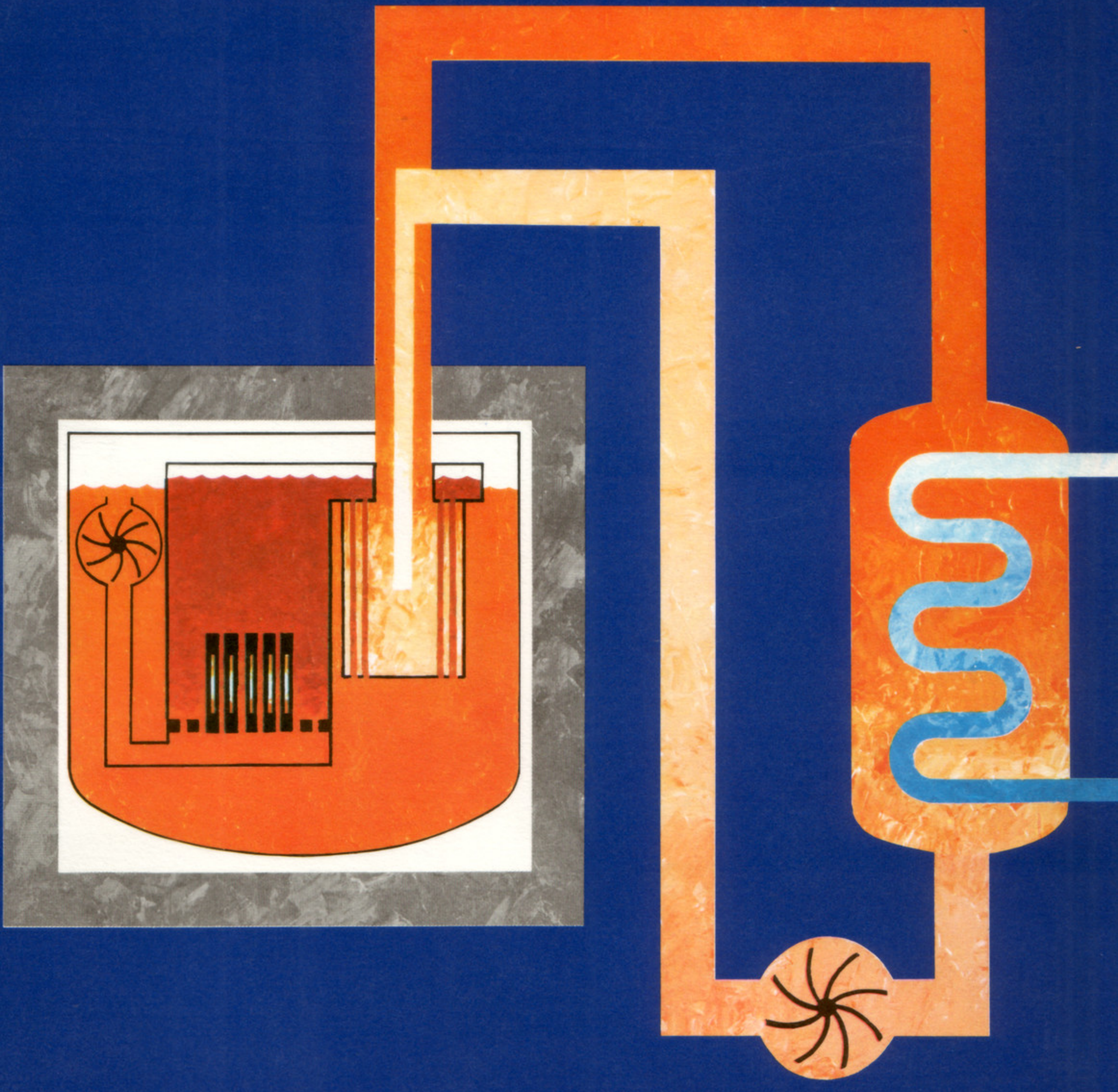
FAST REACTORS IN BRITAIN

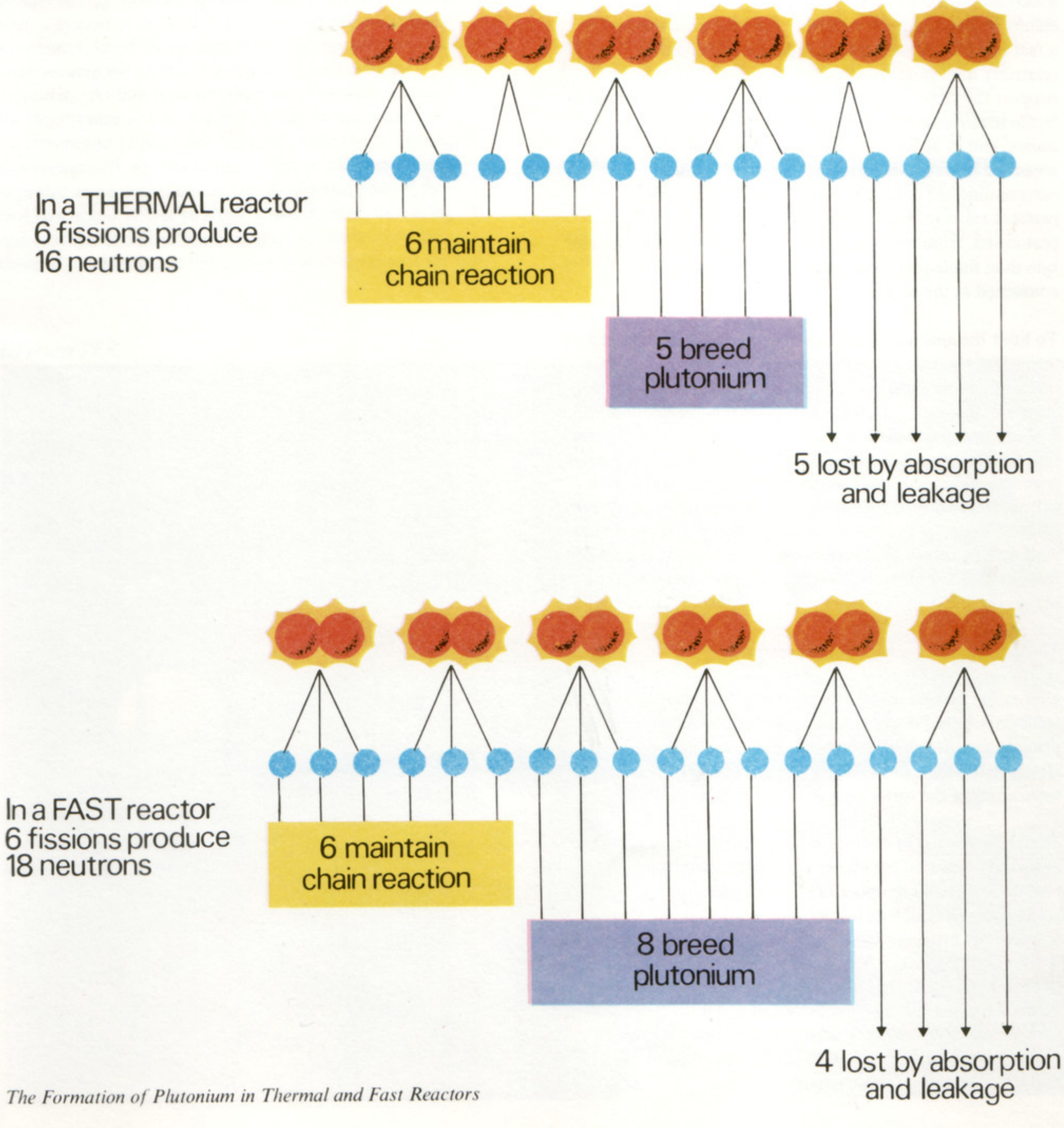


The Development of Fast Reactors in Britain

This booklet traces the development of work on the fast breeder reactor system in Britain by the UKAEA in collaboration with British nuclear industry. As a result of the extensive experience gained over a period of nearly 25 years, the system is now at the threshold of commercial exploitation in preparation for the substantial installation programme of fast reactor power stations which are likely to be needed in the last decades of this century.

Contents

The primary reason for developing fast reactors is that they offer the prospect of obtaining fifty times more heat from uranium than can be obtained with thermal reactors alone. This advantage leads to lower nuclear fuel costs and a dramatic reduction in uranium ore requirements. For countries which, like Britain, have to import uranium, this is a strategic as well as an economic gain.



The Formation of Plutonium in Thermal and Fast Reactors

Characteristics of the System

In a fast reactor there is no moderator, and therefore the neutrons are not slowed down from the high speeds at which they are emitted in fission. This high energy level results in good neutron economy, but the cross-sections in a fast reactor are such that the fuel must contain a relatively high proportion of fissile material in order to support the chain reaction. Excess neutrons are absorbed in fertile material in the core fuel to produce more fissile atoms, and in addition neutrons leaking from the core are absorbed in fertile material in a 'breeder blanket' surrounding the core. The good neutron economy of fast reactors leads to the possibility of 'breeding' fissile fuel, plutonium, from the fertile isotope uranium 238 at a greater rate than fissile fuel—uranium 235 or plutonium—is consumed in the core.

To limit the amount of expensive fissile material required to fuel a fast reactor, thermal power is extracted at as high a rate as possible from each unit mass of fuel. Fast reactor cores are therefore characterised by closely packed fuel, absence of moderator and high thermal ratings. This means that a large quantity of heat has to be removed from a small space; liquid metals are suitable coolants because of their extremely good heat transfer properties. Of those potentially usable, sodium is preferred. It has good physical properties and, despite its reactivity with oxygen and water, it does not raise serious problems of compatibility with other reactor materials.

The hot sodium coolant from the reactor is used to produce steam for the generation of electric power in a turbo-alternator; all fast reactors built so far, however, have a secondary liquid metal circuit interposed between the primary circuit, which removes heat from the core, and the steam generators, so as to provide complete physical separation of the water circuits from the reactor.

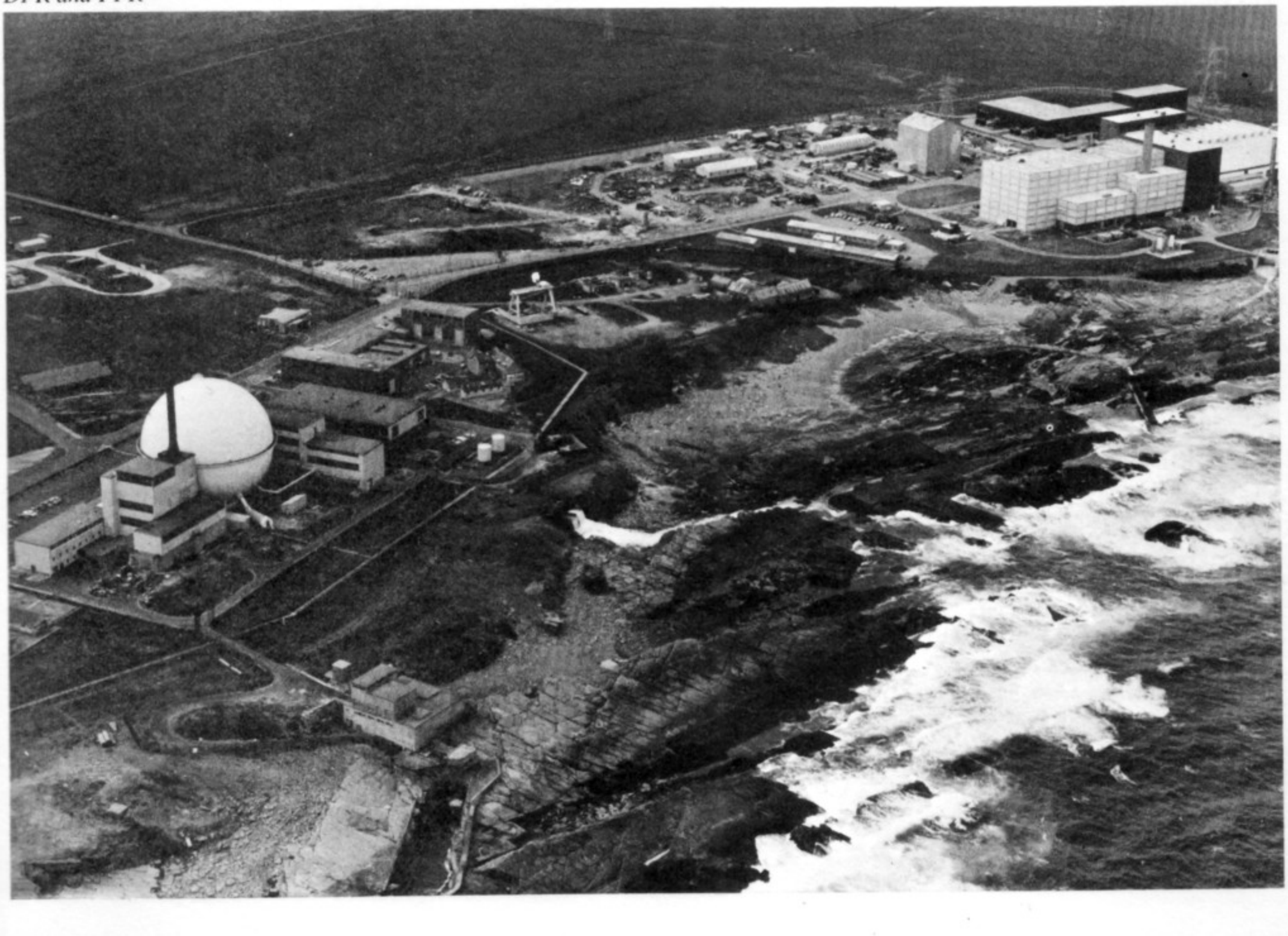
The large volume of sodium in the primary circuit is able to absorb the residual heat when the reactor is shut down with only a slow rise in temperature. This means that the common faults, such as loss of power supplies, which may temporarily interrupt the circulation of coolant are accommodated safely. The sodium is not pressurised, so loss of coolant from the core is almost incredible. In common with thermal reactor systems, the design of a fast reactor includes various safety measures to interrupt the sequence of improbable events which could in principle lead to an accidental release of radioactivity.

Preliminary Studies

The advantages of the fast reactor system described above were apparent to nuclear physicists from the earliest days of atomic energy. Serious consideration of the engineering of such a system in the UK dates from 1951 when studies were put in hand by the Government organisation which later became the United Kingdom Atomic Energy Authority. At that time uranium supplies were scarce and the importance of the system's ability to make the maximum use of the available fissile material by breeding was recognised, so that development of the system was regarded as an essential, though long-term, part of the British nuclear power strategy. Furthermore, the ability of fast reactors to utilise plutonium more efficiently than thermal reactors made them a suitable complement for the short-term UK programme of gas-cooled thermal reactors, from which substantial quantities of by-product plutonium would arise.

As a practical check on the physics of the fast reactor system, a small zero power reactor, ZEPHYR, was built and operated at the Atomic Energy Research Establishment, Harwell, between 1954 and 1958. This was fuelled with 15 kg of plutonium which was found for the purpose although plutonium was at that time a scarce material. Operation of ZEPHYR provided a wide range of basic nuclear physics data, including information on neutron lifetime, delayed neutron fractions and capture cross sections of all the major elements concerned; most importantly, however, it confirmed that breeding was possible.

DFR and PFR



The Dounreay Fast Reactor

Meanwhile, design work had started in the UKAEA's offices at Risley in the North West of England on an experimental fast reactor which would enable the feasibility of the system to be studied. Because of the shortage of plutonium, it was to be fuelled with uranium enriched in the fissile 235 isotope. The quantity of enriched uranium available at the time was an important factor in determining the maximum core heat output, 60 MW. In 1953 it was decided to build the reactor together with its associated fuel element fabrication and chemical reprocessing plants at Dounreay on the North coast of Scotland, and the experimental reactor has become known as the Dounreay Fast Reactor, "DFR". The UKAEA's Dounreay Experimental Reactor Establishment has since had other facilities added, mainly concerned with fast reactor work, and notably in recent years the Prototype Fast Reactor.

The Dounreay site was opened and construction of DFR started in 1955. The design and construction of DFR were preceded by a development programme with liquid metal rigs. Although sodium was available in quantity and was relatively cheap, there was little industrial experience of its use as a heat transfer medium and a new technology had to be developed in UKAEA laboratories covering its use as a coolant and including such problems as those of pumping and purity control in addition to studies specific to a reactor application; for example, compatibility with other reactor materials and effects of radiation. In fact, in view of the lack of experience of working with sodium at the time, the coolant actually chosen for DFR was not pure sodium, as was envisaged would be used for commercial fast reactors, but a 70/30 sodium-potassium alloy ("NaK"). This has a much lower melting point (40°C) than that of pure sodium (98°C), and therefore offered the advantage, in an experimental reactor liable to operate for long periods at low power, of remaining liquid closer to ambient temperature.

In order to provide specific physics information for DFR, a second zero power fast reactor, ZEUS, was built at Harwell. This was closely related to the DFR core design and, like DFR, fuelled with enriched uranium. ZEUS was completed and put into operation in 1955.

Design of DFR

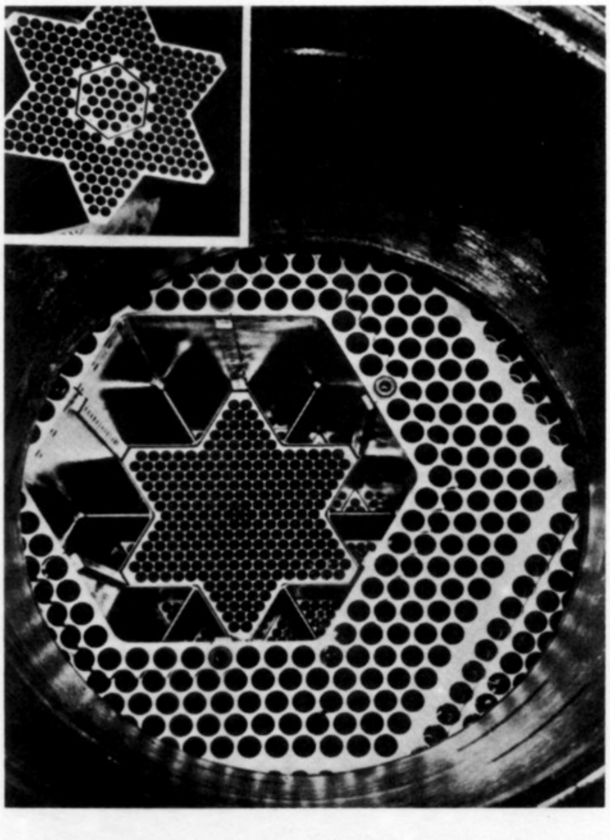
Although the Dounreay Fast Reactor is still operating, it was built at a time when there was no practical knowledge of highly enriched fuel or of liquid metal coolants, and consequently a conservative approach was adopted in many areas of the design. It was, for example, based on the use of large numbers of small coolant loops and components for which experience was already available from the development programme, so as to minimise the extent of extrapolation.

The driving charge of fuel in DFR consists of metallic uranium in hollow cylindrical fuel elements clad in niobium. These fuel elements were built up into a core of approximately 21 in. (533 mm) diameter and an active height of 21 in. (533 mm). Reactivity control is provided by moving groups of fuel elements, located at the core periphery, vertically in and out of the core. The core is surrounded at the sides and top by natural uranium to serve as a reflector and as a breeder blanket for the production of plutonium.

The core and breeder are contained in a reactor vessel 20 ft 9 in. (6.3 m) high by 10 ft 6 in. (3.2 m) diameter; the primary circuit comprises 24 loops, in which coolant is circulated by means of electromagnetic pumps from the core to intermediate heat exchangers situated within the reactor vault but outside the reactor vessel and its surrounding borated graphite shield. The coolant flow through the core is downward. The reactor vessel is closed at the top by two rotating shields through which refuelling is effected (off-load) by direct lift of individual fuel elements.

The intermediate heat exchangers consist of coils of 4 in. (102 mm) stainless steel pipe of total length 300 ft (90 m), surrounded by 6 in. (152 mm) pipe. The design was therefore based on pipework fabrication, avoiding the need to develop sophisticated heat exchangers. The design of the steam generators used the double-wall principle, in which the alkali metal coolant of the secondary circuit (in the case of DFR, NaK) and the water/steam are contained in separate pipes, so that a failure of one pipe only is insufficient to cause cross-leakage between the two, and any leak is likely to be readily detectable externally. In the DFR steam generators the heat transfer takes place through copper laminations which are brazed transverse to the pipes into what is effectively a solid block. Steam from the steam generators feeds a 14 MWE turbo-alternator, or alternatively can be cooled and condensed in a dump condenser; steam conditions at TSV are 150 lbf/in^2(g) [975 kN/m^2(g)], 260°C.

A view of the Dounreay Fast Reactor Core. Inset is the type 'B' Core Tube nest which contains a removable centre section to allow the irradiation of experimental fuel elements.



Commissioning and Operation

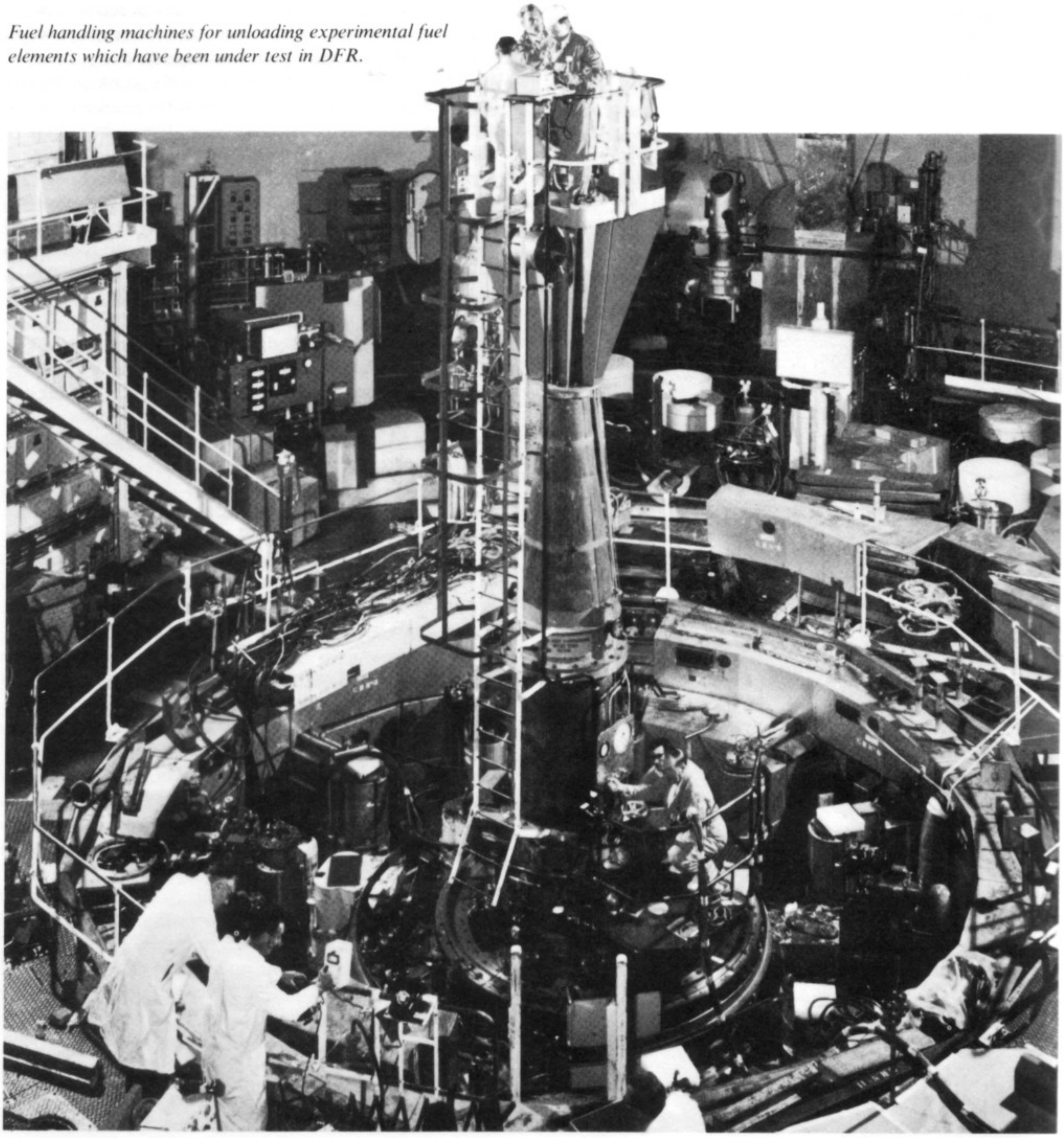
Construction of DFR was started in 1955 and the reactor was made critical on 14 October 1959. It was run at very low power for several months and then at increasing power levels over the next three years, reaching the design power of 60 MW for the first time on 5 July 1963, at which time it was much the most powerful fast reactor in the world. In achieving this power level a number of difficulties, mainly related to the coolant, were encountered and successfully overcome, and the metallic fuel element underwent development and redesign. In addition to providing a wide range of information on reactor physics, fuel and component performance and coolant behaviour, steady runs at various power levels had satisfactorily demonstrated the stability and ease of control of the system.

Electricity was first supplied to the national grid from DFR in October 1962. Although generation of electricity was only a by-product of the experimental work, the reactor has nevertheless been able to supply the needs of the Dounreay establishment and export a surplus during its operating periods.

With the feasibility of the fast reactor system for power operation thus confirmed, DFR has since been used as a fast flux facility, primarily to contribute to the development of future fast reactors, but increasingly in recent years to provide tests on fuel for both British and overseas requirements.

This long period of operation of DFR has provided a steadily increasing fund of experience. A particular instance of this was the successful repair of a primary circuit leak after the reactor had been in operation for some years. This occurred in 1967, when a small leakage of primary coolant was detected and was traced to a crack in a weld in the pipework connecting an intermediate heat exchanger to the reactor vessel, and was repaired by cutting out and replacing the faulty part.

Fuel handling machines for unloading experimental fuel elements which have been under test in DFR.



Fast Reactor Fuel Development

One advantage of sodium as a reactor coolant is that, with its boiling point of 880°C at atmospheric pressure, there is no need for an over-pressure under normal operating conditions, even when these involve temperatures which will provide steam conditions to match modern high efficiency turbines and so provide a thermal efficiency of over 40%. Such operation demands fuel and cladding capable of withstanding hot spot temperatures of 650°C or more, but in a sodium environment fuel can be made to withstand these temperatures to an average burn-up level of more than 10% of heavy atoms at a rating of 200 watts/g.

The DFR fuel is enriched uranium alloy in metallic form, and although this fuel performs very satisfactorily in DFR it is not suitable for the higher temperature and greater burn-up of a commercial power station. However, the ceramic uranium dioxide can be used under these conditions. It had always been intended that the initial enrichment in commercial fast reactors should be provided from by-product plutonium produced in the reactors of the thermal reactor power programme, diluted to the required fissile content by natural or depleted uranium. Studies were therefore begun on plutonium dioxide as the fuel material in combination with uranium dioxide. These proved very satisfactory and mixed oxide was selected as the fuel for the initial charges of the next reactor to be built, the Prototype Fast Reactor. The investigation of alternative ceramic compounds is being pursued, however; particularly a combination of plutonium and uranium carbides, which has the advantage of a higher concentration of fissile and fertile material (by a factor of about 4/3) and higher thermal conductivity than the mixed oxides.

The choice of mixed oxide fuel, with its relatively low thermal conductivity, required the basic fuel element unit to be a small diameter pin at the volume ratings proposed. Two alternative cladding materials were chosen for investigation: an austenitic stainless steel and a precipitation-hardened nickel base alloy. An early decision was made to use a sealed pin, which would retain all the fission product gases released from the fuel in a plenum, rather than a vented pin which would release them into the reactor but would avoid the risk of creep rupture due to build-up of internal pressure. To simplify refuelling, the individual pins were to be grouped into sub-assemblies which would be loaded and discharged as single units.

The first irradiation tests were carried out on individual experimental pins, which were mounted in carriers conforming to the external dimensions of DFR fuel elements and loaded into DFR. A similar 'trefoil' rig was also designed and used to test three pins together, again in a DFR fuel element position. In both these rigs the temperature conditions appropriate to a commercial reactor were obtained by suitable flow control.

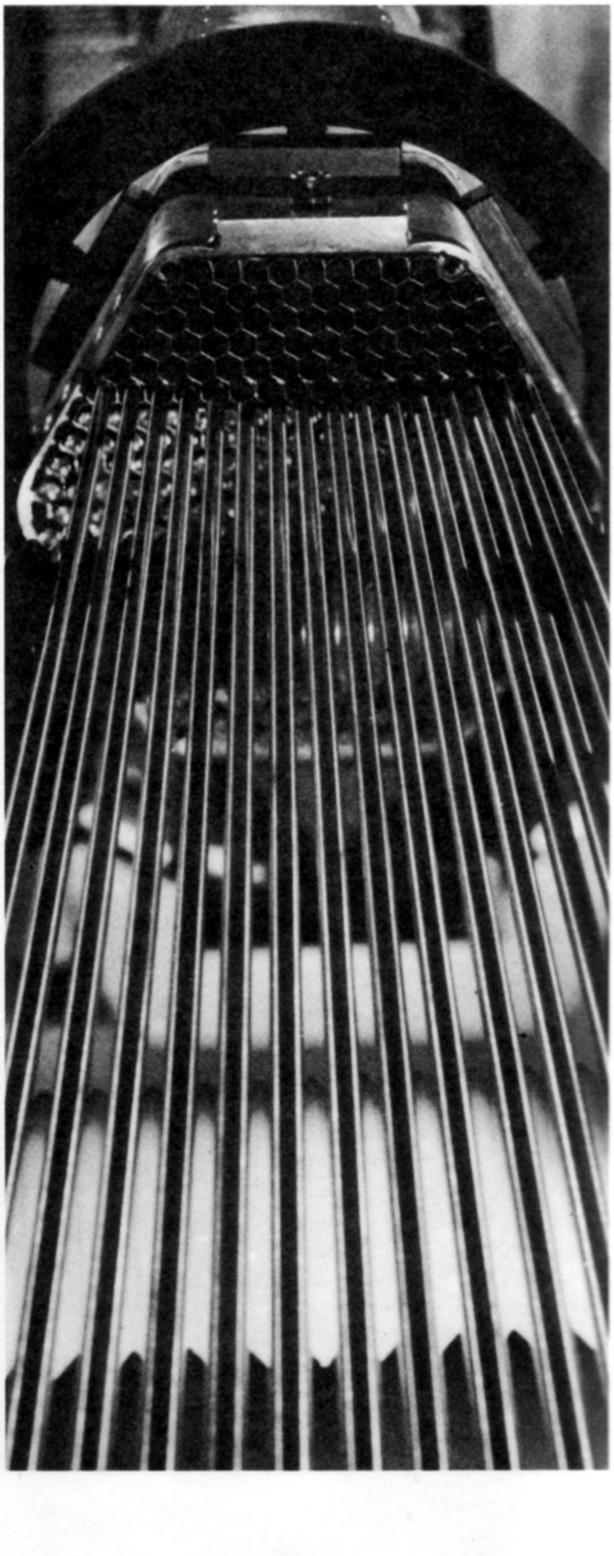
The next two stages, which proceeded simultaneously, were to develop a large-scale manufacturing process for the pins and to study the performance, under irradiation, of clusters of pins. A pilot production line was built at Aldermaston (then part of the UKAEA), where there was considerable experience in handling plutonium backed by substantial engineering support services.

At Dounreay, the central portion of the DFR core structure was modified to accommodate three clusters each containing 77 fuel pins and new facilities were built for their post-irradiation examination. This has made possible an examination of pin supports and interactions between the pins and support grids of the cluster under temperature conditions appropriate to those of the prototype reactor. These large cluster experiments have been manufactured in the Aldermaston facilities. About 1,000 fuel pins have been irradiated and carefully studied subsequently in the Post-Irradiation Examination cells in programmes including a dozen sub-assemblies, extending to a peak burn-up of 14.2%.

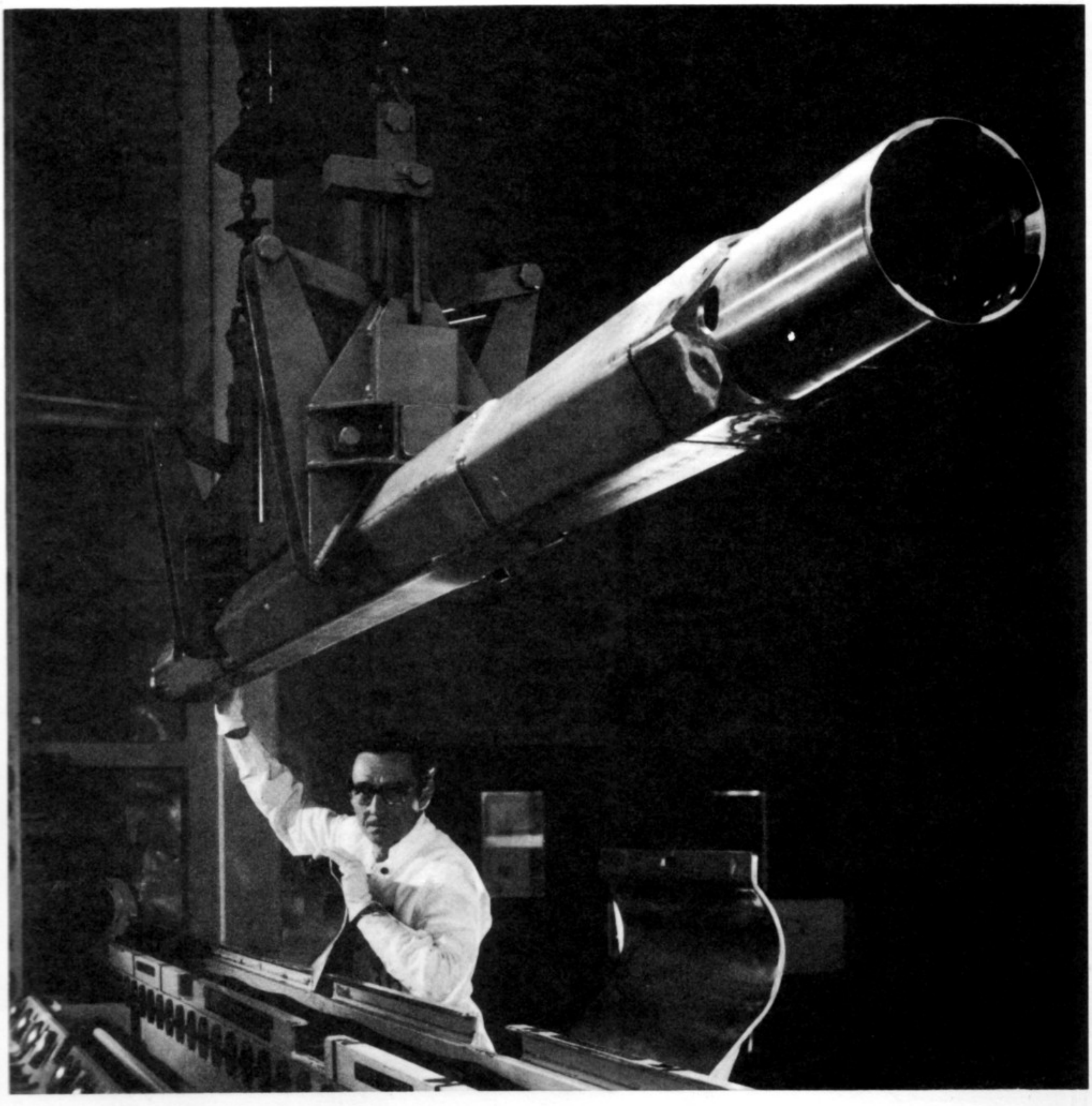
Other aspects of fuel behaviour have been studied out-of-pile concurrently with the irradiation test programme. Detailed flow studies on large-scale fuel element models have been carried out in order to determine flow patterns and the associated hot spot temperatures of the cladding. Hot dynamic flow tests on complete fuel subassemblies have been made in large sodium loops. Compatibility tests have included the study of corrosion of cladding materials by sodium and possible chemical interactions between fuel and cladding, and between fuel and coolant in failed pins.

This extensive development programme for fuel is still continuing. It has led to a design of fuel for the prototype reactor which is confidently expected to exceed the minimum requirements and has scope for good development potential in the future.

In the course of materials testing in DFR, a previously unknown phenomenon was disclosed—that of the formation of voids in the crystal structure resulting from fast neutron irradiation—which has major implications for the selection of structural materials for fast reactor application and the design of the fuel elements and core assembly. To gain an insight into the magnitude of the density change resulting from void swelling at high exposure, tests were arranged in the newly developed Variable Energy Cyclotron at Harwell, which is able to simulate the displacement effects of a reactor lifetime in a matter of days. The combined experimental and theoretical studies have resulted in design rules being formulated for selected structural alloys.



PFR Fuel Pins being loaded into sub-assembly.



A completed PFR fuel sub-assembly.

Detailed consideration of the desirable features of commercial fast reactors began after the completion of construction of DFR. Design studies were undertaken to indicate the main features which should be incorporated in a prototype design. This was supplemented by an increasing flow of information derived from operating experience with DFR, including, in the later stages, the results of irradiation tests on fuel pins and sub-assemblies. In addition, a wide range of development work in other areas of technology had been put in hand and this too was contributing to the available knowledge. A flexible zero power reactor, (ZEBRA) was built, to study the physics of fast reactors with cores and fuel enrichments similar in size to commercial reactors.

Reactor Physics

The early zero power reactors, ZEPHYR and ZEUS, had provided the main physics data related to small fast reactors which are characterised by a 'hard' neutron spectrum, in which most of the neutrons have a high energy. As the reactor size increases the neutron spectrum is softened, a higher fraction of the neutron population has intermediate energies and the data provided by the early reactors are no longer sufficient. In order to obtain reactor physics data for the design of the prototype fast reactor, and subsequently commercial fast reactors, an extensive new programme of both theoretical and experimental work was required; ZEBRA was built for this purpose at the UKAEA's establishment at Winfrith in Dorset, starting operation late in 1962. The ZEBRA core has a maximum assembly size of a 3 m cube, built up from fuel elements in the form of 3 m long square section steel tubes; each fuel element consists of an assemblage of thin plates, mainly 5 cm square and 3 mm thick, of natural uranium, enriched uranium, plutonium, graphite, steel and other materials used in power reactors. Flexibility is achieved by varying the number and arrangement of plates so that a wide range of core designs and sizes can be simulated. ZEBRA is equipped with a 14MeV electron linear accelerator and neutron time-of-flight tube, to permit the study of neutron spectra.

Origins of the PFR Project

It was envisaged that the role of the prototype fast reactor would be:

(i) to demonstrate the reliability and performance of a design incorporating the essential features of a commercial design

(ii) to check the physics and safety features

(iii) to prove the fuel and fuel cycle management, and

(iv) to allow some testing of future design features; in particular of advanced designs of fuel.

It was essential, therefore, that the design of the prototype should be modelled on future commercial design, and for this purpose design studies of commercial fast reactors were made in the early 1960s, at first of 500 MWE and later of 1000 MWE, culminating in a design study of a 2 $\times$ 1000 MWE commercial fast reactor station carried out for the UKAEA by British nuclear industry in conjunction with the Central Electricity Generating Board. These studies led to agreement on the required characteristics and size of the prototype, construction of which on a site adjacent to the DFR at Dounreay was approved in 1966.

The choice of core design was to a large extent dictated by the need to test designs of fuel suitable for the commercial fast reactor ('CFR'), thus fixing the core height of PFR and the size of the fuel sub-assembly. Other factors that affected the choice of reactor size were the need to demonstrate physics and safety characteristics, and to obtain design, manufacturing and operating experience with engineering components, on a scale that could be extrapolated with reasonable confidence to the larger commercial size. The power output chosen, 250 MWE, was judged to be the smallest that reasonably met these requirements.

PFR is designed for ceramic fuel, initially mixed plutonium and uranium oxide, in multi-pin sub-assemblies clad in stainless steel, but the design of the reactor is sufficiently flexible to accept as wide a range as possible of alternative fuels and fuel designs. The primary circuit—core, intermediate heat exchangers, primary pumps and refuelling equipment—is contained in a single tank. Sodium is the coolant, and an intermediate (secondary) sodium circuit is provided, with steam generators of shell and single-wall tube design, separated physically from the reactor; the coolant circulating pumps are mechanical; refuelling is off-load; and the operating temperature is such as to permit steam to be supplied to the turbine at standard modern conditions of 15.9 MN/m^2, 516–566°C. Although it was intended to operate PFR as a demonstration power station, it was considered desirable to include provision for its use as a test facility, and particularly for loading alternative designs of fuel sub-assemblies. It has caves for the dismantling and limited examination of irradiated fuel pins and sub-assemblies in the reactor complex, equipment that permits replacement of individual fuel pins and the irradiation of small clusters of pins, and additional instrumentation for experimental fuel and for coolant analysis. The design also includes provision for testing alternative schemes of core support and different boiler arrangements.

PFR viewed from the sea.

Sodium Technology

The operation of DFR and of the test rigs had provided extensive experience of the handling, purification and instrumentation of sodium and NaK and knowledge of their properties in respect of compatibility, thermal performance, flow characteristics and radiation effects.

The design features proposed for PFR and the commercial reactors required additional data and information. A fresh series of compatibility tests was necessary, covering the new cladding and fuel materials. The decision to use mechanical pumps in place of electromagnetic pumps involved a range of investigations, including the development of bearing materials which would operate reliably in a sodium environment. Closely linked to the work on bearings was the development of various mechanical components such as rolling contact bearings and ball nuts and screws, also to operate in sodium, which would be needed in the handling of fuel elements and control rods. Several sodium rigs were built at the UKAEA's Risley Engineering and Materials Laboratory (REML) to cater for these tests. By using the theories of dimensional similarity it was possible to study problems of flow characteristics in water rigs, which greatly facilitated this part of the work.

Another design feature which required development support was in the steam generators, where heat is transferred from the secondary sodium circuit to water, to produce and superheat steam for the turbine. A rig—NOAH—was built at Dounreay and tests carried out on it to study the effects of a leak from a water or steam tube direct into sodium. The results showed that the damage which occurred was not disastrous, and justified the adoption of banks of water tubes in the steam generators for PFR.

One of the most important lessons learned in DFR was the vital importance of maintaining the impurity level of the sodium at or below a few parts per million, particularly in relation to oxygen. This required the development of methods of maintaining this degree of purity and of instruments capable of measuring it, in both cases to operate continuously. Other instruments have been developed to measure flow, temperature, pressure and the level of sodium.

Engineering Development

Much of the engineering development work for PFR which involved the sodium coolant has already been indicated under Sodium Technology, the two fields of development being closely allied and forming a major part of the work of REML.

The coolant flow studies referred to were carried out on scale models of PFR, to provide information essential to the detailed design of the components of the primary circuit. This information included the measurement of pressure drops and fluid transit times and the study of fluid mixing; both water and air were used as working fluids. The purpose was to minimise vibration and so reduce the risk of fatigue failure in reactor components, and the tests resulted in several modifications in design to achieve this end. The experimental work was supported by vibration analysis and has since been supplemented by further tests during the commissioning of PFR. Other studies were directed to the elimination of the entrainment in the coolant of bubbles of the cover gas, which had proved a serious trouble during the early operation of DFR. The information gained in this work will be of value in the design of commercial fast reactors, for which some further similar studies will probably be needed.

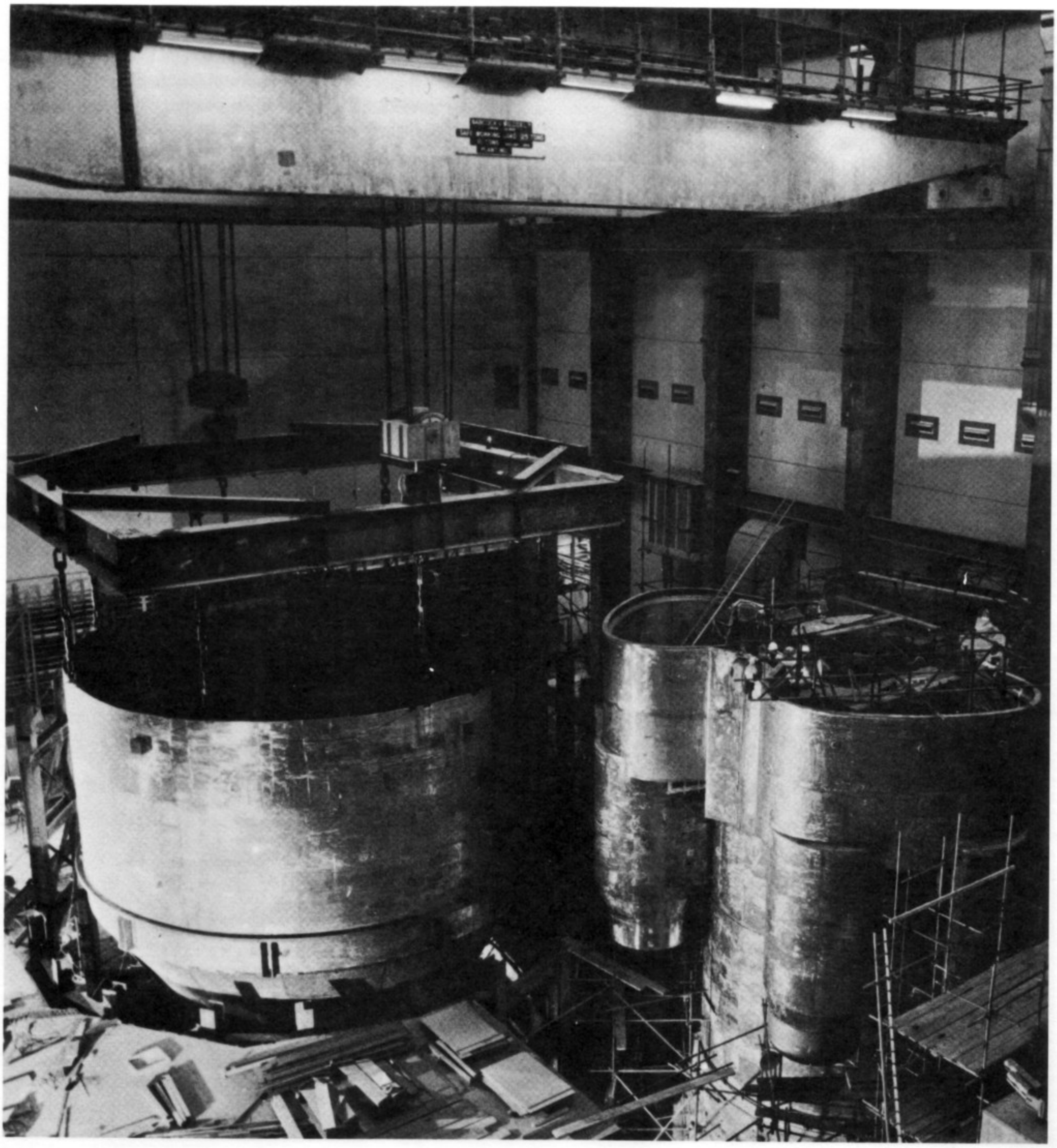
Another typical item of engineering development was the establishment of a technique for welding tubes into the header plates of the intermediate heat exchangers in such a way that the profile of the weld metal produced the minimum pressure drop.

In addition to the development of novel instruments for measuring various properties of the sodium coolant, a computer-controlled system has been developed for the presentation of information generated by the entire reactor instrumentation to the operator on demand. The instrument readings are fed into a digital computer which processes the data, operates the alarm system if any readings reach the pre-set limits, and provides displays, on cathode ray tubes, of all the information relating to a particular component on demand from the operator, together with a continuous display of the main reactor parameters. This equipment has been incorporated in PFR, and the development is likely also to be of value in commercial fast reactor applications.

Specialist investigations such as those just outlined make direct contributions to the design of fast reactor components and are complemented by tests of complete components in the hot sodium environment. One section of REML is devoted to large sodium rigs in which tests were carried out under the correct conditions and functioning programmes on a number of PFR components: pumps; simulated fuel elements; control rods; bearings; and instruments. One of the largest of these rigs, the PFR Pump Rig, provided a sodium flow of 6000 gpm (0.455 m^3/s) at 60 psi head (410 kN/m^2) and 490°C. Another major rig, the High Temperature Loop, allowed components to be tested up to 650°C.

PFR control desk and cathode-ray tube displays.

PFR—Diagrid Support Structure and Reactor Jacket



PFR Design

The standard PFR fuel pin (2.25 m long, 5.84 mm outside diameter) contains mixed oxide fuel as a column of pellets, with axial breeder sections of uranium oxide pellets above and below the fuel section and a lower plenum for the accommodation of gaseous fission products, the whole being clad in stainless steel. The core is divided into sub-assemblies, for the purposes of handling and support of the fuel pins. The sub-assemblies are 3.81 m long and of hexagonal cross-section, 142 mm across flats. The standard fuel sub-assembly contains 325 fuel pins, enclosed in a stainless steel or Nimonic PE16 wrapper and supported at intervals by grids, with a separate cluster of 19 'mixer-breeder' pins above the fuel pins to provide additional breeding and to serve as a mixing device for coolant; this ensures that representative samples are obtained at the top of the sub-assembly for temperature measurements and the detection of failed cladding. The core of plutonium-containing fuel (in two zones, to achieve a more uniform flux distribution—an inner zone containing about 23% plutonium and an outer containing about 30%) is surrounded by radial breeder sub-assemblies of depleted uranium oxide and this in turn by a steel reflector; the core, breeder and reflector all being made up of sub-assemblies of identical cross-section.

After consideration of possible alternatives, a single tank design was chosen, in which the entire primary circuit is contained in a cylindrical vessel, 12 m in diameter and

PFR Main Parameters

General Performance	
Thermal output	600 MW(h)
Gross electrical output	270 MW(e)
Net electrical output	254 MW(e)
Net station efficiency	42·3%

Fuel and Breeder sub-assemblies	
Number of pins per sub-assembly	325
Outside diameter of fuel can	5·84 mm
Length of fuel in core pin	914 mm
Total number of sub-assemblies	78
No. of radial breeder sub-assemblies	51
No. of radial breeder reflector sub-assemblies	81
Weight of mixed oxide fuel in core	4·1 tonne
Weight of 239-PUO_2 equivalent in core	1·1 tonne

Primary and Secondary Circuits	
Core inlet temperature	400°C
Core outlet temperature	562°C
Flow through core and breeder	2920 kg/s
Total flow for three secondary circuits	2920 kg/s
Weight of sodium in reactor vessel	919 tonne
Weight of sodium in secondary circuits	226 tonne

Steam Plant	
Steam temperature at HP and IP TSV's	516°C
Steam pressure at HP TSV	15·9 MN/m^2 (161·7 kg/cm^2)

15 m deep. This tank, its leak jacket and all its components are suspended in a concrete vault from a roof structure, through which pass all connections to other parts of the circuit so eliminating any penetrations of the main tank. The hexagonal core, breeder and reflector assemblies are located in a honeycomb pattern on the diagrid, which is suspended from the roof. Around the breeder and reflector is a neutron shield composed of rods of steel and graphite, mounted on the diagrid support, to reduce the radiation to the rest of the tank. Outside the shield and extending to the top of the tank, is the reactor jacket, which has in its upper part six 'pods' containing the intermediate heat exchangers in three pairs. The purpose of the reactor jacket, an insulated vessel, is to direct the coolant flow and to separate the hot sodium emerging from the core from the cooler sodium in the outer part of the tank. Between the pairs of heat exchangers, but outside the jacket, are the three primary sodium centrifugal pumps, which have outlet pipes leading to the underside of the diagrid. Their drive motors are mounted above the roof.

The sodium coolant almost completely fills the main tank and is in constant circulation. From the pump outlet pipes below the diagrid it flows upwards through the core and breeder and over the inner lips of the pods into the intermediate heat exchangers, where it gives up the heat gained in the core to a separate, secondary sodium circuit. From these heat exchangers it flows over the outer lips of the pods and into the pump intakes. It is then driven through the pumps to repeat the cycle.

The central part of the roof contains a rotating shield, which carries the refuelling machine and its operating console. The replacement of fuel takes place entirely below the surface of the coolant, with the reactor shut down, and consists of transfer movements between the core and the fuel storage rotor. After a suitable cooling period in the rotor the irradiated assemblies can be removed into a flask for transfer to the adjacent inspection caves while the reactor is on power.

Underside of PFR rotating shield showing fuel element charge machine stand pipes

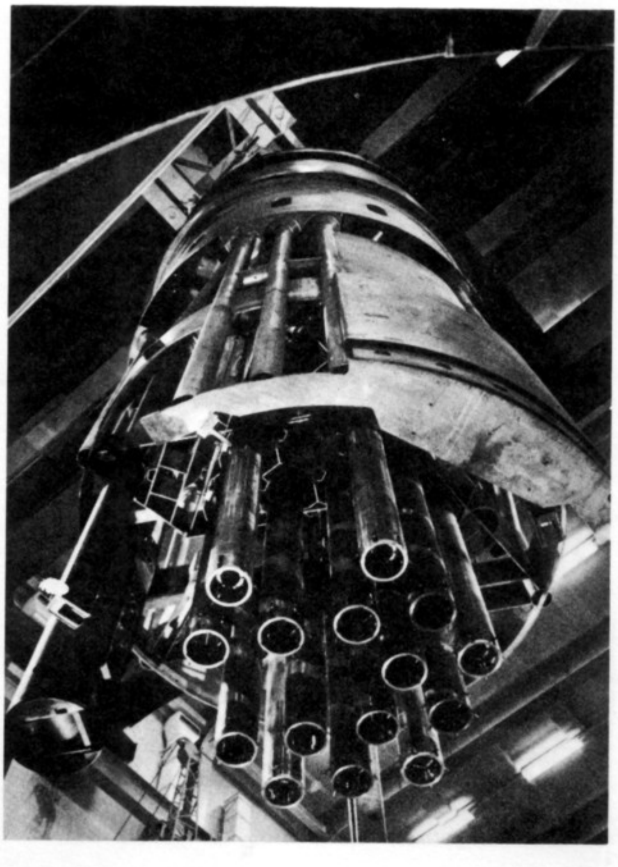
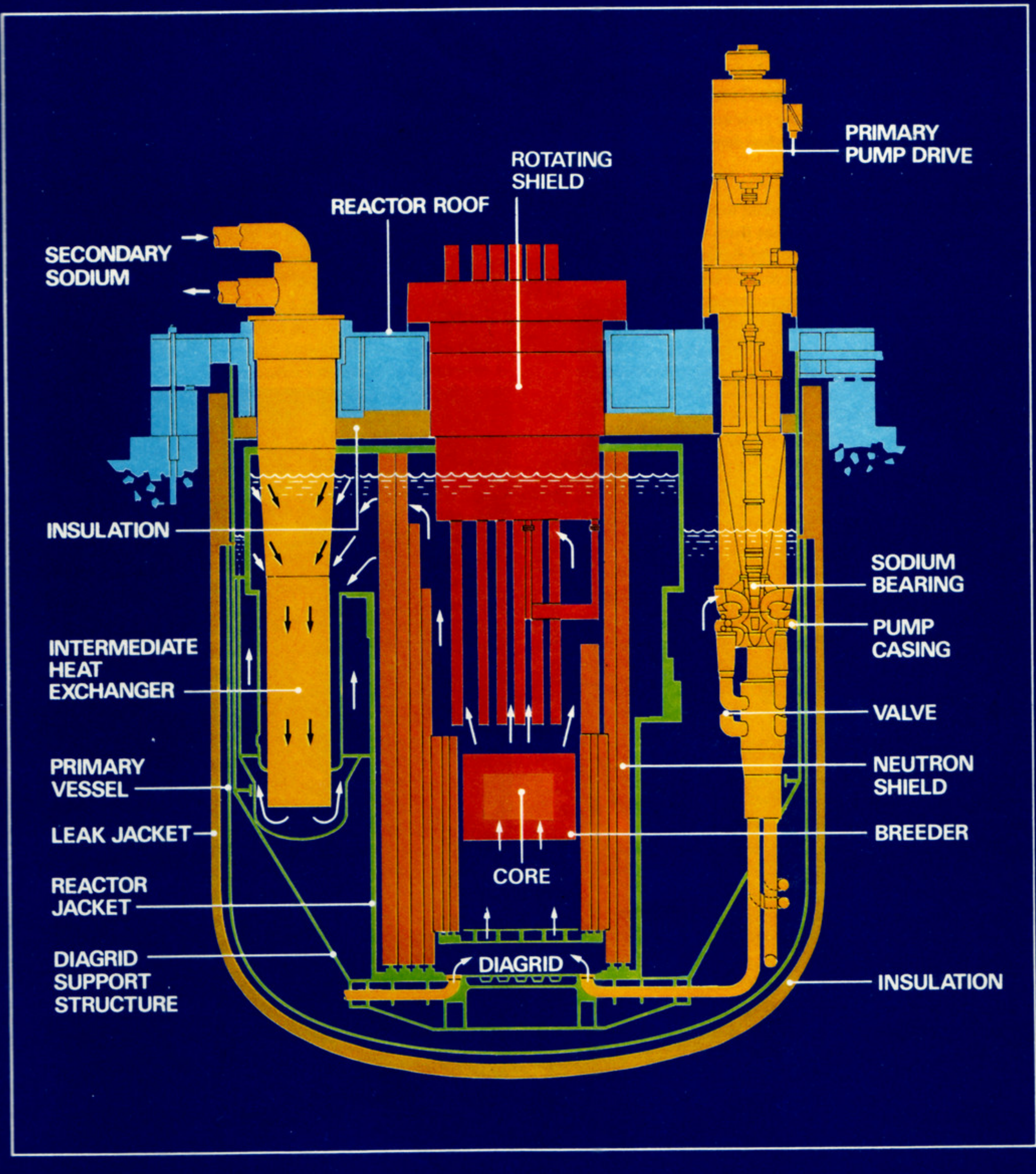


Diagram of the Prototype Fast Reactor



The rotating shield also carries the control and shut-off rods and their housings extend below the roof shield to just above the core. They are of hexagonal cross-section identical to the fuel assemblies and fit into spaces in the honeycomb pattern of the core. Before refuelling, which involves rotation of the shield, the rods are lowered completely into the core and detached from their mechanisms.

The secondary sodium circuit is linked to the intermediate heat exchangers by pipes passing out from the tops of the heat exchangers above the roof to the steam generating building, which is adjacent to the reactor hall. Here the sodium is fed to shell and tube boilers with evaporator, superheater and economiser sections; it is then returned by mechanical pumps to the intermediate heat exchangers. This physical separation of the sodium/water heat exchange ensures that any reaction following the failure of a boiler tube cannot affect the reactor and will not involve the highly radioactive sodium in the primary circuit. Steam from the boilers is fed to a conventional 300 MW turbine-generator set.

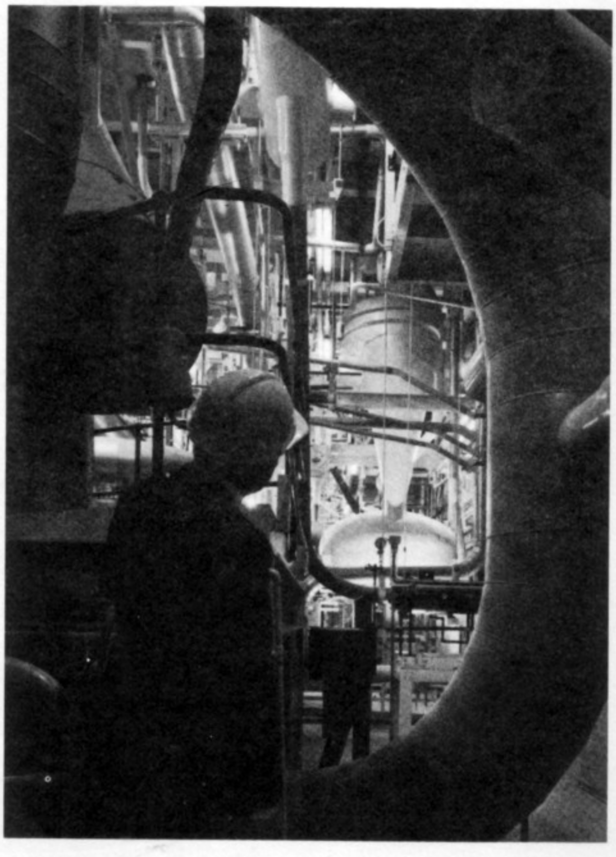
Fuel Processes

Considerable experience relevant to fast reactor fuel cycle operations—of fuel manufacture and of reprocessing irradiated fuel to recover fissile material to feed back to the reactor in new fuel elements—had been obtained at Dounreay from the plants associated with DFR and this experience assisted in the development of the PFR fuel processes.

For DFR, all the processes of the fuel cycle are carried out on the Dounreay site. The DFR Fuel Element Fabrication Plant consists of a line of interconnected glove boxes, in which billets of enriched uranium alloyed with molybdenum are cast into cylinders, machined to size and assembled in refractory metal cans to make up fuel elements. After irradiation, the fuel is treated in the Reprocessing Plant to recover the unburned enriched uranium; the uranium is separated from fission products and other impurities and adjusted to the correct enrichment for return to the reactor by blending in solution with a make-up quantity of enriched uranium before reduction to billets. These processes are carried out on a sufficiently small scale to avoid any risk of criticality.

Basically similar processes are involved for PFR, with the important exception of the substitution of plutonium for enriched uranium. The particular precautions necessary in handling and transporting plutonium are well understood by the UKAEA and by the UKAEA's daughter company, British Nuclear Fuels Ltd (BNFL) (formed in 1971 to assume responsibility for the UKAEA's nuclear fuel

A steam generator cell in PFR.

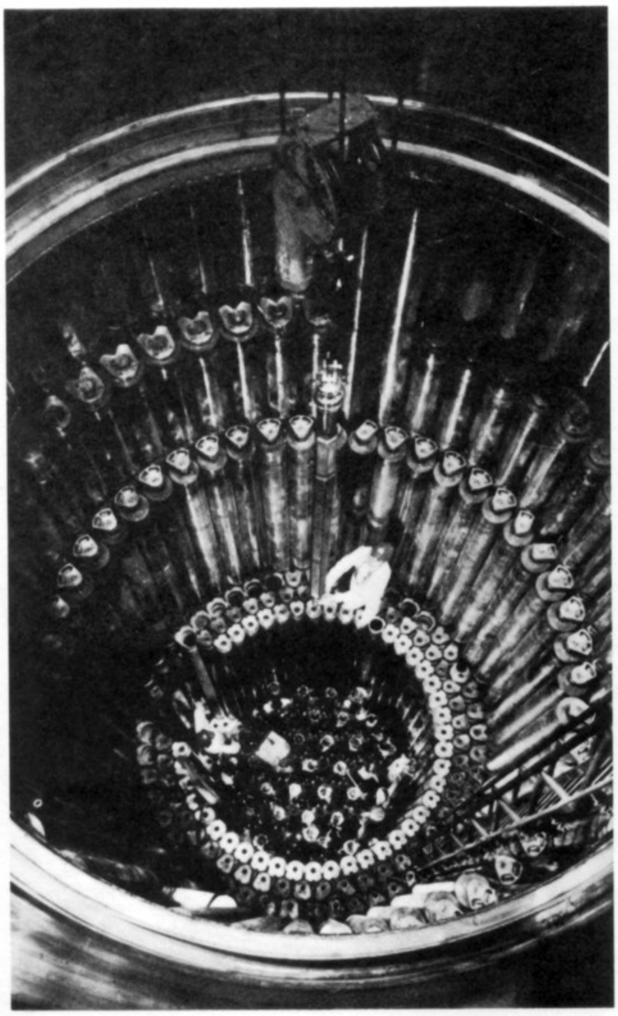


services), as a result of the continuous experience the organisations had derived from the reprocessing of irradiated thermal reactor fuel throughout the development of nuclear energy in Britain. Indeed the BNFL plant at Windscale in the North West of England has processed more commercial plutonium than any other facility in the world. A Plutonium Fuel Plant for making PFR fuel has been built at Windscale, adjacent to the Chemical Separation Plant which reprocesses thermal reactor fuel and provides the initial plutonium supply for the PFR fuel plant. The feed material is mixed plutonium and uranium oxide, co-precipitated from blended nitrate; the mixed oxide is then pelleted in a series of operations in glove box lines; the pellets are loaded into pins in a pin filling line; and the sealed pins are made up into sub-assemblies for despatch to Dounreay. The reprocessing of PFR fuel will be carried out at Dounreay, with special instrumentation to allow optimisation of parameters and to minimise plutonium waste arisings. The resultant plutonium will be fabricated into PFR fuel elements so that the overall fuel cycle performance will be fully demonstrated.

This experience with PFR fuel will form the basis for further development of all the closely-coupled stages of the fast reactor fuel cycle, directed towards the building of larger plants to serve the needs of the commercial fast reactor programme. In this work the UKAEA collaborate closely with BNFL, who will be responsible for operating the fuel plants. On the fuel manufacturing side, a pilot plant is to be built at Windscale for producing mixed oxide fine and coarse vibro-granule fuel by the gel-precipitation route, based on process development work at Harwell. Sub-assembly manufacturing development is undertaken at the UKAEA's Reactor Fuel Element Laboratory at Springfields, Lancs, in close collaboration both with BNFL and with outside suppliers and contractors; for example, studies are being directed to the development of manufacturing methods aimed at producing more accurate, more reproducible and cheaper wrapper tubes for sub-assemblies. Meanwhile, valuable information and experience will be gained from the treatment of PFR fuel in the Dounreay reprocessing plant and is available from associated R and D work relevant to the design of the commercial plants to be built in the next decade.

Particular emphasis has been given in the design of fast reactor fuel process plants to minimising the handling of highly active materials and to reducing the waste arisings at each stage of the fuel cycle. Continuing R and D programmes are in progress on these aspects. In addition attention is being given to the requirements for the long-term storage of highly active materials to ensure that they present no hazard to future generations.

The core tank of PFR with a dummy fuel sub-assembly being lowered into position.



PFR Construction

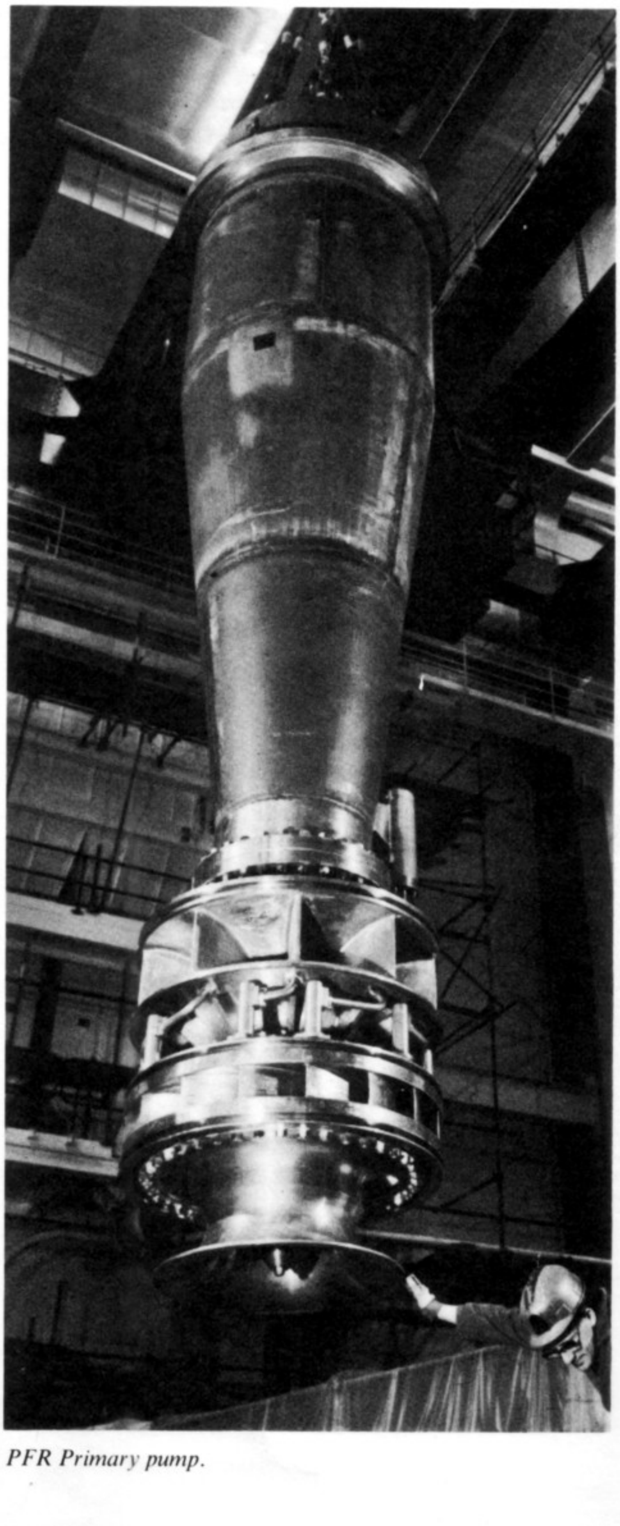
Construction of PFR was approved in February 1966, the site was opened in the autumn of that year and the main construction work started early in 1967. On the reorganisation of the British nuclear industry in 1968/69, the UKAEA placed a contract for the completion of PFR with The Nuclear Power Group, to whom the key staff responsible for the design and construction of the reactor were transferred.

The main contractors engaged on the PFR project are listed below.

The Nuclear Power Group Ltd (management of design and construction)

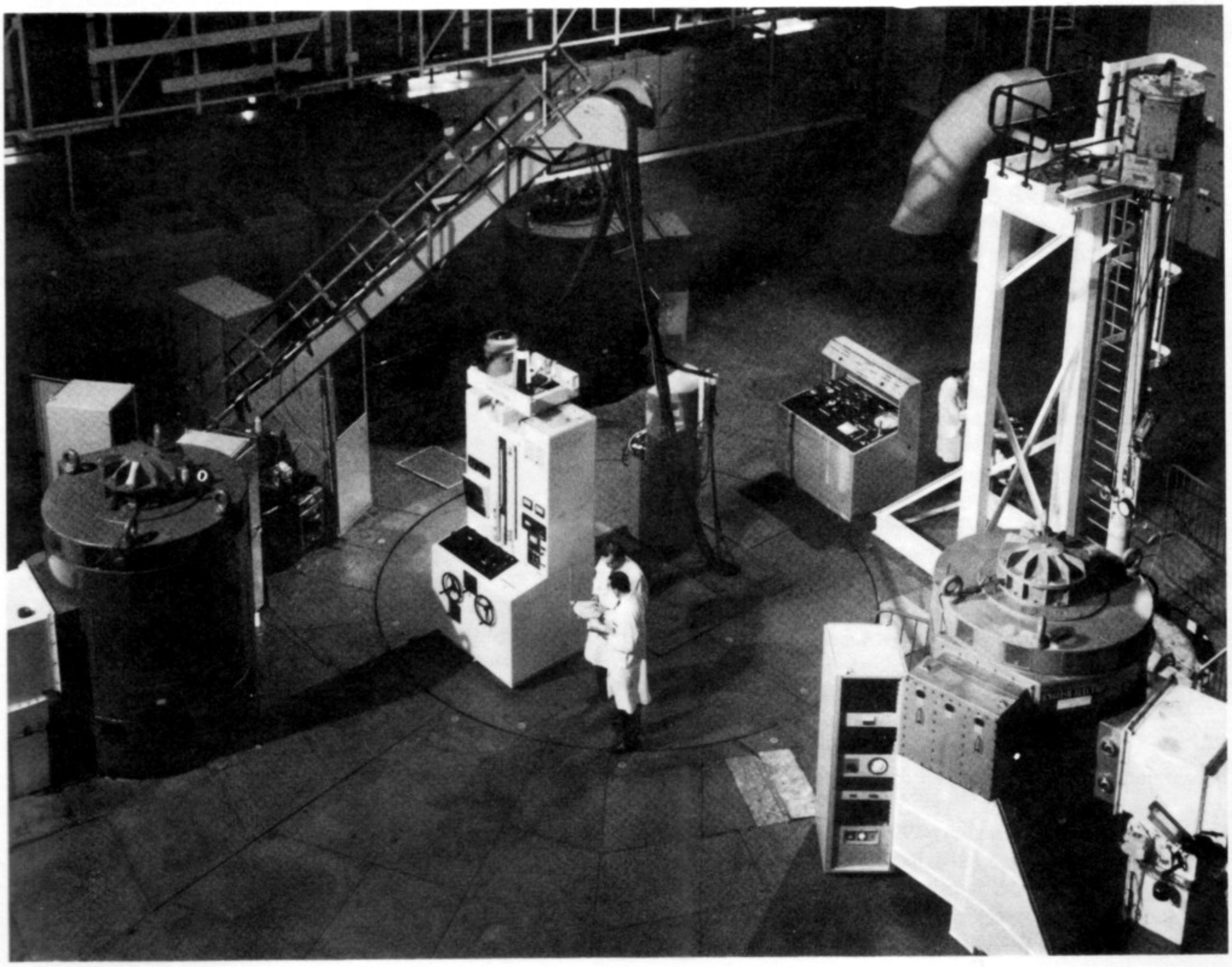
Other contractors concerned in the construction or supplying materials or components include:

English Electric Co Ltd
Babcock & Wilcox Ltd
Taylor, Woodrow (Construction) Ltd
F W Bracket & Co Ltd
Bristol Aerojet Ltd
British Acheson Electrodes Ltd
Chesterfield Tube Co Ltd
Clark, Chapman & Co Ltd
Cochrane & Co (Annan) Ltd
Contactor Switchgear Ltd
Electric Construction (Wolverhampton) Ltd
Fairey Engineering Ltd
Ferranti Ltd
Matthew Hall Ltd
H Hargreaves & Son Ltd
Head Wrightson (Teesdale) Ltd
International Combustion Ltd
J & S Pumps Ltd
R Jenkins & Sons Ltd
Mather & Platt Ltd
Mines Safety Appliances Ltd
Newburgh Engineering Co Ltd
Nuclear Equipment Ltd
Permutit Co Ltd
Wm Press & Sons Ltd
A Reyrolle & Co Ltd
James Scott & Co Ltd
Strachan & Henshaw Ltd
John Thompson Ordnance Ltd
Vickers Ltd
Whipp & Bourne Ltd



PFR Primary pump.

PFR—The Reactor Top showing the charge machine console and the primary pump motors.



PFR Commissioning

Construction of PFR was substantially complete by the early summer of 1973 and thereafter commissioning activities played an increasingly dominant role. During the later stages of construction a number of modifications were made to parts of the design to take account of the latest experimental and assessment work. One was the design of an improved roof cooling system, with additional fans and refrigeration units, to limit the thermal cycles which might be imposed under certain conditions on the outermost roof penetrations. None of these modifications was of a fundamental nature.

After the primary circuit was sealed off, it was pre-heated by the circulation of hot argon, and filled with sodium during August 1973. The primary circuit was then tested with a core of dummy fuel sub-assemblies and the primary pumps were run progressively up to full speed while checks were made on vibration and loading on all major reactor components. Dynamic tests were also carried out on the secondary circuits with water prior to filling with sodium and commissioning. The dynamic testing was followed by in-reactor fuel handling trials, and fuel loading began after satisfactory tests on the reactor control rod system.

These tests gave general confirmation of the design and although some problems arose, these were matters of detailed engineering. In respect of hydraulic performance, there was extremely good agreement between the predicted and measured flow rates and levels during commissioning, the performance being within the tolerance limits of the measuring system. There were failures of one primary pump and one secondary pump during commissioning, in neither case due to any fundamental weakness in the design. Modifications were found to be necessary to the secondary circuit evaporators to reduce the amount of gas entrainment. Experience in dealing with the pump faults and some encountered with the charge machine demonstrated the feasibility of handling large components in and out of sodium using simplified handling techniques and of carrying out major decontamination and dismantling operations.

Fuel loading started in January 1974 and PFR was first taken critical on 3 March 1974. Reactor physics measurements were close to calculated and nothing unexpected was found in some key core parameters at low temperature.

During the latter part of 1974 the reactor operated satisfactorily at low power levels while the commissioning of the steam circuits proceeded. One of the major advances in PFR was the introduction of boilers similar in design to, and approaching the size of, those that would be employed in a commercial plant; in this respect PFR is unique among the world's existing fast reactors. Bringing the PFR boilers on line has therefore been a key stage in the commissioning programme and a high standard of integrity of the sodium-water barrier is required. Three very small leaks were found in the heat exchanger units, and provided important experience in the detection and location of incipient leaks and of methods of effecting their repair.

The PFR turbine, which had previously been part-commissioned on a temporary steam supply, was recommissioned with steam from the steam generating units early in 1975 and was first synchronised with the grid on 2 February 1975.

World uranium supply and demand forecasts suggest that a substantial installation programme of commercial fast reactors will be required in Britain, as probably elsewhere, at some time before the end of the present century. The latest assessments imply that a rapidly expanding programme of commercial fast reactor power stations will become necessary in the UK starting in the mid-1980s. According to these assessments, some 40,000 MW of fast reactor plant would be brought into operation in the UK in the last decade of the century, giving ample scope for the benefits of replication and mass production of components in such a programme. To make adequate preparation the first commercial station of full size, CFR 1, will be built as soon as practicable, so as to start to gain the necessary engineering experience and to take advantage of maximum continuity with the PFR project.

The design and construction of commercial nuclear power stations is the responsibility of the British nuclear industry, in particular the National Nuclear Corporation, with which the UKAEA works in close collaboration. The UKAEA's PFR design team, who were transferred to The Nuclear Power Group (now part of the National Nuclear Corporation), and became responsible for completing the construction of PFR, are working on commercial fast reactor designs; thus British nuclear industry in its present form preserves the continuity of the UKAEA's expertise on fast reactors. As already noted, the UKAEA's fuel manufacturing capability has become a separate but closely associated part of the British nuclear industry, British Nuclear Fuels Limited, which will be responsible for fast reactor fuel manufacture and reprocessing.

CFR Design Approach

PFR was built to demonstrate the feasibility of building and operating a power reactor incorporating as many features as possible of the ultimate commercial plants. In CFR 1 the aim is to incorporate the experience with PFR into a design suited to the needs of the UK Electricity Generating Board's systems. As far as size is concerned, it is envisaged that CFR 1 will be a single reactor station of 1320 MW generated by two standard 660 MW turbo-alternators. In working up the design, high availability has been taken as the key objective. To this end the following design features and principles are being employed:

(i) Component designs are based on those of PFR, modified only where necessary in the light of experience gained during construction and operation.

(ii) Operating temperatures are being kept as low as possible, consistent with reasonable efficiency, in order to ease metallurgical problems. For example, the reactor core outlet temperature is being reduced by about 40 deg C compared with that of PFR.

(iii) Improved provision is being made for access for inspection and maintenance.

(iv) Margins are being built into the capacity of all major components such as boiler units, so that near full output can be maintained on failure of a single unit.

(v) Flexibility is being built into the fuel handling system, so that as more experience is gained with fuel endurance and operation of the plant on the generating system the refuelling cycle can be optimised.

(vi) Component designs are being supported by a substantial development programme covering environmental material testing and model and prototype work on all major components.

The design will thus be conservatively biased, and will be more costly than it would be if it were based solely on optimisation to give lowest capital cost. However, the intention is that the basic concept and layout should allow improvements to be introduced in later plants without major re-design. The design evaluation being carried out also includes examination of the effect on design of introducing carbide fuels so as to improve the breeding performance.

A reference design for CFR 1 was produced in 1973, against which design variants have been studied, and which is forming the basis for consolidation of the design. The variants studied have included the number, and consequently size, of major components; the style and material of the steam generators; and the fuel handling route. Some examination has been made of the alternative 'loop' type arrangement of the primary circuit, with separately contained loops as in DFR, rather than the 'pool' type arrangement used on PFR, where all the primary circuits are enclosed within a single tank. Other countries show a fairly evenly divided preference for these two arrangements. The conclusion from the examination in the context of CFR 1 was that neither arrangement showed a decisive advantage over the other and consequently that there was an incentive to retain the pool arrangement so as to take full advantage of the experience of PFR.

Component Development

The additional engineering development work required for CFR 1 arises from the increase in size of the reactor core and of reactor components, the latter leading to the need for exercise of engineering judgement in deciding the extent of proof testing required for large components, particularly in sodium. Equipment is under construction for the full-scale testing of many CFR components in sodium, with provision for obtaining high temperatures and high heat and coolant flows. Arrangements are also well advanced for the provision of large water facilities to test full-scale sections of the core and primary coolant tank, and smaller scale models of the primary coolant circuit for flow, vibration and acoustic characteristics. These facilities will also allow the flow testing in water of large components, such as a full-size sodium pump, intermediate heat exchanger, and steam generator unit. Test sections and prototype components are being developed by NNC in co-operation with British manufacturers.

Materials Development

The acquisition of sound basic materials data under appropriate environmental conditions, particularly those related to effects in sodium, has been of high priority in the development work. A large experimental programme on the mechanical and chemical behaviour of all circuit materials appropriate to fast reactors is in progress in a series of test rigs in REML; these tests are investigating corrosion and mass transfer in sodium; creep properties; fatigue and stress rupture in air, helium and sodium; and, where relevant, waterside corrosion. Expansion of this programme to meet the requirements of commercial reactors is in hand. Numerous additional rigs will be provided for studying the long-term behaviour of materials in sodium, in particular their mechanical properties. In parallel, information on materials behaviour and sodium chemistry will come from PFR operation and from experiments in both DFR and PFR.

Safety Studies for CFR

With the prospect of a large fast reactor construction programme, it is important that comprehensive safety standards should be agreed at an early stage, and work towards this objective has been in progress in the UK for some years, with the design, development, operating and licensing organisations working closely together to reach a common understanding of the characteristics of fast reactors relevant to safety and to formulate appropriate standards. An increasing proportion of the UKAEA's fast reactor programme is being devoted to safety matters as the design features of a commercial fast reactor become clear. This work has two broad aims: to understand the potential fault sequences and the natural and design feature limitations on fault development; and to confirm the design and performance of components on which the safety of the system depends.

During recent years it has become increasingly clear that European countries with an interest in fast reactors have much to gain by collaboration in safety matters. The UK has participated in the work of the EEC Fast Reactor Co-ordinating Committee and is taking part in collaborative safety programmes with European countries; for example, arrangements are being made for major experiments with France and Germany in French facilities.

The UK programme and the collaborative programmes with European countries are providing quantitative information on the low probability fault sequences and on devices to interrupt these sequences. They include work falling in three broad areas.

(i) Determination of the behaviour of fuel either when starved of coolant or when subjected to an overpower, and of the conditions necessary for the fault to spread; and establishing whether these would constitute a real problem in proposed designs.

(ii) Development of devices to detect local faults, so that the reactor can be shut down before the faults propagate.

(iii) Calculation and measurement of the magnitude of the energy which has to be contained and of the capability of containment designs.

Conclusion

The British fast reactor programme outlined in this booklet has proceeded in stages by building reactors of increasing size, with accompanying development work in all areas. This approach has led to a progressive increase in knowledge and understanding of the system on the basis of which full size commercial reactors can be built with confidence.

The position in several other advanced technological countries is very similar, and this is opening the way to fruitful international collaboration. British organisations are collaborating with other European countries on fast reactors through informal agreements for the exchange of information and the mutual use of facilities, notably with the Debenelux countries and with France. Links are also maintained with fast reactor work in Italy, Japan and the USA, and with that in the USSR by reciprocal visits by specialist teams.

The fast reactor has for many years been the largest of the UKAEA's reactor projects. There are at present over 1,000 professional engineers and scientists working on the system in the UKAEA, in addition to those similarly engaged in the nuclear industry and in the CEGB. These figures are an indication of the importance attached by Britain to the fast reactor, which is regarded as essential for the long-term provision of low cost, strategically secure electric power.

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