SUBMARINE PROPULSION IN THE ROYAL NAVY

BY

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The paper outlines the history of submarine propulsion from the early days, through the hydrogen peroxide plants in Explorer *and* Excalibur *to the setting up of the nuclear submarine programme. The building of the submarine prototype at Dounreay, the purchase of the* Dreadnought *plant from the US and the design and construction of the* Valiant *class submarines formed the base for developments in the 1960s leading to the highly successful* Resolution *and* Swiftsure *class submarines. Lessons learned from the design, building and operation of nuclear submarine propulsion plants are discussed and the future requirements for unproved operational characteristics and for higher nuclear safety standards are examined against the constraints of keeping unit costs under control. The success of the nuclear submarine programme is shown by the position today where the Royal Navy has sixteen nuclear submarines in service, a new submarine class under construction and work on the next generation of nuclear propulsion plants well advanced.*

Introduction

Cornelius van Drebbel is commonly credited with the first successful submarine, or more correctly submersible, when in 1620 he navigated his 'boat' propelled by twelve oarsmen, hardly submerged but more awash, in the Thames. It was not an event of conspicuous military significance. It was to take two and a half centuries and the technical advances of the industrial revolution to produce a submarine of military value, although the attacks by the Confederate steam-propelled submersibles in the American Civil War could be regarded as the first act of a naval policy involving submarines.

By the end of the nineteenth century, the development of reliable electric motors, batteries, methods of steam propulsion, and internal combustion engines, together with the advent of the Whitehead torpedo resulted in a number of submarines being designed and built for various governments. But despite the demonstrable success of many of these designs, naval thinking, particularly in the Royal Navy, failed to perceive the submarine in anything other than a coastal defence role—as a form of mine with some slight ability to manoeuvre. As the undisputed naval power in the years before the First World War, Great Britain did not consider the submarine of any significant value to a strong naval power. This was reflected in the Admiralty view: 'we know all about submarines; they are weapons of the weaker power; they are very poor fighting machines and can be of no possible use to the Mistress of the Seas'.

Two events were to change that view. First, the rapid build up of the French submarine force made the Admiralty embark on a submarine building programme, to gain experience in submarine operation and to develop submarine counter-measures. Lacking an established British submarine design, the Admiralty, in October 1900, decided to buy five boats from the Holland Torpedo Boat Company of America (later to become the Electric Boat Company) (FIG. 1). Messrs Vickers, Sons and Maxim Limited of Barrow

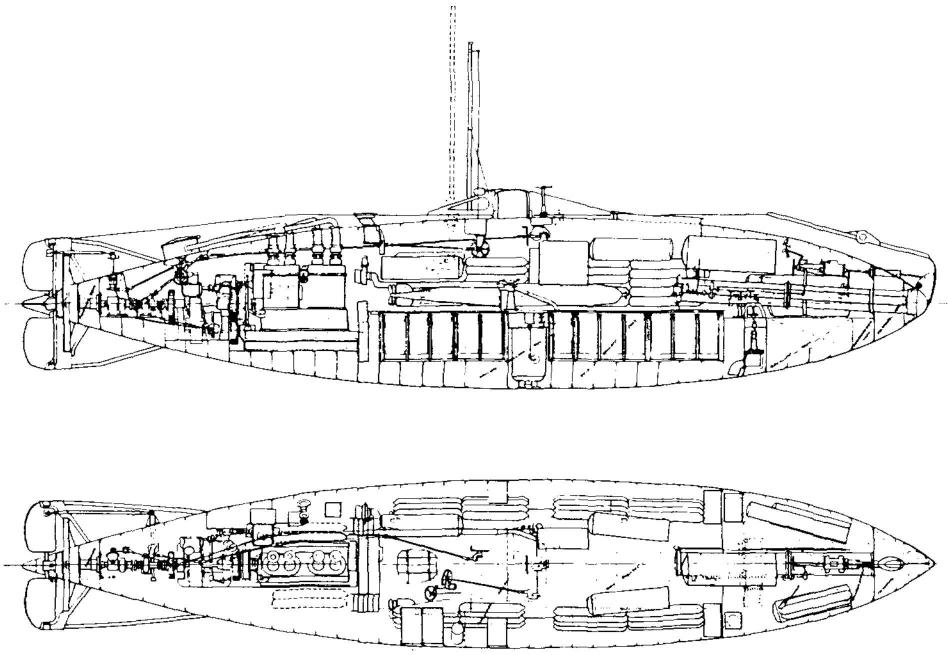

FIG. 1—GENERAL ARRANGEMENT OF SUBMARINE BOATS 1–5 PURCHASED IN 1900

entered into an agreement with the Holland Torpedo Boat Company for the exclusive manufacturing rights of their design. Of interest in the contracts was an agreement to include 'the services of an engineer who has had experience in the manufacture of submarine boats in America'. The second event was the arrival of Admiral Fisher as First Sea Lord in 1904; he alone, amongst the senior naval officers of the time recognized the value of the submarine in an offensive role particularly against warships and merchant shipping. He wrote, 'In all seriousness I don't think it is even faintly realized the immense impending revolution which the submarine will effect as offensive weapons of war.' This view, assuming, as it did, direct contravention of international law, was dismissed as unrealistic—a submarine could hardly comply with the obligation to take off the crew prior to the sinking of war prizes. In the event, the unrestricted U-boat campaign of 1917 came very close to bringing about the collapse of the Allies through the sinking of a quarter of the world's total commercial tonnage. It also forced a major change in the theory of naval strategy regarding the role of the submarine and it produced the most effective counter-measure, the convoy system.

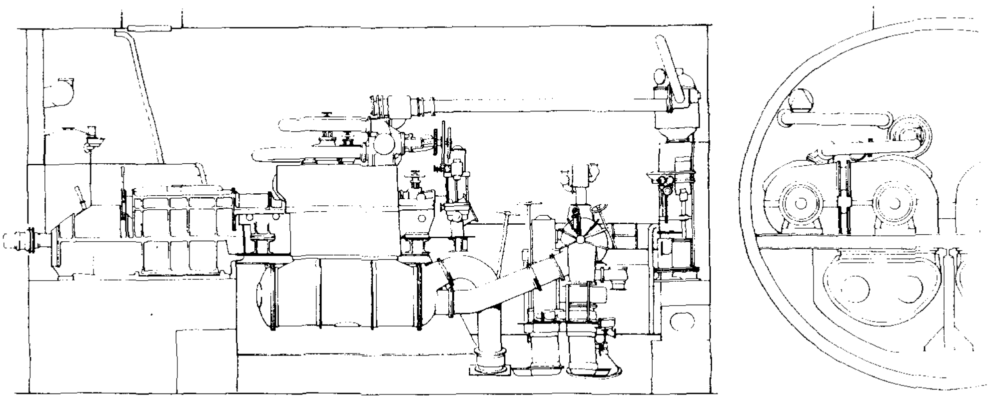

FIG. 2—K-CLASS BOAT TURBINE ENGINE ROOM ARRANGEMENT

In the years between the two World Wars, early technical development centred around improvements to the fleet submarine, aimed at higher surface speed to keep up with the fleet. The three-shaft diesel-engined J-class and the steam-turbine-driven K-class designed towards the end of the First World War had not proved as fast as intended. The K-class proved particularly unseaworthy on the surface in heavy weather.

Despite this the K-class propulsion machinery design with two boilers and geared HP/LP turbines driving twin shafts was a considerable technical success. It is of interest that a 10 500 s.h.p. turbine plant was installed in a main machinery space envelope of 270 m^3. For comparison, the nuclear submarine *Valiant* has a turbine room of more than twice that volume. The K-class machinery consisted of two Yarrow (235 lbf/in^2) type boilers, twin HP/LP Parsons or Brown-Curtis turbines, reduction gearing and shaft clutches. Four propulsion motors provided propulsion when dived, and a single 800 h.p. diesel generator gave limited diesel-electric propulsion on the surface (FIG. 2). Despite achieving commendable levels of reliability for such a novel propulsion plant, the K-class proved to be ill-fated, several being lost through collision and accident. The real advances were made in ocean going diesel-electric patrol submarines, with improved armaments, communications, control, and increased endurance.

The early success of the German U-boats against convoys in the Second World War reflected the high mobility of the surfaced submarine, diving only to evade and attack. However, the increasing use of radar on both aircraft and surface ships drove the U-boats from the surface and they could no longer operate as submersible torpedo boats. This forced further developments to increase submerged mobility and endurance such as the schnorkel, or breathing tube, which allowed the diesel engines to run when submerged at periscope depth. Notwithstanding these improvements which enhanced the submarine's operational capability, the fundamental requirement of any internal combustion engine for both air and fuel presented a practical limitation in terms of surfaced and dived endurance. Even the biggest wartime submarine development, a closed cycle propulsion system invented by Dr. Walther, which used concentrated hydrogen peroxide to provide the oxygen

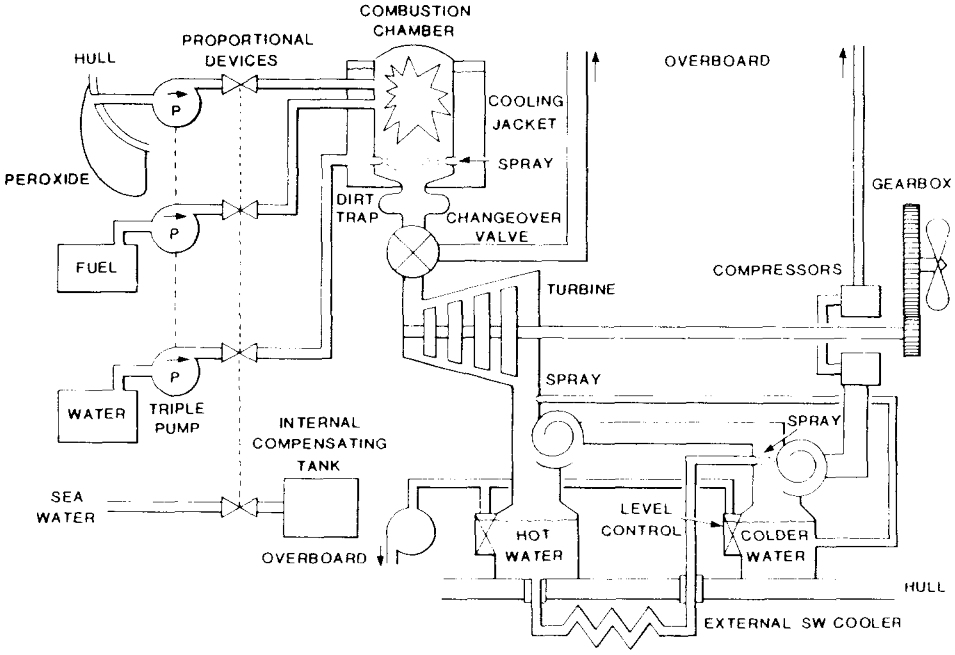

FIG. 3—HTP PROPULSION: WALTHER CYCLE

for combustion when totally submerged, was endurance limited by the quantity of fuel and hydrogen peroxide that could be carried in a submarine (FIG. 3). That this dilemma was recognized early in the submarine's history is borne out by the following comment published in 1918: 'The necessity for a dual system lies in the fact that no satisfactory prime mover adaptable to both conditions has yet been devised, although therein lies the obvious course for the future improvement and development of the submarine'.

Nuclear fission was about to provide the means.

Nuclear Fission

From the initial observations by Otto Hahn in 1938, the understanding of the fission process in uranium atoms and the potential associated with the energy release from a self-sustaining chain reaction grew rapidly so that by the spring of 1939 Enrico Fermi had completed sufficient work to warrant a meeting with the technical assistant to the U.S. Navy's Chief of Operations, Admiral Hooper. The resulting decision to allocate U.S. Navy funds for further investigations heralded the birth of the nuclear submarine and the advent of the true submersible.

Early work in the U.S.A. was on power reactors and separation of the isotope U^{235} from natural uranium. But the increasing threat of war concentrated effort on the atomic bomb to the virtual exclusion of nuclear propulsion. Similarly efforts in Britain had been concentrated on the atomic bomb following Peierl's and Frisch's famous memorandum describing the critical mass associated with a pure U^{235} bomb.

Although the U.S. Navy investigations into nuclear propulsion were severely curtailed they continued to be involved through work on uranium separation plants, whereas in Britain, the Royal Navy wartime strategy disregarded nuclear power. However, at the end of the Second World War, the Admiralty began investigations into future propulsion plants for submarines, the main development effort being directed to the evaluation of an ex-German HTP submarine, renamed H.M.S. *Meteorite.* A combined Admiralty-Vickers design and development team was set up as the Admiralty Development Establishment Barrow (ADEB) with the aim of developing a submarine HTP propulsion plant. The establishment of ADEB under Dr. Forsyth with facilities for design, development, prototype and production testing represented a different management approach in that a small, highly-qualified team was dedicated to a single project covering a programme from initial design through to production testing. Fortuitously, the foundation of ADEB was to provide a sound management basis, on which some years later the nuclear submarine propulsion machinery would be developed. Whilst the HTP project was progressing with the building of two experimental submarines, *Explorer* and *Excalibur,* work in America on a nuclear submarine propulsion plant had advanced rapidly under the direction of Admiral Rickover. The first land-based prototype was operational in the Idaho desert in 1953, and the first nuclear submarine installation at sea in U.S.S. *Nautilus* in 1955. These successes and the increased availability of enriched uranium in the U.K. persuaded the Admiralty in 1954 to commit more resources to nuclear propulsion, first to assess the various reactor systems likely to be suitable for submarine propulsion, and then to build up a team committed to the design and development of a complete nuclear submarine propulsion system.

Dreadnought and the Dawn of Nuclear Propulsion

During 1954, as a positive commitment to the use of nuclear power for submarine propulsion, the Admiralty set up a Naval Section, under Captain (E) S. A. Harrison-Smith as the senior Naval representative at AERE Harwell.

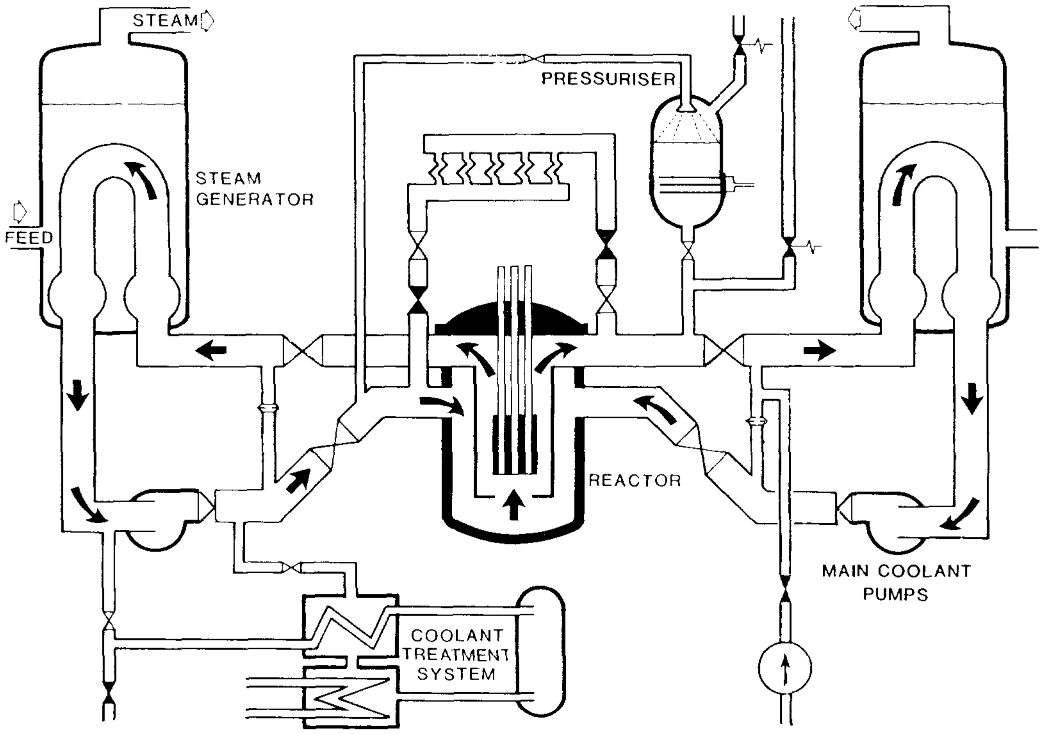

FIG. 4—SIMPLIFIED DIAGRAM OF A PRESSURIZED WATER REACTOR

In the same year U.S.S. *Nautilus* was launched at the Electric Boat Company's Shipyard at Groton U.S.A. In 1955, the Naval Section was expanded with additional officers from the Royal Navy, the Royal Naval Scientific Service, the Royal Corp of Naval Constructors together with engineers from Vickers Armstrongs Limited and the Yarrow Admiralty Research Department. This team was charged with the initial assessment work, the definition of the necessary R and D work to be undertaken, and the subsequent design and development work for a nuclear submarine power plant. The definition of the R and D work, and the co-ordination between the Admiralty, the United Kingdom Atomic Energy Authority (UKAEA) and the various organizations, was the responsibility of the senior Admiralty scientist in the team, Dr. J. Edwards. This increase in the Naval Section at Harwell followed the government decision to allocate sufficient U^{235} to allow R and D work to proceed on the project; the initial aim of the programme was to achieve criticality of a submarine plant by the middle of 1961. In view of the very experimental nature of the project and extremely compact installation arrangement in a submarine, a land-based prototype was deemed early on to be essential. To ensure applicability, it was to be installed within the confines of a submarine hull. A suitable site was chosen adjacent to the existing UKAEA site at Dounreay which could provide the necessary supporting facilities and staff. The programme aims were accordingly altered and target dates for criticality were adjusted to January 1960 for the Dounreay submarine prototype (DSMP) and the middle of 1962 for the first submarine.

The Naval Section reached the same conclusion as Rickover and his team that a light water-moderated reactor fuelled with enriched uranium was the most promising choice. Such a reactor plant would best meet the needs of a submarine propulsion plant offering high power density, control stability, and above all capable of being engineered into a small submarine hull (FIG. 4).

The key industrial companies involved in the programme were Vickers Armstrongs (Engineers) Limited which was to be the main contractor for the prototype set of nuclear submarine machinery, with Rolls-Royce Limited, the main subcontractor responsible for the design and production of the reactor and associated equipment comprising the core, fuel elements, emergency cooler, and reactor and control instrumentation. Foster Wheeler Limited was to be the sub-contractor for the design and manufacture of the reactor pressure vessel, primary circuit and steam generators.

The co-ordination of the R and D, design, and manufacturing work in a programme involving three major engineering companies, Admiralty Design Departments, AERE, and the UKAEA, was the prime responsibility of the Naval Section at Harwell. A new company, Vickers Nuclear Engineering Limited, was formed in which Vickers Armstrong Limited, Rolls-Royce Limited, and Foster Wheeler Limited were partners. The UKAEA provided R and D staff, information, and access to experimental facilities such as the corrosion and heat transfer rigs associated with Leo (pressurized water reactor for land power generation), and the use of Lido, the swimming pool reactor at Harwell, in the shielding design studies which had to be completed at a very early stage in the programme. To meet the deadline of early 1960 for the prototype, it was necessary to define the basic parameters for core design by autumn 1956 to allow zero energy test reactor operation by the spring of 1957. Results from the test reactor had to be available in time to fix finally the core and fuel parameters by April 1958.

After Admiral Rickover's visit to the United Kingdom in May 1957, a British technical mission visited the U.S.A. and obtained valuable information on the U.S. Navy design of submarine propulsion plant; as a result several U.K. design aspects were reconsidered and a decision taken by the team at Harwell to change the type of fuel previously selected for the reactor core.

A major decision was the choice of material for the primary circuit and the major components of the reactor plant; the choice lay simply between austenitic stainless or low alloy steel, but lack of experimental data on such factors as stress corrosion, hydrogen embrittlement, high-temperature corrosion rates, irradiation damage, corrosion product activity, etc. clouded the issue, and created one of the most profound controversies of the project. Despite the increasing understanding of stainless steel metallurgy, the susceptibility of stainless steel to chloride stress corrosion outweighed the relatively higher corrosion rate and slight susceptibility to hydrogen embrittlement of low alloy steel, and it was decided after the most careful consideration to fabricate the reactor pressure vessel, main primary pipework, and steam generator tubes from a chromium-molybdenum low alloy steel. The validity of this decision was later reinforced by the corrosion resistance of low alloy steel proving better than might have been expected, as a result of the build up of an adherent magnetic oxide film (magnetite) following exposure to high temperature water or steam (The system has in fact operated very successfully in DSMP for some seventeen years).

When the order for the first British nuclear submarine was placed by the Admiralty in 1957, the management of the nuclear propulsion plant project was reorganized, with the formation of the Dreadnought project team (DPT) at Bath, to provide a joint Admiralty design team under a project team leader. The Naval Section at Harwell became responsible to the team leader for the experimental work undertaken in support of the project at the various AEA establishments.

Nineteen fifty-seven was an eventful year. By December, site preparation was under way at Dounreay; a full-scale wooden mock-up of the DSMP plant was nearing completion at Vickers Armstrongs Limited works at Southampton; 160 professional staff were directly employed on R and D at Harwell; Neptune the zero energy reactor, the first reactor in the Royal Navy's nuclear submarine programme, was taken critical at Harwell on 7 November

1957. On completion of the initial work in support of the DSMP reactor design, Neptune was dismantled and moved to Derby in 1959 for future development work.

In parallel with these developments, extension of the U.S./U.K. co-operation on nuclear matters provided Britain not only with the opportunity to purchase enriched uranium and further access to design information but also resulted in an agreement in 1958 under which the U.S. government authorized the sale to Britain of one complete submarine nuclear propulsion plant and agreed spares.

The purchase of a complete S5W reactor and associated machinery similar to the plant fitted in the U.S.S. *Skipjack,* for the first Royal Navy nuclear submarine, H.M.S. *Dreadnought,* put the DSMP project in jeopardy. There were those who deplored the use of an American plant in a British warship and what they saw as time wasted on the work in the U.K. Be that as it may, without that work the U.K. could not have participated meaningfully in the bilateral co-operation and the generous offer of the S5W technology might not have materialized. There is little doubt that the Admiralty's objective in having the Royal Navy's first nuclear-powered submarine at sea by 1963 would not have been achieved without the purchase of the S5W reactor plant for reasons discussed in the following paragraphs.

To implement the 1958 U.S./U.K. bilateral agreement it was necessary to set up a new U.K. company to deal with Westinghouse U.S.A., manufacturers of the reactor plant. Rolls-Royce and Associates Limited, a private company registered in January 1959, was formed jointly by Rolls Royce Limited, Vickers Armstrongs Limited, and Foster Wheeler Limited, with controlling interest vested in Rolls-Royce Limited. Since 1959, R-R & A Limited has acted as the Royal Navy's delegated design and procurement authority for reactor plant.

While the Dreadnought project team urgently pursued the design and build of *Dreadnought,* 1959 saw the completion of much of the experimental work at Harwell and the UKAEA establishments in support of the DSMP plant. The Naval Section at Harwell was disbanded and Professor Edwards moved to the Royal Naval College, Greenwich to establish the department for the training of nuclear submarine engineers. The next decision was crucial. Should the future nuclear submarine propulsion programme depend on U.S. technology and machinery or should the U.K. follow its own development, modified by the invaluable information gained from the *Dreadnought* project? Happily the decision at Government level was to stand on our own feet.

But it was still necessary, having purchased the S5W plant for *Dreadnought,* to convince the Treasury of the need for a complete land-based submarine machinery prototype for our own submarine PWR programme.

The progress of the DSMP reactor plant and supporting R and D during the early years of the project reflects the quality and dedication of the teams involved. It was not the reactor theory but its engineering, in the broadest sense, which provided the delaying hurdles. This included the ability to handle new materials in production, fabrication, and inspection; development of welding techniques and post-weld acceptance criteria; working to tighter tolerances, specifications, and requirements for quality assurance together with very high standards of cleanliness; all this had to be learnt the hard way—by experience. Furthermore, in hindsight, insufficient detailed design effort was devoted to the secondary plant; certainly not comparable to that applied to the primary plant.* The reason for this was simple; the secondary plant was

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*To explain the terminology: the reactor plant and associated equipment including steam generators which are all sited within the reactor compartments is termed the primary plant or nuclear steam raising plant; the propulsion and auxiliary machinery sited outwith the reactor compartment is termed the secondary plant.

regarded as established technology in its close general similarity to a surface warship steam propulsion plant, except that steam conditions would be saturated and not superheated. The satisfactory installation of such a plant within the available volume of a small diameter submarine hull was rather taken for granted, with inadequate appreciation at the design stage of the requirement for machinery operation and maintainability. Equally those systems and equipments unique to a diving submarine had successfully evolved over the preceding forty years in particular for the HTP submarine project. They would, it was considered, only require extrapolation to fulfil nuclear submarine applications. The inevitable result was extensive delay to the machinery installation for detailed redesign and modification. Despite these problems the plant was completed and preliminary commissioning started in early 1963.

In September, a number of apparently innocuous leaks were detected in some of the primary circuit nickel alloy small bore pipework when the plant was hot and pressurized. Within weeks the number of leaks had risen to twelve, all related to weld areas in nickel alloy pipework. Preliminary examination revealed that the failures had occurred due to intergranular cracks in the heat affected zone of the welds. A major programme of investigation was put in hand covering examination of weld procedures, material composition, dye penetrant developers, the carburizing effect of oxyacetylene preheating, cleaning agents, cutting oils, tube drawing lubricants, and radiographic acceptance standards, but by the end of 1963 it became clear that a ready solution was not available. Determining the root cause of the failure proved extremely difficult, with several possible conflicting theories hotly argued but unsubstantiated by intensive laboratory testing. The early favourite, a form of sulphur contamination, was later superseded by stress assisted intergranular corrosion cracking.

With one thousand six hundred and fifty-eight nickel alloy welds in the DSMP primary plant and no clear solution in sight, the decision was taken early in 1964 to renew all nickel alloy piping and fittings in chromium-molybdenum low alloy steel, partly because, although replacement in stainless steel was considered, all available supplies were required for *Valiant,* to replace her nickel alloy pipework. Whilst the necessary redesign work was put in hand with little delay, the production of components, particularly valves, was a time-consuming process and resulted in further programme delays. An unfortunate spin-off from the efforts to cut delays was the use of valves to designs available for other duties which were more complex than necessary and brought their own troubles in extra maintenance later on.

Today DSMP is seen as one of the corner stones of our successful nuclear propulsion programme. Not only has it provided a test bed for new technology and the lead plant for sea-going submarine propulsion systems, but it also provided initial practical training for the operators of nuclear submarines. Furthermore, it afforded a test bed for the solution of technical problems that could be expected to arise in the submarine plants.

Valiant Class Submarine

The first British nuclear submarine, H.M.S. *Valiant,* was ordered in August 1960 from Vickers Armstrongs (Shipbuilders) Limited with the nuclear plant to be supplied by Rolls-Royce and Associates Limited.

The design resulted from a study in 1960 to compare the relative merits of the U.S. S5W plant in *Dreadnought* with that intended for DSMP. As a result of the comparative study, *Valiant* was to differ from DSMP in several respects although many of the study report recommendations were not finally adopted due to cost and, once again, the need for the earliest possible completion date—they were to appear in the *Swiftsure* class of submarine some ten years later.

The major changes adopted were:

(*a*) to fabricate the primary circuit and major plant components in stainless steel using American design codes for pressure piping and components;

(*b*) to use a low alloy steel reactor pressure vessel clad with a lining of stainless steel by weld deposition;

(*c*) to simplify the secondary plant, particularly by careful system design to reduce the number of valves and fittings;

(*d*) to provide a circulating-water system cross connection between the main-engine condenser and the turbo-generator condenser;

(*e*) to design for improved access;

(*f*) to reduce the number of remotely operated valves in the reactor compartment and use primary circuit water for hydraulic actuation.

The use of a fabricated stainless-steel primary circuit in *Valiant* acknowledged that the reliability of ferritic steel circuits had not yet been proven in service either at sea or in a prototype and, furthermore, that the benefits of easier fabrication in ferritic steel had not materialized at DSMP, rather the reverse with stainless steel fabrication proving straightforward.

But *Valiant* was not to experience a trouble free programme. Early in the build, the Skybolt missile project to arm the U.S. Strategic Air Command and the V-bombers of the Royal Air Force with a 'second strike' system was cancelled on the grounds of cost. By that time the U.S. had already conceived and put into effect the 'ultimate' role for submarines as a weapon platform for a submarine launched ICBM missile system.

At the Nassau conference in 1962, the United States undertook to provide the missiles and associated systems for a British submarine deterrent force. The warheads and the submarines themselves were to be of British design. In February 1963 orders were placed for four Polaris submarines with nuclear propulsion plants based on the *Valiant* design and H.M.S. *Resolution* was laid down at Barrow-in-Furness in February 1964.

The British Polaris project was an immense and complex undertaking, given the extremely short time-scale, the unprepared state of both industry and shipbuilding to respond to such a project, and the scale of the support organization necessary to underpin an operational Polaris submarine force—to say nothing of the lack of any significant nuclear submarine operating experience; H.M.S. *Dreadnought* was only accepted into service by the Royal Navy in 1964.

Success called for management of the highest order. A Chief Polaris Executive (CPE) was appointed, with overall control of the project. New project management techniques and procedures had to be employed, many culled from the U.S. Navy's own Polaris project, such as status charts, programme management planning, key-event charts, and network scheduling. The time-scale was so short that all major activities had to start concurrently, requiring the systematic breakdown of the project into systems and subsystems. Multiple starts were called for in shipbuilding too, so Cammell Laird was brought in as the second building yard with Vickers as the lead yard. The demand on the submarine deterrent force to meet deployment dates and achieve very high levels of availability in operation called for the extensive use of quality assurance with fully documented quality control for production programmes.

The setting up of the infrastructure necessary to support an operational Polaris deterrent force of four submarines, and in particular their nuclear propulsion plants, involved the establishment of:

(*a*) comprehensive repair and maintenance support facilities in the submarine operating base at Faslane, including an organization for the guaranteed availability of spares, replacement parts, etc.;

(*b*) organization of a Royal Dockyard to refit and refuel the submarines on a cyclic basis;

(*c*) facilities to train nuclear propulsion plant operators with the use of plant simulators to overcome the lack of operational nuclear plants on which to carry out practical training and qualification.

The successful completion of the Polaris submarine building programme from the boat order date in February 1963 to deployment of H.M.S. *Resolution* on the first deterrent patrol in the summer of 1968 can only be regarded as a remarkable achievement in co-ordinating and managing the several hundreds of industrial firms engaged in the project (FIG. 5).

Not surprisingly, the programme to design and build the four Polaris submarines (SSBNs) reduced the priority for resources to complete *Valiant*. The weld failures in DSMP resulted in a major exercise to replace all the nickel alloy pipes and fittings in *Valiant;* the acute shortage of valves resulted in *Dreadnought* spare valves being used. Further delays resulting from difficulties in setting up the neutron flux measuring instrumentation, meant that she was not finally accepted into service in the Royal Navy until 1966, some three years after *Dreadnought*. In hindsight, the additional time spent in resolving the design problems in the propulsion plants of *Valiant*/DSMP ensured that the SSBNs inherited a tested and proven propulsion plant, albeit one that required initially a high maintenance effort to keep it fully operational.

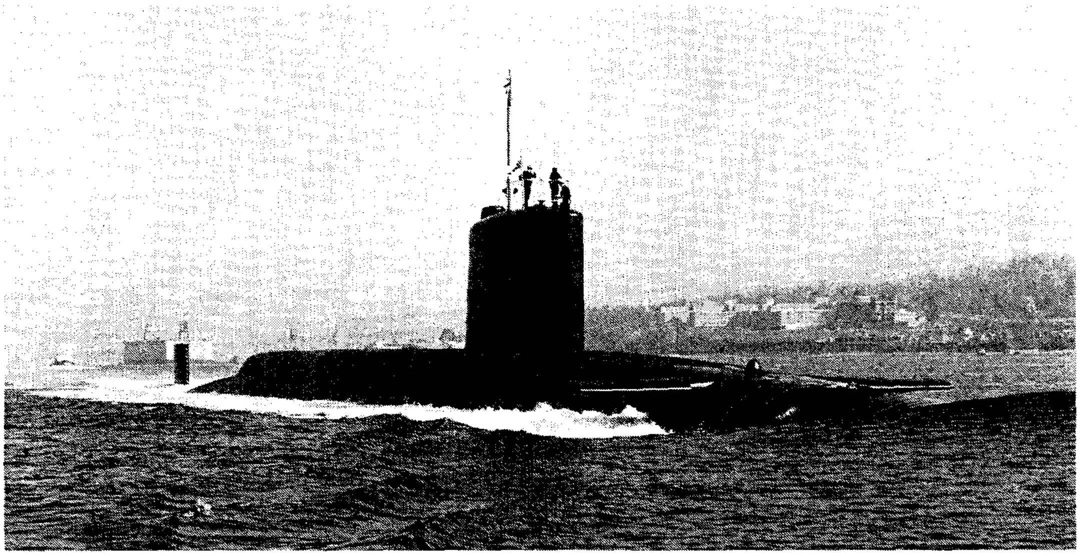

FIG. 5—H.M.S. 'RESOLUTION', COMMISSIONED IN 1968

Second Generation Submarine

With completion of the basic design work in 1961 on the nuclear propulsion plants destined for DSMP and the *Valiant* class, forward design thinking was directed towards a new and improved class of submarine to come into service in the early 1970s.

Admiralty approval was obtained in 1961 to start a core development programme to ensure the continuity of core design expertise in R-R & A Limited; this resulted in a specific design programme to design and produce a higher power core with increased design life.

In parallel with this core design work, a contract was placed with YARD Limited to examine the design basis of secondary propulsion machinery for a future nuclear submarine.

The intervention of the British Polaris project delayed this early design work and it was not until 1964 that the Admiralty was able to divert its full attention and sufficient funds to the new submarine design designated SSNOX. The outline staff requirement was to evolve a design incorporating lessons learnt from *Valiant* and to be a step forward in respect of reduced noise and vulnerability. The propulsion plant was not to be a revolutionary design but an evolutionary advance with emphasis on improved machinery arrangement, ease of operation, and maintainability. Lessons learnt from the design, building, testing, and operation of *Valiant* were many and various. The sheer complexity had been a cross heavily borne by those involved in installation, operation, maintenance, and overhaul of the propulsion plant, in particular the secondary machinery. As an example, the provision of individual condensers for the turbo-generators so as to allow for electrical propulsion by a Ward-Leonard system with the main turbines shut down involved paying a heavy price in terms of additional extraction and circulating water pumps, attendant controls, and instrumentation, and not least the congestion resulting from the 'extra' pipework. In SSNOX, each turbo-generator and main turbine would share a common two-pass condenser. This gave a much simpler circulating-water system with the minimum length of piping inside the hull. The overall length was further reduced by siting the circulating-water pump in the condenser header, pumping between the tube passes.

Similarly the intricate and widespread auxiliary seawater cooling system fitted in *Valiant* not only presented the operators with a heavy maintenance load in terms of cooler fouling, pump mechanical seal problems, and so on, but also a failure of such a system at depth put the submarine at risk: any sudden sizeable failure could lead to the loss of the submarine. The achievement of acceptable integrity in cast nickel-aluminium-bronze components had been, and for large components continued to be, a difficulty. Casting porosity which necessitated extensive weld repair had resulted in protracted production times. Subsequent to these weld repairs, in-service problems were experienced due to de-aluminification of the weld filler material because the more corrosion resistant protective capping layer had been generally removed on weld dressing. Selective attack of the α and β phases of the parent metal and of weld heat-affected zones were experienced in service, requiring periodic inspection of castings and their assessment for further use. Work was put in hand to develop improved NAB casting processes and specifications such that casting porosity would be largely eliminated for SSNOX. By keeping those systems subjected to full diving sea pressure down to an absolute minimum, many of the problems encountered in *Valiant* would be avoided. Thus in SSNOX, auxiliary cooling was designed as a low-pressure, fresh-water system itself cooled by a sea-water/fresh-water heat exchanger mounted close to the hull with short sea-water system pipe lengths. As for the main condensers, the sea-water pumps were to be mounted in the heat exchanger headers. Although this concept was simple and clearly provided a minimum space arrangement, the hydraulic design of the pump in header required major development, with the prize being the potential noise gains. Engineering caution might have opted for a conventional pump.

A nuclear submarine's vulnerability to detection by enemy submarines, suface warships, and maritime aircraft is very largely dictated by her radiated noise signature both in terms of broad-band and discrete noise. Results from *Valiant* had shown that at low submarine speeds, rotational machinery noise from the propulsion plant constituted the majority of the radiated noise signature. Equally, self noise, transmitted through the direct noise path between machinery, hull, and array, directly degraded the ability of the sonar 'hydrophone' arrays to detect other submarines. Experience in *Valiant* had highlighted the incidence of self noise through installations faults (noise short circuits). For SSNOX, much effort was directed towards producing machinery mountings with improved noise attenuation and, by careful systems design, the elimination of noise short circuits. The main propulsion machinery, i.e. main turbines, gearbox, condensers, and turbo-generators, would be mounted on one large machinery raft supported on a constant position mounting system to provide the required noise attenuation at full power and capable of absorbing the higher shaft torque associated with the slower speed SSNOX propulsor (*Valiant's* machinery raft had to be 'locked' solid to the hull at high powers to absorb full-power torque).

Experience of the operation and maintenance of auxiliary machinery in both naval, marine, and industrial plant had shown the inherent advantages of electrically-powered auxiliaries over steam-powered auxiliaries. It had also shown the advantages in machinery arrangement of air-cooled electric motors over water-cooled motors with their labyrinth of small-bore cooling-water pipework.

In summary, the lessons to be incorporated into a new design of submarine would reflect:

(*a*) the need for simplicity consistent with adequate duplication (redundancy) for fault conditions (somewhat cynically, 'what you don't fit can't give you trouble');

(*b*) the need to design for reliability and maintainability;

(*c*) the need for comprehensive prototype/production testing;

(*d*) the need to apply quality assurance and ensure quality control in equipment manufacture and in installation.

In contrast to the secondary plant, the *Valiant* reactor plant had an excellent record. This was largely due to the recognition from the start of the need for high reliability because of its bearing on nuclear safety. The key lay in the establishment of a comprehensive design and procurement organization to achieve the required level of reliability through quality.

Valiant's building period and the production problems encountered on secondary and hull systems highlighted the need for a similar quality assurance system to run from design through build and operation. Only in this way could a consistently high-quality product be achieved.

Swiftsure Class Submarine

In October 1967 H.M.S. *Swiftsure,* the first submarine of the SSNOX class, was ordered from Vickers Shipbuilders Limited. In the same year the first new design reactor core, designated core B, was installed at DSMP, going critical in August 1968. The plant was to be operated at high power for the following two years to achieve significant fuel burn-up and confidence in the design prior to committing the *Swiftsure* core to production.

The comprehensive prototype testing of the secondary machinery was to be undertaken in the Admiralty Development Establishment Barrow (ADEB) close to the shipyard. It would not have been possible to test the secondary machinery at DSMP where the requirement for continuous high power running to achieve fuel burn-up would have conflicted with the prototype machinery testing programme. ADEB had been used for the design and development of the submarine HTP propulsion plants, for shore trials of the DSMP secondary machinery in 1960, and the VALIANT Class plants thereafter, although all the trials were limited to low powers by the capacity of the test boiler.

Extensive modifications to ADEB were undertaken to provide capacity for full-power testing of the secondary machinery, including the provision of a BATTLE class destroyer boiler which gave yeoman service.

To embrace the long-term test requirements for the prototype machinery set and to allow for production testing of follow-on submarine machinery sets, the test facility had to allow for the extensive prototype trials to proceed whilst production sets were erected on a second test bed; the test beds were arranged back to back with a central dynamometer. This proved to be a false economy. The nature of the SWIFTSURE Class propulsion machinery with its large machinery raft incorporating integral gearbox, turbines, condensers, and turbo-generators meant that the test facility was also the assembly site where all the major components came together for the first time; this required the facilities necessary for machinery erection, i.e. machining capacity, pipe fabrication, etc.

Major fabrication problems in the production of the main machinery raft, particularly distortion due to the welding of a complex structure in HT steel, required considerable redesign effort by Vickers engineers to produce an adequately rigid raft structure and, together with pressure on Vickers engineering installation resources, caused slippage in the build programme for the prototype so that the first submarine machinery set (for *Swiftsure*) was on test after only a few weeks of prototype testing—whereas six months prototype trials in advance of the first production set had been planned.

Early problems included a gearbox failure as a result of an overloaded main gearwheel bearing, a primary pinion tooth failure, and main turbine thrust bearing failures. A risk decision was taken, after initial examination of the failures, that the problems were curable without major surgery to the propulsion plant. The *Swiftsure* machinery set was therefore loaded on board to maintain the submarine completion date whilst the solutions were worked out on the prototype set. Happily the risk was justified and modifications were possible *in situ* on board. Thus as trials progressed on the prototype set, design faults changed the emphasis from what had been a prototype trials programme to a machinery development programme, expanding from the planned six months duration to twenty-seven months. But the overall submarine production programme was not delayed and the critical importance of comprehensive prototype testing was reaffirmed.

The *Swiftsure* machinery set production trials completed in April 1970, the submarine was launched in January 1971 and was accepted into service by the Royal Navy in March 1973. Operating experience with the SWIFTSURE Class has confirmed those design changes made from the VALIANT Class propulsion plant. In two vital aspects the design target has been surpassed: propulsion plant reliability and noise performance. The reliability reflects the simpler machinery arrangement enhanced by the higher quality of design, fabrication, and installation work. The noise performance reflects the considerable efforts concentrated on analysis, research, and design development on the noise and vibration front, particularly in the detailed refinement of certain 'sore thumbs' identified during early noise trials in *Swiftsure*. For example, the basic noise advantage of interposing the main circulating-water pumps between the tube passes of the main condensers was originally lost through poor design of the inlet ducts resulting in serious cavitation; re-design of the ducts fully recovered the noise advantage.

Third Generation—Trafalgar Class (A Quieter 'Swiftsure')

Having proven the developments incorporated in the SWIFTSURE Class propulsion plant, it was time to take stock of the situation and consider what further improvements were possible in terms of overall submarine performance, both for operational and through-life reasons. Increased through-life utilization of the submarine was possible if the interval between reactor core refuelling could be extended, and thus reduce the number of major refuelling refits in a submarine life; a very significant through-life cost saving over previous submarine classes would also accrue. Continuing improvements in weapon and sensor technology, in particular noise analysis techniques, dictated that every effort should continue to be directed towards reductions in the radiated and self-noise spectra of the propulsion plant.

As a result, in 1968, R-R & A Limited started development work on the TRAFALGAR Class primary plant with the specific aim of achieving increased core life and reductions in the pumping power and noise at source of the main coolant pumps. Work on the core Z design was completed in 1971 and production of the first core started in preparation for its installation in DSMP where evaluation of the first core B (for the SWIFTSURE Class) was nearing completion. Following a major refit of the complete propulsion plant at Dounreay in 1973/4, core Z1 was installed and testing commenced.

It is worth mentioning work in two primary plant areas—small bore valves and fittings, and main coolant pump vibration. Thermal cycling from frequent power changes is, of course, part and parcel of the day-to-day operation of a submarine reactor plant and poses problems of a different order from those in a land power reactor. The extension of core life brought to prominence consideration of thermal fatigue in certain pipework and fittings. Considerable programmes of work to identify the mechanism of the process in stainless steel resulted in a much improved appreciation of methods of detail design to avoid susceptibility to thermal fatigue. It is probably not generally realized that it is possible to suffer incipient cracking from thermal variations of as little as 10°C under certain loading conditions. Not surprisingly the need to avoid rapid changes in section and the careful location of weldments are critical. Detail pipework system design can also secure significant reduction in the magnitude of cycling. Development work on main coolant pumps has been pursued with two objectives, noise reduction and improved containment integrity. The noise reduction requirements have led to lowering of rotational speed and a reduction in pumping power with increased attention to detail design to improve mass balance and concentricity, stabilizing and reducing the bearing dynamic forces, and analysis of pumping noise. The second objective requires an improved standard of strength welding of the motor casing and better access for weld inspection.

For the secondary plant, the acceptable levels of reliability and maintainability achieved in the SWIFTSURE Class resulted in machinery development work being largely directed towards further improvement in noise performance. Although noise reduction at source is the most logical approach, it can be expensive, with each successive dB noise reduction increasingly costly to achieve; analysis of the noise transmission paths from machinery to sea, and the development of noise attentuation techniques proved in many cases more cost effective even at the price of incorporating new and space-consuming mounting systems. In general, for rotating machines and fluid systems, palliative treatments such as improved mounting arrangements, pipe damping, flow silencing, pipework clipping, and hull damping were applied. The one area of the SWIFTSURE Class main machinery that had not lasted well in service was the raft mounting system, although prototype testing had been satisfactory. Thus for the *Trafalgar* main machinery raft a simpler but equally effective mounting system was developed.

To provide a more comprehensive organization for the analysis and testing of noise improvement design modifications during shore trials and onboard the submarine, a noise and vibration engineering department (NAVED) was set up by Vickers engineers at Barrow. They were also given the task of eliminating 'noise shorts' during the submarine build and machinery installation phases and to undertake noise measurement and analysis during contractor's sea trials.

Prototype Testing

Despite the success of the SWIFTSURE Class prototype machinery testing at ADEB, facilities there had been stretched to the limit. Lack of space produced undesirable congestion for a test facility and, worse, restricted the amount of instrumentation that could be fitted and properly monitored. A further drawback had been the distance separating the test facility from the submarine building berths in the shipyard. Accordingly Vickers were contracted in 1972 to design and erect, close to the submarine building berth, a new test facility capable of meeting future requirements for machinery erection, alignment, and prototype machinery testing in parallel with production testing. It was to provide complete remote control, monitoring, and recording of trials with computer and data logging facilities. The test beds were to be designed so that accurate noise and vibration measurements could be taken on running machinery. Additional testing facilities for individual equipments such as pumps, heat exchangers, and electrical breakers were to be provided.

The Submarine Machinery Installation Test Establishment (SMITE) was commissioned in December 1976 and was used for the production tests of the machinery for SSN12, the last submarine of the SWIFTSURE Class and subsequently SSN13 and SSN14 (FIG. 6).

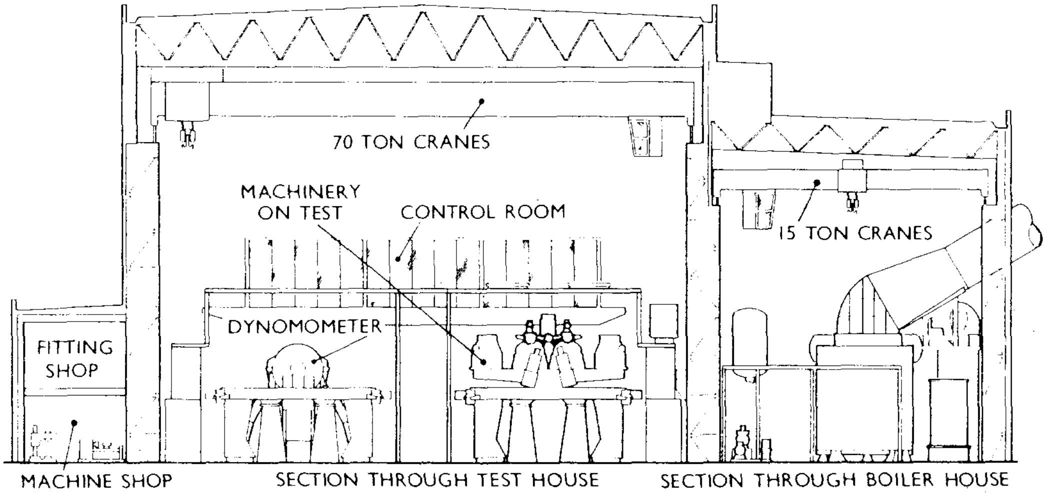

FIG. 6—SECTION THROUGH SMITE FACILITIES

During the building of the VALIANT Class and particularly the SWIFTSURE Class, improved shipbuilding techniques were introduced both as a result of the availability of new technology and the drive for reduced production costs.

Full-scale machinery compartment mock-ups (constructed from timber) had been considered from the start of the DSMP project as an essential prerequisite to achieving an optimum layout of piping and equipment in machinery plants of such high packing density and played a major part in the detailed design process for the earlier submarines. The DSMP mock-up had been constructed at Southampton in 1957 and full-scale mock-ups were built at Barrow for VALIANT and successive Classes of submarines. Although considered essential, mock-ups were both expensive and time consuming to build and, more particularly, to alter at a later stage. With the confidence gained in the development of machinery layouts in the VALIANT and RESOLUTION Classes and with advances in scale modelling techniques, modelling was considered as an acceptable and certainly a more cost-effective alternative for *Trafalgar*. By using a one-fifth scale model constructed from perspex and other plastics, improved accuracy and rigidity was achieved over full-scale mock-ups constructed from timber and cardboard. Optimization of the design configuration is simpler and quicker, while changes can more readily be incorporated at one-fifth scale: above all, scale modelling is considerably cheaper.

Reduction of costs and building time were requirements for the TRAFALGAR Class, and with pipework fabrication, a significant element of both, much effort was devoted to the use of standard pipe components and reduction of the 'one off' traditional shipbuilding approach, with a significant reduction in the number of standards, classifications and processes; change being made easier by the introduction of SI units.

Having effectively reduced the number of components, use of a computer became a practical proposition. Optical information extracted from the model using a three-dimensional telescope system could be processed by a computer to produce isometric drawings and parts schedules. This replaced the traditional time-consuming, labour-intensive process of producing drawings from full-scale mock-ups and taking wires prior to pipe bending. The pipework fabrication process is thus streamlined, and digitized pipe bend cards produced for each pipe for use in bending machines. *Trafalgar* has some 5000 shop made pipes compared with less than 500 for *Swiftsure* (FIG. 7).

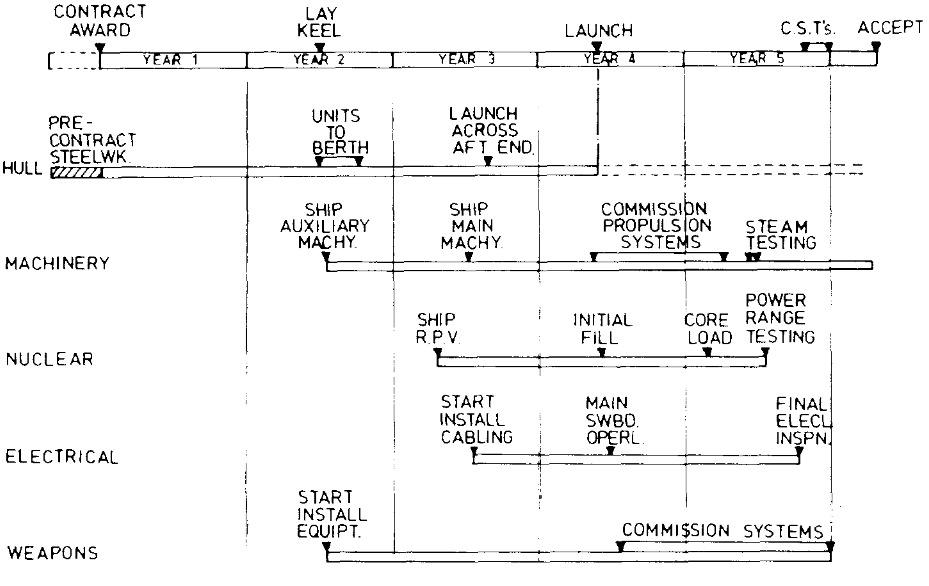

FIG. 7—NUCLEAR SUBMARINE STANDARD BUILD PROGRAMME

Future Development

About as much as possible in terms of power, core life and silence have been extracted from the physical limitations of the S5W/DREADNOUGHT family in the TRAFALGAR Class. Yet the demands for enhanced operational performance continue and studies to this end were put in train.

These forward looking studies re-confirmed the water-moderated enriched-uranium fuelled reactor plant as that best suited for submarine application. Yet there were inherent limitations and problems with the dispersed PWR and alternatives within the same generic family were assessed. One promising alternative appeared to be the integrated saturated-water reactor (SWR) (FIG. 8). The SWR offered advantages in terms of reduced weight and space, lower operating pressure, reduced flow, and pump noise by virtue of a degree of natural circulation, simplification of auxiliary systems, and inherent safety. The early requirements for very high power output had a considerable bearing on this choice.

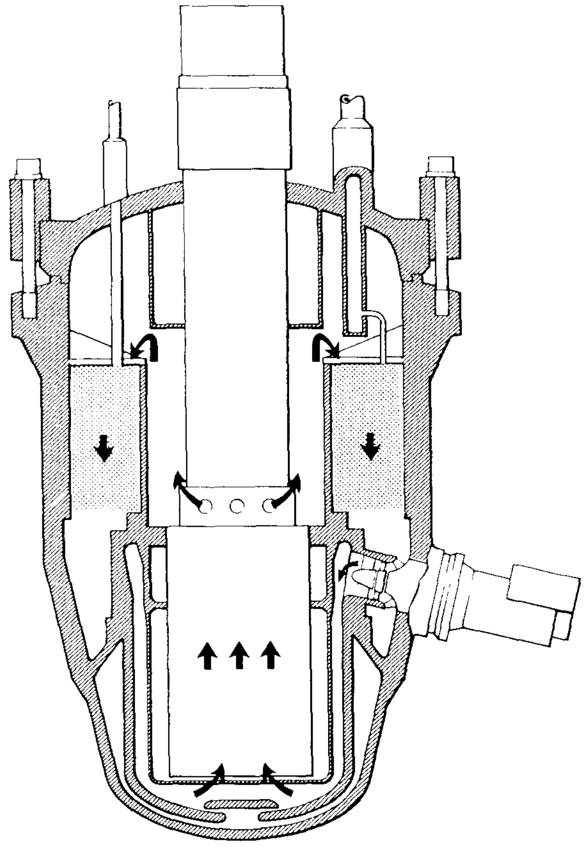

FIG. 8—TYPICAL SATURATED WATER REACTOR

However, as in all engineering, advantages are inextricably tied to disadvantages; by 1975, after three years of intensive design and development, several intractable technical problems remained. Power 'flutter' stemming from reactivity instability was particularly difficult for a submarine propulsion plant; flow stability in the natural circulation mode could be adversely affected by high degrees of boiling in certain parts of the core; excessive pressure peaking resulted from the loss of heat sink associated with the main turbines tripping at high power; the sweep out of voids in the coolant when starting main coolant pumps (MCPs) from the natural circulation mode produced sharp and unacceptable reactivity changes.

The steam generator, of the once-through type contained within the reactor pressure vessel, proved to have several significant problems: water carry-over under heel and trim conditions; performance limitations resulting from the reactor vessel size being constrained; limitations on tube packing density to allow for natural circulation; tube vibration.

After a major review of the project, it was concluded that the problem areas would yield to solution but not without increased project time-scales and further costs. But the original expectations for SWR of savings in space, weight and a reduction in noise were not fully realizable and the continuation of the SWR project was no longer justified. The difficulties with the once-through steam generator and the reactivity flutter were the prime problems that forced this decision which was made easier by a reduction in the maximum power output required. In 1976, therefore, design effort was transferred to the development of a new design of a dispersed PWR plant. The Admiralty Board objectives were firstly to enhance safety margins, secondly to improve the plant design for in-service inspection and thirdly to improve military characteristics.

Since the 1950s there have been major advances in mechanical engineering design processes, greater understanding of the mechanism of crack initiation and growth in structures, and considerable experience of plant operation. Against this background, it has become obvious that the design and safety criteria used thirty years ago were shallow, although they represented the best state-of-the-art at the time. Large safety factors or factors of ignorance were used to cater for the unknown or uncalculable. As knowledge was accumulated, it became possible to enumerate areas previously dealt with on a qualitative basis. The removal of some unjustified pessimism together with improved design techniques allowed the advances mentioned earlier to be implemented. At the same time the knowledge gained from land power PWRs and from refits of submarine plants demonstrated that inspection of components vital to safety was possible as non-destructive testing and remote control techniques improved. This opened the way to validation of nuclear safety by an on-going process of in-service inspection. In this way the steadily increasing demands of the nuclear safety authorities for demonstrable validation of safety have been met.

As originally designed the S5W-based plants did not allow for easy inspection of primary circuit or components. The codes of inspection now established require extensive inspection of active components and this buys up operational time. An aim of the new PWR design is to provide for an easier and reduced inspection task.

In brief, the improved military characteristics were increased power, lower noise, improved shock resistance, and increased core life; the latter was essential to provide increased availability and reduce support costs by reducing the number of reactor refuellings in a given submarine life.

The reactor design, to be known as PWR2, required substantial changes in all major components and their arrangement such that operational proving was necessary before it entered service in a submarine; the requirement for full prototype testing was therefore re-established. The development programme called for building a second shore test facility (STF2) on the same site as the existing DSMP, timed to provide sufficient testing and fuel burn-up prior to ordering the first production core for a new class of submarine.

Unlike the original DSMP, STF2 would not contain a secondary submarine propulsion plant in a hull section, but a simple dump steam facility with turbo-generators for power generation. As before, the requirements for primary plant trials and sustained high-power running to achieve fuel burn-up are incompatible with a prototype secondary propulsion plant development and test programme.

YARD Ltd. were therefore contracted to manage the development of a secondary plant design compatible with PWR2. The design would evolve from the SWIFTSURE/TRAFALGAR machinery taking maximum advantage of latest technology to meet requirements of increased power density, weight reduction, longer operating life between overhaul, improved equipment reliability, improved access for maintenance and operation, reduced noise, lower unit costs etc.—the inevitable collection of conflicting requirements presented to the designer.

As an example of the difficulty and the cost in obtaining such improvements in an evolutionary design, FIG. 9 shows the extensive development programme for the main turbine condenser and circulating-water system. The 'pump-in-pipe' (a totally enclosed circulating water pump), conceived in the late 1960s as an innovative improvement on current designs of circulating-water pump, was aimed at eliminating the problem of sealing the pump shaft against diving depth pressure, improving flow conditions for the pump, hence reducing noise and vibration levels and reducing the size and complexity of the condenser header castings. A feasibility study confirmed that potential gains were significant and that it was possible to combine canned-motor technology with a maximum flow pump within a minimum size of pressure-containing envelope. Doubts about the acceptability of the performance of the proposed materials for the pump, and in particular the water lubricated bearings required full-scale prototype testing. Construction of the prototype was authorized in 1973, backed up by rigs examining the performance of the under flow motor cooling circuit, pump tests, bearing rigs, and shock trials on the chosen bearing design. Despite an early journal bearing failure associated with the use of hard bearing materials to cope with sand laden sea-water, the pump-in-pipe is fulfilling its design expectations; the use of more conventional bearing materials has resulted in intensive investigations into bearing life to extend times between replacement.

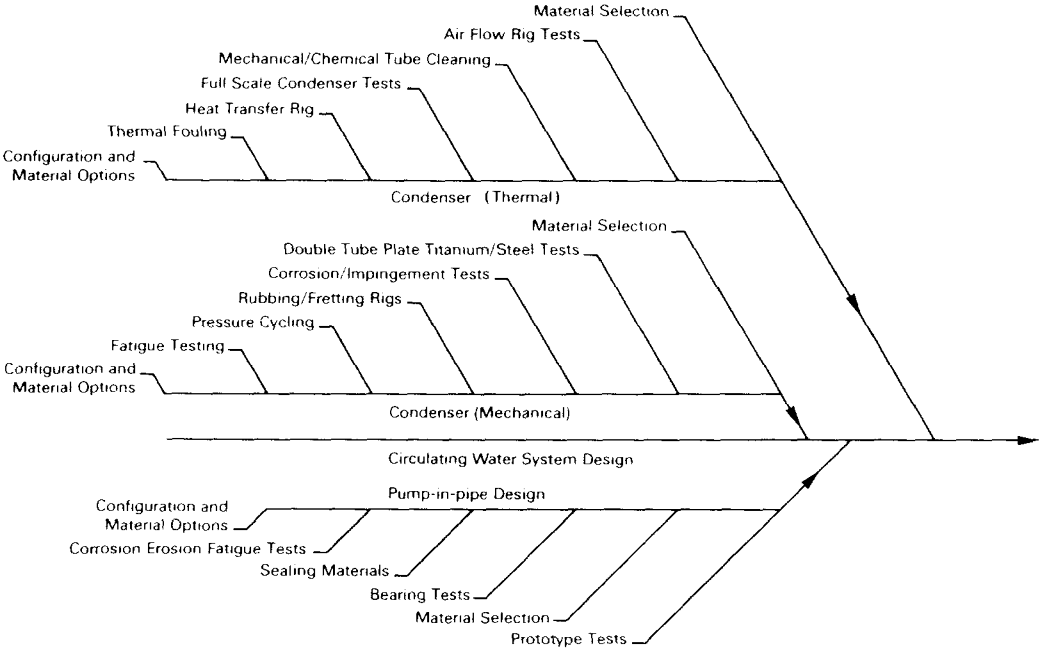

FIG. 9—DEVELOPMENT OF A CIRCULATING WATER SYSTEM

The development of the pump-in-pipe permitted alternative condenser arrangements that led to the adoption of a shorter U-tube condenser which, through the elimination of headers and tube plates, was also considerably lighter. Titanium tubes would be necessary to provide adequate through-life erosion resistance to withstand the high water speeds, particularly under conditions of partial blockage in tube bends, although the risk of this is assessed as no greater than for straight tubes. Use of titanium tubes would also give a worthwhile reduction in weight. The titanium development programme in the Western World was not sufficiently advanced to commit the other large components such as headers to manufacture in titanium; proven production processes for larger section components do not exist while fracture mechanics

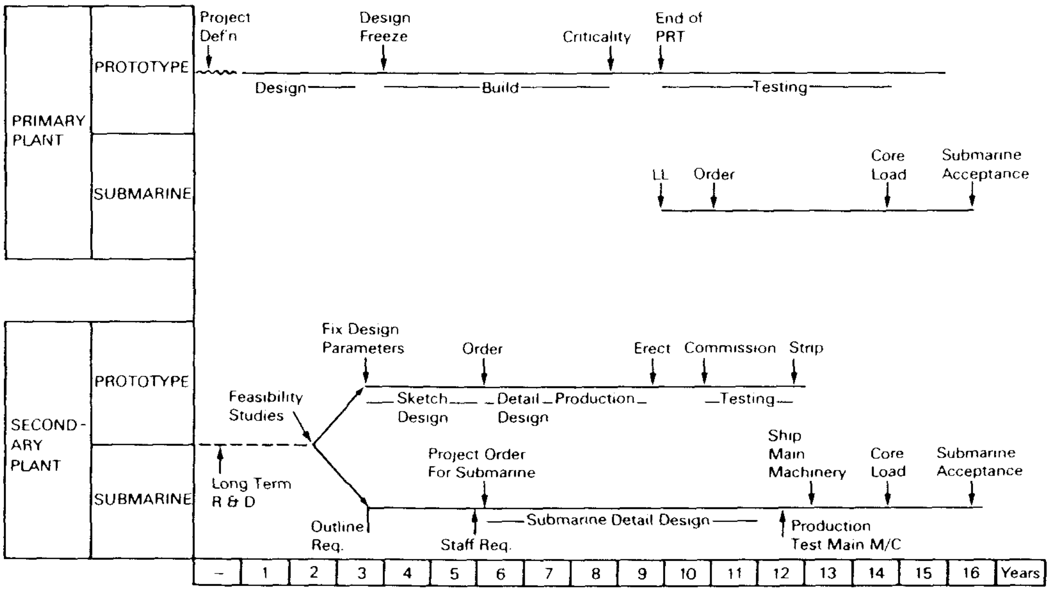

FIG. 10—OVERALL DEVELOPMENT PROGRAMMES

analysis for such sections is in its infancy. Therefore development proceeded on the basis of using nickel-aluminium-bronze for the other circulating water components which raised issues of galvanic corrosion and required rig work to confirm adequate component life.

The design was based on a conventional tube stack arrangement in order to ease the stressing of tubeplates and headers and with the U-tube stack configured to match the turbine exhaust arrangement. With no previous experience of such a design for condensing steam, it has been necessary to confirm thermal performance in a full-scale rig. Other development areas requiring attention included U-bend support, tube end fixing, tube scaling, marine fouling of titanium, and fatigue cycling. In all, fifteen test rigs have been used to develop the titanium U-tube condenser design.

This then is the scale of development work required to support today's design work for which tomorrow's nuclear submarine will materialize; whilst quality allied to sophistication in both design and manufacture equates to product simplicity and fitness for purpose, the process absorbs time and money. The time-scale between concept and fruition is graphically illustrated on FIG. 10 and compares with the twenty-two months for the first of the K boats in 1917; certainly there was no prototype machinery testing involved, but the performance of the K-class plant is all the more remarkable for that.

Conclusion

Today twenty-five years on from those early momentous days in the Naval Section at Harwell, we are fitting out H.M.S. *Trafalgar*, the first of our third generation of nuclear-powered submarines with the next three boats of the class at various stages of their construction in Vickers Shipbuilding yard at Barrow (FIG. 11). For PWR2, Rolls-Royce and Associates design work is nearing final completion at Derby with site preparation work well underway for completion of the STF building at Dounreay this summer. At Barrow, major steelwork fabrication is in hand for the construction of the pressure

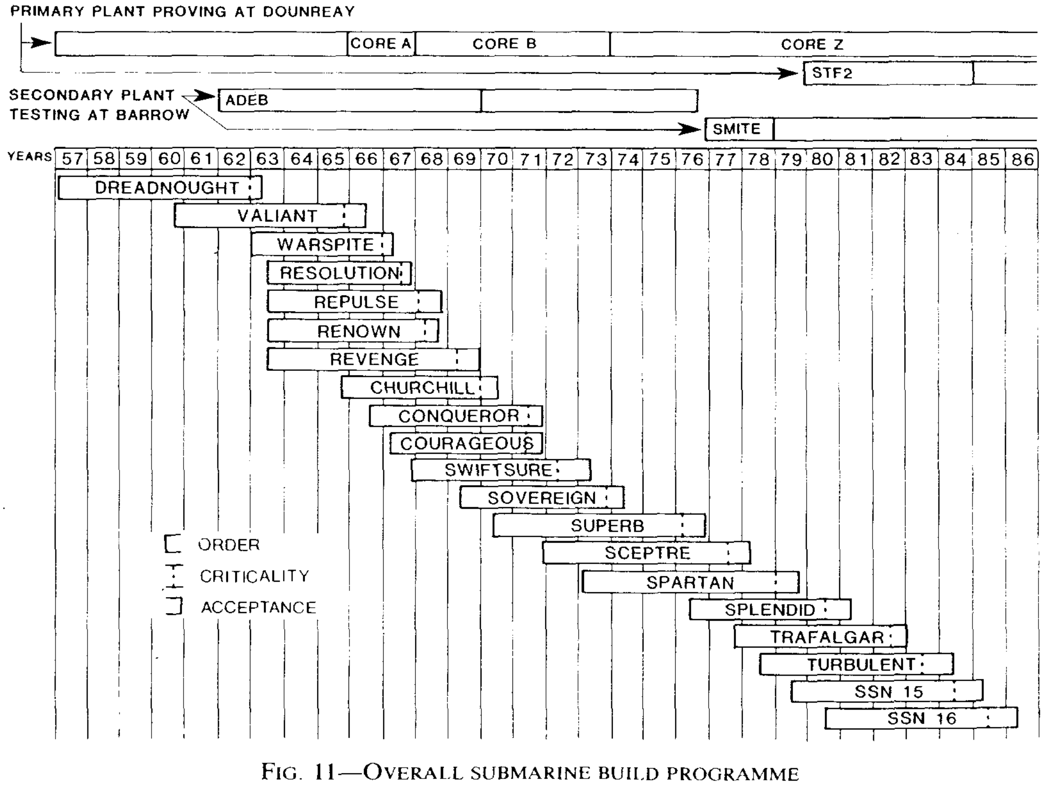

FIG. 11—OVERALL SUBMARINE BUILD PROGRAMME

hull, or rather the containment structure, prior to the installation of the PWR2 prototype primary plant. The completed prototype reactor plant in its containment structure will be transported by sea to Dounreay, on an ocean-going barge, and then overland for installation in the completed STF building prior to core load and initial criticality.

The design development of the secondary plant to match PWR2 has reached the stage of detailed design prior to manufacture and installation at SMITE where it will undergo a full two years of prototype testing.

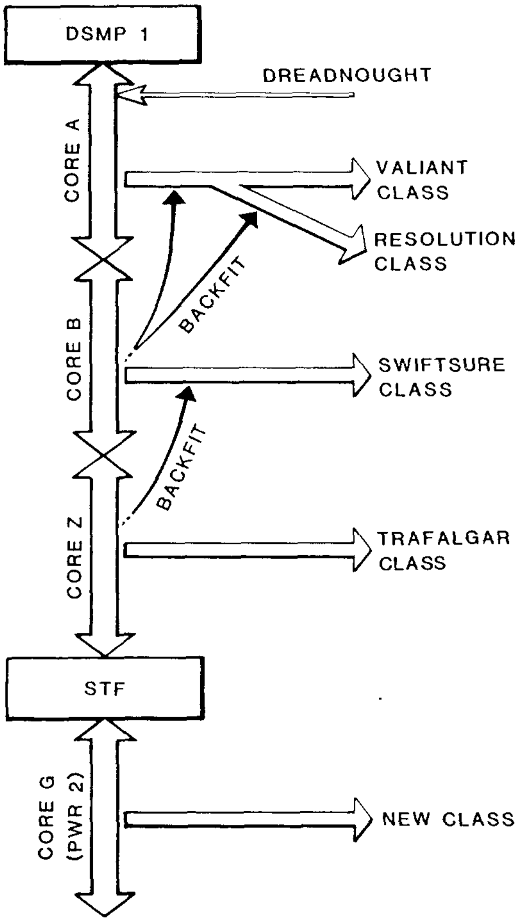

FIG. 12—NUCLEAR PLANT DEVELOPMENT 1955–1985

The early work of the 1950s and 1960s culminated in the first prototype at Dounreay which in many ways was more successful than we realized at the time and is a tribute to the dedication of the early teams. The combination of this work with the very well engineered U.S. SW5 basis plant for *Dreadnought* has enabled the U.K. to develop marine PWR technology for the Royal Navy to a performance level far beyond that envisaged in 1956. This success owes a great deal to many organizations and individuals, but perhaps more than anything else to the impetus in single-minded project management generated in the heady and challenging days when *Dreadnought*, *Valiant*, DSMP, *Warspite*, and four Polaris submarines were on trials or in build and the SWIFTSURE Class in design at the same time. The virtues of evolutionary development of a successful concept by which problems are steadily ironed out, systems and operation simplified, and reliability improved have been amply demonstrated (FIG. 12). The disciplines imposed by the quality assurance so vital to both a nuclear project and a submarine project have assured a methodical approach to problems as they arose, based on documentary records that allowed material to be traced back to source and processes to be recorded. In industry the dedication of Rolls-Royce and Associates as delegated design authority for the nuclear primary plant has been invaluable and demonstrated in particular the virtue of combining design, procurement, and support in a single organization. Vickers Shipbuilders at Barrow have been the prime contractor for the majority of the submarines and have been a sure foundation for the whole programme. Their relationship with YARD, who contribute the secondary machinery conceptual design, has been deepening over the years to the great benefit of the project. Without the continuous operating experience from the prototype trials establishments at Dounreay and Barrow, it would have been impossible to advance so steadily and confidently and the solution of in-service problems would be far more difficult and time consuming. Above all, the requirement for nuclear safety is dominant and it is perhaps this unique requirement that has more than anything else produced the discipline and dedication across all contributors to the project to assure success.

Acknowledgement

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