Vaporise after reading – pyrolysis and waste management on Queen Elizabeth Class carriers

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Synopsis

Gone are the days of "ditching gash" off the quarterdeck. The Royal Navy's Queen Elizabeth Class aircraft carriers incorporate a sophisticated and highly integrated waste management system which culminates in a pair of pyrolysis plants for waste volume reduction on each ship. The inclusion of pyrolysis plants is understood to be a unique installation in the marine sector, other than the ex. HMS Ocean (now NAM Atlântico). The system has many environmental and sustainability benefits over traditional waste systems which compact, incinerate or discharge waste overboard. In naval terms, this results in increased endurance, sustainable operation, reduced pollution, and safeguards the ships' freedom of navigation in environmentally sensitive areas, which may be subject to stricter legislation in future.
This paper explores the history of the system's design; the unique operation of the system and pyrolysis plants; the impact to the Royal Navy and the sailors; recent developments in operation, testing and commissioning; the present and future environmental context; and the potentially exciting future ahead for similar installations.

Keywords: Waste management; Pyrolysis; Sustainability; Emissions; Integration; Marine systems

1. Introduction: the inception of integrated waste management and pyrolysis

In the "bad old days", it was not uncommon for bags of "gash" (naval vernacular for rubbish, garbage) to be stabbed with a knife and ditched overboard to (hopefully) sink. There are even stories from the "Tanker War" of the 1980s of trawlers following Royal Navy (RN) ships in the Gulf to pick up the bags, interrogate their contents, and try to accumulate scraps of intelligence. Modern attitudes, and the adoption of MARPOL, has led to tighter controls on the management of waste at sea. The RN initially used incinerators, but ships now typically incorporate waste volume reduction units, which shred and compact gash for storage in small, manually handleable drums / bags (plastics are heated during the final compaction to create a sealed block). These units are /were / will be variously installed as follows; Types 22, 23, 31, 42 and 45, Albion and Invincible classes, HMS Ocean, HMS Endurance, Royal Fleet Auxiliaries Fort Victoria, Argus, and the Fort Rosalie and Wave classes. The River-class OPVs use a simpler 'Orwak' drum-compactor unit, while the T26 frigates will use a novel 'Ompeco NV' waste converter – this mechanically impacts the waste, heats it to remove water and sterilise microbes, and releases the waste in bags.

Storage of compacted gash affects the endurance of the ship and is unpleasant and labour intensive; thus a system which could perform more drastic and automatic volume reduction of the waste was attractive to the RN. In 2007, a pyrolysis plant was fitted onto HMS Ocean during her refit (supplied by QinetiQ / Compact Power); this was a 150 kg/h system originating from a land-based trials unit. The system proved unpopular as it caused mess decks to overheat when in action, and significant improvements were identified for incorporation into following installations.

The Queen Elizabeth Class (QEC) aircraft carriers were built by the Aircraft Carrier Alliance between 2009 and 2019. Initially, the design incorporated incinerators, but this was changed to fit two 150 kg/h pyrolysis plants (see Figure 1) which were supplied by Babcock (with Qinetiq and Ethos Energy[1]) as part of the ship-wide Integrated Waste Management System (IWMS). The pyrolysis process, the plants, and the IWMS are described in greater detail in Section 2.

[1] Operations since taken over by Pyrocore Ltd.

Authors' Biographies

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Figure 1: Pyrolysis plant, HMS Prince of Wales. Note the spare augur screw in foreground © Royal Navy 2019

2. New solutions for QEC

2.1. The Integrated Waste Management System

The QEC IWMS processes solid waste (such as cardboard, paper, and plastics), glass, metal, food waste, black water, grey water, and sullage oil. It is split into three zoned systems (with suitable cross connections) for redundancy and increased throughput of waste; the forward and aft systems provide a full waste capability, whilst the mid system is for black and grey water only. The system has significant flexibility in the waste routing to suit operational requirements. A functional block diagram can be seen in Figure 2, and the following list provides a short description of each waste process:

- Solid waste – “bin bags” collected, sorted manually, and shredded for pyrolysis.
- Glass – separated from solid waste, shredded, and stored in drums for offload.
- Metal – separated from solid waste, crushed, and stored in drums for offload.
- Food waste – collected from the sculleries by a vacuum system, macerated, dewatered, and stored. Can either be discharged overboard where limits allow, or processed further for pyrolysis, as described below.
- Black water – collected by vacuum, screened, and sent to the membrane bio-reactor (MBR). Bio sludge can either be discharged overboard where limits allow, or processed further for pyrolysis, as described below.
    - NB. MBR screenings (e.g. compressed toilet paper) are removed manually and bagged for offload.
- Grey water – drained, then sent to the MBR.
- Greasy grey water – drained, grease separated, then combined with grey water.
- Sullage oil – collected, water separated for overboard discharge where limits allow. Waste oil can be processed in the pyrolysis plant.

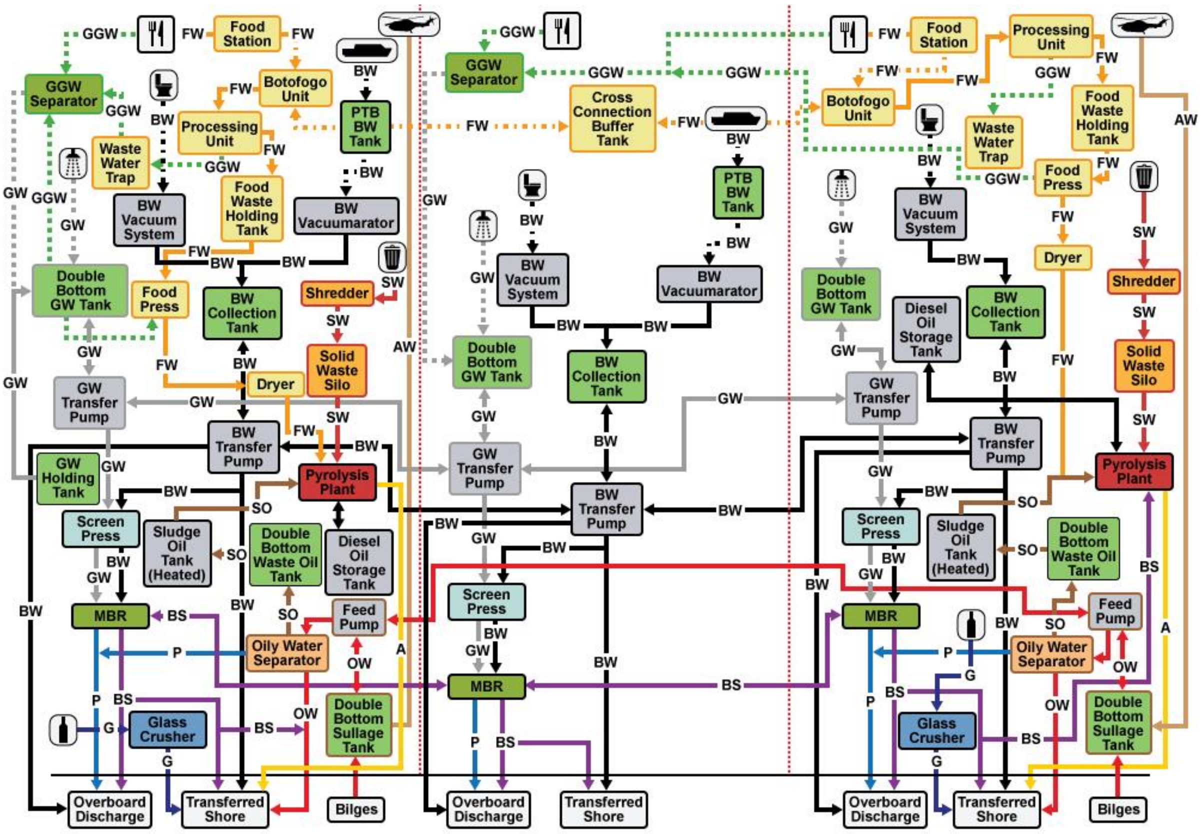

Figure 2: QEC IWMS block diagram © Crown Copyright

2.2. *Pyrolysis process and plants*

Pyrolysis is the thermal decomposition of organic material in an oxygen-starved environment resulting in the simultaneous change of chemical composition and physical phase of the material. The ship's plants process waste as follows (with reference to Figure 3):

- Waste is fed into the plant through the ***knife gate airlock*** and transported through the central ***pyrolysis chamber*** by an augur screw, where it decomposes under high temperature into an inert "char", whilst evolving a hydrocarbon syngas.
- The chamber is exhausted by the ***Induced Draft (ID) fan*** to maintain a negative pressure (relative to atmosphere), air-free environment so that there is no oxygen to support combustion.
- The char leaves the end of the augur screw into the ***gasifier*** and falls to be extracted by another augur screw into drums for removal.
- Meanwhile, the syngas is mixed with a carefully controlled stream of inlet air, downstream in the ***oxidiser***, causing it to combust at around 900 °C. The oxidised syngas is drawn over the outside of the pyrolysis chamber to provide the heat energy to decompose the waste – in this way, a self-sustaining process is achieved.
- The exhaust gas is cooled with atomised water to around 210 °C, passes through the ID fan, and is exhausted via the ship's funnel.
- A diesel fired burner (within the oxidiser assembly) heats the plant to operating temperature on start-up and adds additional heat energy as required if the waste throughput is low, or the waste is of low calorific value.
- An air seal is created at the knife gate waste inlet and in the bin where char is loaded into the drums. This maintains the environment in the plant.
- A central PLC control system automates all plant functions and informs operators when the plant is ready to process – this also links to the ships Integrated Platform Management System (IPMS) to request waste from the rest of the IWMS.

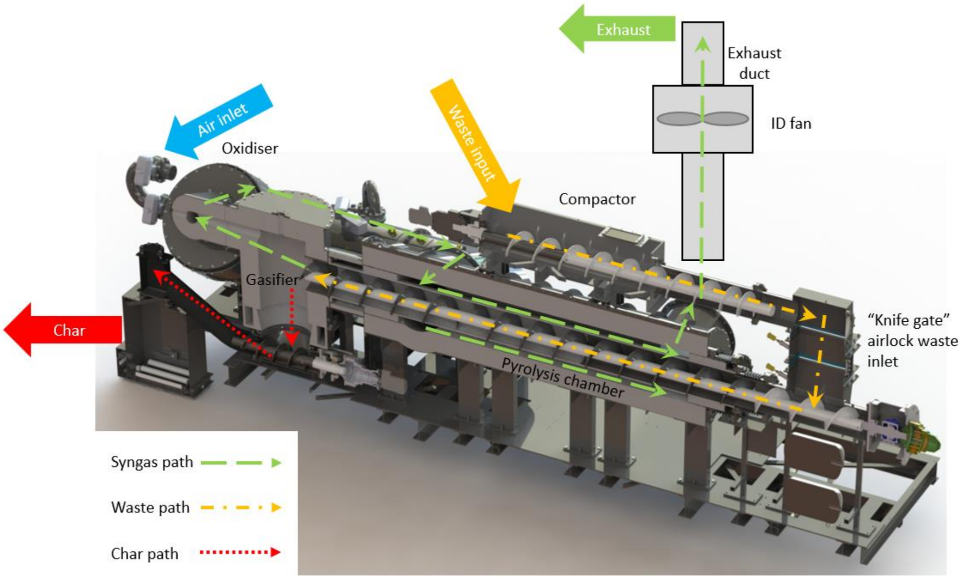

Figure 3: Diagrammatic representation of pyrolysis plant © Pyrocore Ltd.

The pyrolysis plant requires electrical power, diesel, LP air for valves and water atomisation, and a fresh water supply for cooling and fire suppression. The plants have demonstrated a significant capability; a waste volume reduction of approximately 95 %, a mass reduction of 75 %, and a processing rate of between 75 to 150 kg/h (approximately 1.25 to 2.5 m^3/h of shredded solid waste)[2]. From a cold start the plant is ready to process in less than two hours, with a self-sustaining processing achievable within four hours.

2.3. Processing waste by pyrolysis

The unique aspect of the IWMS is the ability to process several different waste streams via the pyrolysis plants; solid waste, waste oil, dried food waste, and dried bio sludge – the equipment for this functionality is co-located in the forward and aft IWMS compartments, which can be seen indicated on Figure 4 along with the pyrolysis plant exhaust routes.

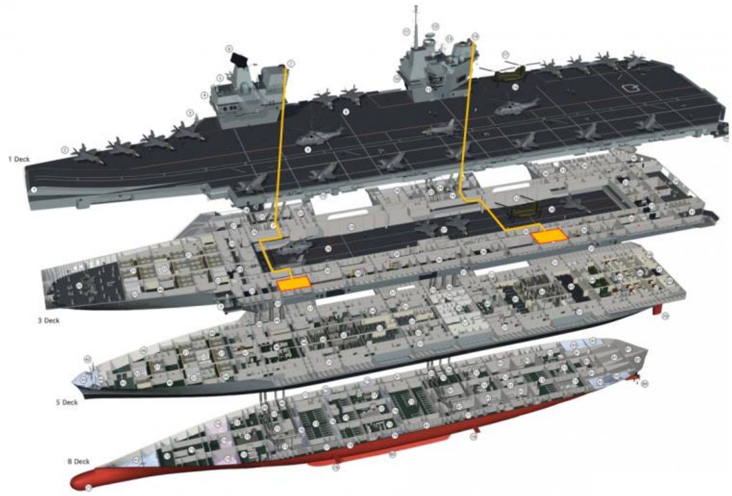

Figure 4: Cut-away of QEC with IWMS compartments and pyrolysis exhausts indicated © MOD 2010

The different waste streams are processed as described in the following paragraphs, with reference to Figure 5. Each process happens automatically once selected.

Solid waste is shredded into ~50 mm wide ribbons and stored in a ~10 m^3 silo, with a fan to remove odours. A walking floor advances the waste to an augur screw which discharges to the pyrolysis plant.

[2] This compares favourably to the 80 % volume and 50 % mass reduction achieved by the T26 Ompeco system.

Food waste (at approximately 4 % dry solids, i.e. 96 % water) is stored in a 4 m^3 holding tank with a homogenisation pump. The waste is pumped up to the deck above, where an augur screw presses it against a sprung flap to force water out to approx. 20 % dry solids. The waste then passes through a knife-gate dosing system into the dryer.

Bio sludge (approx. 2.5 % dry solids) is pumped from the MBR to a 2 m^3 holding tank with homogenisation pump. The waste is pumped to the flocculent station where it is automatically dosed with a polymer flocculent liquid (at a rate of approximately 1 litre / m^3 bio sludge) before being processed by a decanter and then loaded into the dryer via knife gates. The decanter is a 5000 rpm, contra-rotating centrifuge unit which extracts black water to leave the waste at approx. 20 % dry solids. The flocculent "gathers together" the suspended solid particles to improve the efficiency of the decanter, and the dosage rate must be carefully set dependant on the exact, typical composition of the black waste from the MBRs; for example, a UK-centric, navy diet fed to young, fit sailors gives a very different sewage composition to that found on a Caribbean cruise ship. If the rate is too high, this results in excess flocculent entering the MBR resulting in agglomeration of particles in the MBR, whilst a rate which is too low results in a high concentration of fine particulate returning to the MBR – both cases can blind the membranes.

The combined food and bio sludge waste is loaded into a 400 kg capacity tumble dryer, which is heated by hot oil. The waste is dried until it has reached 105 °C – this results in waste of approx. 70 % dry solids which is dry enough to be processed by pyrolysis – and then discharged into the pyrolysis plant via a long augur screw. Chemical analysis of the sample depicted in Figure 6 showed that it comprised approx. 20 % fats, oils and greases (from food waste), 35 % water, and 45 % solids. Note that the contents of the dryer must be a maximum of 45 % bio sludge (the rest being food waste) otherwise there is a risk of the dried waste auto-igniting owing to the high energy content of the black waste.

The pyrolysis plant consumes diesel to bring the plant up to the processing temperature (as described further in Section 2.2), and the burner can also be employed to process waste oil. The waste oil is simply burnt in the plant, and this can take place in isolation or when the plant is processing food / bio waste.

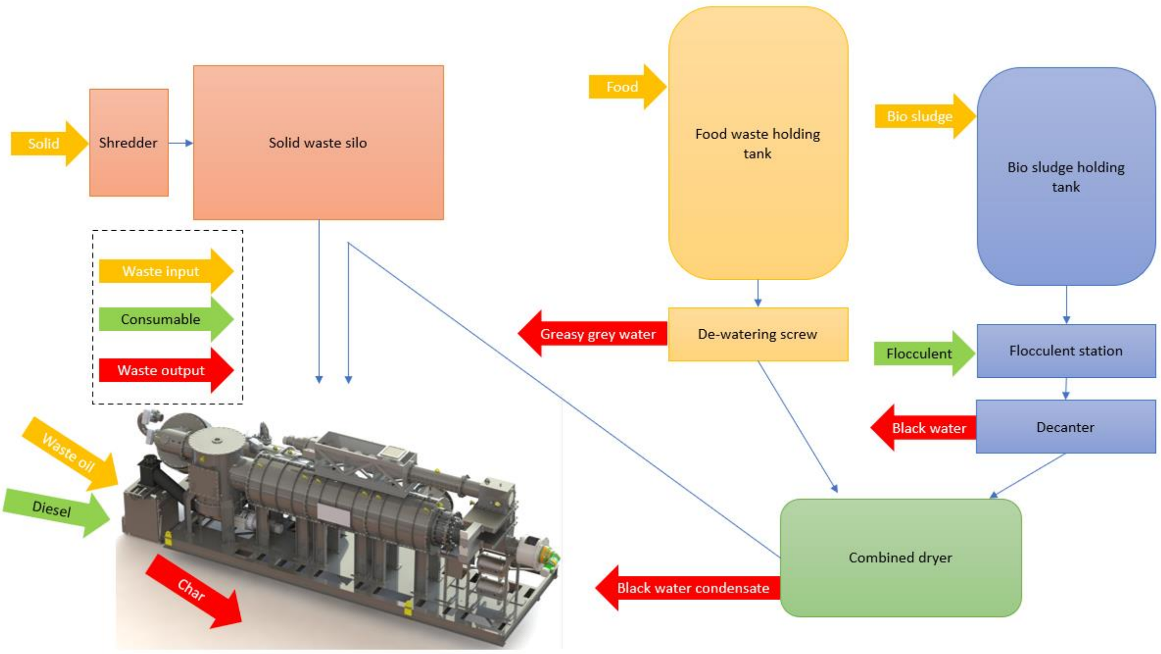

Figure 5: Waste streams for pyrolysis

Figure 6: Mixed bio waste entering the pyrolysis plant: contrast with a “golf ball” of dried, cooled bio waste.

3. Benefits to the RN and sailors

The principal goal of incorporating the pyrolysis plant is waste reduction; the plant achieves approximately 95 % volume and 75 % mass reduction in service. For ships with a large crew, conventionally managed waste would require a very large storage space to prevent it affecting the ships endurance and potentially constraining operations. Further, the practical needs of shipping waste in from the accommodation and out when alongside would drive this space into “prime real estate” (i.e. above the waterline, with good access routes) and thus to compete with other critical operational spaces such as hangars, boat bays, and combat system spaces. Waste management could thus contribute to driving the length, and cost, of the ship. Although the main pyrolysis spaces are in this “prime real estate”, they occupy less space than would be required for waste storage.

The next major benefit is to sustainable operation, as pyrolysis requires less waste packaging (e.g. drums) compared to a typical compaction machine and emits significantly less CO2 and soot when compared with an incinerator, although other pollutants such as HCl may be higher. This is because the pyrolysis process can be finely controlled and tuned to different wastes, and the combusted gases are more readily cleaned to remove exhaust pollutants using an abatement system. The ability to send food and bio sludge wastes to the plant ensures that the ship can operate without restriction in areas which limit the permissible discharge of these waste streams. At present, this is not a significant operational restriction as MARPOL typically permits discharge of comminuted waste outside the 12 nm limit (where an aircraft carrier would expect to operate), however this technology safeguards the ships’ freedom of navigation in environmentally sensitive areas, which may be subject to stricter legislation in future, thus futureproofing the RN’s chief surface assets. Depending on the waste being processed through pyrolysis, the char can be utilised for other applications – for example, processing predominantly biomass waste results in a char suitable for use in activated carbon filtration, although this is not currently viable for the QEC plants.

The wider IWMS also delivers tangible benefits for the sailor; there are fewer personal interactions with the unpleasant waste itself, there is less manual handling, the large silo provides a significant buffer so that solid waste can be processed “out of hours” without needing to be continuously manually loaded to keep the process running, the processed waste gives off no odours, and the co-located and centralised nature of the IWMS equipment improves control of work and intra-departmental communications.

4. Challenges of the system

Inevitably, a complex and unique “system of systems” such as IWMS is prone to teething problems during commissioning and the initial periods of usage, which have been coupled with increased scrutiny from the user and the wider fleet – particularly as the original pyrolysis plant on HMS Ocean was so unpopular amongst the crew. The availability issues have principally arisen from; the complexity of the sub-systems, the variability and variety of waste, design assumptions on waste quantities and composition being challenged, and the older pyrolysis plants lacking the finesse of newer Pyrocore models. Early operational feedback from HMS Queen Elizabeth was fed into the design of the IWMS for HMS Prince of Wales, and there is now a programme of work to install these upgrades back onto the first ship to ensure maximum capability and safety across the class; particularly for the pyrolysis plants.

In particular, the pyrolysis process relies on a lack of oxygen in the main pyrolysis chamber to prevent combustion, and instead support thermal decomposition of the waste. As discussed in Section 2.2, this is enabled by creating a tight seal at the waste inlet and char outlet, a relative-negative pressure being maintained by the ID fan, and careful control of the inlet oxygen for oxidisation of the syngas. The original design relied on a compacted waste plug to create the seal at the inlet, and the oxygen control valves closing to prevent oxygen ingress in case of a shutdown. The plant has undergone several iterations of these features to maximise plant safety; the latest design incorporates a knife gate airlock on the waste inlet, and sprung-shut air inlet isolation valves, which are being installed on to HMS Queen Elizabeth in the near future (see also Section 6).

For any waste processing plant, but particularly for a pyrolysis plant, the key to successful, stable processing is a stream of waste which is consistent in both composition and availability. Operational experience has shown that the crew produce reasonably consistent waste, but that the plants are very efficient at processing it, which means that they are shut down more regularly than a plant in an industrial setting, and the benefits of a self-sustaining process (e.g. reduced diesel consumption, operator familiarity with a single operating point) are not realised as far as they could be.

Metal must be rigorously screened from the solid waste feed as, despite the high temperatures, even an item as small as a paperclip can theoretically cause jams and waste accumulation. In practice, this has posed minimal issues with unscreened metals transiting with the char into the char bin.

For the ship designer, the pyrolysis plants themselves can be very large units (QEC units are approximately 10 x 3 x 3 m) which have layout constraints such as the top-mounted waste intakes, large maintenance envelopes, and the exhaust uptakes to the ship's funnel (see Figure 4). The two IWMS compartments are each arranged over two decks approximately 14 x 7 m in area, with the pyrolysis plant and waste holding tanks occupying the lower deck, and the bulk of the waste processing equipment on the upper deck. For the sailor, these compartments are not overly pleasant to occupy when the equipment is active because of the smell of waste, the elevated temperature, and the noise of the HVAC - although the automated nature of the equipment reduces the requirement for monitoring during processing. Maintenance on the pyrolysis plant requires unbolting the refractory-lined shell panels and fleeting them away, and there are some very large, single-piece components, such as the main augur screw – a spare is stored on the plant for convenience (see Figure 1).

5. Environment, sustainability, and legislation

The incorporation of the pyrolysis plants is an instance of future-looking design to anticipate legislation and standards which are not yet in place regarding ships emissions (to both air and water). As such, there is no clear regulatory framework governing the use of pyrolysis plants in a marine environment, specifically for exhaust gas emissions. Nevertheless, it is acknowledged that the lack of applicable legislation does not remove the requirement to understand and monitor emissions. Thus, a best endeavours approach has been undertaken to establish emissions compliance with the applicable sections of MARPOL MEPC.76(40) for ship-borne incinerators, and Directive 2010/75/EU Industrial Emissions Directive[3] (IED) which covers land-based pyrolysis plants, amongst other waste processing equipment. It should be noted that comparing emissions results is challenging because of the many variables involved in the pyrolysis process – feed rate, waste composition, plant temperature etc. which can cause significant differences in results

Emissions testing in 2020 demonstrated compliance with MEPC.76(40) for soot and CO emissions, and for surface temperatures of the plant in operation.In 2021, baseline tests were undertaken on a Pyrocore land-based demonstrator model using real solid waste taken from the ship. The plant was fitted with a ceramic filtration abatement system dosed with bicarbonate and activated carbon to abate acidic gases, dioxins, furans, PCBs, heavy metals, CO, and dust.

[3] Implemented in UK (England and Wales) law through the Environmental Permitting Regulations 2016.

Table 1 and Figure 7 show the emission results which were taken both before and after the abatement system. The oscillations in the measurements occur as the air-inlet control valves cycle to permit limited volumes of air into the plant; this causes CO to rise and other emissions to reduce as they are diluted. The abatement system was highly effective in reducing CO and HCl[4] to within the limits of the IED.

Table 1: Land based pyrolysis plant emissions results, compared with the IED limits.

Pollutant	Pre-abatement	Post-abatement	IED daily limit
	mg/Nm³ (1)		
CO	376.0	44.0	50
SOx	3.7	0.0	50
HCl	56.4	7.0	10
HF	0.6	0.0	1
NOx	2.3	0.8	400
TOC	-	-	10

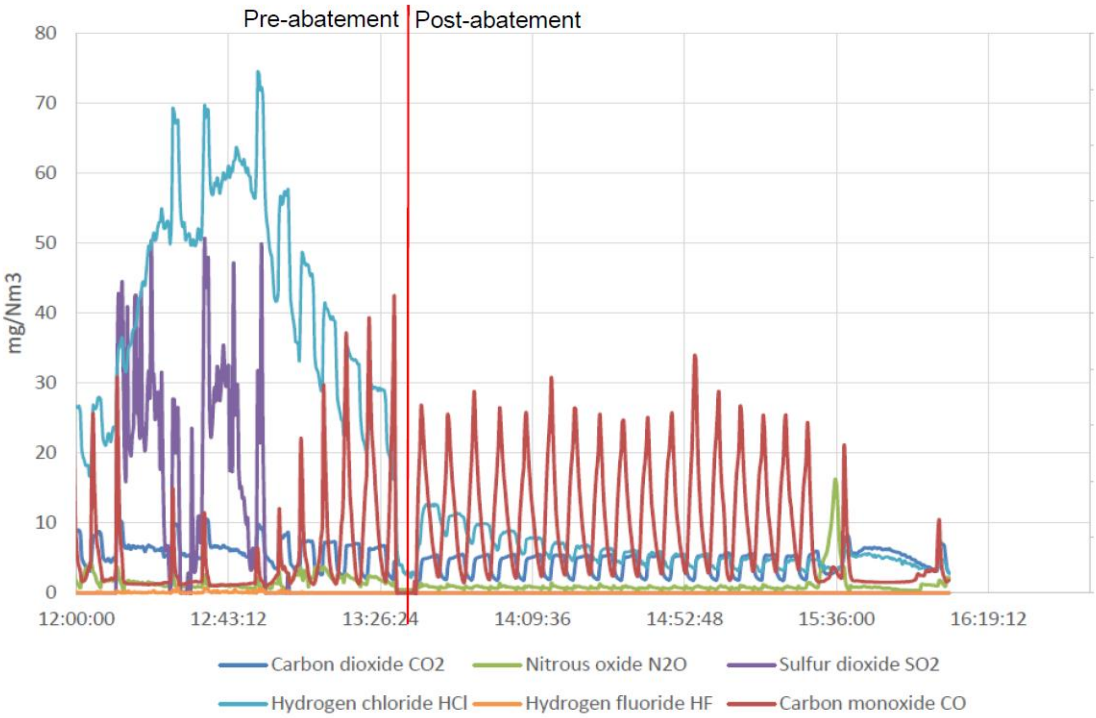

Figure 7: Land based pyrolysis plant emissions testing results

Tests were conducted in November 2021 on HMS Prince of Wales measuring CO, Sox, Nox, HCl, HF, and TOC – readings were taken during processing of all the pyrolysis waste streams as discussed in Section 2.3. Graphs of the readings for CO can be seen in Figure 8. The plants were compliant for Sox, HF and Nox, but CO and TOC readings were above the IED limits in all process modes. This was because the plant had not yet reached a self-sustaining processing mode in each case, which reduces the oxidisation efficiency and requires the burner to activate. The CO measurements oscillate with the burner activation (as above) and generally decrease during a processing period as the plant "settles" to the new waste feed. CO evolution was highest when processing waste oil (which has a high water content and thus results in inefficient combustion), and were higher for solid waste than bio waste, which had levels roughly equivalent to the emissions during start-up.

[4] Chlorine compounds are present in cardboard, and manifest as HCl in the exhaust. Interestingly, HF is typically only evolved when processing a discarded toothpaste tube!

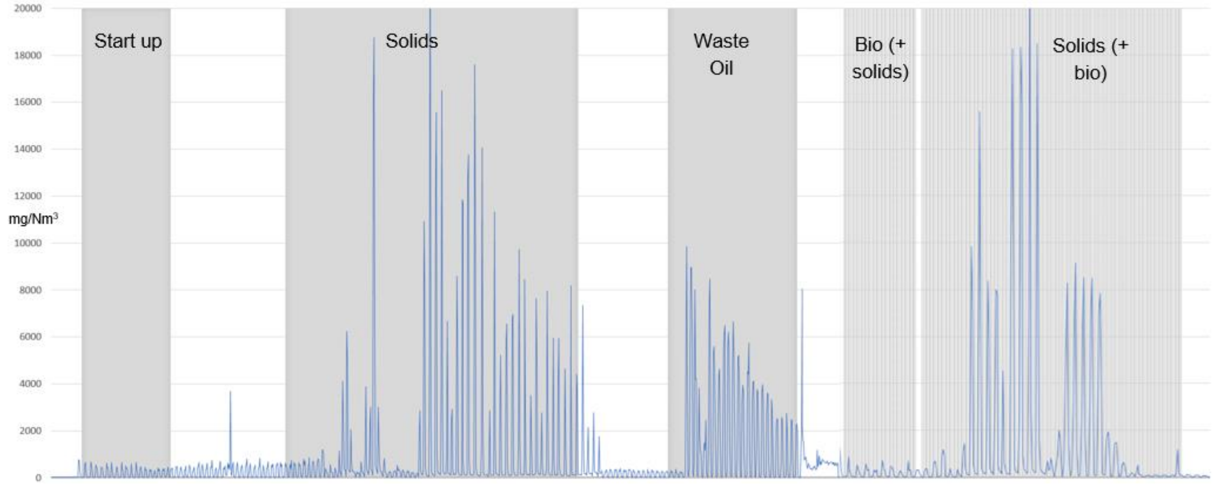

Figure 8: CO Exhaust measurements on HMS Prince of Wales

6. Recent developments

The challenging build programme for the carriers resulted in the IWMS being accepted into service without all elements fully commissioned. Recent efforts have focussed on commissioning and demonstrating the integrated and automated operation of systems to process food and bio sludge through the pyrolysis plants (i.e. the right hand half of Figure 5), which has been made more complex by the variable and unpredictable consistency of the waste being generated. This has been a joint endeavour between the RN, the MOD, Babcock, Pyrocore, BAE, Evac, the OEMs of the various sub-systems, and Lloyd's Register – and resulted in mixed food waste and bio sludge being processed through the pyrolysis plant for the first time in the third quarter of 2021 – this also enabled the exhaust testing as described in Section 5.

Concurrently, the support enterprise has been gathering operational feedback and undertaking a programme of design changes on the pyrolysis plants to improve their availability and safe operation; particularly to apply the improvements realised on the HMS Prince of Wales plants back onto the HMS Queen Elizabeth plants, as described in Section 3. The changes are as follows (with reference to Figure 9):

1. Replacing the gasifier access panel and its integrated insulation, with a split design to aid removal (both ships).
2. Fitting a new Perspex inspection hatch to the waste feed to aid fault finding.
3. Upgrading the waste inlet with a pair of pneumatic knife gate valves, to provide a more effective airlock.
4. Replacing the main gearbox and bearings to improve availability.
5. Replacing a fabric gaiter with a stainless bellows to prevent air ingress.
6. Fitting retaining clips to prevent the insulation from shifting.
7. Replacing the PLCs, which are obsolescent (both ships).
8. Upgrading the char removal system to positively extract char from the outlet (both ships).
9. Fitting "slam shut" valves to the air inlets to provide a more effective airlock when in emergency shutdown.

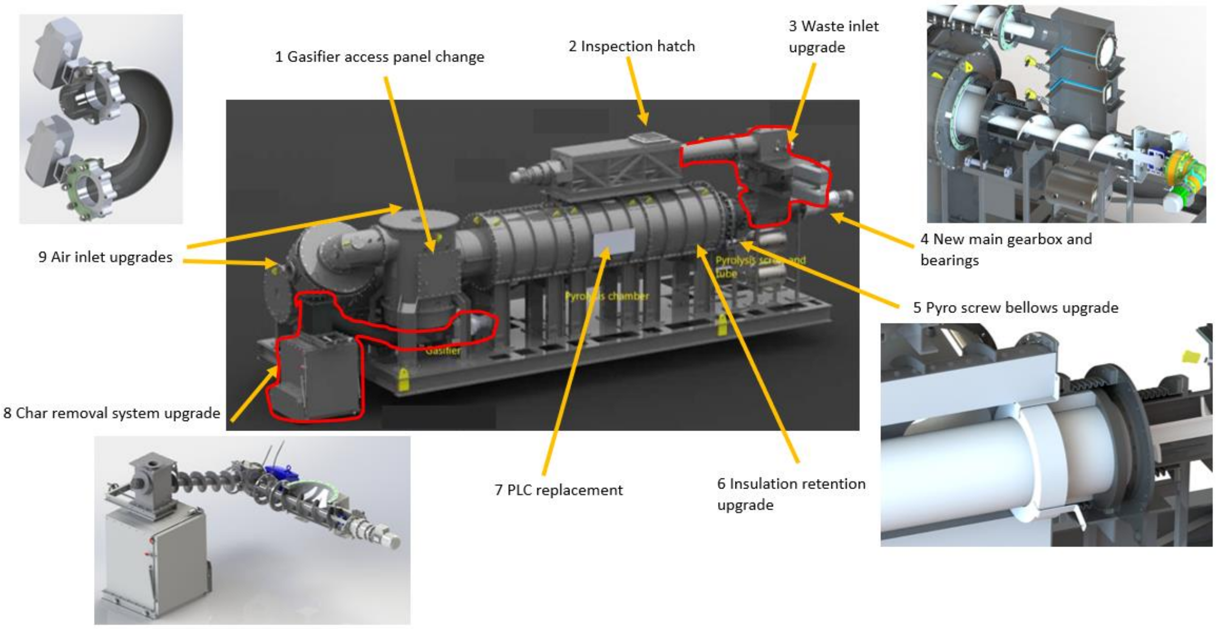

Figure 9: Pyrolysis plant design changes © Pyrocore Ltd.

7. Looking to the future

There is a strong ambition across the enterprise to realise the full capability of the IWMS incorporating the pyrolysis plants, and there is a planned programme of work to bring this to fruition for both ships of the class. Further trials and commissioning activities are being planned for 2022/23 to realise a fully operational food and bio sludge feed system for the pyrolysis plants, which may include trials at sea to provide a fully representative operational environment. Meanwhile, the design changes detailed in Section 6 are in planning for fitting onboard during the various periods of ship availability in the coming months. Scheduling is being driven by a desire to maintain capability of both plants when at sea, the capacity of ship’s staff and Pyrocore to install the changes simultaneously, and physically deconflicting the upgrade packages to ensure a safe fitment programme.

Further design improvement investigations are planned as follows; pyrolysis plant process control improvements and options for exhaust abatement to improve compliance with the IED limits, improvements to the solid waste shredding and feed systems to improve system availability, and mechanisms to dewater the food waste in the holding tank to improve the efficiency of the subsequent processing systems.

8. Conclusions

The IWMS represents a key capability for the QEC aircraft carriers; it safeguards the freedom of navigation for the ships in the future, delivers safe and effective waste management for the sailors, and minimises the impact on the carriers’ operational spaces through dense colocation of the equipment in dedicated compartments.

Significant steps have been taken in developing this unique marine capability through the design, commissioning, and in-service phases of the design lifecycle, with operational feedback and shore trials both contributing to the evolution of the system through the design change process, reinforcing the environmental and sustainability benefits to the RN. Continuous development is being undertaken, which is further improving the environmental and through-life sustainability benefits brought by the integration of pyrolysis technology into the ships waste management system.

This capability is being effectively delivered for the RN and MOD by Babcock under the Marine System Support Partner contract, supported by close relationships with Pyrocore Ltd., Evac, and BAE – and should be recognised as a successful example of cross-enterprise working.

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The views expressed in this paper are that of the authors and do not necessarily represent the views and opinions of Babcock International, Pyrocore Ltd., the MOD, or the RN.

Acronyms/Abbreviations

A	Ash (referred to as char throughout) (Figure 2)	MBR	Membrane bio reactor
AW	Aviation waste (Figure 2)	MEPC	Marine Environment Protection Committee
BS	Bio sludge (Figure 2)	MOD	Ministry of Defence (UK)
BW	Black water (Figure 2)	N2O	Nitrous oxide
CO	Carbon monoxide	NAM	Navio aeródromo multipropósito (multipurpose aircraft carrier)
CO2	Carbon dioxide	NOx	Nitrogen oxides
DE&S	Defence Equipment & Support (UK MOD)	nm	Nautical mile
EU	European Union	OEM	Original equipment manufacturer
FW	Food waste (Figure 2)	OPV	Offshore patrol vessel
G	Glass (Figure 2)	OW	Oily water (Figure 2)
GW	Grey water (Figure 2)	P	(MBR) permeate (Figure 2)
GGW	Greasy-grey water (Figure 2)	PCB	Polychlorinated biphenyls
HCl	Hydrogen chloride	PLC	Programmable logic controller
HF	Hydrogen fluoride	QEC	Queen Elizabeth class (aircraft carrier)
HMS	His/Her Majesty’s Ship	RN	Royal Navy
HVAC	Heating, ventilation, and air conditioning	SO	Sludge oil (Figure 2)
ID	Induced draft (fan)	SO2	Sulphur dioxide
IED	Industrial Emissions Directive	SOx	Sulphur oxides
IPMS	Integrated platform management system	SW	Solid waste (Figure 2)
IWMS	Integrated waste management system	T45	Type 45 destroyer (RN)
LP	Low pressure (air)	TOC	Total organic compounds
MARPOL	International Convention for the Prevention of Pollution from Ships	UK	United Kingdom

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