Written History Paper

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This report was submitted by Rolfe Monteith and was developed over the period 2004-2006 by a group of retired UK civilian and Naval personnel all of whom were associated with the transition from steam to gas turbine. The original paper has been reformatted for this website posting and every effort has been made to faithfully record the original text.

Musings on Warship Propulsion Machinery

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ABSTRACT

Having pioneered the introduction of steam turbines for marine propulsion at the turn of the twentieth century, which greatly increased the propulsion power and speed of vessels, the Royal Navy in the 1960's again took a revolutionary step in abandoning steam propulsion for future surface warships and committing to aero derived gas turbine engines. This radical change of course did not offer such clear advantages as the earlier one had done and a main purpose of this article is to review the merits and demerits of the case for the change with particular reference to the unrealised potential offered by more modern steam plant. The article combines the contributions of a number of retired engineers who have had direct involvement in the design of marine propulsion machinery since the 1940's and knowledge of earlier developments of steam plant, which are briefly covered as an introduction.

Historical Development of the Steam Turbine

2. The development of steam propulsion systems and warships has progressed in parallel since HMS WARRIOR, the first ironclad and with Mr Penn's trunk engines, dominated the seas in the 1860's. When HMS DREADNOUGHT appeared in 1906, another great stride was made in battleship design and in the adoption of steam propulsion turbines, which reputedly saved over 1000 tons through replacement of the massive triple expansion reciprocating engines that had propelled earlier ships. The propulsion potential for steam turbines directly coupled to high speed propellers was revealed to the world by the great engineer Sir Charles Parsons through his dramatic high speed demonstration with the TURBINIA at Queen Victoria's review of the Fleet at Spithead in 1897. Such a demonstration was necessary because turbines had only been used up to that time for small auxiliary applications of up to 3OOkw and it did not seem feasible that they could challenge the supremacy of the massive reciprocating engines with powers ranging up to 10,000shp. The Admiralty was quick to follow up the potential shown by TURBINIA for the Navy and by the time of the battle of Jutland, only 19 years later, nearly all the participating warships were turbine powered.

3. Early steam turbines were directly coupled to the propeller shaft, which because of the high rotational speed would sometimes carry more than one propeller to reduce the blade loading and cavitation damage, as in the case of TURBINIA. An important development occurred shortly before the First World War with the introduction of gearing which allowed the turbine and propeller speeds to be optimised independently. This dramatically reduced the size and weight of turbines, increased their efficiency and also improved the efficiency of the propellers.

4. From his earliest designs of what were called 'Reaction Turbines', Charles Parsons had adopted a 'reaction stage' in which:

- Half the pressure drop occurs in the fixed blades attached to the casing, giving impulse velocity to the steam impinging on the rotor blades.
- Half the pressure drop occurs in the moving rotor blades, imparting a reaction force to the rotor blades through further acceleration of the steam flow.

His designs were conservative in using a large number of stages with small pressure drops, relatively low steam velocities and low blade speeds at optimum efficiency. The adoption of this reaction principle and its cautious application enabled production of turbines that operated at low stresses which were capable of large increases in output by simply scaling up in size without compromising reliability. From their immediate success he was able to establish a worldwide network of licensees.

5. Competition came from the American General Electric Company, who had taken over the pioneering Curtis turbine designs and then teamed up with the British marine engineering firm John Brown Ltd. to market marine propulsion turbines under the name 'Brown-Curtis'. These designs worked on the all impulse principle used by the Curtis Company, which in contrast to the Parsons type, had far fewer stages in which all the pressure drop took place in the fixed nozzles, so producing higher steam and blade speeds and intrinsically higher stresses. Initially they were very successful because they were more compact, simpler and cheaper to make than a Parsons installation of equivalent power and this led to Brown Curtis

taking a lot of Admiralty business; to the extent that half the British warships at Jutland were powered by Brown-Curtis machinery. This changed however when nemesis came with the introduction of gearing referred to earlier, which allowed higher turbine speeds.

6. The advent of gearing allowed two turbines to be connected; a small high pressure, high speed cylinder expanding into a larger low pressure, low speed cylinder, positioned side by side and driving into the connecting gearbox in what is known as a cross compound arrangement. Unfortunately for Brown-Curtis, knowledge of blade - rotor disc vibrations at that time was virtually non-existent and with the higher rotational speeds, their designs became subject to a series of such disastrous failures that they withdrew from the market in the early 1920's leaving the Parsons turbines with a virtual monopoly in steam turbine installations until the 1930's when their limitations of bulk and efficiency came under scrutiny. This led to the development by the US Navy of high speed, all impulse designs to power a range of ships built in a massive expansion prior to the Second World War. These turbines designed by the American General Electric Company performed outstandingly during the War, which led to wholesale adoption of their design principles for virtually all marine steam turbines thereafter.

Boilers

7. Water tube boilers had become accepted as the most efficient and responsive type of boiler at about the same time as the introduction of turbines. By 1939 the boiler types most widely used in the Royal Navy were Admiralty three drum and Babcock & Wilcox two drum sectional boilers, operating at conservative conditions. The first use of a twin furnace boiler to give greater control of superheat, particularly to maintain good superheat at part power, was in the Weapons class destroyers in the mid 1940's. A few ships were completed, including Battleaxe and Broadsword but as the Second World War ended, most were launched and towed straight to the breakers' yards.

8. The DARING class, a development of the Weapon class, was designed in the mid 1940's and a principal aim was to improve plant efficiency after the embarrassing experiences with Royal Navy ships operating with the US Navy in the Pacific, where poor fuel economy required more frequent replenishment than for US Navy ships. Steam conditions were therefore elevated to comparable American levels at the time, 44.8Bar and 454degC (650 psi. and 850degF), to improve cycle efficiency. Two types of twin furnace boiler were adopted; Foster Wheeler D Type and an upgrade of the Babcock and Wilcox Weapons class boilers. These were also the first Royal Navy ships with double reduction, hardened and ground gearing.

9. Later, simplified single furnace boiler units with controllable superheat (the ' Y 100' series) were designed for several classes of ships. The highest steam conditions reached were 47Bar and 510degC (700psi and 950 degF) in the Y102A boilers of the County class destroyers. In comparison, the highest conditions reached in the US Navy were 87.9Bar and 521degC (1275psi and 970degF) in what became known as 'the 1200 pound plant'. The degree of superheat was very similar but the higher pressure of the US plant, although offering an efficiency advantage of 3.5% (6% relative), gave rise to some reliability problems.

10. The last operational steam warship in the Royal Navy, HMS FEARLESS, an LPD ship type designed for amphibious assault, also using Babcock Y100 series boilers, decommissioned in 2001. Delivered in 1967, she was destined for the breakers along with her sister ship INTREPID in the wake of the 1981 Defence Review until hurriedly brought back into service for the Falklands Campaign, in which both ships served with distinction, returning safely after the victory and demonstrating the resilience of steam machinery. It must also be said that gas turbine ships also performed with distinction demonstrating a parallel resilience to steam ships in coping with battle damage. The table below summarises the steam powered Fleet of the Royal Navy from the 1950's through to 2001 when HMS FEARLESS decommissioned.

TABLE 1 - Steam Warships of the Royal Navy post World War 2 and 'O' Class RFA's

CLASS	BOILERS	ENGINES	REMARKS	BUILT
LOCH Class Frigates	2 Admiralty 3 Drum	4 Cyl triple expansion; 2 shafts; 5.5Kihp	225 psi	Laid down 1940's; Completed 1940's
Fleet Aircraft Carriers	8 Admiralty 3 Drum	Parsons geared turbines X cmpd; 4 shaft; 152Kshp	400 psi 750 deg F	Laid down 1940's; Completed 1950's
Fleet Aircraft Carrier VICTORIOUS	6 Foster Wheeler D's	Parsons geared turbines X cmpd; 3 shafts; 111Kshp	650 psi 850 deg F	Laid down 1930's; Completed 1940's Updated 1950's

Light Fleet Carriers	4 Admiralty 3 Drum	Parsons geared turbines X cmpd; 2 shaft; 76Kshp	430 psi 700 deg F	Laid down 1940's; Completed 1950's
TIGER Class Cruiser	4 Admiralty 3 Drum	Parsons geared turbines X cmpd; 4 shafts; 80Kshp	430 psi 750 deg F	Laid down 1940's; Completed 1950's
BATTLE Class Destroyers	2 Admiralty 3 Drum	Parsons geared turbines X cmpd; 2 shaft; 5OKshp	400 psi 640 deg F	Laid down 1940's; Completed 1940's
'CA' Class Destroyers	2 Admiralty 3 Drum	Parsons geared turbines X cmpd; 2 shaft; 40Kshp	300 psi 640 deg F	Laid down 1940's; Completed 1940's
Type 15 Frigates; ex T, U, V & W's	2 admiralty 3 Drum	Parsons geared turbines X cmpd; 2 shaft; 40Kshp	300 psi 640 deg F	Laid down 1940's; Completed 1940's; Updated 1950's
DARING Class Destroyers	2 B&W or 2 Foster Wheeler 4 ships each	Parsons geared turbine X cmpd; 2 shafts; 54Kshp	650 psi 850 deg F	Laid down 1940's; Completed 1950's
Type 14 Frigates	2 B&W Y100	Single cyl all impulse geared turbine; 1 shaft 15Kshp.	550 psi 850 deg F	Laid down 1950's; Completed 1950's
Type 12 Class Frigates	2 B&W Y100	Single cyl all impulse geared turbines; 2 shafts; 30Kshp	550 psi 850 deg F	Laid down 1950's; Completed 1950's
COUNTY CLASS Destroyers	2 B&W Y102A	X cmpd all impulse geared turbines; 2 shafts; 32Kshp max cruise; 4 G6 GT boost 7.5Kshp each	700 psi 950 deg F	Laid down 1960's; Completed 1970's
'0' Class Fleet Tankers	2 B&W	Pametrada all impulse X cmpd geared turbines; 1 shaft; 26.6Kshp	750 psi 950 deg F	Laid down and completed mid 1960's.
TRIBAL Class Frigates	1 B&W Y100	Single cyl all impulse geared turbine; 1 shaft; I5Kshp; 1G6 GT 7.5Kshp boost	550 psi 850 deg F	Laid down 1950's; Completed 1960's
FEARLESS Class Assault Ships	2 B&W Y100	Single cyl all impulse geared turbines; 2 shafts; 22Kshp	550 psi 850 deg F	Laid down and completed 1960's
LEANDER Class Frigates	2 B&W Y100, Y136, Y160	Single cyl all impulse geared turbines; 2 shafts; 30Kshp	550 psi 850 deg F	Laid down 1960's; Last completed 1970's
Type 82 Destroyer BRISTOL	2 B&W Y102A	Single cyl all impulse geared turbines; 2 shafts; 30Kshp; 2 RR Olympus TM1 A boost 15Kshp each	700 psi 950 deg F	Laid down 1960's' Completed 1970's,

11. It is worth adding that perhaps the most successful steam ships of this era were the 'O' Class Fleet tankers, which gave outstanding service in lives parallel with the LPD's, the last paying off in 2000. Designed to keep up with the Fleet Carriers, they had plenty of power and a maximum speed of 23 knots: their more complex successors, the WAVE Class are no match in this regard.

Comparison Between Gas Turbine and Steam Turbine Propulsion Systems

12. While a steam ship operating with isolation of fuel, steam and feed cross connections between shaft propulsion units, offers good integrity and part power redundancy, frigate sized vessels invariably operated with boilers connected and a problem with the feed or steam systems, unless dealt with promptly, which was normally the case, could compromise power to the Command. Gas turbines, being more compact and self contained as internal combustion engines, offer a potentially less vulnerable power source and with a four engine installation greater redundancy. However, they are intrinsically less reliable than steam plant, have a much shorter time between overhaul and are dependent on more complex and less reliable transmission systems or propulsors because of the lack of a reversing power turbine. Whilst a gas turbine change unit (GTCU) can be changed within 24 hours in a large ship at sea, for a frigate or destroyer, it generally has to be done alongside. Most problems with a steam plant can be sorted out at sea unless there is an exceptional failure.

13. The availability of Royal Navy gas turbine frigates and destroyers has been significantly affected by the unreliability of their controllable pitch propellers. Problems with gearing have also been greater than with steam ships but this is largely to do with the adoption of nitrided, hardened and ground gears. Ironically, gas turbines should have allowed a return to quieter, less highly loaded but larger and heavier, unhardened gears, because weight was no longer a problem. Indeed, had this been done, water displacement fuel systems, necessary to maintain stability in many gas turbine escorts, might have been avoided. The changes to electric propulsion are in part, a recognition of the problems experienced with elements of the propulsion systems since the adoption of gas turbines. In capital cost, a gas turbine propulsion system is very much more expensive than an equivalent steam propulsion system and overhaul costs ashore are high. However, at the time of the decision to adopt gas turbines, they did offer a lower manning requirement for operation and on board maintenance, which were major considerations.

14. From an efficiency standpoint, there was little to choose between the first/second generation aero derived gas turbines and contemporary steam plant. However, there had been an enormous and ongoing capital investment made by Government and Industry in the development of gas turbines, and there was a good prospect of continual improvement in the performance of new designs of engine. In contrast there

was a very small level of investment in conventional steam plant development, although the Royal Navy had made some significant advances with boiler combustion and automatic control systems. Taking benefit from the gas turbine investment was undoubtedly a significant factor in the decision to adopt gas turbine propulsion.

15. Thermodynamically, the steam plant using the closed Rankine Cycle offers fundamental advantages over the open cycle gas turbine: the ability to expand to a virtually full vacuum at a temperature of less than 50degC give it a potentially greater Carnot efficiency and the high pressure ratio and much larger specific enthalpy drop through the turbine of the working fluid means only a low mass flow is required. Being an external combustion process, fuel burning can be at a near stoichiometric air/fuel ratio, which limits the size of downtakes and uptakes for air inlet and exhaust and the heat released to atmosphere is mainly only that which cannot be exchanged in the boiler and economiser.

16. By contrast the gas turbine has to expand to atmospheric pressure at a much higher temperature than the steam turbine and it therefore has to gain efficiency through operating at a higher maximum cycle temperature. This temperature is limited by metallurgical considerations as it is for the steam plant but it is in the technology of compressor design, combustion, combustor and turbine blade cooling and the development of high temperature resistant nimonic alloys that the gas turbine moved ahead of the old marine steam plant in efficiency, despite its inherent disadvantages. However, it is more dependent than steam plant on high quality distillate fuel requiring extensive separation and filtration treatment.

17. The gas turbine requires a high mass flow of air (up to 5 times that for the stoichiometric air/fuel ratio), because of the low specific enthalpy drop available for producing power in the turbines. This is due to pressure and particularly temperature limitations required to contain the maximum cycle temperature within the metallurgical limit, demanding cooling of the combustion process with the excess air. This makes gas turbines sensitive to air inlet temperature and density changes, with significant power loss in tropical conditions unless down rated at lower temperatures. Large downtakes and uptakes are required which absorb valuable space, particularly in big ships like aircraft carriers where the engines are deep in the ship. This becomes another driver towards using electric propulsion, which allows gas turbines to be located higher in the ship with less loss of space for downtakes and uptakes.

18. The gas turbine also has problems with its noise and IR signatures. Because of the high air mass flow and open cycle, airborne noise is much louder than with a steam plant and there is also a dependence on noisier diesel engine electric power generation. Unlike a steam plant, where heat rejection in the working cycle is to the sea through the condenser, all heat rejection with a gas turbine is to atmosphere and the resulting high exhaust temperatures, mass flow and velocities give a much stronger IR signature. Regenerative cooling of the exhaust and air entrainment can reduce the IR signature somewhat and silencers, noise absorbing materials, enclosures and isolating mounts can reduce the noise signature but this is at the expense of additional cost and complexity.

Comparison Summary

19. The principal strengths of a gas turbine are:

- Its power to weight ratio and compactness, which allow upkeep by replacement and maintenance in repair facilities ashore.
- Its ease of control and low ship borne manning requirement for operation and maintenance.
- Rapid availability for full power and; good redundancy in multiengine installations.

The principal weaknesses of the gas turbine are:

- Its high capital and maintenance costs.
- Lower reliability than other prime movers.
- Dependence on more complex and costly arrangements for reversing.
- Need for large downtakes and uptakes.
- Its IR and noise signatures.
- Power sensitivity to air inlet temperature.
- Dependence on high quality distillate fuel.

The principal strengths of a steam turbine plant are:

- Lower capital cost and maintenance costs.
- Higher reliability.
- Durability.

- Defects generally repairable at sea.
- Lack of reliance on diesel electric power generation.
- Low detection signatures.
- Greater tolerance of poor quality fuel.

The principal weaknesses of a steam plant are:

- Historically higher sea borne manning and on board maintenance requirements
- Less compact.
- More complex controls.
- Length of notice for power from the shut down state.

Reflections on the Change to Gas Turbine Propulsion

20. After decades of operating gas turbine warships in the Royal Navy, few would challenge the decision to abandon steam, yet experience has not been as good as had been hoped at the time of the decision to change, for reasons mentioned earlier. With the relatively recent withdrawal of the last British steam warship, it is timely to review the experience and issues. FEARLESS demonstrated the viability and durability of steam propulsion over nearly 40 years of service despite her outdated design and resultant high manning requirement. The 'O' Class tankers did arguably even more so with their small complement and outstanding service over the same period.

21. Other navies still operate major steam warships, notably the aircraft carriers of the US Navy. In latter years, their replacement ships have been nuclear steam powered but a decision has recently been reported to again use conventional steam plant. Carriers are uniquely suited to steam propulsion because of their size and the advantages offered by steam catapults for aircraft launching. Gas turbines are not suited to carrier propulsion unless they can be installed high in the ship because of the lost space for ducting. Even when mounted in this way, there remains the problem of launching aircraft without steam catapults and the widespread and hot engine efflux at full power, which can interfere with flying operations. It is also worth recalling it was the Soviet Navy that was first to deploy all gas turbine warships with the KASHIN class in 1962, not the Royal Navy, and they have retained steam propulsion for their larger ships, such as the KRESTA's and their aircraft carriers and reverted to steam for the SOVREMMENY Class in 1981, using pressurised combustion boilers, which was an extraordinary acknowledgement of their faith in steam. The wisdom of abandoning steam propulsion for larger warships does not seem to be shared by the major navies.

An Attempt to Retain Steam Propulsion and Steam Technology Developments

22. During the 1970's a small group was set up by British Companies with an interest in marine steam plant to examine the case for retaining steam propulsion. An important impetus was the knowledge that the steam plants in western naval vessels did not take benefit from the developments that had taken place with merchant ships, where unmanned machinery spaces had been the norm since the 1960' s and maintenance requirements had been reduced to a low level by improvements in boiler design and the simplification of systems. In these ships, the machinery control was totally automated including full bridge control. It was felt that the old criticisms of high manning and maintenance levels no longer applied in the face of this experience but despite this, western European navies were no longer interested in steam.

23. Many of the factors detrimental to the case for steam propulsion related to boilers and it was essential to address these. Required to bum fuels of poor quality, boilers gained the reputation of being dirty and difficult to clean, becoming fouled on both gas and water sides of the heating surfaces. The downtime for boiler cleaning was a major element of the heavy on board maintenance load that was cheerfully left behind with the advent of gas turbines; although, the change to burning 'Dieso' in boilers largely obviated the need for external cleaning. Another maintenance problem was the need for repairs to the refractory materials used at the time to line the" furnace and hotter gas passages. By comparison, the maintenance load with gas turbines was unseen other than engine replacement because it was done in dedicated facilities ashore.

24. For merchant ships, a number of improvements in the design and construction of boiler plant was needed to compete with the slow speed diesel engine. This resulted in the development of high efficiency steam plants of 30,000 shp and above utilising a single main boiler. Improved combustion through adoption of steam atomizing burners, firing along the major axis of the furnace and provision of effective

soot blowers largely reduced external fouling and helped minimise deposits of sodium/vanadium compounds on superheater elements. The adoption of modem welding techniques transformed boiler construction and allowed removal of most of the refractory. Use of 'Dieso' as for the gas turbines, rather than Furnace Fuel Oil (FFO), dramatically reduces gas side fouling but even using much cheaper FFO, modem boiler equipment could cope far better than previously and would still compare favourably with the gas turbine in terms of maintenance.

25. Water and steam side problems have been addressed by adopting modern boiler water chemical treatments and efficient steam separators in the steam drum to ensure the superheater receives only dry saturated steam. Taking the whole feed, condensate, boiler, superheater and steam systems as an entity, the desired conditions at all points can be maintained with suitable electronic control systems to monitor and dose chemicals as necessary. The full application of reliable electronic controls is just as essential for the steam plant as it is for the gas turbine. To minimise manning, reliable control systems are a fundamental requirement to operate and optimise the performance of the steam plant under all transient and steady state conditions, including lighting up and shutting down. This has all been demonstrated in merchant ships.

26. Further improvements in the cycle efficiency of steam plant can be achieved through the use of topping superheaters and re-heaters immersed in fluidised bed combustors using nimonic materials, cooled HP steam supply pipes and condensate cooled turbine blades.

27. Whilst the main focus above has been on boilers and turbines, equal attention must be paid to the auxiliary systems serving them to ensure high reliability and the lowest maintenance requirement through using electric drives, well engineered equipments and minimising steam and exhaust ranges. Efficient and compact designs have been produced and integrated well into modern merchant ship plants unlike many former systems where the approach was often sub optimal, lacking in integration and unsuccessful in the requirement of disproportionate levels of upkeep. To show the potential of modern steam plant, a party of MoD engineers was taken on a short voyage on a large steam powered container ship of 82,000tons, 67sMw and capable of 32 knots. The ship had a crew of only 25, unmanned machinery spaces, bridge control and had operated for 8 years with no plant downtime other than for scheduled statutory boiler inspections.

Conclusions

28. It is evident that a modern steam plant using the developments described above could be employed successfully and competitively to power escort vessels, yielding substantial savings; though, it is recognised such a change of policy would be very unlikely unless the economic case became overwhelming; possibly due to the ever increasing cost of distillate fuel. However, whilst current intentions are to build two aircraft carriers, the most suitable and most cost effective propulsion plant to use undoubtedly would be steam because of its inherent advantages over gas turbine plant in this application in regard to space saving and steam catapults, as discussed earlier. It cannot be argued that the training and manning infrastructure costs of such a change would be too great because the 'Steam Navy' still exists in the nuclear submarine flotilla and has to be supported.

29. Regrettably, the Royal Navy continues to shrink in size despite the continuing demands made upon it and this trend can be expected to continue as long as the US is willing to carry the greater part of Britain's defence burden and that of other, European countries. With real terms decline of budgets and above norm inflation in the defence sector, it is essential to improve the cost effectiveness of the weapons and platforms that are procured. The policy change adopting aero derived gas turbines for all major warships was essentially based on qualitative judgements of a number of factors, which did not seem to include a rigorous cost appraisal. In regard to large warships and particularly aircraft carriers, the wisdom in adopting gas turbines has not been shared by major navies. It should be re-examined with special reference to the intended procurement of new carriers.

