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United Kingdom Submarine Nuclear Propulsion

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ABSTRACT

June 2019 saw the fiftieth anniversary of the first Royal Navy 'Continuous at sea Deterrent' patrol which was carried out by a nuclear-powered submarine equipped with the Polaris missile. This article looks at how the UK undertook the development and deployment of the nuclear propulsion plant for such submarines.

Introduction

On 15 June 1968, HMS *Resolution*, the Royal Navy's first Polaris missile armed submarine, sailed from the naval base at Faslane on the Firth of Clyde. It was the UK's first Polaris patrol, and in the spring of 1969 was joined in that task by HMS *Repulse*. So began what has now been a more than fifty-year period of Continuous At Sea Deterrence (CAS-D). In June 1969, a year after the first patrol, the Royal Navy formally assumed responsibility for the UK's nuclear deterrent.[1]

This article will show that it is the legacy of the political, naval, and engineering decisions, made over sixty years ago, that has since enabled the UK to maintain more than fifty years of CAS-D operations. The deterrent patrols of the Polaris, and successor Trident, armed submarines, were recently renamed *Operation Relentless*. This fittingly recognises this sea-borne strategic deterrent as the UK's longest running military operation.

On 21 January 1954 the US President's wife, Mamie Eisenhower, launched the world's first nuclear powered submarine, USS *Nautilus*. The following year, on 17 January 1955, USS *Nautilus* slipped her moorings and sailed down the Thames River and left Groton, Connecticut for sea trials. At 11:33 a.m., her commanding officer, Commander Eugene Wilkinson, sent the signal: 'Underway on nuclear power'.[2] In the intervening sixty-six

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[1] Peter Hennessy, *Cabinets and The Bomb,* (Oxford: Oxford University Press, 2007), p. 17.

[2] Norman Polmar and Thomas B. Allen, *Rickover,* (New York: Simon and Schuster, 1982), p. 165.

years only five other nations have undertaken the building and operation of nuclear-powered submarines; Russia, Britain, France, China, and India.[3] The nuclear-powered submarine enables those five states to project military power in ways not possible by conventional means. That importance can be seen by the UK having built thirty-two nuclear powered submarines, of which thirty-one have been powered by nuclear reactors designed and built in the UK by Rolls-Royce Plc. A further three *Astute* class SSNs are currently in build, and four successor submarines to replace the Royal Navy's current *Vanguard* class SSBNs have been ordered.[4]

HMS *Dreadnought*, the Royal Navy's first nuclear-powered submarine, was powered by an American S5W reactor bought from Westinghouse. This was made possible by the Anglo-American Mutual Defence Agreement of 1958, which can be seen as one of the foundations of the so-called Anglo-American 'Special Relationship'. The Mutual Defence Agreement (MDA) enabled the US Government and the UK Government to co-operate on atomic energy for mutual defence purposes. In effect, this meant the pooling of resources allowing the transfer of nuclear information, equipment and materials for common defence. However, in relation to submarine nuclear propulsion plants, Article III of the Act enabled the UK to purchase a S5W reactor and steam plant which it was intended would allow the UK to produce future propulsion plants of its own without further demands on the USA. Harold Macmillan wrote that the Americans thought the (MDA) would be all give and would receive little information in exchange, however, in some respects the UK was further advanced in the art [of nuclear weapons] than was the US at the time.[5] That lead did not however extend to nuclear propulsion. Unlike nuclear weapons cooperation which has continued since 1958, there would be no nuclear cooperation on propulsion plants until the mid-1990s when both navies began to exchange senior officers to work in their respective propulsion departments.

Conventionally powered submarines rely on batteries charged by diesel engines and are, by their nature, dependent upon access to air. They must surface periodically, or raise a mast, to replenish the submarine's atmosphere and enable the diesel engines to be run to re-charge the batteries that provide the primary source of motive power when submerged. These submarines are submersibles rather than "true" submarines independent of the atmosphere. Nuclear submarines are true submarines which do

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[3] Brazil has been in the process of constructing a nuclear-powered submarine for some years but that project has yet to reach operational status.

[4] SSN is an acronym for *Ship, Submersible, Nuclear* - a nuclear-powered submarine whose principal role is hunting other submarines and ships. The acronym SSBN denotes a *Ship, Submersible, Ballistic, Nuclear* - a submarine armed with ballistic missiles that would normally carry nuclear weapons of a strategic nature.

[5] Harold Macmillan, *Riding the Storm 1956-1959,* (London: Macmillan, 1971), p. 565.

not need to surface or raise a mast for air. Their submerged endurance is limited only by the crew's wellbeing and food supplies.

Early Missile Launching Submarines

The first missile to be launched from a submarine was fired from the USS *Cusk,* while lying on the surface off the coast of California on 12 February 1947.[6] Following this success the USA converted two *Balao* class conventionally powered submarines, USS *Cusk* and USS *Carbonero*, to carry the Loon missile, a derivative of Nazi Germany's V1 – a crude form of cruise missile. In 1952 the USA converted the *Gato* class conventional submarine, USS *Tunny*, to carry the improved, and nuclear armed, Regulus missile, and in 1955, another *Balao* class submarine, USS *Barbero*, was also converted to carry the same missile. The nuclear-powered submarine USS *Halibut* was commissioned in 1960 and could carry five Regulus missiles, but she had already been made obsolete by the USS *George Washington* of 1959. This first SSBN carried the solid fuelled Polaris missile system which could be launched when the submarine was submerged, whereas the turbo-jet powered Regulus, and pulse-jet powered Loon missiles both required the submarine to surface before launching, which exposed the submarine to detection and attack.

In the Soviet Union, the first conventionally powered *Golf* class ballistic missile submarine was launched in 1958, it carried three R-11FM Scud missiles. Six *Zulu* class conventional submarines were also converted to carry ballistic missiles but could carry only two R-11FM missiles each. The Soviet Union's first nuclear powered and nuclear missile armed submarines were the *Hotel* class which could carry three improved R13 missiles. The USSR's early ballistic missiles all required the submarines to surface for missile launch. The *Hotel* class were followed by the successful *Yankee* class which were armed with the SS-N-6 ballistic missile. The *Yankees*, as well as the contemporary Polaris submarines of the US Navy and Royal Navy, carried sixteen ballistic missiles. These missiles all had vastly improved ranges compared to the earlier generation. This allowed a greater patrol area, and/or the targeting of areas further from the coast. More importantly, these missiles did not require the submarine to surface in order to launch. This new form of SSBN could make full use of its ability to remain submerged for the several months duration of a typical patrol. SSBNs can in effect disappear in the vastness of the oceans. For a belligerent nation, this poses a strategic threat that can not only survive a pre-emptive strike on land-based weapon systems, but can come from almost anywhere the submarine can go.

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[6] John D. Alden, *The Fleet Submarine in the U. S. Navy: A Design and Construction History,* (London: Arms and Armour Press, 1979), p. 136.

Nuclear Fission & Application to Submarines

The harnessing and exploitation of the power of the atom began in 1938, when the Nobel chemist, Otto Hahn discovered an isotope of barium produced by the bombardment of uranium atoms with neutrons. However, it was his assistant, Lise Meitner, and her colleague, Otto Frisch, that appreciated the application for this phenomenon.[7] Meitner and Frisch proposed that the atom could be split into two approximately equal, and lighter elements with the simultaneous release of further neutrons. Their theory was published in the journal *Nature* (in which Frisch coined the term fission) in February 1939.[8] Further work at the *College de France* by Frederic Joliet-Curie and others showed that the fission of uranium was accompanied by the release of further neutrons, although he was unable to promote a chain reaction. Only after further experimentation was it determined that it was not natural uranium ^{238}U, but a rarer isotope, ^{235}U, which constitutes about 0.7 percent of natural uranium, that releases its neutrons during the fission process. By May 1939, conditions had been established for maintaining a chain reaction, and patents had been filed in Paris, for a proposed a nuclear reactor. By the end of 1939, Joliet-Curie and his team had been instructed by the French Minister of Supply to continue their work with the object of developing a submarine engine. Joliet-Curie became the first scientist to lead a team to tackle the problem of submarine nuclear propulsion.[9] In America, Meitner and Frisch's theory was already under discussion in January 1939 at the Conference of Theoretical Physics held in Washington D.C. The Nobel physicists Niels Bohr, and Enrico Fermi proposed that if uranium underwent a process of fission, then the energy released would be enormous. Fermi though, was cautious enough not to propose the possibility of a chain reaction, but Ross Gunn, a physicist at the US Naval Research Laboratory, had no such qualms. Gunn thought it possible to utilise nuclear power to propel a submarine and approached the Chief of the US Navy's Bureau of Engineering, Rear Admiral Harold G. Bowen. Gunn secured $1500 of funding which he allotted to his friend, Merle Tuve, at the Carnegie Institution in Washington, to conduct research into the fission process. So began the US Navy's interest in nuclear propulsion.[10]

In the UK, the MAUD Committee's Report on the use of Uranium as a source of power was published in July 1941.[11] Part I of the report deals with the possibility of a nuclear weapon that would provide a rapid release of a large amount of uncontrolled energy. Part II deals with controlling the release of that energy to create a heat source

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[7] Rowland Pocock, *Nuclear Ship Propulsion,* (London: Ian Allen, 1970), p. 10.

[8] H. D. Smyth, 'Fifty Years of Atomic Physics', *Proceedings of the American Philosophical Society*, Vol. 90, No. 1, (January 1946), p. 5.

[9] Pocock, *Nuclear Ship Propulsion,* p. 12.

[10] Richard G. Hewlett and Francis Duncan, *Nuclear Navy: 1946-1962*, (Chicago: University of Chicago Press, 1974), p. 17.

[11] Acronym MAUD – Military Application of Uranium Detonation.

which could then be exploited as a power source.[12] The MAUD Report led to the formation of the Tube Alloys (TA) Project, the British and Canadian nuclear weapon research and development programme, which, following the Quebec Agreement of 1943, was subsumed into the US Manhattan Project. One of the authors of the MAUD report, Professor Mark Oliphant, was a member of the Royal Naval Scientific Service (RNSS) and led the Admiralty Radar team at Birmingham University in researching valve technology. After Oliphant was seconded to the TA Project in 1943, further Admiralty scientists became involved with atomic energy research by removing them from Admiralty work for secondment to the TA Project at Chalk River in Canada. Wallace Ackers, the Director of the TA Project, wrote to the University (?) Chancellor, Sir John Anderson, to advise that the TA Project was of special interest to the Admiralty because of the: '…possibility that nuclear energy might be used for ship propulsion. This would radically the design of naval vessels, especially Battleships, Aircraft Carriers and Submarines'.[13] This appears to be the first British document to specifically refer to nuclear energy and an application to ship and submarine propulsion.

In February 1946, the Controller of the Royal Navy, Rear Admiral Charles Daniel, submitted a paper to the Admiralty Board on the 'Consideration of Future Naval Development'. Under the section on research and development Daniel wrote:

> All this research and development covers a vast field, and many years may pass before the new navy will emerge. But I believe that it will emerge, and the change from the present to the future, will be as great as the change from sail to steam. For not only have we to consider atomic attack and defence, but also atomic ship propulsion…[14]

This marked the beginning of the Royal Navy's Nuclear Propulsion Programme, from which point the Royal Navy's primary focus was on a submarine application although that decision was not formalised until 1955. In 1947, many nuclear specialists, such as Professor P. M. S. Blackett postulated the use of nuclear energy: '…for very large ships, such as our great liners'.[15] In the same year, Sir John Cockcroft, Chairman of the

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[12] The UK National Archives (hereinafter TNA) AB 4/1014, MAUD Committee Report.

[13] TNA, CAB 126/173, Letter, W. Ackers to J. Anderson, 30 June 1944.

[14] DNP 2 NP184/2011, 'The Dreadnought Project Outline Narrative', 1, 18 February 1946. As a part of the author's PhD research privileged access was granted to unreleased files held by the Royal Navy's Director of Nuclear Propulsion (DNP). At that time the DNP was Commodore Mark Adams RN.

[15] Atomic Challenge: A Symposium, (London: Winchester Publications Limited, 1947), p. 94.

Atomic Energy Research Establishment (AERE) at Harwell spoke of the possibility of applying nuclear power to mobile reactors: 'Ship propulsion would seem to offer a more favourable field'.[16] Also in 1947, on their Third Programme, the BBC broadcast a talk on the subject of *The Propulsion of Ships by Atomic Energy*.[17] However, naval experts envisaged nuclear propulsion in a different type of craft, the submarine. In 1948, R. J. Daniel, a member of the Royal Corps of Naval Constructors, noted that: 'The atomic reactor is well suited to submarine propulsion, developing full power under all conditions, and quite independent of whether the submarine is on the surface or not'.[18]

Although the Admiralty deferred a decision on the type of platform in which to instal the first nuclear propulsion plant the submarine was, from the outset, the primary focus, of the Admiralty. In 1947, an informal committee known as the 'Tea Party' was created in the Admiralty to keep in touch with developments at the Atomic Energy Research Establishment, Harwell. In 1949, the Tea Party, now known as the Atomic Propulsion Working Party, issued a report advising that it would be feasible to build a submarine powered by an atomic reactor.[19] The Admiralty undertook design investigation of both ship and machinery whilst the AERE investigated reactor design. By 1950, the Admiralty had affirmed that the development of a nuclear reactor suitable for submarine propulsion appeared practicable and strongly supported the development of a nuclear powered submarine, discussed in further detail below.[20]

Early UK Research & Development

In January 1946, Jack Diamond, a member of the RNSS, became the first Admiralty scientist to be seconded to the AERE at Harwell where he was head of the Naval Section until March 1953.[21] Diamond had previously been seconded to the TA Project in Canada and had worked there with the Director of the AERE, Sir John Cockcroft.

Britain's early research and development on applying nuclear energy to submarine propulsion was hampered for a number of reasons. With a focus on using nuclear power to generate electricity, the AERE had discounted water-moderated and water-cooled reactors from their scope of work and had decided to concentrate their efforts

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[16] J. D. Cockcroft, 'The possibilities of nuclear energy for heat and power production', *Proceedings of the Institution of Mechanical Engineers* (1947), 206-11 (p. 211).

[17] 'Broadcasting', *The Times*, 21 June 1947, p. 6, Issue 50793.

[18] R. J. Daniel, 'The Royal Navy and Nuclear Power', *Transactions of the Institution of Naval Architects*, Vol. 90, No. 4, (Oct., 1948), 273-90 (p. 285).

[19] Director Nuclear Propulsion File No: NP184/2011The Dreadnought Project Outline Narrative, p. 2.

[20] TNA, DEFE 7/2055 Paper D.R.P. (50)73 5 June 1950.

[21] DNP NP184/2011, p. 2.

on graphite-moderated, gas-cooled reactors. At that time, the AERE only had to consider the Admiralty's requirements when deciding on the direction of their higher priority civil nuclear power generation programme. British reactor design was also hampered by a lack of enriched uranium, so the early reactors were fuelled with natural uranium. That choice of fuel resulted in a sizeable amount of uranium being needed, so the reactor vessels were very large, and completely unsuitable for fitting to a submarine.[22] By discounting water-cooled reactors, based on analysis of the nuclear reactors at Hanford in Washington State (which had shown them to be inherently less safe than similar gas-cooled reactors), the AERE focussed their attention on gas powered reactors for electricity generation.[23] In doing so, development of the first designs for a submarine propulsion reactor would prove to be a cul-de-sac and would delay serious investigation into Pressurised Water Reactors by four years.

From the autumn of 1949, the AERE held exploratory meetings with the British firm Metropolitan-Vickers with a view to constructing an enriched uranium gas-cooled, graphite-moderated power plant. Mark I was to be a land-based prototype for the Mark 2, which was to be installed in a submarine hull. In June 1950, the Admiralty submitted a paper to the Defence Research Policy Committee (DRPC) in which they stated their support for the development of nuclear powered submarines based on the expected tactical advantages over conventional submarines.[24] The proposed submarine's displacement was put at about 2500 tons, and yet within days, the Engineer-in-Chief's (E-in-C) staff had discussed the lengthening of the provisional engine room from 55 feet to 74 feet, thus increasing the displacement to between 4200 and 4600 tons.[25] Initial design investigations confirmed that the first submarine, known as N.1, would be larger than envisaged, with a 25 feet diameter pressure hull and a surface displacement of 3700 tons. Further studies allowing for naval service factors such as shock, pitching and rolling etc, meant that to maintain criticality, the size of the reactor would have to increase so substantially as to make this type of reactor unattractive. The design for this submarine, N.2, would see an increase in the pressure hull to 31 feet and a surface displacement to 4500 tons.[26] It is recorded in an unreleased narrative file at the DNP's office that some work was also carried out on water-moderated and water-cooled reactors, and another submarine design for that - N.3 - was prepared. This concept had a pressure hull diameter of 22 feet and a surface displacement of 2480 tons. It can be deduced from these examples that the

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[22] Enriched uranium involves processing natural uranium to raise the proportion of the isotope ^{235}U.

[23] Rowland Pocock, Nuclear Ship Propulsion, (London: Ian Allen, 1970), p. 50.

[24] TNA DEFE 7/2055, Paper D.R.P. (50)73, 5 June 1950.

[25] TNA AB 6/760, Note, 'N' Class Submarines, 9 June 1950.

[26] DNP 2 NP184/2011, 5.

reactor designers were struggling to reduce the size of the reactor, which in turn was limited by using uranium enriched to only twice its normal 0.7%.

While the Admiralty's designers were increasing the size of the projected submarine to accommodate the 18 feet diameter Mark I reactor core; 'The core diameter of the US submarine was thought by the British to be 6 feet'.[27] The nub of the problem was that the Admiralty required a reactor three times smaller than was technically possible using low enriched uranium fuel. A more compact designed reactor to fit into a submarine hull was only possible with highly enriched uranium fuel, which had already been identified by the AERE in November 1949.[28] At that time ^{235}U was a scarce and expensive commodity in the UK where a small-scale diffusion plant was producing highly enriched uranium solely for Britain's nuclear weapons programme. In September 1951, Jack Diamond conceded that the present reactor design would require a submarine displacement of 5000 tons.[29] In October, Metropolitan-Vickers was requested to submit their final report which was presented in May 1952. With that, the project was effectively mothballed until 1956 when a new high volume diffusion plant became available that could produce enough highly enriched fuel to meet the Admiralty's needs.

In 1953, Diamond resigned from the RNSS to take up an appointment at Manchester University; the Naval Section at Harwell was run down and was staffed only by a Royal Navy engineer, a RNSS scientist and two people from the Admiralty Defence Establishment, Barrow (ADEB). However, by the end of that year the Admiralty decided to commit more resources to the Naval Section, and Captain (E) Harrison-Smith was appointed to head the section in May 1954.[30] In January 1955, Professor Jack Edwards RNSS was appointed senior RNSS representative, and by mid-1955, the Naval Section had increased to eleven personnel; four Royal Navy engineers, five RNSS staff, one from the Royal Corps of Naval Constructors (RCNC), and an engineer from the Yarrow Admiralty Research Department (Y-ARD).[31] This new Naval Section turned its attention towards water-cooled and water-moderated reactor designs using highly enriched uranium as the fuel.

The Pressurised Water Reactor

The use of pressurised water as a coolant and moderator was first proposed by A. M. Weinberg in 1946, and this was chosen by the Americans as the type best suited for

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[27] Margaret Gowing, *Independence and Deterrence: Britain and Atomic Energy, 1945-52 Volume 2: Policy Execution*, (London: Macmillan Press, 1974), p. 275 footnotes.
[28] TNA AB 6/618, Minute The Enriched Uranium Power Reactor, 14 Nov. 1949.
[29] TNA AB 15/2043, Paper - An enriched uranium reactor for submarine propulsion.
[30] TNA AB 6/1051, Letter F. T. Mason to J. Cockcroft, 24 March 1954.
[31] TNA AB 6/1051, Letter, Capt. Harrison-Smith to J. Cockcroft, 16 March 1955.

application in a submarine.[32] After the false start with the enriched gas-cooled reactor, and possibly encouraged by the launch of the USS *Nautilus*, the Naval Section came to the same conclusion in early 1955.

A pressurised water reactor (PWR) is constructed of the following main components; the reactor pressure vessel (RPV) containing the fuel elements, control rods, and the liquid moderator/coolant. External to the RPV and connected to it by pipework are the main circulation pumps, pressuriser, and heat exchanger which together constitute the primary system. Within the heat exchanger the primary coolant heats water from a separate circuit that produces steam for what is known as the secondary system. Steam is fed to turbogenerators that produce electricity while also supplying the steam turbines which propel the submarine. The choice of fuel element, the control medium and the moderator all have a direct effect on the design and critical size of a reactor. How reactor components are manufactured and shaped, and the position into which they are placed within the RPV are also a part of the reactor problem that had to be solved. 'That is in ensuring that just one neutron can survive to continue the chain, no more and no less'.[33]

As soon as the PWR had been selected the project was reorganised. The Admiralty wrote to the Treasury in December 1955, to advise that they intended to design a nuclear propulsion plant of 15,000-20,000 shaft horsepower (SHP) for use in a submarine. The project was foreseen as taking six to eight years at a cost in the region of £10 million.[34] Treasury approval was forthcoming in January 1956, with an agreed expenditure of £300,000 in 1956/57. The Treasury advised that approval for the project was: '…without prejudice to any decision on an advance beyond the prototype of the nuclear power submarine'.[35]

In January 1956, the Admiralty formally wrote to the United Kingdom Atomic Energy Authority (UKAEA) requesting technical advice and assistance in PWR technology. The UKAEA was advised that it was the Admiralty's intention to build a PWR of approximately 80MW output and to commence trials on a land-based prototype by late 1959, with trials in a submarine by 1962. Professor Jack Edwards RNSS observed that the PWR had been chosen as the most feasible reactor for installation in a

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[32] A. M. Weinberg, 'High Pressure Water as a Heat Transfer Medium in Nuclear Power Plants' (Atomic Energy Commission Report MonP-93, 10 April 1946) https://technicalreports.ornl.gov/1946/3445605714956.pdf. Accessed 4 September 2021.

[33] Peter M. B. Walker, ed., *Chambers Dictionary of Science and Technology,* (Edinburgh: Chamber Harrap Publishers Ltd, 2000), p. 797.

[34] TNA T 225/1022, Letter McKinnell to I. de L. Radice, 8 December 1955.

[35] TNA T 225/1022, Letter D.M.35/77/01, 6 January 1956.

submarine because of its compactness and the good prospects for completing the project within a reasonable timescale.[36] Edwards also noted that little was known in the UK of such light water-moderated and cooled reactors because; there were considerable gaps in the available knowledge, and little information was available from the USA. This was a consequence of the US Atomic Energy Act (1946), commonly known as the McMahon Act, which had stopped all transfer of nuclear technology and knowledge from the USA.[37] However, British engineers adopted novel ways to collect information on nuclear energy. There being no official channel for the exchange of nuclear power generation information, as much knowledge as possible was gleaned from Congressional reports, United States Atomic Energy Commission reports, press releases and other published documentation. However, by 1956, a considerable amount of data was being openly published. Fortunately, Admiral Rickover USN, who was in charge of the US Navy's nuclear submarine programme, had committed to publishing information on PWRs that was applicable to civil nuclear power generation. This data came from the US Navy's own reactor programmes, and the Shippingport PWR project.[38] The US Navy's programme had selected zircaloy as the fuel cladding material, and it quickly became evident there were applications for it as a cladding material in civil PWRs. As a result, extensive data was declassified and Rickover deliberately instigated publication to encourage industrial research on the metallurgy of zirconium to stimulate its commercial development.[39]

Fuel Element Decision

In 1957, the UK's Rear Admiral Nuclear Propulsion, G. A. M. Wilson, was considering the choice of materials for fuel elements. It had previously been decided to proceed with uranium oxide/steel elements, partly on the grounds of supply security for British refined zirconium, and partly because it was believed that there was a better long-term development potential for uranium oxide/steel elements. The UKAEA had advised that the use of zirconium would add serious complexity to their proposed chemical separation plant for treating irradiated fuel elements, adding £400,000 to the capital cost, and a further £250,000 to increase British production of zirconium to meet Admiralty requirements.[40] Despite the UKAEA's reservations, there was now a

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[36] Professor J. Edwards, 'Joint Panel on Nuclear Submarine Propulsion: Initial Problems of the Submarine Pressurized Water Reactor Design and the Related Experimental Programme', Lecture to the Institute of Marine Engineers, 23 January 1962, p. 1.

[37] For further information on the McMahon Act see Goodman, 'With a little help from my friends', p. 155.

[38] The Shippingport PWR in Pennsylvania was the world's first purpose built commercial reactor.

[39] TNA AB 6/2492, Note Naval Policy at Harwell, 15 May 1964.

[40] TNA ADM 1/26740, Paper, RANP/23/8, 30 July 1957, p. 4.

revived interest in zirconium. The main reasons for this were a more favourable supply of zirconium that could be purchased from the US and Japan and the fact that: 'A zirconium core uses a little over half the amount of fissile fuel required by the steel core'.[41] A smaller reactor core design could be achieved, and despite the price of zirconium it was likely to give an overall saving. The economy of operation of either core depended on the value of fissile material ultimately recovered and returned to stock. 'If reprocessing of Zirconium fuel elements is practicable the overall economy will favour this type of core'.[42] Wilson argued that there was little to choose between the fuel elements, and the submarine's completion date was unlikely to be affected by this choice. The recommendation was to proceed with uranium oxide/steel elements and the Admiralty notified the UKAEA that the reactor design should proceed on that basis. However, at a later meeting, Wilson noted that the recent reservation expressed by the UKAEA concerning the reprocessing of zirconium cores was unfounded because the USA had recently reprocessed their first zirconium core.[43] Wilson advised that reprocessing data would be made available to the UK; therefore, they should now proceed with the zirconium core and accept a delay of some six months to the UK's project.

The basis for the Admiralty's decision to proceed with zirconium-based fuel elements remains open to conjecture. The meeting at which Wilson advised changing to zirconium also discussed a threat to the HMS *Dreadnought* SSN Project that was posed by political support for a nuclear-powered oil tanker.[44] Wilson had written an earlier paper for the 'Galbraith' Committee stating the case for a nuclear-powered Fleet Replenishment Tanker.[45] In the paper Wilson argued that machinery developed for the Fleet Tanker would be applicable to a merchant ship. Although the tanker was a paper study and was running some three years behind the Dreadnought Project, the First Sea Lord, Mountbatten, was concerned that once people became aware of it there would be support for the tanker and less for HMS *Dreadnought*.

The first Polaris SSBN, the USS *George Washington*, was launched in 1959, and while the UK continued pursuing a policy of what Macmillan called the 'Great Prize' of nuclear interdependence with the USA, the later USA/UK Polaris Sales Agreement lay six years in the future. It was therefore quite prescient of Mountbatten to tell the

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[41] TNA ADM 1/26740, Paper, RANP/23/8, 30 July 1957, p. 1. The core was made of a number of materials including uranium, zirconium and hafnium, and the containment vessel of various other materials.

[42] TNA, ADM 1/26740, Paper, RANP/23/8, 30 July 1957, p. 5.

[43] MB1/I397, Sea Lords' Meeting, 8 Oct. 1957, Item 1.

[44] *HMS Dreadnought*, an SSN was the UK's first nuclear powered submarine.

[45] Full title: First Lord's Committee on the application of nuclear power to marine purposes.

meeting that to adopt the tanker in place of *Dreadnought* would suit the Air Ministry, as it would remove a possible future rival to the RAF's responsibility for the UK's nuclear deterrent.[46] Given these facts it seems entirely probable that while the Admiralty adopted the uranium zirconium element on the grounds of reducing by nearly half the fissile material required for HMS *Dreadnought*, by doing so it also countered possible Air Ministry support for cancelling the nuclear submarine reactor programme in favour of one for the tanker.

Development of the US Navy's Polaris system had begun in 1955, although the US Air Force was influential in providing the RAF and Ministry of Defence with sceptical assessments of its performance.[47] At that time the RAF carried the UK nuclear deterrent in its V- Bomber force and in the late 1950s was developing the Blue Steel stand-off missile system as a means of maintaining the viability of that deterrent in the face of improving air defence systems in the USSR. The UK's own medium range ballistic missile system, Blue Streak, had begun in the mid 1950s and had American support. But this was cancelled in 1960 at a time of cost over runs and the realisation that the need to fuel the missile immediately prior to launch made it very vulnerable to attack. The USA subsequently agreed to allow the UK to join the American Skybolt missile project which was under development at that time. Skybolt was an air launched ballistic missile which the RAF planned to fit to the existing V-Force bombers as a long term and long-range successor to the interim Blue Steel stand-off missile.

The 1950s and 1960s was also a period when the Royal Navy was struggling to define a meaningful role for itself in the UK's defence. It was claimed that any future war with the USSR would quickly turn nuclear and there would be no strategic role for the Royal Navy either during or after a nuclear exchange. The RAF also claimed it could carry out the Navy's maritime surveillance and strike functions from its UK and overseas air stations. Sandys' White Paper on Defence envisaged the Royal Navy undertaking only 'peacetime emergencies or limited hostilities'.[48] But Mountbatten had already discussed Polaris with his US counterpart, the Chief of Naval Operations, Admiral Arleigh Burke. Some years later, Mountbatten confirmed that a Royal Navy missile expert had quietly been seconded into the US Polaris programme from its outset.[49] It would appear that Mountbatten wanted to be certain that if and when the Royal Navy had a viable proposal for a sea-based deterrent they could deliver that proposal to Cabinet Ministers confident in the knowledge that both Polaris and submarine nuclear propulsion were proven, safe, and reliable technologies, and that

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[46] MB1/I397, Sea Lords' Meeting, 8 October 1957, Item 1.

[47] Laurence W. Martin, 'The Market for Strategic Ideas in Britain: The "Sandys Era"', *American Political Science Review*, Vol. 56, No. 1 (March 1962), p. 28.

[48] HCPP Defence Outline of Future Policy; 1956-57 (Cmnd.124), p. 6.

[49] MB1/J40 Letter, Mountbatten to Rear Admiral I. J. Galantin USN, 21 January 1965.

moving to sea-based deterrence was the best future option for the UK. In 1957 Mountbatten certainly had an eye on a future deterrent role for the Royal Navy that was not envisaged either by Sandys or within the Ministry of Defence. Mountbatten wrote: '…I hope we shall now have his [Sandys] wholehearted support for the *Dreadnought* and eventually the *Polaris*-type nuclear submarine'.[50] Indeed, the Prime Minister, Harold Macmillan, would later advise the Queen, that his philosophy was to rid the UK of the land-based missiles in the UK which were targets for the USSR, and the best thing was to move the deterrent out to sea: '…in a submarine, [which] is out of sight'.[51]

Purchase of the American S5W PWR

Two unrelated events, months apart, combined to change the Royal Navy's own nuclear reactor design. As a direct result of the Suez Crisis, Macmillan succeeded Eden as Prime Minister in January 1957. Macmillan already had a good working relationship with President Eisenhower dating from the Second World War and he used that well. Within days the Americans proposed a meeting between of the two leaders in Bermuda. As noted, earlier Macmillan's main foreign policy objective was to secure nuclear interdependence with the USA. Eisenhower agreed with this objective but had his own political difficulties within the US Senate. Macmillan's chance to change US political opinion came when the Soviets launched *Sputnik* 4 October 1957. This event caught the USA unawares, and the realisation dawned that the Soviet Union now had an intercontinental ballistic missile (ICBM) capability. Macmillan wrote to the US Secretary of State, John Dulles, suggesting that the time was right for pooling defence resources although he refrained from mentioning the McMahon Act.[52] Three weeks later, at a meeting in the White House, Eisenhower surprised the British by producing a directive dealing with nuclear collaboration between the two countries, in effect it was the end of the McMahon Act's restrictions on technology transfer to the UK.

The American Admiral Hyman G Rickover is universally acknowledged as the 'father of the US nuclear navy'.[53] Rickover visited the UK in August/September 1956 to hold discussions with staff at the AERE, and in May 1957 gave a presentation at the Admiralty.[54] Rickover invited the Admiralty to send a Technical Mission to the US to learn more about the US nuclear propulsion project, and that took place between 10

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[50] MB1/I300 Quarterly Newsletter, 1 November 1957, p. 9.

[51] Alister Horne, *Macmillan 1957-1986: Volume II of the Official Biography,* (London: Macmillan, 1989), p. 276.

[52] Harold Macmillan, *Riding the Storm 1956-1959,* (London: Macmillan, 1971), p. 314.

[53] Vice Admiral Sir Robert Hill, Admiral Hyman G. Rickover USN and the UK Nuclear Submarine Propulsion Programme', *International Journal of Naval History*, Vol. 4, Issue 2, (Aug. 2005), p. 1.

[54] Broadlands Archive MB1/N104, Memorandum Rickover visit, 8 May 1957.

and 25 June. In October, at a meeting with the First Sea Lord, Selkirk, Rickover raised the possibility of the UK purchasing an American *Nautilus* class propulsion plant at a cost of some $11to 15 million.[55] In January 1958, Rickover was back in the UK and suggested that the UK purchase a *Skate* class (S3W) PWR as a means of freeing up his own staff from the numerous queries now coming from the UK.[56] Rickover advised that it was the Admiralty's decision as to which plant to purchase, the S3W or S5W, but he preferred the *Skate* S3W as it was a proven design.[57] The offer was discussed and the merits deliberated before the Admiralty decided that the S5W reactor plant, with a complete machinery set as fitted in the USS *Skipjack*, was the better proposition for meeting HMS *Dreadnought's* requirements. *Dreadnought* had a similar displacement to *Skipjack* and one propeller shaft; more-over, the S3W plant was rated for 6,600 SHP (and designed for two shafts) whereas the S5W plant was more powerful at 15,000 SHP, and closer to the UK's nominal requirement for a 20,000 SHP plant. Importantly, the S5W was the reactor that was to be installed in the US Navy's own SSBN fleet and should therefore have been capable of incorporation into a future Royal Navy SSBN. Fortunately, Rickover had no significant objections to the Admiralty purchasing a *Skipjack* S5W reactor. Macmillan agreed to the purchase and the USA was informed of the Admiralty's preference in April 1958.[58] This was in time for it to be included in the 1958 Mutual Defence Agreement which was enacted that July, with Article Three of the Agreement covering the transfer of the S5W propulsion plant it was later fitted into HMS *Dreadnought*. The UK's first nuclear powered submarine, an SSN, was laid down on 12 June 1959, it was launched on 21 October (*Trafalgar Day*) 1960, and commissioned on 17 April 1963. She went out of service in 1980.

The Controller of the Royal Navy, Admiral Sir Peter Reid, directed that development of the Dounreay Submarine Prototype Reactor (PWR 1) was to continue except that no further work should be done on the reactor core and control mechanisms until: experience had been gained with the American S5W design; with expenditure in the next three years not to exceed the £14.85 million already planned.[59] The British development of the S5W core design, Core A, was taken critical for the first time on 7 January 1965.[60] Core A type reactors were subsequently installed into HM

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[55] TNA PREM 11/2554, Telegram No. 2138, 19 October 1957. It should be noted that the American offer was for the sale of one PWR plant only. Therefore, the UK had to continue the development of its own reactors and power plants.
[56] TNA ADM 205/178, Memorandum, Mountbatten, 29 January 1958.
[57] Acronym S5W – Submarine 'Fifth Generation Westinghouse' manufactured reactor plant.
[58] TNA DEFE 7/2055, Minute, D-S 535, p. 21 April 1958.
[59] TNA ADM 1/27375, Note P. Reid to R. Baker, 6 August 1958.
[60] Harry Lambert, ed., *Rolls-Royce: the nuclear power connection,* (Rolls-Royce PLC Publication, 2009), p. 56.

Submarines *Valiant*, *Warspite*, *Churchill*, *Conqueror* and *Courageous,* which were all SSNs, and to the four Polaris SSBNs, HM Submarines *Resolution, Renown, Repulse* and *Revenge*. A more powerful British designed Core B, with a longer core life, was installed in the later *Swiftsure* class submarines, and replaced the Core A reactors of the older submarines when they underwent refit. There was one further core improvement for PWR 1 based on enhanced coolant pump performance and a longer core life. Core Z first went critical on 16 December 1974 and was installed in the next generation of *Trafalgar* class submarines, and then also to those older submarines as they came in for refit.[61] Development of PWR 1 had though reached its limits so a new generation of reactor was designed and developed, PWR 2, and this reactor, with Core G, has been installed in the current *Vanguard* class SSBNs which carry the Trident missile system - the successor missile to Polaris. An improved Core H is installed in the current *Astute* class SSNs and allows these submarines to remain in service for 30 years without refuelling.

Conclusion

It has been demonstrated that the legacy of the political, military and engineering decisions, made over sixty years ago, have had a major impact on British political and naval planning and the ability to maintain a continuous at sea deterrent since 1969.

The Royal Navy and its industrial partners in the UK have improved upon the core design of the S5W and have done so independently of the USA. This has justified Rickover's assessment that the UK would in time become technically competent to produce and improve their own nuclear propulsion plants once provided with the initial S5W technology.[62]

Since the late 1990s, the USA and UK have also collaborated on Naval Nuclear Propulsion Information and technology, with each navy seconding a senior naval engineering officer to their respective departments, Director Nuclear Propulsion in the UK and the Office of Naval Reactors in the USA. The next generation UK reactor, PWR 3, is a product of that collaboration, and contains elements of the S9G reactor design which is installed in the USN's latest *Virginia* class SSN.[63] The UK 'Successor Project SSN' is now in the early part of the design stage, and construction of the next generation of UK SSBN – *HM Submarine Dreadnought* has begun, with the three follow-on SSBNs named as; *HM Submarines Warspite, Valiant* and *King George VI*.

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[61] Lambert, *Rolls-Royce*, *p*. 64.

[62] TNA DEFE 69/749, Minute Selkirk to Sandys, 24 January 1958.

[63] Julian Turner, Deep Impact: inside the UK's new Successor-Class Nuclear Submarine' (29 July 2013). https://www.naval-technology.com/features/feature-nuclear-submarine-successor-uk-royal-navy. Accessed 4 September 2021.

Writing to Vice Admiral Sir Robert Hill some forty years after the events discussed above, Professor Jack Edwards wrote:

> Personally, I am still convinced that we would have built our own nuclear submarine entirely on our own efforts – it would not have been as good as Skipjack, and it would have taken us some 2 years longer to get to sea, but it would have been entirely of our own design and would not have made us so dependent on the whim of the U.S. Congress…[64]

In the same letter to Vice Admiral Sir Robert Hill, Jack Edwards conceded that the purchase of the S5W reactor: 'probably assisted in the subsequent Polaris conversion'.

It can be seen that the ongoing British development of submarine nuclear propulsion has been pivotal, not only to the subsequent access to, and success of Polaris, but to the UK's later Trident based nuclear deterrent, and Britain's nuclear powered hunter killer force.

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[64] Professor Jack Edwards and Vice Admiral Sir Robert Hill, personal communication, 10 April 1998.