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SS GREAT BRITAIN: VOYAGE TO CARBON NEUTRAL

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SUMMARY

Brunel's SS Great Britain, the first iron ship, is conserved and displayed in the historic dry dock where she was built. The most vulnerable parts of the original wrought iron hull are preserved by keeping the surrounding air at 20% relative humidity to prevent corrosion. A glass "sea" at waterline level creates a seal, and bespoke desiccant dehumidifiers desiccate the environment inside and underneath the ship. This conservation method relies on natural gas for drying the air, and electricity for circulating it.

A specialist engineer was appointed to develop system-level understanding and ownership of the desiccant plant and develop a strategy to decarbonise the conservation system. Improvements to controls and instrumentation provide new insight into the system's behaviour. Using this information, optimisation and adaptation of the system have both directly reduced emissions and altered the heat demand, introducing the possibility of future decarbonisation via electrification overcoming reliance on natural gas.

1. INTRODUCTION

1.1 THE SS GREAT BRITAIN

Launched in 1843, Isambard Kingdom Brunel's ss Great Britain was the first ocean-going vessel to be driven with a screw propeller and the first to be made from wrought iron, allowing her to be significantly larger than had previously been possible and providing the blueprint for modern-day hull design. She survived being run aground early in her career and went on to enjoy an extraordinarily long and impactful working life, thanks to the strength and longevity of this exciting new shipbuilding material and technique [1]. Ending her working life as a hulk in the Falkland Islands, the ship was salvaged in 1970 and returned to the original Bristol dry dock in which she was constructed, the combination of ship and dock creating a site of international cultural significance which has since been almost continuously accessible to the public.

1.2 THE CONSERVATION CHALLENGE

On her return to Bristol the SS Great Britain was cared for by traditional engineers, but analysis of the hull revealed that corrosion, accelerated by chlorides in the wrought iron structure, meant that without intervention within 25 years the ship would become structurally unsafe and original fabric irretrievably lost [2].

A report commissioned to examine the importance of the ship's historical, technological, and cultural contexts presented an evidence-based argument that preservation of the ship and her original dock was of international importance, with survival of the original iron hull central to any conservation plan [3].

Condition surveys revealed a marked contrast between the topsides and the lower hull and interior. The hull below the waterline and the interior surfaces of the ship were found to be severely corroded and the material infused with chloride, and the exterior of the upper hull less corroded. A conservation strategy was developed adopting two different regimes for the two distinct parts of the structure.

2. CONSERVING THE SHIP

2.1 THE LOWER HULL AND INTERIOR

Previous attempts at protecting the lower hull and interior had proven ineffective, infused chloride causing corrosion to continue beneath any coating which would become compromised, re-exposing the material to ambient air. No practically attainable or sufficiently proven method of removing embedded chloride on the scale of the ship and grade II*-listed historic dry dock structure was available.

Conservation efforts therefore focus on creating a desiccated microclimate surrounding the most vulnerable parts of the iron, to achieve a negligible rate of corrosion while allowing visitor access [4]. A horizontal glass roof creates a seal between the hull waterline and the side of the dry dock, allowing desiccation of the hull exterior below the waterline (Figure 1). Airlock-style doors create an equivalent space within the ship's interior (Figure 2).

Figure 1: The glass plate creates a seal around the hull below the waterline. Ducts and vents are positioned to create a layer of dried air adjacent to the historic iron.

Figure 2: Interior of lower ship's hull, showing iron structure and desiccated air delivery ducts.

Two bespoke desiccant dehumidifiers condition the air inside and underneath the ship, with vents and ducts positioned to form a protective desiccated air curtain adjacent to the hull. This design allows parts of the space furthest from the most vulnerable material to deviate from the target conditions [5], reducing the impact of visitor presence and the energy requirement of the desiccation plant compared with uniform desiccation of the entire envelope.

To derive target conditions for the desiccated microclimate, research was commissioned to identify both 'no corrosion' points and corrosion rates for chloride-infested iron as a function of relative humidity (RH). Laboratory modelling of corrosion mechanisms within chloride-infested iron identified that at a temperature of 20°C, corrosion ceased below 15% RH, was negligible at 20% RH and did not produce a significant impact until 25% RH [6, 7]. A target condition of 20% RH was selected.

The ship's galley, dining saloon and other catering areas in the centre of the interior are sealed in a separate environment which does not include any of the vulnerable original iron. This space is vented via the ship's funnel to prevent moisture from catering activities being incorporated into the climate-controlled envelope.

2.2 THE UPPER EXTERIOR

The upper exterior of the hull has been stripped of corrosion products and is protected from the external environment using a multi-layered coating, formulated to combine the chemical resistance of epoxy resins with the UV resistance of polyurethanes.

The separation of the two regions with differing conservation protocols allows the energy-intensive desiccation treatment to be employed only where the condition of the material necessitates it. This approach minimises the size of the required climate-controlled envelope, offering energy savings compared to encasement of the whole ship in a building, and allows the upper portion of the ship to be displayed as part of the skyline of Bristol's historic harbour.

The glass roof is flooded with a 50mm layer of water, creating the appearance from above that the ship is ready to set sail (Figure 3), enhancing the visitor experience as they descend "underwater" to enter the desiccated dry dock.

Figure 3: A seal at waterline level with a 50mm layer of water on the glass plate provides insulation while creating the appearance that the ship is ready to set sail.

3. SUSTAINABILITY STRATEGY

3.1 DESICCATION SYSTEM, AS DESIGNED

The energy requirement of such a conservation system was carefully considered and justification sought prior to installation [8]. Nevertheless, the solution was designed to be non-interventive and reversible, with no chemical or physical interference with the material. If at some future time the argument for conserving the ship is called into question and the energy expenditure found to no longer be justifiable, the equipment can simply be switched off.

The climate-controlled envelope and desiccation plant were also designed to be energy-efficient. The flooded glass plate acts as insulation and reduces solar gain, providing an estimated 20% energy saving for the desiccation plant, which also utilises water from the floating harbour for cooling. Only the most vulnerable parts of the iron are enclosed in the climate-controlled envelope, and the desiccated air is carefully directed to form a curtain over the iron hull, allowing the fabric of the ship to be kept at 20% RH, while air closer to the dry dock walls is allowed to deviate from the target.

3.2 FUTURE SUSTAINABILITY PLANNING

Following a 15-year period of successful operation, a dedicated "Ship's Conservation Engineer" was appointed by the SS Great Britain Trust to assess the effectiveness of the conservation system, with a view to ensuring it remains fit-for-purpose in the very long term. A particular objective was identified to reduce the energy consumption and environmental footprint associated with the system. Creating an in-house role was intended to allow the Trust to develop understanding of the conservation at a whole system level, in contrast to the previous approach of supplementing the work of maintenance contractors with ad-hoc consultant-led support. This new role would facilitate a programme of research, adaptation, and optimisation to ensure the long-term stability and sustainability of the ship's conservation.

4. 'VOYAGE TO CARBON NEUTRAL' PROJECT

4.1 OPERATION OF THE DESICCATION PLANT

Each of the two desiccant dehumidifiers comprises two streams of air:

- The "supply" stream dries air by forcing it through an adsorbent desiccant, circulates the dried air around the ship or the dry dock, and then recycles it for re-drying and recirculating, mixing in fresh air only if the CO_2 concentration increases beyond a given threshold.
- The "reactivation" stream takes in external air, heats the air using a natural gas burner then uses it to remove moisture from the desiccant, exhausting the now damp air from the desiccant to the external environment. Heat exchangers recover heat from the exhaust air, pre-heating the incoming air.

There is no air exchange between the two streams, but the desiccant material is mounted on a rotor continually moving each segment through the supply stream to extract moisture from the supply air, and then through the gas-heated reactivation stream where moisture is extracted from the desiccant material and exhausted to the atmosphere (Figure 4).

To control the system, relative humidity sensors are positioned in a variety of locations adjacent to the surface of the iron, and the difference between the average of the sensor readings and the target RH is used to control the gas supply to the reactivation heaters via a simple Proportional-Integral (PI) control algorithm. When the RH increases above the target, the supply of natural gas to the burners is increased and the reactivation stream air becomes hotter, removing more moisture from the desiccant material which in turn removes more moisture from the supply air.

The key carbon footprint contributors of this system are the gas supply providing heat to the reactivation stream, and the four fans used to circulate air through the supply and reactivation streams and around the ship and dry dock.

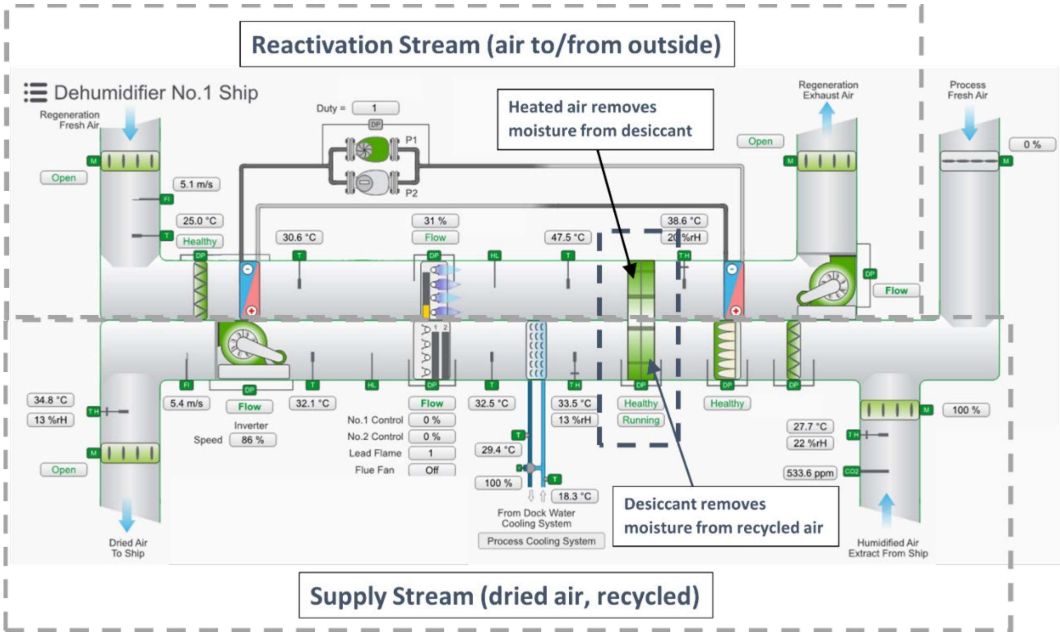

Figure 4: Schematic showing one of the two bespoke desiccant dehumidifiers that create the controlled environment.

4.2 REVIEW OF PLANT PERFORMANCE

An initial review of the system data showed that the average RH was being held broadly stable, but further assessment of the detailed data led to the following key observations:

4.2 (a) Relative Humidity Sensor Performance

Over time, approximately half of the wireless relative humidity sensors had failed. The frequency of data transmission by the remaining sensors was low, resulting in apparent sudden step changes in the average relative humidity. The control algorithm tuning parameters were not appropriately set for the reduced frequency of data transmission. This combination resulted in the system controls exhibiting ‘cycling’ behaviour, repeatedly over- and under-shooting the target RH. During periods when the gas demand was too low, moisture was being actively introduced into the system via cool and damp air in the reactivation stream, and during periods when the gas demand was too high, unnecessary gas was being burned to dry the desiccant, and therefore the space, more than required (Figure 5).

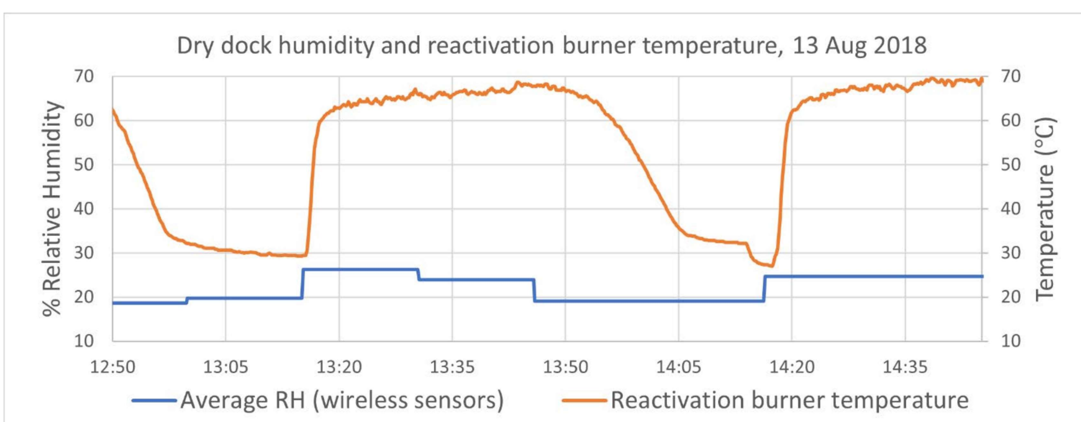

Figure 5: Dry dock dehumidifier reactivation air temperature and average RH cycling.

4.2 (b) Plant Instrumentation

Each sub-component of the air handling systems was found to be instrumented with temperature and relative humidity sensors, with the data from all sensors available via building management system (BMS) software. Prior to appointment of the Ship's Conservation Engineer, the Trust did not have any staff members with the capacity or the experience to utilise the full functionality of the BMS software, which itself was shortly due to become obsolete. Information from gas and electricity meters was also available but had not been studied in detail.

4.3 CONTROL AND INSTRUMENTATION UPGRADES

To address these two challenges, the 'Help the Hull' project was initiated to improve the ship and dry dock RH sensors, and to facilitate easier data collection and analysis from the instrumentation elsewhere in the system. The obsolete BMS was migrated to a newer and more user-friendly software package. The layout and functionality of the migrated system was collaboratively designed by BMS Engineer contractors, the Ship's Conservation Engineer, and the Trust's team of Site Technicians, resulting in a system which is more intuitively navigated and key information more easily accessed by both technically experienced and non-specialist users.

The wireless relative humidity sensors in more accessible ship and dry dock locations were replaced with wired sensors, overcoming the previously identified communication issues, and introducing the additional benefit of not requiring regular battery changes. An additional set of portable wireless sensors were also installed, offering better signal transmission than their predecessors to monitor less easily accessible parts of the ship and dry dock.

4.4 RETRO-FITTING ENERGY EFFICIENCY TECHNOLOGY

The modular nature of the desiccation plant and BMS control system offers the flexibility for individual components to be modified independently of the rest of the system, minimising the expense and embodied energy requirement of plant modernisation. Aided by easy access to data from the new BMS, the system-level understanding developed by the Trust allowed for two relatively simple design modifications to be planned. Energy payback and carbon footprint reduction calculations provided compelling evidence to stakeholders allowing grant funding to be secured.

4.4 (a) Desiccated Air Supply Fan Replacement

On approaching the end of their originally anticipated service life, the belt-driven scroll fans circulating desiccated air around the ship and dry dock were replaced with a more reliable and energy-efficient new design. A grid of smaller direct-drive fans provides an overall electricity saving of more than 20% without the need to modify any other part of the air handling plant or controls, resulting in an energy payback time of less than 3 years.

Figure 6: Belt-driven scroll fan (left, 2005-2021) replaced by a grid of nine direct-drive fans (right, 2022-present).

4.4 (b) Energy Recovery Purge Systems

An energy recovery purge system, an additional heat recovery device in the reactivation air stream, was also installed on each dehumidifier (Figure 7). This device fits onto the desiccant rotors, recovering heat from the desiccant material as it moves from the reactivation stream into the supply stream. The recovered heat reduces demand on the gas burners, and cooling of the desiccant material as it moves into the supply air stream also improves its adsorption performance, as well as reducing the load on the subsequent supply air cooling system.

For the energy recovery purge system to deliver its full potential benefit, it was also necessary to eliminate the "cycling" behaviour in the control algorithms. The combination of higher quality RH sensor data and improved understanding of the system controls which had now become available was used to inform adjustments to the dehumidifier gas supply and the PI controller tuning parameters, improving the stability of the system (Figure 8).

Figure 7: Energy Recovery Purge system fitted to the desiccant rotor on the dry dock dehumidifier.

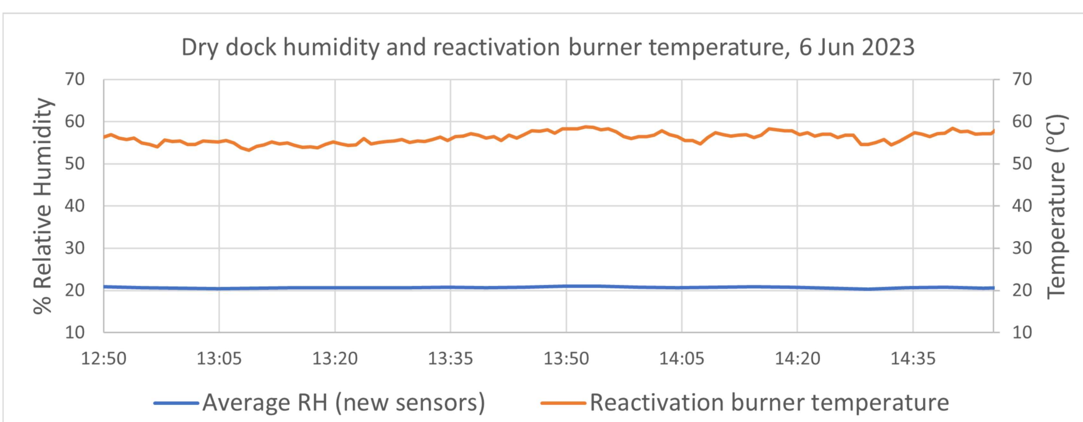

Figure 8: Dry dock dehumidifier reactivation air temperature and average RH, showing improved stability.

5. RESULTS

With the PI control algorithms appropriately tuned to avoid overshoots and the energy recovery purge system installed, the natural gas consumption of the dehumidifiers has been reduced by an average of 28% over a period of 1 year. In addition to delivering energy savings, the combined improvements to the system also result in the desiccant reconditioning taking place at lower temperatures compared with previous operation (Figure 9). This is significant because lower operating temperatures can more easily be achieved with lower-carbon heating methods, such as heat pumps, instead of natural gas. Work is currently underway to determine whether it would be feasible to supply some or all of this heat via heat pumps, perhaps even utilising waste heat from other parts of the system, which would allow for further energy savings and, potentially, complete decarbonisation.

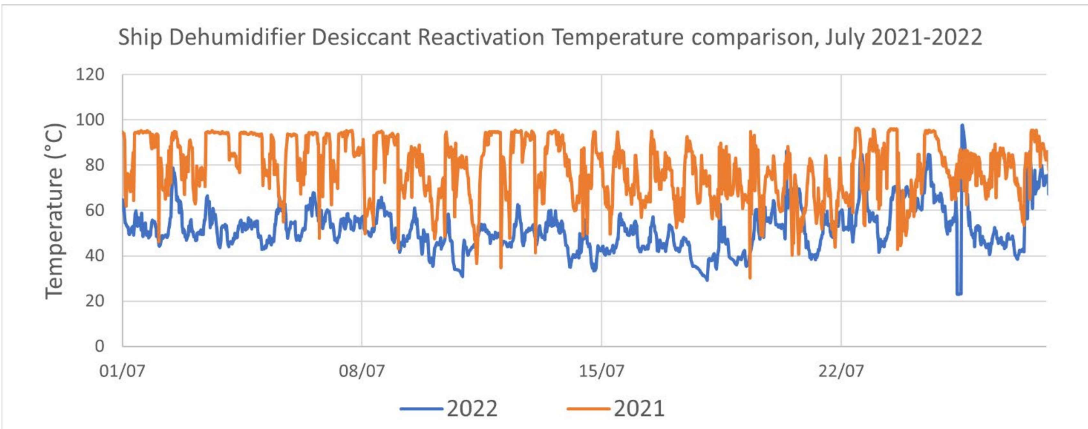

Figure 9: Installation of an energy recovery purge system, combined with control algorithm optimisation, has reduced the temperature at which heat is required for the drying action of the desiccation plant.

6. CONCLUSIONS AND FUTURE WORK

The only feasible method identified to conserve Brunel's SS Great Britain, the first iron ship, is to create a desiccated microclimate around vulnerable parts of the original wrought iron hull to prevent corrosion. A desiccation system was designed to achieve this objective and the environment around the hull has been held broadly stable for more than a decade, albeit with appreciable energy costs and emissions.

The Ship's Conservation Engineer is a new specialist role introduced to review and develop the long-term strategy to sustainably conserve the ship. Following a review of the desiccation plant's performance, improved instrumentation and a new building management system have been designed and implemented. The dehumidifiers have been retro-fitted with new energy-efficient technology and, using new data, the control algorithms have been optimised. This has directly reduced energy consumption and associated emissions, and reduced the temperature at which heat is required for the drying action of the dehumidifiers, introducing the possibility of further decarbonisation, and overcoming reliance on natural gas.

Continuation of this work will develop a deeper understanding of the relationship between factors such as external weather conditions or visitor numbers and dehumidifier behaviour to allow further fine-tuning of the controls, for example using weather forecasting, visitor opening hours and events schedules to pre-empt changes in conditions and further optimise the performance of the system. It is anticipated that this optimisation will work alongside a further design development to recover more waste heat from the system, utilising heat pump technology, to further reduce gas consumption and associated emissions.

7. ACKNOWLEDGEMENTS

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9. AUTHOR BIOGRAPHY

Nicola Grahamslaw graduated with an MEng from St Catharine's College, Cambridge, before working as an analyst and project engineer in aerospace and nuclear energy. In 2018 she was appointed to the newly created "Ship's Conservation Engineer" position at the SS Great Britain Trust, developing a sustainable strategy for the future care of this unique object. She is a Chartered Engineer and holds an MBA. She sits on the International Congress of Maritime Museums Ships Committee and the Institute of Conservation Heritage Science Group Committee. Nicola was awarded Institution of Mechanical Engineers "Young Member of the Year" in 2019 for her work with the ship and as a volunteer STEM ambassador, speaker, and mentor.