by anemones, worms and other invertebrate life.

Figure 280: Finer sediment and examples of individuals colonising the smallest of available hard substrate, further away from the shelter of the main structure and on the hull side

Figure 281: Courser sediment and examples of mussel/brittlestar communities formed below the shelter of the bow and stern, and on the hull side of the wreck

Slightly further from the wreck, and on the hull side, sediment dominates and even small artefacts may act as a secure settlement for more sedentary animals, and offer protection and security in an otherwise exposed location.

Figure 282: Shelter is provided in softer sediment by artefacts from the wreck. Whelk eggs are laid on a wooden davit, barnacles encrust a gas lamp as crab shelter under a gun barrel, anemones and barnacles cover a bottle, and even rope, more likely from salvage, has become home to some.

3.1.9.3 *Fish life and larger animals*

Smaller algae and filter feeding animals also provide refuge and food for larger organisms. From the various seastars and urchins via abundant nudibranches and sea hares to resident and transitory fish species. These in turn attract predators such as seals and guillemots, which were regularly seen diving. Even orca roamed the site while we surveyed in winter, although we were not lucky enough to see them underwater.

The wreck supports several commercially important shellfish and finfish species, primarily scallops, lobster, edible crab, velvet swimming crab, cod, pollock and saithe. Whelks and their eggs were also observed. Various species of resident wrasse and smaller fish found more permanent homes within the structure. Some examples of species seen are below, but this was not exhaustive.

Figure 283: Top to bottom: sea lemon and eggs; scallops and whelk eggs; ballan wrasse and blenny (smaller non-commercial species); cod and ling (commercial species); and larger visitors orca and spider crab

3.1.9.4 *Returning to nature*

Some of the most poignant images from the project resulted from the Northern Diving Group's ensign changes at anniversary remembrance events. Being privileged to dive the site the following year, we were able to witness the succession of life, from bare ensign, to colonised space. We hope that the thought of new life flourishing on the wreck gives some comfort to those who mourn the lost.

Figure 284: Top to bottom: Laying the ensign in remembrance and after two weeks; Ensign the following year; Plumose anemone and velvet swimming crab in their new homes.

4. Discussion

The purpose of the survey was to document the ship in her current condition after 80 years underwater and to analyse the damage, providing greater insight and understanding about her loss. The events and reasons surrounding her loss are outside the scope of the survey and this report, and well documented in the historical record. This section summarises significant findings: it discusses the overall condition of the wreck today; provides new analyses of damage, and contributory factors to the sinking; documents items missing and salvaged, and; describes teamwork that significantly updates the historical record.

During the survey the wreck of HMS ROYAL OAK was found to be in remarkably good structural condition, given the damage inflicted upon her. She lies upturned, resting on her conning tower and guns with her port side some distance clear of the seabed. Her open decks are accessible beneath the hull, angled approximately 40 degrees to the ground. The starboard side of the hull has sunken into the sediment as far as the main deck level, such that the starboard 6" casement gun battery and Shelter Deck are buried in the seabed. In addition to damage from the sinking and subsequent activities to recover equipment and manage oil leaks, there is some evidence of deterioration:

- 1) There is evidence of collapse in the superstructure around the conning tower consistent with it being driven up into the hull by the weight of the ship now bearing down on it.
- 2) At the bow forward of torpedo hole #1 the forefoot and keel have fallen from the wreck and now lie on the seabed.
- 3) Heavy deck mounted equipment such as winches, gun mounts and ammunition lockers are becoming detached due to the effect of corrosion, and some have fallen to the seabed.
- 4) Some superstructure plating has rusted through and, in places where it is subject to stress, has cracked and twisted, for example, the Wardroom & Gunroom forward of X-turret.

Four torpedo strikes caused substantial damage to ROYAL OAK that she was unable to survive. The survey team investigated thoroughly the site of each impact, producing 3D models and conducting detailed technical analyses. The first torpedo clearly made a hole through the ship's bow but did not affect any manned compartments. Flooding was confined to relatively small compartments below the armoured deck and forward of a watertight bulkhead before the anchor capstan machinery. This did not contribute to the sinking. The second torpedo opened a hole ~8m wide by 5m high close to the watertight bulkhead at frame 27. This caused flooding forward and aft of the bulkhead and breached the armoured longitudinal bulkhead that protected the 4-inch HA QF magazine and adjacent refrigeration store. Blast and flash from this torpedo explosion would have entered the ship tearing through the open crew spaces above causing injuries and fatalities amongst the crew. Having severely damaged the 4-inch HA QF magazine, this torpedo strike came close to causing a magazine explosion that would have propagated to adjacent magazines and caused a catastrophic explosion. No evidence of a magazine explosion was found during the survey. The robust construction of the 4-inch HA QF ammunition and boxes ostensibly withstood the effects of the torpedo explosion without evidence of sympathetic reaction. Simple analysis of the flooding suggests that the ship could probably have sustained and survived the damage from the first and second torpedo strikes (3.1.6.7).

Torpedo strikes three and four struck furthest aft at frames 142 and 176. These caused flooding of Boiler Room 3 and the Starboard Wing Engine Room and a loss of power that led directly to the capsize and sinking of the ship. Contrary to eyewitness accounts, no evidence of magazine explosion was found during the survey, however, the torpedo explosions breached the ship's torpedo protection, oil-fuel bunkers and inner

longitudinal armoured bulkhead. Blast and flash would have entered the ship's compartments and companionways, fuelled by burning oil spray & vapour. The loss of power, likely caused by the third torpedo strike to Boiler Room 3 deprived the crew of the use of emergency equipment such as pumps, lighting, radios and winches. This would have combined with the general confusion and disorientation amongst the crew to make effective damage control almost impossible.

The night she sank, ROYAL OAK was a fully worked up, modernised warship of the Home Fleet. She had sortied in the North Sea in search of German warships only days prior to her sinking. She was in a high state of readiness to defend against air attack. Scapa Flow was considered safe from submarine attack. Her sinking shocked the nation; the disbelief of the crew can only be imagined. The survey found over half the accessible scuttles and ports open; either opened for crew comfort in perceived safety prior to the attack or during the sinking by those trying to escape. In safe anchorage, many scuttles, ports, hatches and doors would have been left open for the convenience of the crew. Under threat from submarine attack they would have been kept firmly closed. The high proportion of open scuttles and ports observed during the survey suggests a low alert state with respect to submarine threat. During the torpedo attack the open scuttles, ports, hatches and doors would have allowed blast, flash and subsequent flooding to enter and propagate through compartments and companionways making damage, injury and flooding more widespread, and accelerating the capsize and sinking of the ship. It is likely that the ship would have stayed afloat longer if scuttles, ports, hatches and doors had been closed, enabling more crew to evade injury and escape the sinking ship.

Although the deck side of ROYAL OAK remains remarkably well preserved, some significant sections were not located during this survey. The Main Mast lies alongside the ship in a forward direction underneath the remains of caisson 1 and the radar platform, but the Upper Platform of the Main Mast was not observed in this location (see Figure 108: Annotated 3D Photogrammetry overview of the port side midships section

Figure 109). However, the presence of the HACS range finder lying on the seabed perpendicular to the Main Mast base suggests a more complicated series of events occurred during the sinking. Material potentially from the Upper Platform lies on the seabed outside caisson 2 and includes alloy cabinets and electrical items and Pyrex glass insulator rods. In addition, the Lower Bridge, Upper Bridge and Torpedo Lookout were absent from the forward mast structure. A pronounced gap exists between the ship's side and the remains of the searchlight platforms which are visible crushed underneath and the Spotting Top and Directors. As material from below the missing mast structure is visible under the ship it is not likely that those missing sections are crushed under the hull, they more likely were lost earlier. This is further supported by the discovery of wreckage 318m to the north by sidescan sonar. Two lumps of wreckage are identified as a section of mast strut and material consisting of metal plating, a large bundle of heavy electrical cabling and three voice pipes consistent with those of ROYAL OAK. The largest piece of steel plating resembles a section of platform or deck, the voice pipes are mounted to the plate. A couple of metres to one side is then a section of brass railings, while on the other lies a short length of ladder. The missing compass platform on the Upper Bridge had the only brass railings on the ship's plans. If this wreckage is from the missing bridge area it could indicate salvage, but no reference to removal has been found in historical documents or past survey reports. Notably, if the structure was removed, no damage was done to the Spotting Top, indicating a sophisticated lift. It is also unlikely that the wreckage could have been lifted up and over the shallow top of the hull to the north without snagging, so further investigation is required to support any salvage theory.

While salvage of the propellers and some chain was documented (Annex 8.3), the removal of the anchors was not; they were already absent by 1950. It is likely that they were recovered on behalf of the Admiralty during WWII by the salvage company Metal Industries. While later commercial salvage was prevented by strong objections of the Orkney and surviving Royal Oak communities, evidence of small scale and piecemeal removal of artefacts by recreational divers is present. Propellers are missing from the twin screw motorboat lying underneath the Main Mast (see Figure 118) and the gun sights are absent from the Quad 0.50 Vickers Machine Gun (see Figure 78 and Figure 80 **Error! Reference source not found.**). This is also supported by the documentation of the removal and recovery of the ship's name now housed in the Scapa Flow Visitors Centre and the remains of German torpedoes recovered by local divers.

The discovery of an almost intact German G7e/T2 torpedo close to the wreck adds significantly to the historical record. The heading of this torpedo as it lay on the seabed was such that it is probably the one fired from the stern tube of U-47 and missed the bow of HMS ROYAL OAK by only ~42m. Its discovery by the survey team's divers is significant, the torpedo had not previously been detected by side-scan and multi-beam sonar, and clearly shows the benefit of in-water diving surveys in combination with unmanned remote methods. It is to the credit of the Royal Navy and Harbour Authorities that they authorised the in-water diving survey, which has provided new information to the historical record, and enabled the clear identification and safe disposal of the hazardous live warhead and firing pistol.

5. Conclusions

The wreck of HMS ROYAL OAK is a near pristine battleship sunk in fighting condition. Arguably the most complete example of its kind underwater today, she is of extreme archaeological and historic importance and the grave of 835 sailors. Her position on the seabed provides access to the deck and superstructures from the port side. Exposed 15-inch gun houses, port side casemate guns and port side anti-aircraft guns and directors visible offer a unique insight into the gunnery and control of WWI and WWII battleships. The collection of architectural features, artefacts and items pertaining to the crew offer us a glimpse into life

aboard a wartime shipwreck (these were all found on the exterior of the site or photographed through openings into the ship). Although some decay is evident, as expected for a steel ship underwater for 80 years, she remains a near pristine example.

The opportunity to document a near intact battleship with most of her fire control present and accessible and sunk in an aspect that allows access to most of the open deck structures is unique. The challenge was sharing this with others; how best to complete the visualisation. An extended survey period allowed significant data to be gathered, reviewed, and processed allowing us to best plan subsequent in-water diving activity. Innovative visualisation methods developed during previous surveys were combined, resulting in some of the most comprehensive documentation of a shipwreck yet delivered. Multiple visualisation techniques allowed the whole site to be described accurately and communicated successfully to a wider audience. Integrating documentation, broadscale sonar surveys, and targeted diver surveys to identify key features and artefacts with professional photography and videography, proved highly successful. Filming for 3D photogrammetry was prioritised allowing a significant data set to be gathered and large sections of the wreck to be modelled. Combining 2006 multibeam data with 3D photogrammetry delivered unique visualisations of the wreck for the first time. Multibeam data provides a bathymetrically accurate base model, then integrating photogrammetry augments this with texture and colour, allowing features and details of the wreck to be visualised at high resolutions. Bringing documentary style videography in-house as part of the survey allowed footage to be captured to help tell the story of the shipwreck without compromising data capture and enabled overall control of the footage to be maintained.

The diving methods employed during the survey worked very well and the results prove that a dedicated volunteer team can produce an extremely high standard of work. The use of technical diving equipment and closed circuit rebreathers was imperative, enabling relatively long bottom-times and efficient data capture, and ensuring the impact on the site was kept to a minimum by removing the risk of exhausted diving gases, especially when working under the upturned hull. Teamwork was key to the success of the survey. Building the right team was vital in terms of both skills and attitudes. The combination of in-water subject matter experts (explosives, guns, wildlife, navy personnel), wreck diving specialists and underwater photographers, videographers, and 3DPG experts proved highly successful. Survey logistics were exact and maximised in-water survey efficiency.

Safety was a priority. Careful consideration should always be given to the dive platform in use, team ability, skillset, and equipment requirements. But the team did not work alone. The value of collaboration cannot be overestimated. Access to previous remote survey data enabled the HMS ROYAL OAK 80 survey to increase knowledge and documentation of previously identified targets such as the second pinnacle and to visit and identify new targets. Combined with historical research from archives and newspapers, these informed the survey and data analyses, as did anecdotal evidence of the sinking from survivors and local witnesses.

The team were able to add significantly to the historical record. Specifically, the torpedo damage to HMS ROYAL OAK was substantial and the improved side protection, the torpedo bulges combined with air, oil and water filled internal compartments, were insufficient to withstand developments in underwater weapons. The damage breeched internal compartments, ultimately compromising the watertight integrity of the hull. There is no evidence of magazine explosion, but blast and flash from torpedo strikes and the ignition of fuel oil would have been extensive, causing serious injury to the crew. It tore through the relatively open internal areas of the ship, corroborating eyewitness accounts. This explains the assumptions made by survivors that there were magazine explosions. Open ports, scuttles and watertight doors would have increased the rate of flooding once the ship began to list. Torpedo damage was so significant that sinking was inevitable, but the ship may have stayed afloat for longer had better watertight integrity been maintained. The four torpedo

holes in the wreck of HMS Royal Oak and the G7e/T2 torpedo discovered during the Survey lying on the seabed nearby provide a remarkable historical record of the design and operational effectiveness of the weapons that armed the German U boats at the beginning of World War Two.

More specific local recommendations regarding future management of the site can also be made. Important wreckage, including historically significant artefacts, lie outside the current exclusion zone and are not formally protected. Two contacts to the north may require assessment, but most importantly the second steam pinnace is located 273m to the west. The exclusion zone should be extended to protect this asset.

The absence of activity within the zone has also provided de facto protection to local marine life.

Undisturbed by diving and fishing, the wreck has is now a complex ecosystem itself, providing valuable shelter within the otherwise flat Scapa Bay, it helps support local fisheries and wildlife. The lack of wholesale commercial salvage, the historical restriction on recreational diving on the wreck since the 1980s, and her current status as a controlled site have contributed to its high level of preservation, ensuring her historical and ecological value is maintained.

Engaging with the Royal Oak community brought huge meaning and value to the survey work and allowed the team to fully integrate with the 80th anniversary commemorations. The importance of sharing imagery and narrative experiences of such sites was learned during the Vanguard 100 commemoration. This knowledge was used and developed in the planning of the 80th anniversary of the loss of HMS Royal Oak commemorative events. The survey successfully brought information to the surface to be shared with relatives of the lost sailors and the wider public. It provided unique new imagery to mark the 80th Anniversary and augmenting the historical record. Working closely with the Royal Navy's Northern Diving Group to document their annual ceremonial diving, and HMS Royal Oak Association to ensure continued remembrance, our collaborative widescale dissemination of the results will help ensure that the loss of HMS ROYAL OAK and the sacrifice made by her crew retains international significance.

5.1 Outputs

In addition to publication of this report, a variety of different media have been prepared, including exhibition materials such as pop-up banners, photographs, paintings and presentations for civic, military, and professional events, and museum display.

The 3D visualisation outputs from the survey are primarily 3D point clouds produced through the photogrammetry process. The point clouds were processed for a range of different display technologies and audiences:

- Point clouds (XYZRGB): Displayed in interactive 3D viewing software, Cloud Compare and Wrecksight. Primarily used to study and improve understanding of the wreck's condition.
- Rendered animated sequences: point clouds were loaded into Autodesk Maya software and rendered for use in video outputs (e.g. "Fallen Oak" documentary) for presentation at conferences, social media and public talks.
- Virtual Reality: The point clouds were converted for use as assets in VR experiences at public exposition events. Users were able to view the integrated multibeam and photogrammetry data in a 360° environment.

All media produced was used to enhance the 80th Anniversary Commemorative events in Kirkwall and Stromness and at Portsmouth. Additional media based dissemination of information has been undertaken, including newspaper and magazine articles, and social media based dissemination of imagery is available on the Scapa 100 Facebook page. Further dissemination will be available via the HMS Royal Oak Association Facebook page.

Figure 285: Fallen Oak Documentary

Figure 286: VR experience

6. Recommendations for Future Work

- Extend the exclusion zone to include the pinnacle. Consideration should also be given to extending the exclusion zone to protect the targets identified to the north which are highly likely to be from HMS Royal Oak.
- It is recommended that the survey be repeated every 5-10 years to monitor the site, record deterioration and provide opportunity to extend the 3D photogrammetry and photographic documentation. This information should be widely shared in an appropriate manner.
- ROYAL OAK should continue to be treated as a site of huge historical importance. Notwithstanding her war grave status, she also has a substantial relevance to current naval safety. She is a time capsule into WWI naval architecture, and 21st Century oil removal.
- This work and the techniques used could inform WWII shipwreck surveys and oil removal currently underway on WWII shipwreck in the Pacific by organisations such as the Major Projects Foundation.
- Methods used by the ROYAL OAK 80 survey team have been shown to be highly effective and should be widely communicated to benefit future wreck site surveys and wreck site management.

7. Sources & Bibliography

Admiralty. Main Fleet Base Scapa Flow, Inception, Development and History (ADM116-5790)

ADUS. Royal Oak Survey Report, Prepared for The Ministry of Defence Salvage & Marine Operations IPT/DCS, Annex 8.4, University of St Andrews & University of Dundee, May 2006

BBC. Images reveal extent of HMS Royal Oak torpedo attack. October 2019 <https://www.bbc.co.uk/news/uk-scotland-north-east-orkney-shetland-50033917>

Briggs. Marine Oil Removal Summary, 2010, <https://www.briggsmarine.com/media/1333/royal-oak-oil-removal-programme.pdf>

BSAC. Dive Team Announce HMS Royal Oak 80 Wreck Survey, January 2019 <https://www.bsac.com/news-and-blog/hms-royal-oak-80-wreck-survey-announced/>

Churchill, W. The Loss of HMS ROYAL OAK and the Defences of Scapa (CAB 66/4/3)

Haversham, D. Wolves without Teeth: The German Torpedo Crisis in World War Two, University of Alabama 2004

Hendry, S *et al.* Shiptime Project Report, 2017

Konstam, A. U-47 in Scapa Flow – The Sinking of HMS ROYAL OAK 1939 (pub. RAID) 2015

ORCA. Orkney Research Centre for Archaeology – Marine 62 Report Scapa Flow, 2013

Rowland, C. Fallen Oak, 2020 Documentary film, 26 minutes. Director K, Duncan, Producer, C. Rowland. HMS Royal Oak 80 Survey team, University of Dundee. <https://vimeo.com/460447596/559fe3e0cc>

Rowlands, P. HMS Royal Oak (film), 2002, Ocean Optics, Plymouth

Sarkar, D. The Sinking of HMS ROYAL OAK – In the words of the Survivors, Amberley 2012

Snyder, GS. Royal Oak Disaster, 1976

Times, The. Divers will explore torpedoed battleship on which 800 died, February 2019 <https://www.thetimes.co.uk/article/divers-will-explore-torpedoed-battleship-on-which-800-died-03ttrjp5r>

Turton, E *et al.* HMS Vanguard 100 Survey 2016 – 2017, Survey Report, 2018 <https://www.huskyan.com/diving/hms-vanguard>

Weaver, HJ. Nightmare at Scapa Flow, Cressrelles Publishing 1980-1985 and Birlinn 2008

8. Annex

8.1 Scuttle Arrangement

The tables included below detail the scuttles arrangement visible on the wreck of HMS ROYAL OAK. Detail of the spaces within the ship and any artefacts located within are included. We also note if the scuttles were observed as being open or closed at the time of survey. Also included are any watertight doors, square and oval ports observed.

There are a total of 89 round scuttles, one square port and one watertight door across the visible decks of the starboard side of the wreck. 58% of these are open, 40% were closed and 2% were not observed.

Every port as detailed on the ship's plans can be viewed on the port side of the ship due to her position on the seabed. A total of 87 round scuttles, 3 oval ports, 5 square ports, and 3 watertight doors were observed. 57% of these are open, 40% were closed and 3% were not observed.

8.1.1 Port Side Scuttle Arrangement

Aft Scuttle/Porthole Detail Port Side Middle Deck		
Numbered from Stern	Open/Closed	Detail
1	Closed	Victualling Office
2	Closed	Victualling Office
3	Closed	Captain's Office
4	Closed	Captain's Office
5	Closed	Officer's Cabin No 26
6	Closed	Officer's Cabin No 24
7	Closed	Officer's Cabin No 22

Aft Scuttle/Porthole Detail Port Side Main Deck		
Numbered from Stern	Open/Closed	Detail
1	Open	Admiral's Day Cabin, deck structure visible
2	Closed	Admiral's Day Cabin
Square Port	Closed	Admiral's Day Cabin
3	Closed	Admiral's Day Cabin
4	Closed	Admiral's Day Cabin
5	Closed	Admiral's Dining Cabin
Square Port	Closed	Admiral's Dining Cabin
6	Closed	Admiral's Dining Cabin
7	Closed	Admiral's Pantry
8	Open	Admiral's Pantry, buckled metal shelves, stack of ornate plates and scattered plates
9	Closed	Captains Bathroom
10	Closed	Captain's Toilet

11	Open	Captain's Sleeping Cabin, deck structure visible
12	Open	Captain's Day Cabin. Deadlight visible inside
13	Closed	Captain's Day Cabin
14	Open	Paymaster Commander Cabin, storage box, bed frame, and shelf forwards. A lamp and cable has fallen. The same space is visible through a rotted hole on the hull between scuttle 14 & 15.
15	Open	Officer's Cabin No 16. Corridor visible, Note: the Cabin was inset. Ventilation ducting and a light bulb visible.
16	Open	Officer's Cabin No 14, Bedframe, a dining plate and a decayed closed cabin door. Marked as non water tight on the plans.
17	Open	Officer's Cabins No 12, square ducting, voice pipe, remains of bookshelf.
18	Open	Officer's Cabins No 10, narrow passage to open cabin. A metal grate was observed possible from a folding lavatory as marked on the plans.
19	Open	Officer's Cabins No 8, evidence of a RN commemorative box with plaque, presumed to be a relative's or survivor's ashes. A similar grate observed as 18.
20	Open but partly obscured	Officer's Cabins No 6. Obstruction is possibly vent covering. Visible inside was a bulb, shelf and bedframe.
21	Closed	Officer's Cabins No 4
22	Open	Officer's Cabins No 2, bedframe and shelves.
23	Open	Marine's Mess, dining plate, commemorative urn
24	Open	Marine's Mess, dining plate and cup, commemorative urn
25	Open	Marine's Mess, dining plates, light bulb, metal bar on deck head.
26	Open	Marine's Mess

Forward Scuttle/Porthole Detail Port Side Main Deck		
Numbered from bow	Open/Closed	Detail
1	Closed with bars	Paint Store
2	Closed with bars, partly obscured	Paint Store

3	Closed with bars, partly obscured	Paint Room
4	Closed with bars	Petrol Control Room
5	Open	Electrical Artificer's Workshop, complete lamp with intact light bulb, light bulb, pipework
6	Open	Joiners' Shop. Scuttle is partly obscured with metal debris/sheet/cover. Scuttle door seen on the inside.
7	Closed	Joiners' Shop.
8	Open	Engine Room Artificer's Mess. Drive shaft and gears and pipework.
9	Open	Engine Room Artificer's Mess. Drive shaft and gears.
10	Open	Engine Room Artificer's Mess. Pipework and ducting.
11	Open	Common Space. Corridor with door at the end
12	Open	Chief Petty Officer's (CPO) Pantry, shelves with plates. Plates, bowls and other crockery scattered.
13	Closed	CPO's Mess
14	Open	CPO's Mess. Pipework
15	Closed	CPO's Mess, shelving, drawers fallen down, shoe sole, light fitting and square ducting.

Aft Scuttle/Porthole Detail Port Side Upper Deck		
Numbered from bow	Open/Closed	Detail
Watertight Door	Open	Common Space
1	Not observed	Gunroom and WO toilets
2	Open with partial obstruction	Wardroom toilets

Forward Scuttle/Porthole Detail Port Side Upper Deck		
Numbered from bow	Open/Closed	Detail
1	Open with bars	Chief Petty Officer's (CPO) and Petty Officer's (PO) Urinals. Pipe and light fitting
2	Open with bars	Seamans Heads. Pipes, metal framework and small valves.
3	Open with bars	Seamans Heads, partly obscured by metal plating.
4	Open	Seamans Heads, pipes, small and large valves.

5	Open	Seamans Heads, pipes and valves
6	Open	Seamans Heads, scuttle has fallen into the ship. Pipes and ducting.
7	Open	Seamans Heads, pipes and ducting.
8	Closed	Access to Toilets
9	Closed with bars	Torpedo Parting Space
10	Closed	Torpedo Parting Space. A decayed hole reveals stack of 4 plates, a bulb, a bucket and ducting to a deck vent and a broken valve.
11	Open	Torpedo Parting Space, bulb, stack of plates, square ducting leading to big deck vent.
12	Open	Boys Mess, cup
13	Open	Boys Mess, pipes with heat shield wrapping and a drum shaped artefact.
14	Open	Boys Mess, pipe with heat shield and doorway visible.
15	Open	PO's Mess. Pipes and light bulb.
16	Open	PO's Mess. Vent to deck
17	Open	PO's Mess, buckled frames and loose sheet metal and a vent to deck.
18	Open	PO's Mess, buckles frames, sheet metal.
19	Open	PO's Pantry, shoe sole
20	Open	Artisans' Mess, doorway visible
21	Open	Shipwrights' Mess
22	Open	Shipwrights' Mess, plate, bowl, and cup. Buckled metal sheets.
23	Not recorded	Shipwrights' Pantry

Scuttle/Porthole Detail Port Side Forecastle Deck		
Numbered from bow	Open/Closed	Detail
1	Open	Vegetable Kitchen, light bulb, tiles, 2 x intact glass bottles, 1 x broken bottle, flat broken sheets, light fitting.
2	Closed	Potato Store
3	Closed	Preparing Room
4	Closed	Preparing Room
5	Open	Preparing Room. Light fitting, glass bottle, potato cleaning machine, commemorative urn.
6	Open	Preparing Room. Remains of shelving, view of potato cleaning machine,
7	Open	Preparing Room. Pipework, light fitting, commemorative ensign.

8 – oval port	Closed	Bakery
9	Closed	Bakery. Large rotten hole between port 8 & 9 gives visual access to bakery. Kneading Machine, ceramic/Belfast sink, light fittings, stack of loaf tins.
10 – oval port	Closed	Bakery
11	Closed	Warrant Officer's (WO) Pantry
12	Open	WO Mess. Scuttle has fallen inwards. Plates, ridged bowls, glass dishes, large glass bowls and shelves.
Square Port	Closed	WO Mess
Watertight Door	Open with rotten hole.	4-inch ammunition locker. Sprinkler valve, two closed door to either side. Open door at the back.
13 – oval port	Closed	Gunroom
Square Port	Not observed	Gunroom
14	Open	Gunroom, leather pouch.
Square Port	Open	Gunroom
15	Closed	Gunroom Ante Room
Watertight Door	Closed	Gunroom Ante Room
16	Closed	Gunroom Ante Room
17	Open	Gunroom Ante Room. Scuttles housed in soft patch/hatch. Small anchor hooked in scuttle.

8.1.2 Starboard Side Scuttle Arrangement

On the starboard side the ports on the Forecastle deck are mostly buried although three were accessible during the survey from under the ship via the port side. All three are ports to the Wardroom and two of the three were also observed as being open at the time of the survey. Three scuttles and one watertight door into the Upper Deck are also visible in this manner.

Aft Scuttle/Porthole Detail Starboard Side Middle Deck		
Numbered from Stern	Open/Closed	Detail
1	Closed	Warrant Supply Officer's Office
2	Closed	Warrant Supply Officer's Office
3	Closed	Ship's Office
4	Closed	Ship's Office
5	Closed	Officer's Cabin No 27
6	Closed	Officer's Cabin No 25
7	Closed	Officer's Cabin No 23

Aft Scuttle/Porthole Detail Starboard Side Main Deck		
Numbered from Stern	Open/Closed	Detail
1	Closed	Admiral's Day Cabin
2	Closed	Admiral's Day Cabin
Square Port	Closed	Admiral's Day Cabin
3	Closed	Admiral's Day Cabin
4	Closed	Admiral's Day Cabin
5	Open	Admiral's Sleeping Cabin, bed frame, drawer handle, curtain rail, open door to bathroom.
6	Open	Admiral's Sleeping Cabin
7	Closed	Admiral's Bathroom
8	Closed	Admiral's Toilet
9	Closed	Admiral's Spare Cabin
10	Open	Admiral's Spare Cabin
11	Open	Captain's Bathroom
12	Open	Captain of the Fleet's toilet
13	Open	Captain of the Fleet's sleeping Cabin
14	Open	Captain of the Fleet's Day Cabin
15	Open	Captain of the Fleet's Day Cabin
16	Open	Engineer Commander's Cabin
17	Open	Officer's Cabins No 15
18	Open	Officer's Cabins No 13
19	Open	Officer's Cabins No 11
20	Open	Officer's Cabins No 9
21	Open	Officer's Cabins No 7
22	Open	Officer's Cabins, telephone visible. Cabin No 5. A note on the plans state this was to be for the medical officer.
23	Open	Officer's Cabins No 3
24	Open	Officer's Cabins No 1
25	Closed	Marine's Mess
26	Open	Marine's Mess
27	Open	Marine's Mess
28	Open	Marine's Mess

Forward Scuttle/Porthole Detail Starboard Side Main Deck		
Numbered from bow	Open/Closed	Detail
1	Closed with bars	Paint Store
2	Closed with bars	Paint Store
3	Closed with bars	Paint Room
4	Closed with bars	Boatswain's Store
5	Closed no bars	Small port, prison cells
6	Closed no bars	Small port, prison cells

7	Closed no bars	Small port, prison cells
8	Closed no bars	Small port, prison cells
9	Closed no bars	Small port, prison cells
10	Closed	Kit store
11	Open	Light fitting, kit store
12	Open	ERA's Pantry, plates, bowls other crockery
13	Closed	Common space
14	Open	Plates, tiles, cups. Chief stokers and mechanics pantry. Directly below is a plate on the seabed
15	Closed	Chief Stoker's and Mechanician's Mess
16	Open	Lattice type woodwork from seat lockers in Chief Stoker's and Mechanician's Mess
17	Closed	Chief Stoker's and Mechanician's Mess

Aft Scuttle/Porthole Detail Starboard Side Upper Deck		
Numbered from bow	Open/Closed	Detail
Watertight Door	Open	Common Space
1	Open	Executives Officer's Cabin
2	Open	Executives Officer's Cabin. Glassware, possible vinyl records
3	Not recorded	Common Space

Forward Scuttle/Porthole Detail Starboard Side Upper Deck		
Numbered from bow	Open or Closed	Detail
1	Open with bars	Chief Petty Officer's (CPO) and Petty Officer's (PO) Urinals
2	Open with bars	Seamans Heads. Light fitting and valve hand wheel
3	Closed with bars	Seamans Heads
4	Closed with bars	Seamans Heads
5	Open	Seamans Heads , Tiles and a urinal
6	Open	CPO WC's (toilet cubicles)
7	Open	CPO WC's (toilet cubicles)
8	Open	CPO WC's (toilet cubicles)
9	Open	CPO WC's (toilet cubicles)
10	Open	CPO WC's (toilet cubicles)
11	Open	CPO WC's (toilet cubicles)
12	Open	CPO WC's (toilet cubicles)
13	Open	CPO WC's (toilet cubicles)
14	Open	Anchor Cable Space. Large machinery visible, trunking for anchor cables.

15	Open	Lamp visible, torpedo room
16	Open	Torpedo Room
17	Open	Engine Artificer and Ordnance Artificer's Mess
18	Open	Plates, Cups, Crockery. Engine Artificer and Ordnance Artificer's Mess
19	Open	Plates, Cups, Crockery. Engine Artificer and Ordnance Artificer's Mess
20	Closed	Engine Artificer and Ordnance Artificer's Pantry
21	Closed	Engine Artificer and Ordnance Artificer's Pantry
22	Small and covered	Sick bay toilet
23	Closed	Sick Bay
24	Not observed	Sick Bay
25	Open	Cots are visible in sick bay
26	Open	Cots are visible in sick bay
27	Open	Cots are visible in sick bay
28	Open	Sick bay bathroom, bath visible. Medicine bottles on seabed
29	Closed	Isolation Ward Toilet
30	Open	Isolation Ward, lamp and cot remain.

Aft Scuttle/Porthole Detail Starboard Side Forecastle Deck		
Numbered from bow	Open/Closed	Detail
1	Closed	Wardroom Lobby
Watertight Door	Open	Wardroom Lobby
2	Open	Wardroom Lobby
3	Open	Wardroom Ante Room

8.2 Outlying Acoustic Target Contact Report

8.3 Survey Report 1950

REPORT OF SURVEY OF H.M.S. "ROYAL OAK"

The following report of a survey carried out on the wreck of H.M.S. "Royal Oak" is forwarded.

2. The survey was made by four divers working from R.F.A. Salvage Vessel "Salvictor" under the supervision of Mr J. Alexander, Room Defence & Salvage Officer from 28th August to 11th September, and Captain W.R. Fell, R.N. (Ret'd) from 12th September to 30th September.

3. Weather conditions hampered the work throughout and on 15 days, diving had to be suspended and "Salvictor" steamed to shelter.

On two other days no diving took place due to the divers requiring rest after a succession of long deep dives.

Thus 17 days were lost out of the 35 days spent at Scapa.

On the 18 days that diving took place 248 actual hours of diving time by the four divers was performed.

4. Much time was lost in slipping moorings, stemming to shelter and returning and pulling up moorings again.

5. The entrance to Scapa Bay where the wreck lies is open to all winds and a heavy short steep sea rises rapidly with winds between East through South and West to North West. It then becomes dangerous to hold the Salvage Vessel up to the wreck and work from diving boats is impracticable.

6. The divers worked in pairs from "Salvictor" and one diving boat when weather permitted.

"Salvictor" moored as nearly over the portion of the wreck to be surveyed as possible using a stern anchor laid to windward and two springs secured to the wreck from either bow by divers.

Jeckstays run along the highest portion of the wreck and suspended by spherical floats allowed the diving boat to move fore and aft over the wreck as required.

Divers from the diving boat started their survey from right aft on the wreck working forward from mid level and covering the whole exposed area of hull till the stem was reached. They then worked aft along the upper deck portions of the ship that were above mid level.

A diver from "Salvictor" performed the work of cutting off all four propellers and salvaging them and latterly in recovering 90 yards of chain cable which was found to be all that remained of the port and Starboard cables of "Royal Oak" that lay outside her hull.

7. The wreck lies as charted (Chart No. 35) with her head 062 degrees. She lies on firm fine sand and mud bottom in depths of 98 to 102 feet at Low Water Springs.

She is listed to starboard at an angle of 142 degrees, with her Port bilge keel as the highest part and her turrets, upper works and the upper part of her starboard side resting or partly buried in the sand and silt.

The wreck has little weed on her but a heavy amount of shell and coralline growths cover her.

The water is clear and the light good for diver's work. The Port side can be seen on calm mornings from the surface at low water when there is a least known depth of 15 feet over the wreck.

No obstructions were found projecting above the port bilge which is uppermost, except traces of what appears to be an air lock which has been cut off flush with the highest part found.

The Port's head at the point where the Jack Staff should be is 19 feet clear of the bottom and the starboard side of the upper deck meets the bottom abreast "A" turret.

The Starboard side of the deck is from there aft buried in the silt to within 50 feet of the after end of the quarter deck.

The wreckage of the superstructure between the Foremast and mainmast render survey of the upper deck between these positions extremely difficult.

"A" and "B" turrets are trained on the Starboard beam. The gun barrels are in the silt and the guns have been forced upwards breaking their trunnions and forcing the roofs of the turrets off.

-2-

The gale which drove "Salvictor" from the wreck on September 27th prevented the survey of the upper deck from mainmast to stern being carried out and the condition of 'X' and 'Y' turrets is therefore not definitely known.

8. The whole of the shell plating and bulges that are above bottom level was carefully surveyed and the damage found has been sketched and placed on the attached drawing and model.

There are four areas of damage caused by torpedoes. All torpedoes appear to have hit the Starboard side but the foremost hit caused severe damage to the Port side as well as the Starboard side and has nearly covered the ship.

This foremost damage extends between a position 5 feet aft of stern for 50 feet aft and embraces the foremost 30 feet of bulge and runs round the keel of the wreck and up the Port side for 30 feet from the keel.

The second area of damage lies between frames 38 and 64½ over the whole area of the Starboard bulge.

This damage was penetrated to a depth of 20 feet into the hull through two and possibly three longitudinal bulkheads but owing to nil visibility none of the compartments entered could be positively identified and the inner hull in the vicinity of "A" handling room was NOT penetrated.

The third area of damage lies between frames 140 and 158 and extends from some unknown point below mud level to 4 feet from the keel.

The hole was entered almost No. 3 boiler room but divers were blocked by debris after entering a double bottom compartment.

The fourth and aftermost area of damage lies between frames 167 and 189. It extends from 5 feet above mud level to within 4 feet from the keel.

It is very similar to the third hole in size and shape but proved to be equally difficult of access although one diver penetrated into an oil fuel tank.

9. A diver working from "Salvictor" cut the Port Inner 'A' brackets in two places and then cut through the shaft 9 feet forward of the propeller. Work was started using Oxy-Arc and the Portsmouth type torch. This torch burned out almost immediately and a Malta type torch was then used continuously and gave excellent results during 48 hours of cutting. A "Petbow" generator was used supplying 600 amps at 500 volts.

The cutting of the two "A" brackets and shaft used 16 bottles of oxygen and 149 electrodes.

When the shaft was almost cut through the severed "A" bracket was slung and the weight taken and the cut then completed. Rags of metal held but were broken by jerking the wire sling. The shaft and propeller attached to it then unfortunately slid out of the "A" bracket, but lodged near the keel and rudder. It was then reslung and hoisted inboard.

The Port Outer shaft was then cut through at the Rope Guard immediately before the propeller thus avoiding the necessity to cut the "A" brackets.

This proved to be a much shorter and easier method despite some difficulty found in clearing away the rope guard and in cutting through the gunmetal or phosphor bronze 5/8" sheath round the shaft. This sheath tended to melt and run into the cut and caused delay in cutting. Eleven bottles of oxygen and 101 electrodes were used for the second shaft and a one pound charge fired to sever the shaft when cut was complete.

The third and fourth Starboard shafts were cut off and hoisted inboard in a similar manner, the diver working in less light and between 70 and 85 feet of water. 96 electrodes and 8 bottles of oxygen were used for the Starboard inner shaft and 140 electrodes and 11 bottles oxygen for the outer shaft. Charges of 8 lbs were fired round each shaft to complete its fracture.

The work of shaft cutting was performed by diver Dinadsle under most difficult conditions, with great skill.

10. Divers working from "Salvictor" located the Port and Starboard anchor cables where they left the hawse pipes.

The Port cable ran upwards from the hawse pipe through the foremost damage and then in a northerly direction into the sand.

A wire was secured to a link outboard of the hawse pipe and the link next to it burned through.

-5-

The cable was then hove in and found to consist of a length 130 feet long ending at an undamaged studded link. The cable recovered contained one unmarked joining shackle. It is in fair condition with slight corrosion.

The starboard cable which lead from the hawse pipe direct into the sand was slung out and hoisted in a similar manner, and was found to be 140 feet long ending in a out-through studded link. This link has been carefully examined and there is no doubt it has been cut and not broken at some previous time.

This length contained a joining shackle and a wire mark on the 7" link from it indicating that portions of the 6" and 7" shackles had been recovered.

Consideration was given to an attempt to save cable from cable lockers but as they were situated in the midst of the foremost damage, were nearly upside down and quite inaccessible without extensive cutting, the attempt was not made.

11. The following conclusions were reached by the two salvage officers and the Master of "Salvictor".

- (a) That H.M.S. "Royal Oak" could be raised by air pressure and floated upside down.
- (b) That this operation would entail very heavy expense and at least three seasons work.
- (c) That all superstructure would have to be cut away before floating could take place and in this process the ship would run completely over thus endangering life.
- (d) That after raising the ship her draft would exceed 50 feet unless turrets and all decks above the upper deck were cut away.
- (e) That there was no possibility of righting the ship and floating her right way up unless the anchored main deck was completely sealed off and the damage patched for which the cost in time and labour would be prohibitive if it did not prove to be a physical impossibility.
- (f) Owing to the depth of water and weather conditions off Sase Bay work at all times must be slow and for these reasons alone any attempt at salvage would prove both costly and uncertain.

12. All hands worked excellently, showing great keeness and initiative.

(W. R. FELL)
CAPTAIN, R.N. (Ret'd.)

HMS ROYAL OAK SONAR SURVEY 2006

Prepared for:

**The Ministry of Defence
Salvage & Marine Operations IPT/DCS
S&MO CBIA
Spur 9
Block D
Foxhill
Bath
BA1 5AB**

By:

**University of St Andrews
&
University of Dundee**

May 2006

Crown Copyright

ROYAL OAK SONAR SURVEY 2006

Executive Summary

The Ministry of Defence required a survey of the wreck of the Royal Sovereign class battleship HMS *Royal Oak* that lies in Scapa Bay, Scapa Flow, Orkney. Following a tendering process initiated by the MoD, ADUS of the University of St Andrews undertook a detailed sonar survey of the wreck and the immediately surrounding seabed on 9th and 10th May 2006.

The comprehensive high-definition sonar survey of the wreck was undertaken with a Reson 8125 SeaBat multibeam sonar mounted on the ADUS' Independent Sonar Head Attitude and Positioning (ISHAP) system. The survey included the hull, masts, overhanging features of the wreck and associated seabed debris.

Detailed images of the wreck have subsequently been generated from the sonar data and are of such a resolution that anomalies including hull damage from torpedo strikes, together with damage to the ship's superstructure and gun turrets caused by the sinking have been visualised. In addition many other features of the ship and its armament have been identified. The survey also confirmed and identified the current list and orientation of the wreck.

A detailed topographical survey of the surrounding seabed was undertaken. This extended 800m x 800m centred around the wreck and is of such resolution that it is possible to identify and position scattered debris and other seabed features. Extensive linear features, possibly the remains of anti-torpedo defences, are visible on the seabed and extend to the north, east and west, beyond the survey area. There is also small wreck approximately 300m south west of the *Royal Oak*. All identifiable features are detailed in this report and listed in the Gazetteer of Observations (**Appendix I**).

The sediments around the wreck have been surveyed to a level that enables a full topographical representation to be generated, and any future changes to be monitored by similar repeat surveys. All data generated from the survey has been fully geo-referenced with the processed data represented as point (xyz) data related to WGS 84 UTM Grid (Zone 30 N) for the horizontal datum and Ordnance Datum Newlyn (ODN) for the vertical. The raw data has been passed on as xyz ascii files, Fledermaus Scene files and Maya-derived movie files on CD to allow 3-dimensional visualisation of the wreck using free software (i-View3D and Quicktime). Movie representations of the wreck have also been supplied on DVD for use in any domestic DVD player.

The wreck is in 31m of water (ODN). The wreck is aligned with bows 52° east of UTM grid north, is inverted, and lists starboard side down (to the north) 32.5°. The keel slopes down 2° to the stern.

There is clear evidence of four torpedo impacts from the seven that were fired by U47. Only one of the first salvo of three hit the *Royal Oak*, in the bows, on the

forward aviation spirit storage tank. The resultant explosion blew the forefoot off up to lower deck, and may have created a secondary explosion in the paint and petrol control rooms above, as suggested by the hull plating being pushed out on the port side on the four deck levels above. The solitary stern tube torpedo then fired by U47 appears to have missed. About 12 minutes after the first strike, which was thought on board to be an internal explosion, the next salvo of three torpedoes resulted in three strikes in close succession on the starboard side, each one penetrating the protective torpedo bulge and at least two reaching magazines. Contemporary accounts indicate that that cordite fires swept through parts of the ship and burnt many of the crew. Four relatively small holes in the port side of the ship at upper deck level are likely to be indicative of secondary explosions. The last three torpedo strikes are the ones which resulted in the flooding of the ship and its sinking, and was also responsible for the penetration and initial weakening of many of the fuel oil storage tanks along the sides of the ship.

The ship rolled over to starboard and, as the weight of the vessel came to bear on the fore and main masts and they made contact with the seabed, these were broken off or bent to port. They now lie on the seabed, emerging from beneath the inverted hull. The weight of the ship then pressed on the barrels of the 15" guns, which had swung broadside to starboard as the ship heeled over, and probably supported the wreck higher off the seabed for a number of years.

Eventually the breach ends of the barrels forced the roofs off the four barbettes. This resulted in a settling of the wreck by a further 2.8m sometime after the 1941 RN survey of the site, which recorded a minimum depth of 1.8m and the current minimum depth of 4.6m relative to Chart Datum.

There are at least 14 holes through the upper surfaces of the port torpedo bulge which are likely to be due to corrosion and loss of cover plates over access hatches.

There are numerous identifiable features on the wreck and these are listed in the Gazetteer of Observations (**Appendix I**). There are also many features that ADUS has been unable to identify due lack of appropriate or readable drawings at key points.

Although there is localised corrosion of the steel of the hull, as evidenced on film (**Rowlands 2002**), and also contemporary reports of rivets working loose, as would be expected in a relatively old ship, overall the wreck is in a surprisingly good condition. The ADUS and the SRD multibeam surveys provide slope angles measured across the bottom of the ship and from bow to stern, which show no discernable hogging, sagging or other distortion. Similarly, there is no obvious distortion along the sides of the vessel that can be seen, except for localised damage due to torpedo impacts.

The fabric of a 90-year old ship submerged for the last 67 years will have inevitably deteriorated although there have been no obvious changes detectable between the 2006 high-definition ADUS survey and the 2004 SRD survey. The massive weight of the hull is now physically supported by the superstructure. This has now pressed into the seabed as far as it is likely to go. It is inevitable that there will be a catastrophic collapse of the wreck at some time as the superstructure slowly corrodes and loses

structural integrity. Predicting exactly when this will be is difficult on the evidence currently available, but a major collapse seems likely within the next 10-30 years. Common sense suggests that the structure of the oil tanks scattered through the ship will weaken over time. While many of those on the upper (port) side of the wreck have proved accessible, there are likely to be quantities of fuel oil in other areas of the ship not breached during the sinking which will continue to seep oil unless salvaged.

It is recommended that further surveys of a standard at least equivalent to the 2006 survey (better than IHO Special Order) are undertaken at appropriate intervals in order that truly comparable datasets can be collected. It is also recommended that visual inspection be undertaken of the various off-site features so that they can be better understood. It would also be useful to collect metrical sonar data in the area under the wreck so that a better understanding of the condition of the supporting superstructure can be gained.

ROYAL OAK SONAR SURVEY 2006

Contents

1. INTRODUCTION

2. BACKGROUND

SURVEY AREA

BRIEF HISTORICAL ACCOUNT

3. AIM

4. APPROACH

CHOICE OF EQUIPMENT

METHODOLOGICAL ISSUES

5. INTERPRETATION

6. RESULTS: ROYAL OAK WRECK

INTRODUCTION

OBSERVATIONS AND DISCUSSION

Orientation, List and Pitch

Damage caused directly by enemy action

Deterioration and post-depositional changes

General Features of the wreck

7. RESULTS: OUTLYING FEATURES

INTRODUCTION

OBSERVATIONS AND DISCUSSION

Target 1

Target 2

Linear features

8. RESULTS: SEDIMENT REGIME

9. RESULTS: SURVEY AREA STATISTICS.

10. RESULTS: COMPARISONS WITH PREVIOUS DATASETS.

INTRODUCTION

AREA DATASET COMPARISON

WRECK DATASET COMPARISON

11. RESULTS: POTENTIAL FOR COLLAPSE

12. CONCLUSIONS

13. RECOMMENDATIONS FOR FUTURE WORK

ACKNOWLEDGEMENTS

REFERENCES

APPENDIX 1 - GAZETTEER OF OBSERVATIONS

APPENDIX 2 - SURVEY METHODOLOGY

LOGISTICS

Survey lines

File structure

PLATFORM

ORIENTATION

Shore base station

Onboard survey

Datums

SONAR

Introduction

Sonar Hardware

Sonar Acquisition Software

ADDITIONAL DATA

POST-PROCESSING

VISUALISATION

Point Cloud Processing Versus Surfacing

Depth Cueing

Occlusion Objects

Digital Cinematography and High Definition (HD1080)

APPENDIX 3 - SURVEY DIARY

APPENDIX 4 - SURVEY CONFIGURATION

FIGURES

Figure 1

View of the wreck of the Royal Oak from the south west

Figure 2

View of the wreck of the Royal Oak from the north

Figure 3

View of the bottom of the Royal Oak. Among the features than can be seen are the four propeller shafts (IDs:3-6); the four docking keels (ID: 12-15 and; the strakes of the hull bottom plating (ID: 11).

Figure 4.

Digital terrain model of the seabed within the 800m x 800m survey area. Much of the area is crossed by linear features with regularly spaced lumps (ID: 59). 275m to the sw is a small wreck (ID: 57) and 200m to the south is a 2.2m diameter cylinder 4.8m long (ID: 58).

Figure 5

Buoy positions around the wreck. They are each approximately 95m NE of areas of seabed disturbance indicating the location of their ground tackle.

Figure 6

Detail showing sections of tripod main mast (ID: 20); port after 4" HA Gun (ID: 48) and; seaplane crane turntable (ID: 23).

Figure 7

Port rubbing strake with timber missing (ID: 16); port 6" casemate guns (ID: 49-53) and; holes in port torpedo bulge ((ID: 74).

Figure 8

Tripod main mast (ID: 20) and fore mast (ID: 21) with spotting top and related debris (ID: 21).

Figure 9

What appears to be a ship's 27' Cutter (ID: 34) lying on top of main mast debris (ID: 20).

Figure 12

Section drawing at Station 10 showing strengthening of the bow with armoured and high tensile steel at lower deck level and above.

Figure 13

Diagram of Reson 8125 and POS MV installation on MV Flamborough Light.

Figure 14

ISHAP system concept diagram.

Figure 15

ISHAP system under tow during trials at Fort William.

Figure 16

ISHAP system being assembled on board Flamborough Light.

Figure 17

ISHAP system fastened to the port quarter of Flamborough Light.

Figure 18

1936 as fitted profile drawing of the Royal Oak.

ROYAL OAK SONAR SURVEY 2006

1. INTRODUCTION

- 1.1. The Salvage and Marine Operations section of the Ministry of Defence required a survey of the wreck of the Royal Sovereign Class Battleship, HMS *Royal Oak*, which lies in Scapa Bay, Orkney. Following a tendering process the Ministry of Defence invited the University of St Andrews ADUS to undertake a high definition multibeam sonar survey of the wreck and surrounding seabed (400m by 400m). Although not specified, the work was undertaken to the standards required for the highest survey category (IHO Special Order).
- 1.2. The survey data was collected on the 9th and 10th May 2006. This report details the results of this survey and addresses directly the Aim and Objectives set out in the ADUS tender document and the specifications within the brief supplied by the MoD.
- 1.3. The 2006 survey follows an earlier sonar survey undertaken in 2004 by Sonar Research and Development (SRD) UK Ltd under contract to the MoD.

2. BACKGROUND

SURVEY AREA

- 2.1. The 800m x 800m survey area was located 3000m south of Scapa Pier, in Scapa Bay, Scapa Flow, Orkney (**Figure 4**).
- 2.2. The average depth of the seabed in the survey area was 29.579m below Ordnance Datum, Newlyn (ODN), which equates with 28.179m below chart datum.
- 2.3. The UKHO position for the wreck (centre of the hull) is 500958 6532347 (Easting Northing UTM zone 30) converted directly from 58°55.848N, 02°59.001W [WGD] (**Nelson Mceachan, pers.com.**). This position coincides exactly with ADUS data.
- 2.4. There are four mooring buoys around the wreck together with a green navigational buoy indicating a wreck to the southwest. There are seabed disturbances c.90m southwest of each of the buoy positions indicating the approximate location of their ground tackle (**Figure 5**).
- 2.5. The approximate positions of the buoys around the wreck, in UTM Eastings and Northings (Zone 30), are:

Buoy identification	Easting	Northing
Green Wreck Buoy	500881	6532213
South-west buoy	500996	6532206
South-east buoy	501180	6532382
North-west buoy	500910	6532441
North-east buoy	501077	6532549

- 2.6. The South Pier at Stromness was used as the berth for the survey vessel, *Flamborough Light*.

BRIEF HISTORICAL ACCOUNT

- 2.7. The *Royal Oak* was built in Devonport in 1916 and saw active service at the Battle of Jutland in 1917. In 1922 she was fitted with 'blisters' or anti torpedo bulges along the sides, which were also designed to give additional buoyancy and inhibit rolling. She had a major refit in 1936 at Devonport and, at the outbreak of war in 1939 was sent to the main fleet anchorage in Scapa Flow. Here she acted as an anti aircraft platform to help protect Kirkwall and local military installations.

A short voyage in rough seas in early September 1939 highlighted problems with this aging riveted ship as seawater entered freshwater tanks through the seams between plates, and corrosion around ventilators allowed water to enter the ship from the weather decks.

As she was not considered a front-line ship, the compliment included a high proportion of boy sailors, many of whom died when the U47 successfully scored four hits with torpedoes on the night of 13th October 1939, causing the ship to sink at her anchorage.

3. AIM

- 3.1. The aim of the survey was to gather data of an appropriate type, quality and resolution to:

- Provide **detailed information about the wreck's current condition**;
- Give a **clear graphic representation of the seabed around the wreck**, including sediments, disturbances and the distribution of any man-made material;
- **Supply quantified base-line data** against which future surveys can be compared;
- **Integrate and compare with previous datasets** gathered on the wreck.
- Assess the **potential for fuel oil and munitions to be dispersed** through deterioration of the wreck.

4. APPROACH

CHOICE OF EQUIPMENT

- 4.1. In the course of undertaking many high-definition surveys of shipwrecks for archaeological use, ADUS has gained extensive experience of a wide variety of survey instruments and methodologies. This experience has demonstrated that the most useful data for the study of small areas of the seabed containing archaeological material in relatively shallow water, is that acquired using high definition multibeam systems.
- 4.2. Unlike side scan sonar, multibeam sonar provides bathymetric (depth) data for every part of the seabed that provides an acoustic return, allowing three dimensional digital terrain models (DTMs) to be created.
- 4.3. High-definition side scan sonars can provide excellent images but they lack the positional accuracy of multibeam equipment. This accuracy allowed the production of a Gazetteer of Observations that includes all the main features of the wreck relatively positioned to within 10mm, and absolutely to within 100mm.
- 4.4. There are two main types of multibeam sonar available for use in the marine environment, both of which produce bathymetric data. These are interferometric (phase-comparison) systems and true multibeam sonar (beam-forming) systems. Both measure range and angle to a series of points on the seabed, but beam forming systems measure range for each of a set of angles, and interferometric systems measure angle for each of a set of ranges.
- 4.5. Although both types of system have been used to image archaeological sites in the past the most useful results archaeologically have always been produced from a beam-forming system pioneered by Reson with their 8125 sonar. Since the requirements of the *Royal Oak* survey were akin to the levels of detail expected from archaeological work, the Reson 8125 was the multibeam sonar of choice.
- 4.6. The beam-forming system forms a set of virtual 'beams' mathematically and detects the range to the seabed in each beam. The Reson 8125 sonar covers a 120° swath on the seafloor consisting of 240 dynamically focused beams. The 8125 uses focused true time delay beam forming to provide an unprecedented level of detail. Up to 240 soundings are collected with every pulse of the multibeam across the swath and this can happen up to 40 times per second depending on the depth of water. This density of data (x, y and z Cartesian coordinates) allowed the very high-resolution three-dimensional images of the *Royal Oak* detailed in this report to be produced.
- 4.7. A single head system was employed for this survey since recent research undertaken by the University of St Andrews using a twin head system showed that although there were significant additional costs, there were few advantages for this type of wreck survey.

METHODOLOGICAL ISSUES

- 4.8. The level of accuracy with which the bathymetric data is acquired is dependant on precise knowledge of the position of the sonar head attached to the survey vessel, since the system produces bathymetry relative to the sonar head only. It was therefore important not only to obtain good positional information but also to deploy a motion reference unit with the multibeam to compensate for the movement of the sonar head /survey vessel during the survey.
- 4.9. As the survey speed or range to target increases so the number of pulses (hits) on a target decreases and the resolution diminishes. The methodology used therefore reflects the need to undertake survey passes over the wreck at slow speed and as close to it as possible, without impacting the wreck.
- 4.10. The University of St Andrews' current research projects into high definition sonar surveys, funded by the Aggregate Levy Sustainability Fund (via English Heritage) and also by a University research fund, has identified many methodological issues that impact on the quality of the resulting data. These were fully considered and addressed during this survey and have resulted in the high quality data acquired. Such issues included:
- Rigidity of the mounting of the sonar head to the survey vessel;
 - Accuracy of the measurement of the offsets between the sonar head, positioning and motion reference sensors;
 - Range (distance between the sonar head and the subject of the survey);
 - Operating frequency;
 - Pulse update rate;
 - Pulse length;
 - Accuracy of positional information;
 - Effectiveness of the motion compensation system;
 - Speed over ground of the survey;
 - Noise generated by the survey vessel and its equipment;
 - Experience of the survey master, surveyor and post processor;
 - Skill of the survey vessel skipper;
 - Sea-state.
- 4.11. In an effort to decrease the range between the sonar head and the target, and also to allow better penetration of acoustic energy underneath the overhang created by the wrecks angled, but inverted, attitude, the ADUS Independent Sonar Head Attitude and Positioning (ISHAP) system was deployed. This allowed the sonar head to be positioned at a depth of 6.5m below water level, rather than a more conventional 1.5m.
- 4.12. Full details of the equipment and methods employed during the 2006 survey are in **Appendix 3**.

5. INTERPRETATION

- 5.1. The high quality of the survey achieved with the Reson 8125 system allowed superior images to be generated from the sonar data. This gave access to structural details of the wreck not readily detectable by other methods.
- 5.2. The high level of detail in the survey data gave ADUS the opportunity to use forensic archaeological methodologies in the analysis of the data. This provided evidence for a sequence of events which resulted in the sinking of the ship and to the subsequent changes to the wreck.
- 5.3. ADUS' in-house shipwreck expertise and network of contacts contributed to a detailed level of research which was brought to bear directly on the interpretation of evidence provided by the survey.

6. RESULTS: ROYAL OAK WRECK

INTRODUCTION

- 6.1. The wreck looks in surprisingly good condition apart from the damage caused by the torpedoes and some secondary explosions. There is also possible loss of metal through corrosion suggested by the holes in the torpedo bulges added in 1922.
- 6.2. Analysis of the 2006 survey data indicates that there is no apparent distortion of the hull. The line of the keel is almost straight from what survives at the bow to the skeg ahead of the stern rudder. There is slight sagging at the unsupported bow and stern, but well within the limits likely for a structure of this size and mass.
- 6.3. Although the wreck looks reasonably sound, this has to be balanced against contemporary accounts of problems such as loosening rivets and leaking plates just before the sinking. There is also the evidence on film (**Rowlands 2002**) which clearly shows corrosion around damaged areas.
- 6.4. The weather decks, together with ancillary equipment, armament and the superstructure are more difficult to record because the upturned hull masks them. It is possible to detect general deterioration of non-structural elements using the survey data and features visible on film (**Rowlands 2002**). For instance, the cowlings around the 4" HA guns has dropped off, however, those structural components that are not under stress from the weight of the ship, appear to be in reasonable condition.
- 6.5. The primary damage to the hull indicates it was caused by torpedoes. The location of impacts 2, 3 and 4, suggested by analysis of the survey data, can be identified to within about a metre at three distinct points on the hull. The location of the first strike is a little less precise but can be identified within about 3m; this was determined by the physical evidence and contemporary reports. The impact positions (**ID: 61, 64-66**) are given in feet from the forward perpendicular to aid location on the 1936 profile drawing of the ship (**Figure 18**).

- 6.6. Each of the observations from the analysis of the data has been given an ID number in the Gazetteer of Observations (**Appendix I**); together with a UTM coordinate position to centimetric accuracy.

OBSERVATIONS AND DISCUSSION

Orientation, List and Pitch

- 6.7. The hull structure of the wreck is in one piece but inverted, with the bows aligned 52° east of UTM grid north, and the bottom of the hull heeled over 32.5° down to the north (**Figures 1, 2**). Seven thwart-ship measurement of the angle of heel taken from the flat part of the upturned hull measured between 40m and 131m from the forward perpendicular. These angles do not fluctuate more than 0.5° from a mean of 32.5°, the variation being within the expected tolerance of the measurement method.
- 6.8. The midship section of the starboard sheer is buried in the sediment but both the bow and stern are well clear of the seabed even though the trim is 2° aft (**Figure 1**). This fore and aft angle is the same as reported the day after the sinking whereas the thwart-ship angle was reported to be 40°, according to the diver's report in Admiralty message 2010/20 (**Snyder 1976, p 216**), compared to the 2006 measurement of 32.5°. There is also very slight sagging at the bow and the stern along the line of the keel but not more than might be expected of any structure of this size and mass with unsupported ends.
- 6.9. Some major items missing from the wreck are reported to have been salvaged, for instance the anchors and anchor chains by civilian contractors during the war and the propellers by the Royal Navy in 1960s (**Lewis, pers.com.**).

Damage caused directly by enemy action

- 6.10. There are four torpedo impact points, all approximately at the level of the platform deck, between the hold and lower deck (ID: 61, 64, 65, 66) (**Figure 2**).
- 6.11. The sequence at which the impacts occurred has been derived from contemporary accounts reported in **McKee 1979, Snyder 1976 and Weaver 1980**.
- 6.12. The first torpedo hit the starboard bow about 35' aft of the forward perpendicular, almost directly on one of the two aviation spirit storage tanks in that compartment. The resultant explosion appears to have virtually severed the keel and stem, sheered off the plating to both port and starboard as far back as water-tight bulkhead 15, and up to the reinforced lower deck (**ID: 61**) (**Figures 2, 10, 12**). Air was reported as being forced out of the vents from the inflammable store (**Weaver 1980 p54**) which indicates that bulkhead 15 was no longer watertight.
- 6.13. When the ship turned turtle, sank, and then hit the seabed, most of the forefoot, already loosened by the explosion, separated from the hull. During

this event, those port-side hull plates still attached to the hull, were forced over the lower deck in a curve before the loosened mass separated and landed on the seabed nearby. (ID: 62) (Figures 2, 10).

- 6.14. Buckling and springing of plating on the port side at main and upper deck level suggest a secondary explosion in the petrol control room and the adjacent paint room, possibly due to vapour from the aviation spirit entering these areas through the connecting pipe work (ID: 63) (Figure 10). Other evidence is a report of a secondary flash, which killed at least one man sent down a trunk to inspect the flats below water level, just aft of the paint room (McKee 1966 p39).
- 6.15. The consensus of those on board thought that the damage was caused by an internal explosion in the inflammable store, which is immediately aft of the aviation spirit tanks. The air rushing from its vents (Weaver 1980 p 54) being wrongly interpreted as indicating that store was at the centre of the damage.
- 6.16. The explosion sheared the Blake stopper on the anchor chain, which then ran out to the end before it held (Snyder 1976 p106).
- 6.17. The second torpedo impact took place about 12 minutes later on the starboard side 124' from the bow, at the junction of the 15" and 4" HA magazines. The torpedo penetrated the torpedo bulge on the side and also the original hull plating. The external damage extends from 94' to 146' (ID: 64) (Figure 2).
- 6.18. Four holes in the portside hull plating of the upper deck (ID: 67-70) may have been due to secondary explosions in the magazines.
- 6.19. The third torpedo struck about 15-30 seconds later directly on number 3 boiler room, at about 341' from the bow (ID: 65) (Figure 2). The torpedo again penetrated the anti-torpedo bulge and the original hull plating. The external damage extends forward to about 312', but merges aft with the forth torpedo strike.
- 6.20. There was considerable loss of life in the Stoker's Mess on the main deck above the point of the third impact (Weaver 1980 p60).
- 6.21. The forth torpedo impact took place almost simultaneously after the third, at a point about 400' from the bow, directly on the starboard wing engine room. The anti-torpedo bulge and the original hull plating were penetrated, indicating how ineffective the 1922 modification was against armament in use a decade later. Here the external damage merges with the forward impact and extends aft to about 410' (ID: 66) (Figure 2).
- 6.22. Ignition of the cordite in the magazines servicing Barbette X, just aft of the point of impact, caused blazing gas to sweep through the decks, burning many crew members, particularly in the Marine's Mess on the main deck above the magazines (Snyder 1976 p119).
- 6.23. Immediately after the second torpedo strike, the ship began to list to starboard.

This rotation accelerated after the third and fourth strikes and, when the ship was heeled well over, the retainers holding the 15" guns in their rotating turrets in the normal fore and aft positions, sheared, and barrels were seen to swing outboard to starboard (**Snyder 1976 p130**). Soon after, the ship rolled right over.

- 6.24. When the ship inverted, she stayed afloat for a few seconds with her main and fore masts presumably resting on the seabed, as they would have drawn approximately 10m more than the depth of water. During the final loss of hull buoyancy, the weight of the ship would have been born on the two masts and, inevitably, these broke off. The upper part of the fore mast, including the spotting top, together with the tripod main mast and its upper platforms, now lie on the seabed on the south side of the wreck.
- 6.25. The weight of the ship would have then been transferred to the funnel, which although not evident, would presumably have buckled immediately under the weight of the hull. The more substantial features of the upper works would have then taken the weight, This would have been a combination of the starboard side of the shelter deck, the bridges, and the barrels of the 15" guns, particularly in the highest, Barbette B.

Deterioration and post-depositional changes

- 6.26. Although the surface of the seabed is relatively soft, as indicated by the scours and marks left by intrusive items, and the lack of visible ground tackle for the buoys, presumably because they are buried in the silt, the substrate is obviously much firmer. If it had been soft for a depth greater than about 1.5 metres, more of this heavy wreck would have disappeared into the seabed. It is reasonable to assume that equilibrium was quickly established between the weight of the wreck and the support provided by the stratigraphy of the seabed. The minimum sounding over the wreck of one fathom (1.8m), taken in 1941 by the Royal Navy (**Nelson Mceachan, pers. com.**), was probably after initial stabilisation.
- 6.27. By 1980, the minimum depth over the wreck was reported in commentary on film as being 'about 5m' (**Rowlands 2002**), a difference of 2.8m since the 1941 survey. The 2006 ADUS survey has established the current minimum depth as being 4.6m below local chart datum. Without further evidence, it is difficult to know exactly when the change took place. A likely explanation for the drop in level over the forty years is suggested by the barbette roofs laying on the seabed and most of the 15" breaches being higher (lower in their inverted situation) than the roof line. Others (**Smith 1989**) have reached the same conclusion as ADUS that the muzzle ends of the barrels, forced to maximum depression when they hit the seabed, acted as levers against their mountings and, when these eventually gave way, the breach ends were then forced against the barbette roofs. Eventually the rivets holding each roof to the walls of the rotating part of the turret corroded and sheared, transferring the whole of the weight of the wreck onto the bridges and shelter deck. This would have allowed the wreck to drop a further 3m or so. At this stage it is difficult to know whether this happened slowly in sequence, one Barbette at a time, or whether there was one dramatic drop when support from all eight

guns gave way in rapid succession.

- 6.28. Such a drop could also account for the change in angle of heel from 40° the day after the sinking to the current 32.5°.
- 6.29. Although there appears to be some slight sagging at bow and stern where there is no support from the seabed, it is probably insignificant. Any structure of equivalent length and mass, if supported only along the central section, is likely to droop down a little at either end.
- 6.30. There is no measurable twisting of the hull along the flat part of the bottom of the hull, despite lying on the seabed at an angle of 32.5° with the stern trimmed down by 2°.
- 6.31. General loosening of rivets and loss of water-tightness between plates was reported in 1939 when the ship was last at sea in heavy weather (**Weaver 1980 p98**). The evidence of fuel oil percolating out of storage tanks indicates that this is a continuing problem and it is one which is likely to get worse if the oil is not removed. Experience of ADUS staff while investigating many iron and steel wrecks of the 19th and 20th centuries, indicates that rivets can often corrode faster than the plates which they connect. This may be due to a combination of differential electrolytic potential between the iron or steel components and because the rivets will have been heat treated, sometimes to undesirably high temperatures, followed by severe physical stress during the hammering process of riveting plates *etc.* together.
- 6.32. Some items, for example cable winches once bolted to the decks, are reported in film commentary to be now lying on the seabed beneath the ship (**Rowlands 2002**). These were not identified in the sonar data because most objects under the shadow of the ship are not readily discernable. More exposed items that have been noted as missing include three of the four accommodation ladders. These may have fallen off at the time of sinking due to physical stress, or later due to corrosion of the retaining components.
- 6.33. Post-depositional deterioration is also indicated by most of the side scuttles now being open when, at the time of sinking, most were covered with plywood ventilators of the type used in safe anchorages where both ventilation and a blackout was required (**Snyder 1976 p115**). Acoustic energy can be seen to pass through most of the ports to be reflected back of the deck head inside, indicating that the wood of the ventilators has not survived and that the deadlights had not been closed (**ID: 34**).

General features of the wreck

- 6.34. While there is obvious damage and some deterioration to the superstructure and to the hull, there are many original features that survive intact and most of those that can be identified in the sonar images have been listed in the Gazetteer.
- 6.35. Above waterline features including bulwark rail stanchions (**ID: 33**), hawse holes (**IDs: 27, 28, 29**), davits (**IDs: 30, 31**), jack staff (**ID: 24**), fairleads (**IDs:**

32, 33).

- 6.36. Almost all the scuttles (port holes) (**ID: 34**) on the port side can be identified.
- 6.37. The two recesses at upper deck level for the four torpedo tubes, redundant at the time of sinking, can be identified toward the bow at upper deck level(**ID: 56, 57**) (**Figures 2, 10**). One of the four original accommodation ladders, now hanging vertically upwards, is also evident toward the port bow (**ID: 8**); the others having presumably been dislodged.
- 6.38. The survey line that provides the maximum coverage of the fore deck underneath the upturned hull show an anchor chain arcing down to the seabed, presumably from a capstan, and also the wave deflector (**IDs: 25, 26**) (**Figure 10**).
- 6.39. The tripod main mast is lying broken on the seabed. Two sections of one of the three vertical elements, one at least 8.5m long and another 3m long, are lying separately on the seabed (**ID: 20**) (**Figure 8**). The platforms toward the top of the mast are not readily identifiable, although there is material in the right relative place on the seabed, under what is possibly one of the ship's boats.
- 6.40. The spotting top on the fore mast and the two levels beneath are lying almost exactly in their relative positions on the seabed, together with some of the arms of the range-finding equipment (**ID: 21**) (**Figure 8**).
- 6.41. The vessel carried a seaplane on a ramp attached to the top of Barquette X. On the centre line of the shelter deck was a crane for lifting the plane in and out of the water. The pivot and support for the gibe (**ID: 22**) can be seen just aft of the aftermost of the 4" HA guns, while debris on the seabed at that point may be part of the crane's jib.
- 6.42. Lying across the platforms of the tripod main mast lies the 27' whaler while, nearby on the seabed, are the remains of one of the other ship's boat (**IDs: 35, 36**) (**Figure 9**) presumably having fallen from the overhanging shelter deck. The bow section of the larger boat is probably the one shown on film (**Rowlands 2002**) and described as the remains of a 50' pinnace.
- 6.43. Most of the underwater features of the hull can seen in the sonar records including the two anti-torpedo bulges or blisters either side (**IDs: 1, 2**) (**Figure 3**), together with the bilge keels attached to them (**IDs: 18, 19**) (**Figures 1, 2,**). The port and starboard rubbing strakes (**IDs: 16, 17**) are not clearly identified on the drawings ADUS have access to, but do seem to have been added at lower-deck level to section drawing 180. The sonar evidence indicates that it consisted of two lengths of angle attached to the torpedo bulges, with a continuous run of substantial timber fastened between them (**Figures 1, 7**). The vessel that eventually rescued many of the crew, the steam drifter *Daisy II*, was requisitioned by the Admiralty to act as a liberty ship for the *Royal Oak*. She was tied alongside, close to Barquette Y at the time of the torpedo attack and, as the big ship began to list, *Daisy's* bows were hauled well out of the

water, making considerable grinding noises as her keel slid over the *Royal Oak's* bilges before she was eventually freed (**Mckee 1966 p75**). This event may well explain the greater loss of wood in the stern half of the port side rubbing strake.

- 6.44. The stern rudder and the four propeller shafts, without propellers, can be clearly identified (**IDs: 3 - 7**) (**Figures 2, 3**) while less obvious, but still clearly discernable, are the the four short docking keels (**IDs: 12 - 15**) (**Figure 3**) and two seawater intakes between the aft end of the stern two (**IDs: 9, 10**) (**Figure 11**).
- 6.45. The breach ends of six of the eight 15" guns are visible, two each in Barbettes A and B, and one each in Barbettes X and Y (**IDs: 39, 40, 42, 43, 45, 47**) (**Figures 1, 10**).
- 6.46. The two port-side 4" High Angle guns hang upside down from the shelter deck head, the forward one at high elevation, the after one almost fully depressed (**IDs: 48, 49**) (**Figures 6**).
- 6.47. On platforms either side of the fore mast are the Pom Pom multi-barrelled anti-aircraft guns. The circular port side platform can be identified although the barrels are harder to distinguish in the sonar record (**ID: 55**).
- 6.48. At forecastle deck level, the five port-side 6" casemate guns can be clearly seen with their barrels pointing in various directions (**IDs: 50-54**) (**Figure 1, 7**). The 2002 Rowlands film described the *Royal Oak* as having six 6" guns, but the forward guns on either side were removed during the major 1936 refit because they were alleged to be unusable in heavy seas. (*n.b.* since this was written the survey data viewed in new software shows that there are still six 6" guns on the port side – M.D.)

7. RESULTS: OUTLYING FEATURES

INTRODUCTION

- 7.1. A number of objects and features of interest around the *Royal Oak* were identified in the area survey data,
- 7.2. Two of the isolated objects have been treated as separate targets and one of them may be directly related to the *Royal Oak*.
- 7.3. The others are enigmatic linear features with possible objects associated with them. These cover a total of more than 2.5Km across the survey area and are much longer as they obviously extend outside the area.

OBSERVATIONS AND DISCUSSION

Target 1

- 7.4. A small wreck (**ID: 58**) (**Figure 4**) 275m southwest of the *Royal Oak*. It is 10.8m long with a beam of c. 2.5m, has her bows to the east and lies heeled over 30° to starboard. Structure survives above deck level, possibly the

remains of the wheelhouse, and she has a transom stern. There also appears to be some associated debris astern. This could be the wreck of one the *Royal Oak*'s boats, a 35' launch.

- 7.5. This wreck does not appear in the 2004 SRD dataset as it is just outside their survey area.

Target 2

- 7.6. Unidentified cylinder (ID: 59) (Figure 4) 4.8m long, 2.2m diameter aligned north south, 214m to the south of the bow of *Royal Oak*. It may be a sunken mooring buoy of Admiralty pattern.

- 7.7. This target shows in the 2004 SRD dataset.

Linear features

- 7.8. Extensive linear marks in the seabed pass through the survey area (ID: 60) (Figure 4) and which extend for more than 2.5Km.

- 7.9. These intriguing features show up as 1.4m – 3.0m wide shallow troughs between 0.1m - 0.4m deep. Along one edge of most of them are a regular series of small lumps. In addition there appears to be a series of mounds of c.1.0m diameter x 0.6m height situated parallel to some of the features at c.15m intervals.

- 7.10. It is difficult to be certain what these features represent and we have considered a variety of options ranging from marks left by giant skates, scallop dredging and wartime defences. The most likely explanation is that the scours are created by partially buried cables and that the various lumps and bumps are buried floats and sinkers. The closest parallel seem to be US submarine barrages which had floats at similar spacing (15m) to of some of the larger bumps on the seabed, and which were deployed in Scapa Flow during WW2 (Lewis, pers. com.)

- 7.11. The circular pattern of one linear feature to the north of the *Royal Oak* and the way one seems to have caught around the south side of the wreck, suggest that these features were probably deployed from a boat. The abrupt changes in angle that can be seen in some place suggest that, once on the seabed, that these features are connected, as a cable, and that they have in the past been caught by anchors etc. An example of this is the seabed disturbance for the mooring buoy to the south east of the wreck which also coincides with a sharp change in angle (Figure 5).

- 7.12. A visual inspection by diver or ROV would help explain exactly what these features are and how they relate to the wreck.

- 7.13. The linear features show in the 2004 SRD dataset.

8. RESULTS: SEDIMENT REGIME

- 8.1. Scapa Flow is a semi-enclosed body of water with entrances to the south

(sounds of Switha and Hoxa) and west (Hoy Sound). The main body of Scapa Flow is a glacially scoured basin with an area of approximately 130 square kilometres. The main basin is steep sided with a relatively level bottom, mostly between 25m and 35m deep.

www.orkneyharbours.com/port_environment.html.

- 8.2. The seabed over the main body of Scapa Flow is characterised by mud, sand and gravel sediments. Areas exposed to strong tidal currents tend to have coarser sediment or even bare rock but this is not the case in Scapa Bay where limited tidal flow has meant finer grain sediments and deeper sediment levels. It has been suggested that the blocking of the eastern entrances to Scapa Flow by the Churchill Barriers has altered the tidal regime and may have affected the sediment distribution, with an increase in the extent of the muddy area of the northeast of Scapa Flow

www.orkneyharbours.com/port_environment.html). However, the very limited sediment load of Orkney's waters means that additional deposition will only be likely after a very long period of time.

- 8.3. In any event the presence of the wreck of the *Royal Oak* has had a localised effect on the sediment regime in the immediate area surrounding the wreck and covered by the ADUS survey (0.64Km²). A relatively gentle scour pattern exists around the wreck that can clearly be seen in the illustrations of the area survey as whole. The main scour pattern from the wreck runs to the west and beyond the ADUS survey area and consists of channel approximately 240m wide and an average of 2m deeper than the seabed that bounds it to the north and south. A much more subtle scour pattern also exists running south from the wreck on the eastern side of the ADUS survey area. Again this channel is approximately 240m wide but is less than a metre deeper than the seabed that bounds it the east and west.

- 8.4. An appreciation of the gentle scouring patterns surrounding the wreck suggests a limited tidal flow over the wreck but one that is predominantly to the west.

9. RESULTS: SURVEY AREA STATISTICS.

- 9.1. The area survey covered 0.064Km² (800m x 800m) centred around the wreck of the *Royal Oak*. Within this area, the average depth was 29.579m (below ODN), 28.179m (below Chart Datum). The range of depths in this area was 31.61m to 25.87m (ODN), 30.21m to 24.47m (Chart Datum).

10. RESULTS: COMPARISONS WITH PREVIOUS DATASETS.

INTRODUCTION

- 10.1. Data supplied to ADUS for the purposes of comparison consisted of the 2004 multibeam survey undertaken by SRD UK Ltd. The data supplied took the form of two xyz point files in gridded form: 1606-200.xyz for the hull data and 1606-500.xyz for the area survey. Given that the data was provided as UTM Grid it

was assumed that the datum used for production of these files was WGS84.

- 10.2. A number of positional issues prevented a more comprehensive comparison taking place. A subtraction of 102.16m from the Eastings and a subtraction of 222m from the Northings in the X,Y position of the SRD dataset was necessary to align it with the ADUS dataset and also the UK Hydrographic Office (UKHO) position for the wreck. An increase in the depth of the SRD soundings by 1.086m was also necessary to bring both datasets in line. The disparity here may be in part due to the SRD soundings being relative to Ordnance Datum Kirkwall and the ADUS data being relative to Ordnance Datum Newlyn, the difference between the two, according to UKHO, being 1.66m (**Christopher Jones, pers. com.**).

AREA DATASET COMPARISON

- 10.3. Where the two datasets overlap, no major changes to the seabed around the wreck appear to have occurred since 2002, with the relative range of seabed depths remaining the same.
- 10.4. Having processed both datasets to create DTM surfaces in Fledermaus Pro software, surface difference functionality was utilised to subtract the SRD dataset from the ADUS dataset. The resulting 'difference map' was used to highlight differences between the two datasets as far as the area surrounding the *Royal Oak* was concerned.
- 10.5. The only discernible differences in the datasets relate to the new disturbances to the seabed apparent from the ground tackle of the four buoys surrounding the wreck. It is clear from the new marks in the seabed apparent in the 2006 dataset, that these buoys surrounding the wreck have been lifted and replaced in almost the same position at least once since 2004.

WRECK DATASET COMPARISON

- 10.6. Given the artificial adjustments in height necessary to make comparisons of the data possible, only observations on gross differences were possible. However it is still appropriate to state that:
- There have been no major visible changes to the completeness of the wreck between 2004 and 2006.
 - There have been no measurable changes in the angles of heel and trim of the wreck during the same two year period, and neither has there been any detectable change in the height of key points on the hull.

11. RESULTS: POTENTIAL FOR COLLAPSE

- 11.1. The highest part of the wreck is in 4.6m of water below Chart Datum and so is in the region of maximum water movement, most significant during southerly and easterly storms. However the shape of the upturned hull would probably allow moving water to pass over it relatively freely without putting too much

strain on the hull structure. This would change if the plates at the bottom of the ship were significantly breached, as is likely to happen as the hull becomes progressively weakened by corrosion. Any perforation of the hull would amplify the forces being applied to the wreck by storm water movement, particularly if the size of the holes increased significantly, as these would inevitably accelerate the speed of collapse. Unfortunately, the long-term outlook is not good and eventual major collapse is inevitable. This will accelerate as corrosion of the steel of the hull takes a firmer hold which, when combined with more frequent and stronger winds due to predicted climate change, will have an increasing impact on the site as time passes.

- 11.2. The potential loss of buoyancy due to removal of fuel oil is unlikely to add much additional stress to the hull as the amount remaining is unlikely to provide more than a nominal amount of buoyancy compared to the overall mass of the wreck.
- 11.3. A collapse of the wreck may not be enough in itself to detonate the ordnance on board but it could result in high explosives lying in a more vulnerable position on the seabed.
- 11.4. Although large commercial vessels use facilities within Scapa Flow, there is little risk of a collision as it is in an area not used by vessels of sufficient draft to collide with the wreck.

12. CONCLUSIONS

- 12.1. The wreck looks in a reasonable condition although contemporary accounts suggest loosening of plates and rivets was a problem more than 60 years ago. There are no major discontinuities in the hull structure apart from those due to torpedo impacts and secondary explosions in 1939. There is damage to masts, superstructure and guns caused during the sinking and settling processes, and there are visible isolated perforations, some of which may be due to corrosion of the plating. There is also damage to a propeller shaft which may have occurred during the salvage of propellers in the 1960s.
- 12.2. After sinking in 1939, the wreck was surveyed in 1941 by the Navy. They recorded one fathom clearance over the wreck and this information is still published on current UKHO charts, although it has been converted to 1.8m. Sometime before 1980, the depth over the wreck was reported as being about 5m below chart datum (**Rowlands 2002**) and the 2006 survey gives a clearance of 4.6m over the shallowest part of the hull, midships, southern side, relative to chart datum.
- 12.3. It is reasonable to assume that the 1941 survey was accurate and so the wreck must have settled, either gradually or with one or more distinct movements. A possible explanation is that in 1941 some of the weight of the ship was resting on the barrels of the eight 15" guns that had rotated to the broadside position as the ship lay on its side during the sinking. These barrels, in turn, were forced off their mountings so that the breeches pressed against the roofs of the barbets. The four roofs of the barbets are now

lying on the seabed and six of the eight breech ends are visible above the original rooflines, indicating substantial forces having been applied by the breech-ends of the guns to the roofs. It is possible that anything between one and five catastrophic events took place where the roofs were prized off as the forces overcame the residual strength within the rivets holding the barbettes together, and so sheared them off releasing the roof. This might have happened sequentially or simultaneously, but would have then transferred all the weight of the ship onto the superstructure, perhaps triggering another potential settling episode.

- 12.4. This collapse may also account for the change in angle of heel of the upturned hull from 40° recorded in 1939 (**Snyder 1976, p216**) to the current 32.5°.
- 12.5. Another potential cause of settling is the reduction of buoyancy of the wreck due to loss of oil, either by natural seepage or deliberated removal. However the total buoyancy of the maximum amount of fuel oil on the *Royal Oak* after her sinking is likely to have been an almost negligible proportion of the total weight of the material in the vessel. Similarly, air pockets will have provided some buoyancy, which will have reduced over time but, again, the difference in buoyancy from air between 1941 and 1980 is unlikely to be significant.
- 12.6. Although the SRD data from 2004 has been problematic for ADUS to interpret, it has been possible to do a coarse comparison between the 2004 and 2006 data sets. From this it can be concluded that there has been no apparent change to the angles of heel and trim of the wreck and, as far as one can tell, the level of completeness looks similar. Despite overall issues with the heights of SRD data, it is probable that there have not been any detectable changes in height at any key points on the hull.
- 12.7. Regular high definition surveys are essential for monitoring changes to the wreck. These would also provide proper measurable evidence for the rate of deterioration. The standard of any future survey should, therefore, be equal to, or better than that conducted in 2006, so that high-quality data sets will be available for comparison with the baseline data collected in 2006.

13. RECOMMENDATIONS FOR FUTURE WORK

- 13.1. The 2006 survey of the *Royal Oak* is an indicator of what can be achieved using currently available technology, appropriate methodology and a detailed forensic archaeological approach to interpretation of the data. By undertaking repeat surveys of a similar standard it will be possible to begin to understand the true physical state of the wreck and its immediate environment, and identify any recordable changes between surveys, therefore allowing timescales of deterioration to be established that will be of use in predicting future events.
- 13.2. It is recommended that, at minimum, multibeam sonar surveys to the standard achieved in the 2006 survey be undertaken at yearly intervals in order that comparable datasets can be collected.

- 13.3. It is suggested that future surveys include alternative methodologies to collect higher resolution images from lower in the water column. By placing the sonar head on a suitable remotely operated vehicle (ROV) or Autonomous Underwater vehicle (AUV) the quality of the data could be improved by being closer to specific areas of interest. The sonar head of a Reson 8125 could also be angled sideways to obtain beam coverage from the horizontal on one side, down to vertical and then to 30° on the other side. This would provide better sonar head-to-target geometry than the conventional symmetrical spread of 120° pointing straight down, while still covering a useful width beneath the ROV. In this way, there would be a better chance of detecting smaller areas of damage on the ship, ordnance and other items on the seabed, as well as hull damage in areas difficult to ensonify from the surface because of masking by the current overhang of the upturned hull.
- 13.4. A visual survey of other targets by diver or ROV could provide valuable information. The wreck 275m to the west (**ID: 58**) needs to be identified as it may be one of the *Royal Oak*'s own boats lost at the time of the sinking. An attempt also needs to be made to identify the cylindrical feature 200m to the south (**ID: 59**). Visual inspection would help solve the identification problem of the linear features and also sort out the relationship they have with the wreck.
- 13.5. It is suggested that a regime of environmental monitoring is instituted so that the effects of waves, currents and other significant factors can be more accurately factored in to models of structural collapse and cargo dispersal.

ADUS
University of St Andrews
University of Dundee
July 2006

Acknowledgements

ADUS would like to thank Craig English of Salvage and Marine Operations, Ministry of Defence, for his help onboard during the field survey, and also gratefully acknowledges the assistance given by the staff at Orkney Harbour, particularly Captain William Sclater.

Seatronics Ltd supplied the multibeam sonar system, together with all the ancillary shipboard equipment, and ADUS are grateful to Alistair Coutts and his colleagues in Aberdeen for their assistance. The shore base station for the Real Time Kinematic (RTK) position corrections was provided by Survey Solutions Scotland Ltd and the advice and assistance provided by David Cameron-Mackintosh was gratefully received. As always, helpful advice was provided by staff of Reson Offshore Ltd. particularly Richard Hill, John Frazer and Danny Wake. The later assisted with the setting up of the sonar processor and with the data collection during the initial part of the survey. Not only were all these individuals and companies efficient and helpful, but all their equipment operated to specification and without problems during the survey.

Very useful comments and advice on boom defences and torpedo barriers was received from Lewis Munro of the Lyness Heritage Centre, Orkney. Finally ADUS is indebted to Charlie Dowie and Jackie Price of R & D Launches of Orkney, the skipper and crewman of the vessel *Flamborough Light* for their services and assistance during the survey.

ADUS is indebted to Al Young, post-graduate engineering and design student at the University of Cambridge, for his comments on the design of ADUS' Independent Sonar Head Attitude and Positioning (ISHAP) system.

Martin Dean (ADUS) managed the project on behalf of the University of St Andrews. Mark Lawrence (ADUS) and Martin Dean directed the survey, undertook the fieldwork and wrote this report. . Mark Lawrence, Chris Rowland (ADUS) and Martin Dean undertook subsequent interpretation and data manipulation. Chris Rowland produced the three-dimensional movie visualisations of the data.

References

Books

Mckee A., 1966, *Black Saturday: the tragedy of the Royal Oak*. Hamlyn Publishing Group, Feltham.

Rowlands P., 2002, *HMS Royal Oak (film)*. Ocean Optics, Plymouth.

Smith P. L., 1989, *The Naval Wrecks of Scapa Flow*. The Orkney Press, Kirkwall.

Snyder G. A., 1976, *The Royal Oak Disaster*. William Kimber and Co., London.

Weaver H. J., 1980, *Nightmare at Scapa Flow: The truth about the sinking of the Royal Oak*. Cressrelles Publishing Co., Peppard Common.

Websites:

http://www.orkneyharbours.com/port_environment.html

Personal Communications:

Christopher Jones, Deputy Head of Tides, UK Hydrographic Office, Taunton, Devon

Nelson Mceachan, Wrecks Officer, UK Hydrographic Office, Taunton, Devon

Lewis Munro, Curator, Lyness Heritage Centre, Hoy, Orkney

APPENDIX 1 - GAZETTEER OF OBSERVATIONS

FEATURE No.	DESCRIPTION	UTM E	UTM N	SURVEY LINE NO.	EXAMPLE IN FIGURE	COMMENT
	General features of the ship					
1	Torpedo bulge - port	501012.68	6532379.62	28	3	
2	Torpedo bulge - starboard	500925.85	6532332.88	67	3	
3	Propeller shaft – port wing	500915.91	6532306.11	39	3	
4	Propeller shaft – port inner	500908.46	6532304.44	39	3	The support brackets and end of shaft are missing. This may be due to the salvage of the propellers by the RN in the 1960s.
5	Propeller shaft – starboard wing	500908.70	6532312.98	39	3	
6	Propeller shaft – starboard inner	500904.93	6532307.01	39	3	
7	Rudder	500898.00	6532300.34	25	1	
8	Accommodation ladder - port forward	501003.03	6532363.03	16		
9	Seawater intake – port aft	500939.61	6532328.70	39	11	
10	Seawater intake - starboard aft	500935.41	6532334.22	39	11	
11	Bottom strakes	500933.73	6532345.80	39	3	The bottom plates are difficult to see in some data sets. Cross 'lighting' accentuates the overlapping of strakes in survey line 28.
12	Docking keel - port forward	500998.16	6532371.95	35	3	
13	Docking keel - starboard forward	500991.67	6532381.20	35	3	
14	Docking keel - port aft	500947.29	6532330.54	35	3	
15	Docking keel - starboard aft	500940.10	6532341.93	35	3	
16	Rubbing strake - port	500982.69	6352345.80	23	7	Feature recorded at lower deck level in section 180.
17	Rubbing strake - starboard				2	
18	Bilge Keel - port	500953.51	6532327.62	41	1	
19	Bilge keel - starboard	500937.92	6532345.70	21	2	Aft section hanging near vertically down to seabed at site of 3 rd torpedo impact.
20	Tripod main mast debris	500982.34	6532334.36	64	8	
21	Foremast debris including spotting top	500996.31	6532339.31	66	8	Stands c.4m off seabed + a range-finding device c.6m off seabed.
22	Seaplane ramp	500944.70	6532313.93	64	1	Under Barbette Y.
23	Seaplane crane boom mounting	500957.89	6532325.26	66	8	
24	Jack staff	501043.45	6532398.75	66		
25	Foredeck wave deflector	501021.28	6532381.34	22		
26	Anchor chain	501025.87	6532387.83	66	10	Hanging from foredeck to seabed.
27	Hawse hole - starboard Sheet	501034.50	6532400.66	17	2	
28	Hawse hole - port Bower	501040.51	6532398.75	28		
29	Hawse hole - starboard Bower	501037.74	6532402.11	17	2	
30	32' whaler davit – port forward	500973.66	6532332.83	66		

31	32' whaler davit – port aft	500979.77	6532337.22	66		
32	Fairlead port bow	501042.66	6532400.98	66		
33	Handrail stanchion	500941.07	6532311.79	64		One of numerous examples along the port side bulwarks.
34	Scuttle	501025.28	6532384.95	64	1	Most forecandle and upper deck port holes are visible.
35	27' Cutter	500980.14	6532335.14	64	9	Tentative identification.
36	Forward section of a boat	500983.36	6532329.06	64		Identified in Ocean Optic's film as part of a 52' steam pinnacle.
37	Unidentified linear feature on hull	500977.58	6532368.55	39		There is a 2 nd similar feature nearby – both likely to be intrusive.
	Armament					
38	Barbette A	501013.44	6532370.82	66	10	
39	Barbette A 15" gun - port	501013.60	6532327.28	66	10	
40	Barbette A 15" gun - starboard	501012.14	6532372.05	66	10	
41	Barbette B	501004.01	6532361.04	66	10	
42	Barbette B 15" gun - port	501004.24	6532363.62	66	10	
43	Barbette B 15" gun - starboard	501001.70	6532361.77	66	10	
44	Barbette X	500945.59	6532317.10	66	1	
45	Barbette X 15" gun - port	500944.58	6532315.56	66	1	
46	Barbette Y	500933.36	6532309.45	66	1	
47	Barbette Y 15" gun - starboard	500932.52	6532311.49	66	1	
48	4" HA twin gun - port fwd	500984.59	6532341.15	66		
49	4" HA twin gun - port aft	500968.15	6532329.77	66	6	
50	6" casemate gun - port 1 - fwd	500989.98	6532349.03	64	7	
51	6" casemate gun - port 2	500958.14	6532342.67	64	7	
52	6" casemate gun - port 3	500978.28	6532339.21	64	7	
53	6" casemate gun - port 4	500970.66	6532332.45	64	7	
54	6" casemate gun - port 5 - aft	500962.38	6532327.29	64	7	
55	Pom Pom AA gun - port	500978.51	6532336.72	66		Circular mounting adjacent to foremast.
56	Starboard torpedo tubes	501013.55	6532389.11	18	2	Recessed into hull.
57	Port torpedo tubes	501018.94	6532392.87	67	10	Recessed into hull.
	Off site features					
58	Wreck 275m south west by west of RO	500648.54	6532178.30	59	4	10.8m boat with a transom stern. Bows to east, heeled over 30° to the south, with debris astern. Possibly a 35' launch from the <i>Royal Oak</i>
59	Cylindrical object c.200m south of RO	501041.89	6532181.86	49	4	2.2m diameter cylinder x 4.8m long, lying north south, 1.9m proud of the seabed. Possibly an Admiralty mooring buoy.
60	Linear features totalling > 2.5Km in length within the survey area	501127.82	6532478.30	50	4	There appear to be regularly spaced features along them, which may be weights and/or floats. These features may be WW2 anti-submarine defences.

	Damage to the ship					
61	Torpedo impact – bow	501031.77	6532401.26	28	2	1 st impact estimated at c. 35' – almost directly on aviation spirit tank. Closest section station 10 at 36'. Stem, keel and platform deck missing to station 15 at 56' up to lower deck, which survives almost intact to the stem.
62	Torpedo damage – bow	501039.54	6532409.23	28	2	Forefoot debris on seabed and port-side plating curved over inboard suggesting the weight of the debris when attached curved it over before separating
63	Torpedo damage – port bow	501036.01	653395.30	28	10	Buckling and springing of plates at main and upper deck level suggest secondary explosion at paint and petrol control rooms.
64	Torpedo impact – starboard bulge	501008.37	6532391.11	17	2	2nd impact estimated at 124' – at junction between 15" and HA 4" magazines. Closest section station 46 at 142'. External damage spreads between 94' - 146'.
65	Torpedo impact – starboard bulge	500950.27	6532353.67	21	2	3 rd impact estimated at 341' – direct on No.3 boiler room. Closest section station 144 at 337'. External damage spreads forward to c. 312' and aft it merges into 4 th impact.
66	Torpedo impact – starboard bulge	500938.15	6532342.76	21	2	4 th impact estimated at 400' – direct on starboard wing engine. Closest section station 180 at 410'. External damage extends aft to 433' and merges forward with 3 rd impact. Forward part of Barbette Y 15" magazine within external damage area.
67	Hole starboard side at upper deck level in forecastle	501017.14	6532373.67	28		Between scuttles - possibly caused by secondary explosion - c. 0.7m across.
68	Hole starboard side at upper deck level in forecastle	501014.98	6532371.61	28		Between scuttles - possibly caused by secondary explosion - c. 0.7m across.
69	Hole starboard side at upper deck level in forecastle	501002.23	6532360.31	64		Between scuttles - possibly caused by secondary explosion - c. 0.6m across.
70	Hole starboard side at upper deck level in forecastle	501000.21	6532358.86	64		Between scuttles - possibly caused by secondary explosion - c. 0.6m across.
71	Barbette A roof	501015.60	6532369.67	66		Detached - lying on seabed.
72	Barbette B roof	501012.70	6532366.89	66		Detached - lying on seabed and overlapping roof of Barbette A.
73	Barbette X roof	500947.25	6532315.66	66	1	Detached - lying on seabed.
74	Barbette Y roof	500934.82	6532309.84	66	1	Detached - lying on seabed.
75	Holes in top of port torpedo bulge	500972.40	6532330.31	64	7	One of 14 observed. Largest 0.6m across. Some may be corrosion; others may be where cover plates are missing from inspection holes.
76	Brackets and end of inner port propeller shaft missing	500907.83	6532303.57	39	3	This damage may have occurred during removal of the propeller by the RN.
	Salvage features					
77	Hollow-cut gate valves	500933.89	6532334.17	39	11	One example of c.64 - most located.
78	Hollow-cut ball valves	500941.59	6532328.15	39	11	One example of a four - all located.

APPENDIX 2 - SURVEY METHODOLOGY

LOGISTICS

Survey lines

The hull survey of the *Royal Oak* was conducted with the skipper of the vessel making full use of the digital image of the wreck and immediate seabed, generated in real-time on a helm monitor, to ensure full coverage.

29 passes were made parallel to the wreck to obtain data of both the upturned hull and the superstructure lying underneath. The sonar head on the ISHAPs system was deployed at 6.5m below the surface for passes along the north and south sides, and at 4.5m for those passes over the wreck where there was risk of collision. By exploiting the longer ISHAP system at low water, it allowed good data to be collected from lower in the water column.

For the area survey the sonar head on the ISHAP system was deployed at a fixed depth of 4.5m. The relatively uniform seabed depth allowed 50m separation between 17 survey lines for the helmsman to follow. Each pass was 800m long and ran either due north or south.

There was no problem steering the lines due to tidal flow or adverse winds.

File structure

One survey line represented one recorded database file. Each database file was given a unique, sequential number.

The survey lines recorded were as follows:

Sequence No./ Survey line	Description
0001 to 0014	Calibration and test lines etc.,
0015 to 0030	Detailed passes along and over <i>Royal Oak</i>
0031 to 0034	Area survey west of <i>Royal Oak</i>
0035 to 0042	Detailed passes along and over <i>Royal Oak</i>
0043 to 0058	Area survey east of <i>Royal Oak</i>
0059	Pass over small wreck to the south west
0060 - 0067	Detailed passes along and over <i>Royal Oak</i>

PLATFORM

The survey vessel was the 15m general workboat *Flamborough Light* an MCA category 2 work boat operated by D & L Launch Services, a small boat charter boat company Orkney.

The vessel was chosen because:

- Its size enabled it to manoeuvre safely around the wreck;
- It could effectively house all survey equipment within the wheelhouse;
- It had the capability of handling ADUS's ISHAP system;
- It was locally based;
- It was available for the proposed survey period;
- The skipper was familiar with the area and the site, and had previously been contracted as a support vessel for *Royal Oak* oil recovery operations.

For ease of operation the ADUS ISHAP system was attached to the port quarter of the survey vessel using strops and ropes, instead of being towed astern of the vessel. The single large screw of *Flamborough Light* effectively prevented close quarter towing of the system directly astern. This in itself made no difference to the survey since the ISHAP system is self-contained and it does not need to be fixed in a conventional way to prevent movement between the boat the sonar head. It was possible to remove and re-attach the 8.5m long system without the need for time-consuming recalibration every time.

ORIENTATION

Shore base station

A trimble 5700 RTK base station for this survey was located on the roof of Orkney Harbour Authority Offices, at Scapa Bay, approximately 3km from the site of the *Royal Oak*. The position of this base station (Scapa 2) was as follows:

Datum	Latitude/ Easting	Longitude/ Northing	Height
WGS84	58° 57'40.49335" N	002° 58'11.09544" W	60.015m (ellipsoid)
OS Grid / ODN	344322.760	1008633.777	8.523
UTM Grid (Zone 30N) /ODN	501739.958	6535737.384	8.523

The OS co-ordinates listed above are based on a modified version of WGS-84 that is tied to the European continental plate called ETRF-89. the geographical co-ordinates here are not true WGS-84 but based on the position of WGS-84 for 1989. This is

because the land mass is moving underneath the WGS-84 system so if WGS-84 is always used then the co-ordinates for the station move year by year. The Ordnance Survey have therefore adopted ETRF-89 as their system and these are what are given here. However, since the tectonic plate effect is only 2.5cm per year the co-ordinates entered into the base station were straightforward WGS 84 (UTM Zone 30 N) for simplicity. Having the base station position in these other formats is however useful for future reference.

In order to ascertain an accurate position of the base station at Orkney Harbour Offices, the base station was set up ahead of the survey and programmed to gather raw observations of satellites. GPS post processing software was then used, courtesy of Survey Solutions Scotland, to import RINEX data from the OS active network for the collection period.

The data (8 hours of observations) collected by the base station was then imported into the software. Precise ephemerides from NASA were downloaded for best accuracy (actual rather than predicted satellite Keplerian elements), along with an ionospheric model from University of Bern. The data was then processed using L1 and L2 to OS stations Thurso, Inverness, Braemar and Aberdeen, leaving all baselines activated so loop closures could be calculated. All noisy data was removed and QC checks undertaken at this point.

The data was then adjusted using all the data (least squares adjustment) and holding OS stations fixed in ETRF-89. After adjustment OSTN'02 and OSGM'02 were used to provide co-ordinates in OSGB'36 National Grid and OS datum. As a check the whole process was redone using only the nearest OS station – Thurso, and a very similar result was achieved.

With the RTK positioning system centimetric accuracy was achieved in three dimensions (X, Y and Z) in real time. The accuracy was improved by having the base station at a relatively short distance (3km) from the site of the *Royal Oak*. Separate measurement of the continuous changes in tidal height was therefore not required.

Onboard survey

The survey and navigation system onboard consisted of an Applanix POS-MV 320 (Position and Orientation System for Marine Vessels) that combined Real Time Kinematics (RTK) with the most accurate of the commercially available motion reference compensation systems. RTK works on a similar principle to conventional differential GPS, but phase-based corrections are applied using a dedicated base station instead of publicly available long-distance range-based corrections.

RTK CMR+ correction messages from the RTK base station located on top of Orkney Harbour Authority's Office at Scapa were provided to the POS-MV via a Vodafone GSM modem data link. The POS-MV was then able to operate in 'tightly coupled' fixed RTK mode.

Vessel movement was compensated for with the Applanix POS MV utilising two Novatel GPS antennas mounted on the ISHAP frame, 2m apart, to deliver heading and motion information and its inertial motion reference unit to correct heave, pitch

and roll. Great attention to detail was given to the measurement of the lever arms (offsets) between the sonar heads and the motion and positioning sensors during the original construction of the ISHAP, using a laser line to achieve accuracies of less than 3mm.

Datums

Data acquired onboard the survey vessel was collected in UTM Grid (Zone 30 N) with corrections (CMR+) being received from the base station position. Since the base station position was accurately derived before the survey, soundings were manually adjusted in the QINSy software by subtracting 51.492m to convert WGS84 ellipsoid height to Ordnance Datum Newlyn (see table above)

SONAR

Introduction

Full survey configuration details are given in Appendix 4 and include survey input details, POS-MV GAMS results, patch test results, and survey parameters. A diagram of the multibeam installation onboard *Flamborough Light* shows how the various components were linked (**Figure 13**).

Sonar Hardware

The bathymetric instrument used for the survey was a Reson 8125 SeaBat 455kHz Ultra High Resolution Multibeam Echosounder used together with an RTK enabled Applanix POS-MV 320, a Trimble RTK GPS base station, a Valeport MiniSVS Sensor for beamforming assistance at the sonar head and a Valeport 650 MK2 Self Recording SVP for measurements of the speed of sound throughout the water column.

Components of the sonar system comprised the sonar head itself, a sonar processor unit, sound velocity probes and a dual processor PC with increased hard disk capacity running QPS' QINSy v7.5 acquisition and survey software.

One sound velocity probe was attached as close as possible to the sonar head on the ISHAP pole. This probe provided continuous measurements for the beam forming process employed by the Reson system. A second sound velocity probe was used for obtaining sound velocity profiles through the entire water column at regular intervals during the survey.

A separate sonar processor for controlling the acoustic parameters of the sonar head, was placed alongside the system PC inside the wheelhouse. Constant adjustment to this processor unit was required during the survey, aided by a visual display of the raw sonar data. Various settings for range, gain and pulse length limited the number of bad soundings acquired during the survey and facilitated post-processing.

Sonar Acquisition Software

The QINSy survey and acquisition software running on the PC was used to control the survey with a navigational chart backdrop for the positioning of survey grids and the provision of detailed navigational information (which could be displayed on a separate helm screen) to aid *Flamborough Light's* skipper during the running of

survey lines.

The QINSy software co-ordinated a database of all aspects of the system setup which included the offset measurements necessary between the various components and also water column sound velocity profile data. The software also created appropriate file folders during data acquisition to aid data file management.

The data collected by the system comprises QINSy database files for each individual survey line, and optional point files (as XYZ ASCII text). The point files could be imported immediately into other visualisation software (such as Terramodel Visualiser or Fledermaus) to view the data just collected in three dimensions during or after the survey. This was very useful in determining whether any problems existed with the data during the survey.

The QINSy database files were the initial results of the field survey. These files were then replayed to generate new XYZ files, following adjustments to important variables, such as patch test settings, tidal data, and sound velocity information).

ADDITIONAL DATA

For each ping the SeaBat 8125 also outputs two channels of backscatter data (multibeam side scan). One channel represents the sum of the port beams, the other the sum of the starboard beams. The QINSy software was set up to store all the backscatter data during the survey. These have been archived and not been processed for this survey as it was not a requirement; the results are unlikely to have added much to the interpretation.

POST-PROCESSING

The post-processing was conducted by ADUS staff using Terramodel and Fledermaus Pro software to examine and clean the data and ignore erroneous soundings. This process required an experienced eye to manually ignore bad soundings, and not inadvertently remove subtle features represented by only a few soundings.

Patch test values were applied in real-time, as was the single sound velocity value from the Valeport MiniSVS Sensor at the head (typically 1520m/sec) for refraction. Sound Velocity Profiles were regularly measured and showed the velocity to be the same throughout the water column. QINSy is able to use the GPS RTK height in real-time, so that fully corrected soundings were recorded to processing data files in real-time, and available for editing immediately at the end of each line.

The method employed for this survey produces a vast number of bathymetric points. To ensure that complete coverage was provided for the wreck the survey lines often overlapped and therefore any one object was likely to be ensonified a number of times during different survey passes. Errors in the positioning system and/or motion reference unit will be carried through into positioning errors for the individual soundings. Even these small errors will lead to objects appearing 'blurred'.

Single passes at as slow a speed as possible (c.3Kn) were used to collect the maximum detail of various parts of the wreck for analysis in Terramodel and

Fledermaus software.

The level of positional accuracy provided by the RTK system on this survey is essential for future surveys if meaningful comparisons are to be made for monitoring purposes.

VISUALISATION

Point Cloud Processing Versus Surfacing

The sonar data is edited in the form of point clouds. Point clouds are simply xyz co-ordinates that locate a sonar reflection in 3D space. It is possible to convert the point cloud data into surface data but this process adds new data to the scene as the surface fills in the spaces between the individual points producing an image that compromises the integrity of the original data set. Our method retains the integrity of the sonar data throughout the process.

Depth Cueing

Point clouds have a number of characteristics that have to be considered when the wreck images are rendered. Each point is equal in size to every other point in the data set irrespective of its distance from the viewer, *i.e.* point A lying 5 metres from the viewer is perceived to be the same size as Point B which lies 25 metres from the viewer. This can cause perception difficulties when a large number of points (up to 2 million) are viewed in the same scene. ADUS use a number of proprietary software based depth cueing devices to alleviate this problem. These include the use of colour ramps oriented along the primary axes of the scene, opacity maps, occlusion objects and digital cinematography.

Occlusion Objects

ADUS have developed the use of occlusion objects to assist accurate perception of the wreck data. Point clouds allow the viewer to look between groups of points and see other points in the distance. We place an occlusion object within the main body of the point cloud which echoes the shape of the wreck scene. The occlusion object effectively blocks the renderer from displaying those points on the far side of the wreck scene in the same way that the opaque surface of the wreck would prevent the human eye from seeing through it in reality. The occlusion object is rendered with a non-diffusive material to prevent the viewer from observing it in the scene.

Digital Cinematography and High Definition (HD1080)

A key feature of displaying point cloud data is the fact that perception of the 3D form is enhanced by the use of digital cinematography. In particular, camera movement over the scene significantly improves the perception of depth and detail in the data. Therefore ADUS has exploited the use of 3D camera moves across the wreck data to help the viewer to visualise the scene more effectively. The relative movement of points over distance helps the viewer to discern which points are closer to the camera than others through the apparent speed of their movement, *i.e.* points further away move more slowly than those that are closer.

The final scenes are rendered as digital movies in High Definition format (HD 1080). The pixel resolution is 1920 x 1080. This format shows much higher levels of detail than the standard PAL (normal TV) resolution of 720 x 576. The resulting moving

images have less tendency to flicker during playback. At present, the UK has not adopted a standard for HD video. This has led to a delay in the mass production of HD playback devices e.g. DVD players.

However, a number of Apple computers can play back HD resolution video successfully and domestic DVD players will be available in the near future. Therefore ADUS has mastered the wreck video sequences in this new format whilst also producing a standard PAL version for use on standard DVD players and computers.

APPENDIX 3- SURVEY DIARY

Date	Events
25/05/06	ADUS staff travel to Orkney
26/05/06	ADUS staff assess the <i>Flamborough Light</i> as a survey vessel and also investigate the potential for an RTK base station on the roof of Scapa Harbour Authorities Office.
27/05/06	ADUS staff set up RTK base station on Scapa Harbour Office and collect raw satellite observations for processing accurate base station position using OS GPS network before the potential survey start date.
28/05/06	Base station recovered and ADUS staff return from Orkney.
06/06/06	ADUS staff travel to Orkney.
07/06/06	Mobilisation of survey equipment onboard <i>Flamborough Light</i> in Stromness Harbour. RTK Base station erected on the roof of Scapa Harbour Office, processed position entered as UTM grid and ODN Height.
08/06/06	Deployment of the ISHAP system followed by a POS-MV GAMS calibrations and Patch Test off Stromness. Weather calm during morning but stiff south-westerly wind develops in afternoon creating choppy sea conditions.
09/06/06	Survey of <i>Royal Oak</i> Hull in good sea conditions.
10/06/06	Survey of <i>Royal Oak</i> Hull and surrounding area in good sea conditions.
11/06/06	Demobilisation of survey equipment.
12/06/06	ADUS staff return from Orkney.

APPENDIX 4 - SURVEY CONFIGURATION

Survey Inputs	Sensor	Remarks
Position Sensor	POS-MV 320, & Trimble RTK	Antennae mounted above IMU box on ISHAP system.
Motion Sensor	POS-MV 320	-"
Heading Sensor	POS-MV 320	-"
MBES	SeaBat 8125	ISHAPS configuration, Aft, port, quarter, over the side temporary mount.
Surface SVEL	Valeport MiniSVS Sensor	
Column SVEL	Valeport 650 MK2 Self Recording SVP	
Software	QPS QINSy v7.5	
PPS Timing (Y/N)	Yes	Reson PPS box

POS-MV GAMS results:

Separation	DX	DY	DZ
1.998 M	0.014	1.998	-0.006
1.998 M	0.023	1.997	-0.001

Two POS-MV GAMS calibrations were completed, giving acceptable results.

Patch Test results:

Latency	Roll	Pitch	Yaw
N/A (GPS PPS)	0.41°	-0.7°	-0.3°

One Patch Test was undertaken using seabed features south of Stromness harbour. The Patch Test results were applied in real-time.

Survey Parameters:

Item	Value	Remarks
Horizontal datum	WGS-84	
Spheroid	WGS-84	
Projection	UTM	
Central Meridian and Grid Zone	3W Zone 30	
Vertical datum	OD Newlyn	Base station height derived as 8.523m ODN via GPS network. Manual offset of 51.492 applied to soundings to convert WGS84 to ODN.
Sounding line direction (°)	000 / 180	
General water depth (m)	31.61m to 25.87m	ODN
Sounding line spacing (m)	Typically 50m	
Cross-line direction (°)	-	
Cross-line spacing (m)	-	
Sounding speed (kn)	Typically 4 knots or less	lowest speeds possible over the wreck.
Across track overlap	Typically 10%	
Along track overlap	Typically 25%	
Squat correction (Y/N)	No	
MBES Ping rate (Hz)	7 – 30	Sonar range setting dependant.
MBES Frequency (kHz)	455	
MBES Range Scale (m)	10m – 50m	
MBES PULSE LENGTH (µSECS)	33 - 42	
MBES IMAGERY (Y/N)	Yes, SSS	

Figures

Figure 1

View of the wreck of the Royal Oak from the south west.

Figure 2

View of the wreck of the Royal Oak from the north.

Figure 3

View of the bottom of the Royal Oak. Among the features than can be seen are the four propeller shafts (IDs:3-6); the four docking keels (ID: 12-15 and; the strakes of the hull bottom plating (ID: 11).

Figure 4

Digital terrain model of the seabed within the 800m x 800m survey area. Much of the area is crossed by linear features with regularly spaced lumps (ID: 59). 275m to the sw is a small wreck (ID: 57) and 200m to the south is a 2.2m diameter cylinder 4.8m long (ID: 58).

Figure 5

Buoy positions around the wreck. They are approximately 95m NE of disturbed areas of seabed indicating the location of their ground tackle.

Figure 6

Detail showing sections of tripod main mast (ID: 20); port after 4" HA Gun (ID: 48) and; seaplane crane turntable (ID: 23).

Figure 7

Port rubbing strake with timber missing (ID: 16); port 6" casemate guns (ID: 49-53) and; holes in port torpedo bulge ((ID: 74).

Figure 8

Tripod main mast (ID: 20) and fore mast (ID: 21) with spotting top and related debris (ID: 21).

Figure 9

What appears to be a ship's 27' Cutter (ID: 34) lying on top of main mast debris (ID: 20).

Figure 10

Port side bow distorted hull plating, probably from a secondary explosion, beneath the torpedo strike (ID: 62). The recess for the ship's port torpedo tubes (ID: 56) show as a dark rectangle and a section of anchor chain (ID: 26) can be seen curving down from the deck to the seabed. Beneath barbettes A and B the breach ends of two pairs of guns are visible (ID: 38, 39, 41, 42).

Figure 11

The two seawater intakes (ID: 9, 10) and salvage valves (ID: 76, 77) close to the after docking keels (ID: 14, 15).

Figure 12

Section drawing at Station 10 showing strengthening of the bow with armoured and high tensile steel at lower deck level and above.

Figure 13

Diagram of Reson 8125 and POS MV installation on MV Flamborough Light.

Figure 14
ISHAP system concept diagram.

Figure 15
ISHAP system under tow during trials at Fort William

Figure 16
ISHAP system being assembled on board Flamborough Light

Figure 17
ISHAP system fastened to the port quarter of the Flamborough Light.

Figure 18
1936 as fitted profile drawing of the Royal Oak