DOUNREAY

NUCLEAR SUBMARINE PROTOTYPE

BY

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Introduction

'Vulcan' Naval Nuclear Propulsion Test Establishment, situated 10 miles to the west of Thurso in Caithness on the north Scottish coast, is an outstation of the Sea Systems Controllerate and houses the Dounreay Submarine Prototype (DSMP). This remote site was selected in the late 1950s because of the presence at Dounreay of the Atomic Energy Authority experimental establishment and the availability of AEA land upon which to build the naval prototype. There were also obvious benefits to be gained in co-locating two establishments engaged in the development of similar and very new technologies, and even in the 1950s the location of a reactor site was a sensitive issue. Work on the site started in May 1957 and after a construction programme that was not without difficulties, both technical and political, first criticality was achieved in January 1965. DSMP has now reached the end of its nuclear life and, after evaluating 3 reactor cores, will finally shut down in June 1984.

The primary purpose of DSMP has always been to undertake the acceptance, trials, and development of prototype nuclear submarine systems and equipments. Superimposed upon this task for much of the life of DSMP has been the responsibility for providing initial operator training for naval and civilian personnel within the naval nuclear programme. This training task included classroom teaching, simulator training, and live plant operation.

The establishment has operated under three titles in its 25 year history. Until May 1970 it was the Admiralty Reactor Test Establishment (ARTE) but at this time the establishment was given Fleet Establishment status and became H.M.S. *Vulcan* within the Naval Home Command. However, naval operator training was moved to H.M.S. *Sultan* in December 1980 and in 1981 'Vulcan' NNPTE reverted to its original R and D function only and became once again an outstation of the Warship Department.

This article will illustrate specific benefits that have resulted from 'Vulcan's part in the naval nuclear programme and attempt to show that, despite the high cost of operating a development facility on the scale of 'Vulcan', the various decisions taken in the late 1950s were perceptive and justified and that 'Vulcan' has earned her keep.

The Organization

The organization at 'Vulcan' is unique: it comprises a blend of naval, MOD civilian, and commercial interests. Since May 1961 the establishment has been under the direction of a Captain Superintendent who is supported by a small naval overseeing staff of nuclear operators and is responsible to the Ministry of Defence for nuclear and radiological safety on the site. The site (including the prototype) is operated and maintained by a commercial company, Rolls-Royce and Associates Ltd. This company was formed in 1959 with Rolls-Royce Ltd a major shareholder in association with Vickers and Foster Wheeler and, later, Babcock and Wilcox. The Company was formed to act as the agents of the Ministry for the design, development, and procurement of the steam raising plant and machinery for the nuclear submarine programme. The use of a civilian contractor in this way was to ensure the development of a groundbase of knowledge and experience in a new technology and at a level that could not be sustained from within the Ministry's own resources. Equally it was seen to be very desirable that the design agent should be responsible for operation of a live submarine plant. Many benefits have accrued by having such close ties between the design authority and the prototype operators but conversely the management of the project by the Ministry has required the observation of carefully established communication links. These links and the management structure at 'Vulcan' are illustrated on a simplified chart in FIG. 1.

In addition to his responsibilities for nuclear safety the Captain Superintendent is the Quality Assurance Representative for the Operation and Maintenance contract and responsible for the facilities on site (all of which are provided by the Ministry). Without any immediate management control over the workforce (except under accident or emergency conditions) the Captain must rely upon a harmonious relationship with the Executive Manager and this has been a long-established feature of the site.

DSMP1 Design and Build

In his paper 'Submarine Propulsion in the Royal Navy'[1] Admiral Horlick has identified the key events in the early days of the nuclear programme which led to the decision to construct a shore prototype to demonstrate the feasibility of the submarine installation. The target date for criticality and the commencement of a full life evaluation of the plant was set for January

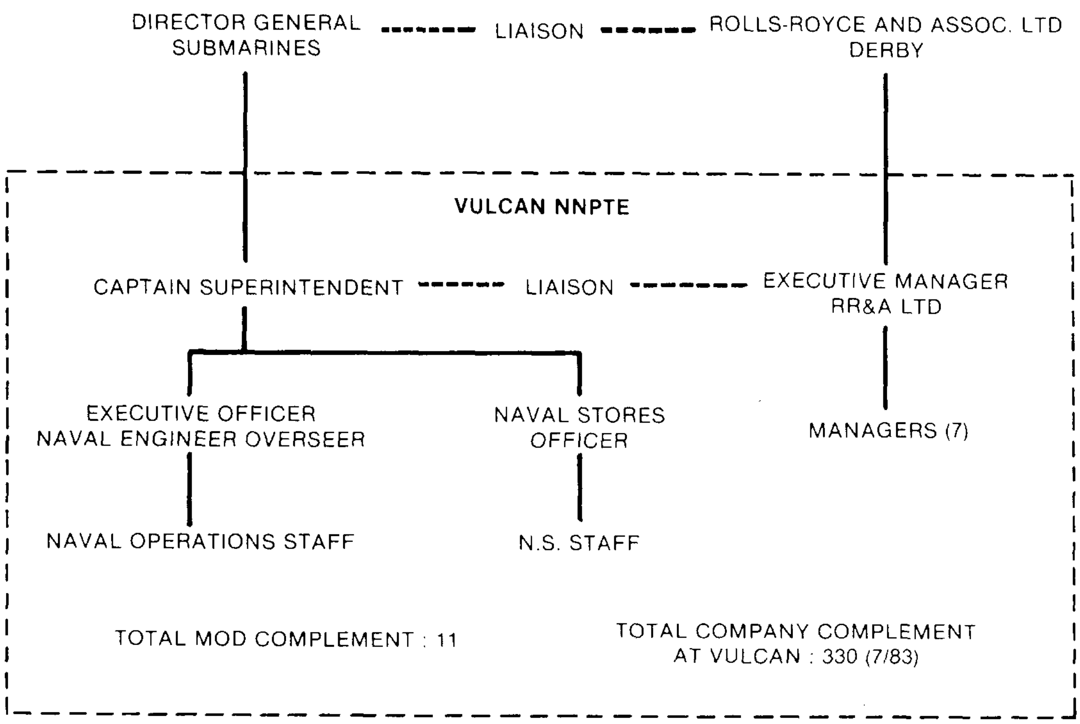

FIG. 1—'VULCAN' MANAGEMENT STRUCTURE AND LINES OF COMMUNICATION

1960. However the purchase from the U.S. of the reactor plant for H.M.S. *Dreadnought* led to inevitable delays in the DSMP programme and commissioning did not commence until early 1963. It was during this phase that a major technical difficulty emerged—the failure of welds in the primary circuit nickel alloy small bore pipework. After some months of extensive investigation the decision was taken to replace all the affected pipework and fittings in chrome-molybdenum low alloy steel. The equivalent pipework in the first all-British submarine H.M.S. *Valiant* was changed to stainless steel. A BATTLE Class boiler was installed at 'Vulcan' at this time to permit testing and operation of the secondary plant which had already laid idle for 2 years, and first criticality was finally achieved on 7 January 1965. For those involved at Dounreay the production of a high technology facility from a green field site some 700 miles from the DG Ships home base was a heady experience and the culmination of much effort in frequently hostile climatic conditions. The site had the appearance of a frontier town with the workforce accommodated in a wartime RAF camp alongside; management problem-solving meetings were convened at all hours and in all places and Thurso slowly became accustomed to the influx of strangers.

The prototype is contained within a building of some 20 000 square feet. FIG. 2 gives a diagrammatic representation of the plant and how it relates to a submarine. In FIG. 3 the points to note are the biological shield tank furthest from the camera (this tank provides additional shielding around the reactor compartment fulfilling the function of the sea for a submarine) and the section of the hull over the motor room which has been cut away to improve access. The Heenan and Froude dynamometer is closest to the camera.

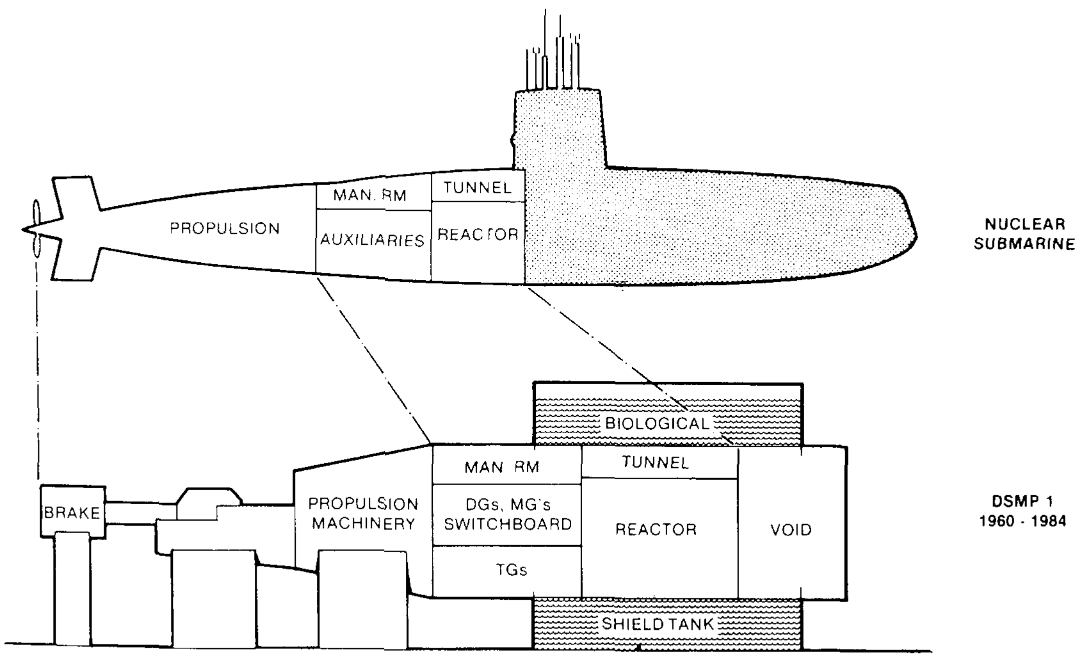

FIG. 2—SUBMARINE/PROTOTYPE RELATIONSHIPS

The reactor plant is a dispersed pressurized water design and was originally identical to the VALIANT Class installation, the first core design (Core 'A') being the same as that fitted initially to the earlier nuclear submarines. Strong and Nash[2] provide an outline description of this type of plant.

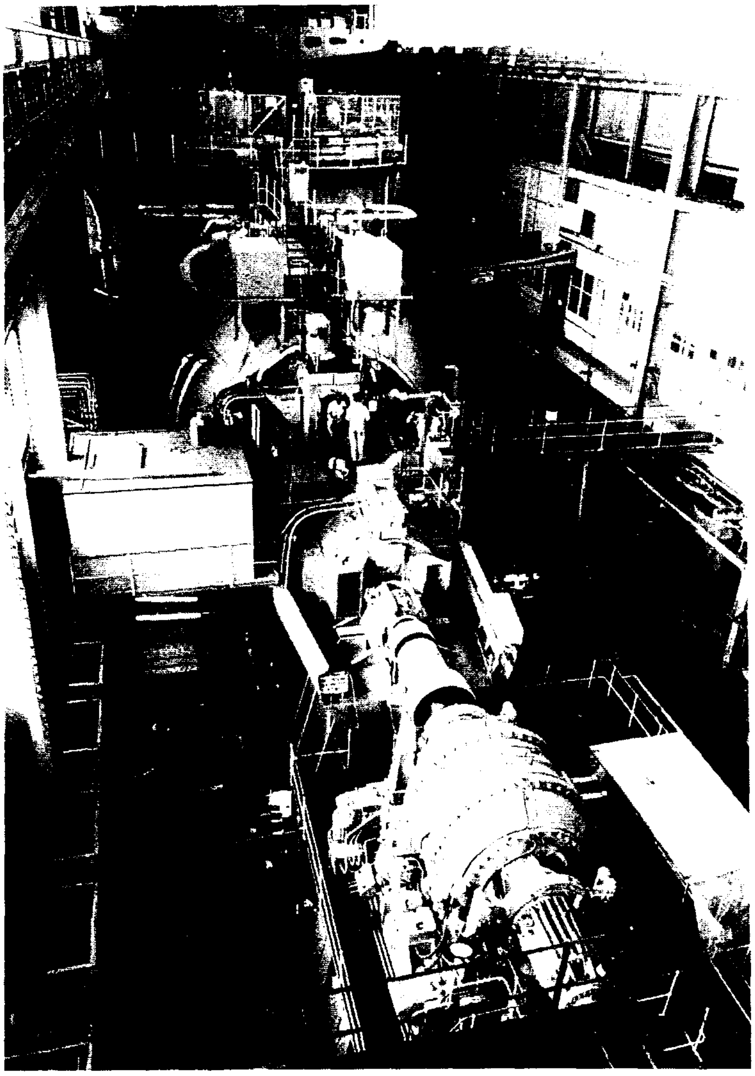

FIG. 3—DOUNREAY SUBMARINE PROTOTYPE

Operation of the First Core

The plant was to be operated for some $2\frac{1}{2}$ years to evaluate the performance of the nuclear core over its life, to test the complete installation, to develop operating procedures and practices, and to provide operator training. It is worth noting that during this busy trials period 800 start-ups were carried out, the reactor was critical for some 10 000 hours and, an overall plant availability of 47% was achieved. More than 500 specific trials were conducted.

Reactor physics tests were carried out at regular intervals during core life and in most cases theoretical predictions conformed closely with experimental results. One exception was that control rod worths (the ability of control rods to absorb neutrons) were lower at the end of core life than the predicted values. It is the results of reactor physics tests that provide the essential design feedback which leads to longer life and higher power cores for the future in addition to providing updated data for the use of submarines fitted with the same core.

The secondary machinery performed satisfactorily. There were steam and water leaks, some problems with main turbine bearing wear, and tube erosion in both main engine and turbo-generator condensers was excessive and required baffling in the former and reduction of condenser vacuum in the latter case.

Engineers who had received their steam training in surface ships and now found themselves operating a nuclear plant had to revise their standards in several areas. Not least of these was the control of water chemistry in both primary and secondary circuits. The presence of chlorides and oxygen under high temperature conditions could induce stress corrosion cracking of stainless steel which is the material of primary pipework including steam generator tubes. Primary water chemistry is therefore controlled within the limits of 0·1 ppm for chloride, 0·01 ppm for oxygen (by dosing with hydrazine and hydrogen) and, in the secondary circuit, pH is controlled by phosphate dosing; 1250 ppm is the current limit for total dissolved solids in the steam generators. At 'Vulcan' secondary chemistry standards are now maintained by continual dosing using variable delivery pumps as opposed to 'slug' dosing which is still used in submarines. In the early days of DSMP and *Valiant* difficulty was experienced in meeting the standards for chloride, and the problem was eventually traced to excessive evacuation of turbine glands which were drawing lubricating oil through the labyrinths; the oil was OEP-69 in which the EP additive is chlorine and this was sufficient to show a 'cloud' in the feed water. Operators who today worry about water chemistry and curse the standards imposed may be interested to learn that some of the earliest advice to the Captain Superintendent suggested that the operator's task could be minimized by dosing with sufficient sulphite to eliminate oxygen thus allowing almost unlimited (1000 ppm) chloride; it was even suggested that phosphate dosing was quite unnecessary!

The First Refit and Refuel

The plant was shut down on 14 October 1967 for its first refit and refuel which was planned to last for 9 months—an optimistic timescale which in the event was extended to 11 months. Time was saved in the defuelling by removing fuel modules one at a time (the wet unit module system) rather than all at once (the core cartridge system) which would have involved removal of the reactor compartment tunnel; nonetheless the refuelling phase over-ran its planned programme and several unexpected defects significantly increased the total work package. Some cracking of toroid welds was detected between control rod drive motor support tubes and the reactor pressure vessel head and this generated a delay of more than a month; several defects on the steam generator internal feed rings required the quick production of modifications and this added to the delay. Horizontal joint faces of main turbines and turbo-generators were eroded in several areas and, despite running on reduced vacuum, turbo-generator condenser tube erosion had continued. Internal corrosion of the dynamometer required metal spraying of the end casing and renewal of the ahead rotor. Apart from the toroid welds mentioned above there were no areas of notable concern in the primary plant. Setting to work was extended by a plague of defects well known to engineers who have ever experienced post-refit dramas in dockyards; criticality of the new Core 'B' was achieved on 14 August and power range testing was completed by 1 October 1968.

Operator Training

From the earliest days of the DSMP concept it had been recognized that the prototype would provide the essential facilities for practical training of naval nuclear operators. The first trainees arrived at the end of 1964 and operated the secondary plant using the shore steam boiler. During the period of Core 'A' and Core 'B' operation the training requirement was dominant and up to the start of the first refit 24 operator courses and 7 health physics and atmospheric control courses had been completed with 352 students passing through the establishment. Scapa House had been opened in 1963 as the naval mess in Thurso, and new classroom accommodation had been provided at the site. A manoeuvring room simulator was commissioned in 1967 and this, in addition to providing an essential prerequisite to live plant operation and a training facility when the plant was not available, also allowed students to exercise procedures that could not be practiced with the live plant.

By the time that Core 'B' was operating the establishment held an important position in the training of naval personnel and in recognition of this was given fleet establishment status and commissioned as H.M.S. *Vulcan* on 1 May 1970. This situation prevailed until December 1980 when the training task was centralized at H.M.S. *Sultan;* practical operator training (for all classes of submarine) is now provided on simulators and the trainees must await their first submarine for their first whiff of nuclear steam. In some 16 years in the training business 'Vulcan' received more than 3000 trainees comprising officers, ratings, and MOD civilians. In parallel, Rolls-Royce and Associates has maintained six shifts of qualified operators. 'Vulcan', as the NNPTE, has now reverted to its R and D role and is an outstation of the Sea Systems Contollerate within the Procurement Executive.

The Second Core

Core 'B' was operated from August 1968 until July 1972 without any notable difficulties associated with the primary plant. Secondary problems predominated: diesel generators and turbo feed pumps were generally temperamental, the port after main turbine journal suffered excessive wear as a result of a potential between the shaft and casing, the dynamometer required a new rotor and end casing, and the difficulty of repairing steam leaks in the cramped machinery space installations was an aggravating loss of operational time. A sad and unfortunate accident in August 1971 caused an 8 month shutdown when a steam generator header handhole door failed under test and caused the death of two men. The main reason for the length of this shutdown was the need to re-justify the reactor plant for critical operation following the accident and this demonstrates the thoroughness and care that is applied to all technical aspects of the programme. (The 'justification' of a nuclear plant is the detailed and documented validation of the design, construction, modification and operation of all parts and aspects of the installation that have an influence on the nuclear safety of the plant).

The Second Refit

By the time the planning for the second refit started the Ship Department was well advanced with designs for the next class of SSN—the TRAFALGAR Class. The dominant design aims (as with all nuclear submarines) were increased core life and consequent increase in time between refits, reduced machinery noise, and reduced manning. The opportunity was therefore taken to evaluate as much as possible at Dounreay and there was consequently an extensive work list:

(*a*) Defuel Core 'B' and install Core 'Z'.

(*b*) Replace both steam generators.

(*c*) Replace all main coolant pumps.

(*d*) Fit in-core instrumentation.

(*e* Fit new generation motor-generators.

(*f*) Rebuild manoeuvring room with miniature panel meters and Decca ISIS data logging system.

Core 'Z' was taken critical on 14 December 1974 but there was a delay in achieving normal operation while some anomalous indications on the recently installed instrumentation were investigated. Further delays were occasioned by leaking manhole door joints on a steam generator.

The Third Core

As stated earlier, a major target of core development is the improvement of core life and the success that has been achieved in this area is well illustrated in Fig. 4 which shows also that, although much of the calendar time has been taken up by the extensive R and D programme, the core performance proving has generally been completed in advance of the acceptance of the associated first of class submarine. By the end of its life in June 1984, Core 'Z' will have been critical for approximately 21 000 hours and it will have been subjected to some 650 start-ups. An important feature of the work that is done by Rolls-Royce and Associates Ltd. in support of the core design is the need continually to re-justify critical operation, in discrete steps, as physics data is gathered from trials. These justifications are subjected to close scrutiny by MOD and by the Safety and Reliability Directorate (SRD) of the UKAEA. SRD is appointed by MOD to act as independent assessors for all matters concerned with nuclear safety within the naval programme, a position they have held since the earliest days of the naval nuclear programme.

The programme of trials on other elements of the primary and secondary plant has continued throughout Core 'Z' operation: there has been a series of chemical trials to assess the effect of dosing feed water with amines (morpholine and butanolamine) to reduce internal corrosion of pipework; a most important series of trials has compared design predictions with actual results under no coolant flow conditions within the core, and operational trials have included assymmetric operation of steam generators, to give just a few examples. Between 1975 and 1984 more than 300 individual trials have been conducted on the plant. A long shut-down was programmed from July 1981 to May 1982 to rejuvenate the conventional plant and to install additional trials equipment; apart from this period the plant has operated a normal cycle of three short maintenance periods each year.

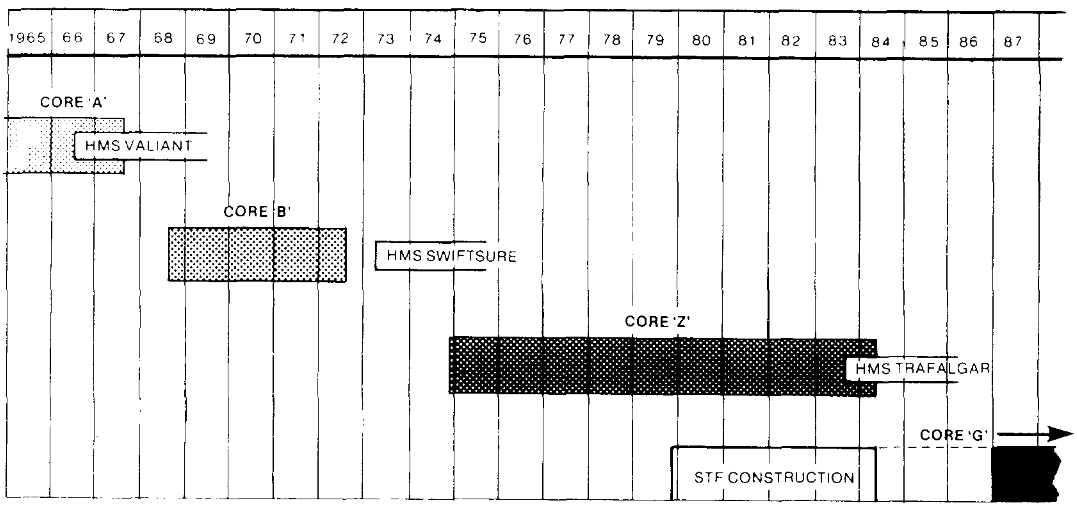

Fig. 4—Core development at 'Vulcan' compared with associated submarine acceptance

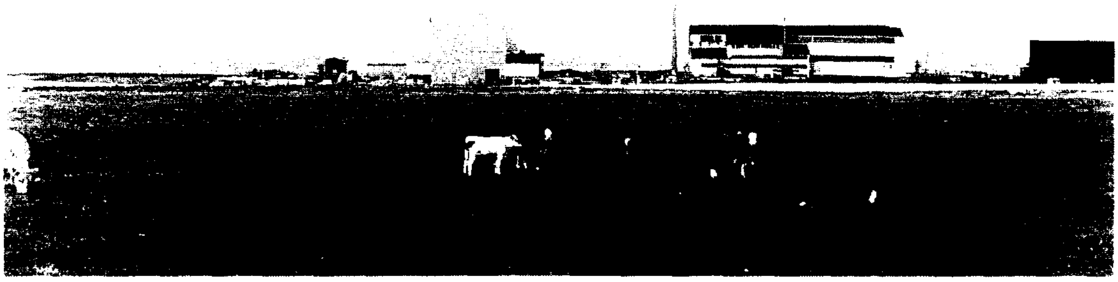

Fig. 5—S.T.F. and D.S.M.P. buildings at Dounreay

The Benefits

As with so many endeavours in the field of Research and Development it is not possible to indulge in a meaningful cost benefit analysis. The benefits are amply demonstrated in the success of the naval nuclear programme and the determination of H.M. Government to maintain a viable SSN flotilla and to pursue the replacement of the ageing SSBNs. Whilst many areas contribute to the naval nuclear programme, 'Vulcan' has had a consistently important part to play from the earliest days of proving the feasibility of the installation, through the years of training and core development to specific areas of technical achievement.

The Future

DSMP will be defuelled and decontaminated during 1984 and then modified in preparation for a series of trials called the Post Core Removal Programme (PCRP). Primary systems will be fitted with additional pipework to provide controllable leak paths and the reactor will be fitted with an electrically heated core to heat the primary circuit and provide a reasonable simulation of decay heat. This will enable normal operating temperature and pressure to be achieved in the primary circuit before subjecting the plant to leak conditions. Various loss of coolant accidents (LOCA) will be simulated and plant performance under these conditions will be monitored for comparison with predictive studies. This will be the first time that a full-scale plant has been used for the production of LOCA data and will greatly strengthen confidence in those operating procedures which, hopefully, will never be used in earnest. Furthermore these trials will provide the information on plant behaviour necessary for training simulators to be programmed to give accurate response under these fault conditions. This will improve training in accident prevention and management; so at the end just as at the beginning of its life DSMP will make an important contribution to operator training.

PWR2 is the next generation of naval reactor plant and, although still a dispersed design, it is significantly different to the installation arrangement for current classes. The reactor will be installed in a prototype reactor assembly (PRA) which is now under construction at Vickers in Barrow and the assembly will be shipped to 'Vulcan' where a new test house—the Shore Test Facility (STF)—is nearing completion. The installation will not include secondary plant as in DSMP; power will be absorbed in a steam condenser and future submarine propulsion machinery will be tested at Barrow. Fig. 5 shows the STF under construction alongside the existing prototype building.

Operation of PWR2 is programmed to commence in 1987 and, although the days are numbered for the 'submarine in a shed', the future of 'Vulcan' as an important contributor to the naval nuclear programme is assured.

Acknowledgement

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References

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