

A Lean, Mean, Green Atomic Queen? - The ultimate mission module

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Synopsis

The Queen Elizabeth class is an amazing asset for the Royal Navy which provokes endless operational debate about planes, ramps, catapults, propulsion, etc. It is well known that she is a long-life, upgradeable, flexible asset, with a large hangar, large flight deck, and large electrical power system. As one of the world's largest integrated full-electric propulsion warships, there are many questions about why her grid was conventionally powered, not nuclear, with answers such as cost, maintainability, disposal, and entering nuclear free zones cited as various reasons. This paper, authored by the QE power system designer, poses the idea, why not make her nuclear? Not with a big, costly refit, or billions of pounds, but over a weekend. She has the unique flexibility with her electrical power system for that not to be a crazy notion.

Small, containerised micro nuclear reactors are coming; many are in development and testing, with a number of companies looking to containerise them and place them in neighbourhoods around the world, of course managing the safety case around these modular micro reactors.

If you can drop it off a truck into a neighbourhood and plug it into a grid, then why not fit it into a warship that is already electric and already has a high-power plug on her power system, waiting for such innovation? Ratings of such units are quoted as 2-20MW, ideal for a ship's microgrid like those on the QE. This paper discusses and suggests the realistic application of modular micro reactors for the QE, from a size, system integration and decarbonisation perspective.

Containerised, fitted in the hangar, integrated into the power system, slashing the carbon footprint in a weekend, removable if you had a mission to a nuclear-free zone, well capable of providing a large amount of baseline and cruising power, refuellable in a weekend, developed and tested by industry with rapid insertion by a Navy.

Cruise nuclear, sprint conventional, perhaps; parallel operation of conventional and nuclear prime movers are eminently possible. It opens up all sorts of possibilities, which will be explored in the paper, from using excess power on board to manufacture e-diesel for the ship to powering Portsmouth when she is in harbour, rather than the other way around.

Imagine the Queen Elizabeth carbon neutral, reverse-RASing her escorts with e-diesel and telling her hometown, "When the Queen is in town, your bills go down."

Keywords: IFEP; Nuclear; Propulsion; Integration; Marine systems; QE; Micro; Reactor; Container

1. Introduction: Decarbonisation and Density

Decarbonising is hard, decarbonising transport is hard, decarbonising land transport is difficult enough but decarbonising maritime is even harder. Perhaps only aviation is harder still. Maritime transport, for many vessels, has gone through an optimisation phase: can routes be optimised, can speeds be optimised, can vessels be arranged to run on fewer engines, more efficiently, can engine speeds be varied to suit economical engine speeds, rather than speeds required by the propeller.

Electric propulsion has played a key part in this for many vessels: the ability to operate fewer engines, more efficiently, share prime movers, gain even better performance by using energy storage, not to store the voyage energy but to further optimise the operation of the generator sets.

As well as allowing optimisation of the present, ships' electric grids offer a clear ability to host tomorrow's technology on platforms built today, not only new weapons, sensors, and mission systems, but accommodating the changing nature of some of these. There is a rush for directed energy weapons to counter new threats, and a key enabler for these is the electrical energy to power them.

The same is also true for the electrical energy production. Whilst such systems allow prime movers to be optimised, they also allow new power sources to be hosted on existing networks, whether this is new fuels in existing engines, and the ability to cope with any associated transients and different combustion characteristics, or

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whether the new sources are solid state fuel cells or flow cells, or energy storage, kinetic or chemical. It's a compelling argument that many new sources will be integrated and interfaced electrically rather than mechanically.

The other great challenge to the maritime sector is the [lack of] power density of not only energy storage, but cleaner fuels, such as hydrogen. These fuels may make a large impact in decarbonisation, such as hydrogen from renewables, burnt cleanly in turbines, stored in large tanks on land. Short duty-cycle transport, such as buses, cars and taxis, will no doubt benefit, but long-range shipping is a tougher challenge, and warships are tougher still, as they are long range, compact and fast.

They can only be optimised so much, and it may take a while for green fuel energy density to be high enough to compete with diesel. Of course, high performance maritime has struggled with even the energy density of marine diesel, which limits the range of SSK submarines and means replenishment tankers are never far away from warships.

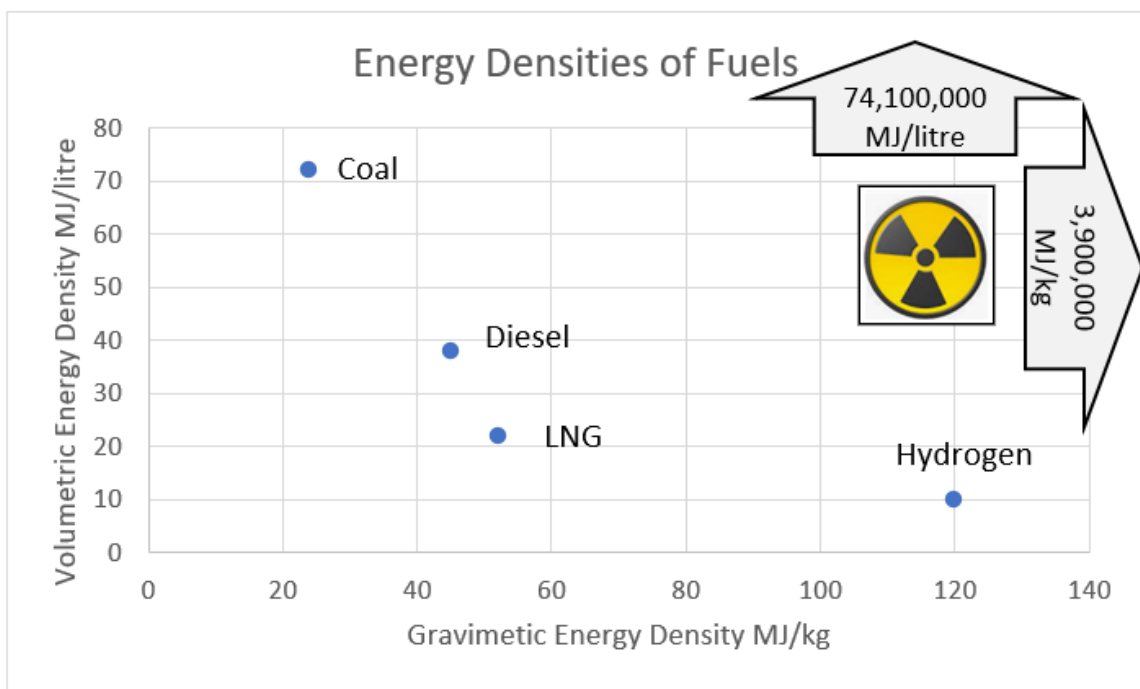


Figure 1: Volumetric and Gravimetric Densities of Marine Fuels

Surprisingly hydrogen is the most power dense fuel you can get, its 3x more power dense than diesel, but unfortunately that's by weight, and hydrogen sits at the light end of the periodic table. If you can liquify it, it's about one third the power density of diesel by volume.

Interestingly from the diagram in Figure 1, as the maritime sector transitions from coal to diesel to LNG and perhaps to hydrogen, it is moving from high volumetric energy density to high gravimetric energy density.

2. Extreme Transport Comparison

Table 1 is a simple comparison, between a 747 and its aviation fuel, the space shuttle and its hydrogen fuel and the QEC carrier and its diesel fuel.

Platform	Litres	Kg	MJ Total
Boeing 747	216,847	165,000	6,600,000
Space Shuttle	1,497,440	105,000	12,600,000
QEC	4,000,000	3,600,000	162,000,000

Table 1: 747 vs Space Shuttle vs QEC Fuel Tanks

The comparison ignores the solid rocket boosters on the Space Shuttle as it's the fuel tank in the middle that's of interest. A 747 in its tiny inboard tanks holds more fuel by weight than is in the Space Shuttle's hydrogen tanks, and amazingly almost half the energy, but the shuttle holds more, due to the energy density of hydrogen being much better, by weight. You wouldn't think looking at the fuel tanks below that a 747 carries half the energy of the space shuttle's large hydrogen tank in its hidden wing tanks.

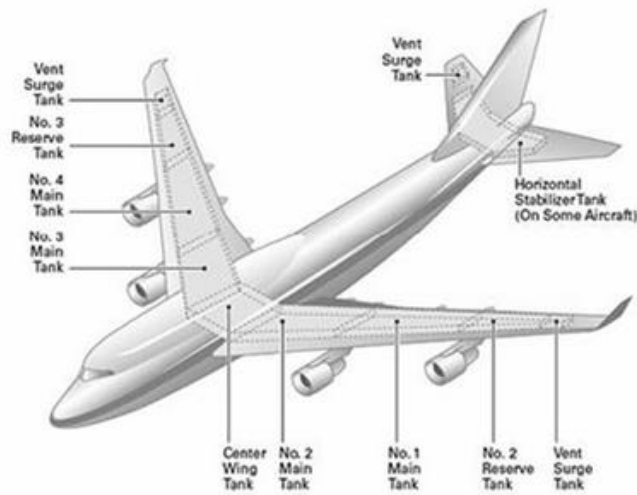


Figure 2 – 747-400 Wing-Integrated Fuel Tank Arrangement



Figure 3 - Space Shuttle (orange) Main Hydrogen Tank. Credit: NASA

If you have never thought about it before, it's one of the reasons why rockets have used hydrogen - so much more power dense than other fuels by weight, which is key for a rocket, and they live with the larger tanks. We don't bat an eyelid when the space shuttle sits on top of its massive fuel tank which dwarfs the orbiter, but of course we would find such a tank curious on a 747.

Shuttle engineers clearly prize weight over volume, and interestingly the huge extra drag of large fuel tanks at hypersonic speeds is tolerated, probably due to the short duration in the atmosphere. This is a simplistic comparison, and of course the space shuttle tank also includes oxygen which the 747 scoops up in its engine intakes.

One would however laugh at such large tanks on a ship, just to accommodate fuel. Normally ship designers worry about displacement being a factor on ships. Interestingly, hydrogen ships, with the same installed energy, would be much lighter, saving displacement and reducing fuel. However, the volume of the tanks would perhaps start to produce more air resistance and windage to the upper decks.

Based on the final values in table 1, the QEC energy comparison, using figures from the Royal Navy's website, is 13x the installed hydrogen energy capacity of the space shuttle, or 25 747s.

3. The Nuclear Ace Card

To be really power dense, you need to look at the other end of the periodic table. The heavyweight elements are where the real volumetric power density lies. Navies have always had an ultimate ace card if you can afford, build and maintain it and live with its special challenges: that's to go nuclear. With an energy density by volume of 39,000,000 compared to diesel, uranium is a clear winner.

So this is the other end of the scale. Now you don't really need a fuel tank as such, you have a fuel tank that is often filled only once at the build of the vessel. Of course filling up with nuclear fuel is an expensive business, hence the emergence of nuclear electric, to allow even the almost limitless energy, be used more efficiently and last longer, so it doesn't have to be refuelled mid-life. So nuclear electric has a future, not just in large thermal power stations, but in smaller and smaller installations.

- Large thermal power stations need electricity to distribute their energy.
- Next generation submarines need electricity to up their efficiency.

4. Nuclear Micro-Reactors

The world is starting to see a huge amount of development by many different countries and companies in small "micro" nuclear reactors. There are an array of different technologies, but these are generally small, "intrinsically safe" micro reactors that can produce for example 0-10MW rather than hundreds of MW. This is not a paper about the different technologies of these reactors, more of the potential basic application of these reactors, whichever technology wins out. There is real commercial momentum to develop and fit these units for distributed generation to act as neighbourhood generating sets that don't need refuelling, or replacing batteries that never need recharging. The expectation is that these reactors will be containerised in a [ISO] standard 40 or 45 feet container; perhaps one or two containers per location.

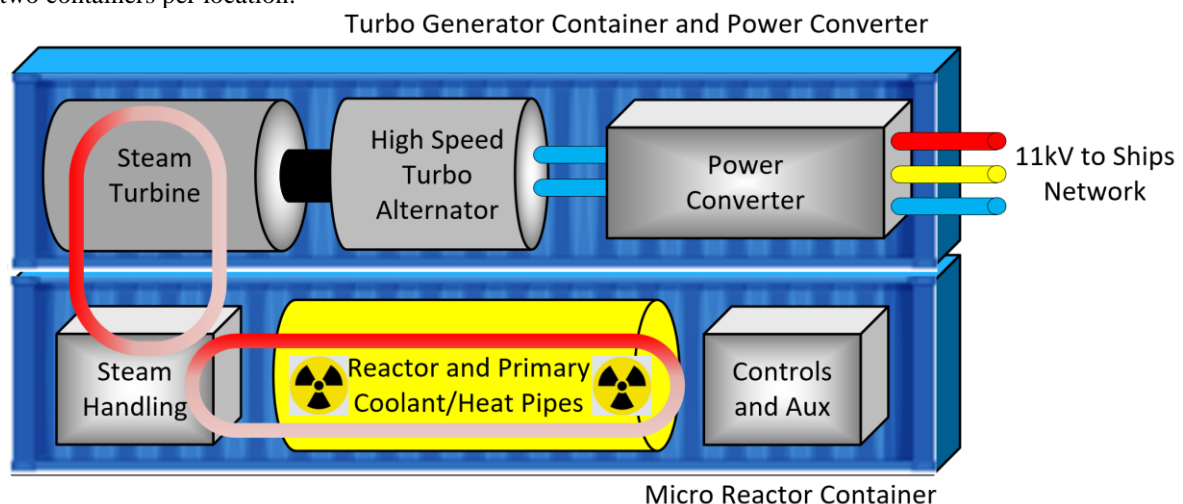


Figure 4 - Basic Layout of a 2 Container Micro Reactor

The expectation is they will consist of self-contained, truck-transportable modular units, probably in pairs. One would probably be a thermal container, containing the reactor, the protection and the steam raising plant, the second would be the steam turbine, high-speed generator and the power conversion machine to produce a voltage suitable for the network.

Almost certainly a high speed genset would be used, these are generators where, due to the uses of a power convertor, the speed of the machine is not determined by the electrical frequency, which allows the possibility of higher speed gensets, producing either DC directly or high frequency AC into the power convertor stage. The expectation is that the safety case and the intrinsic design will make these reactors suitable to be located in neighbourhoods and not requiring a classic large containment vessel. The author does not wish to debate the safety features of individual companies' designs, and the overall safety case, but simply to say that if it gets approved for the neighbourhood, then a more controlled environment such as a naval base or a warship should be justifiable. Clearly neighbourhood units would have to be considered for impact damage, vandalism, and in certain areas in the world, "recreational" gunfire, which convertor, energy storage, solar and wind installations are subject to from time to time.

5. Neighbourhood Nuclear Warships

Fast forward a few years when neighbourhood micro-reactors are available and have been safety-certified in the field. How could these be applicable to decarbonising warships and what do you need to consider for a retrofittable containerised micro reactor on a warship? You need an **electric ship** to interface into, such as the Albion Class, Type 45 or the QE Class. You need space, so that might be a challenge for a Type 45 without sacrificing the hangar, but Albion and QEC have large spaces and flight decks. You also need the requirement for a lot of electrical power. HMS Queen Elizabeth has to be a candidate as she meets all of these criteria.

6. Queen Elizabeth (Class) (QEC) – Not Nuclear...Initially

The author was an integral part of the power and propulsion design team for the QEC, and one line in the specification caused the most clarity, as well as the most questions for the next 25 years: “*QEC will not be nuclear powered*”. Associated with this were many facets of cost, performance, refuelling, handling, ports, safety case, etc. The other decision was, if not nuclear, then she should be electric, such as many complex vessels of high tonnage are, for example Queen Mary 2 cruise liner, etc, to maximise flexibility and energy efficiency.



Figure 5 - HMS Queen Elizabeth - A 110MW Power System with a Large Flight Deck and Hangar
(Credit: crown copyright 2020)

Another inherent enabler with electric ships is their upgradability and flexibility to host future power and mission equipment. If you install a full electric grid on a vessel, you can change prime movers and energy sources through life, as well as mission systems, sensors and weapons at the consumption end. This paper outlines the opportunity to consider one of these technologies, the micro/modular reactor, which has an external electrical interface at high power, exactly as QEC has the capacity to receive it.

Figure 6 is the public domain single line diagram for the QE class power system, used in a number of different papers. The system distributes at 11000V AC, with transformers to drop the voltage down to ship services at 440V and propulsion at 4160V. The network was designed with future upgrades in mind, so there are a number of spare breaker compartments around the switchboards.

The high-power connections were also provided for an EMCAT or EMALs¹ system to be fitted as part of a future upgrade, either for full scale jets, after the F35B, or for smaller and more numerous manned or unmanned platforms. So the microreactor containers could readily interface into the ship's power network. Two containers would be required for each system module, one for the reactor, one for the electrical generating plant. As well as the EMCAT feeders there are spare breakers on board and the port and starboard shore connections could also be used as additional power connections at sea. So the system is ready to receive at 11kV-level large amounts of power input or output.

¹ Electromagnetic catapult or aircraft launch system

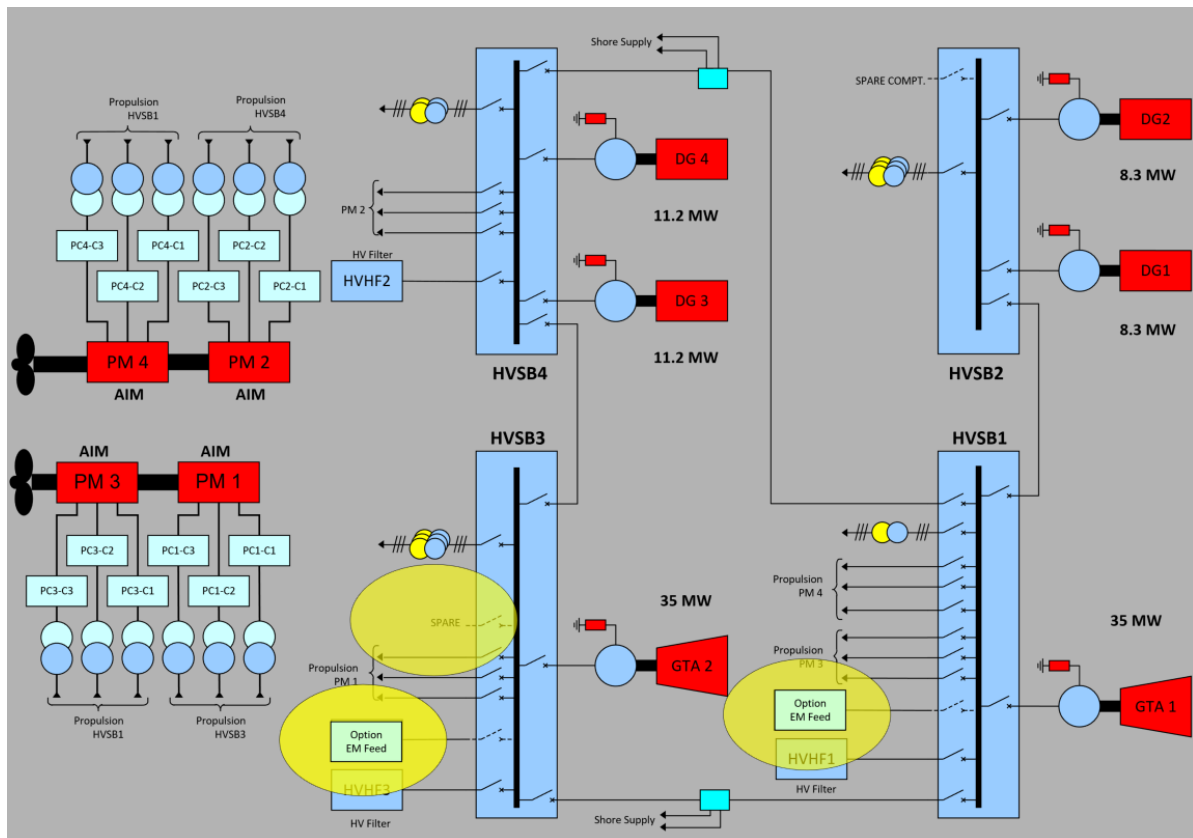


Figure 6 - Existing QE Class Single Line Power Diagram

7. Fitting the Containers Onboard

The units are claimed to be fully self-contained, not requiring any external cooling, but it's not the end of the world if some ship's cooling were required to be made available. It takes two to three days to unload a 10,000 container ship, that's about two a minute. If containership ports can unload two a minute with the right equipment off a cargo ship, even if we add a margin of 2000x, that is still a single weekend to drive some containers onto an aircraft carrier hangar.

Where to put the containers? The hangar is the obvious choice, but they could also potentially be on deck, away from the flight areas. To position and cable up two containers is expected to be undertaken in a matter of hours in the neighbourhood reactors, depending on the cable interface preparation. Trucks could potentially drive the containers straight into the hangar and unload them, like they would in the neighbourhood. Many sea trials have taken place with containers in the hangar or even on the flight deck at times. As far as connection is concerned, the expectation of the neighbourhood containerised solution is that they would be completely self-contained and simply plug in by a power cable into the grid, so the expectation here is the same, an 11kV cable would connect into the ship's power network and other services would not be required. Of course, we will see whether there is local air ventilation required, which may or may not be dissipated within the hangar space, should it be required.

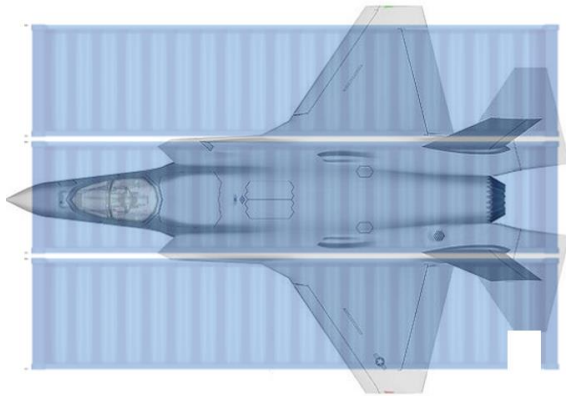


Figure 7:
ISO containers compared to the plan view of an F35

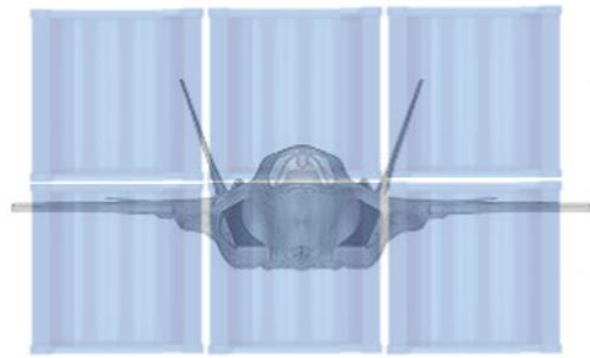


Figure 8:
ISO containers compared to the front view of a F35 aircraft

How much space would they take up? Figure 7 indicates the relative space of three 45-foot standard ISO containers, taking up similar space to a F35C aircraft. The frontal view is also shown in figure 8, a little off the ground to allow for the undercarriage.

Actually, the QEC has a much higher hangar in places than is required for simply parking the F35, so figure 9 is perhaps a bit more relevant, which shows the approximate maximum hangar height declared, and using HiCube taller containers.

So, give or take a little, and notwithstanding considerations such as weight, there is space to fit around nine HiCube 45-foot ISO containers in the footprint of a single F35. The power densities claimed by these reactors vary – one to 10 MW per container. These are large containers, at 45-foot and HiCube, so let's assume a pair delivers 5MW, then for the space of an F35 you could potentially deliver over 20MW. If we take the mid-range estimate of 10MW, that would be 40MW. This is a serious amount of electrical power, even for this large ship, certainly capable of running the ship at cruising speeds without the other prime movers.

The aim would be not to replace the prime movers and fuel tanks, it would be simply to supplement them. It would make the system like a super hybrid vehicle: running around most of the time on zero carbon, full-electric power and, when required, sprint using diesel. The full-electric system on the QEC would allow this seamlessly to happen.

So, in principle, within one parking spot of an F35, installed, or removed in a weekend, the QEC could be made conventional or nuclear, or both, as the mission requires.

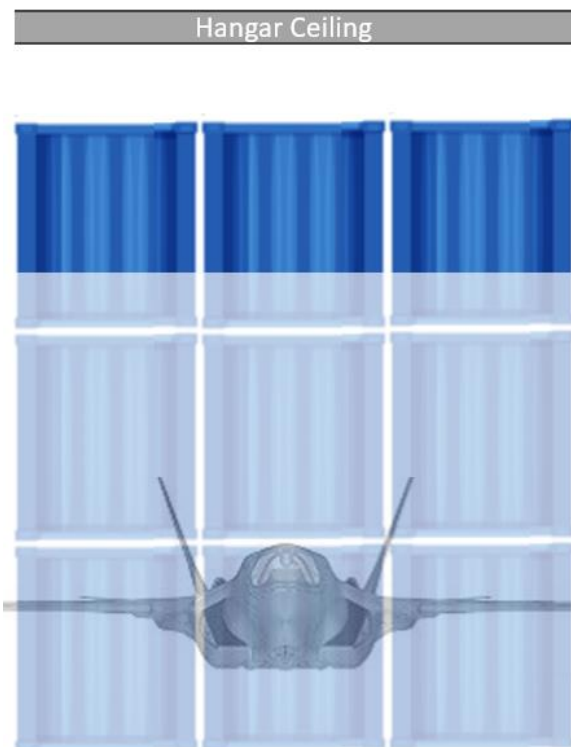


Figure 9 - nine ISO Containers in the QEC hangar footprint of an F35

As with any radical proposal, there are a number of things to consider - logistics, hearts and minds, safety - but the technologies are coming, and fast. It's true to say that soon we will be able to drive a nuclear reactor onto the QEC hangar deck and plug it in, and produce serious power, making the QEC, for large parts of its mission, emission free. This is very different as a proposition compared with existing, expensive, fit-for-life nuclear, such as in submarines and other navies' carriers.

8. Considerations in Warship Applications

They could be “peacetime” nuclear batteries, that could be removed in conflict rapidly if required. They could even be considered ejectable under damage conditions, such as aircraft and bombs have been onboard aircraft carriers after battle damage. Another lesson from Star Trek, in times of trouble they often eject the warp core at early signs of danger.

The ship could run around full of diesel ready for operations, but not consuming it until required, significantly not only reducing emissions, but also removing the requirement to be chased by oilers so closely. Of course the power could be used to charge and recharge drones, available for DEW, propulsion, single engine operation, just like an infinite capacity HV battery.

When the ship goes into port, a shore supply would no longer be required, although you might want to still connect to the shore supply in order to export power into the land-based network. Imagine how popular it might be that whenever the QEC came into port, it halved everyone’s electricity bill in the city?

It also opens up the possibilities of the production of synthetic fuels on board from waste carbon, electricity and water. Fuels such as hydrogen, methane, ammonia or eventually even e-diesel, could be produced and burnt in the existing QEC machinery, some would require space for bunkering on board, others could use or be mixed in the existing tanks. In the future this could mean that perhaps the QEC could refuel its own tanks, in port or underway. Why stop there? If the ship produced its own liquid fuel, why couldn’t it reverse RAS² that to its escorts, pumping fuel to the smaller ships instead of receiving it from the oilers? With electric ships, not only could you transfer fuel, but you could also transport electricity, so escorts such as a Type 45 would be emission free whilst connected to the carrier, a sort of “electric towing”.

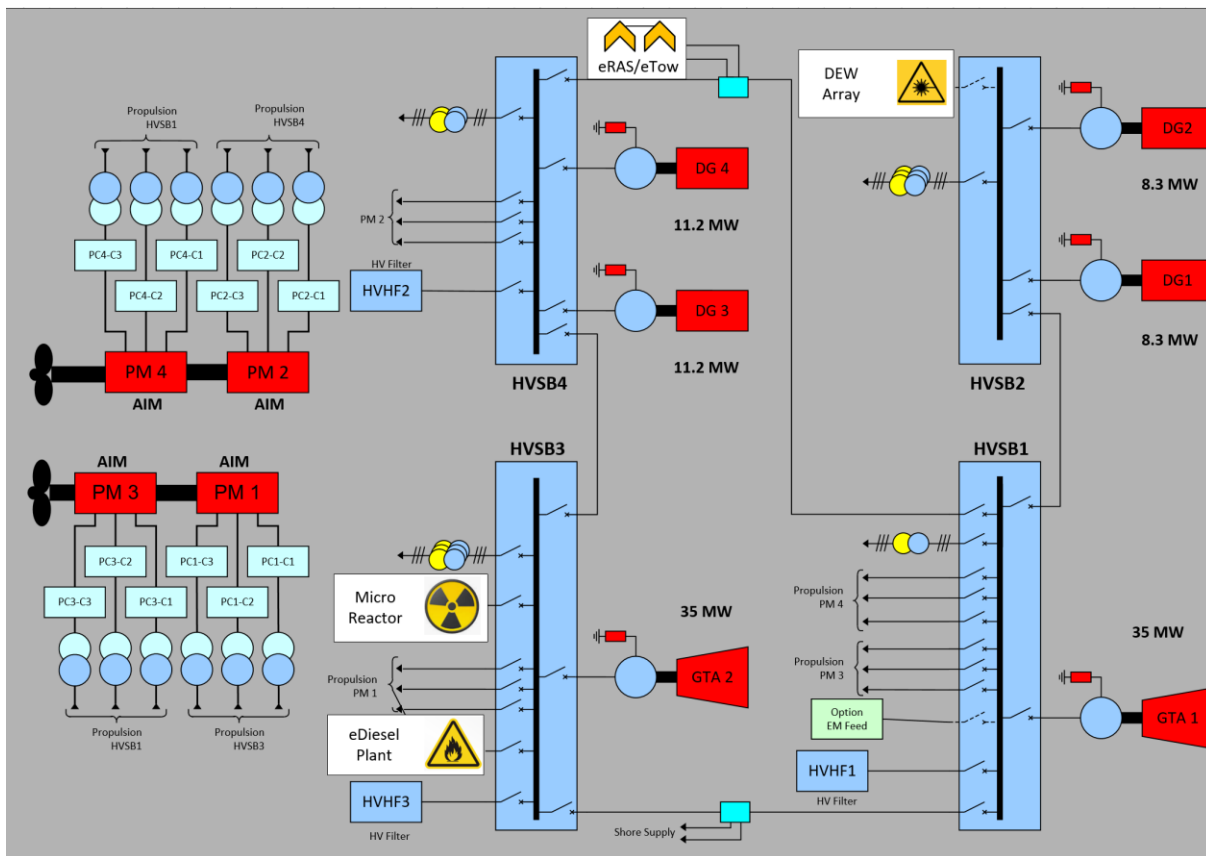


Figure 10 - QE Single Line Diagram with Micro Reactor, eDiesel, eRAS eTow and DEW Arrays

² Replenishment at sea

Figure 10 shows the addition of Micro Reactors, eDiesel Plant, eRAS, eTow and Directed Energy Weapon (DEW) arrays, without any extra breakers or modification to any of the existing power system. It shows the flexibility of the existing IFEP installed network.

Could we devise a system where the carrier could move the containers to an escort if required, at sea? Chinooks can lift 10 tonnes, so it's not impossible. Could we see a system where the carrier can propel its escorts for longer than just RASing? A true mothership. A sort of electric towing."

The micro reactors would be modular; one set could be moved from HMS Queen Elizabeth to HMS Prince of Wales, depending on deployment. Half a set could fit HMS Bulwark. A quarter of a set could fit a Type 45, the electric ships could all take them, even the hybrid-electric configurations of Type 23 or Type 26 could cruise on nuclear if you used the hangar.

It isn't clear at the moment what the costing of the different reactors would be, but as they are aimed at commercial neighbourhoods for use potentially as boost or emergency power supplies to add additional capacity, the expectation would be that they would be compatible with naval fuel costs for ships such as the carriers.

The containers potentially represent ship-sized super batteries, with perhaps a five or 10-year life with no requirement to recharge on board. When expended the containers would be replaced with new ones, that have been refuelled on land. Ships are seeing challenges with conventional batteries' energy density, old nuclear is very expensive and very restrictive, emission targets are getting tighter, hydrocarbons are becoming more expensive. Such small nuclear systems should be seen as super batteries, perhaps not AAA or even D Cells, but perhaps NNN Cells, which could easily be added to ships that are already electric, as much of the UK fleet is. As mentioned previously, they could be shared between ships, missions and could even potentially be passed from one ship to another in local and foreign ports, if required. They are intended to provide emergency support in neighbourhoods if there is power loss due to equipment failure, this could equally be the case here, if a prime mover were lost on an electric warship, the micro reactor containers could be deployed to temporarily replace that prime mover capacity to complete the mission or return to port.

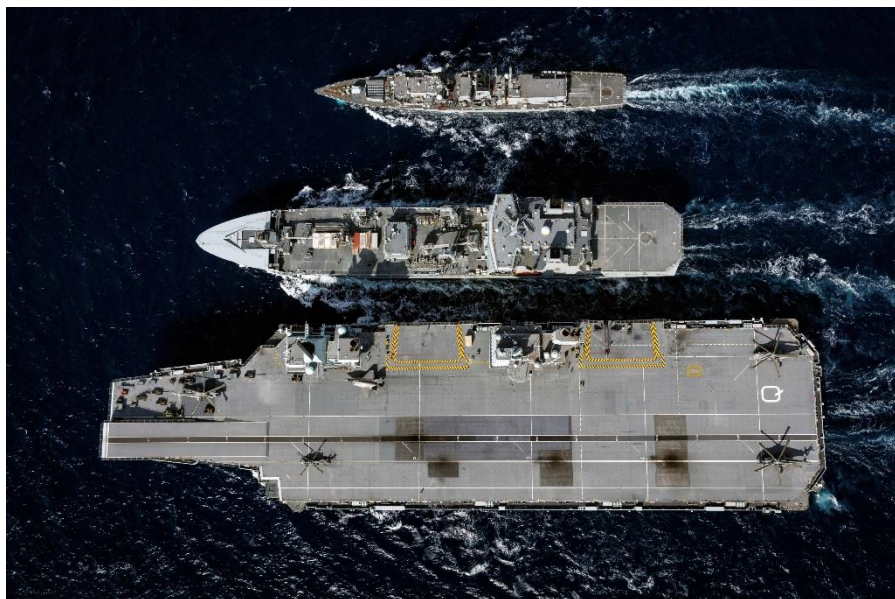


Figure 11 - Cut out the Middle Tanker and Reverse RAS eDiesel from the mother ship to the escorts
Credit: © crown copyright 2019

If the concept were taken to its ultimate conclusion and the ship used the micro-reactors, not only for its own propulsion and electrical power, but used any excess capacity to make eDiesel, then fewer support tankers would be required, and literally we could cut out the middle man and reverse the fuel flow, so the carrier becomes truly a mothership that could download fuel to its escorts by RASing and during this operation could export electrical power too. This could have a fundamental impact on the tanker fleet; clearly aviation fuel and solid provisions would still be required.

9. Pros and Cons

Pros

- Emission-free cruising power
- Huge reduction in carbon footprint possible, whilst maintaining lethality.
- Huge reduction in diesel fuel bill.
- An addition to present capabilities, none are removed. (except one F35 Space)
- Full diesel tank cruising in peacetime, so always at full capacity
- Dramatic reduction in DG set running hours, as well as GT.
- Technology development mostly done by the commercial sector.
- 10-year battery
- Deployed and removed in a weekend on the ship.
- Commonality with neighbourhood nuclear
- Minimal or no modifications required to the ship.
- Opportunities for e-diesel or other fuel production (If/When Available)
- Opportunities for reverse RAS
- Opportunities for no shore power requirements to achieve zero emissions.
- Opportunities to export power in port
- Electric towing
- Silent mode with no DGs or GTs running becomes possible.

Cons

- It's a mindset change.
- Civilian neighbourhood safety case would need to be transferred/upgraded to a warship.
 - At sea, in port, in peace, at war

10. Conclusion

Decarbonisation is hard, there are no easy options, warships can't compromise lethality for emission reduction, nor can they afford to be tied to fossil fuels for the long term. The technology is coming, we need to be brave enough to apply it safely sometimes. It's a mindset shift, but this proposal is not decades away, it's years away. It's a great example of the flexibility of electrical warships. When the Author was involved in designing the QEC Power system we fitted a large grid and breakers to attach future tech. We had no idea we might consider a neighbourhood nuclear reactor connecting to one of those spare breakers, but it's perfectly possible.

It's an example of the upgradeability that electric ships really give you, the ability to accommodate the future, whatever it looks like and whenever it arrives. As electrical engineers, we don't have to understand all the detail within the container. It's interfaced electrically and we know the connections are already aboard HMS QE. As we decarbonise the world, we will always have to look for technology, there used to be huge gaps, but they are closing. Opportunities like this, the technology is coming, it's electric and soon the challenge isn't going to be technical, it's going to be hearts and minds and getting our heads around what it takes to accommodate the future.

Thankfully, due to its powerful electric grid, HMS Queen Elizabeth can sit and wait in the knowledge in the end, it just might be plugged in over a weekend, sometime in the future.

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The views expressed in this paper are that of the author and do not necessarily represent the views and opinions of GE Vernova's Power Conversion business.