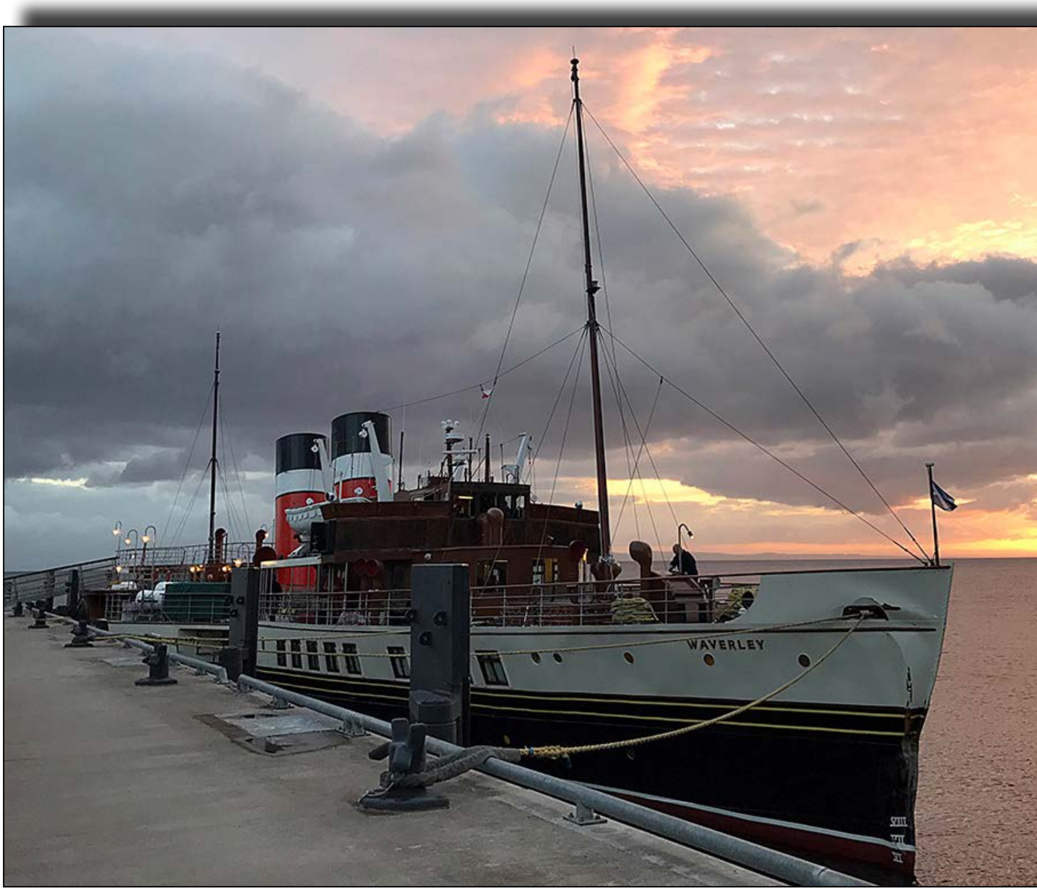
ACCIDENT REPORT

MAIB
MARINE ACCIDENT INVESTIGATION BRANCH

Report on the investigation of the contact made by the paddle steamer *Waverley* with Brodick pier, Isle of Arran, Scotland on 3 September 2020



SERIOUS MARINE CASUALTY REPORT NO 3/2025 FEBRUARY 2025

The United Kingdom Merchant Shipping

(Accident Reporting and Investigation)

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"The sole objective of the investigation of an accident under the Merchant Shipping (Accident Reporting and Investigation) Regulations 2012 shall be the prevention of future accidents through the ascertainment of its causes and circumstances. It shall not be the purpose of an investigation to determine liability nor, except so far as is necessary to achieve its objective, to apportion blame."

NOTE

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Waverley

GLOSSARY OF ABBREVIATIONS AND ACRONYMS

°	-	degrees
bar	-	metric unit of pressure
C/E	-	chief engineer
C/O	-	chief officer
CSM	-	customer service manager
DOC	-	Document of Compliance
ECDIS	-	Electronic Chart Display and Information System
HP	-	high-pressure
ISM Code	-	International Safety Management Code
kts	-	knots
LP	-	low-pressure
m	-	metre
mb	-	millibar
MCA	-	Maritime and Coastguard Agency
MP	-	medium-pressure
PMS	-	Planned maintenance system
psi	-	pounds per square inch (imperial unit of pressure)
QM	-	quartermaster
SHA	-	Statutory Harbour Authority
SMC	-	Safety Management Certificate
SMS	-	safety management system
UTC	-	universal time coordinated
WEL	-	Waverley Excursions Limited
WSN	-	Waverley Steam Navigation Co Limited

TIMES: all times used in this report are UTC +1 unless otherwise stated.

SYNOPSIS

On 3 September 2020, the paddle steamer *Waverley* made heavy contact with the eastern pier at Brodick, Isle of Arran, Scotland while attempting to berth following a 2-hour afternoon excursion along the Isle of Arran coast. Twenty-one of the 186 passengers and three of the 27 crew on board sustained injuries because of the impact and *Waverley* suffered damage to its bow above the waterline.

During the approach to the berth, the vessel's bridge team ordered astern propulsion on the engine to slow the vessel as it approached the closed end of the pier. As part of the process to achieve astern propulsion, the chief engineer stopped the engine, but it would not restart when the controls were moved to the astern position. By the time the chief engineer managed to resolve the problem and restart the engine to achieve astern propulsion it was too late to take effect; *Waverley* hit the concrete wall at the closed end of the pier at a speed of approximately 2.8 knots.

The investigation identified that:

- The engine could not immediately be restarted because when it was stopped the high-pressure steam piston came to rest at the top of its travel, referred to as its dead centre position, which prevented the engine running either ahead or astern.

- Dead centre events were a known phenomenon but they had only occurred infrequently. The chief engineer was unfamiliar with the system indicators that warned of a dead centre event or how to anticipate and prevent its occurrence.

- The engine was slow to restart due to a steam lock at top dead centre because of an incorrectly secured piston valve, which advanced engine timing and resulted in excessive steam entering the cylinder ahead of top dead centre.

- The loss of experienced engineering personnel inhibited the training of new and less experienced crew.

- The absence of an effective safety management system and reliance on historic maintenance documentation resulted in the failure to capture maintenance issues accurately.

- The occurrence of a dead centre event during arrival into a closed-end berth and the risks associated with that had neither been assessed nor effectively mitigated.

Following the accident *Waverley*'s managers, Waverley Excursions Limited, carried out an internal review of its safety management system and:

- developed and implemented an electronic planned maintenance system;

- revised the risk assessment process to require that all berthing activities are fully risk assessed;

- implemented a competency-based training and development programme for engine and deck crew.

In light of the actions taken and the time elapsed since the accident no recommendations have been made.

SECTION 1 – FACTUAL INFORMATION

1.1 PARTICULARS OF *WAVERLEY* AND ACCIDENT

VESSEL PARTICULARS	
Vessel's name	*Waverley*
Flag	UK
Classification society	Not applicable
IMO number	Not applicable
Type	Paddle steamer, passenger vessel
Registered owner	Waverley Steam Navigation Co. Limited
Manager(s)	Waverley Excursions Limited
Construction	Steel
Year of build	1947
Length overall	73.13m
Registered length	71.63m
Gross tonnage	693.13
Minimum safe manning	19
Authorised cargo	Passengers

VOYAGE PARTICULARS	
Port of departure	Brodick, Isle of Arran, Scotland
Port of arrival	Brodick, Isle of Arran, Scotland
Type of voyage	Coastal
Cargo information	186 passengers
Manning	27

MARINE CASUALTY INFORMATION	
Date and time	3 September 2020 at 1646
Type of marine casualty or incident	Serious Marine Casualty
Location of incident	Brodick pier
Place on board	Bow
Injuries/fatalities	24 injuries (21 passengers and 3 crew)
Damage/environmental impact	Hull penetration at the bow above the waterline
Ship operation	Berthing
Voyage segment	Arrival
External & internal environment	Clear, daylight, good visibility; wind variable but predominantly westerly force 3, gusting force 5
Persons on board	213

1.2 BACKGROUND

Waverley **(Figure 1)** was a heritage paddle steamer passenger vessel propelled by two midship paddle wheels, which were directly driven by an inclined single triple-expansion steam-powered reciprocating engine **(**see section 1.8 and **Annex A)**. *Waverley* originally operated solely on the Firth of Clyde, Scotland, providing regular passenger services until the vessel was withdrawn from service in 1973. The vessel was purchased for £1 the following year by the Paddle Steamer Preservation Society. In 1975, *Waverley* re-entered service, operating seasonally on the Firth of Clyde and around the wider UK to provide daytime pleasure excursions during a nominal operating season from April to October. At the time of the accident, *Waverley* was the only seagoing paddle steamer operating anywhere in the world.

In May 2019, *Waverley* was withdrawn from service to have its boilers replaced (see section 1.10.1) and its planned return to service in 2020 had been delayed until August 2020 due to the COVID-19 pandemic. At the time of the accident, the vessel was operating a reduced programme of cruises on the Firth of Clyde because of the COVID-19 restrictions in place at the time.

Image courtesy of Waverley Excursions Limited

Figure 1: *Waverley*

1.3 NARRATIVE

1.3.1 Events leading up to the contact

At 1115 on 3 September 2020, *Waverley* departed Greenock, Scotland for a scheduled passenger excursion, calling at Largs at 1235 before arriving at Brodick, Isle of Arran at 1409. Having disembarked and embarked passengers, *Waverley* departed Brodick at approximately 1436 with 186 passengers on board to undertake a return sightseeing excursion down the east coast of Arran to the vicinity of the island of Pladda **(Figure 2)**. The vessel then returned north along the coast of Arran and, at 1612, passed Brodick Bay toward High Corrie Burn where, at 1626, *Waverley*'s quartermaster[1] (QM) took over at the helm as the vessel turned back for its scheduled 1650 arrival at Brodick. The master briefed the QM on the intended approach and berthing at Brodick, which was to enter Brodick Bay; manoeuvre the vessel towards the eastern berth at Brodick pier; and apply a 10° turn to port during the final approach to the berth. At 1634, just outside Brodick Bay, the vessel slowed from 12 knots (kts) to 8.1kts to allow a ferry to leave Brodick pier.

At 1640, *Waverley* entered Brodick Bay making 13kts over the ground; the relief master was standing next to the QM at the helm in the enclosed wheelhouse; and the chief officer (C/O) and master were on the open starboard bridge wing **(Figure 3)**. At about 1644, with *Waverley* travelling at 9.6kts, the master ordered slow ahead on the engine order telegraph[2]. The master then ordered dead slow ahead as the vessel shaped a course to approach the berth at the closed end[3] of the eastern pier and *Waverley* slowed down. The master ordered slow astern when the vessel was 100m away from the berthing position and, as planned, ordered the QM to apply a 10° turn to port as *Waverley* passed the end of the pier **(Figure 4)**.

The chief engineer (C/E), who was manually controlling the engine from the engine room, complied with the telegraph orders by stopping the engine. When the C/E attempted to restart the engine in the astern direction it would not run. The C/E quickly realised that the engine had stopped with its high-pressure (HP) piston in the dead centre[4] position. The C/E tried to use the application of full impulse steam pressure[5] on a different piston to rotate the crankshaft and enable steam pressure to act on the HP piston to 'restart' the engine.

The C/E's initial attempts to operate the engine in the astern direction using impulse steam were unsuccessful and, with *Waverley* approaching the closed end of the pier at a higher speed than desired, the master ordered half astern on the telegraph, quickly followed by full astern. Realising there was a problem in reducing speed, the master then ordered double full astern[6] via the ship's telegraph.

The crankshaft still did not move, so the C/E then admitted steam to the HP cylinder in the ahead direction. This action shifted the HP piston from its dead centre position and allowed the C/E to move the control lever to the astern position, restart propulsion and drive the paddle wheels astern. At 1646:21, *Waverley*'s bow made heavy contact with the concrete structure at the closed end of the pier at a speed of 2.8kts over the ground **(Figures 4** and **5)**; no impact warning or instruction to brace was broadcast to the passengers before the impact.

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1 The person charged with steering the ship at the wheel under the direction of the officer of the watch or master. The person with the most helm experience usually performs this role when coming alongside or departing a berth.

2 A signalling device for transmitting orders from the bridge of a ship to the on-watch engineer to indicate the desired direction and speed of the engine.

3 A closed-end berth terminated at one end of the mooring position by a structure at a right angle to the berth. This means that an approaching vessel cannot pass the berth by, which restricts the options for vessels without lateral thrusters both for manoeuvring alongside the berth and if the approach to the berth needs to be aborted.

4 The position of the piston at the top of its travel (see also section 1.8.5).

5 The application of steam to the medium-pressure or low-pressure cylinders to nudge the HP piston from its dead centre position.

6 An emergency command to put the engine and paddle wheels full astern, achieved by ordering full astern twice in rapid succession on the telegraph.

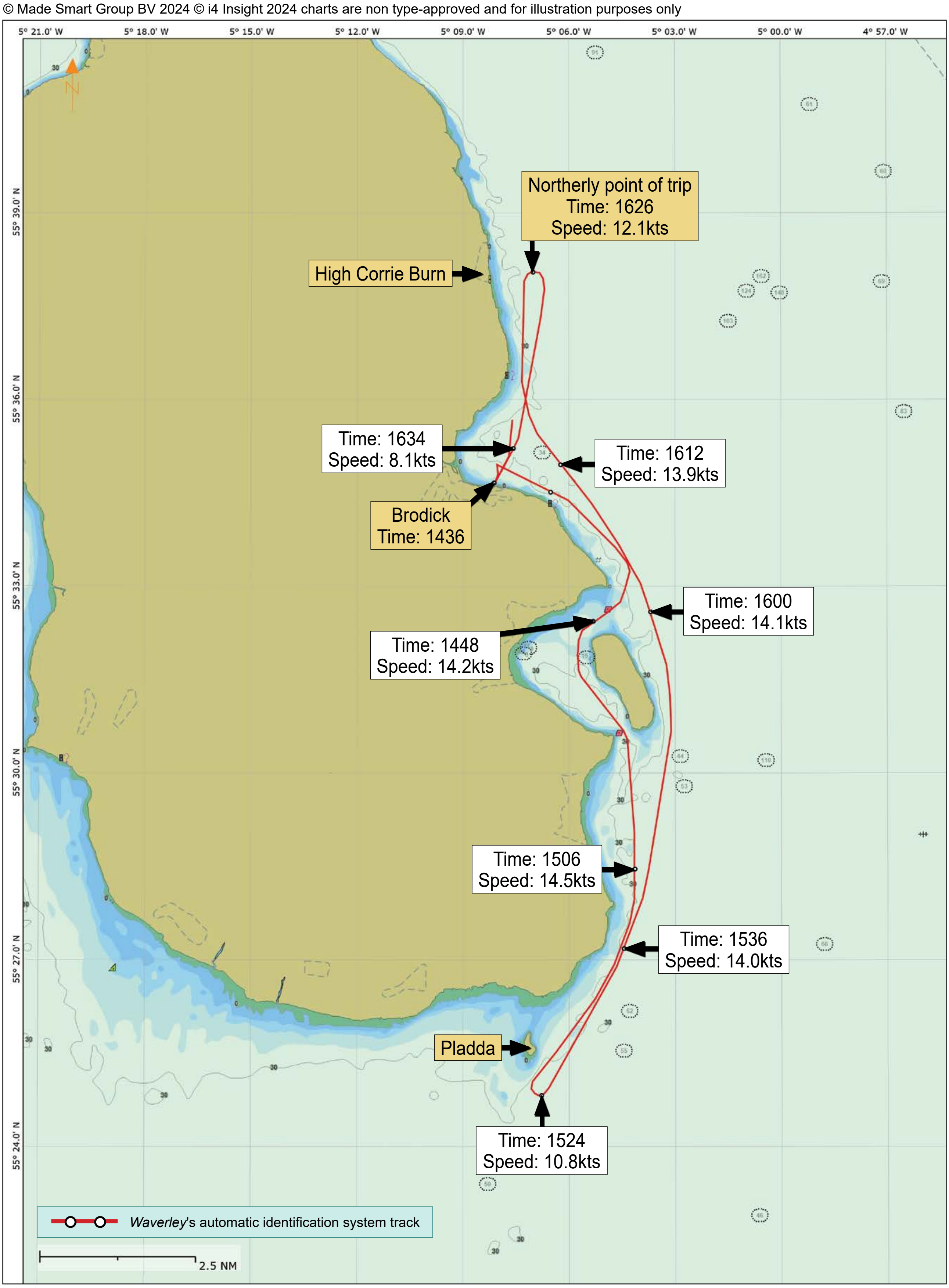

Figure 2: *Waverley*'s passage from Brodick to the vicinity of the island of Pladda, and return, on 3 September 2020

For illustrative purposes only: not to scale

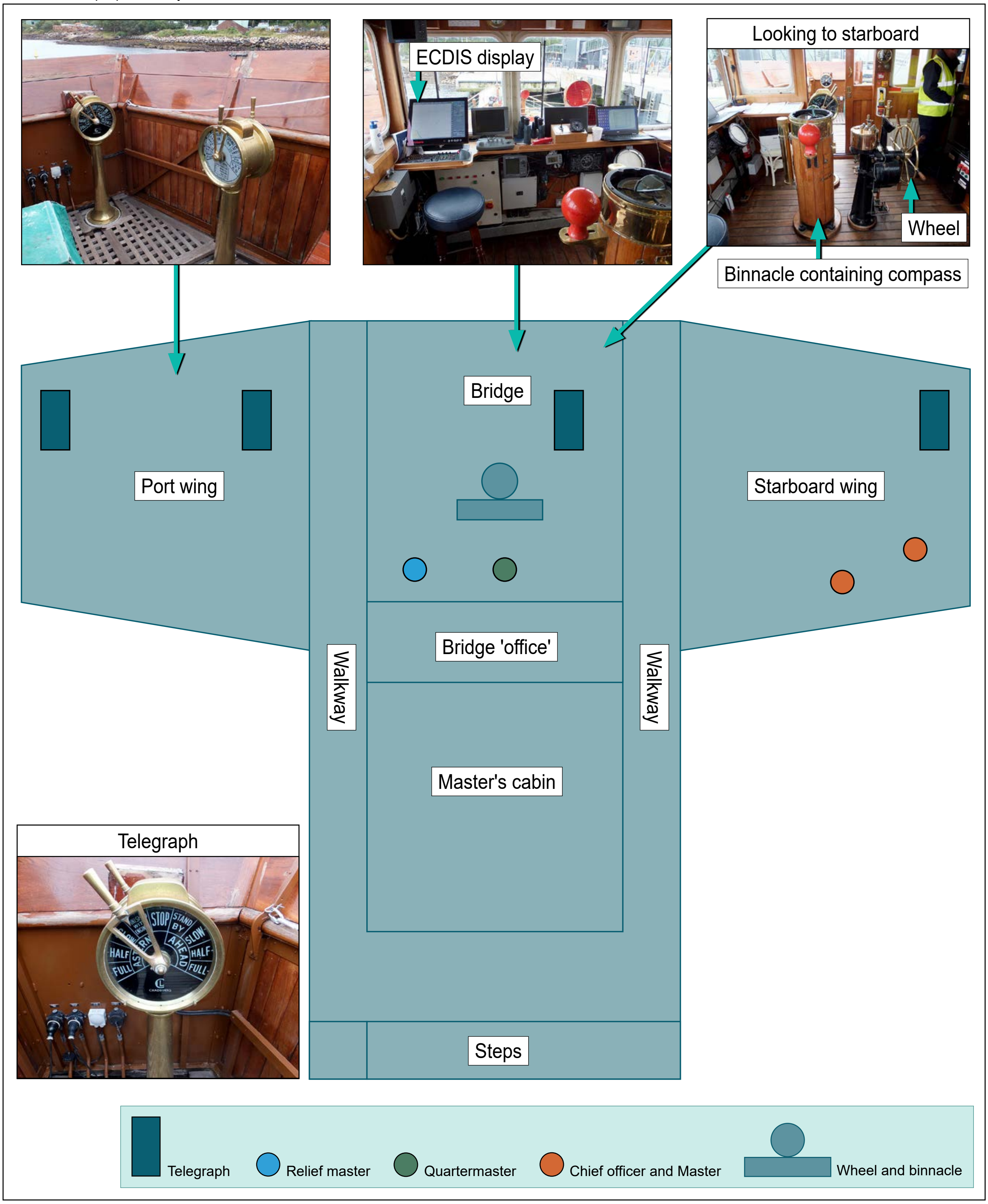

Figure 3: Bridge layout and positions of bridge team during the accident

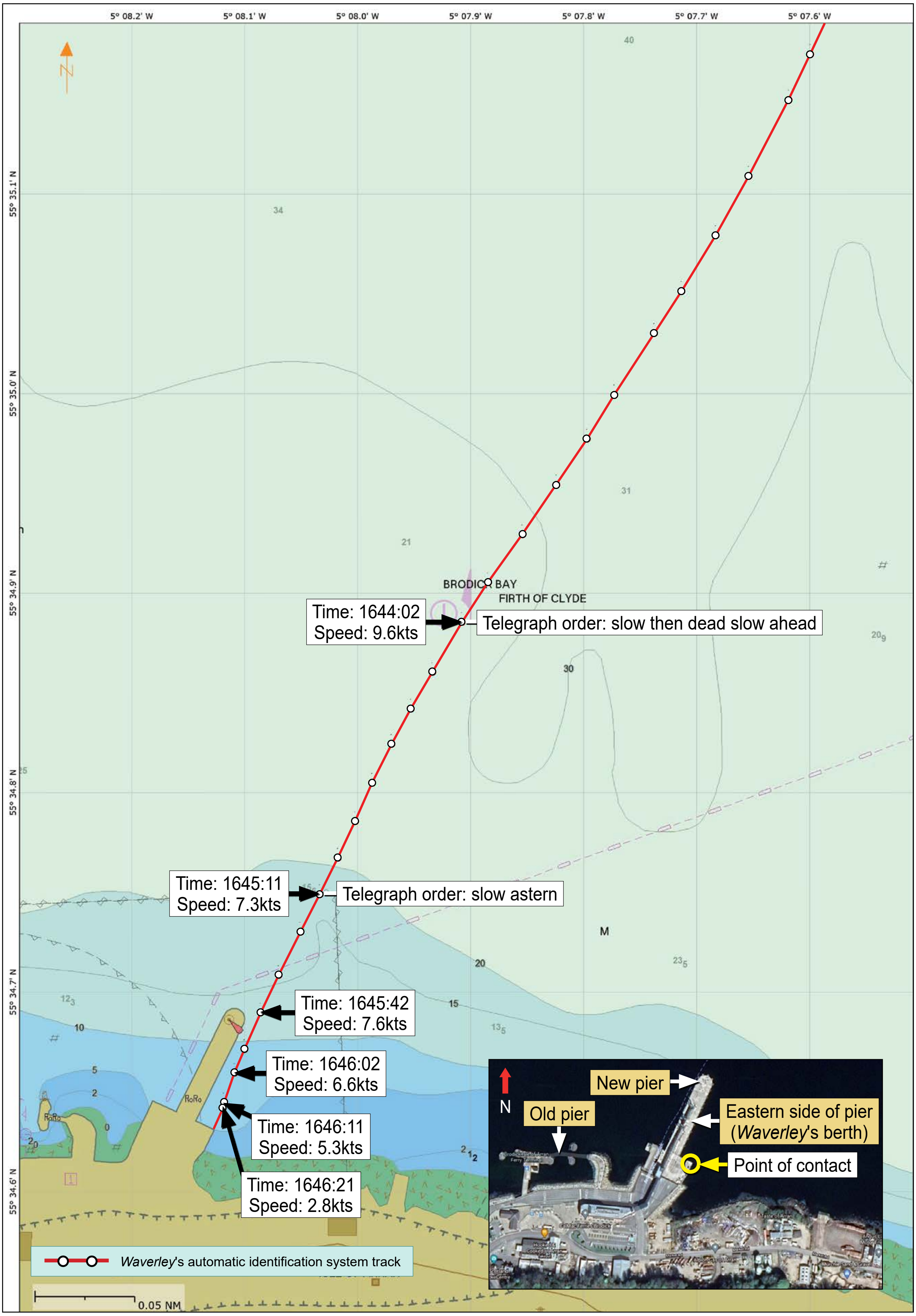

Figure 4: *Waverley*'s approach to Brodick pier on 3 September 2020 and (inset) aerial image of Brodick new and old piers

Images courtesy of Caledonian MacBrayne

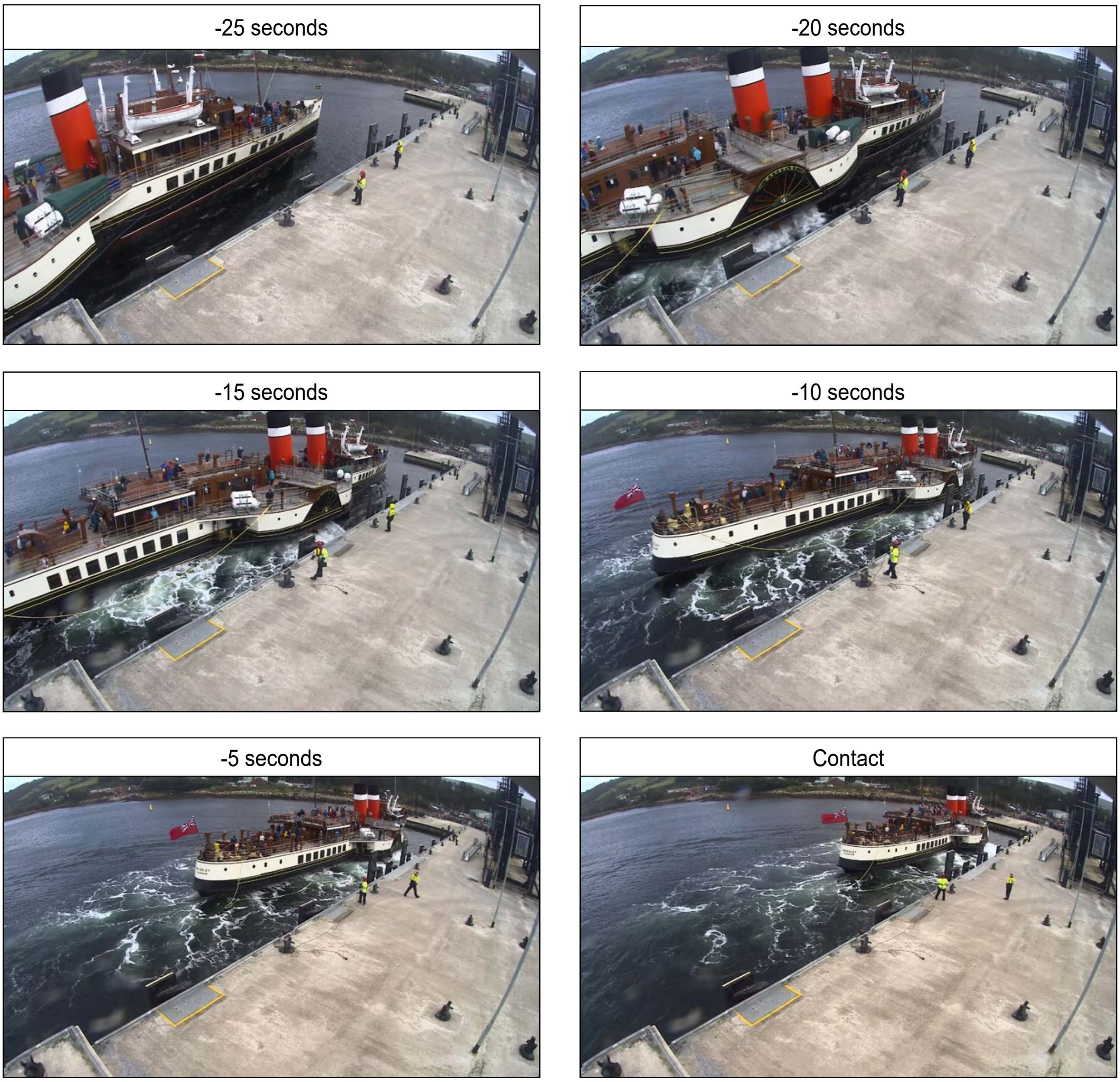

Figure 5: CCTV stills showing *Waverley* moving down the pier before making contact with the pier structure at 1646 on 3 September 2020

1.3.2 Events after the contact

When *Waverley* struck the pier many of its passengers and crew were standing up to watch the arrival from positions on the open Aft Boat Deck and Promenade Deck **(Figure 6)** and they either fell to the deck or made contact with the vessel's structure or fixtures and fittings as they were thrown forward. The engine continued to operate astern just after the collision, propelling *Waverley* backwards along the pier. The master stopped the engine and ordered the crew to pass the vessel's mooring lines ashore. The C/O left the bridge to conduct a damage assessment of the bow and the crew passed mooring lines from the deck, which were then secured to bollards on the quay by the waiting linesmen. The vessel was made fast at 1650. The QM made an announcement to reassure the passengers, and crew members who were not involved in the berthing operation provided first aid support to the injured passengers. The master coordinated the immediate incident response with Brodick's port manager and staff. The C/O returned to the bridge and advised the master that the forepeak had been breached above the waterline and that there were no signs of flooding.

Once berthed, a gangway was placed between *Waverley* and the pier and two shoreside advanced first aiders embarked to assist. Various emergency services assets and personnel subsequently attended the scene, including the island's two ambulances. The uninjured passengers were disembarked from *Waverley* to the island's ferry terminal. Six passengers were transferred to a mainland hospital, two of whom were transported by an air ambulance and coastguard search and rescue helicopter. Nine passengers were also taken to Arran's local hospital. The uninjured passengers, who had reboarded *Waverley* earlier in the day, were transferred to the mainland by ferry during the evening.

1.4 INJURIES AND DAMAGE

1.4.1 Passenger and crew injuries

Twenty-one passengers and three crew were injured and required treatment. Of these, three people suffered serious back and pelvis injuries, two of whom were the passengers evacuated by helicopter. The other injured passengers sustained bruising and cuts due to falling onto the deck or making contact with fixtures and furniture when *Waverley* struck the pier.

1.4.2 Vessel and berth damage

Waverley's bow was buckled inwards by the impact, resulting in three holes in the bow plating above the waterline **(**see **Figure 7)**.

Waverley remained at Brodick pier while temporary repairs were undertaken to the bow and approved by the Maritime and Coastguard Agency (MCA). On 9 September 2020, *Waverley* sailed from Brodick to Glasgow, Scotland for full repair to the bow and remained out of service for the remainder of the 2020 season. *Waverley* returned to service in June 2021, after the MCA had conducted a full assessment of the repairs and directed a set of sea trials.

Brodick pier sustained minor scrapes to its concrete structure and light scuffs to its fixed rubber fenders **(**see **Figure 7)**.

1.5 ENVIRONMENTAL CONDITIONS

At the time of the accident there was a gentle westerly wind of 12kts (force 3), occasionally gusting to 21kts (force 5), and an air temperature of 17.7°C. High tide was 2.98m at 1409 and the predicted low tide was 0.63m at 1924. There was a slight southerly tidal stream of about 0.1kts in the bay. The weather was sunny with little cloud.

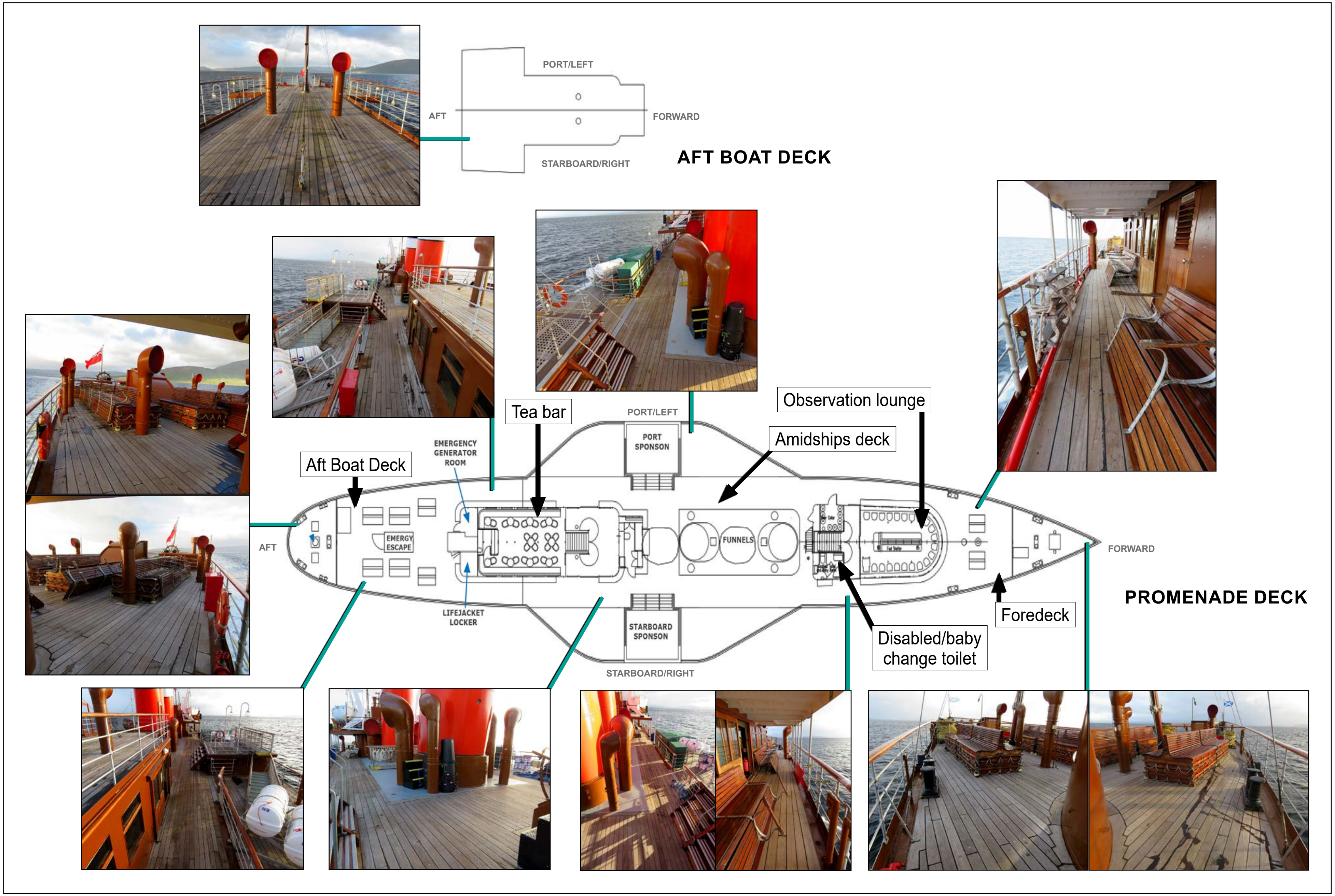

Figure 6: Layout of *Waverley*'s Promenade Deck and Aft Boat Deck (above Promenade Deck) with views of external areas after the accident with deck furniture stowed

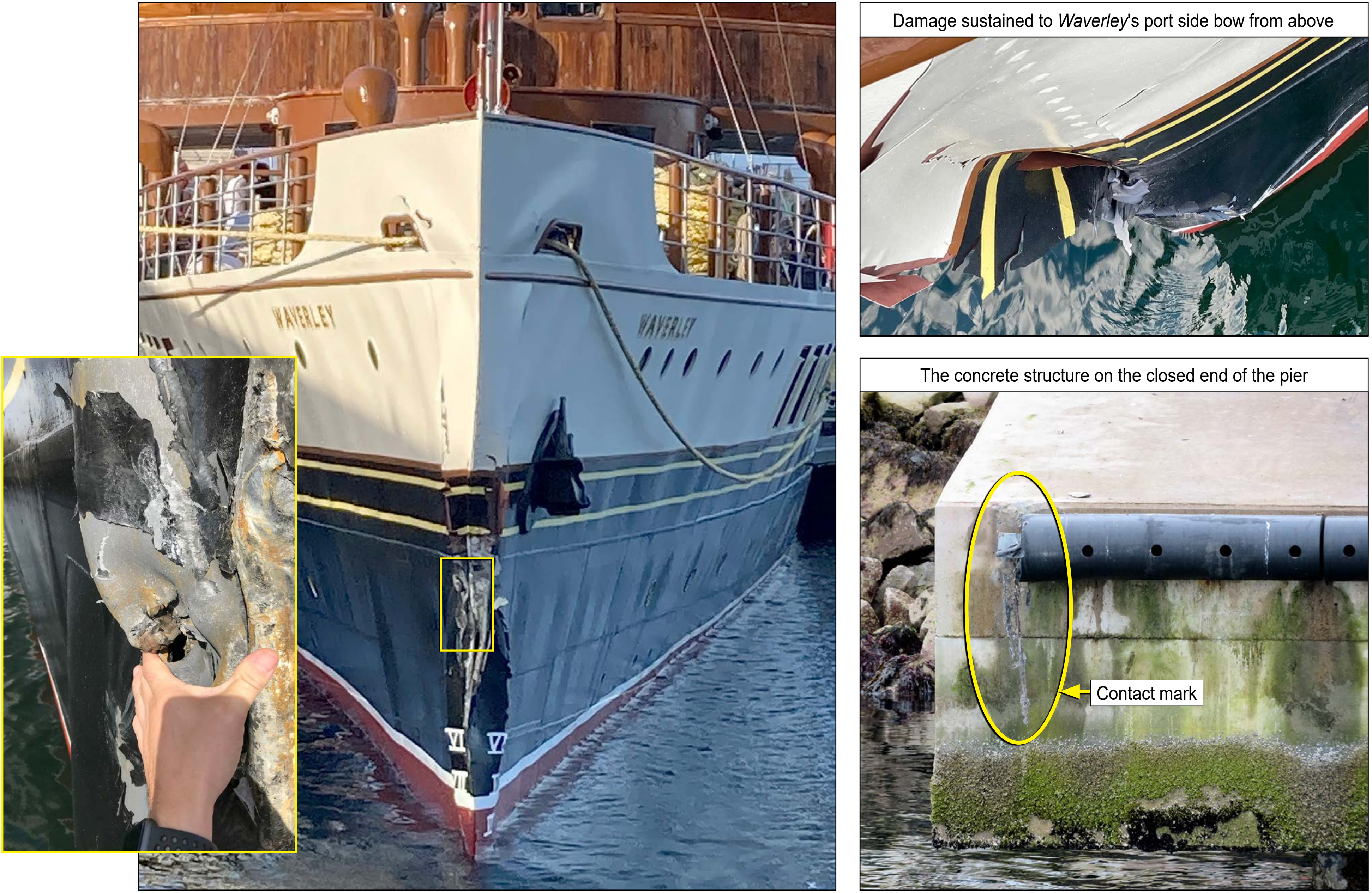

Figure 7: Damage sustained to the vessel's bow and the berth

1.6 *WAVERLEY*

1.6.1 Vessel overview

Waverley's hull was originally constructed using riveted steel, but welding techniques had been used during subsequent repairs and refits. The engine room was located aft of the paddle wheels and the boiler room was forward of the engine room; both spaces occupied the full height of the hull. The vessel otherwise comprised three principal decks:

- the lower Orlop Deck, which contained crew spaces and a passenger bar;
- the Main Deck, which predominantly accommodated passenger dining areas and walkways either side of the engine and boiler rooms that included an open area for viewing the engine room;
- the upper external Promenade Deck, which provided passenger seating and supported two deckhouses: the forward deckhouse contained an observation lounge and the aft deckhouse housed a tea bar and passenger services area **(**see **Figure 6)**. The Aft Boat Deck was situated on top of the aft deckhouse and provided further passenger seating.

The enclosed wheelhouse was located on top of the forward deckhouse. The main conning position when berthing was from the bridge wing closest to the berth; the open bridge wings were each equipped with an engine order telegraph. A voice pipe (speaking tube) to the engine room **(**see **Figure 3)** was in the bridge next to the wheel. The vessel's primary means of navigation was paper charts. A Transas Navi-Sailor 4000 Electronic Chart Display and Information System (ECDIS) was installed in the wheelhouse and was operating at the time of the accident[7].

1.6.2 Ownership and vessel management

Waverley was owned by the Waverley Steam Navigation Co. Limited (WSN), a registered charity that conducted fundraising to support the vessel's preservation and restoration. The charity had owned *Waverley* since the vessel's 1975 re-entry into service as a pleasure excursion vessel. *Waverley* was operated by Waverley Excursions Limited (WEL), a private limited company and wholly owned subsidiary of WSN. *Waverley* was the only vessel operated by WEL at the time of the accident.

A combination of paid and volunteer personnel supported WEL. Its chief executive and director of safety reported directly to the company's chair and board of directors. The operations director, who was also the nominated Designated Person Ashore, reported directly to the chief executive.

1.6.3 Operations and technical management

There had been several personnel changes during *Waverley*'s 2015 to 2018 operating seasons. In late 2016, most of the engineering department left the company, including the technical superintendent and C/E at the time, who were the main sources of historical knowledge on the engine machinery. The departing C/E left handover notes for their successor but these were lost in 2017, during which

[7] In 2021, the ECDIS was adopted as the vessel's primary means of navigation.

time there were two successive technical superintendents. The lost notes were found during the 2019 refit. Throughout that period WEL had employed new, less experienced crew who had participated in some of the machinery overhauls.

The operations director at the time of the accident was appointed by and started full-time with the company in November 2017; they were the fourth individual to hold the position that year. Since their appointment, the operations director had presided over all survey and maintenance works and made considerable efforts with the MCA to formalise *Waverley*'s maintenance documentation.

At the time of the accident the operations director was also acting as the technical superintendent and had sought additional maintenance data, technical information and knowledge from previous C/Es and superintendents to support the development of an electronic planned maintenance system (PMS).

1.7 *WAVERLEY* CREW AND TRAINING

1.7.1 Crew

The vessel's deck and engineering crew were professional seafarers and at the time of the accident only the QM was a volunteer. On board passenger services were supported by a mix of professional and volunteer personnel.

The Safe Manning Document required a minimum of 10 crew without passengers and 19 with passengers embarked, although extra trainees and hotel services crew were often carried. Minimum manning required two crew to work on the bridge and three engineering crew: two for the engine and one for the boiler room.

Waverley operated a one-watch system because excursions usually started mid-morning and finished in the evening, after which the vessel moored up overnight. This schedule allowed the crew to work an 8 to 10-hour day with breaks at stops and to rest overnight.

The master in command at the time of the accident had extensive paddle steamer experience and had worked on *Waverley* for 26 years, including 6 years as the senior master and another 14 years as master or relief master[8]. The master held an STCW[9] II/2 Master (unlimited) certificate of competency and the appropriate Pilotage Exemption Certificate for the Clyde port area, although this was not a requirement for vessels visiting Brodick.

The C/E held an STCW III/2 Motor (unlimited) certificate of competency with a dual endorsement for steam engines. The C/E had worked on *Waverley* since 2017 and had served on other steam-powered vessels earlier in their career, although these were controlled differently to *Waverley*'s triple-expansion engine. The C/E had manned the engine controls during berthing and unberthing at Brodick the previous week. At the time of the accident the C/E was rested, had slept well and was not on any medication.

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[8] The master was a full-time WEL employee. Relief masters were those employed to allow the full-time master to take time off during the season.

[9] Standards of Training, Certification and Watchkeeping for Seafarers 1978, as amended.

The QM was an experienced volunteer who had first acted as Waverley's helm in 1993. The QM did not hold a professional certificate of competency but was a company authorised helm who had held this position until taking a break from volunteering in 2009. The QM had returned to the vessel 10 days before the accident and was helming under supervision at the time.

1.7.2 Training

The operation, maintenance, and general husbandry of *Waverley* relied on the expertise of its crew and volunteers. The vessel's unique mode of propulsion meant that it was only possible for deck or engine crew and volunteers to gain operational experience through practical training on board. No formalised, documented training system was in place and there was heavy reliance on 'learning through doing', either at sea or during maintenance periods. Crew would act as understudy in a certain watchkeeping position and, through the gradual process of gaining experience, would progress until the master or C/E assessed them as competent in the role.

Engineers learned to operate the engine under the guidance of more experienced crew while *Waverley* was operating at sea, although limited training opportunities arose during sea trials and preparation cruises for the upcoming season. Less experienced engineers were progressively entrusted with more complex and safety critical engine operations, such as those during berthing, as their knowledge developed. The operating capability of individual engineers was not formally documented or standardised. The bridge team were able to recognise different engineers by their response to engine orders; for example how quickly, and at what level, power was applied to the paddle wheels from the engine.

1.8 PROPULSION MACHINERY

1.8.1 Propulsion system

Waverley was propelled by two eight-bladed wooden feathering paddle wheels that were located one per side at midships and were directly driven by a three-cylinder triple-expansion steam reciprocating engine. The vessel's normal service speed was about 13kts, with a maximum speed of 18kts. The paddle wheels **(Annex A)** had the capability to provide significant stopping power, enabling *Waverley* to stop in its own length when travelling at 16kts and within a distance of 10m at a speed of 5kts. The vessel had a single stern-mounted rudder and no lateral thrusters. The slender nature of the hull form and its shallow draught meant that *Waverley*'s turning circle of 548.7m (almost 3 cable lengths) was large for a vessel of its size.

1.8.2 Triple-expansion engine

Waverley's incline-mounted, triple-expansion steam reciprocating engine was built in Greenock, Scotland by Rankin & Blackmore Ltd **(Annex A)**. It operated using 12.4 bar (180 psi) saturated steam generated by two boilers in the boiler room to drive a HP, medium-pressure (MP), and low-pressure (LP) piston, each housed within its own cylinder. The three pistons were each connected via a connecting rod and crank[10] to the single crankshaft **(Figure 8)**, which directly turned both paddle wheels; it was not possible for the paddle wheels to turn at different speeds or in different directions simultaneously.

[10] Each of these three systems was technically a separate engine.

Images taken from *A Simple Guide to PS Waverley's Machinery*, produced by *Waverley*'s engineering team and modified by MAIB.

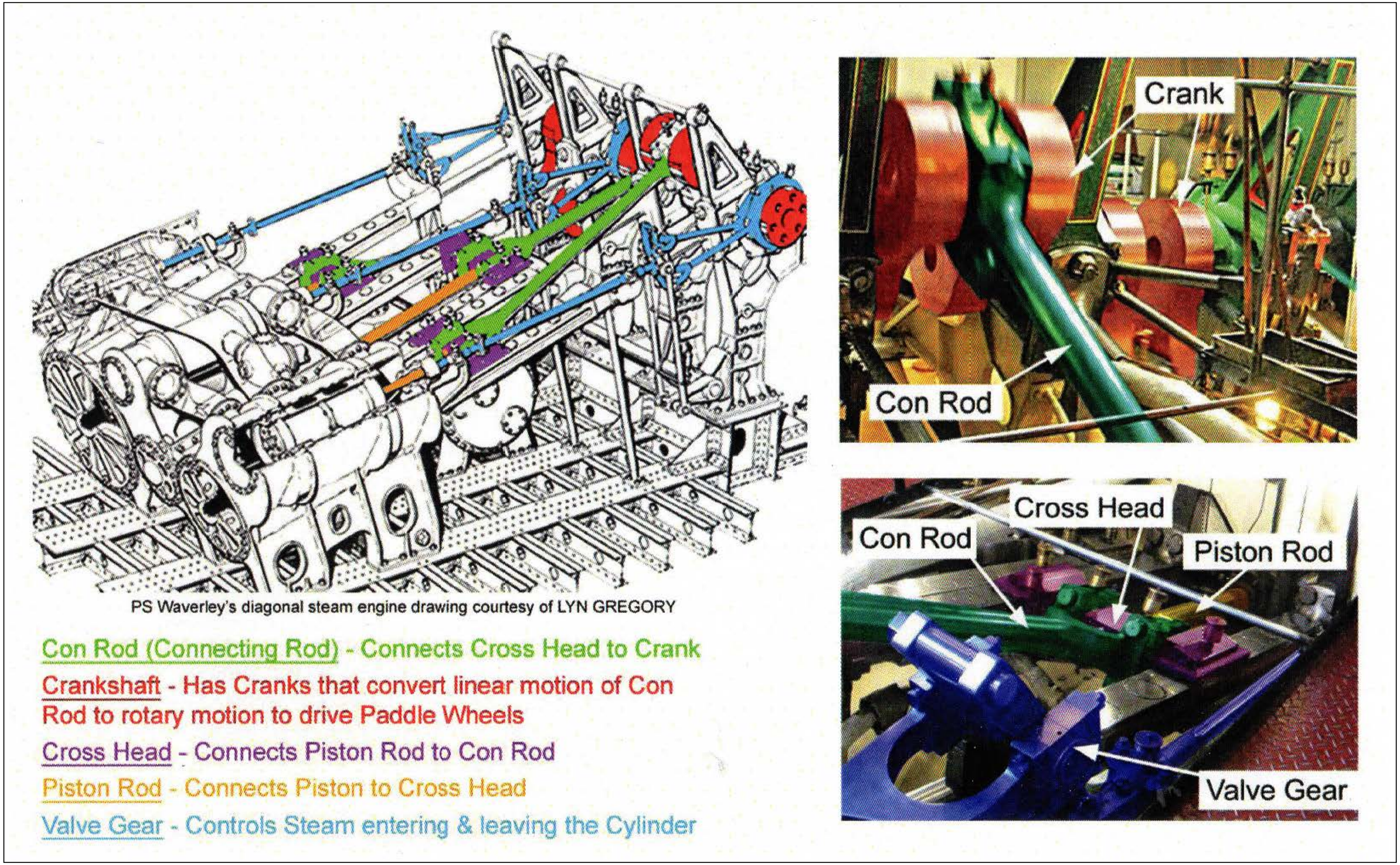

Figure 8: Diagram and photos showing the location of the three cylinders and the condenser

1.8.3 Steam flow through engine

The steam from the boilers provided the motive force to progressively drive each piston in its respective cylinder in turn; the steam pressure reduced and increased in volume as it passed through the HP **(Figure 9)**, MP and LP cylinders in turn, resulting in an equal power output from each cylinder.

Piston valves controlled the steam flow through the HP and MP cylinders, with a slide valve[11] controlling the LP cylinder. The piston valves reciprocated in their own cylinders attached to the side of the HP and MP cylinders and allowed the steam to pass from the piston valve cylinder to the HP and MP pistons to drive the double-acting pistons[12] in the desired direction at the correct time[13].

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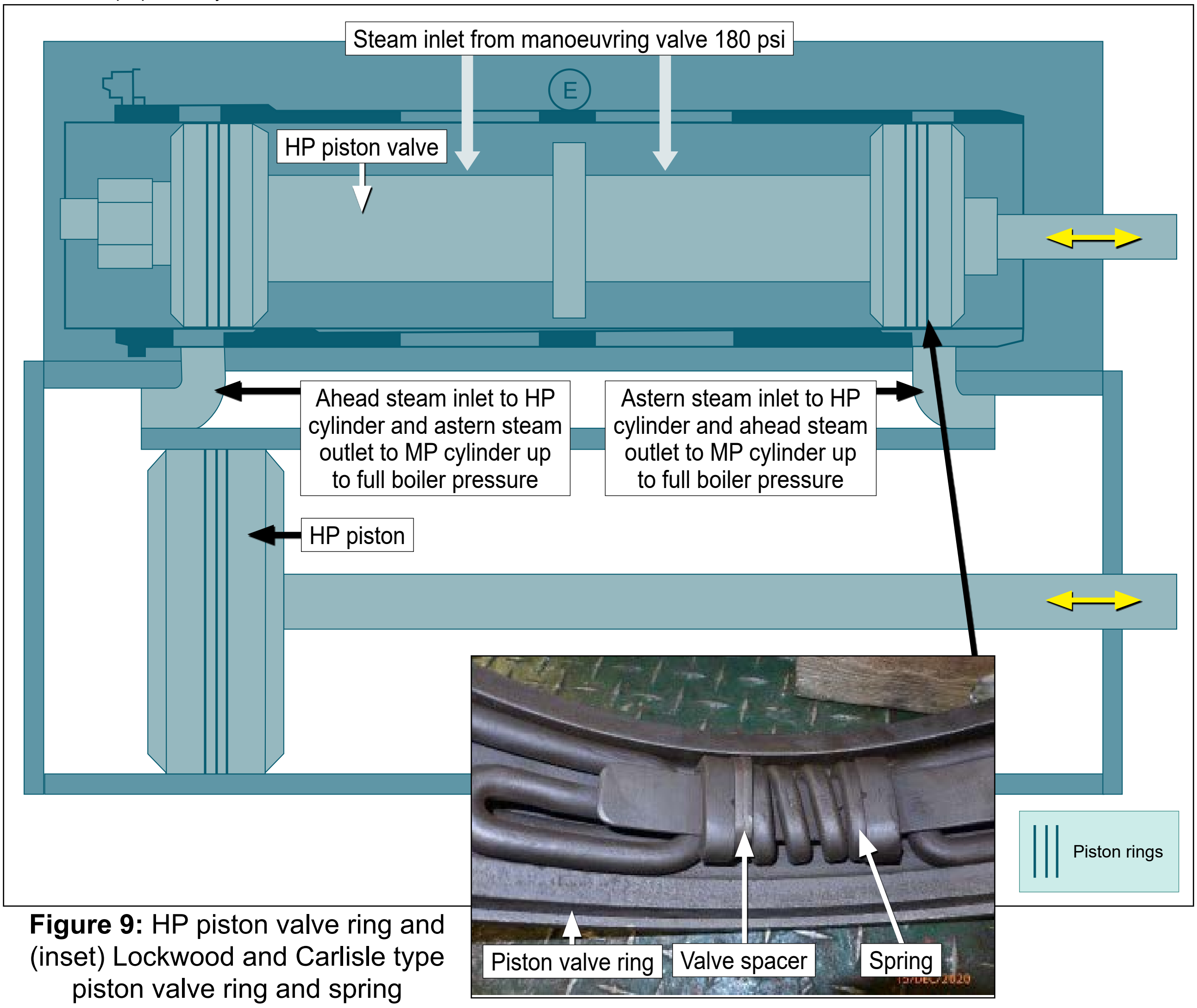

Figure 9: HP piston valve ring and (inset) Lockwood and Carlisle type piston valve ring and spring

[11] Piston and slide valves used different methods to admit steam into the cylinder of a steam engine. A piston valve was more effective at higher temperatures and provided less resistance to the flow of steam. Slide valves were typically used with lower working pressures.

[12] Provided pressure in both directions so that steam could act on either side of the piston within the piston cylinder.

[13] Engine timing was maintained by correct adjustment of the piston valve control rods and linkages.

Cast iron piston valve rings acted as seals between the piston valve and the cylinder wall. In order to ensure a tight fit within the cylinder, the diameter of the piston valve ring could be adjusted by springs and spacers **(Figure 9** inset**)**. Steam pressure could be lost through poorly fitted piston valve rings.

The HP piston valve piston was secured in position on a rod with locking nuts, washers and a spacer at the cover end[14] to adjust the cut-off of steam into the engine. A split pin was inserted into a hole at the end of the rod as a final safety measure to prevent the piston valve detaching from the rod. The purpose of the spacers was to lift the nut clear of the studs on the valve face, with additional washers/spacers fitted to try to get the assembly hard against the split pin at the end of the rod.

Once the steam had completed its passage through the engine it was cooled via a condenser to condense it back into feed water, which was then returned to the boiler. A vacuum, necessary to ensure an efficient flow of steam through the engine, was maintained in the condenser through condensation of the steam and by the operation of the condenser vacuum pump.

The vacuum pump contained 36 diaphragm valves, which opened and closed during the pumping operation to create the vacuum.

1.8.4 Engine control

The on-watch engineer operated the engine directly from the engine control station in the after end of the engine room overlooking the engine **(Figure 10)**. This required the use of six control levers, three primary and three secondary **(Figure 11)**, to manually direct the flow of steam through the cylinders to achieve the required direction of crankshaft rotation to provide forward or astern propulsion.

The three primary control levers had separate functions:

- The **HP regulating steam valve** lever controlled the amount of steam entering the HP cylinder;

- The **Engine reversing mechanism** lever changed the direction of the crank rotation and, although part of the procedure to reverse the direction of the crankshaft, was unconnected to the steam system to the cylinders; and

- The **Starting and Impulse steam** valve lever provided steam to the MP or LP cylinders to assist in starting the crank rotation.

The three secondary levers enabled cylinder drainage during the engine's warm-up in preparation for its operation to prevent a build-up of condensate and possible hydraulic lock in each cylinder.

Waverley's engineers controlled the engine in response to telegraph orders passed from the bridge. The orders usually involved a repeated ring of the telegraph to indicate the need for a series of sequential changes through each engine speed[15],

[14] The bottom (lower) end of an inclined engine design was called the cover end, and the top (higher) end was referred to as the crank end.

[15] The telegraph rings at each stage of a change of order, from stop through each of the following steps: full ahead; half ahead; slow; dead slow; stop; dead slow astern; slow astern; half astern; and full astern.

although this sequence could be bypassed if required. Voice pipes were also fitted and used to contact the engine room crew before berthing operations, but not used for engine orders due to ambient noise.

When a new engine order was received from the bridge, the on-watch engineer adjusted the HP regulating steam valve lever **(Figure 11)** to manage the amount of steam entering the HP cylinder and in turn control the speed of the crankshaft and the paddle wheels.

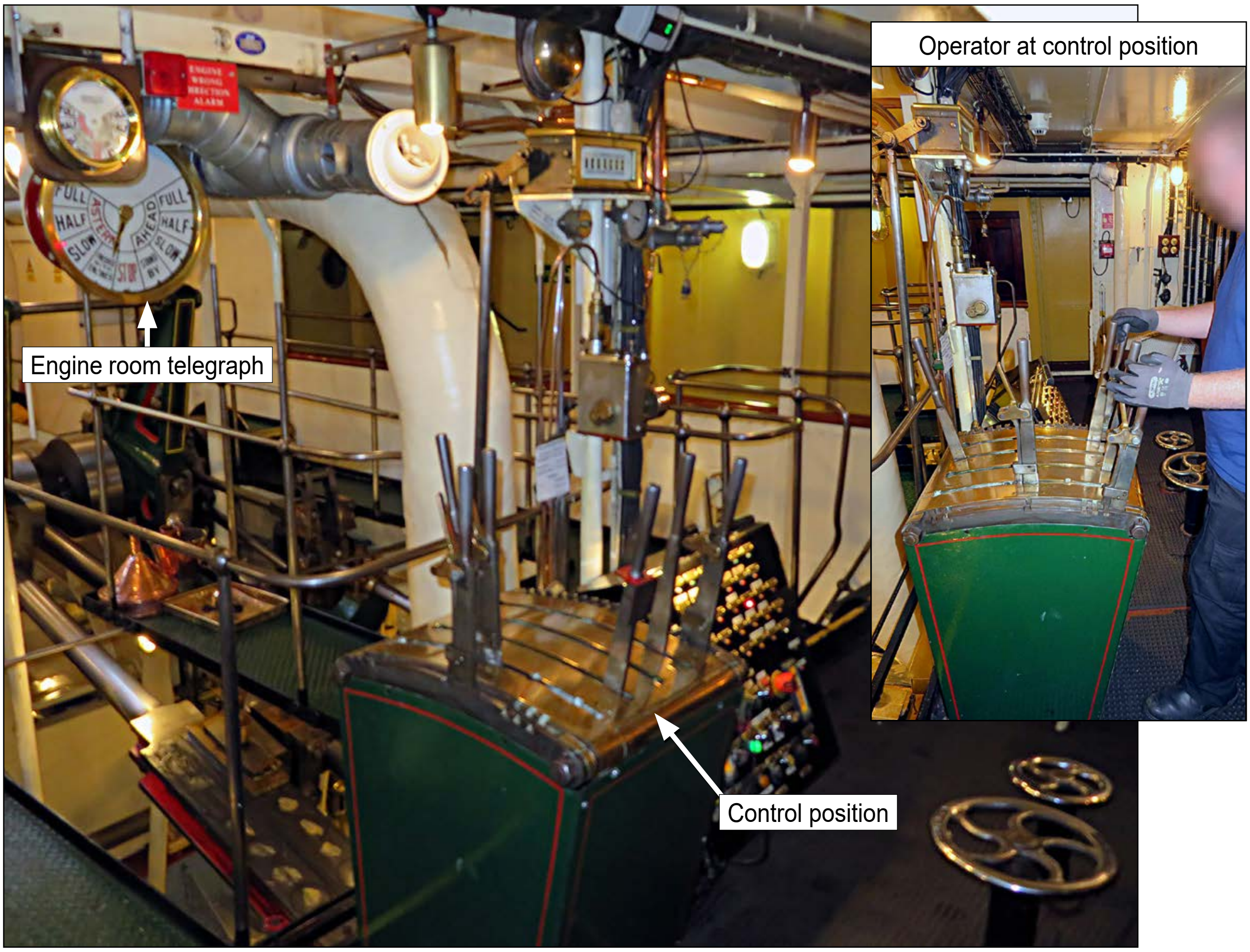

Figure 10: View of the engine room looking forward to starboard and (inset) an operator at the engine control position

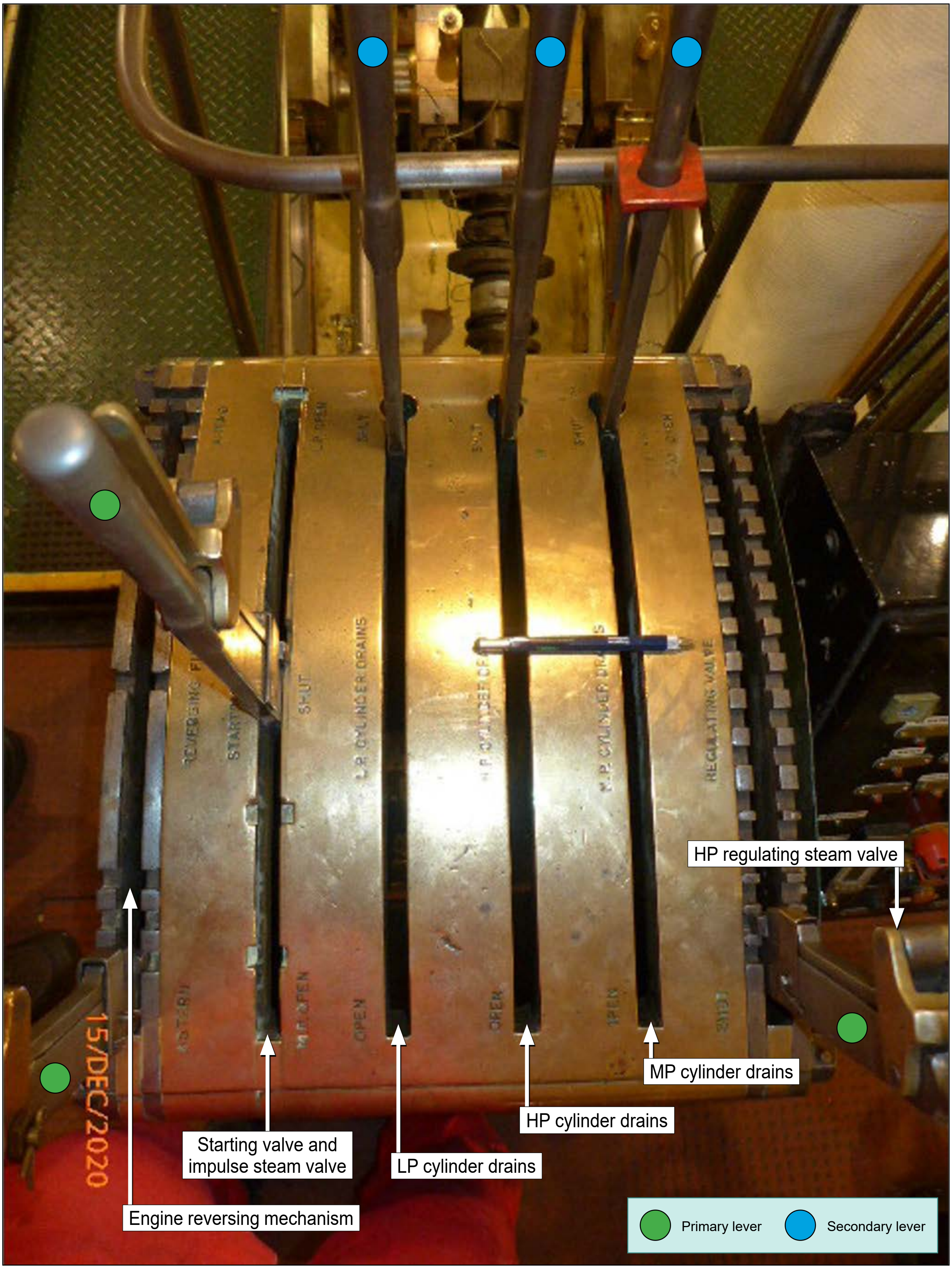

Figure 11: Engine control levers at the engine control position

1.8.5 High-pressure piston dead centre event

The HP, MP and LP pistons were connected to the crankshaft with an angular displacement between them of 120° **(Annex A)**. When the engine stopped, the three pistons came to rest at no specific crank angle position.

If the HP piston stalled at the full extent of its travel, either at the cover end or crank end, it was referred to as a dead centre event, which was rare. The crew did not routinely practice the procedure for resolving the situation as it was difficult to replicate since the engine would, in normal operation, pull on the LP piston, assisting the engine away from being locked dead centre.

An HP piston dead centre event prevented steam from flowing through the engine. To overcome this, the engine was designed to enable impulse steam to be admitted directly into the MP or LP cylinders to start the engine rotating in the desired direction, or to reverse direction with steam applied.

1.9 POST-ACCIDENT INVESTIGATION

1.9.1 Attempt to recreate the dead centre event

On 9 September 2020, investigators witnessed the sea trials conducted during *Waverley*'s return passage to Glasgow following the accident. One of the objectives of the trials was to replicate the HP piston stopping in the dead centre position, but it was not possible to do so despite numerous attempts.

On 15 December 2020, investigators witnessed the post-accident inspection of *Waverley*'s steam engine and associated machinery. The inspection found that:

- Three of the condenser vacuum pump's 36 diaphragm valves **(Figure 12)** were blocked. This resulted in a vacuum of 796 millibar (mb) rather than 846mb, which reduced the engine's efficiency.

- The locking nuts that secured the HP piston valve to its piston rod were loose **(Figure 13)**. The washers in use were not an original design and had probably been introduced to reduce the gap between the end nut and the split pin. The fabricated nature of the washers made tightening the nuts difficult. The loose nuts extended the piston valve's travel by 5.4%, causing the piston valve to open or close prematurely and impacting the engine's timing.

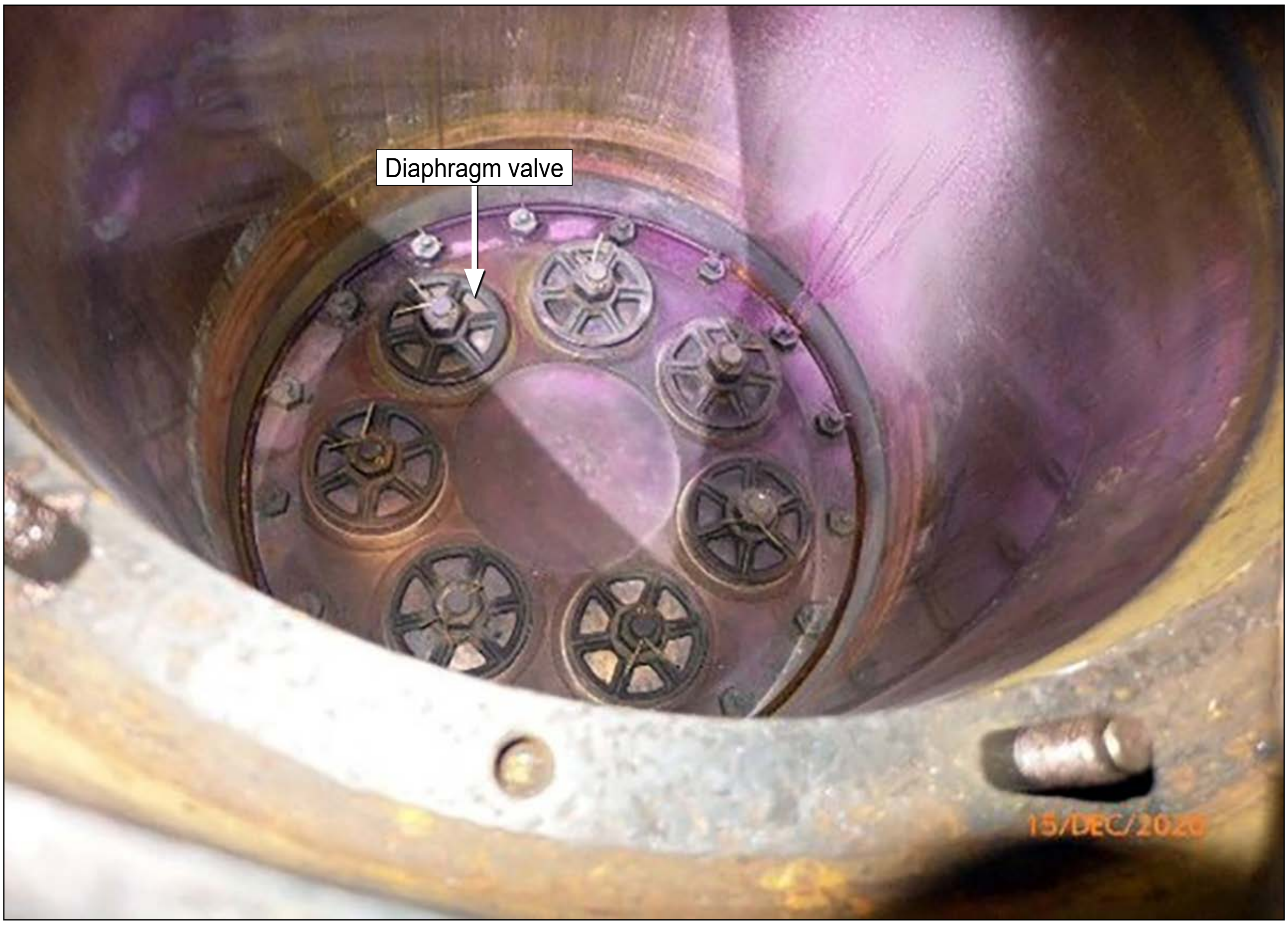

Figure 12: Vacuum pump diaphragm valves

Figure 13: Piston valve rod locking nuts and washers

1.10 MAINTENANCE OF ENGINE COMPONENTS

1.10.1 Maintenance schedule planning

Routine maintenance, such as greasing and functional testing, was performed by the engineering crew during *Waverley*'s operating season. Major maintenance tasks, such as the removal of machinery for inspection, testing, survey and evaluation, were undertaken by the crew with some contractual assistance during the winter layovers. This programme was adapted to include the vessel's certification schedule[16], which had been agreed with the MCA after the 2000 refit and was based on a 5-year rolling cycle. The need to improve the system supporting maintenance planning had been recognised by WEL during the replacement of *Waverley*'s boilers in 2019.

1.10.2 Maintenance documentation

Maintenance activities were outlined in the C/E's standing orders, which comprised several manuals written by previous C/Es and staff using experience and extracts from historical engineering documents. The schedule for maintenance was detailed but supporting documentation and previous maintenance activities had not been formally recorded. The available technical documentation was presented in different formats and held in various locations. Engineers also relied on knowledge gained either from working on the engine with more experienced engineers or from their own work off the vessel.

At the time of the accident, the technical superintendent had identified the state of engineering documentation as a risk and WEL was developing a formalised PMS in close consultation with the MCA.

1.10.3 Previous defects

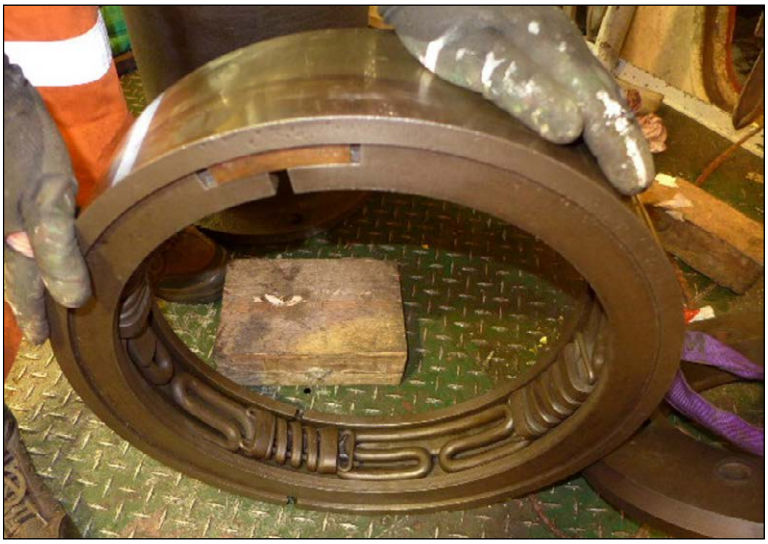

Figure 14: Piston valve ring

During the 2015 winter engine overhaul period, *Waverley*'s crew had found that the HP piston valve rings **(Figure 14)** were worn and required replacement. New rings were fabricated and installed but these failed after approximately one week as they had been manufactured using an incorrect material. The original piston valve rings were subsequently reinstalled while the correct material was identified and sourced. The original HP piston valve rings were still in place at the time of the accident.

[16] The certification schedule would include major items such as a boiler survey.

1.11 BERTHING

1.11.1 Waverley Excursions Limited berthing guidance

WEL's safety management system (SMS) provided guidance on safe navigation practices, including under keel clearance, berthing procedures and the importance of passage planning. The SMS did not provide specific guidance on how to manage berthing hazards, although a document titled Piers Book contained local information about every port visited by *Waverley*, including Brodick **(Annex B)**, that the deck team could refer to for navigation planning. The WEL SMS provided no risk assessments for encountering navigational hazards, including during berthing.

There was no procedure to instruct passengers to be seated, or to hold on to a secure fitting during berthing, as is common practice on board high-speed passenger ferries.

1.11.2 Brodick pier

Opened in 2018, the 110m two-berth finger pier at Brodick was constructed as a replacement for the original pier and it had been designed so a new class of island ferry could berth on a linkspan on its western side. The pier was located to the south-west of Brodick Bay and aligned on a north-north-easterly orientation, protruding at almost right angles to the shore. The eastern side was available for berthing of other vessels, although it was 'closed' by a concrete ramp that was about 2m above the mean high water level. The harbour was owned by Caledonian Maritime Assets Ltd (CMAL) and operated by CalMac Harbours, a division of CalMac Ferries Ltd.

CMAL was the Statutory Harbour Authority (SHA) for Brodick and had issued a statement of compliance with the Port Marine Safety Code and published terms and conditions for harbour users that required every vessel *approaching, entering, or leaving the Harbour* to be *fit for purpose* and *compliant with national and international legislation, regulations, national standards and codes of practice*. *Waverley* had successfully berthed on the eastern side of the pier 29 times, of which four were during 2020 **(Figure 3)**.

1.11.3 Passage and pilotage plan

All vessels were required by SOLAS[17] Chapter V Regulation 34, Annex 24 and 25 – Guidelines for Voyage Planning[18] to develop a voyage or passage plan that included *detailed planning of the whole voyage or passage from berth to berth*.

WEL did not produce detailed navigational passage or pilotage plans and, to provide customers with interesting coastal excursions, allowed master's discretion for *Waverley*'s routes. WEL supplied its masters with a standard generic arrival plan, but the detail depended on the master's port and berth knowledge, as well as the information contained within the Piers Book. Formal, navigational pilotage briefs were not delivered before berthing.

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[17] The International Convention for the Safety of Life at Sea, 1974.

[18] International Maritime Organization Resolution A.893(21).

1.11.4 Normal approach to Brodick pier

Mindful of *Waverley*'s unique handling characteristics, the normal approach to the new Brodick pier was to reduce the vessel's speed to about 7kts, dependent on wind and tide, at approximately one vessel's length from the berth. On deck, the crew would ready the mooring lines before berthing.

The master would order the engines half astern as *Waverley*'s starboard paddle wheel came level with the end of the pier. If a westerly breeze was present the helm would turn the vessel to port by between 10° and 15° to offset a reduction in wind effect as the vessel came into the shelter of the pier, which could pull *Waverley* in towards it.

The master would order full astern when *Waverley*'s bow was estimated to be halfway along the pier. The deck crew would then throw the mooring lines to the line handlers on the pier, the plan being to use a burst of astern propulsion would stop the vessel in the middle of the pier.

Depending upon the conditions, *Waverley* would be stopped within 10m of the closed end of the pier and the deck crew then operated the capstans to pull the vessel alongside using the mooring lines.

To enhance the visitor experience it was possible for passengers to witness the berthing operations from suitable vantage points of their choice on the open decks. No advisory broadcasts concerning sudden movements or jolts were given ahead of *Waverley*'s berthing operations.

1.12 REGULATORY OVERSIGHT AND SAFETY MANAGEMENT

1.12.1 Overview

Waverley was not certified by a classification society due to the vessel's age, unique power plant and propulsion, and the MCA retained responsibility for the survey and certification role for the vessel. For the past 20 years, the vessel had been inspected by surveyors from various MCA offices, including Southampton, Dover and latterly Glasgow. The vessel's dedicated customer service manager (CSM) had worked with *Waverley* for 3 years before the accident and was closely involved with all aspects of the vessel's upkeep. The CSM was a marine engineer with 8 years' service as a C/E and 3 years' surveying experience who had been mentored by *Waverley*'s previous CSM.

1.12.2 International Safety Management Code requirements

Although *Waverley* was operated as a domestic passenger vessel, WEL elected to operate it under a more comprehensive safety management scheme and followed the International Safety Management (ISM) Code[19] rather than the Safety Management Code for Domestic Passenger Ships[20]. The ISM Code required commercial marine companies to comply with many safety requirements, including:

- training, qualification, and competency

[19] The ISM Code provided an international standard for the safe management and operation of ships and for pollution prevention. The IMO adopted the Code as Resolution A.741(18) in November 1993 and it came into force on 1 July 1998 through SOLAS Chapter IX – Management for the Safe Operation of Ships.

[20] Merchant Shipping Notice 1869(M) Amendment 1, issued March 2017.

- safety management system design and management ashore and on board
- vessel and maintenance.

The ISM Code stated that:

> *The Company should identify equipment and technical systems the sudden operational failure of which may result in hazardous situations. The SMS should provide for specific measures aimed at promoting the reliability of such equipment or systems. These measures should include the regular testing of stand-by arrangements and equipment or technical systems that are not in continuous use.*

While not formally captured as such in the company's SMS, WEL regarded the main engine, boilers, paddle wheels and rudder as safety critical items as failure of these items would place the vessel in a hazardous situation.

The ISM Code required that: *The Company should establish procedures to identify describe and respond to potential emergency shipboard situations.* [sic]

1.12.3 Safety management system certification

On 19 June 2019, the MCA issued a Document of Compliance (DOC)[21] confirming that WEL's SMS met the requirements of the ISM Code. The DOC was valid until 7 July 2024. The company's SMS was available on board *Waverley* in printed and electronic form and included information on managing shipboard hazards, reporting, safety training and general guidance on navigational practice and passage planning.

In August 2020[22], the MCA issued *Waverley* with an Interim Safety Management Certificate (SMC) valid for 6 months as the vessel had been out of service for 2 years while undergoing refit. The attending surveyor had insisted on a full crew evacuation drill and interviews to make sure issues noted with crew drills during the last inspection had been addressed.

1.12.4 Industry guidance

At the time of the accident, *Waverley* was the last known seagoing paddle steamer in the world. Although several river-going paddle steamers and heritage vessels still operated triple-expansion steam engines, the original equipment manufacturers (OEMs) had long since ceased to support the equipment, provide space parts or issue safety alerts. Further, no generic industry guidance on operational best practice was available for such vessels beyond technical reference books to provide explanatory notes; for example, *Verbal Notes and Sketches for Marine Engineer Officers* by J.W.M. Sothern, which was first published before 1900. More operating companies existed in the heritage railway sector, which had developed information and guidance on safety practices that was issued by the Office of Rail and Road[23] and the Heritage Railway Association[24].

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[21] A certificate issued to a shipping company that complied with the requirements of the ISM Code.

[22] The COVID-19 pandemic severely disrupted operations in early 2020. WEL sought to operate the vessel at the end of the 2020 season.

[23] https://www.orr.gov.uk/about/who-we-work-with/railway-networks/minor-heritage-railways

[24] https://www.hra.uk.com/storage/HGR-A0000%20Guidance%20on%20Minor%20Railways.pdf

1.13 PREVIOUS ACCIDENTS INVOLVING WAVERLEY EXCURSIONS LIMITED VESSELS *WAVERLEY* AND *BALMORAL*

In August 2017, *Waverley* made contact with the pier at Rothesay in the Firth of Clyde because the on-watch engineer mistakenly operated the engine ahead rather than astern during the vessel's departure. No MAIB investigation was conducted.

In June 2009, *Waverley* made heavy contact with Dunoon pier due to insufficient allowance for the leeway and tidal stream. No MAIB investigation was conducted.

In July 2006, *Waverley* grounded briefly on departure from Girvan Harbour, Scotland (the MAIB completed a preliminary assessment[25]) during a lower than predicted tide that had not been registered due to the absence of a tide gauge.

In October 2004, the WEL passenger vessel *Balmoral* grounded on the Dagger Reef, Gower Peninsula, Wales (MAIB Report 14/2005[26]). WSN and WEL were jointly recommended to:

2005/176 *Establish proactive control measures to assure all WEL staff comply with the procedures contained in the company's safety management system.*

2005/177 *Review shipboard emergency procedures to ensure that timely and accurate information is given to passengers during an emergency.*

In June 2004, *Waverley* grounded on the edge of Boiler Reef, south of Sanda Island, Scotland (MAIB report 1/2005[27]). The vessel was damaged but remained watertight. Because of a subsequent accident, WEL was recommended[28] in a letter from the Chief Inspector of Marine Accidents to:

> *Conduct a comprehensive risk assessment of the company's navigational policies and procedures. This risk assessment should include, but not be limited to, the company's instructions to Masters, the suitability of the navigational equipment outfit on both vessels, an assessment of the capabilities of all navigational watchkeepers, including masters, and the effectiveness of current bridge team practices. The ability of ship's staff to deal with likely emergency scenarios should also be properly evaluated, especially with respect to the care and safety of passengers. Corrective action should be completed before further passengers are carried.*

The MAIB made further recommendations to WEL to:

2005/101 *Require that all voyages undertaken by its vessels are planned and conducted in accordance with requirements of SOLAS V and IMO guidance.*

2005/102 *Ensure that all navigational procedures are validated by a person with relevant training and experience, and that these procedures are then audited to the required standard.*

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[25] https://www.gov.uk/maib-reports/grounding-of-paddle-steamer-passenger-vessel-waverley-while-departing-girvan-harbour-scotland

[26] https://www.gov.uk/maib-reports/grounding-of-passenger-vessel-balmoral-on-dagger-reef-off-the-gower-peninsula-wales

[27] https://www.gov.uk/maib-reports/grounding-of-paddle-steamer-passenger-vessel-waverley-on-reef-near-sanda-island-off-the-west-coast-of-scotland

[28] MAIB recommendation 2004/243, issued 8 November 2004.

SECTION 2 – ANALYSIS

2.1 AIM

The purpose of the analysis is to determine the contributory causes and circumstances of the accident as a basis for making recommendations to prevent similar accidents occurring in the future.

2.2 OVERVIEW

Waverley made heavy contact with the closed end of Brodick pier because astern propulsion was not achieved within the expected timeframe as part of the intended arrival procedure. Twenty-four people sustained cuts and bruises, three of whom suffered serious back and pelvis injuries caused by contact with the vessel's structures. The propulsion delay was caused by the engine stopping in the dead centre position. The analysis will assess the factors that contributed to the accident and the crew's emergency preparedness.

Due to the nuances of crank position, engine speed, steam input, paddle wheel momentum and the timing of valve movements, the post-accident trials were unable to replicate the HP piston dead centre event.

2.3 ENGINE PERFORMANCE AND CONTROL

2.3.1 Chief engineer experience

The C/E was aware that a HP piston dead centre event could occur that would prevent steam flowing through the engine (see 1.8.5) but did not expect it to happen on the day of the accident and only became aware of a problem when the engine did not operate astern as ordered. The engine stopping in a dead centre position was known to be a possible outcome for this type of engine, but the C/E had not experienced it during a berthing manoeuvre. As WEL had neither captured dead centre events in its company instructions or procedures nor formally trained the crew in how to respond to them, the C/E's response to the event was not fast enough to prevent the vessel making contact with the pier.

2.3.2 Response to high-pressure piston dead centre event

More experienced engineers were attuned to the possibility of a dead centre event occurring as the engine slowed. Although not formally recorded, the accepted onboard practice was to keep the engine in motion, though this was not possible when its direction of rotation had to be changed. If the engine did stop with the HP piston in the dead centre position, the engine design allowed the admission of impulse steam into either the MP or LP cylinders. The crankshaft would then rotate in the direction most favourable to the crank angle, moving the HP piston off its dead centre position. The impulse steam would then be stopped, and steam readmitted into the HP cylinder to cause the crankshaft to rotate in the desired direction. The C/E was most likely unaware that the HP piston valve had slackened, and that the subsequent effect on the engine timing would make moving from a HP top dead centre position difficult as more steam than normal was allowed into the cylinder in advance of top dead centre to provide 'cushioning' of the piston. This condition was peculiar to inclined steam engines where the top of the engine was below the crankshaft.

The C/E applied impulse steam to the MP cylinder in an attempt to rotate the engine crankshaft sufficiently to try to move the HP piston from the dead centre position to restore propulsion. This procedure was typical of reciprocating engines and operators should be made aware of the recovery procedure. However, it was ineffective in this instance because:

- The engine timing was affected by the slack HP piston valve rod, allowing steam to enter or leave the HP cylinder either too early or too late in the propulsion cycle; and
- The ahead rotation force on the paddle wheels generated by *Waverley*'s forward movement through the water counteracted the effect of the impulse steam.

To overcome these issues, the C/E needed to have been trained to monitor the position of the pistons and pre-emptively apply more steam pressure to keep the engine in motion. This would have been difficult to achieve as the engine's rotation was being changed and the issues above made it difficult to predict the piston's stopping position.

2.3.3 Anticipating and preventing dead centre events

The crew on board *Waverley* at the time of the accident were aware of the HP piston having stopped dead centre only once before when the vessel was in open sea. A dead centre event was not considered critical to the safe operation of *Waverley* in situations where the risk of collision was absent, for example when changing direction or speed during passage. There was no documented risk assessment for a dead centre event while undertaking berthing manoeuvres in a closed berth, its likelihood had not been assessed, and no additional mitigation measures had been identified to help reduce the risk of a grounding or collision. In normal circumstances, avoiding top dead centre events was aided by the pull of the vacuum on the LP piston as well as the appropriate use of the impulse steam on the MP or LP cylinders to keep the crankshaft in motion.

2.4 MACHINERY MAINTENANCE

2.4.1 Maintenance guidance and knowledge

Waverley's maintenance was planned around the cycle of MCA machinery and vessel inspections and the vessel's operating season. In the absence of OEM guidance, maintenance activities relied heavily on the accumulated knowledge and expertise of *Waverley*'s engineers and superintendents. This, in turn, depended upon the company employing and retaining staff who had operational knowledge of the vessel.

In late 2016, many of the experienced engineering personnel left WEL. The C/E's handover notes were misplaced during a turnover of senior engineering personnel the following year, resulting in the further loss of specific engine maintenance information and knowledge.

The resultant lack of corporate knowledge was exacerbated by the absence of a formal, documented PMS within WEL, as demonstrated by the purchase of the incorrect piston valve rings in 2015. At the time of the accident, *Waverley* was operating under an Interim SMC and WEL was in the process of addressing the partially documented maintenance guidance. Although WEL's lack of engineering experience, knowledge and procedures had been recognised, the vessel re-entered service with inexperienced crew and worn machinery.

2.5 ENGINEER TRAINING AND EXPERIENCE

The practice for new and inexperienced engineering crew on board *Waverley* was to learn on-the-job, with little documented training provided beyond the safety induction and the management of specific hazards such as a fire on board. The crew were supervised by other employees and volunteers while they learned, but there was no formal process to develop skills and knowledge. Training was therefore reliant on the supervision and assurance provided by more experienced people, which became limited following the departure of many engineering department personnel in 2016/2017.

Engineers with appropriate steam certification and experience were recruited by WEL to address the loss of engineering expertise. Some engine operation and maintenance information was available to the new recruits, but this was not organised in a structured and centralised manner. There was no method to capture the fundamental engine characteristics and skills that the crew needed to be familiar with to reduce the risks of or to manage a dead centre event.

Many heritage organisations depend on the retention of skilled, knowledgeable, experienced personnel to operate their vessels. To do so safely, it is essential to capture relevant information that supports people to gain the knowledge necessary. The SMS must reflect how this information is captured, retained and delivered.

2.6 BERTHING AND CONTROL

2.6.1 Closed-end piers

The closed-end Brodick pier limited the sea room available for a vessel to stop, turn or reverse to in the event of an aborted approach.

The berthing of *Waverley* was affected because:

- The vessel's large turning circle required an early decision to abort an approach to a closed-end berth.
- The paddle wheel propulsion resulted in bespoke handling characteristics;
- The engine was controlled manually; and,
- A high vessel speed was required to maintain steerage on approach to a berth.

2.6.2 Berthing risk assessment and passage planning

In response to an earlier MAIB recommendation the Piers Book provided guidance on the waypoints to be followed for certain passages. However, on the day of the accident there was neither a detailed berth-to-berth navigation plan nor a full appreciation of the risks associated with berthing at a closed-end pier.

Waverley had successfully docked 29 times at the new Brodick pier and the C/E operating the controls at the time of the accident had been at the controls during arrival and departure the previous week. The crew were practised in berthing at Brodick.

The manual handling characteristics of *Waverley* required careful control of speed and engine state during berthing manoeuvres and the on-watch engineer was vital to any change in the provision of propulsion. The combination of these two factors increased the importance of thoroughly assessing the operational risks at each berth and adopting suitable control measures where increased risks of collision or grounding were identified.

2.7 EMERGENCY PREPAREDNESS

At the time of impact *Waverley*'s passengers were in various locations around the vessel, and many were standing. No impact warning or instruction to brace was broadcast and 24 of the passengers and crew were injured. This number might have been smaller had sufficient warning been given.

When it became evident that the engine response to go astern was compromised there was little time to warn passengers that contact with the pier was imminent. However, it was foreseeable, given the need for *Waverley* to maintain steerage speed when approaching a closed-end berth, that any delay in achieving astern propulsion would likely result in an impact. An assessment of the characteristics of each closed-end berth used by *Waverley* might have identified those with an increased risk of low-warning impact so appropriate mitigation measures could be implemented, such as instructing passengers to remain seated until the vessel was safely alongside.

Despite the lack of warning, *Waverley*'s crew immediately reassured passengers after the accident and the injured were swiftly attended to.

SECTION 3 – CONCLUSIONS

3.1 SAFETY ISSUES DIRECTLY CONTRIBUTING TO THE ACCIDENT THAT HAVE BEEN ADDRESSED OR RESULTED IN RECOMMENDATIONS

1. The accident happened because astern propulsion was not achieved as *Waverley* approached the closed-end pier at Brodick. [2.2]

2. Astern propulsion was not achieved because when *Waverley*'s engine was stopped the HP piston came to a halt at dead centre, which prevented the transition of propulsion from ahead to astern. [2.3.2]

3. The potential for *Waverley*'s HP piston to stop at dead centre was a known possibility that had not been effectively risk assessed. [2.3.1]

4. The ability for *Waverley*'s steam engine to provide astern propulsion was affected by factors that included worn or incorrectly adjusted system components and an inability to reliably predict a dead centre event. [2.3.2]

5. The specific skills and techniques needed to recognise and avoid the potential for a dead centre event were neither formally documented within *Waverley*'s SMS nor included in training. [2.3]

6. The rectification of worn or incorrectly adjusted components was dependent on engineering knowledge and experience. The loss of WEL's engineering expertise in the years preceding the accident led to maintenance being undertaken with insufficient knowledge. [2.4]

7. Training on *Waverley*'s steam machinery relied on supervision and assurance provided by a limited number of experienced people. [2.5]

8. *Waverley*'s operational risk assessments did not effectively cover the hazards posed by manual control of the engine and the engine stopping dead centre during berthing manoeuvres. [2.6]

9. An assessment of the characteristics of each closed-end berth used by *Waverley* might have identified those with an increased risk of low-warning impact so appropriate mitigation measures could be implemented, such as instructing passengers to remain seated until the vessel was safely alongside. [2.7]

SECTION 4 – ACTION TAKEN

4.1 ACTIONS TAKEN BY OTHER ORGANISATIONS

Waverley Excursions Limited has:

- Reviewed its SMS and:
    - With the assistance of other heritage/conservation societies, devised and implemented a formalised training regime for engine and deck crew resulting in the development of formal competency-based heritage vessel training and development programmes, including bespoke training days at sea without passengers.
    - Revised the risk assessment process and SMS templates for all company operations, with relevant crew involved.
    - Incorporated elements into the SMS to encourage feedback from staff when mistakes occur; outlined how the organisation intends to learn effectively from adverse events; and, clarified individual safety responsibilities throughout the organisation.
    - Required all berthing and pier-related activities to be fully risk assessed before *Waverley* visits a berth.
    - Established passenger safety procedures and drills that include specific procedures for multiple casualty accidents; amended emergency checklists and added awareness of sudden movements while berthing to the passenger safety briefings.
    - Improved the berthing-related hazard information available to the bridge crew in the Piers Book.
    - Introduced crew briefing procedures ahead of berthing and standardised its briefing material, including updating incident checklists.
    - Revised the drills matrix to include multiple casualty events; provided paramedic-led training to assist the crew in casualty triage; and conducted live passenger evacuation drills.
- Conducted a technical evaluation of all safety-critical engine components to ensure they operate within the expected parameters.
- Appointed a technical superintendent experienced in *Waverley*'s operation and engineering to support the operations director to oversee engineering training and competency development through the heritage programme. As a previous C/E the technical superintendent is also able to advise on maintenance issues.
- Recruited additional permanent staff, including a master and C/E, to ensure skilled and knowledgeable crew are available throughout *Waverley*'s operational season.
- Developed and implemented, with MCA oversight, a bespoke planned maintenance software system to support engine maintenance.

- Increased spares holdings to ensure that adequate spare machinery components are available on board to cover all maintenance operations when at sea.

- Increased the minimum bridge officer manning to three, to support the master in emergency events and serve as an additional leadership resource during operations.

- Conducted regular sea trials to develop engine operator performance criteria and competency assessments, team training and berthing trials.

- Reviewed supervision and recording of engine movements (Bell Book) and installed a camera to record engine control movements to assist in incident investigation.

SECTION 5 – RECOMMENDATIONS

In view of the actions already taken and the time elapsed since the accident, no recommendations have been made.

Annex A

P.S. Waverley Machinery Layout leaflet

P.S WAVERLEY MACHINERY LAYOUT

Built and installed by Rankin & Blackmore, Eagle Foundry, Greenock

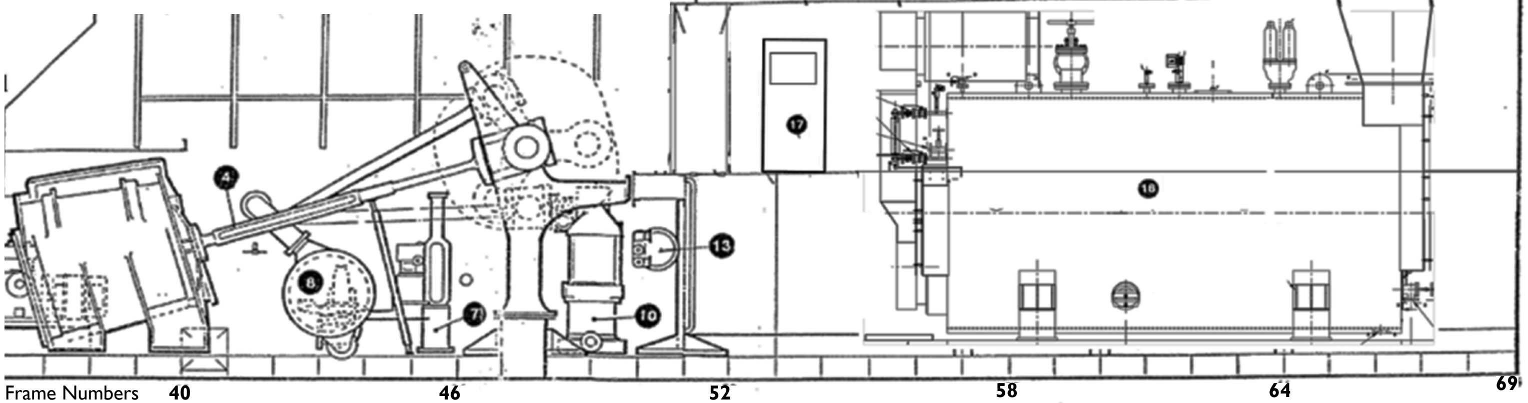
BOILERS

3 pass wetback reversal chamber built and designed by Cochran of Annan, installed April 2020 during the Boiler Refit.
Fuel: Marine Gas Oil, Pressure: 180 psi, Output: 22500 lbs/hr, 105" dia X 199" long Steel barrel. 184 X 2" dia Steel tubes. Welded with rolled in fire tubes construction, condensing, forced draft fan, steam feed pump, electric feed pump, feed water heater, whistle, Originally fitted with a double ended Scotch boiler, this was replaced in 1981 with a Babcock Steambloc boiler.

MAIN ENGINE

Diagonal Triple Expansion. 24" + 39" + 62" X 66". Built 1947 by Rankin & Blackmore Ltd. at Greenock Design: Paddle Inside PV on HP. Outside PV on M.P. Bal SV on LP valve. Stephenson valve gear. Power: 2100 HP Engine Number 520. Normal service speed of 13 knots at 44 rpm. Maximum speed 18 knots at 57 rpm. Shell and tube surface condenser. Full set of steam auxiliaries.

1. High Pressure cylinder with inside-admission piston valve.
2. Medium pressure cylinder with outside-admission piston valve
3. Low pressure cylinder with Andrews & Cameron balanced slide valve
4. Crosshead slide bars with grease-retaining rings
5. Port paddle shaft
6. Built-up pattern crank-shaft, with cranks set at 120° relative angle
7. Brown Bros. steam-hydraulic reversing engine
8. Condenser, wherein sea water cools and condenses the exhaust steam
9. Centrifugal condenser-circulating pump by Drysdale, Yoker, Glasgow
10. 24" diameter Weir "Mono" air pump, drawing condensate from the condenser
11. Electric Condenser Cooling pump
12. Direct acting Weir boiler feed pumps, with ditto stand-by
13. Feed water heater, Weir manufacture
14. Electric Feed Pump
15. Fire & General service pump by Dawson & Downie, Clydebank
16. General service pump by Dawson & Downie
17. Boiler Control Panels
18. 2 x Cochran ST 36 Triple Class Boilers 10,766 Kg/Hr, 12.4 BarG, Saturated Steam
19. Stephenson Link Valve Gear
20. Port Gen, Port Main, Starboard Main and Starboard Gen Fuel Tanks 40,000 litres MGO
21. 2 x Caterpillar C 7.1 Diesel Alternators - each producing 118 KW, 415V, 50Hz
22. Caterpillar C 4.4 Diesel Alternator producing 86 KW, 415 V, 50 Hz
23. Victor Marine 15 ppm Oily Water Separator
24. MCA Approved Sewage Treatment Plant



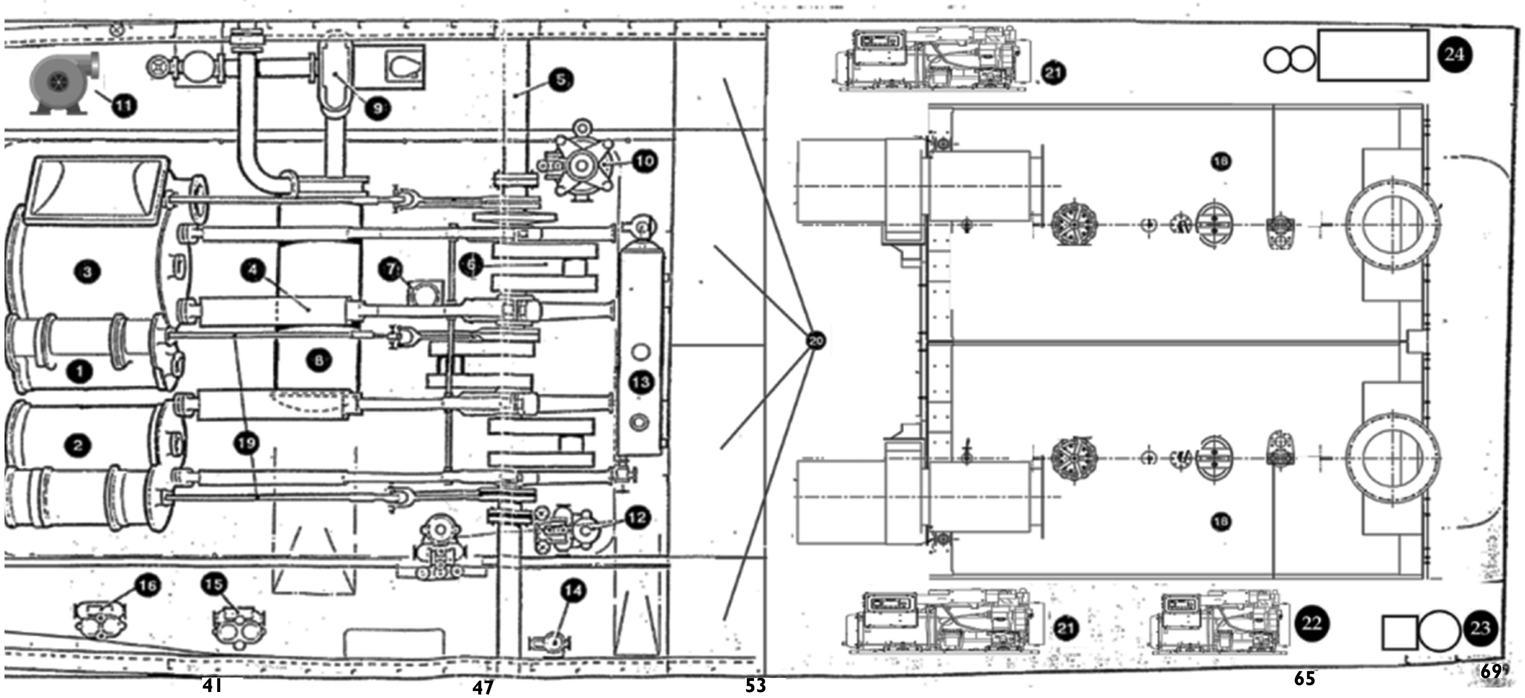


Image courtesy of Waverley Excursions Limited

Image courtesy of Waverley Excursions Limited

How it works

Waverley was launched on 2nd October 1946 at the former A. & J. Inglis yard on the Clyde by Lady Matthews, the wife of the chairman of the London & North Eastern Railway Company. The steamer is 239.6 feet long and 30 feet broad (excluding the paddleboxes), with a tonnage of 693 gross and 327 net. Her triple expansion diagonal steam reciprocating engine was built by Rankin & Blackmore, of the Eagle Foundry, Greenock, and is direct acting on to the two paddle wheels.

The engine is 2100 I.H.P. (Indicated Horse Power) and has three cylinders through which the steam passes progressively. The High Pressure (H.P.) cylinder is 24 inches in diameter, the Medium Pressure (M.P.) 39 inches and the Low Pressure (L.P.) 62 inches. All three cylinders are double-acting, which means that the piston is first pushed up the bore by the steam entering at the lower end, and then it is pushed back down by steam entering at the top end. The stroke of the three pistons is 66 inches, and the valves controlling the inlet and exhaust of steam through the cylinders are operated by Stephenson Link Valve Gear. The H.P. and M.P valves are piston type, and the L.P. is a slide valve.

Steam comes from the boiler by the large lagged pipe which runs almost the full length of the engine room. This leads to the Regulating Valve, which controls the entry of steam to the H.P. cylinder, and hence the speed of the ship. The other levers, in order from right to left, are the cylinder drain valves for the M.P., H.P. and L.P. cylinders, the starting valve (or "monkey valve") lever which can direct high pressure steam into the M.P. and L.P. cylinders, and on the extreme left the reversing gear lever. For running astern each cylinder has a second eccentric on the crankshaft, and when the reversing gear is operated this is made to control the timing of the cylinder valves. The engineer moving the reversing lever forwards (ahead) or backwards (astern) operates a steam servo unit which moves the heavy gear more easily.

Facing the engineer at the controls is the Telegraph, by which orders from the Bridge are transmitted, and the gauge-board, which indicates the pressure in the Main Steam Line and in each of the cylinders, and also the degree of vacuum in the condensers. At the normal " full ahead" setting, the pressure is approximately 180 lb. per square inch (p.s.i.) in the H.P. cylinder, 50 p.s.i. in the M.P. and 3 p.s.i. in the L.P..

Exhaust steam passes through the condenser – the large cylinder mounted transversely on the ship's bottom beneath the engine. Brass tubes inside the condenser are cooled by sea water and this condenses the exhaust steam back into the water, thus creating a vacuum in the L.P. cylinder so that the maximum possible power is obtained from the steam. This water, called the condensate, is pumped back into the boiler, where it is converted into steam again. On the way, it passes through the Feed Water Heater which is heated by the exhaust steam from the auxiliary machinery, resulting in further economy. The boiler water is thus recycled continuously, and this reduced to a minimum the topping-up of fresh water supplied on board.

Waverley's original boiler was a coal fired Scotch Type Double-ended boiler, with three furnaces at each end at first, but it was converted to oil firing in 1957. This boiler was replaced in 1981 with a Babcock Steambloc boiler at a cost of more than £200,000. Grants for this important milestone in the ship's career came from the Scottish Tourist Board and many local authorities, but a large proportion of the money was raised by the Paddle Steamer Preservation Society.

The 1981 boiler had only two furnaces with one burner in each. They were rotary cup burners, which means that the cups through which the oil is pumped were rotating, and sprayed oil into the furnace. Air for these came from electric fans connected directly into each burner.

With the installation of the new boiler, a much larger electrical capacity was required. After much investigation, it was decided that two diesel generators were to be fitted. These were Caterpillar six-cylinder generating sets giving 110 kilowatts each at 440 volts. Transformers for 240 volts and 110 volts are required for lighting, fridges etc.

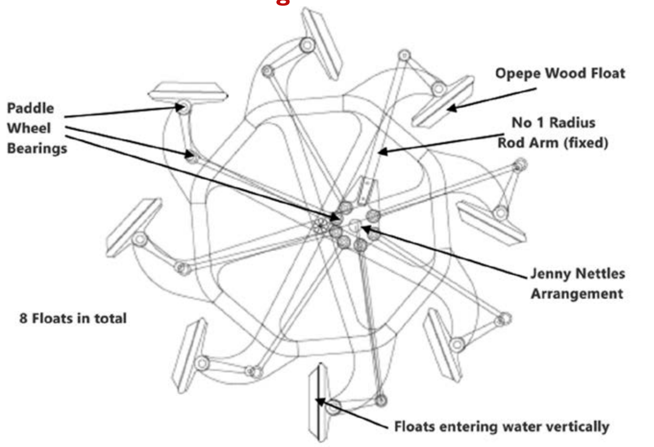
During the Heritage Rebuild in 2000 the Babcock Boiler was replaced with 2 Cochran Wet Back Fire Tube Boilers. On completion of the Heritage Rebuild, Waverley had 2 Scania 120 Kwe Diesel driven Alternators which replaced the 1981 Caterpillar engines.

During the Boiler Refit of 2020, where 2.3 million pounds was raised by public donations and a £1 million grant from the Scottish Government, two new Cochran ST36 Firetube Boilers were installed each giving a steam generation of 10,776 kg/hr at 12.4 Barg. Also, during this Refit, the Main and Emergency Switchboards were renewed, a Power Management System installed and two Main Diesel driven Caterpillar Alternators type C 7.1 developing 119 Kwe each and a Harbour Diesel driven Caterpillar Alternator type C 4.4 developing 86 Kwe was also installed giving the vessel additional electrical power for any future requirements. During the Winter Maintenance period from late October each Year till mid-May the following Year, electricity is supplied to the Vessel at Pacific Quay, Glasgow, by a shore power connection.

In 2020 the Bilge 15 ppm Oily Water Separator was renewed with a Victor Marine CS 500 OWS having a bilge throughput of 500 litres / hour. All of the Boiler Room insulation was renewed with MCA / Class approved Marine Insulation.

All of the original steam reciprocating feed pumps, air pump, general service and fire pumps and condenser circulating pump, which are originals from 1947, are still operating and in service. Out with the Engine Room the steam powered capstan and forward windlass / winch are still used daily during berthing operations when the vessel is in Passenger Service along with the steam powered steering engine which is a horizontal type with 2 steam cylinders.

Feathering Paddle Wheels



Waverley has two rimless paddle wheels, each with eight flat wooden floats, as were fitted to almost all paddlers of the L.N.E.R. and its predecessor, the North British Railway. Exceptions were *Marmion* (1906) and *Talisman* (1935) which were originally fitted with curved steel floats, although in both cases these were soon replaced. Also, *Jeanie Deans* (1931) had floats which, although wooden, were angled to give an approximately curved cross-section.

Waverley's wheels are 13 feet 10 inches in diameter across the pivots, giving an overall diameter of about 18 feet, and the floats are 11 feet long, 3 feet broad and 3 inches thick. The timber originally specified was Canadian Rock Elm, but this tree is now a protected species and supplies are unobtainable. After trials with many different types, an African hardwood called Opepe was selected, and is now in use.

The floats are pivoted near each end, and made to "feather" by an arrangement of rods rotating round a centre called the "star centre". The operation of this is entirely automatic, and it is designed so that each float enters and leaves the water as nearly vertical as possible, and remains so for all the time it is in the water. This created the minimum disturbance, and therefore uses the engine power as efficiently as possible.

£2.00

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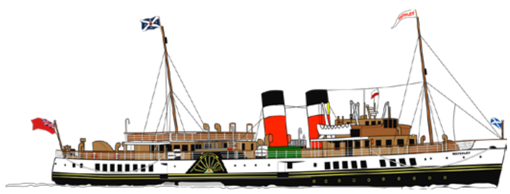
Paddle Steamer **WAVERLEY**

Machinery and paddle wheels

Drawings of Paddle Steamer Waverley's machinery and paddle wheels, with simple descriptions of how they work.



Waverley Excursions Limited Piers Book entry for Brodick

Brodick

General Description

Brodick is the main ferry port of the island of Arran. The pier itself is owned and managed by the ferry operator Caledonian MacBrayne. A ferry service runs at regular intervals throughout the day which causes very little disruption to our timetable. Very Well-built pier which is ideally suited to our operation.

Heading of Berth 206 Degrees true

Tidal Information

Tidal information

HT Required: ON FLOOD N/A m ON EBB N/Am

HT REQUIRED FOR BERTHING REFERENCENED AGAINST PORT OF: None

ADDITIONAL TIDAL INFO:

COMMUNICATIONS

PIER/BERTH CONTACT CALMAC : 01770302597 & PIER 01770302166

MOORING AND BERTHING PERMISSON ARRANGED THROUGH PORT MANAGER BEFORE ARRIVAL

ADDITIONAL NOTES FOR MASTERS

1. BERTH IS 110M LONG AND WELL FENDERED
2. EAST SIDE OF PIER IS EXPOSED TO EASTLERY WINDS AND SWELL
3. GREY BUILDING WITH BLUE DOORS IS OPEN ON FINAL APPROACH
4. VERY LITTLE TIDE
5. ALWAYS STARBOARD SIDE TO APPROACH
6. TIDAL RANGE 3.6M SPRING TIDE
7. KEEP PIER SLIGHTLY OPEN TO STARBOARD
8. 2M ABOVE CHART DATUM TOP GANGWAY LEVEL WITH PIER
9. 6M AT BERTH ABOVE CHART DATUM

Marine Accident Report

INVESTORS
IN PEOPLE