A Collaborative Approach to the Removal, Overhaul and Replacement of the Port and Starboard Electric Propulsion Motors on a T23 Duke Class Frigate

John Wood BSc (Hons), BEng (Hons) IEng IMarEST
Mark Sullivan MBA, BEngs (Hons), CEng CMarEng FIMarEST

Babcock International Group

Synopsis

The main propulsion drive on the T23 Duke Class Frigate is two DC Electric Motors connected permanently in line, one on each shaft. These unique motors are designed to enable the Class to perform lower speed manoeuvring, especially during their key operational tasking of anti-submarine warfare. Due to the significant capability the T23 has delivered, five ships were identified for a Life Extension (LIFEX) refit/revamp package; a massive joint undertaking by the Royal Navy and Babcock to add an extra decade to the life of the Fleet workhorses. Once in dry dock, and as part of pre-refit and LIFEX surveys, a unique defect was identified. This defect was associated with the port and starboard propulsion motors and was limited to two vessels of the Class. To rectify this defect, and assure the additional availability vital for the Royal Navy, both electric propulsion motors would need to be removed, overhauled and replaced. This presented Babcock Devonport with a major engineering, commercial and logistical challenge. With no formal motor removal and replacement process in existence, this placed significant technical focus into deriving a safe, efficient and repeatable solution for the Royal Navy. Resolution of the defect would involve determining the extent of the damage, the various repair options and the ultimate action necessary to deliver the extended life of the propulsion motors. The Babcock Warship Technical Authority (WTA), the MOD Representative at the waterfront in Devonport, was tasked to lead the development and implementation of a suitable repair method. Utilising established decision rights, the WTA was able to take responsibility for a multitude of lines of approval and sign-off activity on behalf of the T23 Warship Approval Authority (WAA) and Equipment Approving Authority (EAA). Very early on, as the repair gathered impetus, it was clear that to achieve success the collaboration required across all key Enterprise Stakeholders (WAA, WTA, EAA, Babcock Service Provider and Original Equipment Manufacturer (OEM)) would be significant. This paper outlines the situation, the courses of action to rectify the defect and the final solution chosen that would assure the continued use of the propulsion motors during the extended life of the T23 Class. It also touches upon the Enterprise approach to decisions and approvals that achieved crucial success and the Learning from Experience (LfE) identified for future projects.

Keywords: Babcock, Royal Navy, Warship Technical Authority, Duke Class, Type 23 Frigate, Electric Propulsion Motor.

Caveat

Due to the security classification, this report reflects only unclassified or public domain information that has been agreed by the Platform and Equipment Authorities and MOD Communications.

Authors' Biographies

John Wood is currently employed as a Senior Platform Systems Engineer at Devonport Warship Technical Authority. Previously he has worked on a number of projects including new-build and design for support tasking. Having served for over 30 years in the Royal Navy in a range of roles including propulsion engineer officer, John is an experienced Incorporated Engineer of the IMarEST.

Mark Sullivan is currently the Class Lead Engineer for T23s and Chief Engineer. Previously he was the Technical Director for a private renewables firm having served over 34 years in the Royal Navy in a range of senior operational, support and acquisition appointments. Mark is an experienced Chartered Engineer, Chartered Marine Engineer and Fellow of the IMarEST.

1. Introduction

The main propulsion motors of the Type 23 Frigates are ultra-low noise signature, open ventilated, nominal 750V DC 1500 kW machines. All manoeuvring, lower speed and astern operations are from these propulsion motors, which are a fixed and integral part of the shaft line. They are designed and manufactured under Lloyds Register Rules and Regulations for the Classification of Ships. As part of the preparations for a recent T23 Docking Period, key assets were surveyed as part of the Pre-Upkeep process. This included a check of the Propulsion Motors, which was conducted by the OEM. During the inspection it is usual to find that the motor armature and surrounding area have deposits of oil and carbon dust which can be removed by cleaning. However, the inspection also noted degradation of the insulation to the forward coil support rings on both motors, which resulted in repair options and subsequent action to bring the motors back to within design intent. This level of overhaul had never been undertaken before and the methods required to facilitate this task needed to be devised and approved.

2. Background

The motor armature is wound to Class F (BS 2757), the armature coils extending from the core are clamped in a manner to react to the mechanical force and stop any cyclic movement due to electro-magnetic forces. Without mechanical clamping, it is likely that the copper would suffer from work-hardening and fretting of the insulation, which would lead to premature failure. The banding not only locates the insulation but also imparts a retained hoop stress suitable to maintain a full shock capability.

Large clamping forces are achieved by using high-tensile epoxy banding which retains a very high hoop stress. The support ring is fully insulated to eliminate any electrical tracking pathway and has a bed of insulation packing to react to the radial clamping force created by the banding. The banding system, which was tested during OEM Factory Acceptance Testing and included an overspeed test, compresses the coil end winding overhang on to the support ring. The ring is spaced away from the end of the armature core, such that a flow of cooling air can be provided to the end winding slot entry.

The mainpoles and compoles, at Figure 1, are located around the armature and have set gaps which are crucial to correct motor operation. The motor has no inbuilt bearings and is reliant on the alignment of the gearbox quill bearings and the forward plummer block to maintain the required airgap. Variations in this airgap will influence the motor in terms of noise, commutation and thermal performance.

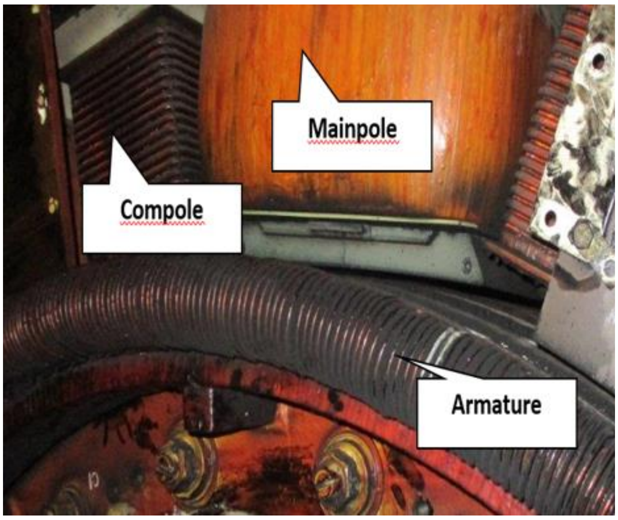


Figure 1 - Mainpole and Compole

3. OEM Survey Report

The inspection report noted that there was serious degradation with the insulation on the forward coil support ring. The insulation had split in a number of areas around the ring and the insulation packing was also migrating in several places. One of the damaged insulation sections was removed from the starboard motor and found to have migrated to such an extent that it was completely off the coil support ring. It was also noted that there was only a small amount of carbon dust contaminating the insulation, indicating that this movement was recent.

The report concluded that there was very little of the insulation still on the coil support rings, significantly reducing the insulation thickness between the coils and the support ring. This would heighten the risk of a major failure occurring with potentially extensive damage to the motor. The released packing can be seen in Figure 2.

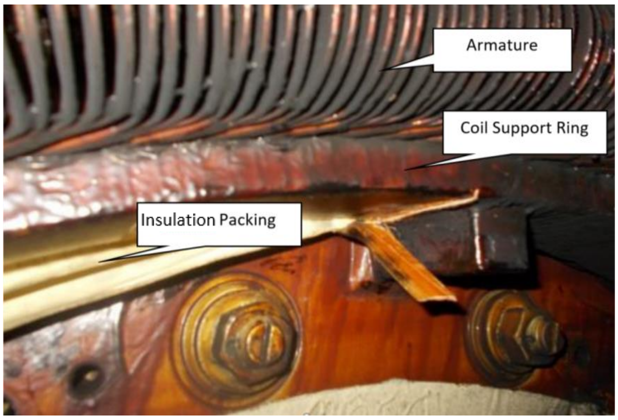


Figure 2 - Insulation Packing Detail

3.1 Report Impact

The outcome of the report had serious consequences to the ship repair schedule, subsequent future availability and required prompt action. As part of the Enterprise approach, the lead to devise a solution was the WTA in Devonport and within the first few weeks a number of concurrent actions were undertaken.

A DC Motor specialist was requested to carry out an independent review of the Technical Report and undertake an inspection of the damage to the motors. Whilst agreeing with the report's conclusions, the specialist recommended that an in-situ repair was investigated. Five large electrical motor repairers were also individually briefed and asked for independent technical assessments to ascertain what repair options could be carried out. The following observations were made:

- No damage was found on the rear support ring. This indicated that banding release on the front ring was caused by high temperature; a slight blockage in the air cooling duct could have worsened this effect.
- Analysis by the OEM of the packing sample removed indicated that sound manufacturing processes were followed.
- Due to the declination of the propeller shaft line, the motors could not be lifted vertically without risking damage to the motors. A motor removal and replacement option would have to include movement of the shaft line.
- There are no bearings in the motors, the motor is supported either side by the shaft line. Any repair would have to include support of the motor.
- If the motors were to be removed, each would need to be locked in place following OEM direction, beyond this point the shaft line could not be turned.
- To assure the repair, it would be necessary to test both motors together.
- Motor concentricity should be checked throughout and would have to be exactly restored post-repair.

3.2 Repair Options and Assessment

With this knowledge, and the fact that there were no existing methods to remove the propulsion motors, several repair options were generated by the WTA for consideration.

1. **Do Nothing**
   This option would leave both motors unserviceable and render the vessel out of action. **Not considered further.**

2. **Replace Both Motors from a Donor Ship**
   A donor ship would have to be identified and docked to allow removal of the shaft lines and motors, this would double the activity necessary to remove, repair and replace the motors. All T23 propulsion motors are a bespoke fit for the life of the platform. Additionally, the motor is an integral part of the shaft line that rotates continuously; to install different motors would require line boring of the motor coupling fastening holes to provide new, matched sleeves and bolts. This is a challenging and time-consuming deliverable. The T23 Class is an Anti-Submarine Frigate therefore individual motor signatures are important. It is sometimes necessary to carry out a motor commutator skim and, as well as identifying

how much commutator copper is left, the wider material state and remaining life would have to be investigated. **Not considered further.**

3. **Carry out a Local In-Situ Repair within the Motor Gear Room (MGR)**
This local banding repair carried high risk with Design Intent not being restored. After the repair there would be no way of completing comprehensive tests and trials until the ship was at sea; this level of repair could also potentially degrade shock and overspeed performance. Any in-situ repair would require strict environmental and personnel control which would severely hamper other upkeep work in the MGR and impact ship availability down the line. **Not considered further.**

4. **Carry out a full in-situ repair within the MGR**
This option entailed a tandem repair to both motors to reduce overall time and attracted high risk and practical difficulties. A full in-situ repair includes the separation and lifting of the motor frames and armature, stripping of the old windings, removal of insulation, cleaning, re-establishment of the high-tensile banding, rewinding the armature and application and curing of varnish within the MGR. The processes and tools to undertake these activities needed development. The motors would be extremely dirty and during disassembly mica and insulation dust can be very dangerous for personnel and mechanical/lubrication systems; therefore the protection of personnel and equipment in the MGR would require significant effort. Following a risk and environmental impact assessment, it was identified that the resultant dust and use of highly volatile chemicals would close the MGR to any other activity, impacting the schedule significantly. Finally, there was no facility to conduct test and commissioning that would match the original Factory Acceptance Tests. **Not considered further.**

5. **Overhaul Both Motors at a Repair Facility; Remove, Repair and Replace**
This entailed removing both motors for repair to a controlled environment where quality and established controls and processes were in place. This option would also enable full testing of the motors including overspeed and back to back testing, whilst enabling a thorough forensic analysis to determine the root cause of failure. There were no processes in place for the removal of the motors from the MGR and this work would need to be completed. This option represented the lowest risk and highest likelihood of continued reliability for the remaining life of the platform. **This was the WTA recommended option.**

Option 5 - to remove, repair and replace the propulsion motors - was approved by the Enterprise

3.3 Option 5 Risks and Opportunities

There were a number of risks and opportunities that were considered as part of the repair process and these were reviewed throughout. In summary:

3.3.1 Risks

- Novelty of the repair; this task had never been carried out previously.
- Non-standard construction of the DC motor – an ultra-low noise machine.
- Support equipment required to remove and replace the motors.
- Limited spatial envelopes around the motors and during removal.
- Motors could be damaged during removal and replacement.
- Incorrect re-alignment of the propeller shafts.
- Industry SQEP capacity.
- Enthusiasm bias – a can-do attitude at all costs.
- Lack of a robust repair specification.
- Impact to other equipment and systems within the compartment.
- Structural integrity due to the size of the hull opening to be cut to remove the motors.

3.3.2 Opportunities

- Armatures and fields windings will be returned to an as built condition.
- The Hopkinson Test will prove motors at full power and check temperature rise characteristics.
- Root Cause Analysis would be undertaken and can be applied across the T23 community.
- Deeper understanding of motor characteristics

Through a commercially stringent competitive selection process the **OEM was selected as the repairer**.

4. Systems Engineering

Almost all engineering projects follow a similar approach, starting with the definition of high-level customer requirements and cascading through to verification and validation, and was the case with the motor repair. A V-diagram in Figure 3 graphically displays the prepare-repair-test process. The left-hand side represents the decomposition of requirements and specifications and the right-hand side the integration and validation process.

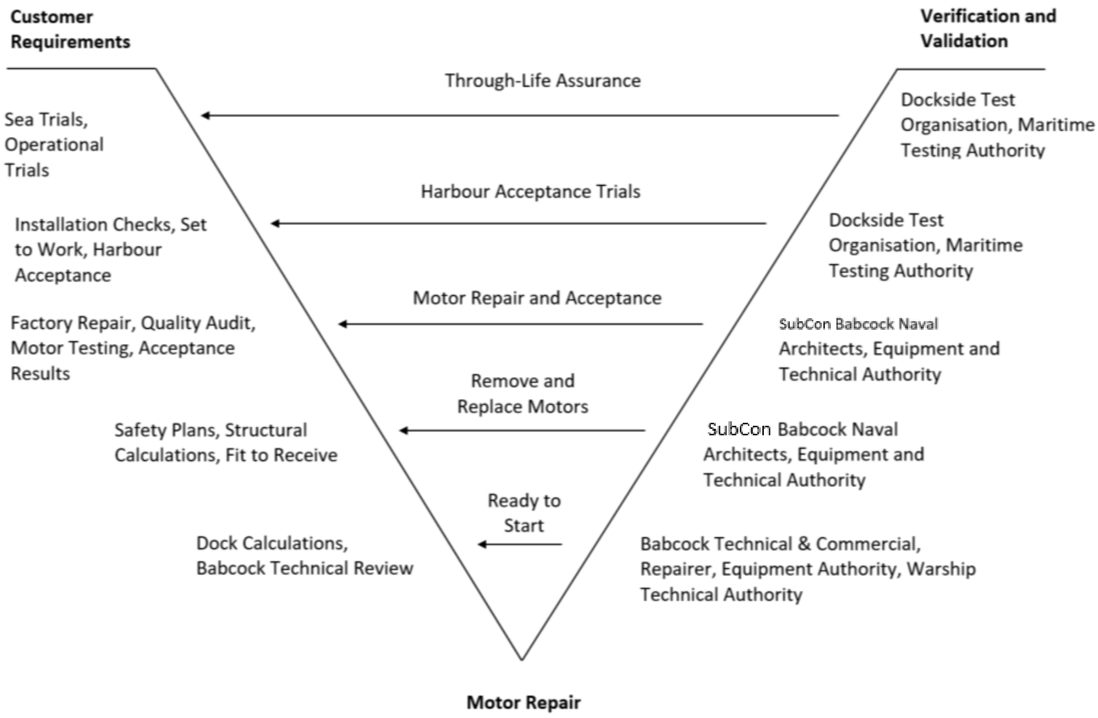


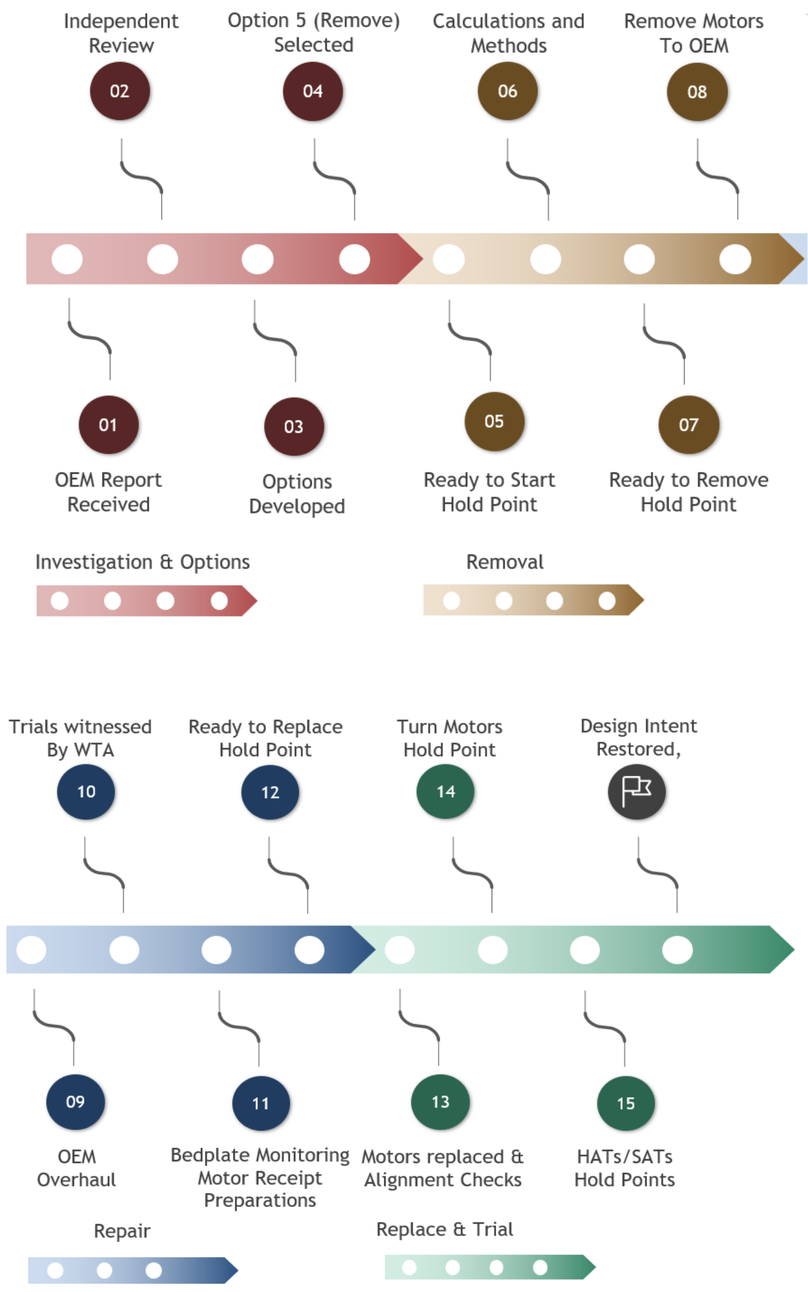
Figure 3 - V Model for Motor Repair

As preparations to remove the motors continued, a repair schedule was developed using six Hold Point Reviews. Each review would include all Enterprise stakeholders with clear Responsible, Accountable, Supported, Consulted and Informed (RASCI) matrices developed. The six stages were;

- Ready to Start,
- Ready to Remove,
- Ready to Replace,
- Turn Motors on Turning Gear,
- Harbour Acceptance Trials
- Sea Acceptance Trials.

The timescale was taut; from initial report of the problem until the motors were removed from the vessel took approximately four months. As most of the manufacturing had taken place over twenty years ago, a lot of previous machining techniques had to be re-learnt and machining jigs developed. The motor repair took approximately nine months, and as these are unique motors the test and trials took 4 weeks to complete.

A summary of the actions to recover design intent are in Figure 4 a and b.



(a)

(b)

Figure 4 – (a and b) Motor Repair Activity

5. Removal

5.1 Preparations

Whilst selection of the repairer was progressing through technical and commercial checks, Babcock faced the challenge of how to remove and replace the motors. Although large engine and equipment changes are regularly undertaken at Devonport, these activities have proven lifting equipment and fully developed Risk Assessments and Method Statements. The propulsion motors had never been removed and there were no supporting method statements.

Babcock Naval Architects carried out a technical assessment concluding that removing the motors, by cutting access through the ship side, would not permanently deform the structure. As part of the refit, Babcock were undertaking other major Platform upgrades, including an extensive Power Generation and Machinery Controls Upgrade (PGMU). Most of the heavy lifting was being undertaken by a single lifting specialist and it was decided to contract this specialist for continuity.

It is interesting to compare the build methodology for a T23 with the issues that were being encountered in a live ship with Work in Way (WiW). The routine during build is at Figure 5 which shows the MGR Module with the two propulsion motors on their seats and the shaft line yet to be installed.

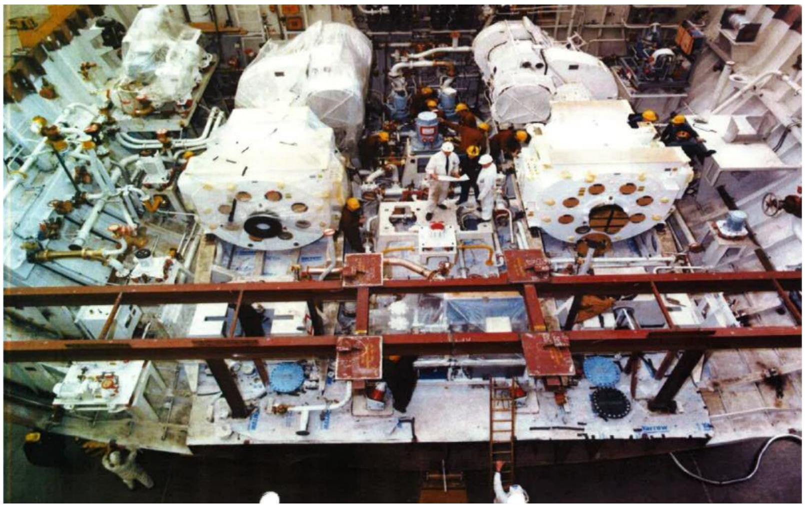


Figure 5 - T23 MGR Build Stage

The reality in service is all equipment and systems are installed with significant WiW barriers; a swept path analysis was undertaken to ensure that systems and equipment were accounted for and would not impact removal. The equipment and system preparations required to remove the motors is illustrated at Figure 6.

Figure 6 - T23 MGR

The removal route in Figure 7 involved traversing the motors across to the starboard side of the MGR and lowering them into the dock bottom.

- The motors were jacked from their position by approximately 0.5 m to achieve motor horizontal orientation and lowered onto pads.
- Two steel tracks were assembled, and the motors lowered onto these.
- Hydraulic rams operating within the tracks pushed the motors across the MGR and onto a platform outside of the ship.
- The motors were then lowered to the dock bottom and due to spatial constraints, transported to the end of the dock. Craneage lifted the motors from the dock floor and onto transport for delivery to the repairer.

With the OEM selected as the motor repairer, the motors were safely delivered to their factory.

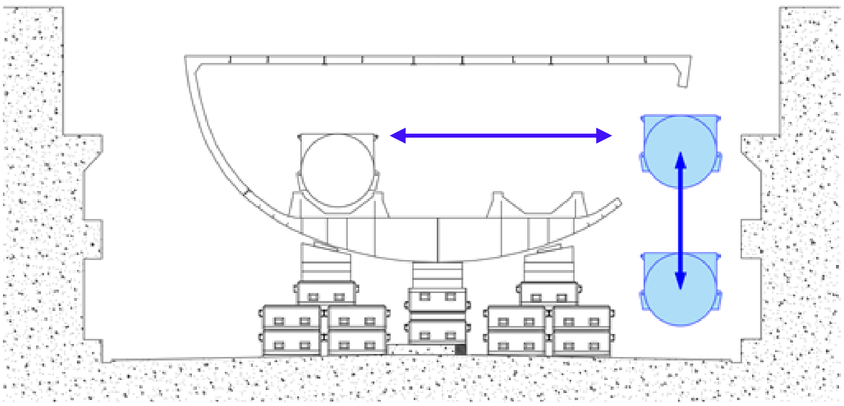


Figure 7 - Motor Removal Option

Figure 8 shows the starboard motor already removed and the port motor prepared for removal.

Figure 8 - Motor Prepared for Removal

Figure 9 highlights the limited clearance between the ship and dock side.

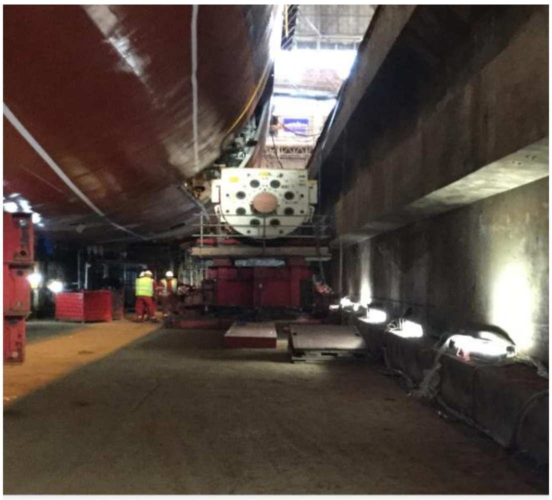


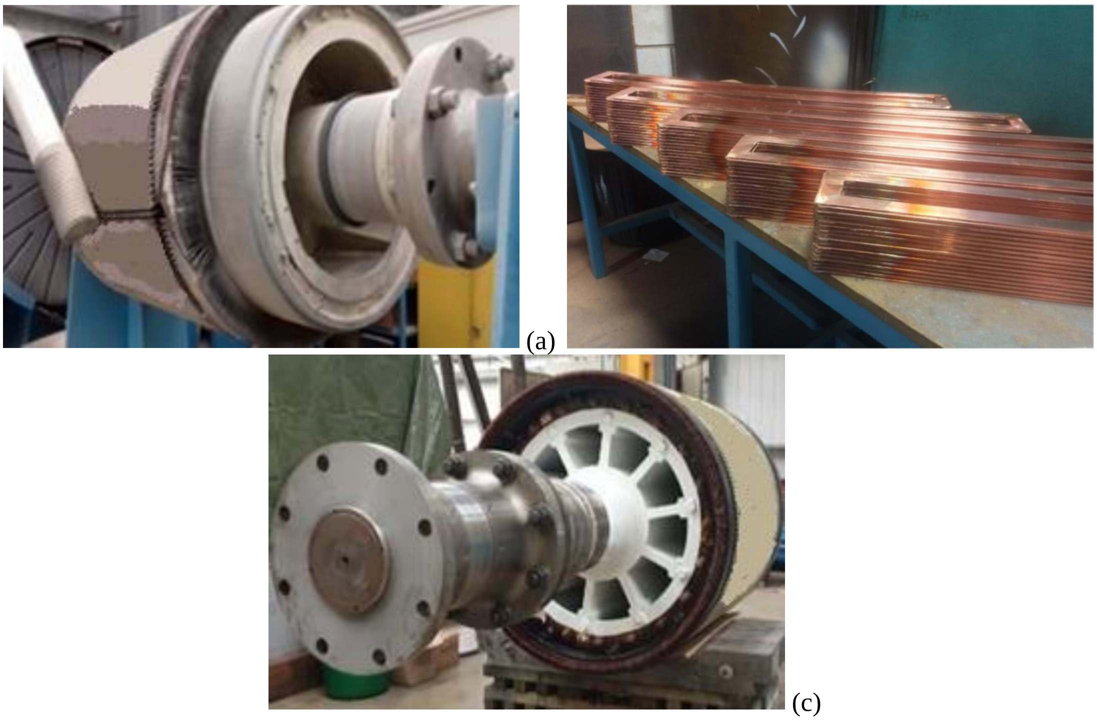
Figure 9 - Motor Removal

6. Repair

6.1 Strip and Restore

One of the key requirements was assurance that the motors would be restored to their Design Intent. The motors were heavily contaminated with oil and carbon dust, which is a known in service challenge and remedied with a regular cleaning regime. However, when the motors were delivered to the OEM's facilities the motor casings, which had not been removed for over 17 years, revealed further issues. These motors were the very first to be opened within the Class and revealed a distinctive debris pattern, that suggested that there was a loss of cooling air flow along the motor armature.

Post strip down, the re-assembly progressed with all line testing completed and reported. Some stages are shown in Figure 10 (a, b and c)



(a) (b) (c)

Figure 10 - (a) Armature Cleaning, (b) Compole Manufacture and (c) Armature Varnishing

6.2 Testing

The full testing procedure included, but was not limited to, the following:

- Resistance and IR Test Records
- Air Gap Test Records
- No Load and Full Load Speed Data, Light Run and Overspeed Test Records
- Full Load Temperature Rise (Heat Run) and Vibration Measurement Test Records

Figure 11 (a, b, c and d) shows the preparations for testing. Testing took approximately 3 weeks at the repair facility, which was attended by the WTA and the EAA.

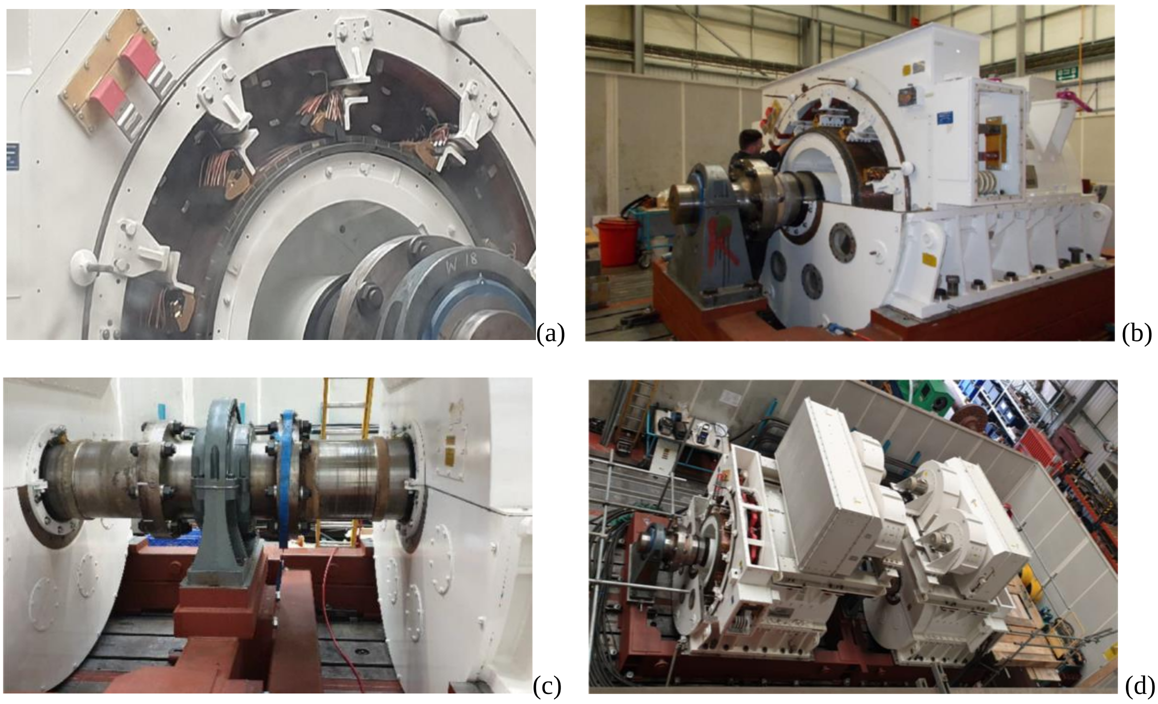


Figure 11 – (a) Brush Bedding, (b) Motor on Bedplate, (c and d) Motors Connected for Back to Back Testing

6.3 Hopkinson's Test

The main test involved a Hopkinson or Back to Back Test. To carry out this test, both machines are mechanically connected. The first machine is configured as a motor and connected to an external dc supply. The mechanical output of the motor drives the second machine, configured as a generator and the electrical output of the generator is used to supply the input to the motor; the output of each machine acts as the input to the other machine. Speed can be adjusted via a shunt field resistance to achieve the required motor speed and consequently generator speed. Similarly, a rheostat controls the voltage output of the generator. When both machines are running on full load, the supply input is equal to the losses of the machines, so the external power input is small.

Advantages of the Hopkinson Test

- This method is very economical – with the generator supplying the motor, the only external power required is equal to the losses of the two machines
- Temperature rises and commutation can be checked under rated conditions
- Stray losses can be considered and efficiency performance at various loads can be determined
- The speed of the motor and output of the generator can be closely controlled by adjusting the individual rheostats

Disadvantages of the Hopkinson Test

- The main disadvantage of a Hopkinson Test, which was negated in this instance, is the necessity for two identical machines to perform this procedure.

<u>Testing passed all criteria and the motors demonstrated design intent performance at the factory</u>.

7. Replace

Whilst testing was underway, preparations were ongoing to ensure the MGR was ready and safe for the motor return. The Lifting Specialist submitted new Risk Assessments and Method Statements to replace both motors. The replacement activity took approximately two weeks to complete and is at Figure 12 (a and b).

(a)


(b)

Figure 12 – (a and b) Installation of Motor

7.1 Shaft Alignment

Accurate shaft alignment is necessary for correct internal alignment of the main reduction gear, the clutch, the intermediate plummer blocks and the direct shaft mounted electric propulsion motor.

The primary aim of the shafting system alignment is to ensure that the main reduction slow speed output quill shaft is properly aligned. Specifically, that the bearing loads are within acceptable limits set by the gearing manufacturer and plummer loads are within bearing manufacturer design limits. As the motor has no inbuilt bearings, changes to the shaft alignment would require the motor frame to be moved to maintain acceptable internal air gaps as part of the alignment process. The motor air gap is critical to the operation of the motors and significantly influences motor noise and heating of the windings within the motor. It also has a secondary effect on commutation, airflow and armature heating in the motor.

7.2 Motor Bedplate Movement

To mitigate the alignment risk, additional arrangements were put in place to monitor the motor bedplate movement. Prior to removing the motors, three datum plates were welded on to each rail of the bedplate, to monitor the X, Y and Z plane movement Figure 13. There were six datum plates per motor, see Figure 14, which enabled alignment readings to be recorded. Readings were taken with theodolites in the X, Y and Z co-ordinates, Figure 15.

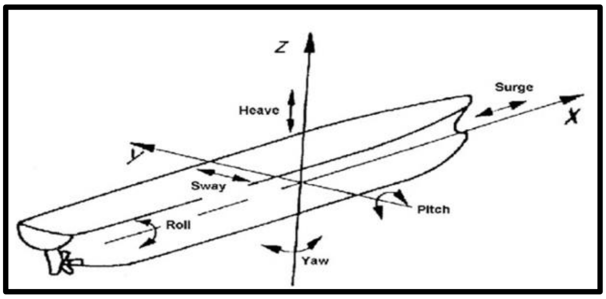


Figure 13 – Diagram of X, Y and Z Planes

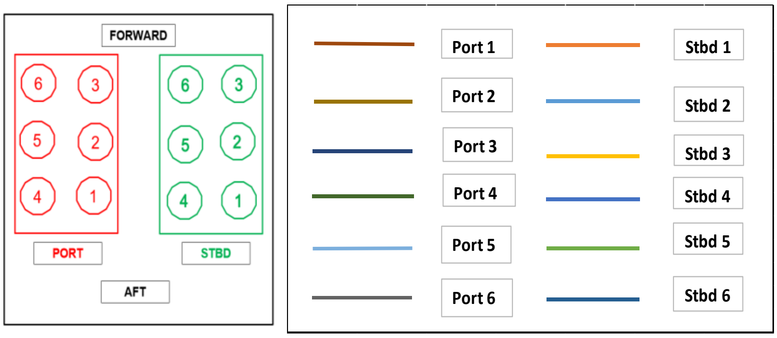


Figure 14 – Datum Plate Theodolite Positions

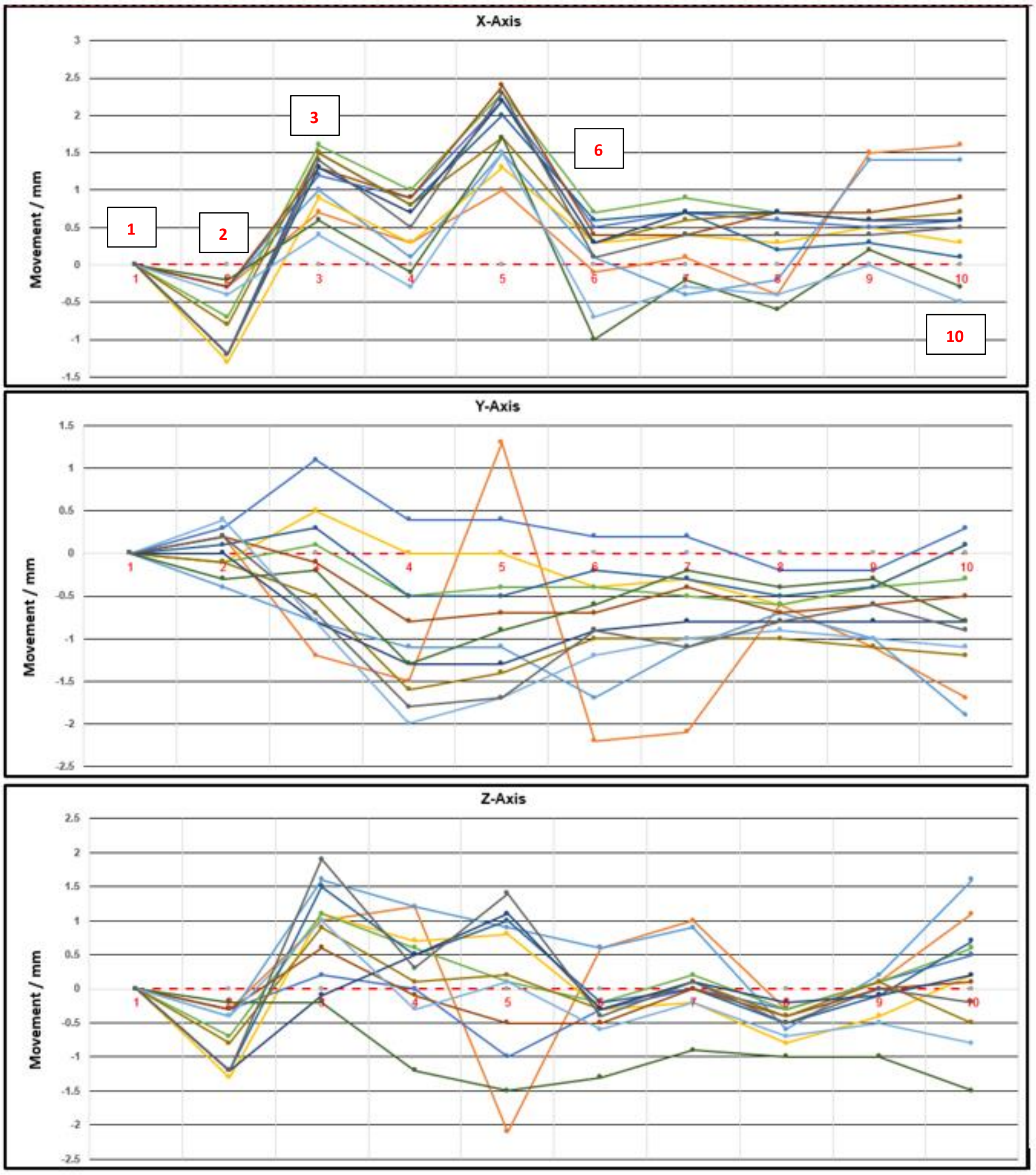


Figure 15 – X, Y, Z Readings for Port and Starboard Bedplates

Table 1 – Port and Starboard Motor XYZ Axis Analysis from Figure 15

Position	Event
1	Datum readings - the shaft line fully connected and in tension
2	Motor disconnected from shaft line, still on bedplate. The motor bedplate is experiencing the full weight of the motors (40 tonnes each motor). With the motors released from the shaft line but still in place, both bedplates moved slightly in the Z axis due to the bedplates being in greater compression with the weight of the motors.
3	Motors removed. With no beam tension from the shaft line or weight from the motor, both bedplates have moved forward towards the gearbox. The range of movement from motors in the Y axis was approximately 2 mm and although this is witnessed in both Port and Starboard direction, there is clearly more movement of both bedplates to Starboard. The insert cut into the Starboard side of the MGR hull may have influenced the movement of the motor bedplates.
6	Ongoing monitoring with associated deflections witnessed, motor replaced
10	Shaft line aligned and reconnected. The readings for the starboard motor show higher when compared to Port. This may explain why the starboard motor was more of a challenge to re-align and required greater adjustment.

8. Learning from Experience (LfE)

An Enterprise approach was absolutely key. Open engagement and collaborative working throughout this project between the MOD, Babcock and industry specialists, was the route to successful rectification in ship 1. Using the agreed methods and processes, Functional Procedures for the end to end process have been produced and were ustilised for ship 2, and will be again, for future vessels.

The unusual dirt patterns observed at the repair facility led to an ongoing independent study into the motor cooling, which is informing analysis for future availability and may lead to minor design changes.

Whilst the motors were at the factory for repair, in order to support intended deeper motor cleaning maintenance, the OEM trialled a new motor cleaning rig, which allowed the motor casings to be split in situ. This ensured the cleaning rig was fit for purpose, safe and assured the method statements to increase cleaning options in service.

The original shipbuilder shaft alignment data was not available, therefore monitoring the movement of the ship structure throughout the repair period allowed a greater appreciation of the motor alignment, particularly starboard and reduced shaft alignment risk. The importance of the bedplate flexural monitoring throughout the process was confirmed as vital and this was rolled into ship 2 with even greater emphasis and captured into Functional Procedures.

9. Conclusions

Following an upkeep inspection of the port and starboard propulsion motors of a T23, insulation degradation to the forward coil support rings on both motors was identified as being outside design parameters and would impact future ship availability. This resulted in the WTA and Babcock providing several repair options to bring the motors back to within design intent; Option 5 was agreed by the Enterprise. This level of overhaul had never been undertaken before and the Removal, Repair and Replacement of the propulsion motors presented a unique challenge for Babcock in Devonport, with some important Learning from Experience (LfE) captured.

Had a shipping route been available to enable removal of the propulsion motors, this task would have been much simpler. Design of a complex warship considers many aspects and requirements, which can change over the life of that vessel. Not everything can be designed for, and it is the responsibility of the accountable engineers and ship builder at that time to overcome these real-life problems; as it was in this instance.

The major engineering, commercial and logistical challenges presented to the Enterprise and specifically Babcock Devonport were not underestimated. It was identified right at the start, that only through collaborative working with the MOD, several of Babcock's technical disciplines and industry partners, that a successful outcome could be achieved in the time available. This preparation led to a clear and agreed route to achieve a successful return to design intent of both propulsion motors, where ship 1 and ship 2 have fully completed this repair. Ship 1 has been fully trialled and is back at sea and available.

The correct through-life support solutions for platforms operating globally, enable the engineer to fully operate, maintain, diagnose and repair systems and equipment. Future build programmes are ensuring that design for support has a strong weighting during the design process. Lessons like these identified within legacy platforms, will continually improve this design activity. Coupling the expertise and agility of the ship engineers and ship builder to overcome complex issues, will ensure the sustainability of critical systems and equipment will continue, even if the requirement, role and life of the asset changes.

10. Acknowledgements

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