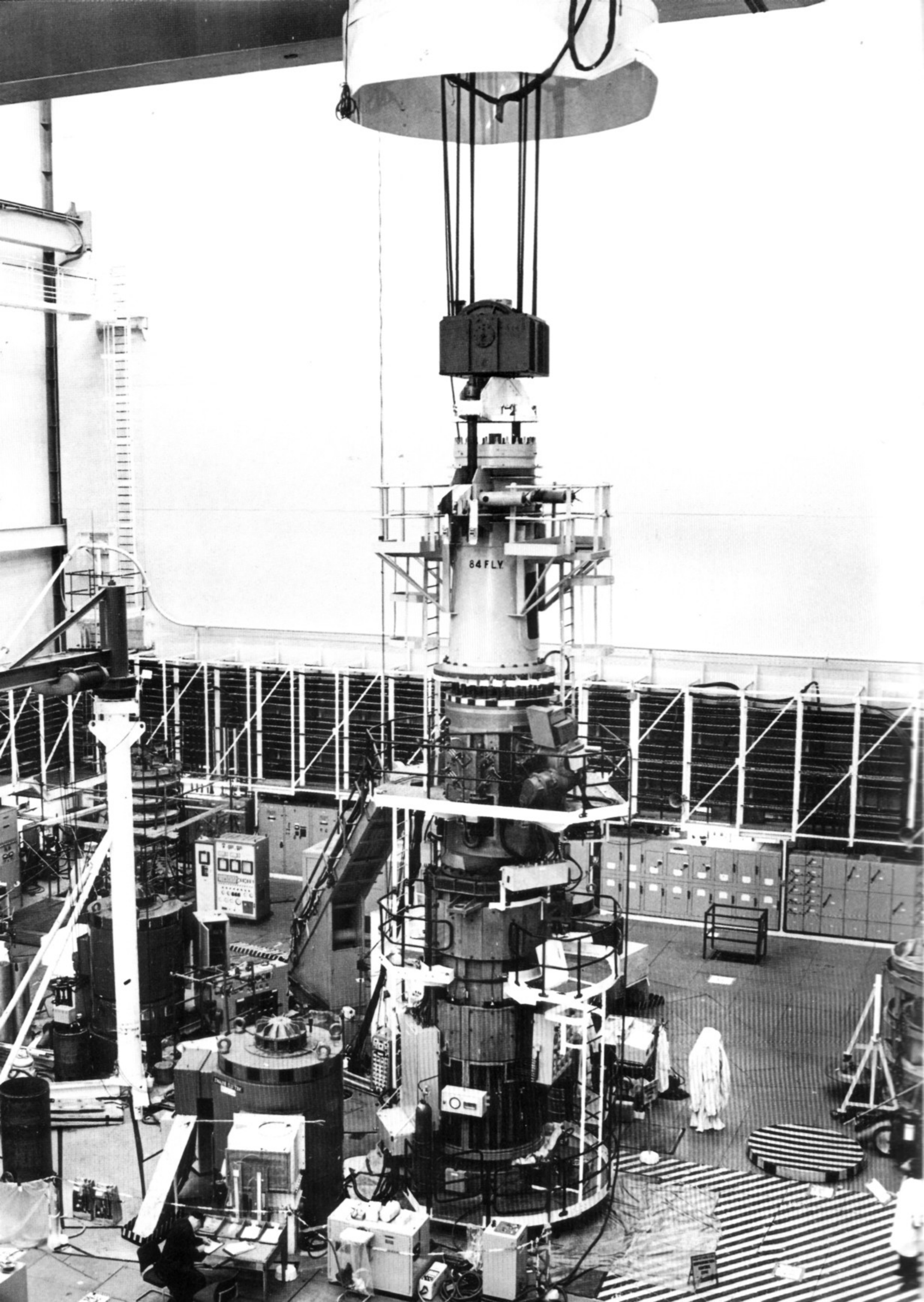
The Prototype Fast Reactor

Dounreay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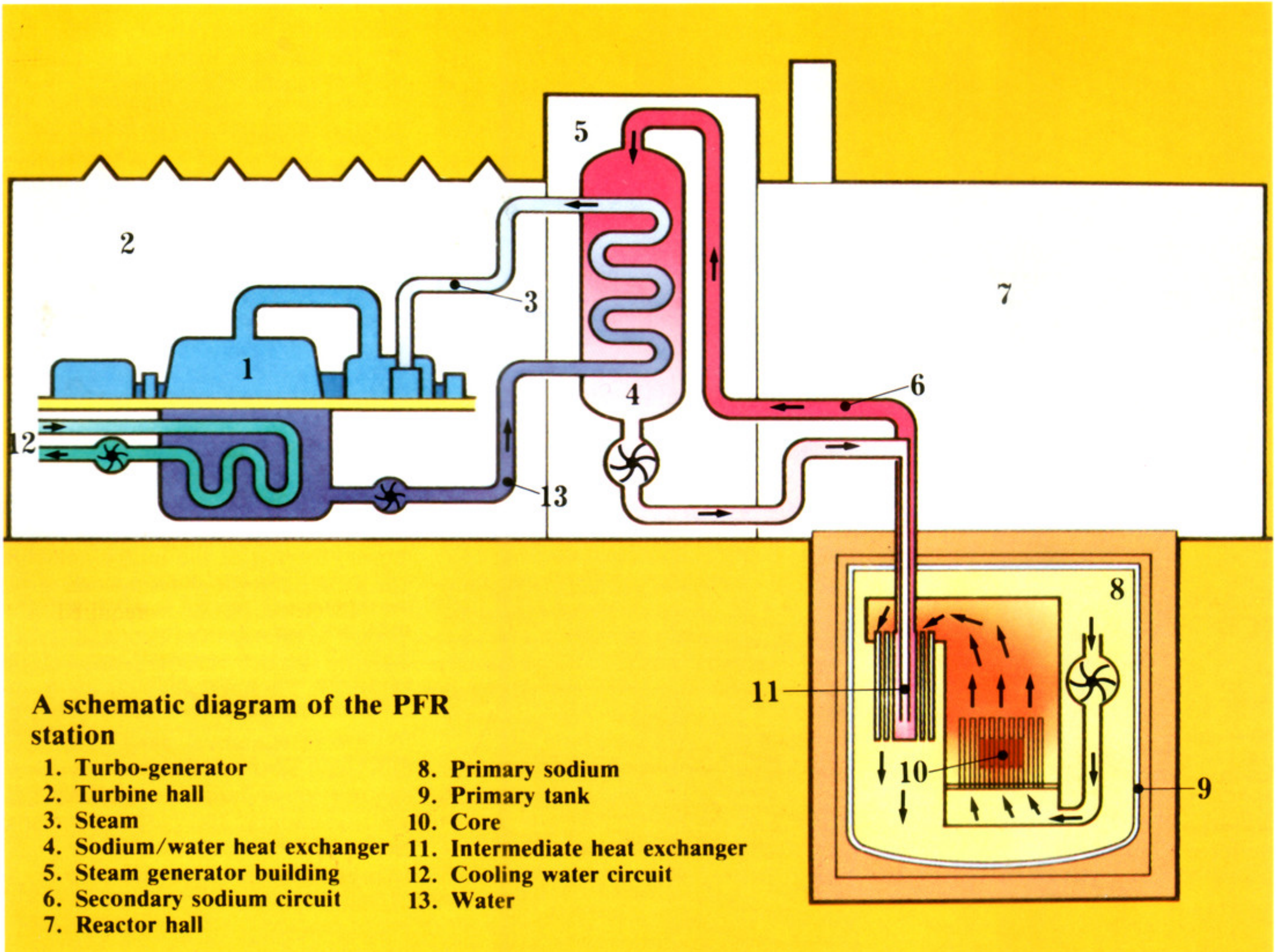
The Prototype Fast Reactor



A schematic diagram of the PFR station

1. Turbo-generator
2. Turbine hall
3. Steam
4. Sodium/water heat exchanger
5. Steam generator building
6. Secondary sodium circuit
7. Reactor hall
8. Primary sodium
9. Primary tank
10. Core
11. Intermediate heat exchanger
12. Cooling water circuit
13. Water

Introduction

The first steps towards the development of commercial fast reactors in Britain were taken in the early 1950s. The physics of the system was studied in a zero energy reactor, ZEPHYR, which began operation in 1954, and it was demonstated that a fast reactor would breed. The following year a second zero energy reactor, ZEUS, was used to provide specific information for the Dounreay experimental fast reactor (DFR). The DFR, with a thermal power of 60 MW and an electrical output of 15 MW, confirmed through its 18 years successful operation the feasibility of the engineering concept.

In 1959 once DFR started operating, detailed consideration of the desirable features of commercial fast reactors began. An electrical output of 1000 MW was selected as an appropriate size for early commercial reactors and design studies were undertaken which indicated the main features to be incorporated in a prototype design. These were supplemented by an increasing flow of information derived from DFR including, in the later stages, the results of irradiation tests on fuel pins and fuel 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 energy reactor, ZEBRA, was built at Winfrith to study the physics of fast reactors with core dimensions and fuel enrichments similar to those of commercial reactors.

The early fast reactors including DFR had metal fuel, but it was soon realised that a commercial reactor would have to have oxide fuel. The viability of oxide fuel was proved by test irradiations in DFR.

The next step was to build a prototype of a commercial reactor. The size of the Prototype Fast Reactor (PFR) was chosen so that the features necessary for the commercial fast reactors could be represented adequately and statistically reliable information could be obtained on the performance of fuel and components. These considerations led to a reactor with a nominal design heat output of 600 MW with a corresponding net electrical output of 250 MW, using fuel and breeder elements which would be appropriate to commercial fast reactors.

Basis of design

From information gained from design, development, physics and fuel studies, the following basic features of the PFR design were determined:—

The initial fuel should be mixed plutonium and uranium oxide, in multi-pin assemblies clad in stainless steel and of a size suitable not only for the PFR but also for a subsequent larger commercial reactor. The design of the reactor should be sufficiently flexible to accept as wide a range as possible of alternative fuels and fuel designs.

The primary coolant circuit for transfer of heat from the core, including the heat exchangers and pumps, should be contained in a single tank.

The primary coolant should be sodium, and there should be a secondary sodium circuit so that the steam generators could be well away from the reactor and its highly radioactive materials.

The sodium circulating pumps should be mechanical.

Refuelling should be done off-load without removing the irradiated fuel from the primary sodium coolant. This required a fuel store (the "rotor") within the primary circuit.

The steam generators should be of a design that could be manufactured economically on a commercial scale.

The operating temperature should be as required for modern steam plant conditions, ie 538°C (1000°F) at the turbine. As with its predecessor, DFR, it was considered desirable to include provision for the use of PFR as a test facility, and particularly for loading alternative designs of fuel assemblies. With this in view, various experimental facilities were provided which would not be found in a commercial power station, including caves, adjacent to the reactor, for the partial dismantling and initial examination of irradiated fuel assemblies.

Design and site layout

Most of the PFR plant is located in one large building complex with the principal units of the power-producing chain (reactor, steam generators, turbine-generator set) arranged, in that order, as close together as possible on a common centre line. This arrangement minimises pipe and cable runs and simplifies staffing during operation, so reducing costs. Ancillary plant is housed in annexes to the main buildings.

The entire primary sodium circuit, contained in a stainless steel tank, is installed in a concrete-lined vault set in the natural rock below ground level. This means that radiation shielding to protect the operating staff is required only over the reactor roof. To provide this the roof structure is filled with a sufficient thickness of concrete, and the rotating central section, which has a number of penetrations, is thicker and is filled with iron and epoxy resin to increase its effectiveness and shielding.

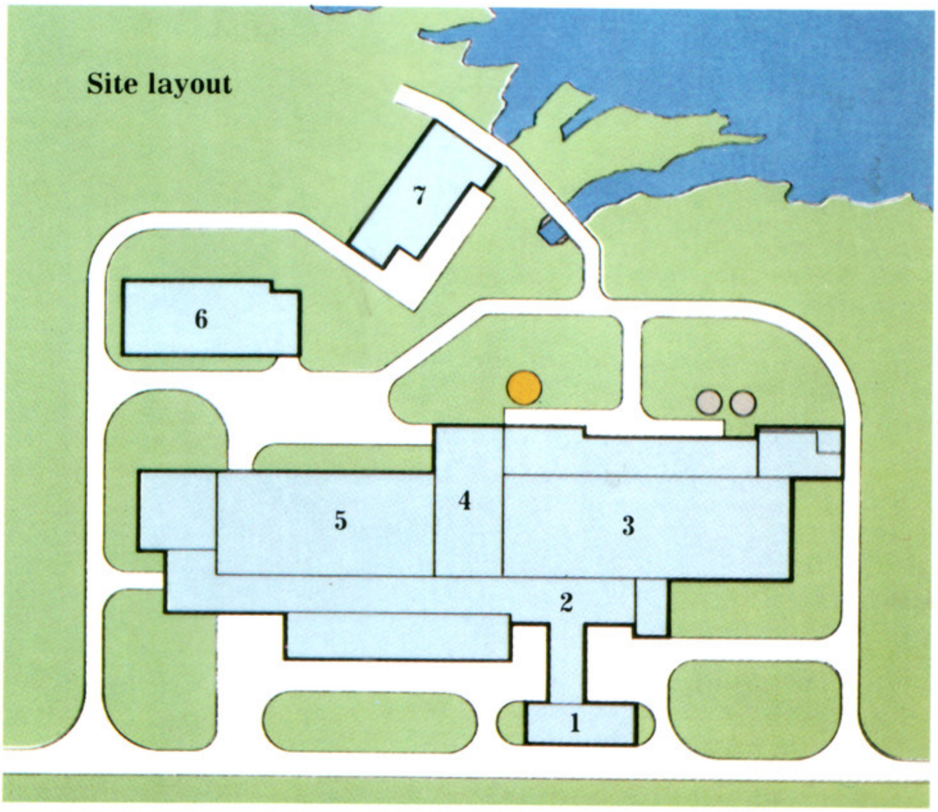
The choice of sodium as a heat transfer medium means that the primary circuit tank is virtually unpressurised. The high pressure steam system is entirely outside the reactor building, which itself is the secondary containment to prevent any release of radioactive material to the environment. This arrangement means that the reactor building does not have to be able to withstand a large buildup of pressure, because there are no sources of pressure within it.

In addition to the reactor itself, the reactor building contains facilities for the handling and examination of both new and irradiated fuel, for the purification of the primary sodium and for the decontamination and maintenance of reactor components.

Heat is transferred from the primary sodium circuit to the steam raising plant by the secondary sodium circuits. The steam generator building, which is next to the reactor building, contains the steam-raising plant and also the secondary sodium purification plant. The turbine hall is of conventional layout with the main electrical distribution plant in an electrical annexe on the south side. Guaranteed standby electrical supplies are provided by two diesel generators located at the west end of the turbine hall and by batteries in the electrical annexe.

Buildings which are separate from the main group are the seawater pump-house, located at the intake point on the shore, and the sodium store.

Electrical power from PFR is exported to the North of Scotland Hydro Electric Board via their sub-station adjoining the site.



Key
1. Administration building
2. Control room
3. Reactor building
4. Steam generator building
5. Turbo-generator building
6. Sodium store
7. Seawater pump-house

Primary circuit

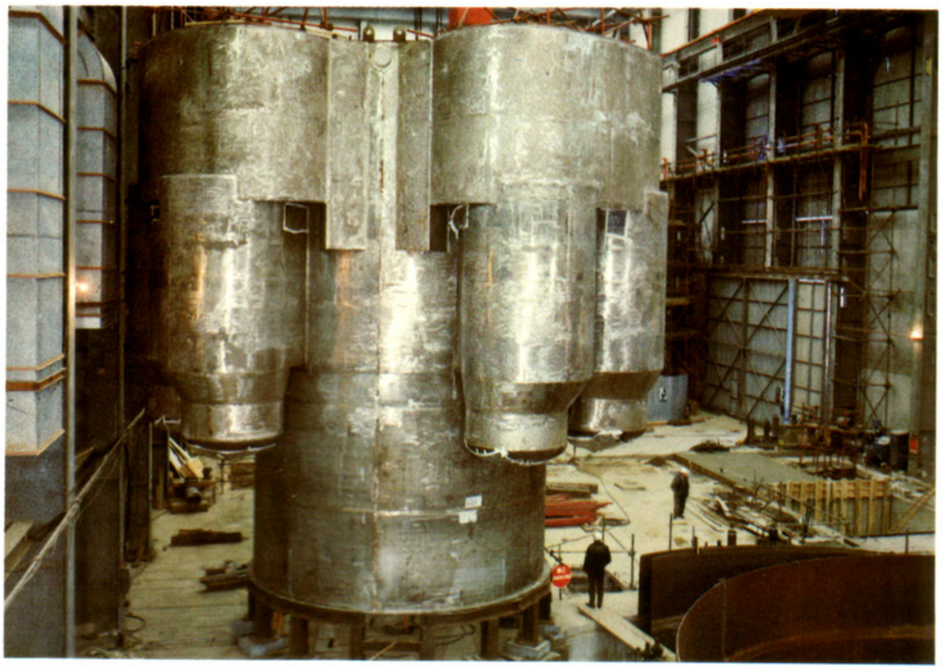
The primary tank is made of 12.7mm thick stainless steel, 12.2m in diameter and 15.2m deep, and is enclosed in a close-fitting thermally insulated outer tank or "guard vessel." Both primary and outer tanks are suspended in a concrete vault from the reactor roof, which spans the vault. The reactor roof also carries the components of the primary circuit, so that the primary tank bears no loads apart from the weight of the sodium it contains. Also it has no entry points below the sodium coolant level. These features ensure that the risk that the primary tank might fail and the sodium be lost is very small indeed.

In the centre of the reactor roof is a rotating shield which carries the refuelling machine. Within the primary tank is the support structure which carries the fuel, breeder and reflector assemblies, and the surrounding neutron shield rods. Outside the shield is the reactor jacket, which extends to almost the full depth of the tank. The upper part of the jacket bears three pairs of 'pods' which contain the six intermediate heat exchangers. The jacket is insulated because it separates the hot sodium leaving the core from the cooler sodium leaving the heat exchangers. The gaps between the pairs of pods provide space for the three primary sodium circulating pumps.

The heat exchangers are of counter-flow shell and tube type, with the primary sodium flowing through the tubes. They are supported from flanged plugs in the reactor roof and are removable for maintenance. The secondary sodium, on the shell side, enters and leaves the heat exchangers by pipes passing through the roof plugs.

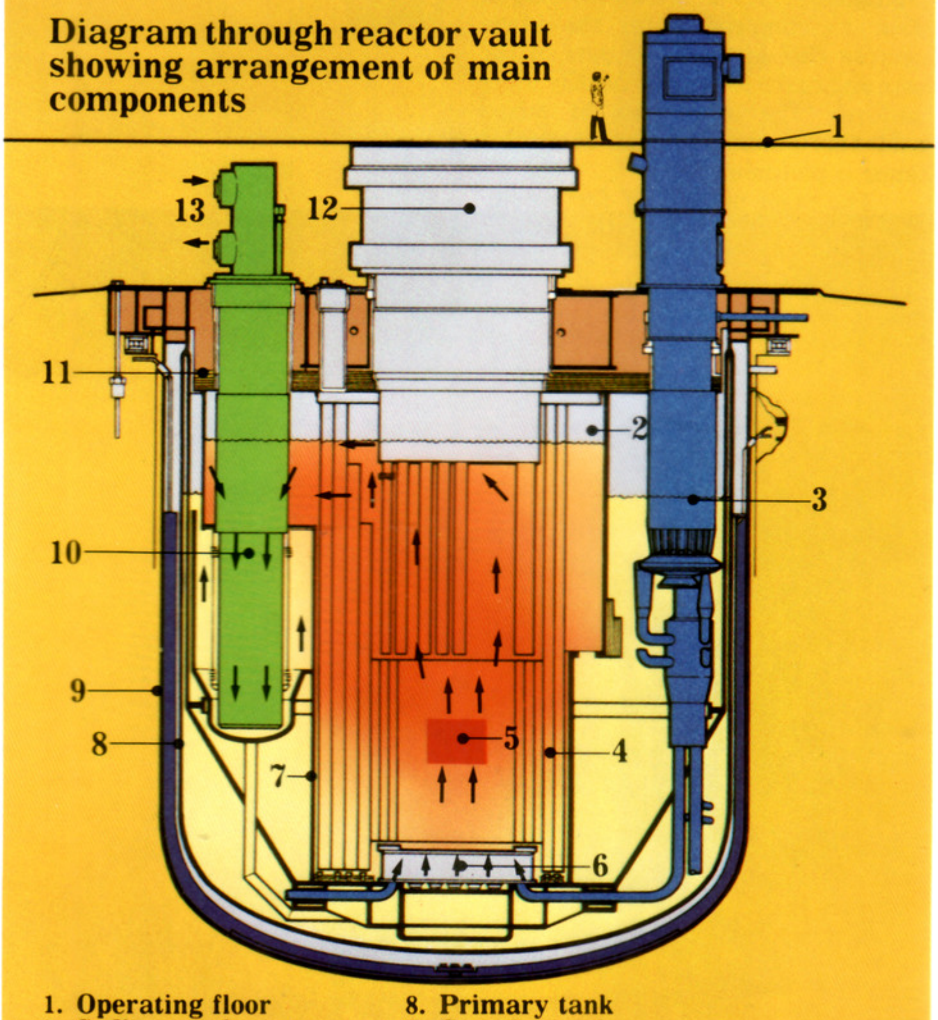
The sodium pumps are mechanical with vertical shafts driven by electric motors mounted above the roof. They also are carried on flanged plugs and can be removed. Each pump shaft has an oil-lubricated bearing at the upper end, above the roof shielding, but the bottom bearing is immersed in sodium, and is lubricated by sodium injected from the pump output.

The pumps draw sodium from the pool in the outer part of the primary tank and deliver it downwards through isolating valves to pipes which feed it to the bottom of the core. From there it flows upwards through the reactor core, picking up heat. It then flows through the intermediate heat exchangers where its heat is transferred to the secondary sodium. From the heat exchangers the cool sodium flows back into the pool outside the reactor jacket.



View of the reactor jacket, before suspension in the vault, showing two of the intermediate heat exchanger pods.

Diagram through reactor vault showing arrangement of main components



1. **Operating floor**
2. **Sodium surface**
3. **Primary sodium pump**
4. **Neutron shield**
5. **Core**
6. **Diagrid**
7. **Reactor jacket**
8. **Primary tank**
9. **Guard vessel**
10. **Intermediate heat exchanger**
11. **Thermal insulation (roof)**
12. **Rotating shield**
13. **Secondary sodium circuit**

Fuel and core structure

The reactor core, breeder and reflector are made up of hexagonal assemblies each 3.81m long and 142mm across. A standard fuel assembly contains 325 fuel pins, each 5.84mm in diameter and about 2.25m long, supported at intervals by honeycomb grids.

Each fuel pin consists of a stainless steel sheath containing pellets of mixed plutonium and uranium oxides in the centre with breeding material in the form of uranium oxide pellets at either end.

Additional breeder material above the fuel pins is contained in a cluster of 19 shorter, thicker pins each 19mm in diameter.

The reactor core consists of two zones of standard assemblies. In the inner zone of about 28 assemblies the fuel contains 22% plutonium and 78% uranium and the outer zone of about 44 assemblies has fuel with 28.5% plutonium, 71.5% uranium. This is done to compensate for the lower neutron flux in the outer part of the core and make the power density more uniform. The total mass of mixed oxide fuel is about 4 tonnes, of which 1 tonne is plutonium.

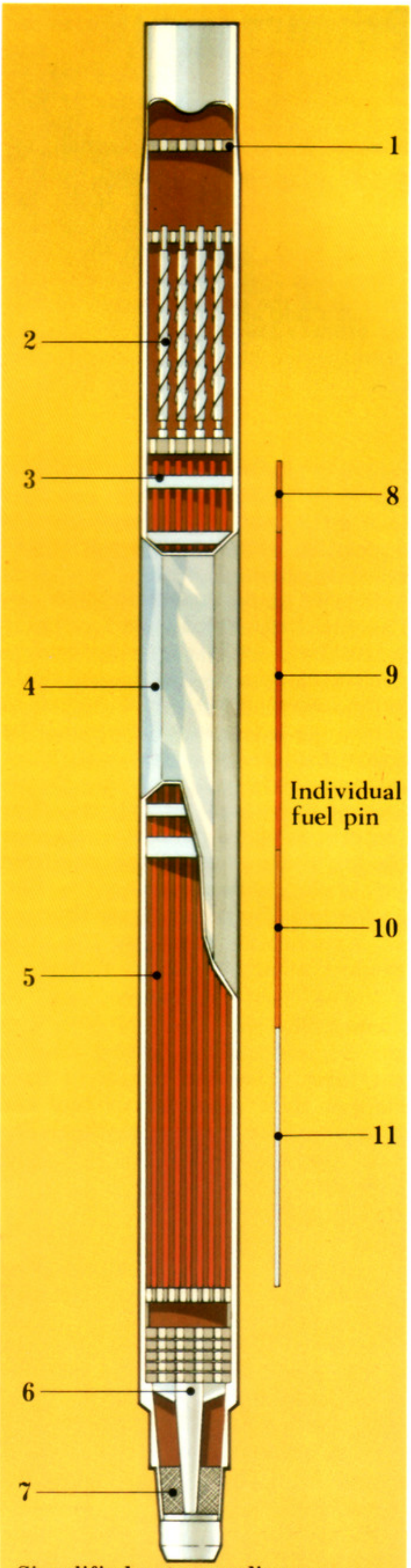
The exact number of fuel assemblies is varied from time to time as they are replaced by experimental assemblies containing fuel of advanced design or other materials undergoing tests. Other locations in the core are occupied by control and shut-off rods. A typical core layout is shown in the diagram.

The core is surrounded by the radial breeder. A radial breeder assembly holds 85 pins, each 13.5mm in diameter, sheathed with stainless steel, and containing depleted uranium oxide.

The radial breeder is in turn surrounded by the breeder reflector which consists of assemblies filled with steel rods which serve to return to the core some of the neutrons which would otherwise escape.

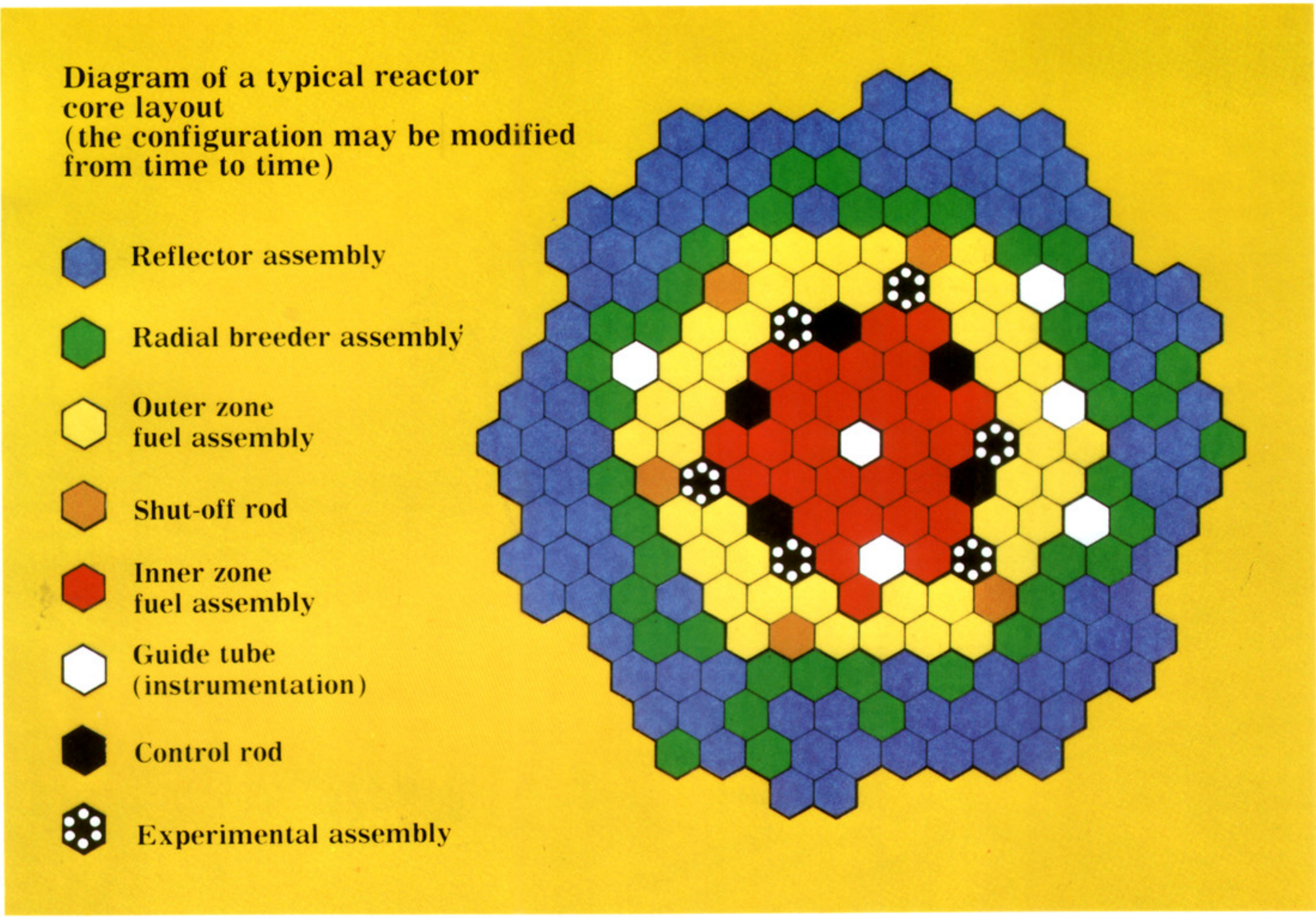
The whole array of assemblies is surrounded by a neutron shield consisting of six rows of steel tubes filled with graphite. This prevents neutrons from the core reaching the secondary sodium in the intermediate heat exchangers, for if they did it would become radioactive.

PFR fuel assembly, before irradiation, showing main component parts.

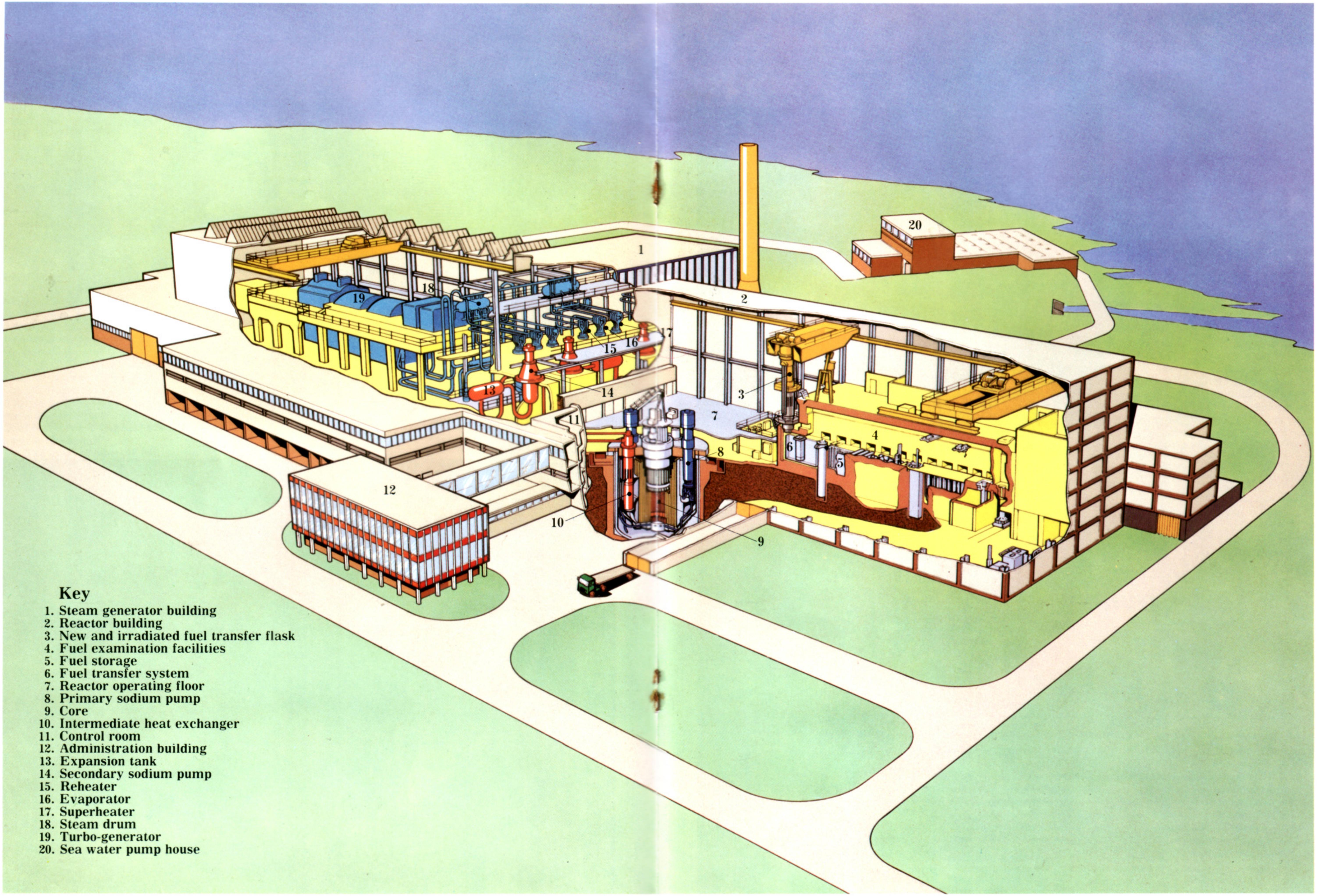


Simplified cutaway diagram of fuel assembly

1. Top gag
2. Axial breeder
3. Grid
4. Wrapper
5. Fuel pins
6. Spike assembly
7. Filter
8. Depleted uranium breeder
9. Mixed uranium/plutonium oxide fuel
10. Depleted uranium breeder
11. Gas plenum



Dummy fuel loading trials in the reactor core during construction.



Key

1. Steam generator building
2. Reactor building
3. New and irradiated fuel transfer flask
4. Fuel examination facilities
5. Fuel storage
6. Fuel transfer system
7. Reactor operating floor
8. Primary sodium pump
9. Core
10. Intermediate heat exchanger
11. Control room
12. Administration building
13. Expansion tank
14. Secondary sodium pump
15. Reheater
16. Evaporator
17. Superheater
18. Steam drum
19. Turbo-generator
20. Sea water pump house

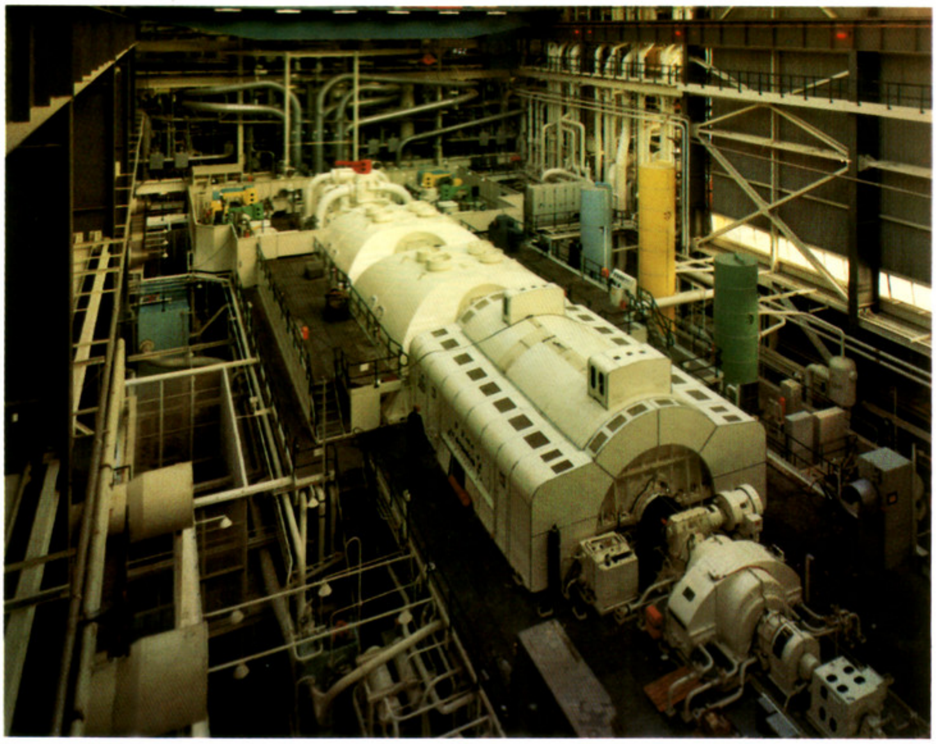
Heat removal and steam plant

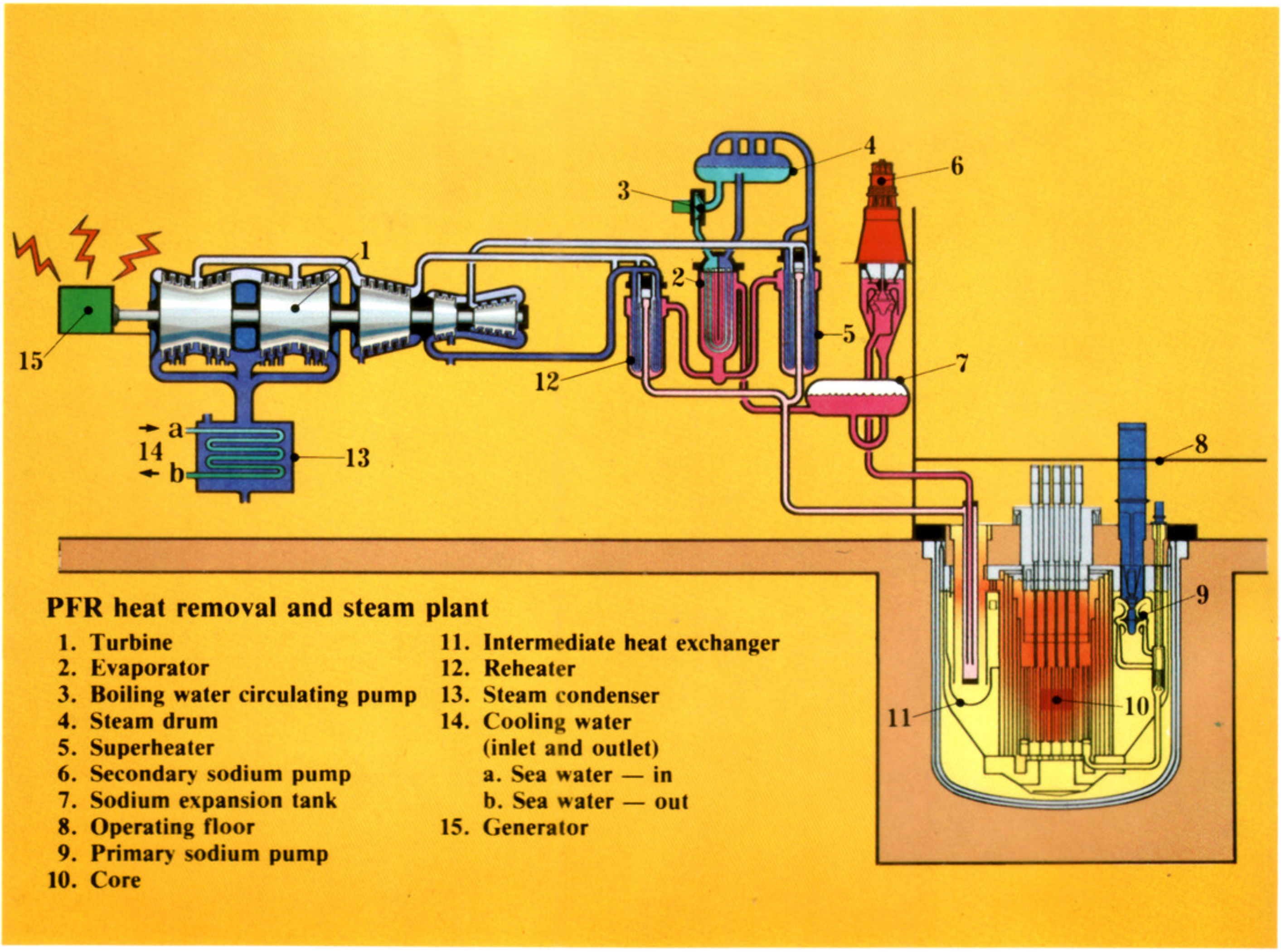
The secondary sodium system consists of three separate circuits each of which serves two of the six intermediate heat exchangers of the primary system.

Secondary sodium is pumped in its independent pipework through the intermediate heat exchangers where heat from the hot primary sodium is transferred to it. It leaves the intermediate heat exchangers and is delivered to a superheater and a reheater. After leaving these units the flow is combined and passed through an evaporator and then returns to the intermediate heat exchangers via a secondary sodium pump.

Steam is generated from water in the evaporator and the mixture of steam and water flows to the steam drum where the steam is separated and passed to the superheater. Superheated steam is piped to the high pressure stage of the turbine, where 30% of its energy is extracted. It returns to the reheater and then goes back to the intermediate and low pressure stages of the turbine. It is then condensed to water in a condenser which is cooled by seawater, and passed via feed heaters and the boiler feed pump back into the steam drums. The turbine rotates at 3000 rpm and drives an alternator which generates up to 250 MW of electric power.

The 300 MW turbo-generator.





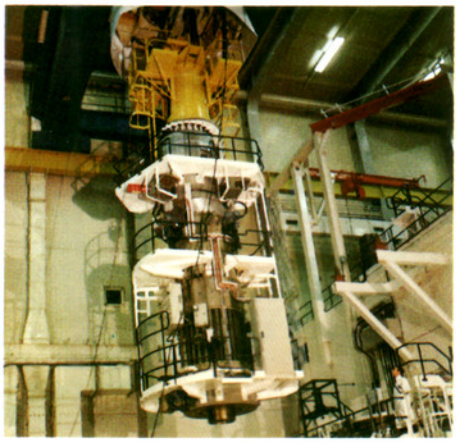
PFR heat removal and steam plant

1. **Turbine**
2. **Evaporator**
3. **Boiling water circulating pump**
4. **Steam drum**
5. **Superheater**
6. **Secondary sodium pump**
7. **Sodium expansion tank**
8. **Operating floor**
9. **Primary sodium pump**
10. **Core**
11. **Intermediate heat exchanger**
12. **Reheater**
13. **Steam condenser**
14. **Cooling water (inlet and outlet)**
    a. **Sea water — in**
    b. **Sea water — out**
15. **Generator**

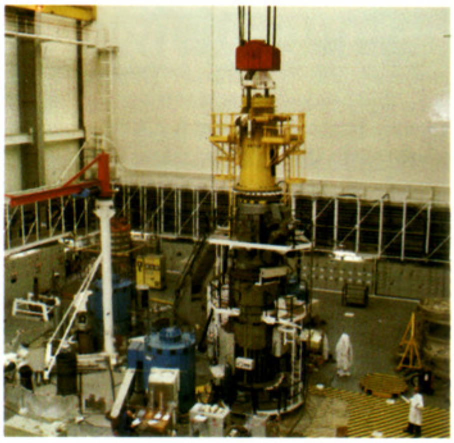
Fuel handling

Core and breeder refuelling is carried out when the reactor is shut down. A rotating shield in the reactor roof accepts the refuelling machine, which has a chute on extensible arms. A combination of rotation of the roof shield and extension of the charge machine arms enables any assembly in the core, radial breeder or reflector to be selected and drawn up into the chute. The assembly is then deposited in a carrier in the transfer rotor, from which a new assembly is taken and loaded in its place. The discharged fuel assemblies can be stored in the rotor submerged in the reactor sodium pool for a cooling period until they are required for post-irradiation examination or reprocessing.

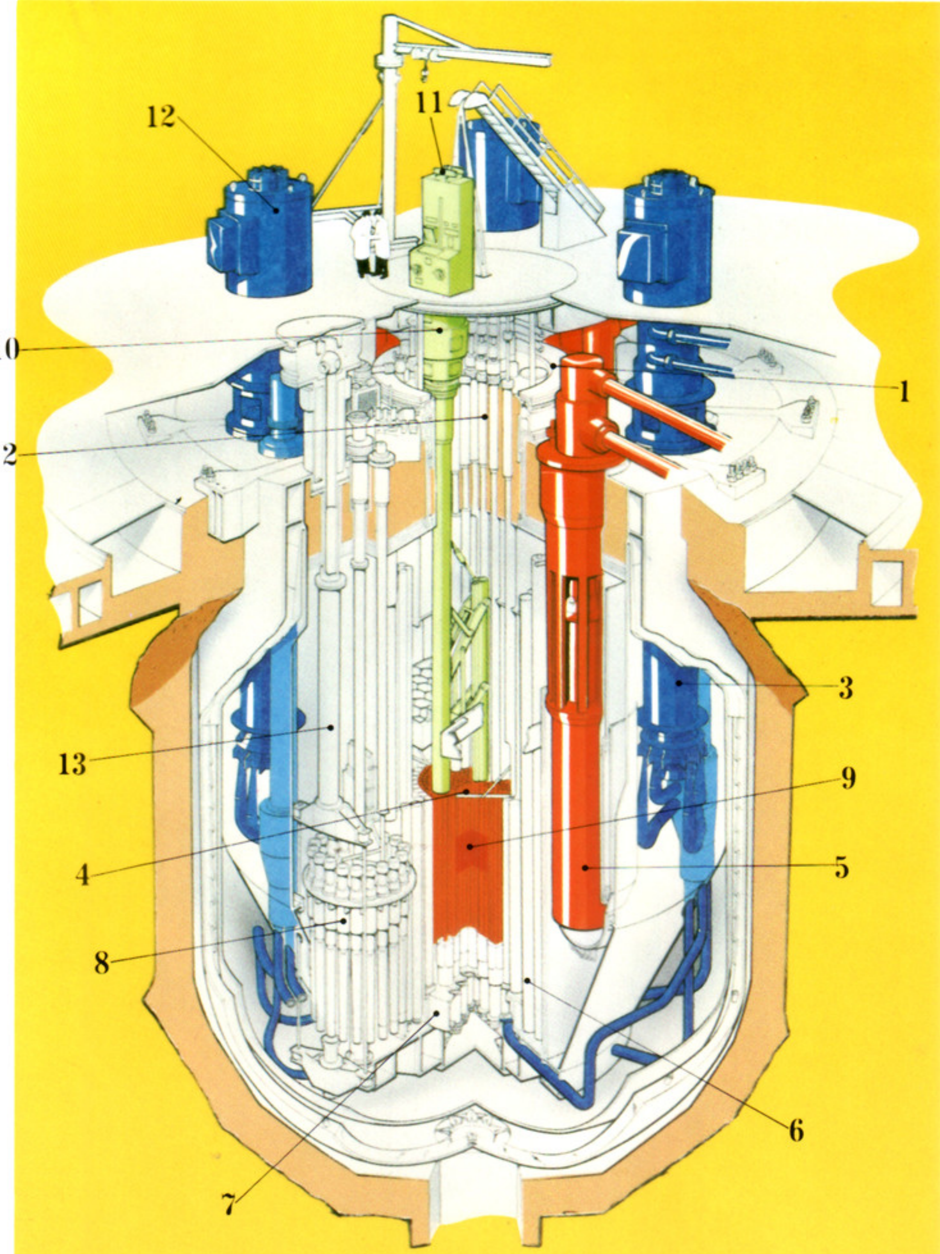
The charge machine is removed from the reactor into its shielded flask before the reactor starts operating. The system is designed to charge the reactor with up to 13 fuel assemblies every 60 days, enabling refuelling to take place within a short shut-down period. The transfer rotor has 20 carriers each holding one fuel assembly. The normal routine is to store fuel assemblies for about 30 days after withdrawal from the core to allow radioactivity and heating to decrease. The carriers containing irradiated fuel assemblies are then removed from the rotor and transferred in a shielded container to the nearby irradiated fuel caves. This operation can be done while the reactor is operating.



Fuel transfer flask about to be lowered to operating floor.



Fuel transfer flask in loading position above rotor transfer tube.



Cutaway diagram showing fuel and fuel handling equipment

1. Rotating shield
2. Control rod actuators
3. Primary sodium pump
4. Core sweep arm
5. Intermediate heat exchanger
6. Neutron shield
7. Diagrid
8. Fuel storage rotor
9. Core
10. Charge machine
11. Charge machine console
12. Sodium pump motor
13. Transfer tube

Operating floor 14ft. above the reactor showing the three primary sodium pump motors.

Instrumentation

The reactor and turbo-generator are operated from a central control room. There are nearly 3000 instruments on the plant measuring such things as neutron fluxes, radiation levels, temperatures, pressures, coolant flow rates and many others. Data from all these instruments are processed by a computer and used for various functions.

(a) The operators can select displays of information about any of several hundred aspects or parts of the plant. These displays are presented on VDUs (like television screens) in the control room or at various other places. They can be in the form of numerical data, mimic diagrams, or graphs of performance.

(b) When an important part of the plant is behaving abnormally an alarm is automatically presented in the control room.

(c) Some operations are controlled automatically by the computer.

(d) A record of the performance of the whole plant is kept automatically.

Control

The reactor is controlled, and changes in the reactivity of the fuel are compensated for, by five control rods. These contain neutron-absorbing tantalum and boron carbide and are located round the edge of the inner core. When they are inserted into the core the reactor power falls, and when they are withdrawn it rises. They are moved so as to maintain a constant selected steam temperature at the turbine. Constant steam pressure is also maintained automatically by adjusting the speeds of the sodium pumps to produce the required rate of heat removal.

Protection against loss of cooling is ensured by the design of the main primary vessel and the surrounding close-fitting guard vessel which prevents loss of the primary sodium even if the main vessel should leak. In the event of damage to or failure of the secondary sodium circuits the primary sodium can be cooled by three independent standby heat rejection circuits. It has been demonstrated at PFR that, even with the primary pumps switched off, natural circulation of the primary sodium will remove the residual heat from the reactor core and reject it safely via these standby circuits to the atmosphere.

In an emergency to protect the reactor and to prevent damage which might lead to the release of radioactivity to the environment, two independent trip systems are provided which release the five control rods and five shut-off rods into the core and thereby shut down the reactor. Both trip systems are operated by multiple sensors to provide a fail-safe system. Thus, to take a simplified example, the coolant temperature is measured by three independent thermocouples. If any two of them indicate that it is too hot the trip system is activated and the reactor is shut down.

PFR central control room.

PFR performance

Construction of PFR started in 1967 and the reactor first began operation in March 1974. After testing at low nuclear power the reactor and sodium circuits settled down to reliable, essentially trouble-free operation.

Synchronisation with the Grid and sustained electrical generation were achieved in February 1975 and the station first reached full thermal power in February 1977.

The performance of the reactor itself, including its fuel and primary sodium coolant system, has been very satisfactory, and since 1974 the reactor has been in operation for about 93% of the time (apart for refuelling periods). For a number of years, however, the power level and load factor for electricity generation were not high, mainly because of a number of small leaks in the steam plant evaporators. These allowed minute quantities of water to enter the secondary circuits and react with the non-radioactive secondary sodium.

A cure for the problem in the form of sleeves to cover the welds which were the cause of the leaks was developed, and during the period 1982-84, after extensive testing, 3000 sleeves were fitted to all the welds in three evaporators. This treatment proved completely successful and no more leaks occurred. This has shown itself in a marked improvement in the load factor, which rose from 16% over the period 1974 to 1983, to 65% in the latter part of 1984. PFR achieved its designed power output of 250 MW electrical in 1985.

In operating PFR priority has been given to developing the technology of the fast reactor system and its fuel cycle. The reactor is highly instrumented and incorporates experimental facilities to provide detailed data on operating characteristics, the performance of all its components, and the behaviour of standard and more advanced fuel and reactor materials exposed to fast neutron irradiation and the sodium coolant. A wide range of information has been obtained and evaluated, and incorporated into the design of a future commercial demonstration fast reactor.

Experimental facilities

The purpose of PFR is to demonstrate its reliability as a power station and to carry out experiments on materials, fuel performance, heat transfer, chemistry and safety.

Performance tests in the reactor can be carried out on a large scale to fuel material and its form, cladding material and variants of the standard fuel assembly. PFR is also equipped to dismantle both standard and experimental fuel assemblies, to examine and test non-destructively individual fuel pins and to re-assemble them into rigs for a further period of irradiation.

View from operating floor, looking down the reactor hall showing maintenance area and, above on left, a row of component transfer flasks.

Inside Front Cover
View of operating floor 14ft. above the reactor showing fuel transfer flask.

Facing page
Outside the steam generator cell, between the steam generator and turbine hall.

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This design is sculptured on a stone table in the foyer of the Prototype Fast Reactor at Dounreay. It blends Pictish symbols with allusion to reactors and the Caithness environment. The Latin inscription is "From Caithness to the World" and the "double disc" and "crescent" signs are the personal badges of Pictish rulers.

DOUNREAY

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