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COMPILATION OF DATA
AND DESCRIPTIONS
FOR UNITED STATES AND FOREIGN
LIQUID METAL
FAST BREEDER REACTORS

MASTER

HANFORD ENGINEERING DEVELOPMENT LABORATORY
Operated by Westinghouse Hanford Company
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COMPILATION OF DATA
AND DESCRIPTIONS
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LIQUID METAL
FAST BREEDER REACTORS

E. R. Appleby

August, 1975

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COMPILATION OF DATA AND DESCRIPTIONS
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LIQUID METAL FAST BREEDER REACTORS

E. R. Appleby

ABSTRACT

This document is a compilation of design and engineering information pertaining to liquid metal cooled fast breeder reactors which have operated, are operating, or are currently under construction, in the United States and abroad. All data has been taken from publicly available documents, journals, and books.

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I. RAPSODIE

LOCATION: Cadarache Nuclear Center
Cadarache, France

OPERATION: 1967
Fortissimo 1970

Rapsodie has been in operation at the Cadarache Nuclear Center in France since January 1967. It is essentially a test bed for fast reactor fuels, and an installation for gaining operating experience for future fast reactor power stations. The 20 MWt reactor was designed and built and is operated by The Commissariat a' l' Energie Atomique. Operation has been satisfactory, with availability averaging about 84%. Incidents which contributed to downtime consisted mainly of problems with the control rod mechanisms, the electricity and computer control systems, the argon circuit, and the fuel handling equipment. In 1970, a "Fortissimo" core was loaded, raising the power to 40 MWt.

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Table - 1

GENERAL PARAMETERS

FORTISSIMO (Ref. 13)

Type	Pot type	Pot type
No. loops	2	2
Coolant	Sodium	Sodium
Core inlet temp (°C)	450	400
Core outlet temp (°C)	540	514
Flow direction	Upward	Upward
Driver fuel	UO ₂ - PuO ₂	UO - PuO ₂
Blanket fuel	UO ₂ depleted	UO ₂
Core diameter (cm)	38	
Core volume (liters)	40	~ 40
No. enrichment zones in core	3	
Output MWe/MWt	0/20	0/40
Neutron lifetime	8 x 10 ⁻⁸ sec.	
Delayed neutron fraction	0.00520	
Max. can temp (°C)	625	650
Linear power, max.	380 w/cm	400 w/cm
Neutron flux, total	2 x 10 ¹⁵ n/cm ² sec.	3.2 x 10 ¹⁵ n/cm ² sec.
Doppler (ΔK/K) /°C total	10 ⁻⁸	
Power Density	407 kw/ℓ	>1 Mw/ℓ
No. Driver elements	53	64 to 66
No. Radial blanket elements	500	Nickel reflector
No. In-core control elements	6	6
Goal burnup	5%	6.5%

I. RAPSODIE

Table 2

CORE AND BLANKET

	Driver zone	Axial blanket	Radial blank	FORTISSIMO (Ref. 13)
Fuel material	UO ₂ - PuO ₂	UO ₂ depleted	UO ₂ depleted	UO ₂ - PuO ₂
Form	----- Sintered pellets -----			
Composition	80% U - 20% Pu			30% PuO ₂
Stoichiometry	2.00 ± 0.05			1.97 - 1.98
²⁴⁰ Pu	10.2%			
²³⁵ U inner zone	60%			85%
outer zone				
Density	96% TD			92% TD (84% smear)
Pellet OD (mm)	5.7		15.4	4.3 axial 14.5 mm
Rod cladding	316 SS	316 SS	316 SS	SS
OD (mm)	6.7			5.1
Wall thickness (mm)	0.45			0.37
Fuel-clad gap (mm)	0.23			0.13
Bond material	Helium			
Column length (mm)	340	200 x 2	1090	320 mm axial + 60 mm axial + 106 mm
Gas plenum length (mm)	101		110	Below fuel
Pin length (mm)	485			<div> { Top axial blanket replaced by stain- less steel rods; radial blanket by nickel reflectors. } </div>
Vented/non-vented	No			
Assembly material	SS			
Shape	Hexagonal			
Across-flats dia. (mm)	49.8			
Wall thickness (mm)	1			
Overall length (mm)	1661.5			
No. pins/assembly	37	7 x 2	7	61
Pin spacing	Spiral fins		Spiral wire	Spiral wire
Pin pitch	P/D = 1/12			
Assy. in core	53 to 64		500 + reflectors	64 to 66
Volume fraction (%)				
Fuel	42.2	44.2	58.3	
Steel	22.8	19.8	15.6	
Sodium	33.5	35.4	25.4	

I. A. CORE AND BLANKET

A mixed oxide fuel was chosen for the first Rapsodie core. Axial blanket sections of depleted UO_2 occupied the top and bottom regions of the driver assembly, the 7-pin bundles being held by grid devices in the hexagonal can. The gas plenum was above the fissile core. A buffer pellet of UO_2 was placed at each end of the fuel pellet stack, which was held by a spring in the plenum section. The stainless steel clad pin has integral spiral pins. Bonding was helium, and the pins were sealed. (Refs. 1, 10.)

Filters designed for installation in the foot of each subassembly were found to be inconvenient and were discarded (Ref. 6). Hold-down has been made more certain by a system of flexible blades in the assembly foot, which engage in the grid. (Ref. 9,) (Figs. I.A-1, I.A-2, I.A-3)

An assembly with the U-Mo-Pu tertiary alloy as fuel was also studied. Pin cladding consisted of an inner niobium cylinder joined to the fuel by a metallurgical bond, and an outer stainless steel cylinder. The thermal bond between the niobium and the stainless steel tubes was sodium. Spacing was by a spiral wire wrap.

Radial and reflector assemblies have the same hexagonal can dimension as the driver assemblies. Pin spacing for the radial assembly is by spiral wire wrap (wire dia. 0.0365 cm). The gas plenum is 11 cm. Pins are sealed. The Fortissimo version replaces all radial blanket assemblies with nickel reflector assemblies. (Fig. 1. A-5.)

FORTISSIMO CORE

A new core (Fortissimo) was loaded in 1970. The fuel section consists of 67 rods. The mixed oxide fuel is slightly substoichiometric, with a smear density of 84% TD. Fuel length is 320 mm; gas plenums occupy 60 mm below and 106 mm above the fuel section. Pellet-clad gap is 0.13 mm. The top axial blanket is replaced by stainless steel rods, and the radial blanket elements are replaced by nickel reflector elements. (Fig. I.A-6) (Ref. 13)

Figure I.A-1. Rapsodie Fuel Assembly (Ref. 7)

Figure I.A-2. Grid For Holding Pins (Ref. 2)

I.A-4

Figure I.A-3. Foot of Fuel Assembly (Ref. 2)

Figure I.A-4. Radial Blanket Assembly

I.A-5

SECTION A-B

Figure I.A-5. Reflector Assembly (Ref. 2)

Figure I.A-6. Fortissimo Assembly (Ref. 15)

RAPSODIE I.A.

I. B. CORE SUPPORT AND VESSEL INTERNALS

The core grid gives axial and radial positioning of fuel, fertile, and reflector assemblies and control rods; distributes the sodium flow; and controls the flow through different zones in the core. The grid assembly has been modified from the original design to allow for a greater number of assemblies to receive high-pressure sodium, providing for a possible increase in core diameter.

The grid assembly consists of two horizontal plates separated by 206 mm. The top,

or guide, plate is 35 mm thick, and has openings for passage of assemblies. The bottom, or support, plate is 90 mm thick, and rests on a support flange. The central parts of the two plates are connected by a hexagonal sleeve. The central area is the high-pressure zone. (Fig. I.B-1, I.B-2, I.B-3.)

The core-catcher assembly ("recuperator" in Fig. I.B-4) was omitted because of questions as to its usefulness and accessibility. The revised plenum arrangement is illustrated by Fig. I.B-5.

Figure I.B-1. Support Grid-Top View (Ref. 2)

I.B-2

Figure I.B-2. Grid Plenum Cross-Section (Ref. 2)

Figure I.B-3. Assembly Foot in Grid-plenum Device (Ref. 2)

Figure I.B-4. Different Types of Lodgings in the Grid Support (Ref. 2)

Figure I.B-5. Vessel With "Recuperator" and Annular Diaphragm (Ref. 2)

Figure I.B-6. Revised Vessel Arrangement with Diffuser (Ref. 5)

I. C. REACTOR VESSELS AND SHIELDING

The reactor vessel is a cylindrical structure of 316 stainless steel, connected at the lower end to the inlet sodium pipe. The main sleeve has a wall thickness of 15 mm, and receives the outlet piping. A double jacket surrounds the reactor vessel and sodium pipes, providing for circulation of a gas (nitrogen or argon), preheating, and evacuation of residual heat in case of cooling loop malfunction.

The fixed core cover is a steel plate located about 15 mm above the assembly heads; it reduces sodium flow at the assembly outlets. A large rotating plug is centered on the fixed plate by self-centering ball bearings. A handling channel and two experimental channels pass through it. The small rotating plug is off-set, and supported on the large rotating plug by self-centering ball-bearings. Rapsodie top seals are rotary seals containing a bismuth-tin alloy, fitted in series with a plastic seal. The reactor vessel and vessel covers are suspended at the upper part of a fixed concrete structure in the form of a circular cornice. (Fig. I.C-1, I.C-2, I.C-3 and I.C-4)

Originally, vessel support was designed to transmit the weight of the vessel and internals to five support posts through a support flange, while the fixed plug rested on five rings and supported the two rotating plugs. (Ref. 3, 4, 5.)

A containment tank, the safety vessel, is a mild steel cylindrical structure with a 15 mm thick wall (Fig. I.C-1 and I.C-2). Thermal insulation consisting of steel caissons filled with steel mesh or alumina elements occupies the space between the vessels. Gas at the interface is nitrogen. Around the safety vessel there is a 600 mm thick ring of borated graphite bricks and a 400 mm thick cellular concrete ring. The 70 mm space between the two rings is cooled by circulating gas. Ordinary and reinforced concrete form the outer shielding layers, with a sleeve of special concrete around the sodium outlet piping that penetrates through the structure. (Ref. 2.)

Figure I.C-1. Rapsodie, Vertical Section (Ref. 4)

I.C-3

Figure I.C-2. Horizontal Cross-Section of Rapsodie Vessels and Shielding (Ref. 2)

RAPSODIE I.C.

Figure I.C-3. Rotating Plug Structure (Ref. 2)

Figure I.C-4. Upper Part of Rotating Plugs and Freeze Seals (Ref. 2)

I. D. CONTROL ELEMENTS

There are six control assemblies located in the periphery of the core. Each rod moves up and down in a hexagonal sleeve 49.8 mm across the flats. The rod consists of a cylindrical sleeve filled with boron carbide pellets and fitted with a gripping-head similar to that of the fuel element. The boron carbide pellet is 1.5 - 1.6 in. dia. The rods are sealed and include a gas plenum for helium generated by neutron reactions with boron.

Drives are located in the upper part of the small plug and can be changed according to the desired function: handling, shim, oscillation. The rod moves a distance of 450 mm in the sleeve. (Fig. I.D-1, I.D-2.)

Vented assemblies are being tested in Fortissimo; both sintered and valved vents are being studied.

7-pin bundle

B₄C pellets: 38 mm dia.

Column: 440 mm

Pin OD: 1.5 in.

Bottom tantalum pellet: 28 mm high

Hexagonal assembly, 7 rods

Max, specific power: 160 w/cm³

Antireactivity, 1 rod ³1700 pcm

Na coolant flow 500 cm³/sec: 410°C inlet

(Ref. 13.)

CONTROL ROD DATA

	Regulating control rod	Safety and compensation
No. of rods	2	4
L of borated rods (cm/in.)	45/17.7	45/17.7
Dia borated rod:		
ID (cm/in.)	31.4/12.4	31.4/12.4
OD (cm/in.)	43.5/17.1	43.5/17.1
B ₁₀ (kg/lb)	0.1/0.22	1.0/2.2
B, in boron (%)	18.8	90
Total travel (cm/in.)	45/17.7	45/17.7
Velocity:		
Raise, (cm/sec)/(in./min)	0.5/11.8	36.0/850
Lower, (cm/sec)/(in./min)	0.5/11.8	360.0/8500
Scram		0.4 sec for 90% of travel
		(Refs. 2, 3.)

Figure I.D-1. Rapsodie Control Rod and Sheath (Ref. 2)

Figure I.D-2. Rapsodie Control Rod Mechanisms (Ref. 2)

I. E. HEAT TRANSFER SYSTEMS

Heat transfer is by means of a two-loop system. The two primary loops have double-wall piping, and each is located in a separate chamber. Primary pipes are jacketed and heated. Sodium flows into the core through the inlet piping at the lower end of the reactor vessel, is distributed into high-pressure and low-pressure zones in the plenum structure, flows upward through the core to the outlet piping. Flow is to the shell side of a vertical tube-and-shell heat exchanger. A vertical centrifugal pump moves the sodium from the intermediate heat exchanger back to the reactor.

Parameters

Piping, reactor → IHX 300 mm dia
 Power/loop 10 MWt
 Flow 496,000 lb/hr
 Core inlet temperature 410-450°C
 Core outlet temperature 500-540°C
 Max velocity of sodium in core 6.4 ft/sec
 Pressure drop in reactor 49 psi
 Pressure drop in loop 3.8 psi

Secondary coolant is sodium (NaK was called for originally). Loops are of single wall stainless steel piping. Flow is downward through the tubes of the intermediate heat exchanger and to the terminal sodium-air heat exchanger. It is pumped back to the intermediate heat exchanger. There is no shielding for the inactive sodium system. (Refs. 5, 8.)

The intermediate heat exchanger is a vertical tube-and-shell unit with a floating lower tube sheet. It is installed in a vertical sleeve which maintains the sodium surface. Expansion bends in the upper parts of each tube compensate for differential expansion between tubes. The units are top-suspended. (Fig. I.E-1.)

Specifications

	Primary (shell) side	Secondary (tube)
Inlet Temp (°F)	644	428
Outlet Temp (°F)	428	590
Op. pressure (psig)	2.9	24
Flow (lb/hr)	675 X 10 ³	875 X 10 ³
Shell ID (in.)	34.8	
Shell wall (in.)	0.63	
No. tubes		888
Tube OD (in.)		0.551
Tube wall (in.)		0.079
Tube pitch (in.)		0.78
Effective tube surface (ft ²)		904

(Ref. 5, 8.)

The primary pump, located in the cold leg, is a vertical centrifugal unit with a free sodium level. Delivery is axial and aspiration is lateral. The outer cylinder is fixed, while the pump unit can be dismounted and includes a shield plug. The unit is top-suspended. (Fig. I.E-2.)

For Fortissimo, the impellers of the pumps were changed to increase output to 550 m³/hr per pump.

Secondary pumps are also vertical centrifugal units. (Ref. 5.)

An electromagnetic pump collects sodium at the outlet of the terminal heat exchanger and sends it to a cold trap in the secondary circuit purification line. Flow is 1000 kg/hr. The rate is controlled by an electromagnetic flow-meter at the cold-trap outlet.

In the primary loop, an electromagnetic pump withdraws sodium into the overflow reservoir and sends it back to the reactor through 33/42 mm dia. piping which feeds the purification line. (Fig. I.E-3.) (Ref. 8.)

Figure I.E-1. Rapsodie Intermediate Heat Exchanger (Ref. 5)

Figure I.E-2. Rapsodie Primary Pump (Ref. 5)

Figure I.E-3. Rapsodie Electromagnetic Pump (Ref. 1)

I. F. SODIUM PURIFICATION AND INSTRUMENTATION

Each of the secondary loops has a purification circuit which includes an alternating current electromagnetic pump, a cold trap, a filter, and a plugging indicator. (Fig. I.F-1.) There is no safety vessel or radiation shielding. (Ref. 8.)

The secondary cold trap (Fig. I.F-2) is a cylindrical vessel, cooled externally with a flow of air and containing an exchanger-economizer coil and steel wool for trapping the oxides.

Na flow (kg/hr) 1000

Exchanger operation: Na inlet temp (°C) 550
Na outlet temp (°C) 160

Purified Na inlet temp (°C) 130

Purified Na outlet temp (°C) 520

Trap operation: inlet temp (°C) 160
outlet temp (°C) 130

Air flow (kg/hr) 4050

(Ref. 8.)

The plugging indicator (Fig I.F-3) consists of a finned tube cooled externally by a flow of air and enclosing the return pipe. Sodium cooled in the annular space passes through six orifices of the plugging indicator and leaves by a tube interior to that of the cooler. The four-meter length of the two concentric tubes constitutes an economizer.

Flow (kg/hr) 200

Economizer inlet temp (°C) 540

Economizer outlet temp (°C) 512

Plugging indicator inlet temp (°C) 188

Plugging indicator outlet temp (°C) 160

Cold point, temp minimum (°C) 110

Air flow (kg/hr) 200

All equipment of the primary purification circuit is in shielded cells (Fig. I.F-6). The circuit consists of an exchanger-economizer, a plugging indicator, the Rhometer circuit, and cold-traps. The exchanger-economizer is a bundle of 19 tubes welded to two tube plates. The body of the exchanger is a hairpin-shaped pipe. The plugging indicator and filter are identical to those of the secondary circuit. The Rhometer circuit consists of an exchanger-economizer as a bundle of seven tubes welded to two tube plates, and a finned tube cooler. Sodium

circulates inside this piping. The annular space formed by a cladding is supplied with a flow of nitrogen. There is a buffer reservoir with sodium. All valves in the system are of the single-bellows type, enclosed in a steel box with outer insulation and heating. (Ref. 6, 8.)

The primary cold trap (Fig. I.F-7.) differs from the secondary cold trap by the provision of biological shielding and direct cooling of the interior by means of a coil for nitrogen circulation. There is no economizer. Equipment for the primary purification line is contained in a metallic shield located in another cell.

Flow-meters are of the electromagnetic type. A double safety containment is provided. The flow in each primary loop is regulated by a flow-meter; others are provided for different pipe-lines of the installation.

Temperatures are measured by chromel-alumel thermocouples clad in stainless steel, lodged in gloved fingers in pipes or equipment (Ref. 2.)

Level indicators are of two types. Continuous probes (Fig. I.F-8.) monitor the level between two defined points. They consist of three vertical stainless steel tubes connected at the lower part, in a box within which there is a resistance compensator for temperature effect. The box is located at the end of a support tube welded to the upper part of the vessel to be monitored. The box is supplied by direct current.

The discontinuous probe (Fig. I.F-9) consists of a stainless steel tube located vertically in the reservoir to be monitored. It is closed at the bottom. An insulated stainless steel wire passes into the interior and is welded to the base of the tube. It is fed by alternating current between the reservoir mass and the copper wire by means of an adjustable resistance. For the two primary loops, there are about sixty of these probes, varying in length from 0.5 to 3 meters. (Ref. 2.)

Figure I.F-1. Rapsodie Secondary Purification Circuit (Ref. 8)

Figure I.F-2. Rapsodie Secondary Cold Trap (Ref. 8)

Figure I.F-4. Rapsodie Cold Trap Regulation (Ref. 8)

Figure I.F-5. Rapsodie Plugging Meter Regulation (Ref. 8)

Figure I.F-6. Rapsodie Primary Purification Loop and Chamber (Ref. 8)

Figure I.F-7. Rapsodie Primary Cold Trap (Ref. 8)

Figure I.F-8. Rapsodie Continuous Sodium Level Probe (Ref. 2)

I.F-9

Figure I.F-9. Rapsodie Intermittent Level Indicator (Ref. 2)

RAPSODIE I.F.

I. G. COVER GAS AND AUXILIARY SYSTEMS

Cover gas is argon. It is distributed to the vessel heat exchangers, pumps, and all equipment having a free sodium level, from a storage reservoir where the gas is held at a pressure of about 5 kg/cm². Contact manometers regulate the pressure. Argon from the reservoir is dried and purified in sodium. (Fig. I.G-1.)

Large-diameter hydraulic valves are included in the system to avoid over-pressure in the argon blanket. (Ref. 2, 6.)

A sodium vapor trap (Fig. I.G-2) prevents vapor from being transmitted to the cold argon piping, where it could condense and cause blockages.

To avoid thermal stresses in the metal of the core plugs and vessels, a system is provided to evacuate about 100 kw of heat to two cooling beds. The first is located at the first 300 mm of the graphite, and the second above the mild steel plate. About 90% of the heat is dropped in the first boron carbide layer. Air in open circuit provides the cooling.

The reactor vessel is preheated before sodium loading by means of circulating hot nitrogen in the gap provided by the double jacket surrounding the vessel. Nitrogen flow is 7000 m³/hr at 250°C. (Ref. 2.)

I.G-2

Figure I.G-1. Rapsodie Primary Sodium and Argon Loops (Ref. 2)

Figure I.G-2. Rapsodie Sodium Vapor Trap (Ref. 2)

I. H. TERMINAL HEAT EXCHANGER

There is no power take-off for Rapsodie. Heat is evacuated by means of the Terminal Heat Exchanger--a tube bundle containing the Na to be cooled--which is located in a flue cooled by forced air circulation.

Tube bundle: 262 tubes in parallel, attached to inlet collector and outlet collector. Arrangement is in a grouping of 786 tubes in staggered array. Tubes are finned.

Ventilator: Standard high-yield type.

Terminal HX parameters (sodium-to-air):

Na inlet temp (°C) 310

Na outlet temp (°C) 220

Air inlet temp (°C) 30

Air outlet temp (°C) 185

Tube dia (mm) 21 ID, 24 OD

No. tubes 262

Heat exchange area (m²) 115

(Refs. 2, 8.)

RAPSODIE I.I.

I. I. REACTOR INSTRUMENTATION AND CONTROL

Information from various measurement channels is collected in a single control building. A complete information system with centralization and data recording allows much of the system to be automated. Indicators and controls at the console are reduced to essentials and grouped in displays arranged in logical order. One operator can control the reactor. There are two read-out instruments for each measurement channel. A special incident channel gives information on power surges to about 140 MW.

Of the twelve control channels, three are for startup (fission chamber monitors),

three are for power rise, five for linear power (two control and three safety), one for the incident channel.

Three fission chamber monitors and eight compensated ionization chambers are located in the graphite shield.

In the Rapsodie reactor, an instrument called the reactimeter is used to monitor startup and approach to power. It consists of a power measurement channel, a calibrated circuit, and an electronic divider. Reactivity is measured continuously and instantaneously. Response time is 0.1 second. (Ref. 16.)

I. J. FUEL HANDLING

Rapsodie refueling is accomplished by means of two rotating plugs; the smaller plug is off-set, and has a handling channel vertically through it. This channel can be aligned with any assembly by rotating the plugs. Originally, a single fuel handling machine was used, but early in the program, this machine was replaced by a system of two lighter machines. Assemblies removed from

the core are not stored in the reactor vessel, but transferred by primary cask car to an examination cell. A secondary cask car moves the assembly out of the reactor building into a decay pool area. New fuel is stored in a shielded area, canned, and brought to the reactor by reversing the above procedure. (Ref. 14.)

I.J-2

Figure I.J-1. Rapsodie Circulation of Assemblies (Ref. 5)

Figure I.J-2. Rapsodie Fuel Handling Channel (Ref. 5)

Figure I.J-3. Rapsodie Primary Cask Car (Ref. 2)

Figure I.J-4. Rapsodie Primary Cask Car Gripper (Ref. 2)

Figure I.J-5. Rapsodie Examination Cell (Ref. 2)

Figure I.J-6. Rapsodie Secondary Cask Car (Ref. 2)

I.J-8

Figure I.J-7. Rapsodie Active Building Decay Pool (Ref. 2)

Figure I.J-8. Rapsodie New Fuel Storage Building (Ref. 5)

I. K. CONTAINMENT

An air-tight vessel, 50 meters in height, houses the reactor, part of the cooling loops, the sodium purification equipment, air-conditioning system, and transfer equipment for fuel handling. The vertical cylindrical building is steel, with a hemispherical head. The reactor is located below ground-level in a closed concrete cavity. There is a working gallery at the upper part of this cave. Two ports connect with the active building or the conventional building. There is access for large equipment. A bridge crane at a height of 14 meters serves the 23 meter diameter area.

The building is separated into two essentially independent zones by a concrete floor 1.6 meters thick at about - 2.8 ground level. Air pressure in the upper part is kept constant, at a temperature of 10 to 30°C. In the lower zone, the atmosphere is nitrogen-enriched air at constant pressure and a temperature not above 60°C. (Fig. I.K-1.)

The conventional building contains the control rooms and various personnel offices. (Ref. 2.) (Fig. I.K-2.)

Figure I.K-1. Plan View of Rapsodie Reactor Building (Ref. 2)

Figure I.K-2. Rapsodie Reactor Building (Ref. 2)

Figure I.K-3. Rapsodie Conventional Building (Ref. 2)

II. PHENIX

LOCATION: Marcoule, France
(Rhône River)

OPERATION: 1974
First Nominal Power
March 12, 1974

Studies for the 250 MWe prototype fast reactor Phenix were initiated in 1967 by the French Commissariat à l'Energie Atomique. Construction was begun in 1968 at Marcoule, on the Rhône River. Final design and construction was placed in the hands of a team staffed with members of Technicatome, an organization formed by CEA and Electricité de France, and the Groupement Atomique Alsacienne Atlantique, a private concern. The team is directed by a CEA official. Phenix achieved criticality in August 1973 and was coupled to the grid on December 13, 1973. Full power was reached in March 1974. Technicatome has developed a stretch version of Phenix rated at 450 MWe.

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Table - 1

GENERAL PARAMETERS

Type	Pot Type
No. loops	3
Coolant	Sodium
Core inlet temp.	400°C
Core outlet temp.	560°C
Flow direction	Up. Velocity 7.4.m/sec. Max
Driver fuel	UO ₂ -PuO ₂ +UO ₂ (2 zones)
Blanket fuel	UO ₂
Core height	850 mm
Core diameter	1394 mm
Core volume	1227 ℓ
No. enrichment zones in core	2
Output MWe/MWt	250/563
Breeding ratio	1.12
Neutron lifetime	3.3×10^{-7}
Max. can temperature	700°C
Fuel central temperature	2300°C
Linear power, max.	422 W/Cm
Neutron flux, total	7.2×10^{15}
Power Density	406 kw/ ℓ
No. Driver elements	103 (2 zones)
No. Radial blanket elements	90
No. In-core control elements	6 (vented rods)
Goal burnup	50,000MWD/T

PHENIX II

Table - 2

CORE AND BLANKET

	Driver zone	Axial blanket	Radial blanket
Fuel Material	UO ₂ -PuO ₂ + UO ₂	UO ₂ depleted	UO ₂ depleted
Form	Sintered pellets	pellets	pellets
Composition	19 and 25% PuO ₂		
Stoichiometry	1.94-2.00	lower 2.00 - 2.02	2.00-2.02
²⁴⁰ Pu	14%		
Density	80% TD		
Pellet od	5.5 mm	Top, 12.6 mm Bottom, integral with core	12.6 mm
Rod cladding	Stainless steel	Stainless steel	Stainless steel
od	6.55-6.6 mm	Top 13.10 mm Bottom integral core	13.4 mm
Wall	0.45 mm	Top 0.5 mm	0.9 mm
Fuel-clad gap	.15-.20 mm calculated		
Bond	He		
Column length	850 mm	Top 260 mm Bottom 300 mm	1668 mm
Gas plenum	Lower and upper chambers upper containing the spring		
Pin length	1793 mm		
Vented/non-vented	No		No
Assembly material	Stainless steel	Stainless steel	Stainless steel
Shape	Hexagonal	Hexagonal	Hexagonal
Across flats	126.7 mm		126.7 mm
Wall thickness	3.5 mm		3.5 mm
Overall length	4300 mm		4300 mm
Weight	~ 200 kg		~ 270 kg
No. pins per assembly	217	Top 37	61
Pin spacing	1.15 mm dia. wire		1.08 mm dia. wire
Pin pitch	7.7-7.75 mm calculated		
Assy. in core	103		90
Fuel	36.8%		
Sodium	35.0%		

II. A. CORE AND BLANKET

The Phenix fuel assembly is 4300 mm high and weighs 200 kg. The hexagonal can is extended at the bottom by an 800-mm long section that slides into the sleeve in the support grid. It is supported at the top by an upper neutron shielding section 1300-mm high to which the 37 upper axial blanket pins are attached. The lower axial blanket is integral with the fuel pins and is located just below the fuel column. The lower fission gas chamber is below the lower breeder section. An upper chamber above the fuel column also contains a spring that holds the fuel pellets in place. Pin spacing is by a 1.15-mm diameter wire wound helically around the cladding with a pitch of 150 mm.

Both UO_2 - PuO_2 and UO_2 fuel are in the core, about half-and-half, although the arrangement is not known. There are two enrichment zones. Enrichment of the inner zone, with 55 assemblies, is $\text{Pu}[\text{PuO}_2 (\text{PuO}_2 + \text{UO}_2)]$ 18%; the outer zone, with 48 assemblies, has 25% enrichment. Outer rings are composed of 89 radial blanket assemblies, 216 reflector elements, 41 storage positions, 175 small graphite logs, 240 large graphite bars and 240 large steel bars. The central fuel assembly has experimental access, as do two of the outer fuel assemblies. Six control assemblies are located in the inner fuel area. (Refs. 7, 27.)

The fuel assembly (Figure II.A-1) is a hexagonal can containing fuel and axial blanket pins. The lower ends of the fuel pins are machined to run in profiled rails of varying lengths to form pin bundles. Each rail is machined to fit in two beams carried

on a support beam. When the fuel bundle is assembled, it is introduced into the outer hexagonal can by displacement of the support, which then slides home into a bore at the assembly bottom. The bottom of each fuel assembly holds it upright, ensures sodium inlet flow, provides hydraulic hold-down and orients the subassembly by means of cams that bear on ramps in the heads of adjacent subassemblies. The upper portion of the assembly is a neutron shielding block supporting the upper axial blanket pins. The lower axial blanket is integral with the fuel pins; the large fission gas plenum is located in a cold area below the lower axial blanket. (Ref. 7.)

Sodium inflow to the assemblies is radial, the sodium flowing first through passages machined in the grid sleeves and then through orifices drilled in the assembly foot. Six orifices are drilled at different levels; each sleeve includes six slots corresponding to the number of passages, varying with the position of the assembly. Depending on the desired flow rate, the assembly bottom is fitted with one or more central hole diaphragms or annular diaphragms. (Figure II.A-2)

The radial blanket assembly has the same outer geometry as the fuel assembly. Its weight is about 270 kg. The lateral neutron shield assemblies also have the same geometry. They contain stacks of stainless-steel-clad iron and graphite cylinders. The cylindrical "log" of an outer shield assembly is made up of cylinders of iron and graphite stacked in a 304L stainless-steel tube. (Ref. 7.)

PHENIX II.A.

Figure II.A-1. Phenix Fuel Assembly (Ref. 27)

Figure II.A-2. Schematic of Phenix Assembly Foot (Ref. 21)

Figure II.A-3. Phenix Blanket Assembly (Ref. 14)

II. B. CORE SUPPORT AND VESSEL INTERNALS

The fuel assemblies are supported by a grid plenum assembly, which also distributes sodium to the core elements, acting as an almost constant-pressure feed tank. This assembly consists of a cylindrical vessel 3500 mm in diameter and 965 mm high, the bottom and top being related by means of a series of upright tubes located according to the lattice step of the core. The free annular volume between the sleeve and this dense tube structure acts as a calming area for the sodium. Each tube receives the foot of an assembly, with forced cooling. Distribution is to 103 fuel assemblies, 90 radial blanket assemblies, 216 or 222 steel assemblies, 41 or 17 assemblies in storage and six control elements. The lattice tubes

are attached to the bottom and top plates of the support structure by a screw piece, which serves as the tight support of the assembly at the top and the guide for the assembly foot at the bottom. The lateral surfaces of the tubes each have six drilled orifices, the lengths depending on the area of location. (Fig. II.B-1.)

A supplementary support similar to the grid assembly receives the logs of the lateral shielding. The device consists of six elements located around the grid-plenum. These elements are steel plates pierced at the lattice locations for each of the log types. (Ref. 15.)

Figure II.B-1. Phenix Flow Adjustment System (Ref. 7)

II. C. REACTOR VESSELS AND SHIELDING

The integrated concept locates the primary loops in the immediate vicinity of the reactor vessel within the main vessel. The reactor vessel opens freely into the main tank. The grid-plenum device rests on a supporting framework at the bottom. The vessel is hung from the cover slab, which is a 60-cm thick circular plate filled with concrete and welded to the safety vessel. The diameter of the reactor vessel is 6.7 m.

The main vessel is 11.5 m in diameter and 12 m high. It contains all of the primary sodium. It is reinforced by a ring to which suspension beams are welded. Support is from a concrete slab forming the upper part of the reactor block. The vessel is closed at the top by a flat plate (roof) with openings for the passage of pumps and heat exchangers, and connected to the sleeve of the rotating plug. Final closure is the rotating top plug.

The leak vessel is a double-wall structure surrounding the main vessel. The gap between vessels is 100 mm.

The carbon-steel safety vessel is 12 m high and 14 m in diameter with a 25-mm thick wall. It surrounds the other vessels and is located 80 cm from the leak vessel. It is welded to the slab and kept in a nitrogen atmosphere. The cooling circuit for the surrounding concrete can also evacuate residual power in case of sodium loop failure. (Fig. II.C-1.) (Ref. 14; see also Section II.G.)

The final top closure for the reactor vessel is the rotating plug, a thick circular plate secured to a sleeve and filled internally with a stack of metal plates, with gas layers, insulation, and supplementary radiation shielding. Joints are liquid-tight. (Ref. 14.)

PHENIX II.C.

Figure II.C-1. Phenix Reactor Block (Ref. 14)

Figure II.C-2. Phenix Reactor Block Showing Top Structures (Ref. 14)

II. D. CONTROL ELEMENTS

Control is by six identical assemblies located at the vertices of a hexagon at the approximate midpoint of the fuel zone radius. Each assembly may be used as a shim, safety, or fine control rod. Each assembly consists of a guide thimble (a cylinder 4100 mm long and 113.7 mm in diameter) and a control rod, which are loaded separately. The bottom of the guide thimble is similar to that of the

fuel assembly. The thimble body has stellite bearings for guiding the movements of the control rod. The rod is a cylindrical stainless-steel tube 95 mm in diameter containing seven absorbing pins. Each pin contains enriched B_4C and is 28 mm in diameter and 1150 mm long. The B_4C pellet column is 900 mm high. The pins are vented. (Figs. II.D-1 and II.D-2.) (Ref. 7.)

Figure II.D-1. Phenix Control Subassembly (Ref. 7)

Figure II.D-2. Venting of Phenix Control Assemblies (Ref. 17)

II. E. HEAT TRANSFER SYSTEMS

Phenix is pool-type reactor with core, blankets and shields, three pumps and six intermediate heat exchangers located within the main vessel, which contains about 800 tons of sodium. The blanket is argon. The intermediate heat exchangers are located in a ring around the reactor vessel. Cold sodium enters through the collectors of the assemblies at the lower part of the vessel through short pipes, which are the only pipes in the primary circuit. Flow is upward through the assemblies into the reactor vessel and into the heat exchangers. From the heat exchangers, sodium passes to the main vessel pump inlets, which direct the cold sodium back to the collectors.

Each of the three independent secondary loops includes the two intermediate heat exchangers, a steam generator located between two reservoirs, a mechanical pump located in the expansion reservoir and the piping connecting this equipment. The expansion and buffer reservoirs have isolating valves and rupture disks. The steam generator has motorized isolation valves to limit the amount of sodium available to react with water during a leak and to prevent general contamination of the circuit by reaction products. The pump is at the cold point. Hot sodium leaves the intermediate heat exchanger through two 355-mm-diameter pipes, which are joined into a single 508-mm-diameter collector a short distance from the equipment in the reactor building. The sodium is directed toward the buffer reservoir; inlet is lateral and outlet is axial. The collector at the buffer reservoir outlet feeds, in parallel, the superheater and re-superheater through 457-mm-diameter pipes. On leaving this equipment, the sodium is mixed and directed through the economizer--evaporator by a 508-mm-diameter collector. Cold sodium leaves the steam generator by a 508-mm-diameter pipe and passes through the expansion reservoir. The pump takes it and returns it to the intermediate heat exchangers. (Fig. II.E-1.)

Two intermediate heat exchangers operate in parallel in each secondary loop. The unit is a thick tubular plate exchanger with straight pipes arranged in 19 concentric rings around a central pipe for secondary sodium inlet. This tube is a concentric pipe with an isolating layer of nitrogen in the annular space. Secondary flow is downward through the central pipe and upward through the IHX tubes. Primary sodium enters the unit by passing under a bell that acts as a flow guide, flows downward around the tubes and back to the main vessel where it is sucked up by the pumps. (Fig. II.E-2)

The exchanged power from six heat exchangers is 563 MW. Primary and secondary flows are 2760 and 2211 kg/sec, respectively. The heat exchanger area is $6 \times 465 \text{ m}^2$. (Ref. 15.)

The primary pump, which is similar to the Rapsodie unit, is a vertical centrifugal pump with side suction and axial discharge. It is 10 m high and weighs 20 tons. It is equipped with an inertia wheel that allows it to reach 1/10 speed in 60 sec. Flow at the core inlet plenum intake is 1000 kg/sec with a head of 76 m of sodium at 400°C. Pump speed is 900 rpm. (Fig. II.E-3.)

The secondary pump is also a vertical centrifugal unit with axial discharge into a reservoir that has a free sodium surface under an argon atmosphere. There is no non-return valve or inertia wheel. Nominal operating flow is $0.86 \text{ m}^3/\text{sec}$ under a manometric depth of 65 m of sodium at 350°C. Pump speed is 925 rpm. Estimated efficiency is 0.80. (Figs. II.E-4 and II.E-5.) (Refs. 5, 15.)

II.E-2

Figure II.E-1. Phenix Secondary Loop Schematic (Ref. 15)

Figure II.E-2. Phenix Intermediate Heat Exchanger (Ref. 22)

II.E-4

Figure II.E-4. Phenix Secondary Pump (Ref. 15)

PHENIX II.E.

Figure II.E-5. Phenix Expansion Reservoir and Secondary Pump (Ref. 22)

II. F. SODIUM PURIFICATION AND INSTRUMENTATION

The cold trap and the plugging meter are the primary purification components. Purification system and monitoring are part of the primary circuit.

The primary cold trap (Fig. II.F-1) is a vertical vessel surrounded by a static NaK-filled double shell cooled by an organic liquid. Sodium is cooled first in an economizer external to the trap, then in an internal economizer as it enters the trap, and finally while passing near the double shell before penetrating the mesh. Total flow is 250 ℓ /hr minimum and 750 ℓ /hr maximum. Nominal operating temperature is 185°C.

Each of the secondary loops includes a cold-trap and a plugging meter. The secondary cold trap (Fig. II.F-2) is similar to the primary trap in geometry and flow characteristics but does not have an economizer. The organic coolant flows in a coil that cools the sodium directly without the intermediate NaK double-wall device. Nominal operating temperature in the secondary trap is 160°C.

There are two plugging meters for on-line sodium purity survey (Fig. II.F-3). One is operated continuously and the other discontinuously in an automatic and cyclic mode. Nominal characteristics are as follows:

- Total minimum sodium flow -- 250 ℓ /hr
- Maximum sodium flow -- 750 ℓ /hr
- Flow in meter through channels -- 200 ℓ /hr
- Differential pressure -- 150-160 mb
- Inlet temperature -- 180-450°C depending on operating condition

Sampling devices like those used in Rapsodie were selected: the Tastena type, which dips into the sodium pool for the sample, and a bypass flow-through sampling tube. In the latter, the sampling device is located in a cell on a bypass of the purification loop. Sampling is by means of two pairs of removable parallel tubes upstream and downstream of the primary cold trap. (Fig. II.F-4.)

Flow and sodium levels are monitored by electromagnetic flowmeters and intermittent or continuous level gages. The level probes are based on the variation of the mutual inductance of two intercepted windings. Flowmeters on the primary and secondary loops are installed on large-diameter tubes.

A boiling detector to be tested in Phenix utilizes a monitoring principle based on the level of ultrasonic noise at the assembly outlets and the occurrence of boiling due to partial plugging. There are 12 boiling detectors for the reactor. Each measurement channel has a waveguide, a piezoelectric crystal, an amplifier, a high-pass filter and a zero-time correlator.

Failed fuel detection is by delayed neutron monitoring of a sodium sample. All mechanisms are packed in the failed element location plug in the reactor rotating plug (Fig. II.F-5). Argon sampling is also used. Samples are taken from the reactor upper plenum and monitored for fission product Kr and Xe by means of an ionization chamber. Electrostatic precipitation counts the solid fission products Rb and Cs. Tagging the fuel assemblies with gaseous Kr and Xe stable isotopes is planned to start with the second core loading. (Ref. 5.)

II.F-2

NOMINAL CONDITIONS

QNa: $30\text{m}^3/\text{h}$ CAPACITY: $5,10\text{m}^3/\text{h}$

BNa: (INLET) 185°C WEIGHT: $7,4\text{t}$

BNa: (OUTLET) 165°C MATERIAL: Z6CN18.10

Figure II.F-1. Phenix Primary Cold Trap (Ref. 9)

NOMINAL CONDITIONS

QNa = $30\text{m}^3/\text{h}$ CAPACITY: 5m^3

BNa (INLET) = 160°C WEIGHT = $7,32\text{t}$

BNa (OUTLET) = 130°C MATERIAL: Z6CN1810

Figure II.F-2. Phenix Secondary Cold Trap (Ref. 9)

II.F-3

Figure II.F-3. Phenix Plugging Meter (Ref. 9)

Figure II.F-4. Phenix Sampling Cell (Ref. 9)

PHENIX II.F.

PHENIX II.F.

Figure II.F-5. Phenix Failed Fuel Location (Ref. 5)

II. G. COVER GAS AND AUXILIARY SYSTEMS

The argon circuit contains discharge reservoirs having a total volume of 600 m³ and is equipped for radioactive purification. No description of the circuit has been found.

See Section II.E for a description of sodium purification.

Emergency cooling is furnished by heat exchange (radiation and conduction) between the main vessel and the double-wall vessel and by radiation and natural convection in the double-wall insulation. The safety container and its cooling circuit constitutes

a thermal shield; the water circuit protects the bottom and sleeve of the safety vessel, the slab, and the passages. Cooling is by a double network of welded tubes in the container wall. Tubes are parallel and spaced 150 mm apart. The flow direction is reversed and the lattice step changed in two neighboring tubes. In emergency conditions, 2100 kW can be evacuated. If one of the piping networks is lost, the flow still available is 70 m³/hr. The circuit can be supplied directly with raw water from the Rhone River. (Figures II.G-1, II.G-2 and II.G-3.) (Ref. 25.)

Figure II.G-1. Phenix Double-Wall Vessel Insulation (Ref. 25)

Figure II.G-2. Ultimate Safety Circuit, Phenix Primary Container (Ref. 25)

II. H. STEAM GENERATORS

The steam generator is a once-through, single-casing pipe bundle. There is no tube sheet. Each water tube bends, penetrates the shell and terminates in an outside water or steam subheader. Modules and the water and sodium headers are installed inside an insulated, self-supporting, rectangular containment box. A butterfly control valve proportions the sodium flow between superheater and reheater. A small nipple at each tube end allows for tube plugging in the event of a leak. Modules can be removed for repair or replacement. Sodium shutoff valves are located at the exit and entrance to the steam generator unit in each loop. Valves and piping can provide rapid dumping of both water/steam and sodium. (Fig. II.H-1.) (Ref. 12.)

Each generator consists of 12 economizer--evaporator modules, 12 superheater modules and 12 reheater modules. (See Table II.H-1 for module specifications.) Each module is a seven-pipe bundle in an S-shaped

casing for the superheater and reheater (double-S for the economizer--evaporator). Each generator has the following ancillary equipment: steam separator, decompression and nitrogen system, hydrogen detection system, exhaust air system, safety valves and fittings. (Fig. II.H-1.)

The sodium--water reaction discharge system (Fig. II.H-2) consists of rupture disks and their discharge pipes, a 0.8 m discharge heater channeling reaction products to the hydrogen separator, a hydrogen separator (a vertical cylindrical tank of about 100 m³ capacity fed tangentially from the discharge header and containing an inner cyclone) and a 0.6-m ID chimney topping the separator dome and exhausting the hydrogen above the building roof. Normally, the nitrogen inside of the discharge system is maintained at a slightly positive pressure to prevent external air from leaking into the system. (Ref. 12.)

Table II.H-1. Steam generator specifications (Ref. 5)

	Economizer evaporator	Superheater	Reheater
Steam water pipes (mm)	dia. 28 x 4	dia. 31.8 x 3.6	dia. 42.4 x 2
Ring (mm)	dia. 193.7 x 6.3	dia. 193.7 x 5.4	dia. 193.7 x 5.0
Exchange length per module (m)	60.8	26.9	21.9
Exchange area per module (m ²)	26.7	14.5	18.5
Exchange area of the 12 modules (m ²)	320	174	222

PHENIX II.H.

Figure II.H-1. Phenix Steam Generator (Ref. 12)

Figure II.H-2. Phenix Sodium/Water Reaction Discharge System (Ref. 12)

II. I. REACTOR INSTRUMENTATION AND CONTROL.

Reactor monitoring includes measurement of neutron flux over an 11 decade dynamic range. There are two pre-startup channels with BF_3 detectors under the reactor vessel or high-temperature fission chambers in the vessel. Three start-up pulse channels are associated with under-vessel boron counters. Three power channels associated with under-vessel ionization chambers provide log and period measurements, a linear measurement and a reactivity measurement in the range 10^{-2} to 1.3 nominal power. Control measurement channels are associated with under-vessel ionization chambers.

A boiling detector to be tested in Phenix utilizes a monitoring principle based on the level of ultrasonic noise at assembly outlets and the occurrence of boiling during partial plugging. There are 12 boiling detectors. Each measurement channel has a waveguide, a piezoelectric crystal, an amplifier, a high-pass filter, and a zero-time correlator.

Failed fuel detection will be by delayed neutron monitoring of a sodium sample drawn from the vessel at the IHX intake and argon sampling for detection of fission product Xe and Kr. Electrostatic precipitation will be used to count solid fission products Rb and Cs. (See Section II.F for a description of sodium instrumentation.)

Two computers operating separately are used for central data processing. They individually monitor the nuclear boiler circuitry and the electric generator plant circuitry. They do not share in the automatic system except for the failed fuel detection system. (Ref. 5.)

An ultrasonic under-sodium scanning device has been tested for use as an obstacle detector. An ultrasonic projector operated by an electronic transmission system transmits wave trains to a vertical waveguide. The wave guide is filled with a liquid having acoustical properties similar to those of sodium. There is a 90-deg elbow with a reflector towards the lower end for deflecting the ultrasonic beam horizontally through an acoustic window. Echos reflected by obstacles are captured by an identical waveguide system that terminates at a transducer at the top. The transducer is connected to a receiver. The scanning system is rotated and vertically controlled by a suitable mechanism. Display is by means of a CRT. The height and bearing of the object is reproduced and the coordinates and shape of the object can be determined. (Fig. II.I-1)

There is no general automatic startup or shutdown feature and no general regulating system to adjust the power level to the grid. The reactor does not have load-following capability. (Refs. 5, 10.)

Figure II.I-1. Phenix Under-Sodium Viewing (Ref. 10)

II. J. FUEL HANDLING

Facilities for handling fuel assemblies include (1) a new element line, (2) a fixed argon-leak-tight assembly for transferring the element from one housing to another within the reactor by means of the rotating plug and transfer arm and (3) a spent element line where elements are processed in a nitrogen-filled hot cell after storage outside the reactor. After handling, spent elements are transported to the reprocessing plant or to solid-wastes storage. (Fig. II.J-1). Loading and unloading is done six times yearly, about 15-17 fuel assemblies and 8-11 fertile assemblies being unloaded during a handling period. The fuel assemblies release a heat power of 6.5 MW or less; fertile assemblies release 1.2 MW at end of life. During transfer, the fuel assembly releases 40 kW maximum residual power. The assembly is kept immersed in sodium and its maximum can temperature is below 550°C. In the core storage housings, the heat power of each assembly is below 120 kW (fission and gamma radiation) when the reactor is operating. The fuel elements are placed in the rotor of the storage drum when being unloaded.

In the spent elements cell (Fig. II.J-2), the elements are extracted from the drum by means of a blower grapple. Nitrogen flow cooling is used. Fuel and fertile pins are placed in cans for transport to the reprocessing plant. The neutral atmosphere

transport cask carries eight cans containing pins from four assemblies and dissipates 10 kW of heat. Reactor elements are taken to the storage drum by the carriage via argon lock and ramps.

The L-shaped new element line (Fig. II.J-3) is inside the handling building. One leg includes the assembly storage rooms; the other includes the assembly inspection area and the zone of transfer to the storage drum. On arrival, new elements are located in a storage area consisting of 156 housings placed 300 mm apart and shielded by 30 cm of concrete.

Components handled include primary pumps, intermediate heat exchangers, control rod mechanisms, experimental fuel stringers, the in-reactor part of the transfer arm with its oral plug, secondary pumps, cold traps and drum auxiliaries. There are two special flasks for processing large components handled by the traveling crane in the reactor building. The special handling transfers them to the handling building by the traverser. A storage pit is partly in the reactor building and partly in the handling building. There are wash-down and decontamination pits; a pit for assembling, servicing, and repairing components; a dismantling cell for working on very active components; and a station for component testing. (Figs. II.J-4 and II.J-5.) (Refs. 5, 15.)

Figure II.J-1. Phenix Fuel Handling Line (Ref. 15)

Figure II.J-4. Circulation of New Equipment (Ref. 15)

Figure II.J-5. Circulation of Irradiated Equipment (Ref. 15)

II. K. CONTAINMENT

The reactor containment system is a combination of a highly leak-tight envelope and a secondary envelope with underpressure and filter trapping. High-efficiency filters serve the reactor hall and air is released through a 70-ft stack. The base of the stack and the reactor hall are monitored and an alarm is given in case of accident or failure in the ventilating system.

The controlled leakage reactor building is kept at an underpressure of a 5 mbar and can resist a 40-mbar overpressure. The underground part of the structure is of welded steel plates. (The bottom plate is 10 mm thick and the side plates are 5 mm thick.) Cement and resin injections were used to ensure sealing of all seams. The superstructure outer walls are prefabricated panels secured to concrete posts cast in place (the structure is prestressed). The floor of the lower stage is at the -10.50 level, which is the level of the base of the reactor cave.

The handling building, annexed to the reactor building, has two main sections. One section is reserved for handling core elements, with storage drum, dismantling cell, and hall for preparation, storage, and testing of new assemblies. The second section; the special handling hall, is reserved for reactor equipment, with cells for dismantling and examination, storage pits, wash-down areas, testing areas, etc. This building has a special ventilation supply with absolute filters. Air is rejected to the stack. The building is at a slight underpressure.

The steam generator building is alongside the main building. No special tightness or ventilation is required. The only portion underground is that which contains steam generators supplied with sodium reservoirs, sodium/hydrogen separators, auxiliary sodium loops, etc.

The machine hall and control buildings are standard. (Refs. 5, 15, 25.)

III. SUPER-PHENIX

LOCATION: Crey's-Malville
France
(Rhône River)

CONSTRUCTION TARGET: 1975

OPERATION TARGET: 1979-1980

Super-Phenix, a 1,000 MWe commercial fast reactor, will be built at Crey's-Malville on the Rhône River. Official designation for the station is Creys-1. The French government has authorized the formation of the Société Centrale Nucleaires Européenne Neutrons Rapides SA (NERSA) for construction and operation. Members are Electricité de France (51%), Italian ENEL (33%), and West Germany's RWE (16%). The French CEA is preparing the preliminary safety analysis report. Construction target is 1975 and projected date of operation 1979 or 1980. A German version to be built by NERSA will be under way about 1981.

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III. A. CORE AND BLANKET

Driver fuel is $\text{UO}_2\text{-PuO}_2$ in stainless steel cladding; blanket material is depleted UO_2 . There are two enrichment zones in the core.

The core assemblies resemble those of Phenix, with the exception that the upper and lower axial blanket pellets are inserted in the fuel pin. Neutron shielding is incorporated at the top. (Fig. III, A-1)

Both the fuel pins and the fuel assembly are larger. There is no core clamping, but the hexagonal cans are fitted with pads that are in contact when the reactor reaches a pre-determined temperature. Lateral neutron shielding has been designed to impart good rigidity.

Parameters

Core height ~1 meter
 No. driver assemblies (2 regions) 196 + 162
 Pins/assembly 271
 Hex. can, distance between flats
 (internal) 163.8 mm
 Fuel pellet od 7 mm
 Fuel clad (stainless steel) od 8.65 mm
 Gas plenum (bottom) 850 mm
 Pin length 2,700 mm
 Spacer: helical wire wrap
 Subassembly overall height 5,400 mm
 Max. cladding temperature 620°C
 Max. Linear power 450 w/cm
 BU 70,000 MWD/T

(Ref. 1,8)

III.A-2

Figure III.A-1. Super-Phenix Fuel Subassembly (Ref. 1)

III. B. CORE SUPPORT AND VESSEL INTERNALS

Subassemblies are held by two support plates.

Room is provided under the core support grid for a core-catcher assembly, built of metal plates. This assembly is still under study. (Fig. III B-1) Alternately, the main vessel bottom would serve as core catcher. (Ref. 1,5)

Figure III.B-1. Super-Phenix Possible Design for Core Catcher (Ref. 5)

III. C. REACTOR VESSELS AND SHIELDING

The reactor vessel is closed by a bottom-insulated slab, with the insulation set in the argon cover gas. The vessel is cooled by a sodium flow. The main vessel is surrounded by a safety vessel, which serves as a leak-proof vessel and is part of the primary containment. The primary containment is completed by a metallic dome

surmounting the reactor. It is slightly larger than the safety vessel. (Fig. III C-1)

Two circulating water loops around the safety vessel serve as an emergency circuit for decay heat removal. (Fig. III C-2) Circulation of water to these loops is handled independently. (Ref. 1,5)

III.C-2

Figure III.C-1. Super-Phenix Reactor (Ref. 1)

Figure III.C-2. Super-Phenix Emergency Cooling System (Ref. 5)

SUPER-PHENIX III.D.

III. D. CONTROL ELEMENTS

The core includes control rods of two types. The primary shutdown system, has twenty-four rods of the Phenix type set over two subassembly rows. The standby shutdown system, under development, will probably consist of three rods actuating only reactor shutdown. (Ref. 1)

III. E. HEAT TRANSFER SYSTEMS

Super-Phenix is a pool-type system. There are four sodium pumps and eight intermediate heat exchangers, closely resembling Phenix equipment. Pump check valves have been replaced by built-in valves allowing for pump operation even if one has stopped. The intermediate heat exchanger also has built-in valves. Primary pumps are driven by frequency shift generators, with a fly-wheel ensuring 1/2 the flow rate after 50 seconds of electrical power failure. Pumps are located at the cold point. (Fig. III E-1)

Auxiliary sodium-argon loops are not unusual except for primary sodium purification. Two cold traps are located in the main vessel, with special nitrogen cooling and plugging indicators.

Core equipment includes thermocouples located above each core assembly, equipment for fuel clad failure detection, sub-assembly sodium sampling, sonic detection, and a neutron flux measuring unit below the main vessel.

A monotubular helical-tube steam generator has been under investigation by Babcock-Atlantique. The module is formed by a vertical cylindrical shell of austenitic stainless steel, 2.9 m dia and 22 m high. It contains a group of 357 helical tubes 25 x 2.6 mm, made of Incoloy-800. Each tube penetrates individually into the shell by means of a thermal collar, and exits from one of the tube plates of the four steam chests arranged in the upper part of the shell. Full length of each tube is 87 m. Heat exchange surface is 1920 m². Sodium

enters at the top through two systems of pipes, flows downward, and exits through a single pipe at the bottom. Water enters from four outside water chests, circulates in cross counter flow into the tubes, and exits as superheated steam into the upper chests.

Stein Industrie has developed a modular straight tube steam generator, each module consisting of a vertical tube nest with 1389 tubes for the evaporation and 583 tubes for the superheater. The module is connected at its ends to two tube plates forming the bottom of the water and vapor collectors. The tube nest is housed in a slim, vertical cylindrical shell, with a diameter of 2.27-2.37 m and an overall height of 27.5 m. Economizer and superheater are in series. Sodium enters near the center of the module, rises into the ring shaped space between the shell and the jacket of the nest, passes into the tubular nest below the free level, flows down between tubes to the thermal screen protecting the lower tube plate, rises again to the ring-shaped space as far as the outlet at the mid-section of the shell. Water enters from the lower water chest of the economizer, rises into the tubes and exits as slightly superheated steam into the upper chest. Steam goes through a separator and into the lower chest of the superheater, passes through the tubes and out into the upper chest.

Both generators have been dimensioned for the Super-Phenix steam cycle. They are both single-wall and gravity-drained. (Ref. 7)

Figure III.E-1. Super-Phenix Primary, Secondary, Steam-Water Loops (Ref. 5)

Figure III.E-2. Super-Phenix Secondary Sodium Loop and Steam Generator (Ref. 1)

III. J. FUEL HANDLING

Handling is by means of two rotating plugs. The small plug bears the transfer machine for shifting assemblies in the reactor. Subassemblies are removed from the reactor in sodium pots, transported by a carriage over a ramp, and lowered into rotating storage by another ramp. No internal storage is provided. After outer storage cooling, the subassemblies are transported in sodium-filled pots to the reprocessing plant. (Fig. III J-1) (Ref. 1)

III.J-2

Figure III.J-1. Super-Phenix Subassembly Loading System (Ref. 1)

III. K. CONTAINMENT

The reactor building, as designed, is a cylindrical concrete structure, of the kind used for light water reactors. Four buildings housing four steam generators will be located around it. Between these buildings, others housing auxiliary water and ventilating circuits, organic circuits, etc. will be located. (Fig. III K-1, III K-2) (Ref. 10)

III.K-2

Figure III.K-1. Super-Phenix Reactor Building (Ref. 1)

III.K-3

Figure III.K-2. Super-Phenix General Layout (Ref. 1)

SUPER-PHENIX III.K.

IV. BR-5/BR-10

LOCATION: Obninsk, USSR

OPERATION: 1959
Reconstruction,
BR-10, 1972

In 1956, the USSR decided to construct the BR-5 reactor, both to gain experience in operating a multi-loop, liquid-metal-cooled reactor and to test fuel elements and equipment for future fast reactors. The reactor was assembled within the biological shielding of the dismantled BR-2, a small, liquid-mercury-cooled critical facility. The BR-5 PuO_2 core achieved criticality in January 1959; on July 21, it reached its design power of 5 MWt.

Due to signs of leaking fuel elements, the reactor was shut down from September 1961 to March 1962 for examination of the fuel and to clean up the primary loop components. The reactor continued to operate through 1963 with leaking elements in the core. In November 1964, BR-5 was shut down to load a new UC core and started up with the new core in May 1965. Rated power was achieved in June 1965. In 1972, the reactor was modified for 10-MWt operation and a new PuO_2 core was loaded. Criticality was reached in March 1973. The installation has since been known as BR-10.

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Table 1

GENERAL PARAMETERS

	BR-5		BR-10
	CORE-1	CORE-2	
Type	Loop	Loop	Loop
No. loops	2	2	2
Coolant	Na/Nak	Na/Nak	Na
Core inlet temp.	430°C	360°C	
Core outlet temp	500°C	500°C	
Flow direction	Upward		Upward
Driver fuel	PuO ₂	UC	PuO ₂
Blanket fuel	U	U	
Core Diameter	280 mm		
Output MWe/MWt	5 MWt	5 MWt	10 MWt
Breeding ratio	1.9		
Delayed neutron fraction	0.25	0.67	
Max. can temperature	600°C	670°C	
CL temperature	1300°C	2200°C	
Neutron flux, Max.	1×10^{15}	4.8×10^{14}	2×10^{15}
Doppler ($\Delta K/K$)/°C Total	Negative	Negative	
Power Density (Max)	500 kw(t)/ℓ	285 kw/ℓ	
No. Driver elements	80	80	
No. Radial blanket elements	40	40	
No. In-core control elements	*		
Test positions			
Burnup achieved	7%		

*Reactor is controlled by movement of an inner and outer cylindrical reflector. Two control rods in the outer cylinder provide skin adjustment.

Table 2

CORE AND BLANKET

	BR-5, 1st CORE		BR-5, 2nd CORE		BR-10	
	CORE	BLANKET	CORE	BLANKET	CORE	BLANKET
Fuel Material	PuO ₂	U-MO	UC	U	PuO ₂	U
Form	Pellet	Slugs		Slugs		
Composition	U-9 Mo					
Stoichiometry	~1		>1			
Enrichment	90% 235U					
Density	93% TD		12 gm/cm ³			
Fuel od.	4 mm	9.04 mm	7.65 mm	7.7 mm		
Stack height	280 mm	280 mm	380 mm	280 mm		
Rod Cladding	SS	SS	SS	SS		SS
od	5 mm		8.55 mm			
Wall thickness	0.4 mm		0.4 mm			
Fuel-clad gap	0.1-0.4 mm					
Bond Material	He	NaK	He	NaK		
Gas plenum	2-3 mm		50 mm			
Pin length overall	500 mm					
Vented	No	No	No	No		
Assembly material	SS		SS			
Shape	Hexagonal	Hexagonal	Hexagonal	Hexagonal		
Across flats (dia.)	26 mm		26.1 mm			
Wall Thickness	0.5 mm		0.3 mm			
Overall length	830 mm		833 mm			
Weight						
No. pins assembly	19	7	7	7		
Pin spacing	Spiral wire	Spiral wire	Spiral wire			
Pin pitch	9.05 mm					
Assy. pitch	27 mm					
Assy. in core	80		100			
Reflector-Material	Nickel					

IV. A. CORE AND BLANKET

The first BR-5 core contained eighty hexagonal fuel assemblies, each with a 19-pin bundle of stainless-steel clad PuO_2 pins. Pellets were loaded into the cladding and the pin sealed after charging with helium. Pins were rigidly fixed to the top and bottom of the assembly. Alternate pins were wound spirally with stainless-steel wire. The lower part of the assembly ended in a cylindrical split bushing with a central hole for feeding coolant into the assembly. This bushing was also used to fix the assembly in the bottom support plate. Grooves along the sides of this tail-piece allow coolant to be removed from the core. (Fig. IV.A-1.)

The inner radial blanket contained forty assemblies, each with seven pins 9 mm in diameter and 280 mm high. Each pin contained two U-9Mo alloy pellets.

The carbide core had the same general dimensions, each assembly having seven larger diameter pins. A gas plenum was provided above the fuel core.

The core for 10-MWt operation, loaded in 1972, is PuO_2 . (Ref. 6)

1. UPPER END PIECE
2. UPPER SPACING LATTICE
3. HEXAHEDRAL CASING
4. FUEL ELEMENT
5. LOWER END PIECE
6. LOWER SPACING LATTICE

Figure IV.A-1. BR-5 Fuel Assembly (Ref. 6)

IV. B. CORE SUPPORT AND VESSEL INTERNALS

The assemblies are supported at the bottom by a perforated plate. The fuel assembly has a bottom conical nozzle that centers it in a certain support grid hole. Hydraulic hold-down is provided by a groove prepared in the lower plate, a band with beveled sides and four lengthwise grooves in the collar of the fuel assembly. (Fig. IV.B-1.)

The bottom support structure is made of nickel and comprises a 370-mm thick lattice that serves as a lower end shield, a ring with bayonet catch and twelve expellers.

No lateral restraint is provided and there is no top grid plate. (Ref. 1,6)

1. OUTLET OF THE MAIN STREAM OF THE COOLANT
2. PACKET
3. COLLECTOR PLATE
4. INPUT OF THE MAIN STREAM OF THE COOLANT

Figure IV.B-1. BR-5 Hold-Down Arrangement (Ref. 6)

IV. C. REACTOR VESSELS AND SHIELDING

The central part of the structure is a stepped pipe 330 mm in diameter that contains the fuel and uranium elements. The central pipe has a double wall. The annular gap between the inner and outer walls is used both to warm the reactor prior to sodium filling and to maintain the shut-down reactor in a warm state by a pumped circulation of hot air through the gap.

The side reflector is a nickel cylinder 975 mm in diameter and 900 mm high installed in a special metal tank within the water shield tank. The part of the reflector adjacent to the central tube consists of two coaxial movable cylinders that act as reactivity compensators and safety elements. The moving and fixed parts of the reflector are cooled by air from an upper distribution chamber.

Side shielding is provided by a 500 mm thick layer of water enclosed in 400 mm thick cast iron and surrounded by an 1100 mm

thick layer of heavy concrete. The water shield is in the form of an annular tank with the inner cavity containing the central part of the reactor and the reflector. Top shielding consists of three plates, the cast-iron lower and middle plates and the concrete upper plate. A removable plate of paraffin and boron carbide is located over the central pipe of the shield. Lower shielding is provided by a layer of water, 400 mm of cast iron and removable paraffin-boron carbide plates. There is a gastight hood over the central pipe.

A horizontal graphite column penetrates one side of the shield to permit horizontal and vertical experimental location.

When the hood of the central pipe is removed, fuel reloading proceeds by means of special mechanisms placed on a small rotating plate. (Fig. IV.C-1.) (Refs. 1, 6)

1. GASPROOF HOOD OF THE CENTRAL PIPE
2. UPPER SHIELD
3. CONCRETE PLATE
4. ROTATABLE PLATE
5. CENTRAL PIPE (VESSEL)
6. CORE
7. MOBILE SCREEN
8. FIXED SCREEN
9. VERTICAL EXPERIMENTAL CHANNEL
10. GRAPHITE (THERMAL) COLUMN
11. GATE VALVE OF THE THERMAL COLUMN
12. WATER TANK
13. CENTRAL EXPERIMENTAL LOOP
14. LOWER SHIELD
15. LOADING-UNLOADING MECHANISM
16. CONTROL OF THE CENTRAL LOOP MECHANISM
17. NEUTRON BEAM CHANNEL
18. GATE VALVE OF THE NEUTRON BEAM CHANNEL
19. SIDE SHIELD (HEAVY CONCRETE)
20. CAST IRON SIDE SHIELD
21. DRIVE OF THE MOBILE SCREEN
22. RAILING

Figure IV.C-1. BR-5 Reactor Structure (Ref. 6)

IV. D. CONTROL ELEMENTS

BR-5 is controlled by moving the inner layers of the nickel reflector. The compensating layer, located just behind the casing of the central tube, is a cylinder 50 mm thick and 340 mm high. The second moving layer of the reflector, the shield compensator, is placed behind the first layer. It is 105 mm thick, 475 mm high, and has an outside diameter of 710 mm. Two automatic regulating rods are located on its inner surface in opposite grooves. Each rod

is 30 x 40 mm in cross-section and 400 mm long. The control units are cooled by air from an upper distribution chamber.

The total reactivity introduced by the control elements is as follows:

- Compensating cylinder: 63×10^{-3}
- Shield compensator: 28×10^{-3}
- Automatic rods: 0.9×10^{-3}

(Ref. 6,7)

IV. E. HEAT TRANSFER SYSTEMS

The primary heat transfer fluid is sodium (NaK was originally used for the intermediate loops). Sodium enters at the bottom of the central tube and flows upward, leaving the tube through two 110-mm diameter tubes into two similar loops. Each loop has an Na-NaK intermediate heat exchanger and a pump that returns the sodium to the central tube. Non-return valves are located in each loop. All primary sodium pipes outside hermetically sealed locations are provided with protective sleeves filled with argon. The sealed caves in which primary loop equipment is located have nitrogen atmospheres. These areas are observed by means of television. The intermediate heat transfer fluid was changed to sodium when the modifications for 10-MWt operation were undertaken.

An air heat exchanger is installed in one of the intermediate NaK loops, heat being removed by air flow from a fan. An evaporator is installed in the other loop. The heat is being used to generate steam. Oxide traps are fitted to the liquid-metal loops for sodium and NaK cleaning. (Fig. IV. E-1.) (Ref. 7).

The Na-NaK intermediate heat-exchanger (Fig. IV.E-2) is a U-shaped tube bundle. Branches of the bundle are included in their own cylindrical shells and are arranged at a small angle with respect to one another. The bend of the bundle is enclosed in a drum connecting both halves of the heat exchanger into one unit. Flow is countercurrent, with primary sodium in the inter-tube space. Heat exchange surface is 1120 m². Sodium inlet and outlet temperatures are 500 and 300°C, respectively. NaK inlet and outlet temperatures are 273 and 453°C, respectively.

The NaK-to-air heat exchanger installed in one intermediate loop is a vertical shell with U-shaped bundles inserted in it (Fig. IV.E-3). During modification for 10 MWt operation, two additional sodium-air heat exchangers were added. (Refs. 3, 6)

The BR-5 primary pump is a centrifugal, hermetically-sealed, submerged-type pump with a vertical shaft. The hydraulic part and the electric motor are located on the same shaft. This design has been a drawback since it makes it impossible to install or remove a pump without cutting the sodium pipeline and draining the loop. Also, it is necessary to unseal the loop to replace the electric motor (Fig. IV.E-4). Up-dated pumps were installed in 1967.

A spiral electromagnetic pump operating on radioactive NaK was used in an experimental loop. Its jacket was water-cooled. (Ref. 6)

During modification for 10 MWt operation, the pumps were replaced by electromagnetic pumps.

Bellows-type valves and non-return valves are used in the BR-5 sodium and NaK loops (Fig. IV.E-5, IV.E-6). The valves are hermetically sealed, welded structures. The large bellows valves on the main pipelines of the primary loop have an electric drive with a duplicating distance control, and manual control on the circulation pipelines and drain lines of the second loop.

Figure IV.E-1. BR-5 Heat Removal Scheme (Ref. 6)

- 1 and 5 SODIUM INLET AND OUTLET
- 2 and 4 SODIUM-POTASSIUM ALLOY INLET AND OUTLET
- 3 — — DRUM
- 6 — — PIPE PANELS

Figure IV.E-2. BR-5 Intermediate Heat Exchanger (Ref. 6)

- (b) AIR HEAT EXCHANGER

1. WATER FROM THE COOLING SYSTEM OF THE UPPER BEARING	11. FLOUROPLAST SEAL
2. UPPER RÖLLER BEARING	12. WATER LINE FOR COOLING THE CAVITY OF THE LOWER BEARING
3. THERMAL INSULATION	13. LOWER ROLLER BEARING
4. DISCHARGE NOZZLE	14. WATER TO THE JACKET TO THE ELECTRIC MOTOR
5. PUMP HOUSING	15. 16 and 17 ROTOR, STATOR AND HOUSING OF THE ELECTRIC MOTOR RESPECTIVELY
6. PUMP TANK	18. COOLING JACKET OF THE ELECTRIC MOTOR
7. SUCTION NOZZLE	
8. SPIRAL	
9. IMPELLER	
10. PUMP SHAFT	

Figure IV.E-4. BR-5 Primary Pump (Ref. 6)

IV.E-5

- 1. PACKING
- 2. SIGNALING DEVICE FOR LEAKAGE THROUGH BELLOWS
- 3. BELLOWS
- 4. STELLITE WELDING
- 5. VALVE

Figure IV.E-5. BR-5 Bellows-Type Valve (Ref. 6)

- 1. DIRECTION OF COOLANT FLOW
- 2. SHELL
- 3, 4. DISK IN CLOSED AND OPENED POSITIONS
- 5. SEAT

Figure IV.E-6. BR-5 Nonreturn Valve (Ref. 6)

BR-5/BR-10 IV.E.

IV. F. SODIUM PURIFICATION AND INSTRUMENTATION

Each loop contains a cold trap (Fig. IV.F-1) cooled by toluene. In this cold trap, sodium enters the recuperator and passes into the outer cavity of the trap to a settling basin and is cooled to 120 to 230°C. It enters the cavity filled with stainless-steel shavings, passes from the trap to the recuperator and back to the loop.

The sodium impurity content is monitored by plugging indicators (one in each loop). (Fig. IV.F-2.) (Ref. 6)

Sodium level is monitored by potentiometer-type level gages. The detecting element is a steel pipe divided into several sections of equal resistance. A stainless-steel wire lead from each section is fed by a low-voltage transformer. When the level touches the lower end of the section, the supply current passes through all sections and voltage proportional to the value of the supply current and the resistance of the sections is released. (Fig. IV.F-3)

A Soviet-developed radio-interference level gage was also installed in BR-5. It works on the principle of fixing the position of the minimum of a standing wave that forms as a result of the addition of

the incident wave and the wave reflected from the liquid. Automatic monitoring is possible with differential data units consisting of two detectors and coupling coils in which voltage is induced. The detecting element receives its power from an amplitude-modulated, high-frequency generator. (Ref. 6)

Coolant flow in Br-5 is measured by magnetic flowmeters. A potentiometer is used as a secondary instrument of the detecting element assembly. The detecting element is a horse-shoe magnet with a base plate of armco iron. (Fig. IV.F-4)

The BR-5 uses membrane manometers as pressure transmitters. The detecting element is a shell containing a coil with plunger and the elastic sensitive element (membrane and lower and upper flanges).

The BR-5 has six membrane units. (Fig IV.F-5.) (Ref. 6)

Temperature is monitored by Chromel-Alumel and Chromel-kopel thermocouples. Communication to the secondary instrument is by a single wire insulated with porcelain beads. (Ref. 6)

IV.F-2

1. TOLUENE CAVITY
 2. COOLING ZONE
 3. TOLUENE VAPOR CONDENSER
 4. PULSE TUBE FOR MEASURING PRESSURE
 5. HEATER CAVITY
 6. THERMOCOUPLE POCKET
 7. FILTRATION ZONE
 8. GRID
 9. SETTLING TANK
- LEGEND: 1) TOLUENE

Figure IV.F-1. BR-5 Cold Trap (Ref. 6)

1. VALVE WITH SLOTS ON THE VENT
2. DISPLACER
3. SEALING FILLER
4. COILED PIPE
5. CASING OF THE SODIUM-AIR HEAT EXCHANGER
6. THERMOCOUPLE POCKET

Figure IV.F-2. BR-5 Plugging Indicator (Ref. 6)

BR-5/BR-10 IV.F.

- 1. POTENTIAL OUTLETS
- 2. MEASURING TUBES
- 3. SUPPLY TUBE

Figure IV.F-3. Potentiometer-Type Level Gauge (Ref. 6)

- 1. SIGNAL ELECTRODES
- 2. PIPE
- 3. MAGNETIC SYSTEM

Figure IV.F-4. BR-5 Magnetic Flowmeter (Ref. 6)

1. LID	11. WASHER	22. WASHER
2. TEFLON LINING	12. TEFLON BUSHING	23. LOWER FLANGE
3. WASHER	13. CONNECTING PIECE	24. BOLT
4. LUG	14,15. CONTACTS	25. MEMBRANE
5. INTERLINING	16. SPRING	26. ROD
5. BOTTOM	17. TERMINAL PANEL	27. UPPER FLANGE
7. BOLT	18. SHELL	28. SPRING
8. CONNECTING PIECE	19. SCREEN	29. WASHER
9. CONDUCTOR	20. FRAME	30. NUT
10. TEFLON LINING	21. RING	31. CONNECTING PIECE

Figure IV.F-5. Pressure Transmitter of the Type Used in BR-5 (Ref. 6)

IV. G. COVER GAS AND AUXILIARY SYSTEMS

A number of auxiliary circuits are provided for cooling and heating the reactor elements, shielding reflectors, water-shield tank, thermal column, experimental loop and water loop of the experimental channel. The nickel reflectors are cooled by filtered air, which flows downward along cooling channels and is ejected to the atmosphere through a tall pipe. Heat released from the water-shield tank and the experimental channel is removed by forced circulation of distillate along the closed circuit, the heat being transferred to running tap water in the jacket-and-pipe heat exchanger. The distillate is pumped back to its tank and returns to the pump intake through a buffer reservoir along an overflow pipe.

The gas heating system of the central reactor tube is a disconnected heating loop. Air passes through an electric heat radiator and goes to the heating system of the central tube and the first loop gate valves where it mixes with air from the reflector cooling system and is ejected with it. (Fig. IV.G-1.) (Refs. 1,6)

Argon cover gas is circulated continuously through a silica-gel drier and through copper-coated silica gel heated to 250°C.

Preliminary sodium purification is by vacuum distillation. The main unit of the BR-5 system is the evaporator, which is equipped with an electric furnace and a condenser, with distillation under vacuum. (Fig. IV.G-2.) (Ref. 6)

Figure IV.G-1. Diagram of the BR-5 Gas-Heating System (Ref. 6)

Figure IV.G-2. BR-5 Sodium Distillation System (Ref. 6)

IV. H. STEAM GENERATOR AND FINAL HEAT TRANSFER

The BR-5 steam generator is a vertical shell unit with 61 coaxial tubes inserted in it. Outer straight pipes are welded at their ends to an upper tube plate and into the plate of a mercury chamber located in the upper part of the shell. Inner, inverted U-shaped tubes are fastened into lower tube plates. Mercury fills the annulus of the double-wall tubes and the space between the tube plates. Pressure in this cavity is lower than the steam pressure and higher than the NaK pressure.

The generator consists of two shells connected in series. Circulation on the water-steam side is by a once-through circuit with no separators. Steam and water flowthrough the inner tubes countercurrent to the NaK (Figs. IV.H-1 and IV.H-2). At

the end of 1960, the steam generator was replaced by a NaK-air heat exchanger. (Refs. 6, 8)

The NaK-air heat exchanger consists of nine sections arranged in the casing, which is 1.5 x 1.5 x 2 m. Each section is a cluster of 62 U-shaped tubes, each 25 mm in diameter with 1.5 mm thick walls. The staggered arrangement is sealed into the tube plate of the chamber section. NaK passes into the upper collector and is distributed along three parallel three-section tubes and is carried out of the heat exchanger through the lower collector. Cooling air flows from the bottom to the top. Heat exchanger sections are fabricated of stainless steel. (Ref. 8)

Figure IV.H-1. BR-5 Steam Generator (Ref. 6)

1. STEAM GENERATOR
2. CONDENSER
3. FEED TANK
4. CYLINDERS WITH NITROGEN
5. FEED PUMP INCLUDED IN THE CIRCUIT DURING THE PERIOD OF ADJUSTMENT OF THE SGU
6. CIRCULATION PUMP OF THE THIRD CIRCUIT

Figure IV.H-2. BR-5 Design Diagram of the Steam Generator Unit (Ref. 6)

IV. I. REACTOR INSTRUMENTATION AND CONTROL

Two BF_3 counters are located in the water-shield tank to measure flux level at startup. There are eleven ionization chambers for use when the reactor is at power. These boron chambers are fitted with a boron-coated steel cylinder. The thickness of the boron coating increases linearly with the length of the cylinder so that chamber sensitivity varies with reactor power.

Monitoring the fuel element cladding leak-tightness provides both a continuous check for damaged fuel elements and constant monitoring of the activity level of fission products in the primary loop. (Ref. 3)

The activity of gases sampled from gas spaces in the central reactor tube and the primary loop pumps is monitored by means of a spectrometer recorder. One of the primary pumps is equipped with a recirculation line

with a sealed gas blower, by means of which gas from the gas space of this pump is recirculated over the spectrometer recorder. (Ref. 4)

Delayed-neutron monitoring of the coolant is accomplished by special sensors using corona discharge counters. Six sensors are installed directly on the heat insulation of the primary piping. Secondary installations on a central board record the averaged data from all sensors on a chart. (Ref. 3)

The reactor is controlled by nickel reflector cylinders suspended on steel rods and connected by cable to servodrives in the upper box of the reactor by means of electromagnets. In scram situations, they drop by their own weight. Two automatic regulating rods located in grooves in the shield compensator cylinder furnish shim control. (Ref. 6)

IV. J. FUEL HANDLING

With the hood of the central reactor tube removed, special handling mechanisms are mounted on the small rotating plate above the core. The gas cavity of the central tube communicates through locks with the gas cavities of the mechanisms. The channel in the small rotating plate is aligned with the assembly to be removed, and further operations are done with a reloading container suspended from an overhead crane. The reloading container is a cylindrical body filled with lead 200 mm thick. The inner part has a vertical cylindrical pipe containing a rod with

tongs that pulls the assembly into the container. A conical ground cock in the lower part closes the channel tightly. Inert gas can be circulated in the container. The inner channel connects with the channel of the small plate. The surface of the plate is sealed to the lower surface of the container by a rubber ring. After removing the fuel assembly and sealing the container, the space between the cocks is blown with pure gas and the container moved to the assembly storage tank by the overhead crane. New assemblies are loaded in reverse order. (Fig. IV.J-1.) (Ref. 6)

1. ROD WITH TONGS
2. DRIVING ROLLERS
3. CARRIAGE
4. SCREW OF CARRIAGE DRIVE
5. CRANE CONTROL MECHANISM
6. SEAL OF THE ROD
7. CONTAINER
8. TONGS
9. COCK
10. GASKET RING
11. GAS INLET
12. CARRIAGE GUIDE

Figure IV.J-1. BR-5 Reloading Container (Ref. 6)

IV. K. CONTAINMENT

BR-5 has no outer containment building. Both the massive concrete structure around the water-shield tank and the water tank itself serve as biological shielding. Primary loops are housed in separate concrete cells and the secondary loop equipment is in a single compartment. Additional shielding to protect operating personnel was provided during modification for 10-MWt operation.

V. BOR -60

LOCATION: Near Melekess, USSR

OPERATION: March 1970

BOR-60 is an experimental loop-type fast reactor. Design started at the end of 1963 and construction in May 1965. The reactor went dry critical in December 1968 and reached criticality with sodium in December 1969. Until the end of 1970, the reactor operated at 60 MW with air-dump heat exchangers. A steam generator was installed in 1970. A second steam generator of different design was installed and put into service in 1973.

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Table 1

GENERAL PARAMETERS

Type	Loop-type, enriched UO ₂ fuel
No. loops	2
Coolant	Sodium
Core inlet temp.	360-480°C
Core outlet temp.	500-600°C
Flow direction	Upward
Driver fuel	UO ₂ , fully enriched
Blanket fuel	UO ₂ , depleted
Core height	40 cm
Core diameter	40.4 cm
Velocity in core	8m/sec (max. 10 m/sec)
No. enrichment zones in core	1
Output MWe/MWt	60 MWt
Max. can temp.	750-800°C
Linear power, max.	500 w/cm
Neutron flux, total	3.7×10^{15} n/cm ² /sec. (max.)
Power density	16.7 kw/ft. max.
No. Driver elements	80 initial load*
No. Radial blanket elements	158-178
No. In-core control elements	7 (Sealed B ₄ C)
Goal burnup	10%

*It was reported in Nuclear Engineering for May 1974 that BOR-60 was operating with 113 fuel assemblies in the core.

BOR-60 V

Table - 2

CORE AND BLANKET

	Driver zone	Axial blanket	Radial Blanket
Fuel material	UO ₂	depleted UO ₂	depleted UO ₂
Form	Annular pellet	Annular pellet	pellet
²³⁵ U inner zone	90%	depleted	depleted
Density	10.2 g/cm ³		
Pellet od	5.1 mm Central hole 1.7 mm dia.		
Pellet length	10 mm		
Rod cladding	Stainless steel	Stainless steel	Stainless steel
od	6 mm		14.5 mm
Wall thickness			0.35 mm
Fuel-clad gap	0.1 - 0.2 mm		
Column length	400 mm	100 mm x 2	900 mm
Gas plenum length	150 mm top 100 mm bottom		
Vented/non-vented	No		
Assembly material	Stainless steel	Integral with fuel core	Stainless steel
Shape	Hexagonal		Hexagonal
Across flats	44 mm		44 mm
Wall thickness	1 mm		
Overall length	1495 mm		
No. pins/assembly	37	37 x 2	7
Pin spacing	Spiral wrap, oval wire		
Pin pitch	6.7 mm		15.2 mm
Assy. pitch	45 mm		
Assy. in core	80 - 1000		158-178

V. A. CORE AND BLANKET

The BOR-60 core consists of hexagonal assemblies loaded with a pitch of 6.7 mm for the fuel and 15.2 mm for the radial blanket assemblies. Pin cladding is a USSR-modified type 316 stainless steel (16 Cr - 15 Ni-3 Mo - 0.8 Nb). Pin spacing is by a spiral wrapping of oval stainless-steel wire. The axial blanket pins are loaded into the top and bottom of the hexagonal can. A gas plenum at the top is 150 mm high. The bottom plenum (100 mm) contains a spring to hold the fuel column. Although the cladding is sealed, vented elements will be tested. The fuel assembly has an upper head that provides a gripping area for the reloading machine and a lower end piece for positioning in the throttle socket of the grid-plenum assembly. The shafts of the driver assemblies have lateral inlets 5 to 5.5 mm in diameter for the delivery of sodium from the high-pressure

plenum. Spiral seals are used to reduce leakage. The radial assembly shafts have similar equipment to take sodium flow from the low-pressure plenum. (Figs. V.A-1, V.A-2 and V.A-3 (Refs. 4, 19, 10)

The design called for an initial core loading of 80 driver elements. Criticality was reached with 68 elements. In the May 1974 issue of Nuclear Engineering International, it was reported that BOR-60 was operating with 113 fuel assemblies in the core.

Assemblies containing experimental specimens can be placed in the active zone. Some radial blanket assemblies can also be used for irradiation.

The cover gas is argon.

NUMBER OF ASSEMBLIES IN CORE AND
RADIAL BLANKET 158-178

Figure V.A-1. BOR-60 Core Design (Ref. 4)

Figure V.A-2. BOR-60 Fuel and Blanket Assemblies (Ref. 4)

Figure V.A-3. BOR-60 Fuel System (Ref. 4)

V. B. CORE SUPPORT AND VESSEL INTERNALS

The grid-plenum assembly supports for the fuel and blanket assemblies and distributes sodium into the core. The bottom ends of the assemblies are fastened to the grid plates while the top ends are free. Radial restraint is by core clamping. The plenum is suspended from the core "basket", a stepped cylinder resting on the upper flange of the vessel.

The inlet plenum is divided into high-pressure and low-pressure zones. The high-

pressure zone is the area between the 50 mm thick upper and lower support plates. These plates are joined by nozzles into which the driver and radial assemblies are positioned. The cavity between the lower plate and the bottom of the reactor vessel is the low-pressure zone. This zone acts to reduce the upward force on both the core assemblies and the plenum zone that feeds the blanket elements, thermal shield and reactor vessel wall. (Figs. V.B-1 and V.B-2 (Refs. 2,4))

Figure V.B-1. BOR-60 Core Support Structure (Ref. 4)

Figure V.B-2. BOR-60 Sodium Inlet Plenum (Ref. 4)

V. C. REACTOR VESSELS AND SHIELDING

The reactor vessel is a vertical cylindrical structure 6500 mm high with a wall thickness of 16-22 mm. The vessel diameter at core level is 1100 mm; maximum diameter is 1500 mm. It is enclosed in a leaktight secondary vessel. The space between the vessels is used for warming the reactor with gas. There is a 300 mm inlet duct welded into the elliptical bottom head and two 300 mm outlets located above the tops of the assemblies. The internals are removable, the thermal sleeve of the outlet pipes being split to accommodate removal. (Fig. V.C-1.)

The radial thermal shield consists of concentric steel cylinders located between the core and the reactor vessel. The total

thickness of the radial thermal shield is 24 cm. Shielding below the core consists of the lower fuel assembly extensions. Upper biological shielding is supplied by the alternate layers of steel and borated graphite of the double rotating plugs. Gastight sealing of the plugs is obtained by the use of freeze seals fitted with a bismuth-tin alloy. Drives for the control elements, and the fuel-transfer-tank connection, are on the small rotating plug. The side biological shielding is fabricated of layers of steel, ferrous oxide and concrete. (Fig. V.C-2.)

There is no core-catcher device provided. (Ref. 4.)

1. FUEL EXCHANGE CASK
2. DRIVE FOR THE CONTROL ROD SYSTEM
3. GATE OF FUEL EXCHANGER CASK
4. FUEL EXIT PORT OF FUEL EXCHANGER CASK
5. BASKET SUPPORT FOR CORE
6. STEEL SHIELDING
7. CORE
8. REFLECTOR
9. PLATES FOR THE GAMMA HEAT SHIELD
10. HIGH PRESSURE PLENUM
11. REACTOR VESSEL
12. SECONDARY CONTAINMENT
13. SODIUM INLET
14. HIGH-PRESSURE INLET ZONE
15. LOW-PRESSURE INLET ZONE
16. SODIUM OUTLET DUCT
17. SUPPORTING FLANGE
18. CONTROL ROD
19. THERMOCOUPLE
20. ROTATING PLUGS
21. DIP SEAL
22. ROTATING PLUG DRIVE MECHANISMS

Figure V.C-1. BOR-60 Reactor (Ref. 4)

Figure V.C-2. BOR-60 Reactor Vessel Shielding (Ref. 4)

BOR-60 V.D.

V. D. CONTROL ELEMENTS

The BOR-60 is controlled by three safety rods and two shim rods located in the core and two regulating rods in the radial blanket. All elements are similar in design and consist of bundles of rods containing boron. The elements are connected with servodrives installed on the rotating plug. During reloading, the elements are lowered and disconnected from the drives.

The rods are composed of bundles of pins containing pellets of boron carbide enriched 80% in ^{10}B . Pin cladding is a modified 316 stainless steel. The pin is sealed with a bottom plenum equal in volume to the volume of B_4C . The plenum is connected to the junction by a filter. The rod bundle is in a cylindrical guide tube that moves within a hexagonal outer

duct. Pin design for all rods is similar and varies only in the number of pins per element. (Ref. 11.)

For a maximum thermal power output of 60 MW the efficiency of the control system is reported to be as follow:

- Efficiency of three
scram (safety) rods: 3.3%
- Efficiency of temperature
compensating rod: 1.0%
- Efficiency of burnup
compensator: 1.7%
- Efficiency of two
control (regulating) rods: 0.48%

The reactivity temperature coefficient is $-4 \times 10^{-5} (\text{°C})^{-1}$; the reactivity power coefficient is $1.5 \times 10^{-4} (\text{MW})^{-1}$. (Refs. 1,4.)

V. E. HEAT TRANSFER SYSTEMS

The primary circuit includes, for each loop, the reactor, hot piping with valve, intermediate heat exchanger, cold piping and a pump. The secondary loop includes the intermediate heat exchanger, a steam generator with buffer tank and a circulation pump. An air heat exchanger is mounted in by-pass in the steam generator; it can evacuate 50% of the reactor power and can be connected with either of the two secondary loops.

Sodium enters through a 300-mm diameter inlet duct welded to the elliptical bottom head of the reactor. The flow from the high-pressure zone passes into the zone between the support plates where it is directed into the core assemblies and to the low-pressure zone below the lower support plate. Flow through the core is upward to two 300-mm diameter outlet ducts above the tops of the assemblies. Flow to each assembly is controlled by means of slots in the throttling sleeves of the inlet plenum, covering a given number of side holes in the bottom ends of the assemblies. Flow through the blanket elements is supplied from the low-pressure inlet plenum and is controlled by an orifice located at the bottom of the assembly.

Primary piping is doubly contained out to the stop valves, with bellows to accommodate differential thermal expansion. (Refs. 4, 5.)

All piping in the secondary circuit is 200 mm in diameter. The use of bellows in the secondary piping permits compact piping arrangement in the steam generator rooms. Bellows are used only on vertical runs of hot-leg piping. They are formed of U-span type. (Fig. V. F-1.) (Ref. 4.)

Both primary and secondary pumps are vertical centrifugal units. The primary pump is submerged with a bottom radial hydrostatic bearing operating in the sodium, a top journal thrust oil bearing and a gas-tight oil seal on the shaft. The pump is fitted on the upper cover of the primary loop box and the motor is accessible for servicing during operation without breaching the primary piping. Pumps are single stage, single suction. Speed is controlled at 350 to 1500 rpm by an ac-dc motor generator system. There are no pony motors for emergency cooling. All pumps are installed in cold legs. (Table V. E-1.) (Ref. 4.)

TABLE V. E-1. Pump Characteristics (Ref. 5.)

Characteristic	First Loop	Second Loop
Nominal production, m ³ /hr	600	830
Nominal water column height, m	85	60
Inert gas pressure in gas cavity, kg/cm ²	0.1-0.5	0.5
Nominal rpm	1500	1500
Minimum rpm	200	200
Nominal shaft power, kw	250	250
Continuous current, V	330	330
Weight (dry), kg	20,300	17,300
Biological shield thickness, mm	700	0

The intermediate heat exchanger (IHX) (Fig. V. E-2) is a vertical cylindrical vessel containing a tube bundle with a floating lower head. Primary sodium flows in the space between the tubes from top to bottom and secondary sodium flows upward in the tubes. The IHX is mounted on the top cover of the primary loop boxes and can be removed without breaching the primary piping. The central down-comer tube for secondary sodium inlet uses a bellows in the lower end to accommodate differential expansion. There are no baffles on the shell side. The IHX is blanketed with nitrogen. (Ref. 4.)

A gate valve, similar to the BN-350 gate valve, is used for the primary loop intake lines. It was designed for possible removal of the working elements by remote control for servicing or replacement without cutting the pipelines and has a built-in biological shield in the valve lid. (Fig. V.E-3) Bellows-type valves are used in the pressure lines of the first loop and on all other liquid-metal systems of the unit. They are analogous to the BR-5 fittings. (Fig. V.E-4.) (Ref. 9.)

Figure V.E-1. BOR-60 Secondary Piping Expansion Bellows (Ref. 4)

V.E-3

Figure V.E-2. BOR-60 Intermediate Heat Exchanger (Ref. 9)

Figure V.E-3. Bellows-Type Valve of the Kind
Used in BOR-60 (Ref. 9)

BOR-60 V.E.

V. F. SODIUM PURIFICATION AND INSTRUMENTATION

The BOR-60 cold trap is a conventional design but is steam or water cooled. Low-pressure steam is used to keep the sodium molten and to provide fine control on the trapping temperature. A low melting-point, lead-base alloy is used as a thermal bond between the steam vessel and the cold-trap vessel. In addition, two metal walls separate the steam and water from the sodium (Fig. V.F-1). Both the primary and secondary circuits are equipped with cold traps. (Refs. 4, 5.)

Chromel-Alumel thermocouples are installed at the outlets of individual fuel assemblies to indicate sodium temperature. Not all of the assemblies are monitored.

Instruments for fuel failure detection based on delayed-neutron monitoring are located on the outlet pipe of the IHX. The activity of the coolant is measured after the test loops have been cut off from the main circuit by means of valves. One of the test loops has its own pump and is supplied with an oxide trap, sampler and isotopic dosimeter. There are two loops for monitoring fission product pollution. (Ref. 5.)

Coolant flow rate through the core assemblies is measured by a special flow-meter consisting of an 8-m long rod with a measuring pipe fastened to one end. The measuring pipe has two pickups, one magnetic and one electromagnetic. (Fig. V.F-2.) (Ref. 10.)

Figure V.F-1. BOR-60 Cold Trap (Ref. 4)

- 1. PICKUP WITH PERMANENT MAGNET
- 2. PIPE FOR OVERFLOW PASSAGE
- 3. ASSEMBLY HEAD
- 4. ELECTROMAGNETIC PICKUP

Figure V.F-2. BOR-60 Flowmeter (Ref. 10)

V. G. EXPERIMENTAL FACILITIES

A special channel near the center of the core is provided for studying fuel element operation. The channel is an assembly externally identical to the other assemblies but fitted with various indicators and fastened to a rod containing the leads for the indicators. During discharge, the assembly is removed from the core and rotates with the plugs.

There are four horizontal bundles for physics investigations and ten vertical uncooled channels, including some 300 mm in diameter. A large number of assemblies with experimental specimens can be loaded into the core at the same time. (Ref. 2.)

V. H. STEAM GENERATORS

BOR-60 began operating as a power station in December 1970 when the first steam generator was installed in one of the two loops. This unit is a once-through coil steam generator consisting of two cylindrical frames, each with a diameter of about 1 m. The evaporator tube bundle has sixty coils and the superheater has ninety coils. The steam generator is fitted with means for control and protection in the event of either tube leakage or water or steam entering the sodium (Fig. V.H-1)

The second steam generator, developed and manufactured in Czechoslovakia, was installed and started up in 1973. This 30-MW unit has eight separate modules. The individual units are small. Fault location is possible in the modules. The double tube plate design prevents water from contaminating the sodium in the event of leakage through the weld between tubes and plate. (Ref. 8)

BOR-60 V.H.

Figure V.H-1. BOR-60 Steam Generator (Ref. 4)

V. I. REACTOR INSTRUMENTATION AND CONTROL

The automatic control system is designed to maintain a given power level and coolant outlet temperature. A temperature controller, accepting signals from a temperature-setting device and sensors, controls the power setting device by moving it to a position so that the coolant outlet temperature coincides with the set temperature. The temperature-sensor time constant is ~10 sec.

The safety system shuts down the reactor in the event of either an unacceptable deviation from preselected parameters or when hazardous disruptions occur in the heat transfer systems.

Delayed-neutron detection instruments for detecting fuel failures are located at the IHX outlet pipe. Fission-gas detectors capable of detecting ^{133}Xe and ^{85}Kr are located in the cover gas. (Refs. 4, 12.)

V. J. FUEL HANDLING

Fuel is handled by means of double rotating plugs. All charging and discharging operations are conducted through a special port in the small rotating plug, which contains all of the connections. The fuel charge-discharge machine (Fig. V.J-1) is brought into place and sealed to the port by a small plug. The machine, a coffin with a gripping device, is mounted on a gantry crane and is able to move along coordinate axes. The assembly is raised into the coffin in an inert atmosphere and transferred in the coffin to external storage. Charging and discharging are carried out by the same machine. Assemblies to be loaded are first heated to 300°C in an electric furnace. A

closed gas circuit in the charge-discharge machine removes decay heat (estimated at about 5 kW) from discharged elements. The fuel is cleaned by steam and nitrogen in the transfer coffin. (Ref. 4.)

Experience with the fuel-handling devices has shown that it is better to distribute refueling operations among separate simple machines rather than to utilize a single all-purpose machine. Some changes have been made to simplify operation and improve control of the procedure. Also, a system for inspecting the assembly inside the coffin by television has been installed. (Ref. 8.)

1. CONTAINER
2. ARGON-AIR HEAT EXCHANGER
3. AIR BLOWER
4. CLOSURE OF CONTAINER
5. BRIDGE
6. CARRIAGE
7. COMPRESSOR

Figure V.J-1. BOR-60 Fuel Handling Machine (Ref. 4)

BN-350. VI

LOCATION: Shevchenko, USSR

OPERATION: July, 1973

BN-350 was brought into operation in July 1973 at Shevchenko, in the Kazakh SSR. Actual work on the project was begun in 1964. The reactor supplies 150 MWe to the grid, and power for the distillation of seawater. By the end of 1973 the station was operating at 20-30% capacity. Delays in further development were due to water leakages to the sodium and to the steam generator evaporators.

Construction is based on the design and experience from BR-5 operation. It is adaptable to loadings with various fuels. First core loading was enriched UO_2 . Later cores will probably be mixed oxide.

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Table - 1

GENERAL PARAMETERS CORE-1

Type	Loop-type
No. loops	6
Coolant	Na
Core inlet temp.	300°C
Core outlet temp.	500°C
Flow direction	Upward ^k
Driver fuel	UO ₂ enriched
Blanket fuel	UO ₂ depleted
Core diameter	1495 mm (1.5 m)
Core volume	1870 ℓ
No. enrichment zones in core	2
Output MWe/MWt	350 MWe/1000MWt
Breeding ratio	1.5
Neutron lifetime	4.5×10^{-5} sec.
Max. can temperature	680 - 700°C
Fuel Centerline Temperature, Max.	1800°C
Neutron flux, total	10×10^{15} N/cm ² sec.
Doppler ($\Delta K/K$)/°C total	Negative
Power Density, ave.	480 kw/ℓ
No. Driver elements	199 (211)
No. Radial blanket elements	440
No. In-core control elements	12
In-Vessel Storage Positions	41
Goal burnup	5%

Table - 2

CORE AND BLANKET CORE-1

	Driver zone	Axial blanket	Radial blanket
Fuel material	UO ₂ , enriched	UO ₂ , depleted	UO ₂ , depleted
Form	Annular pellet		
235 _U inner zone	26%		
outer zone	17%		
Density (effective)	8 g/cm ³ (75% TD)	9.5 g/cm ³	
Pellet od	4.28 mm		
Rod cladding	stainless steel	stainless steel	stainless steel
od	6.1 mm	12 mm	14.2 mm
Wall thickness	0.35 mm	0.4 mm	0.5 mm
Fuel-clad gap	0.6 mm		
Column length	1060 mm	600 mm x 2	
Gas plenum length	20-25% of volume		
Pin length	1140 mm		
Vented/non-vented	No		
Assembly material	stainless steel	stainless steel	stainless steel
Shape	Hexagonal	Hexagonal	Hexagonal
Across flats (dia.	96 mm		96 mm
Wall thickness	2 mm		2 mm
Overall length	3500 mm		3500 mm
No. pins/assembly	169	37 x 2	37
Pin spacing	Spiral wire, alternate pins, wire dia. 0.85mm, spiral pitch 100mm		
Pin pitch	7.0 mm		14.8 mm
Assy. pitch	98 mm		98 mm
Assy. in core	199 (211)	(with core assembly)	440
Volume fraction			
Fuel	44.7%	44.7%	60.8%
Steel	24.2%	24.2%	17.6%
Sodium	31.1%	31.1%	21.6%

VI. A. CORE AND BLANKET ASSEMBLIES

UO₂ was decided upon for the first loading. There are two enrichment regions in the core, the elements differing in the design of the end fittings. The radial blanket elements are reportedly interchangeable to provide for adjusting the critical size of the core. (Ref. 5.)

The driver assembly is a stainless steel hexagonal can containing the fuel and fertile pins. Spacing is by spacer pads, for a close-packed core. (Fig. VI.A-1)

Fuel pins are 6.1 mm diameter, with a cladding wall thickness of 0.55 mm. The fuel pin bundle is made up of 169 pins. Spacing is by helical wire wrapping of alternate pins to give a pin pitch of 7.0 mm. Fuel pins are welded at the bottom to a spacer grid; upper are free ends. The cans are sealed at the end by argon arc welds. There is practically no gas plenum. The free volume consists of the central hole formed by the annular fuel pellets and a 20-25 mm space at the upper end of the element. Fuel-clad gap is 0.1-0.5 mm. (Fig. VI.A-2)

Axial blanket pins are 12 mm diameter with a wall thickness of 0.4 mm. They are physically separated from the fuel pins. There are two 37-pin bundles, at the top and bottom of the core subassembly. (Ref. 4.)

For the second loading, the hexagonal can will contain 127 pins, 6.9 mm in diameter, with a gas space in the lower, colder, part of the element. The lower blanket is combined with the fuel core in a single jacket. The lower 230 mm of the core directly joining the end blanket will consist of solid rather than annular pellets. The effective density of this portion is 86% TD (from 75% TD). (Fig. VI.A-2.)

An alternate design provides for the incorporation of both end blankets into a single jacket. (Ref. 4.)

The upper head of the core subassembly is designed to accommodate the reload manipulators. The lower ends are shanks which fit into the support grid. Lateral openings in the bottom shank admit sodium which leaves through a port in the top head. At the end of the bottom shank and in its upper section there are spiral seals to reduce sodium leakage. Throttling devices in the subassembly shanks and in the support grid distribute sodium flow. In the shank, this device consists of a number of holes in the closed-end tube. (Fig. IV.A-4.) (Ref. 6.)

The radial blanket element differs in shank design from the core subassemblies to locate them correctly in the support grid.

Figure VI.A-1 BN-350 Core Subassembly (Ref. 3)

Figure VI.A-2 BN-350 Fuel Assembly and Fuel System (Ref. 3)

Figure VI.A-3 Fuel Element Design for Second Loading of BN-350

Figure VI.A-4 BN-350 Seals for Controlling Leakage in the Core Subassembly (Ref. 3)

VI. B. CORE AND BLANKET ASSEMBLIES

Core restraint is provided by the core support structure. There is no lateral restraint provided except for the subassembly cans, radial blanket assemblies, and radial shielding. The subassemblies are free at the top.

The support structure is a pressure header consisting of an upper and lower plate, forming a high-pressure section. Openings

in the top plate accommodate the lower bends of the subassemblies, which fit into the lower plate. Leak-proof seals are located on the assembly shank. (See Section VI.A, Fig. VI.A-4.) Throttling devices in the pressure header and in the subassembly shank regulate coolant flow.

The header is supported on flanges inside the vessel. (Fig. VI.B-1, B-2.) (Ref. 3.)

Figure VI.B-1 BN-350 Fuel Assembly Hydraulic Holddown (Ref. 3)

Figure VI.B-2 BN-350 Pressure Header (Ref. 2)

VI. C. REACTOR VESSELS AND SHIELDING

The core, blanket, refueling mechanism, and other components are enclosed in a sodium-filled vessel of changing diameter. The vessel is steel-lined stainless steel, 2.2 m to 6 m in diameter. Overall height is 13 m, with 300 mm thick walls. There are six inlets for the primary sodium near the bottom. Inlet piping is 500 mm in diameter. Outlet piping, located above the core, is 600 mm in diameter. (Fig. VI.C-1.) Secondary sodium containment is provided by a 10 mm thick envelope around the vessel. (Ref. 5.)

The reactor vessel support was originally by means of a flange at mid-height, with support columns (Fig. VI.C-2). This has apparently been changed, with a cylinder or flexible plates being used. (Ref. 3.)

A thermal shield consisting of 60 mm thick stainless steel forms an annular gap around the reactor vessel. Two per cent of the total sodium flow is directed into this space to cool the reactor vessel to 420°C. Internal radiation shielding is provided around the blanket and the upper region of the vessel. Two rotating plugs are supported by the upper part of the vessel. The reactor cave is formed by 2 m of concrete.

The rotating plugs rotate on ball bearings. A low-melting point tin-bismuth eutectic alloy is used in an electrically heated seal during rotation. It is solid during operation. There is a rubber seal for back-up during normal operation. (Ref. 3, 5.)

Figure VI.C-1 BN-350 Reactor Vessel (Ref. 3)

Figure VI.C-2 BN-350 Reactor Showing Vessel Support (Ref. 2)

VI. D. CONTROL ELEMENTS

A sealed design was adopted for BN-350 control rods. For the regulating, compensating and safety rods the absorbing material is boron carbide enriched in ^{10}B . In rods to compensate for fuel burnup, the material is the same as for the core. Stainless steel is the jacketing material. There is no jacketing on the operating length of the automatic and safety rods, and none in the upper operating link of the compensating rod. Rods are arranged in vertical guide

bushings in the core; they are cooled directly with the primary sodium. Free volumes are provided for collection of helium.

There are two automatic control rods, three safety rods, and a total of seven power and temperature compensating and burn-up compensating assemblies; six of the compensating rods are fueled units. Drop time for the safety rod is 0.7 second, speed of motion is 1.3 mm/second, with a stroke of 1260 mm. (Fig. VI.D-1.) (Ref. 7.)

Figure VI.D-1 BN-350 Control Assemblies (Ref. 1)

VI. E. HEAT TRANSFER SYSTEMS

Primary sodium enters at the bottom of the reactor vessel through six inlet pipes, 500 mm diameter. It is distributed by a pressure header to the core subassemblies, flowing upward through the core to six outlet pipes above the core. These pipes are 600 mm in diameter.

There are six parallel primary loops, five being used during operation and one held in reserve. Each primary loop contains an intermediate heat exchanger, a pump, a check valve, and two gate valves with freeze seals. Auxiliary equipment of the primary loops includes drain tanks and cold traps. Sodium inlet temperature is 300°C, outlet 500°C. Flow is upward through the core at the rate of 14,150 metric tons/hour. All primary loops and components are located in sealed, steel-lined cells.

The intermediate circuit consists of six loops, five in use at rated power and one on standby. The circuit transfers heat to the steam-water system, sodium from the heat exchanger entering the superheater section of the steam generator at 453°C. It leaves at 416°C and passes through an evaporator section where the temperature is reduced to 273°C. The intermediate sodium is then pumped back to the heat exchanger. Primary loop and components are in sealed cells under nitrogen atmosphere. (Fig. VI.E-1) (Ref. 5)

The intermediate heat exchanger is composed of two sections connected in parallel. Each section is a horizontal tank in which three heat-transfer bundles are immersed. Each bundle contains 343 U-shaped tubes mounted in sets. A flow-smoothing baffle is located in the shell (primary) side before the first tube bundle. Secondary sodium enters the U-tube bundles from above, primary sodium at the ends of the horizontal tank, creating a cross-flow heat removal regime. The tube bundles are removable, and the heads have biological shielding. (Fig. VI.E-2)

Basic IHX Characteristics

Thermal power capacity	200 MW
Primary Na, inlet	500°C
outlet	300°C
Intermediate Na, inlet	273°C
outlet	453°C
U-tube dimensions	28 mm dia., wall thickness 2 mm, spacing (square lattice) 35 mm
Material	18-9 stainless steel
Heat exchange surface	1120 m ²

(Ref. 5, 9)

Primary pumps are sealed, single-stage centrifugal units with vertical shafts, located in the cold leg. The pump shaft is mounted on one radial bearing and one radial thrust bearing. The lower bearing does not operate in sodium. Rated capacity is 3200 M³/hr., rated head 110M, shaft speed 250-1000 rpm. (Fig VI.E-3)

The secondary pump has an overhung impeller with complex shaft bearing and cooling arrangements. The shaft is short. It has a Nak freeze seal.

Capacity is 3850 M³/hr., sodium head 70 m, shaft speed 250-1000 rpm.

Maximum rating is 1100 kw. (Ref. 1)

Gate valves and check valves are used in each loop. The gate-valves are bulky, forged bodies: bored-out forgings; cylinder forged down to ~ 1-in. flats on outside. Double-disk wedge gates have provisions for draining between the disks, water-cooled stem freeze seals are backed up by mechanical packing in the primary and secondary system. Diameter is 600 mm. Gate valves are electrically operated. (Fig VI. E-4)

Check valves are easily removable, 600 mm diameter units. There is hydraulic damping of the valve-disk closing, pin and bearing materials, and provision for low-pressure drop during natural circulation. (Ref. 3)

NB-350 VI.E.

Figure VI.E-1 BN-350 Reactor Flow System (Ref. 2)

Figure VI.E-2 BN-350 Heat Exchanger (Ref. 2)

VI.E-3

1. LEAKAGE OF OIL FROM THE GAS SEAL ASSEMBLY OF THE SHAFT
- 2 & 3. OUTLET AND INLET RESPECTIVELY OF THE COOLING WATER FROM THE SEAL ASSEMBLY OF THE SHAFT
4. OIL TO THE SEAL
5. GAS FOR BLOWING
6. OIL TO UPPER BEARING
7. OIL TO PIVOT
8. OIL FOR COOLING THE SHAFT
9. OIL FROM THE PIVOT UPPER BEARING AND THE SHAFT
10. OIL TO THE LOWER BEARING
11. SODIUM-POTASSIUM ALLOY FOR COOLING THE SHAFT
12. OIL FROM THE LOWER BEARING
13. MAXIMUM LEVEL OF SODIUM LOADING
14. INITIAL SODIUM LEVEL OF THE PUMP
15. IMPELLER
16. GUIDING DEVICE
17. BIOLOGICAL SHIELD
18. SHELL
19. COOLING BELT
20. RADIAL BEARING
21. THRUST BEARING
22. SHAFT

Figure VI.E-3 BN-350 Primary Pump (Ref. 8)

BN-350 VI.E.

BN-350 VI.E.

1. PACKING
2. COOLING CHAMBER WITH A DOUBLE WALL
3. REMOVABLE PART
4. STEM
5. WEDGE PLUG
6. CASE

Figure VI.E-4 BN-350 Gate Valve

VI. F. SODIUM PURIFICATION AND INSTRUMENTATION

Sodium arrives at the site in drums. It is heated in electric furnaces and recirculated through cold traps to less than 50 ppm of oxygen by weight. (Fig. VI. F-1) On-line oxygen is checked by plugging meters.

There are six Nak-cooled cold traps in the primary circuit, with two to four in operation at one time. Housing is a single-wall cylindrical vessel 6 m high and 1 m dia. Nak circulates through coiled pipes located in the cooling zone. An additional coiled pipe is situated in the settling tank. Heat is evacuated by electromagnetic pumps to two Nak-air heat exchangers mounted on the wall of the main reactor room. These exhaust through the wall directly to the outside. (Fig. VI. F-2) (Ref. 3, 8.)

A special manometer was developed for measuring the coolant pressure. It has a pickup device which consists of three basic units: intake tube with lower diaphragm, housing, and upper flange with upper diaphragm, induction coil and lead-out cable. (Ref. 8.)

Magnetic flow-meters measure coolant flow in BN-350. The magnetic system includes two permanent magnets and magnetic circuit, pole and end pieces forming an air-gap. It is arranged with respect to the pipelines so that the electrodes welded to the measuring section are perpendicular to the magnetic flux in the gap. In most cases, emergency shielding and interlock systems will be activated by the flow-meters in the primary circuit. (Fig VI. F-4)

Level measurement is by means of induction level gages. A discrete inductance level meter which operates by relay determination of the presence or absence of a signal has been developed. Pickup is a set of coaxial inductance coils.

Temperature is measured by chromel-alumel thermocouples and resistance thermometers. These are mounted in a protective sleeve.

Detection of leaks in the steam generators is by the detection of hydrogen in the sodium. (Ref. 9, 10.)

1. TO VACUUM	9. ELECTROMAGNETIC PUMP
2. GAS OUTLET	10. OXIDE PLUGGING INDICATOR
3. GAS INLET	11. PLUGGING-INDICATOR HEAT EXCHANGER
4. TO SECONDARY SYSTEM DRAIN	12. AIR BLOWER
5. SECONDARY SYSTEM DRAIN TANKS	13. COLD TRAP
6. TO ATMOSPHERE	14. TRANSPORT CONTAINER
7. NaK OUTLET	15. STEAM TRAP
8. NaK INLET	

Figure VI.F-1 BN-350 Sodium Receiving System (Ref. 3)

1. CONTROL INSERT
2. SODIUM EXIT
3. DISCHARGE OF SODIUM WITH GAS
4. EXIT OF SODIUM-POTASSIUM ALLOY
5. SODIUM INLET
6. RECUPERATOR
7. RECUPERATOR BYPASS
8. COILED PIPE OF THE COOLING ZONE
9. FILTRATION ZONE
10. OVERFLOW PIPES
11. GRILLS
12. INLET OF SODIUM POTASSIUM ALLOY
13. COILED PIPE OF THE SETTLING TANK
14. THERMOCOUPLE POCKETS

Figure VI.F-2 Type of Trap Used in BN-350 (Ref. 8)

1. SPECIFICATIONS OF THE INSTRUMENT
2. WASHER
3. INDUCTION COIL
4. CASING
5. PLUNGER
6. FLUOROPLAST BLOCK
7. FLANGE
8. UPPER MEMBRANE
9. UPPER FLAT DISK CENTER
10. ROD
11. CENTERING WASHER
12. CASING
13. GROOVED PAD
14. CENTRAL INSERT
15. PROTECTIVE COVER
16. RECEIVING NOZZLE
17. LOWER MEMBRANE
18. LOWER FLAT DISK CENTER
19. SIGNAL WIRE
20. CAPILLARY
21. DIA-MAGNETIC TUBE
22. SCREEN

Figure VI.F-3 BN-350 Sodium Pressure Transmitter (Ref. 8)

- 1. TERMINAL BOX
- 2. CONNECTIVE BOX
- 3. MAGNET
- 4. POLE END PIECE
- 5. ELECTRODE
- 6. MAGNET

Figure VI.F-4 BN-350 Detecting Element for Flow Gage (Ref. 8)

VI. G. COVER GAS AND AUXILIARY SYSTEMS

Sodium purification and instrumentation:
See Section VI. F.

Cooling of the seals and fittings of the pumps is provided by an independent Nak system.

Drainage tanks of the primary circuit can drain the sodium from the whole circuit; ten tanks of 50 M³ each are provided. They are connected in pairs to hold gas and metal respectively, each pair being located in a separate box. In an individual box there are two such tanks connected to the gas cavity of the reactor; these keep fluctuations in gas pressure with changes in volume or temperature of the sodium within acceptable limits.

Drainage tanks of the secondary circuit can drain any two loops simultaneously; there are four tanks of 50 m³ each.

Primary and secondary circuits are filled from the drainage tanks by linear electromagnetic pumps. Primary circuit pumps also pump the coolant through the cold traps.

Cover gas for the reactor is argon.
(Ref. 11.)

The upper section of the rotating plugs is cooled by air blown through special ventilating ducts. Air is discharged through a special system. The reactor vessel is heated with gas circulated between the vessel and the secondary containment. Sealed, steel-lined cells in which primary piping and equipment are housed are cooled by between-wall cooling; cell atmosphere is nitrogen.

VI. H. STEAM GENERATORS

BN-350 has six steam generators, each with two parallel evaporator sections, two parallel superheater sections, and a surge tank. The sections are connected by long runs of piping. Sodium from the IHX enters the superheater section at 453°C and leaves at 416°C. It passes through the evaporator section, where the temperature is lowered to 273°C. The secondary sodium is then pumped back to the IHX. (Fig. VI. H-1)

The evaporator section has bayonet tubes closed at the bottom end, with a concentric downcomer tube inside each tube. A single tube sheet holds the upper ends of the outer tubes, separating the sodium in the lower portion of the shell from the water

and steam above. Above the tube sheet and evaporator section, there is a space for natural separation of water and steam, the steam rising and passing through the pipe to the superheater section. Water is re-circulated downward to the evaporator tubes, and feedwater added by a header below water level.

The superheater is a counter-flow shell-and-tube heat exchanger with sodium on the shell side and water inside the single-wall tubes. The surge tank is a cylindrical vessel serving as part of the cover-gas system of the steam generator during normal operation. (Ref. 5.)

Figure VI.H-1 BN-350 Steam Generator (Ref. 5)

VI. I. REACTOR INSTRUMENTATION AND CONTROL

The overall centralized control system for BN-350 includes measurement and control of reactor power and period, automatic control system, reactivity change compensating system, and the reactor safety system.

An emergency shutdown cooling system makes it possible to calculate the temperature field of the reactor, the IHX, the steam generator, and the liquid metal circuits. Rapid operation occurs only in exceptional cases. Most of the signals go to the slow emergency system which reduces the power by a factor of 2.7 in 100 seconds. (Ref. 1.)

VI. J. FUEL HANDLING

The refueling system consists of double rotating plugs with drives; an in-vessel fuel handling machine; two inclined elevators for moving fuel between the reactor and position below the refueling-cell handling-machine gripper; an exit port to a shielded refueling cell; a refueling cell transfer machine for pickup and deposit and translation along the refueling cell; two transfer rotors cooled by Nak for interim transfer storage; a fuel-handling transfer machine in a shielded cell above wash stations; an exit port to the decay-storage water pool; and the water pool. (Fig. VI. J-1) (Ref. 3.)

Provision is made for reloading the reactor every six weeks to two months. Core elements which have reached their predetermined burn-up are transferred to a storage pit located at the periphery of the radial blanket region and fresh core elements installed.

Refueling is done with the reactor shut down. (Ref. 12.)

The in-vessel fuel handling machine can lift and rotate and has a hold-down. The

elevator is inclined 17° to the vertical and consists of a guide, a pot, a carriage, a drive rod, and a chain transmission. The carriage travels 16.5 ft. at 10 ft/min. and requires a 0-83 kw drive. (Fig. VI. J-2)

The refueling elevator contains a transfer pot at the bottom of the elevator. The pot is always filled with sodium and is always in a vertical position as it travels upward. The head of the fuel assembly is grasped by the transfer machine above sodium level. (Ref. 3.)

The refueling cell is a narrow box-like sealed compartment tangential to the reactor. It has an argon atmosphere. The feed mechanism in the transfer cell moves the assembly to the channel of the drum for spent elements and drops it into one of the receptacles. Reverse order is used in loading fresh fuel. The spent element is transferred from the drum to a receptacle in the wash box, and after washing it is moved to the holding tank.

All operations are automatic by command from a control panel. (Ref. 12.)

1. LARGE ROTATING PLUG
2. SMALL ROTATING PLUG
3. REACTOR EXIT PORT
4. REFUELING-MACHINE CARRIAGE
5. REFUELING CELL
6. WASH CELL
7. WASH PORTS
8. USED ASSEMBLY TRANSFER ROTOR
9. FRESH ASSEMBLY TRANSFER ROTOR
10. IN-VESSEL FUEL TRANSFER MACHINE
11. ELEVATOR
12. WASH-CELL FUEL TRANSFER MACHINE
13. NEW FUEL POT
14. REFUELING-CELL FUEL TRANSFER MACHINE

Figure VI.J-1 BN-350 Refueling System (Ref. 3)

Figure VI.J-2 BN-350 In-Vessel Fuel Handling Machine and Refueling Elevator (Ref. 3)

VI. K. CONTAINMENT

The reactor and basic auxiliary systems are located in an industrial type building. The building is divided into structural units consisting of a section for control rooms, electrical and electronic information equipment, general ventilating equipment etc.. A reactor area includes loops of the primary and secondary circuits, steam generators and auxiliary systems; a section accommodating

the transport system including water tanks for storage of depleted fuel, the hot cell, and the gas systems equipment. There is also a section accommodating the technological ventilating systems. Rooms of the reactor section are metal-lined, and contain a pit for the reactor. (Fig. VI. K-1) (Ref. 12.)

1. REACTOR
2. WATER POOL FOR FUEL DECAY AND STORAGE
3. REFUELING CELL
4. TWO TRANSFER ROTORS
5. FUEL WASH STATIONS

Figure VI.K-1 Vertical View of BN-350

VI.K-1

VII. BN-600

LOCATION: Beloyarsk, USSR

OPERATION: 1975 (Target)

The BN-600 reactor is an integral, pot-type system. Construction, begun in 1968, is scheduled for completion in 1975. The nominal electrical power rating of the BN-600 reactor is 600 MWe; the thermal power is 1470 MWt. The first core, which is somewhat flattened, will use uranium dioxide canned in stainless steel. Target burnup is 10%. The BN-600 reactor is designated Unit 3 of the Kurchatov station.

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Table - 1

GENERAL PARAMETERS CORE-1

Type	Pot-type integral design
No. loops	3
Coolant	Sodium
Core inlet temp.	380°C
Core outlet temp.	550°C
Flow direction	Upward
Driver fuel	(First core) UO_2
Blanket fuel	UO_2 , depleted
Core height	0.7 m
Core diameter	2.048 m
No. enrichment zones in core	2
Output MWe/MWt	600 MWe/1470 MWt
Breeding ratio	(1st core: operation as converter)
Max. can temperature	690°C
Fuel Centerline temperature	2500°C
Doppler ($\Delta k/k$)/°C total	$-1.64 \times 10^{-5} \%/^{\circ}C$
Specific power	840 kw/l (peak), 550 kw/l (ave)
Power Density	16.1 kw/ft. (max)
No. Driver elements	397
No. Radial blanket elements	37
No. In-core control elements	27
In-Vessel Storage Positions	126
Goal burnup	10% (1st core 5%)

Table - 2

CORE AND BLANKET CORE-1

	Driver zone	Axial blanket	Radial blanket
Fuel material	UO ₂ enriched	UO ₂ depleted	UO ₂ depleted
Form	Annular	Annular	Annular and solid
²³⁵ U Inner zone	28% (235 assy)		
Outer zone	21% (162 assy)		
Density (smear)	80% TD		
Pellet od/id	5.7-5.9 mm/1.8 mm		
Rod cladding	Stainless steel		Stainless steel
Od	6.9 mm		14.2 mm
Wall thickness	0.4 mm		0.4 mm
Fuel-clad gap	0.1-0.5 mm		
Column length	0.7	0.4 m x 2	0.4 m
Gas plenum length	0.8 m, bottom		
Vented/non-vented	No		
Assembly material			
Shape	Hexagonal		Hexagonal
Across flats	96 mm		96 mm
No. pins/assembly	127		37
Pin spacing	Wire wrap		Ribs, od over ribs 15.25 mm
Pin pitch	8.05 mm		
Assy. pitch	98 mm (59 mil pads)		
Assy. in core	397		

VII. A. CORE AND BLANKET

The first BN-600 core, which uses enriched UO_2 as fuel, will contain sealed fuel elements. Vented elements are under consideration for use in future mixed-oxide cores. With the exception of the addition of a large gas plenum, the fuel assembly is very similar to that of the BN-350. Both the upper and lower blanket pellets in the pin have been incorporated into the same jacket with the fuel pellets. The pellets are annular with a smear density of about 80% TD. The pins are spaced by radially-wrapped wire. (Fig. VII.A-1).

The first two rows of radial blanket assemblies also contain annular pellets

while the outer assemblies contain solid pellets. Stainless-steel 3-rib-tubes (rib diameter = 15.25 mm) are used for cladding. Radial blanket assembly geometry is similar to fuel assembly geometry.

Throttles in the assembly tails distribute the sodium coolant. The sodium inlet is radial and provides hold-down. The assemblies are combined into four, five and seven assembly modules fixed to bushings in the outlet plenum structure. No radial restraint is provided.

There are 126 fuel storage positions outside the radial blanket. (Refs. 1, 2.)

1. TOP END CAP	5. CLADDING
2. POROUS PLUG	6. SPACER TUBE
3. BLANKET	7. SPACER WIRE
4. FUELED SECTION	8. LOWER END CAP

DIMENSIONS IN MM

Figure VII.A-1a BN-600 Fuel Assembly (Ref. 3)

Figure VII.A-1b BN-600 Fuel System (Ref. 3)

VII. B. CORE SUPPORT AND VESSEL INTERNALS

The reactor tank is supported by a ring girder that also supports a bridge-truss structure spanning the bottom of the tank. The reactor core intermediate heat exchangers, radial shielding and pump shells are all supported by the truss structure. A primary flow shroud nests the radial blanket and shielding.
(Ref. 2.)

VII. C. REACTOR VESSELS AND SHIELDING

The reactor vessel contains both the core and all of the components of the primary circuit. It is a cylindrical tank 12.8 m in diameter with a tapered upper part and an elliptical bottom. Its height is 12.6 m; the wall thickness is 30 mm for the cylindrical and bottom part and 50 mm for the upper tapered part. All components except the rotating plugs are mounted on a support girdle, which in turn is mounted on a support ring that forms an integral part of the vessel. The rotating plugs are supported on the upper, tapered part of the vessel. The vessel is enclosed in a tight jacket extending above sodium level, the gap between vessels being filled with inert gas at a slight over-pressure. Sodium leak warning devices are mounted in the gap. There are six cavities for heat exchangers and three for pumps in the upper part of the vessel; the difference in thermal expansion

between the vessel and components is compensated by means of bellows. A "top-hat" structure encloses control and instrumentation mechanisms.

The reactor is mounted on a concrete base. A cylindrical supporting shell is welded to the lower part of the vessel. This shell rests in two roller supports mounted on the base beam. The vessel is kept from turning by four radial keys. The rollers and their guides are cooled by air entering for reactor vessel cooling. (Fig. VII.C-1.) (Ref. 1.)

Intravessel shielding consists of a set of steel plates adjacent to the core and several rows of vertical steel tubes filled with graphite at the periphery of the shielding.

Figure VII.C-1 BN-600 Reactor (Ref. 3)

VII. D. CONTORL ELEMENTS

There is a total of 27 safety and control elements in BN-600. Of these, two are automatic control rods, 19 are burnup and temperature compensators and six are safety elements. B_4C is the absorbing material for the automatic control rods and the safety elements. The burnup and temperature compensators will contain B_4C or tantalum. The automatic safety system occupies two cells in the central part of the low-enrichment zone. The assemblies are sealed. (Refs. 1,2.)

VII. E. HEAT TRANSFER SYSTEMS

Two pressure pipes deliver the primary circulating sodium into the distribution chamber of the primary tank. From there it is directed among the fuel and blanket assemblies. Part of the incoming flow is used to cool the reactor vessel, the assembly storage points and the inner shield. Sodium enters the assemblies radially, flows upward and, at a temperature of 550°, exits to the six intermediate heat exchangers through an annular gap in the shielding around the core. The primary sodium flows downward in the shell-side of the heat exchangers and exits at a temperature of 380°C. It then enters three overflow chambers where it is fed to pumps that deliver it back to the reactor. Secondary sodium flows upward through the tube side of the IHX and downward in the economizer-evaporator section of the steam generator.

The IHX is a vertical tube-and-shell unit. Pressure in the secondary sodium side exceeds pressure in the primary side. There are six IHX's.

Pumps circulating primary and secondary sodium are mounted in cold-legs. They are immersible, single-stage, double-suction units with a fixed coolant level in the pump tank. Sodium-lubricated hydrostatic bearings are used at the impeller end and oil-lubricated radial and thrust-bearings are used outside the sodium and sodium-vapor space. Rotating gas seals retain the inert-gas blanket over the sodium pool. Pump capacity is 32,000 gpm.

Check valves are installed inside the pump casings below the impeller in the discharge. There are no stop valve in the primary or secondary circuits, a loop being shut down by closing the check valve in the pump of that loop. (Refs. 1, 2.)

VII. F. SODIUM PURIFICATION AND
INSTRUMENTATION

Cold traps are used to maintain satisfactory oxygen concentration. The BN-600 cold-trap design is similar to the BN-350 trap. It is cooled with NaK and only one metal wall separates the coolant from the sodium.

Information on other sodium monitoring and instrumentation systems is not available. In-sodium hydrogen diffusion meters are being studied and development is proceeding on other on-line monitors, e.g., electrochemical oxygen meters and carbon diffusion cells. (Ref. 2.)

VII. H. STEAM GENERATORS

The reference design for BN-350 steam generation is for three once-through, single-wall steam generators. Each has two 3.6 m diameter units. The economizer and evaporator are located in one 12 m high unit. The second unit, 17 m high, contains the main and reheating steam superheaters. Secondary sodium passes through the superheater and evaporator sections in succession. Each unit has a free sodium level with the space above the sodium filled with argon at a slight over-pressure. The generators are provided with a special system to ensure the discharge of sodium-water reaction products in the event of water leakages into

the sodium. This system consists of 250-m³ separators in series mounted on top of the steam generator room for each of the three secondary loops. A fast-response stop valve on the feed-water line is provided in case of leakage in a steam generator. Steam at 505°C and 140 ATM is directed from the steam generators into three turbo-generators. Thermal capacity per set is 480 MWt. A startup steam separator would be passed during normal power operation.

A modular version of the steam generation system is under consideration.
(Refs. 1, 2.)

VII. J. FUEL HANDLING

The fuel handling system is similar to that of the BN-350. It includes two rotating plugs, two handling devices, two elevators, a handling casket for assembly transport, and two fuel-handling drums. The large rotating plug is mounted on the tapered part of the reactor vessel with the small one placed eccentrically on it. Loading and unloading follows the same sequence as in BN-350. (Fig. VIII.J-1.) (Refs. 1, 2.)

Figure VII.J-1 BN-600 Fuel Handling System

BN-600 VII.K.

VII. K. CONTAINMENT

The reactor building is a conventional-type building about 47 m high. A steel-lined concrete cell contains the main reactor tank. The steam generator and auxiliary building, and the turbine building, are separate, adjacent structures. (Ref. 2.)

VIII. JOYO

LOCATION: O-Arai Center, Japan

Joyo is an experimental fast sodium-cooled reactor. Construction was begun in 1971 at the O-Arai Engineering Center, Japan. First step power will be 50 MWt. Final design power is 100 MWt. The project is being conducted by the Power Reactor and Nuclear Fuel Development Corporation of Japan. Joyo is a two loop system.

The preliminary design was done in 1964, and the first conceptual design was begun in August 1967 and completed in May 1968. In October 1967, the Power Reactor and Nuclear Fuel Development Corporation (PNC) was established. PNC has assumed responsibility for design, R & D, construction and operation of the reactor. PNC gave contracts to five industrial consortia for the third conceptual design, which was submitted to PNC in March 1969. Application for a construction permit was filed in June, 1969. As of July 1974 construction was nearly completed. It was reported that fuel assemblies were being installed, and blanket assemblies were being assembled, while instrumented assemblies were still under design.

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Table - 1

GENERAL PARAMETERS (Mark-1)

Type	Loop-type
No. loops	2 + 1 auxiliary
Coolant	Sodium
Core inlet temp.	370°C
Core outlet temp.	435°C
Flow direction	Upward
Driver fuel	UO ₂ -PuO ₂
Blanket fuel	UO ₂ depleted
Core diameter	73 cm
Core volume	250 l
No. enrichment zones in core	1
Output MWe/MWt	50 MWt
Breeding ratio	1.0
Fuel centerline temp.	~ 1400°C
Neutron flux, total	1.1×10^{-15}
Doppler ($\Delta k/k$)/°C (Core)	-1.6×10^{-3}
No. Driver elements	67
No Radial blanket elements	191
No. In-core control elements	6
In-Vessel storage positions	32
Goal burnup	25,000 MWD/T

Table - 2

CORE AND BLANKET (Mark-1)

	Driver zone	Axial blanket	Radial Blanket
Fuel material	UO ₂ -PuO ₂	UO ₂ depleted	UO ₂ depleted
Form	Pellet - solid	Pellet - solid	Pellet - solid
Composition PuO ₂ /(PuO ₂ + UO ₂)	17.7 w/o		
²⁴⁰ Pu	19.0%		
²³⁵ U	23.0%	0.2%	
Density	93.5% TD	94%	94%
Pellet od	5.3 mm	5.3 mm	13.6 mm
Rod Cladding	Stainless steel		Stainless steel
od	6.3 mm		15 mm
Wall thickness	0.35 mm		0.6 mm
Bond material	Helium		Helium
Column length	60 cm		140 cm
Gas plenum length	40 cm (top)		
Pin length	190 cm		190 cm
Vented/non-vented	No		No
Assembly material	Stainless steel		Stainless steel
Shape	Hexagonal		Hexagonal
Across flats (dia.)	78.5 mm		78.5 mm
Wall thickness	1.8 mm		1.8 mm
No. pins/assembly	91		19
Pin spacing	Spiral wire		Spiral wire
Pin pitch	7.6 mm		16.4 mm
Assy. in core	67		191
Volume Fraction			
Fuel (vol %)	37.6		
Steel	40.6		
Sodium	20.4		

Upper and lower axial blanket pellets
are loaded into the same cladding with the fuel pellets

VIII. A. CORE AND BLANKET

Core fuel pins have sintered pellets of mixed oxide fuel, with axial blanket pellets of depleted UO_2 loaded above and below in the same can. A top plenum is provided to contain the fission gases. Wires, 1.2 mm dia., are wrapped spirally around the pins to provide a pitch of 7.6 mm. The plenum sleeve and plenum spring are loaded into the gas plenum space to prevent the fuel column from moving up and down. The hexagonal assembly holds 91 pins, and is connected to a handling head at the upper end and to an entrance nozzle at the lower end. A fixing-box and knock-bars at the lower end hold the fuel pins in place. Two spacer pads are provided on the side walls of the assembly. The radial assembly has the same shape and size as the core assembly.

It holds 19 pins of greater diameter. Spacing is by spiral wire wrap to give a pin pitch of 16.4 mm. (Fig. VIII.A-1)

Reflectors are stainless steel hexagonal rods. (Ref.5.)

The MARK-2 core preliminary surveys have been done by Sumimoto Electric Industries and Mitsubishi Atomic Power Industries. Design studies are continuing. The preferred solution seems to be a two-region core with 32.5 ~ 27.7 w/o plutonium enrichment. Pellet diameters from 4.5 to 5.0 mm were investigated. The MARK-2 core is to have an output of 100 MWt and a maximum neutron flux $> 5 \times 10^{15} \text{ n/cm}^2 \text{ sec}$. (Ref. 4.)

Figure VIII.A-1 JOYO Fuel Assembly (Ref. 5)

VIII. B. CORE SUPPORT AND VESSEL INTERNALS

A grid-plenum structure supports the core and serves as a high-pressure plenum for the inlet sodium. The support grid is a sandwich-type structure composed of two 50 mm-thick perforated plates spaced 350 mm apart by connecting tubes and a surrounding cylinder. The high-pressure plenum is between the plates and supplies sodium to the fuel and inner blanket regions. The low-pressure plenum is below this structure, between the lower plate and a supporting structure for the grid-plenum assembly.

This supporting structure is bolted to a support lug in the reactor. A flow guide pipe attached to it directs the sodium from the spherical plenum to the supporting structure. The bottom of this pipe has a labyrinth connection. (Fig. VIII.B-2)

The core barrel consists of six cylindrical sleeves held apart by spacers. It serves as shielding around the core. (Fig. VIII.B-1) (Ref. 1)

Figure VIII.B-1 JOYO Core Support and Barrel (Ref. 1)

Figure VIII.B-2 JOYO Labyrinth Structure (Ref. 1)

VIII. C. REACTOR VESSELS AND SHIELDING

The reactor vessel is a stainless steel, double-walled cylindrical structure approximately 3.6 m. id and 10.5 m high. Nitrogen gas fills the annular space. Two inlet nozzles are located at an angle of 90° to each other in the base, with outlets in the upper part. An inlet for emergency cooling sodium is just below the main outlets, with an outlet for the emergency sodium on the opposite wall. There are also nozzles for a liquid sodium over flow system, an argon gas system, and other systems in the upper part. There is a spherical bottom plenum. (Fig. VIII.C-1, C-2, C-3) (Ref. 2)

The vessel encloses the core, rotating fuel storage racks, core support structures, material monitoring racks etc. Top closure consists of two rotating plugs, each with its own drive mechanism. They consist of layers of stainless steel, carbon steel, and graphite, with a thickness of about 2.5 m. Cooling is by internal circulation of nitrogen gas. All mechanisms are installed in the small plug. (Fig. VIII.C-3) The vessel is hung by a top flange. (Ref. 2)

A graphite shield, one meter thick, serves as a safety vessel. Concrete biological shielding surrounds the vessel and shield. (Ref. 2)

VIII.C-2

Figure VIII.C-1 JOYO Vessel Showing Nozzles (Ref. 1)

The drawing consists of two main views: Section P-P and View A-A.

Section P-P: A circular cross-section showing concentric rings. The outermost ring is labeled $R 5 \times 80$. The innermost ring is labeled $4 \times A$. The section is divided into segments by radial lines, with angles of 15° and 30° indicated. The total diameter is 4000ϕ , and the inner diameter is 3890ϕ .

View A-A: A longitudinal section showing the internal structure. It includes a central circular component with a diameter of 750 and a radius of $600R$. The section is divided into segments by radial lines, with angles of 15° and 30° indicated. The total diameter is 4000ϕ , and the inner diameter is 3890ϕ . The section is labeled $P-P$ and $A-A$.

Section P-P:

Section P-P is a circular cross-section of a structure. It features concentric circles representing different layers. The outermost layer is labeled $R 5 \times 80$. The innermost layer is labeled $4 \times A$. The section is divided into segments by radial lines, with angles of 15° and 30° indicated. The total diameter is 4000ϕ , and the inner diameter is 3890ϕ .

View A-A:

View A-A is a longitudinal section of the structure. It shows the internal components, including a central circular part with a diameter of 750 and a radius of $600R$. The section is divided into segments by radial lines, with angles of 15° and 30° indicated. The total diameter is 4000ϕ , and the inner diameter is 3890ϕ . The section is labeled $P-P$ and $A-A$.

JOYO VIII.C

Figure VIII.C-3 JOYO Rotating Plugs (Ref. 1)

Figure VIII.C-4 JOYO Reactor Structures (Ref. 1)

VIII. D. CONTROL ELEMENTS

Reactor control is by means of four control rods and two safety rods, arranged symmetrically in the core region. Rods consist of seven elements, 70 cm long, containing B₄C pellets enriched in ¹⁰B. Containment is a stainless steel tube. Travel distance is about 90 cm. They are driven by a ball-nut screw mechanism, with springs to accelerate insertion into the core. (Ref. 1)

VIII. E. HEAT TRANSFER SYSTEMS

Joyo has a two-loop heat transfer system. All primary system piping is double walled. The space between the walls is filled with nitrogen gas. Each main loop includes an intermediate heat exchanger and a pump. In the secondary system heat is rejected by means of an air-cooled heat exchanger. Pumps are in cold legs. The system includes cold traps and a plugging meter.

Sodium enters the fuel assembly from the high pressure plenum through lateral orifices in the assembly, and flows upward through the core. In the blanket region, sodium from the high-pressure plenum enters the low-pressure plenum through orifices in the ends of the reflectors and flows into the blanket assemblies at the bottom ends. Flows merge into one above the core in the reactor vessel and are led to the heat exchangers through the outlet nozzles and the hot leg piping. Primary sodium flow is downward through the IHX to the main pump, which returns it to the reactor. An overflow system maintains the sodium level constant. Cover gas is argon. Dip plates prevent surface ripples.

The main pipes have the following parameters:

Reactor to IHX	0.484 m dia.
IHX to pump	0.391 m dia.
Pump to reactor	0.340 m dia.
Straight pipe distance	
Reactor to IHX	34 m
IHX to pump	17 m
Pump to reactor	50 m

Total flow is 2174 t/hr. (Ref. 1, 2)

Secondary system sodium circulates at a higher pressure than in the primary system. Piping is single-walled. Heat is rejected by means of a sodium-air heat exchanger, which is a finned, multitube, forced air cooled unit. (Fig. VIII.E-1) Four such units are installed in the secondary loops. (Ref. 1)

Primary and secondary pumps are vertical, free-surface, centrifugal units, with a hydrostatic bearing operating in sodium and double mechanical seals in the top part. (Fig. VIII.E-2) The auxiliary cooling system uses linear induction type electromagnetic pumps.

The IHX is a vertical, free-surface, shell-and-tube unit. Sodium surface is covered by argon gas. Primary sodium flows downward through the shell side, and secondary sodium circulates in the tubes. Inlet temperature of the primary sodium to the IHX is $\sim 420^{\circ}\text{C}$, outlet about 355°C . (Fig. VIII.E-3)

The emergency heat-transfer system is a separate system, with a primary and secondary loop and its own intermediate heat exchanger and air-dump heat exchanger. Heat transfer fluid is NaK. (Fig. VIII.E-4, E-5) (Ref. 1)

VIII.E-2

Figure VIII.E-1 JOYO Main Air Cooler (Ref. 1)

Figure VIII.E-2 JOYO Primary Pump (Ref. 1)

VIII.E-5

Figure VIII.E-4 JOYO Emergency Cooling System Flow Design (Ref. 1)

JOYO VIII.E

Figure VIII.E-5 JOYO Emergency Intermediate Heat Exchanger (Ref. 1)

VIII.E-6

VIII. F. SODIUM PURIFICATION AND
INSTRUMENTATION

Primary sodium purification is performed by cold traps, with oxygen concentration being maintained at less than 10 ppm. The purification system is connected both to the main loop and to the overflow tank. Sodium for purification is provided by an electromagnetic pump from the suction line of the main pump. After purification, sodium is returned to the shell side of the IHX. Cold-traps can be by-passed when monitoring for oxygen indicates a satisfactory level. The purification loop has one electromagnetic pump, one sampling pot, three plugging sets, one cold trap economizer, two cold traps (one is a spare), and an NaK/air heat exchange unit. (Fig. VIII.F-1)

The secondary purification system is provided by an air-cooled cold trap. It has two loops, with electromagnetic pumps, plugging meter sets, sampling pots, cold traps.

The NaK which is used for the auxiliary cooling system and for cooling the primary loop cold traps is purified by an air-cooled cold trap in a one-loop system. (Ref. 1)

Figure VIII.F-1 JOYO Primary Cold Trap (Ref. 1)

VIII.F-2

VIII. G. COVER GAS AND AUXILIARY SYSTEMS

The primary argon, which is radioactive, is provided by a recirculating system consisting of a buffer tank, pressure regulating tank, vacuum tank, sodium vapor trap, mist catcher, and compressor. Purge argon used in operation of the refueling machine, blow-down argon for the control rods, and sealing argon for the rotating plugs is supplied from the buffer tank. The

secondary, non-radioactive argon is supplied from a secondary argon supply tank. Pressure of the secondary system argon is higher than primary blanket argon pressure. (Fig. VIII.G-1) (Ref. 1)

Nitrogen is used in the spaces in jackets and in the piping annuli. The shield tank and rotating plugs are cooled by forced flow of nitrogen. (Fig. VIII.G-2)

Figure VIII.G-1 JOYO Argon Gas System (Ref. 1)

Figure VIII.G-2 JOYO Nitrogen Systems (Ref. 1)

VIII. I. INSTRUMENTATION AND CONTROL

For sodium instrumentation see Section F.

Reactor power is manually controlled. The plant control system keeps the inlet sodium coolant temperature constant by changing the air flow rate of the main air-cooled heat exchanger. This system is automatically or manually controlled by the signal from the inlet temperature monitor. Neutron monitoring systems monitor neutron flux level and reactor period during start-up, operation, and shut-down. There are two startup channels, three intermediate power channels, and three linear power channels. Process-instrumentation systems monitor plant performance by measuring temperature, pressure, and flow-rates of sodium and argon gas. Ordinary thermocouples measure the temperature. Electromagnetic flow meters measure sodium flow. Sodium leak detectors are located at many points.

The reactor protection system has automatic functions of shut down by insertion of control rods, and reactor containment isolation by closing valves of pipes and ducts penetrating the enclosure. It also has an interlock system to prevent reactor malfunction.

Delayed neutron monitoring of the sodium coolant, and measurement of fission gases released to the argon cover gas, are used for failed fuel detection.

Instrumentation and control systems are centralized in a control room in the reactor building. (Ref. 2)

VIII. J. FUEL HANDLING

A refueling machine is used to move the fuel assembly from its core position to an in-vessel storage rack. This machine is set on top of the double rotating plug for the exchange. It can hang any fuel or blanket assembly, and can move it between the core and the storage rack in a liquid sodium environment. The storage rack is used to relay new and spent fuel, and to cool the spent fuel. (Fig. VIII.J-1)

To introduce assemblies into the vessel or to remove them, a charge-discharge machine is used. This machine moves along a rail or a bridge. It moves fuel between the reactor vessel and a transfer rotor. (Fig. VIII.J-2) The transfer rotor can be used for temporary storage of new fuel or for temporary cooling of spent fuel. Fuel is moved between transfer-rotor and new-fuel or spent-fuel storage by a self-driven cask car.

Spent fuel is stored and cooled in a water-pool after washing.

VIII.J-2

Figure VIII.J-1 JOYO Fuel Transfer Machine (Ref. 1)

VIII.J-2

Figure VIII.J-2 JOYO Charge-Discharge Machine (Ref. 1)

JOYO VIII.J

VIII. K. CONTAINMENT

The containment vessel is a steel cylinder with a hemispherical top and semi-ellipsoidal bottom. Total height is about 60 m, with 30 m above ground. Inside diameter is about 28 m. The cylindrical part is surrounded by a concrete wall, with the space between vessel and wall at negative pressure. Air-tight doors are at all accesses. Separation valves are installed in pipes and ducts between the containment vessel and the annex building.

The operating floor is at ground level. The space above the floor contains atmospheric air. The space below the floor is normally filled with nitrogen gas. A polar crane is installed to handle heavy equipment within the containment vessel. The reactor vessel is located a little north of center. The fuel handling facility is within the containment structure. The intermediate heat exchangers, primary pumps etc. are installed near the reactor vessel.

An annex building partly surrounding the containment vessel has a fuel handling facility, a central control room, a blower-room, waste-gas tank room etc. In another part of the annex building, an emergency diesel generator room, battery room, secondary system rooms and rooms for air-conditioning, liquid waste etc. are located. Secondary cooling systems are in a main-cooling building. The maintenance building is for maintenance and repair of equipment. In the waste disposal building, liquid-waste tanks and solid-waste storage are in the basement, and waste-treatment facilities are on the ground floor. (Fig. VIII.K-1) (Ref. 2)

Figure VIII.K-1 JOYO Reactor Building (Ref. 7)

MONJU IX

LOCATION: Japan

Monju is a 300 MWe prototype fast reactor. It uses a loop-type configuration. Single-wall piping will be used instead of the double-wall piping called for in the first design studies. Safety analysis reports were continuing in 1974, and critical mockup experiments of the Monju core are being conducted. Sites are being considered for construction of the station.

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Table - 1

GENERAL PARAMETERS

Type	Loop-type
No. loops	3
Coolant	Sodium
Core inlet temp.	390° C
Core outlet temp.	540° C
Flow direction	Upward
Driver fuel	UO ₂ - PuO ₂
Blanket fuel	UO ₂ depleted
Core diameter (equivalent)	1780 mm
Core volume	2230 ℓ
No. enrichment zones in core	2
Output MWe/MWt	300 MWe/714 MWt
Breeding ratio	~ 1.2
Max. can temperature	<700° C
Linear power, max.	457 W/cm
Neutron flux, total	4×10^{15} n/cm ² sec. (ave.)
Power Density	292 KW/ ℓ
No. Driver elements	196
No. Radial blanket elements	174
No. In-core control elements	19
In-Vessel storage positions	80
Goal burnup	$\sim 80,000$ MWD/T

Table - 2

CORE AND BLANKET

	Driver zone	Axial blanket	Radial blanket
Fuel material	UO ₂ + PuO ₂	UO ₂ depleted	UO ₂ depleted
Form	Sintered pellet	Sintered Pellet	Sintered Pellet
Composition	Inner 16 v/o PuO ₂		
	Outer 22 v/o PuO ₂		
²³⁵ U/U	0.2 w/o		
PuO ₂ /(PuO ₂ + UO ₂) inner	22.64 a/o		
outer	31.0 a/o		
²⁴⁰ Pu	25%		
Density	85% TD	93% TD	93% TD
Pellet od	5.4 mm		
Rod cladding	Stainless steel (316)		Stainless steel (316)
od	6.5 mm		11.6 mm
Wall thickness	0.45 mm		0.5 mm
Bond material	Helium		
Column length	900 mm	350 mm x 2	1600 mm
Gas plenum length	1130 mm Top		
Vented/non-vented	No		No
Assembly material	Stainless steel		Stainless steel
Shape	Hexagonal		Hexagonal
Across flats (dia.)	110.6 mm		110.6 mm
Wall thickness	3 mm		3 mm
Overall length	4200 mm		4200 mm
No. pins/assembly	169		61
Pin spacing	wire or honeycomb grid		wire
Pin pitch	7.9 mm		13.1 mm
Assy. pitch	115.6 mm		
Assy. in core	196		174
Fuel (UO ₂ + PuO ₂)	32.8%		
Steel	23.4%		
Sodium	41.3%		

Upper and lower axial
blankets are integral with
the core fuel.

IX. A. CORE AND BLANKET

The Monju core has 196 fuel assemblies with 2-region enrichment, 174 blanket assemblies arranged in three rows around the fuel core, nineteen control assemblies, and four rows of stainless steel reflectors. Assemblies are sealed. In the fuel assembly the upper and lower axial blanket pins are integral with the fuel core. Control assemblies have B₄C as an absorber.

Each fuel assembly has three grid supports for the pins. Pin pitch is maintained over the length of the element by a 1.3 mm od stainless steel wire spacer or a honeycomb grid spacer. Radial blanket pins are spaced by stainless steel wire. Fixed orifices, in the bottom of the assembly, control sodium distribution to the core.

MONJU IX.B

IX. B. CORE SUPPORT AND VESSEL INTERNALS

A core support structure is above the sodium inlet plenum. The plenum has a hydraulic holddown arrangement for the assemblies. A core restraint mechanism applies restraining force against radial motion and positions the core during refueling.

The support grid consists of upper and lower plates with openings for the assembly feet. The outer core-clamping mechanism is similar to mockup experiments for FFTF and AI demonstration reactors. An inner clamping system applies to laterally movable pads on central control or fuel assembly surrounded by six assemblies.

IX. C. REACTOR VESSELS AND SHIELDING

The reactor vessel is a double-walled vertical cylinder, with three 26-in. diameter inlet nozzles at the base and three 32-in. diameter nozzles above the core. Upon completion of the third design, it was decided to incorporate a leak-tight barrier around the reactor and primary system. The space between vessels will be filled with nitrogen gas. The addition of this leak or guard vessel has made it possible to use single-wall piping rather than double-wall piping for the primary loops. The reactor vessel is about 6.3 m in diameter and 16.0 m

high. It is closed at the top by a double shield plug, which has only one rotating piece. The vessel is hung by a device on the upper part. These vessels are housed in a safety vessel which is inside the concrete biological shield structure. (Fig. IX.C-1)

The fixed plug has a diameter of ~ 8 m. The rotating plug diameter is about $4\frac{1}{2}$ m. Overall thickness is 2-3 m. Freeze seals are used. Ref. (4,7)

Figure IX.C-1 MONJU Reactor Structure (Ref. 4)

MONJU IX.D

IX. D. CONTROL ELEMENTS

There are nineteen control elements, consisting of three regulating rods, nine shim rods, four safety rods, and three back-up shut down rods. B₄C is the poison material.

IX. E. HEAT TRANSFER SYSTEMS

There are three primary and three secondary loops. Each primary loop includes an intermediate heat exchanger, pump, check valves and piping. The secondary loop includes flow control and stop valves, a steam generator set, pump and piping. Pumps are located in cold legs. All piping is single-walled. With adoption of the single-pipe system, a siphon-breaker system included in earlier designs has been dropped. All primary heat transport systems are placed in guard vessels, which let the primary system act in an auxiliary coolant mode in case of sodium leakage. (Fig. IX.E-1)

When the primary system is utilized as an auxiliary or emergency core cooling system, primary sodium flows from the reactor vessel across the auxiliary heat transfer coil, which is contained in the same shell (IHX) as the main heat transfer section. The auxiliary section is a coiled type tube heated outside the shroud. The main section of the IHX is a straight vertical type tube with no free sodium surface. Each auxiliary coolant section feeds to its own, independent secondary system, with heat rejected by air coolers. Electromagnetic pumps move the fluid in these auxiliary loops. (Fig. IX.E-2)

The primary pumps are long-shaft centrifugal units with free sodium surface. Internals are removable. They are equipped with cyclic converter type controllers. The same controller is used in case of auxiliary mode operation at 15% of the maximum operational speed. Overflow is a simple overflow type column type with the overflow piped back to the suction of the pump. The pump is operable with the sodium level inside the reactor at approximately 4.5 m below normal level. Pump design is still under development.

Monju has an auxiliary 3 MW loop driven by an electromagnetic pump which can lower the sodium level to inspect the tops of fuel assemblies. Each assembly has flow-holes near the upper end which allow a small sodium flow to be maintained.

A major development program for valves is in progress. Two globe-type twelve inch valves, one with a bellows seal and one with a freeze seal, are first in the program. Twenty-two inch gate valves and twenty-six inch check valves have been manufactured and tested. Butterfly valves are under construction. A thirty-two inch valve is being considered for primary system use. Cold traps and flow-meters are being studied. (Ref. 5)

Figure IX.E-1 MONJU Flow System (Ref. 7)

Figure IX.E-2 MONJU Intermediate Heat Exchanger (Ref. 5)

IX. G. COVER GAS AND AUXILIARY SYSTEMS

(Emergency auxiliary cooling system.
See Section E)

Cover gas is argon. The circulation system is closed-cycle and pressure of the cover gas is about $0.3 \text{ kg/cm}^2\text{g}$. Reactor cover gas can be closed off in case of primary sodium leakage. There is a full-flow gas cleaning system of the nitrogen cooled fractionating type.

The preheating system for the primary system is under investigation. The system being considered is a combination of electric resistance heaters, inner argon preheating system, and outer nitrogen preheating system. (Ref. 5)

IX. H. STEAM GENERATORS

Each secondary loop includes one steam generator set. The system consists of an evaporator, a reheater, and a superheater. Thermal output for full load is 238 MW per loop. The generators have been designed for a series-parallel reheat cycle, with an evaporator and a superheater operating in series, and a superheater-reheater operating in parallel. Monju will operate down to 30% partial load. At full load the generators will operate as a once-through unit, but this may be changed to recirculation operation, depending on the outcome of studies.

Sodium at 515°C from the IHX separates and flows into the superheater and reheater. Flow ratio is regulated by a flow control valve and fixed orifices at locations in the secondary system. The sodium is then recombined before entry into the evaporator. Temperature at this time is about 454°C. It leaves the evaporator at 320°C and is sent back to the IHX.

On the water side, slightly superheated steam extracted from turbine flow goes through a water-steam separator located between evaporator and superheater. Outlet

steam flows into the superheater and exits at 487°C and 133 kg/cm²g to the high pressure turbine. Low pressure steam from the turbine returns to the preheater to generate reheated steam.

Cover gas and sodium are monitored for hydrogen to detect sodium-water reactions. A relief system is provided which includes a reaction product separator. The hydrogen gas after separation is blown out to the atmosphere via a check valve. (Fig. IX, H-3)

The steam generator is a helical coil type with downcomers and a free sodium surface. The top head is assembled with the lower shell and bolted flanges. The tube support bundle is supported from the top head and is removable. Tube sheets are sodium. A stainless steel liner is installed between the helical coil bundle and the main shell. An overflow and a sodium makeup nozzle are installed. No such nozzles are used for the superheater or reheater. (Fig. IX.H-1, H-2) (Ref. 8)

Figure IX.H-1 MONJU Steam Generator Flow Diagram (Ref. 8)

Figure IX.H-2 MONJU Steam Generator (Evaporator) (Ref. 8)

Figure IX.H-3 MONJU Typical Relief System (Ref. 8)
IX.H-3

IX. J. FUEL HANDLING

An under-the-plug-system by means of a single rotating plug and a rotating arm fuel handling machine is designed for Monju. Spent fuel is transferred from the core position to an in-vessel storage rack. There are eighty storage positions available. A charge-discharge machine transfers the element to an ex-vessel transfer machine. A cask-car is used to transfer the element to a spent fuel storage tank. A cleaning facility and a spent fuel water pool

complete the sequence. After inspection, new fuel follows this path from a new fuel storage position to the core or blanket position. From forty to forty-two fuel assemblies and twenty-three blanket assemblies are exchanged at approximately six month intervals.

IX. K. CONTAINMENT

The reactor vessel is a low-leakage steel structure. A reactor pit contains the reactor, and a reactor access pit. Equipment cells are kept in an atmosphere of nitrogen. The cylindrical steel containment structure is located in the center of a rectangular reactor building.
(Fig. IX.K-1) (Ref. 7)

Figure IX.K-1 MONJU Reactor Building (Ref. 4)

X KNK

LOCATION: Karlsruhe, Germany

OPERATION: August, 1971

The KNK reactor was designed by Interatom in 1964 as a prototype sodium-cooled, zirconium hydride moderated reactor for energy production. It has been decided to introduce a fast core, which is targeted for operation in 1975. KNK-1 began operation in August 1971. The fast-core system is known as KNK-2. It will serve as a test bed for fast reactor fuel elements.

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4

Table - 1

GENERAL PARAMETERS

Type	ZrH moderated thermal reactor, loop-type
No. loops	2
Coolant	Na
Core inlet temp.	410° C
Core outlet temp.	560° C
Flow direction	Upward
Driver fuel	UO ₂
Core diameter	1292 mm
No. enrichment zones in core	1
Output MWe/MWt	20 MWe/58 MWt
Linear power, max.	500 W/cm ²
Doppler ($\Delta k/k$)/°C total	positive
Power Density Ave.	33 MWt/T
No. Driver elements	66
No. In-core control elements	9
Test positions	14
Goal burnup	10,000 MWD/T

KNK-1 X

Table - 2

CORE AND BLANKET

	Driver Zone
Fuel material	UO ₂
Form	Pellet
²³⁵ U	6.8 a/o
Pellet od	8.7 mm
Rod cladding	Stainless steel
od	9.5 mm
Wall thickness	0.3 mm
Bond material	He
Column length	1045 mm
Assembly material	Stainless steel
Shape	Cylindrical
Diameter	~ 128 mm od
No. pins/assembly	44
Pin spacing	Lower grid
Assy. pitch	129 mm
Assy. in core	66
Volume fraction	
Fuel Vol. %	18.3
Steel	6.0
Sodium	34.9
Z r H	40.4

Table - 3

GENERAL PARAMETERS

Type	Loop
No. loops	2
Coolant	Sodium
Core inlet temp.	360° C
Core outlet temp.	594° C
Flow direction	Upward
Driver fuel	UO ₂
Test zone fuel	UO ₂ -PuO ₂
Blanket (axial) fuel	UO ₂ depleted
Core dia., effective	~ 80 cm
Core volume	Driver zone 240ℓ
No. zones in core	2. Inner zone serves as test bed
Delayed neutron fraction	6×10^{-3}
Doppler (normal operation)	$-1.7 \times 10^{-6}/^{\circ}\text{C}$
Neutron lifetime	$4.3 \times 10^{-7}/\text{sec}$
Max. can temp.	~ 685° C
No. driver elements	22
No. test zone elements	7. Central element is SNR-type bundle
In-core control elements	6 + 2 independent shutoff rods
Test positions	6
Linear power, max.	460 W/cm
Goal burnup	90,000 MWD/T

KNK-2 X

Table - 4

CORE AND BLANKET

	Driver Zone	Test Zone	+ Axial Blanket
Fuel material	UO ₂	UO ₂ -PuO ₂	UO ₂ depleted
Form	Pellet	Pellet	Pellet
Composition		30 w/o PuO ₂ 70 w/o UO ₂	
²⁴⁰ Pu		14 - 18%	
²³⁵ U	40 a/o	80 a/o	
Density	Smear 83% TD	Smear 80% TD	
Pellet od		5.1 mm	
Rod cladding	Stainless steel	Stainless steel	
od	8.2 mm	6 mm	
wall thickness		0.38 mm	
column length		600 mm	200 mm x 2
pin length		1350 mm	
Assembly material	Stainless steel	Stainless steel	
Shape		Hexagonal	
No. pins/assembly	102 (moderated) 121 (unmoderated)	211 Central element has 169	
Pin spacing		Grids	
Pin pitch		7.9 mm	
Assembly pitch		129 mm	
Assembly in core	22	7	

X. A. CORE ASSEMBLIES

KNK-1 had a thermal core composed of sixty-six UO_2 fuel elements moderated by zirconium hydride. The assembly was round or ring-shaped, with two rings of fuel rods enclosed between a central cylinder of stainless steel - clad ZrH and an outer ZrH cylinder. The inner, centrally bored moderator was about 55 mm od, the outer ring about 12 mm thick and 128 mm od. Pin cladding was stainless steel, 9.5 mm od with a wall thickness of 0.3 mm. Each assembly had forty-four pins, with an active fuel length of 1045 mm. All voids were filled with sodium. (Fig. X.A-1) The thermal core became critical in August 1971. (Ref. 1, 5)

KNK-2 will have two zones - a driver zone consisting of UO_2 fuel elements, and a test zone with UO_2 - PuO_2 elements. There are two types of fuel elements in the test portions. Six of the elements have rounded edges of the wrappers and an extra row of fuel pins (211), and six tie rods in the corners. (Fig. X.A-2)

The central element has SNR geometry, except for active and overall length.

Assemblies in the test zone have an upper and lower axial blanket section. Pins are spaced by grids. Grid types to be tested are honeycomb spot welded grids, brazed ferrule spacers attached to the wrapper tube, and spark-eroded spacers attached to the six tie rods. Eight spacer grids per bundle are used. The head has a mixing device. Steel/ZrH reflector elements form an outer ring around the core. Steel and blanket elements are located inside this ring. (Ref.5)

The test zone has seven fuel assemblies. The central one is instrumented. The driver zone contains twenty-two fuel elements, six on an inner ring in contact with the test elements. Reflector assemblies surround the driver zone. Blanket elements for testing can be inserted into these positions, or the reflector elements can be replaced by additional driver elements. Driver elements may also be replaced by reflector elements. To improve the Doppler coefficient ZrHx will be incorporated into the driver. Some assemblies containing ZrHx pellets are canned in steel tubes similar to the fuel rods. Radial reflector assemblies will be cylindrical since they touch on the outer reflector segments. The wrapper tube for these assemblies will be filled with an undetermined number of single pins. Radial reflector assembly od is 129 mm. (Ref. 4) (Fig. X.A-3)

Figure X.A-1 KNK-1 Fuel Assembly (Ref. 5)

KNK X.A

Figure X.A-2 KNK-1 Core Cross-section (Ref. 11)

X.A-2

Figure X.A-3 KNK-2 Fuel Assembly, Test Position (Ref. 5)

CORE CROSS SECTION KNK II

- REFLECTORELEMENT (Steel / ZrH_x)
- ▨ REFLECTORELEMENT (Steel)
- △ CENTRAL ELEMENT (Pu)
- ⊗ SECONDARY SHUTDOWN
- ⬡ DRIVER FUEL (UO_2)
- ▤ TEST FUEL (Pu)
- ⊙ CONTROL ROD
- ▩ BLANKET
- ⊖ ORIENTING POSITION
- ⬢ MATERIAL TEST ELEMENT

Figure X.A-4 KNK-2 Core Cross-section (Ref. 5)

X. C. REACTOR VESSELS AND SHIELDING

The reactor vessel is a cylindrical structure 10.5m high and 1.9 dia., filled with sodium. The free surface has an argon blanket. A rotating cover 2.8 m thick is made of heavy concrete which protects a fully accessible operating room. An outer tank is provided as a leak-vessel. The annulus between the two vessels is filled with nitrogen gas. The biological shield is of high density concrete, which is nitrogen-cooled. The reactor tank is supported from above by a flange located in the cold area. (Fig X.C-1.)

The rotating shield plug system consists of a large rotating plug centered over the reactor vessel, and a smaller rotating plug off-set within it. Each plug contains, from bottom to top, 38 steel plates, 2 mm thick with 7.8 mm separation, a flat for forced cooling by nitrogen, shielding of basalt granules and high density concrete, a steel plate to support the bearings. Inflatable seals with buffer gas monitoring are used. Ball bearings support and center the plugs. (Fig. X.C-Z) (Ref. 10.)

Figure X.C-1 KNK Reactor Vessel and Structures (Ref. 1)

Figure X.C-2 KNK Detail of Rotating Shield System (Ref. 10)

X. D. CONTROL ELEMENTS

KNK control elements contain B_4C enriched in ^{10}B as an absorber. The first system for KNK-1 consisted of rigid rod-bundles positioned above the core. At the end of 1966 the licensing authorities required a second fast-acting, independent system for the reactor. This second system consisted of an absorber chain of articulated rods, also positioned above the core. Three of these elements were located around the core. On order to scram, the absorber chain was released to drop into an annulus formed by a guide tube and a central BeO displacement rod. Absorber chains were in shutdown condition during fuel handling. The first and second systems were electrically connected via a lag-time relay. (Fig. X.D-1.)

KNK-2 control rod system consists of six combined shim-safety rods positioned above the boundary between the two zones, and two independent shut-off rods positioned at the outer edge of the core. Absorbing material is B_4C with 60% ^{10}B enrichment. Reactivity requirements for the central shim rods will be 10% k/k and for the shut-off rods 2.4% $\Delta k/k$. Release time will be 250 sec. maximum and drop time 2600 msec. (Ref. 7.)

Figure X.D-1 KNK-1 Shutdown Systems (Ref. 7)

X. E. HEAT TRANSFER SYSTEMS

There are two primary and two secondary heat transfer loops. Low alloy ferritic steel is used. The intermediate heat exchangers are cylindrical shell and helical-tube structures. Flow is counter-current. Inlet temperature at the IHX is 306°C, outlet is 539°C. Pumps are centrifugal units. Cold traps and plugging meters are provided.

Primary sodium flows upward through the core. Pressure in the primary system is 4.5 atm. In the secondary loops it is 8.3 atm. The primary systems are in nitrogen-filled compartments, kept above atmospheric pressure.

Cover gas is argon. It is monitored by gas chromatography. (Ref. 2, 8.)

X. H. STEAM GENERATORS

The KNK steam generator is a concentric tube-in-tube system. Two units consist of twenty eight tubes each, with a maximum 1 MW per tube. Feed water at 200-235°C flows up the central tubes, and superheated steam at 570°C. Sodium flows downward in the annulus. The pressure-relief system consists

of shutoff devices at entrances to the sodium tubes, a depressurizer, a rupture disc, the pressure-relief line, the reactor products separation tank, and fast shutoff valves at both sides of the sodium heaters. The generator is a once-through type. (Ref. 8.)

Figure X.H-1 KNK-1 Steam Generator Concept (Ref. 9)

X. J. FUEL HANDLING

KNK fuel handling equipment includes a fuel handling machine with a gas-cooling circuit, an uncooled component handling device, a sodium-filled nitrogen-cooled storage tank for fuel assemblies, an inspection station, and a subassembly transport flask for transporting new and irradiated subassemblies. (Fig.X. J-1.)

The fuel handling machine consists of a superstructure and an undercarriage, a refuelling flask with bottom gate valve and an over-head hoisting unit, control and interlock devices. Its working area is bounded by its circular path around the stationary turning column and by the translational motion of the superstructure. The refuelling cask is sealed by a bottom gate valve with inflatable seals flanged to the flask. A sealing skirt provides a leak-tight connection with the shield plug transfer tube. The control panel is on top of the superstructure, with TV supervision. The machine is connected via the rotating column to argon cooling loops installed beneath the floor. Four different grippers can be coupled to the upper gripper assembly. (Fig.X. J-2.)

The large rotating plug is centered over the reactor vessel, with the smaller rotating plug positioned eccentrically within it. The fuel storage tank is closed at the top by a stationary plug. A rotating "Lazy-Susan" fuel assembly storage system is suspended from this plug. Each position can be served by one of six loading holes.

The transport flask for irradiated assemblies is a cylindrical vessel with a manually driven hoist unit on top. It transports assemblies to the inspection station and to stations located outside the containment. The inspection station is a shielded leak-tight cell in which components can be disassembled and inspected. Spent assemblies can be shipped to the reprocessing plant in a shipping flask after about ninety days decay. The fuel storage tank has a capacity of up to seventy-six sub-assemblies. (Ref. 10)

Figure X.J-1 KNK Schematic of Vessel, Storage Tank, and Fuel Handling Machine (Ref. 10)

Figure X.J-2 KNK Fuel Handling Machine (Ref. 10)

X. K. CONTAINMENT

KNK safety containment is provided by a cylindrical steel structure 17 m. dia, with a hemispherical head. A concrete containment structure is outside. The structure holds the reactor and primary system compartments, handling equipment and nitrogen systems. Auxiliary systems such as air-cooling, rad-waste, laboratories and

radiation monitoring stations are in an annex. Separate buildings house steam generators with the secondary sodium plant and argon system; turbine-generator plant, control switchboard, supplies and offices; and workshops, emergency power supply and feed water preparation.

XI. SNR-300

LOCATION: Kalkar, Germany

OPERATION: Target, 1979

In 1966, an industrial consortium was formed by Siemens/Interatom for long-term cooperation on fast reactor projects. The consortium made a study of a sodium-cooled fast breeder reactor, NR-2, which was a first approach to the SNR design. In 1968 the firms Belgonucleaire (Belgium) and Neratoom (The Netherlands) were added. Design of the SNR-300 has been done by Interatom. Participation in the project by the German, Netherlands, Belgium interests is about 70-15-15 percent respectively.

SNR-300 is a loop-type system using mixed oxide fuel. Construction was started in 1973 near Kalkar on the lower Rhine River. Operating target is 1979.

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Table - 1

GENERAL PARAMETERS MARK-1 CORE

Type	Loop
No. loops	3 + emergency loop
Coolant	Sodium
Core inlet temperature	377°C
Core outlet temperature	546°C
Flow direction	Upward
Driver fuel	UO ₂ -PuO ₂
Blanket fuel	UO ₂
No. enrichment zones	2
Output MWe/MWt	300/762
Max. can temperature	685°C (midline)
Fuel centerline temperature	2400°C Max.
Linear Power	354 n/cm max.
Neutron flux	6.4×10^{15} n/cm ² sec. max.
No. driver elements	205
No. radial blanket elements	96 + 186 steel reflectors
No. in-core control elements	12
In-vessel storage positions	0
Goal burnup. max.	90,500 MWD/T

Table - 2

CORE AND BLANKET MARK-1A

	Driver Zone	Axial blanket	Radial blanket
Fuel material	UO ₂ -PuO ₂	UO ₂	UO ₂
Form	Dished pellets	Pellets	Pellets
Composition U:Pu	80/20-70/30	Depleted U	Depleted U
Stoichiometry	1.97		
Density	86.5% TD		~ 90% TD
Pellet od	5.09 mm		8.3 mm
Rod cladding	Stainless steel	(Stainless steel)	Stainless steel
od	6 mm		11.6 mm
Wall thickness	0.38 mm		0.5 mm
fuel/clad gap	75 μ m		0.1 mm
column length	950 mm	2 x 400 mm	1750 mm
gas plenum length	Bottom 650 mm		Bottom 650 mm
Pin length	2475 mm	(axial blanket is integral with fuel core)	
Vented/non-vented	sealed		sealed
Assembly material	Stainless steel		Stainless steel
Shape	Hexagonal		Hexagonal
Across flats	110 mm		110 mm
overall length	3700 mm		3700 mm
pins/assembly	166 + 3 tie rods	61	
pin spacing	Honeycomb grids		Spiral wire
pin pitch	7.9 mm		12.92 mm
assy. in core	205		96

XI. A. CORE AND BLANKET

SNR-300 has been developed by Interatom. The Mark 1A core will have 205 driver assemblies, 96 radial blanket assemblies, 12 control rods, and 186 reflector assemblies. (Fig. XI.A-1)

The fuel assembly is a hexagonal stainless steel can 110 mm across the flats, containing a bundle of 166 fuel pins and three tie rods, located in the can by means of a honeycomb grid or egg-crate structure. Head and foot structures are welded to the wrapper can. The head contains a coolant mixing device. Overall length is 3700 mm.

The fuel pin is a 6 mm od stainless steel tube, with a wall thickness of 0.38 mm. It contains a 950 mm high stack of $\text{UO}_2\text{-PuO}_2$ pellets, dished at both ends. The pellet-clad gap is $75\text{ }\mu\text{m}$. Above and below the fuel core there is a 400 mm stack of UO_2 pellets forming the axial blankets. At the bottom, there is a 650 mm gas plenum. Pin spacing within the assembly can is by means of honeycomb grids, which give a pin pitch of 7.9 mm. There is an anchor plate at the lower end of the bundle. Fourteen or fifteen spacer

grids are supported axially by tie rods located in lattice positions. The tie-rods are solid, with the same dimensions as the fuel pins. The grid is assembled from stainless steel strip shaped and spot-welded to form a lattice of single hexagonal cells, except at the periphery where the cells are pentagonal. At the grid mid-plane, each cell has three ovoid dimples located 120° apart to provide contact points with the fuel pin. The gap between pin and dimple is about 1 mm. Centering pads are provided on each of the six lateral faces of the structure. (Fig. XI.A-2, XI.A-3) (Ref. 4, 19)

Radial blanket assemblies have 61 pins spaced by spiral wrapped wire. Pin diameter is 11.6 mm, and the pin-pitch is 12.92 mm. The hexagonal wrapper tube has the same dimensions as those of the fuel assembly.

The Mark-II core will have pins 7.6 mm od, with cladding wall thickness 0.50 mm. The assembly will contain 127 fuel pins. Spacers will be by grids. Pitch/diameter will be 1.16. The core will have 205 driver elements. (Ref. 9, 27)

Figure XI.A-1 SNR-300 Mark-1A Core (Ref. 24)

Figure XI.A-2 SNR-300 Fuel Assembly (Ref. 14)

Figure XI.A-3 SNR-300 Honeycomb Spacer Grid (Ref. 19)

XI. B. CORE SUPPORT AND VESSEL INTERNALS

The core of SNR is supported below the fission zone on a support plate surrounded by a shroud. A second plate is located above the active core. The plates are fabricated of ferritic steel, so that the differential thermal expansion between the ferritic rings and shroud and the austenitic structural material of the core affords the loosening required during refueling, when reactor temperature is lowered. The upper and lower plates are rigidly connected by struts. Plates are about 100 mm thick. The structure is supported at the vessel wall by a conical skirt. A grid-plenum structure below the core support and shroud directs inflowing sodium to the core, blanket, and reflector assemblies. The cold sodium penetrates by inlet lines through the hot tank wall, in the gas space between normal sodium level and the tank cover, via a conical

transition sleeve. The inlet pipes carry the sodium down to the collector vessel, and are welded to it. This lower plenum tank has a gas separating device to prevent large gas bubbles from passing through the fuel region. Sodium heated by passage through the core enters an outlet collector space formed by a cylindrical outlet skirt and an upper dip plate, exits through openings in the outlet skirt into an outer annular space to three outlet pipes. (Fig. XI.B-1) (Ref. 15,9)

A passive core restraint system is used, consisting of two ferritic steel rings located above and below the core. The arrangement is tight below the core, and provides a 6 mm clearance in the upper plane. (Fig. XI.B-2) (Ref.1)

Figure XI.B-1 SNR Core Support and Grid Structure (Ref. 5)

XI. C. REACTOR VESSELS AND SHIELDING

The cylindrical stainless steel reactor tank is 6.2 m in diameter, with 40 mm thick walls. It is surrounded by a stainless steel safety vessel. The gap between the vessels is about 300 mm, providing a space into which TV cameras can be introduced during shutdown for inspection of the vessel walls. The reactor vessel wall, in contact with sodium, has a thermal lining. All pipework lines are accommodated below the emergency sodium level, entering at the top of the vessel and dropping down to the bottom collector vessel. The pipes are welded to the bottom collector vessel, which is supported on the bottom of the reactor tank. The reactor vessel is supported by a top flange and supporting girders. A dip plate serves as instrument carrier and holddown. The tank wall is protected from pressure surges by a perforated inner enclosure, which consists of the bottom collector vessel, the shield tank, and the upper dip plate. Structural connection between the dip plate and the bottom collector vessel is through the reactor tank wall. The wall thickness of the inner pressure enclosure is 50 mm. (Fig. XI.C-1) (Ref. 5)

The top closure is a system of three rotating plugs, nested eccentrically into each other. Each cover has a lower arrangement of austenitic steel sheets acting as heat reflector, a shield zone filled with granular basalt, and an upper cast steel plate, which is 600 mm thick. Individual covers are held down by bearing rings, and the whole system is bolted down to carrier beams. Sealing is by means of two consecutive inflatable seals, with the space between them filled with an inert gas. The covers are centered and carried by ball bearings. (Ref. 2)

An ex-vessel cooling system, to protect the containment system against melt-through and to maintain long-term

confinement of fuel immersed in sodium, consists of a large collecting tank located below the safety vessel and inside the biological shield. It is designed for the assimilation of 582 tons of sodium at 900°C, corresponding to a volume of 790 m³. The tank is lined with inner insulation to keep the wall temperature $\leq$ 520°C. This insulation consists of fused cast press stones made of B-alumina. An additional protective wall is in front of these stones. The catch-tank wall is enclosed in a 5 cm wide cooling slot, with nitrogen distribution from pressure-relief channels. The upper edge of the catch tank is of conical construction. The whole base is filled with steel granulate. A base cooler between the fuel catching shell and the base of the sodium catch tank consists of hairpin tubes running parallel and connected to two circumferential connectors. These contain circulating NaK. The contact medium between the fuel catching shell and the cooling tubes is the sodium which enters the sodium catch tank, passing under the fuel catching shell during melting of the reactor tank and the safety tank. The catch shell is provided with small boreholes to prevent the formation of an insulating gas buffer.

Diameter of the fuel catching shell is 5.4 m. It has a protective coating. It is located on a support grating, which in turn is located on the base of the catch tank. Dynamic forces and pressure waves originating from falling parts or from fuel/sodium interactions are transmitted to a concrete foundation and to the containment concrete. A conical, truncated fuel directional spreader is located in the center of the fuel catching shell. The sodium catch tank is located on a 0.85 m high base of temperature resistant concrete. The outer reactor tank is located on the conical shell within the sodium catch tank. (Fig. XI.C-2) (Ref. 7)

Figure XI.C-1 SNR-300 Reactor Vessel (Ref. 5)

1. CORE CATCHER SOCKET
2. Na - CATCH PAN
3. INNER INSULATION
4. COOLING GAP
5. OUTER INSULATION
6. NaK - COOLING DEVICE
7. CORE - CATCH PAN
8. DISTRIBUTION DEVICE
9. GUARD VESSEL SUPPORT
10. GUARD VESSEL DRAIN
11. STEEL GRANULATE

Figure XI.C-2 SNR-300 Core Catcher (Ref. 7)

XI. D. CONTROL ELEMENTS

The SNR-300 has twelve control assemblies in the core. Three of these form the auxiliary or emergency shut-down system. Enriched B_4C is the absorbing material. At the beginning of life, surplus reactivity will be compensated by diluent rods in some of the fuel element positions.

The nine elements of the first system are composed of nineteen-pin bundles enclosed in a movable circular guide tube. The outer duct is hexagonal. The control elements are suspended above the core and drop into place. The absorber pins are sealed, with finned spacers. Studies have been done on vented pins using porous plugs.

In the second, or emergency system, the absorber is a flexible chain of three rod bundles containing highly enriched B_4C . During normal operation

these elements are kept in the lowest position below the core by a scram magnet above the core, which tensions the accelerating spring. On scram signal, the inductor current to the magnet is interrupted and the released armature plate is pushed upward. A transfer rod connected to the plate pulls the absorber into the core on a fast stroke. The transfer rod has a shock absorption piston which enters a shock cylinder after 80% of the lift stroke. During this operation the acceleration spring is re-tensioned. The second system does not operate at every scram, but only if the primary system fails. During refueling, the connecting rods must be disconnected and the three safety elements left below the core. (Fig. XI.D-1) (Ref. 13)

All nine of the compensating rods represent a total reactivity of about 7.5%. The safety rods provide a further 3.6%. (Ref. 24)

Figure XI.D-1 SNR-300 Shutdown Systems (Ref. 13)

XI. E. HEAT TRANSFER SYSTEMS

SNR-300 has three primary and three secondary loops, plus a separate emergency cooling system. Arrangement of the system allows for natural circulation. The primary system has no isolation valves, but a throttle valve in each primary loop reduces thermal shock after shutdown. Primary pumps are located in hot legs, secondary pumps in cold legs. Each primary loop includes the shell sides of three intermediate heat exchangers. All piping is single-wall. All nozzles and nearly all sections of the primary piping are located above the emergency sodium level in the reactor vessel. Parts located below this level are surrounded by limited-volume guard vessels to avoid unacceptable loss of coolant in case of a leak. Diameters of the primary and secondary pipework vary between 300 mm and 600 mm, and wall thicknesses between 6 mm and 14 mm. Operating pressure of the secondary system is greater than pressure in the primary system. (Ref. 12)

The intermediate heat exchanger is an 85 MW straight tube unit with a bottom floating head. The vessel is placed on a skirt which is outside the insulation. Primary sodium enters at the upper level and flows downward in the shell side. Secondary sodium enters at the top and flows down through a central downcomer to the lower tube plate, from which it is directed upward through the tubes. Each of the three loops will include three intermediate heat exchangers, for a total of nine. The unit can be removed and replaced if necessary. (Fig. XI.E-1) (Ref. 10, 27)

The SNR-300 prototype pump is a vertical, free-surface type with a single-stage radial flow impeller. The shaft is supported by a sodium-lubricated hydrostatic bearing near the impeller, and an oil-lubricated roller bearing at the top. Anti-vortex baffles are provided in the upper part of the pump, and air-cooled thermal baffles keep the temperature of the biological shield, the sealing, and the upper bearing under 80°C. The three SNR primary pumps and three secondary pumps have been ordered. The main pumps have 5300 m³/hr, 140 m head, and 13m NPSH. (Fig. XI.E-2) (Ref. 11)

There are six butterfly type isolation valves in the primary and secondary loops, one valve located at the suction side of each pump. The valve is a special design selected to control flow at after-heat-removal conditions, flow in the secondary loop with loss of the primary loop, stop reverse flow under conditions of pump failure. The valve has an eccentric axle. Pipe diameter is 609.6 mm. The freeze seal is cooled by forced convection. The guide tube carries a bushing with brazed cooling fins. There is a safety gasket with an intermediate gas seal. (Fig. XI.E-3) (Ref. 20)

Auxiliary loops will be equipped with bellows seal valves up to a maximum width of 100 mm. These have a forged housing, with upper and lower parts connected by welding. Cones are connected to the shafts by flexible joints. Three bores at the circumference of the shaft head connect the bellows cavity with the main duct. Drive is electro-mechanical. (Fig. XI.E-4) (Ref. 21)

In addition to the main system, a separate emergency cooling system is provided. When in use, heat is removed from the core coolant by six coolers immersed in the sodium between the shield tank and the reactor vessel. Each immersed cooler has its own secondary sodium system which transfers the heat to two groups of air coolers. In the emergency case, the radial blanket serves as the connection between the upper plenum and the pressure region for sodium backflow to establish natural convection stream paths. The higher power density in the core results in a temperature difference between core and blanket sodium. Core sodium rises, and on reaching the sodium level, may be distributed radially to the six immersion coolers. Because of a temperature differential in the sodium column on both sides of the shield vessel--due to refrigeration in the immersion coolers--a sodium current will stream downward in the outer annulus, and enter the inner annulus through holes in the shield vessel. The inner sodium column is heated by heat transferred from the blanket. The flows are connected in the upper part of the blanket where cold sodium from the coolers enters the blanket elements radially through perforations. During normal

SNR-300 XI.E

operation about 10% of the total flow passes through the blanket. In the emergency case, total flow passes through blanket and core, in series. Special blanket throttles called cascade diodes are planned. (Fig. XI.E-5) (Ref. 22, 27)

Figure XI.E-1 SNR-300 Intermediate Heat Exchange (Ref. 15)

Figure XI.E-2 SNR-300 Primary Pump (Ref. 11)

- 1. BLOWER BOX
- 2. SHAFT
- 3. FLAPPER
- 4. SUPPORT TUBE
- 5. FREEZE SEAL CLAD EXTENSION
- 6. COOLING BODY
- 7. DRIVE
- 8. GUIDE BEARING
- 9. ELECTRICAL POSITION ALARM

Figure XI.E-3 SNR-300 Butterfly Valve and Armature (Ref. 20)

Figure XI.E-4 SNR-300 Bellows Seal Valve (Ref. 21)

Figure XI.E-5 SNR-300 In-Tank Natural Circulation Stream Paths (Ref. 8)

XI. F. SODIUM PURIFICATION AND INSTRUMENTATION

Level measuring techniques consist of continuous and discontinuous probes, operating on the induction principle. The cladding tube can be welded into the vessels to be monitored. Functions extend from monitoring of normal operation to direct shutdown criteria for the first and second shutdown systems. For large leakage measurements under the reactor tank and level monitoring of vessels with highly radioactive sodium, a discontinuous flexible level probe with a maximum of two measuring points and a possible insertion length of 25 m has been developed. (Fig. XI.F-1)

The permanent magnet method of flow metering has been selected for the SNR-300. The measuring device is mounted on the closed pipe carrying the sodium, and can be mounted and removed without opening the system. A uniform family of magnet systems up to a pipe diameter of 100 mm has been developed. Permanent magnets are also used on pipe diameters up to 600 mm. These require special mechanical supports. Flow measuring functions extend from monitoring the main lines with switching into the reactor protection system, and the measurement of practically all pipes carrying sodium to measurement components of instrumentation devices, such as plugging meters. About forty-five flow meters will be used.

Pump head for required coolant flow and the inert gas pressures, and sodium system pressures, are monitored by absolute pressure and differential pressure transducer systems. The high temperature resistant liquid for the transducer system is NaK eutectic.

Plugging meters are used to monitor sodium purity. Sodium to be monitored passes through a cooling section and a narrow point, upstream of which the sodium is measured simultaneously with the flow rate. When saturation temperature is reached, impurities precipitate at the narrowed point and the flow rate drops, the plugging temperature being that at which the decreased flow begins. Measuring can be manual or at intervals automatically. (Fig. XI.F-2)

Cold traps are used for sodium purification. Cooling of the traps is by nitrogen gas in the primary system and air in the secondary system. The traps include separate economizers. (Fig. XI.F-3)

In the case of a leak in the single-wall sodium/water steam generator, hydrogen is formed in a sodium-water reaction, and the increase in hydrogen concentration in the sodium is an indication of the leakage and its size. The SNR-300 hydrogen detection system is based on the use of a pure nickel membrane, which is selectively permeable to hydrogen. An ion atomizing pump is installed. At constant suction capacity the ion current is proportional to the hydrogen partial pressure in the sodium and thus to the hydrogen concentration. The instrument was designed to contain all components allowing operation regardless of the state of the plant. (Fig. XI.F-4)

Sodium samples are taken from the plant in crucibles and brought in a transport chamber to the laboratory, where oxygen and carbon are determined or complete analysis done. (Fig. XI.F-5)

Chromel-alumel sheathed thermocouples are used to monitor fuel element, and some breeder element, outlet temperatures. Four thermocouples are provided for each measurement. A probe has been developed, into the point of which the four thermocouples are brazed, and passed over a total length of 8 m in a leak-proof welded steel sheath to the collector. A heating element is installed at the upper end, and radial seals are provided in the cover zone.

Coolant flow rate is measured in four fuel elements by eddy-current flowmeter.

A combined inductive and measuring device is placed into the change tube of the in-vessel fuel transfer machine, by which direct observation of the fuel transfer process is possible. It is located about 200 mm above the sodium level. By manipulation of the gripper rod system, the core element position can be determined. Distinction between different fuel element types is also possible. (Fig. XI.F-6) (Ref. 25)

Figure XI.F-1 SNR-300 Sodium Level Measuring Device (Ref. 25)

Figure XI.F-2 SNR-300 Plugging Meter (Ref. 26)

Figure XI.F-3 SNR-300 Cold Trap (Ref. 15)

Figure XI.F-4 SNR-300 Hydrogen Detection System (Ref. 26)

Figure XI.F-5 SNR-300 Sodium Sampling System (Fig. 25)

Figure XI.F-6 SNR-300 Core Element Positioning Device (Ref. 25)

XI. H. STEAM GENERATORS

The steam generating system will consist of three steam generator cells, two equipped with straight-tube generators and one with a helical-tube generator. The steam generator consists of an evaporator and a superheater, each cell will have three evaporators and three superheaters installed.

The steam generator with helically coiled tubes can be operated in parallel with the straight tube generator, and is interchangeable with it. The tube bundle comprises a number of concentrically fitted helically coiled tubes, which pass the vessel shell individually via thermal sleeves and come together at a central header. Water/steam flows upward from a ring header through the tubes. Sodium enters radially at the upper part of the cylindrical vessel, flows downward around the tubes, and leaves radially. Uniform distribution of the sodium is created by a flow skirt around the bundle and by cylindrical and annular circular plates above and below the bundle. A by-pass sodium flow is devised inside the vessel

for hydrogen detection. Rupture disks are positioned near the sodium inlet and outlet. The evaporator and superheater units are identical in design. (Fig. XI.H-1)

In the straight tube version, evaporator and superheater are essentially the same in design. There is no reheater in the SNR-300 set. The unit consists of straight tubes between tube sheets. The shell is provided with a bellows to allow temperature differences between tube and shell. Support grids are provided along the tubes. A dodecagonal flow skirt closely surrounds the tube bundle. Sodium inlets and outlets are annular chambers followed by a perforated cylinder. Pressure relief systems at the sodium inlet and outlet are connected to two nozzles. Sodium flow is downward, water/steam flow upward. Thermal shielding is provided at the tube sheet region and at the point where the tube sheet is connected to the shell. (Fig. XI.H-2) (Ref. 16)

Figure XI.H-1 SNR-300 Steam Generator, Helically Coiled Tubes (Ref. 16)

Figure XI.H-2 SNR-300 Straight Tube Steam Generator

XI. J. FUEL HANDLING

Under-plug refueling with the triple rotating plug was selected for SNR-300. Transfer from reactor vessel to ex-vessel storage is by a shielded, gas-cooled machine. Ex-vessel storage and other handling equipment are installed in special handling cells. Spent fuel transfer through the wall is by a gate which is removable only when the reactor is down, eliminating the need for an air-lock and a second handling machine. There is no in-vessel storage of irradiated fuel. (Fig. XI.J-1, XI.J-2) (Ref. 9)

The ex-vessel handling machine is a shielded cask, moving on a bridge and equipped with a forced circulation gas-cooling system. Spent and new fuel is transported in sodium-filled canisters. Fuel storage is in a sodium-filled vessel with sodium circulation and nitrogen

cooling. Emergency coolant loops are provided, which circulate the sodium to air coolers.

The in-vessel handling machine is positioned on the rotating plug, and can be positioned over any fuel, blanket, control or reflector assembly. The grab rod allows both up and down and rotational movement of the assemblies. (Fig. XI.J-2)

An auxiliary handling machine is provided for refueling preparation and post-refueling operations on the reactor, manipulation of control rod actuators and instrumentation, transport of contaminated material, etc. It is a shielded, gas-tight cask handled by the building cranes in the reactor building, and between buildings by a special gantry. (Ref. 9,17)

Figure XI.J-1 SNR-300 Arrangement of Refueling Equipment (Ref. 17)

Figure XI.J-2 SNR-300 Decay Tank for Irradiated Elements (Ref. 26)

Figure XI.J-3 SNR-300 In-vessel Handling Machine (Ref. 17)

XI. K. CONTAINMENT

Containment is divided into two main zones. The inner contains the reactor and primary system. An additional volume, the pressure-relief room, is located at an elevated position within the inner containment. This volume limits the pressure peak and provides a flat temperature profile by natural convection of the containment atmosphere in case of an excursion. A low oxygen concentration is maintained in the inner containment during operation. The foundation below the reactor vessel is protected by a structure ensuring low temperatures of the containment boundary in case of a molten core penetrating the reactor

vessel and guard vessel. An NaK cooling system is installed in the lower part of this structure. See Section C.

The outer containment includes the fuel handling area, the primary sodium auxiliary systems, nitrogen systems and operating floor. Its boundary is a steel-lined concrete wall. The gap between the concrete wall and the steel liner is connected to a reventing system to insure zero leakage directly after an accident. The gap between the reactor building and the outer containment is about 2 m, and is used for the installation of cables and piping. (Fig. XI.K-1) (Ref. 9)

Figure XI.K-1 SNR-300 Reactor and Handling Building (Ref. 17)

XII DOUNREAY

LOCATION: Dounreay, Scotland

OPERATION: 1959
Full Power, 1963

Consideration of the engineering of a fast breeder reactor in the United Kingdom dates from 1951. Original work involved physics, engineering, metallurgy, heat transfer, fuel and sodium technology. A zero-energy facility, Zephyr, was built and operated at Harwell from 1954 to 1958. The zero-energy facility Zeus followed, with a core using enriched uranium and closely related to the core design for Dounreay. Construction of Dounreay began in 1955, and the reactor became critical November 14, 1959. Since July 1963 Dounreay has operated at its full power level using redesigned fuel elements.

Dounreay uses enriched uranium fuel and NaK as coolant. It is a multi-loop system, with coolant flow downward through the core. Fuel elements are of the vented design.

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Table - 1

GENERAL PARAMETERS

Type	Loop	Loop
No. loops	20 + 40 breeder	24
Coolant	Nak	Nak
Core inlet temperature	200° C	200°C
Core outlet temperature	400°C	~350°C
Flow direction	Downward	Downward
Driver fuel	U-1/2 Cr alloy	U-7 Mo alloy
Blanket material	Natural uranium	Partially Replaced by Ni/SS
Core diameter	21 in.	21 in.
Core volume	4.2 ft ³	
No. Enrichment zones	1	2 (Variation in fuel thickness)
Output	15 MWe/60 MWt	15 WMe/60 Mwt
Max. can temperature	515° C	500° C
Fuel centerline temperature	~800°C	650° C
No. Driver elements	361-367	
No. Radial blanket elements	1872	
In-core control elements	12 groups of fuel elements +3 ¹⁰ B rods	Same. Some positions used for testing.
Goal burnup	~2%	
Power density (per unit vol. core)	14,250 kw/ft ³	
Specific power	286 kw/kg ²³⁵ U	

Table - 2

CORE AND BLANKET

	1st Core	Mark - III
Fuel material	Uranium alloy	
Blanket material	Uranium alloy (Mgnox)	
Composition	U-1/2 Cr	U-7 Mo
²³⁵ U → core	30%	75%
blanket	Natural	
Fuel form	Hollow rod	Hollow rod
Blanket material form	Solid rod	
Fuel thickness		Inner zone 0.1 in. Outer zone 0.13 in.
Fuel od/id	0.698 in./0.316 in.	Both zones 0.65 in. od
Cladding-fuel	Outer Nb tube	Outer Nb tube
	Inner V tube	Inner V tube
od	Nb 0.752 in.	
	V 0.298 in.	
Fuel-clad gap		U-Nb 0.028 in. U-V 0.004 in.
Cladding-radial blanket	Stainless steel	Partially replaced
Bond material	Sodium	Sodium
Fuel length	21 in.	21 in.
Radiation blanket length		Partially replaced
Axial blanket length	5.6 in.	(Replaced)
Vented/non-vented	Vented to coolant	Vented to coolant
Assembly	Element components are the end-piece, breeder end pieces, 7 hollow fuel slugs (stacked), adapter washer, inner and outer cladding tubes, top and bottom fittings. Elements are located in groups of 7 in a core tube nest.	General design essentially unchanged. For core modifications see Section A.

XII.A. CORE AND BLANKET

Core fuel elements consist of a breeder end piece of natural uranium solid rods, the fuel section composed of seven interlocking hollow slugs forming a 21-inch length, with cladding and support furnished by an inner vanadium can and an outer niobium can. The top plug has vent holes for venting to the coolant, the bottom plug is solid. The outer niobium can has integral spiral fins. Top end plugs of stainless steel locate the element in the top core plate. Eight radial holes in the fitting allow coolant to pass through the plate. The bottom end fitting serves to guide the fuel element into position and locate it in the bottom end plate. Fuel-clad bonding is NaK. The fuel elements are located by groups of seven in a core tube nest. (Fig. XII.A-1a, XII.A-1b)

The original fuel was a U-1/2 Cr alloy. After early power runs this was replaced by a 45%-enriched U-20 Mo alloy. Mark III elements, loaded in 1963, have an enrich-

ment of 75% and are fabricated of a U-7 Mo alloy. The fuel pieces are not interlocked. A two-zone core is used, differing in the thickness of the fuel. There is a large radial fuel-can gap. The axial blanket has been replaced by stainless steel and the first three rows of the radial blanket by nickel, with the first row mainly devoted to experiments. The central hexagonal block of the core has been replaced by two rhomboid blocks containing slightly modified standard elements, and the first experimental assembly containing 77 $\text{UO}_2\text{-PuO}_2$ pins loaded into the third rhomboid block. The central space of these blocks can be used for instrumented experiments. These may also be located in four of the twelve control rod carrier center positions. DFR center flux is 2.5×10^{15} n/cm²/sec., dropping off to 1.9×10^{15} n/cm²/sec. at the core edge. (Fig. XII.A-2) (Ref. 5, 8)

XII.A-2

Figure XII.A-1a Dounreay Core Tube Next (Ref. 1)

XII.A-3

Figure XII.A-1b Dounreay Core Element Details (Ref. 1)

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XII.A-4

Figure XII.A-2 Dounreay Core Plan (Ref. 8)

XII.B. CORE SUPPORT AND VESSEL INTERNALS

The breeder support box is the main structural member supporting the core and breeder, and acts as a header box for the breeder outlet coolant. It has a series of T-section ribs with continuous circular plates covering the top and bottom of the box. The top plate has holes for breeder coolant flow. The bottom end of the breeder element can be changed to control flow through these holes. The bottom plate slopes for drainage to coolant outlet pipes. There are circumferential stiffeners adjacent to the hexagonal hole in the center of the box.

The inner breeder assembly is a vertically mounted skirt of hexagonal cross-section. It encloses the five inner rows of breeder elements. It consists of six sides bolted together, with plates fitted at top and bottom and a spacer plate midway between them. Spacer tubes with continuous spiral fins on the bore and outside diameter are fitted in counterbores in the plates in the second and fourth row. All breeder rods in this section have a 1.63 in. equilateral pitch.

The outer breeder support consists of two plates, the bottom plate mounted on the breeder support box and the upper plate mounted on the inner breeder skirt

assembly at the inside, and the reactor vessel at the outside. Elements in the first two rows have a pitch of 1.55 in., all others 1.507 in. The outer section forms an annular blanket varying from nine to fourteen rows.

The core skirt is a fabricated, hexagonal tube which hangs vertically from a flange located on the top plate of the inner breeder assembly and passes through the breeder support box at the lower end. The skirt acts as a duct for coolant flow through the core and supports the core tube nest. It also provides bearing tubes for control rod carriers.

A support location for the core tube nest is provided just above the bottom of the skirt.

The core tube nest is built up from a series of long and short interlocking tubes, the long tubes located in counter-bores in the top and bottom plates. Side plates enclose the tube nest, and the whole is positioned within the core skirt as one complete unit. The tubes are circular, but machined to a hexagonal cross-section at the core centerline. They are built together to form a continuous diaphragm at the core center. The tube in the center of each group of seven fuel elements is omitted. (Ref. 1) (Fig. XII.B-1)

Figure XII.B-1 Dounreay Core Support Structures (Ref. 3)

XII.C. REACTOR VESSELS AND SHIELDING

The reactor vessel is a stainless steel cylindrical structure 20 ft. high and 10 ft. 6 in. internal diameter. It is closed at one end and open at the other, with an outer casing of stainless steel forming a leak jacket. The lower main shell is designed as a coolant-retaining stress-free casing with no external loads of perforations. Main reactor loads from the core and breeder are carried by an internal cylindrical skirt to the top flange. The skirt forms an outer annulus over 2/3 of the vessel depth into which tubes for control mechanisms, thermocouples and heaters are built. A thin inclined plate at the bottom of the skirt seals the annulus between skirt and vessel. At the top of the skirt another plate connects vessel and skirt and acts as a seal between the interior of the vessel and the top flange. A support ring around the base of the skirt carries the load of breeder and core assembly.

The top of the vessel is joined to a thick fabricated ring with an od greater than that of the vessel. The ring rests on rollers on support columns. The top face of the support flange receives the outer and inner rotating shields with their auxiliaries. The inner shell of the support flange extends down into the vessel and is joined to the top of the skirt.

An outer casing surrounds the sides and bottom of the vessel, and extends at the stub pipes to form an annulus around the pipes. This space is filled with nitrogen gas, and is connected to a liquid-metal leak detector.

Support consists of two sets of columns, 24 per set, one set on a 24-ft. pitch circle diameter and the other on a 21 1/2 ft. pitch circle diameter. The columns are about 32 ft. high and are interconnected at the 11-ft. level and at the top. The vessel is supported from the top of the inner columns. The weight of the vessel and internals is transferred to the top of the upper flat plate through a stainless steel block bolted to the underside of the vessel flange. The column structure also forms a support for the inner neutron shield. (Fig. XII.C-1)

The two rotating shields form the top closure of the reactor vessel, and orient the charge and discharge machine. They are lowered and rotated only after the reactor is down. Sealing is by mechanical bolted seals and by liquid metal dip seals. The outer casing is the boundary of the coolant circuit, the inside being sealed from the coolant and vented to the atmosphere. The inner shield fits eccentrically into the outer shield.

A thermal shield consisting of 4 ft. of graphite with a small amount of boron surrounds the reactor vessel. Shielding above the core is built into the rotating plugs. There is a 2 ft. 9 in. plug, and above this a layer of thermal insulation. Loose concrete blocks are fitted around the reactor top, and a removable, thick steel shield covers the reactor top. (Fig XII.C-3) (Ref. 1)

Figure XII.C-1 Dounreay Reactor Vessel and Support Structure (Ref. 9)

Figure XII.C-2 Dounreay Section through Rotating Shields (Ref. 1)

Figure XII.C-3 Dounreay Radiation Shielding (Ref. 1)

XII.D. CONTROL ELEMENTS

Dounreay has twelve control and safety elements, and three ^{10}B rods provided as spares. The elements consist of groups of ten fuel elements divided into two safety rods, six control rods, and four shutoff rods. Control is manual by the operator. Startup and control consists of insertion of safety, shutoff, and control groups, with interlocks provided to ensure this sequence. The ^{10}B shutoff rods can be dropped by gravity into the inner breeder. The control unit is offset, with the drive located outside the rotating shields. An electromechanical drive is used. The

reactivity controlled by the control group is 3.6%, by the shutoff group 2.4%, and by the safety group 1.2%. Three speeds were available: slow-in, slow-out at 0.003 in./sec. and fast-out at 0.15 in./sec. Maximum rate of reactivity addition was $2 \times 10^{-4}\%$ /sec. (Fig. XII.D-1)

Subsequent modifications to the drive mechanism has provided a very simple single speed output which permits reactivity addition at ten times the original rate, and the rod selector switch has been modified to prevent the movement of more than one rod at a time. (Ref 1,6)

DOUNREAY XII.D.

Figure XII.D-1 Dounreay Control Rod Mechanism (Ref. 1)

XII.E. HEAT TRANSFER SYSTEMS

The primary circuit consists of 20 core loops and four breeder loops, all designed for the same heat transfer conditions. Each loop includes an intermediate heat exchanger and a cold-leg electromagnetic pump. Expansion tanks are fitted to the primary circuit. Four of these have level-indicators and six have blanket gas pressure transmitters. Cold traps and hot traps are used. The whole of the primary circuit is enclosed in a 5-ft. thick concrete vault. Cold and hot traps, pump windings, level indicators and flow-meters are installed at the top of the primary circuit and supported from the vault roof with access through roof liner tubes closed by shielded plugs. Each primary circuit and the vessel are enclosed in a leak jacket. All pipework is hung from a network of steel supports on the underside of the vault roof. (Fig. XII.E-1)

Nak coolant leaves the bottom of the reactor, after flowing downward through the core, at 350° C, passes through the IHX, an electromagnetic pump, and a thermal siphon heat exchanger before re-entering the vessel at about 200° C. The thermal siphon unit in a small heat exchanger fitted to the top leg of each primary loop and connected to the natural-draft air-cooled heat exchangers located in the stack outside of the containment sphere. There are four of these air-dump units. They can remove 1.8 MW of decay heat 30 minutes after shut-down from a power level of 60 MWt. Piping is 4-in. in diameter contained within a 6-in. guard pipe.

There are twelve secondary loops, each serving two of the primary loops. Nak coolant circulates through the IHX to a Nak-water heat exchanger. Each loop has two electromagnetic pumps installed in parallel in the cold leg. Two cold traps are installed in by-pass loops in parallel with the main loop at the top of each loop, with

an expansion tank in series. Free surfaces are blanketed with an inert gas. The loops include flowmeters, level indicators, and pressure transmitters. Loops are constructed of 6-in. diameter stainless steel pipe with mineral-wool insulation.

The intermediate heat exchanger has a heat-transfer duty of 3MW. It consists of an inner stainless steel pipe 300 ft. long and 4 in. diameter, surrounded by an outer, 6-in. diameter stainless steel pipe, formed into seven complete loops. Spiders hold the inner and outer pipes in place. Secondary coolant flows through the annulus, entering at 180° C and exiting at 330° C. Primary sodium flows in the inner pipe, entering at 350° C and leaving at 200° C. Flow is counter-current. (Fig. XII.E-2)

Pumps are electromagnetic flat-linear induction pumps, consisting of a flat thin-wall pump tube with a clamped linear stator on either side. There are no moving parts. The pump tube is welded into the loop. Each primary pump operates within a deep steel pressure vessel forming a leak jacket. Secondary pumps are of similar design and construction, but have no shielding plugs. (Fig. XII.E-3)

Expansion tanks fitted to the primary loops are constructed of two cylinders, the inner one of stainless steel. The outer cylinder is mild steel and forms a leak jacket. Each tank has a stand-pipe near the reactor vessel end, which passes vertically upward through the vault roof to terminate in a flange. Four of these flanges carry level indicators and six carry pressure transmitters. (Fig. XII.E-4) (Ref. 1)

Modifications to the original design include the installation of a separately pumped cold trap loop and improved cold traps in three of the primary circuit by-pass loops.

XII.E-2

Figure XII.E-1 Dounreay Primary Loop Pipe-Work (Ref. 1)

Figure XII.E-2 Dounreay Intermediate Heat Exchanger (Ref. 1)

Figure XII.E-3 Dounreay Primary Pump (Ref. 1)

Figure XII.E-4 Dounreay Expansion Tank (Ref. 1)

XII.F. COOLANT PURIFICATION AND INSTRUMENTATION

The primary cold trap is a vessel with single wall construction in the upper section and double wall construction in the lower part to just above the highest coolant level. A section of the double wall interface sandwiches a layer of aluminum, with machined grooves in the aluminum to provide a leak path down to the leak jacket. A finned bronze sleeve is shrunk on the outside of this compound tube. Nak at 200° C enters the trap at the bottom and flows upward through a central tube and down through the tubes of a regenerative heat exchanger, leaving at 125° C. Flow is then upward through the compound tube where it is cooled by air drawn from the biological shield cooling system, and enters a basket containing stainless steel rings at 115° C. After 5 min. residence time in the basket, the Nak enters the shell side of the regenerative heat exchanger and leaves the exchanger and the cold trap vessel at 195° C. A 1-in. bypass loop connects the trap to the pump outlet, with return connected via an expansion tank to the main loop at the reactor vessel inlet. (Fig. XII.F-1)

Secondary cold traps are similar in design. In this case two traps are installed in a bypass loop in parallel with the main loop, with an expansion tank in parallel with the two cold traps.

The hot trap vessel is 22 ft. high and 1 ft. 3 in. in diameter. A shell-and-

tube regenerative heat exchanger in the lower section heats the incoming Nak from 200° C to 580° C. The coolant then passes over the 7 in. diameter heater container tube and is heated to 600° C. Flow is then downward through a container of zirconium foil onto stainless steel bobbins which are 8 in. in diameter. Nak is cooled by a heat exchanger to 200° C before leaving the hot trap. A return connection to a low pressure section of the loop is by means of a 3/4 in. diameter pipe. (Fig. XII.F-2)

Hot traps are used only in the primary circuit.

Primary and secondary loop instrumentation includes electromagnetic flow meters, chromel-alumel thermocouples, coolant level indicators which operate on the buoyancy principle, and blanket gas pressure transmitters fitted on top of expansion tank tubes above the tank roof. Oxide corrosion meters, oxide sampling units, and resistivity meters are installed in hot and cold-trap vessels of the primary loop. A rhometer in the primary circuit measures coolant resistivity. (Ref. 2)

Sub-assembly monitoring by thermocouples located in the coolant outlet stream beneath the element was instituted when assemblies containing multiple pins were inserted for test operation. Other methods developed for sub-assembly monitoring are thermal noise analysis at coolant outlet thermocouples, acoustic monitoring, or the incorporation of tracers in the experimental pins and blanket gas sampling. (Ref. 7)

Figure XII.F-1 Dounreay Cold Trap (Ref. 1)

Figure XII.F-2 Dounreay Hot Trap (Ref. 1)

DOUNREAY XII.G

XII.G. COVER GAS AND AUXILIARY SYSTEMS.

The DFR originally used a nitrogen blanket over the primary coolant, but it has since been converted to an argon cover gas system. Because of the use of vented elements, the external gas blanket pipes have been shielded.

X. B. CORE SUPPORT AND VESSEL INTERNALS

Fuel elements fit into a lower grid plate and are locked from above by means of a hold-down device. No alterations to the reactor vessel or grid-plate assembly are necessary for conversion to KNK-2.

The grid plate structure subdivides the tank volume into a lower pressurized plenum and an upper plenum with a free sodium surface. The fuel elements are held in a tightly-packed triangular lattice within the hexagonal boundary formed by the steel reflector. (Fig. X.B-1.) (Ref. 1.)

Figure X.B-1 KNK Reactor Structure (Ref. 1)

XII.H. FINAL HEAT REJECTION

Nak coolant circulates from the intermediate heat exchanger through a Nak-water/steam heat exchanger. These 6 MW units consist of thirteen rows of twenty heat-transfer elements in each row. The elements were constructed of copper-laminated stainless steel tubes. Nak flows in the tubes from bottom to top, and on the steam/water side connections are made to the economizer, evaporator, and superheater sections of the boiler plant. Heat exchangers are lodged in cubicles made of thick steel packed with mineral wool insulation and having penetration for the Nak, steam, and water pipes and heat-exchanger support rods. The bottom of the cubicle has deflector plates to guide Nak leakage into a tray. This

tray has a leak detection element. The cubicle is also fitted with fire-fighting equipment, with external connections for portable equipment. (Fig XII.H-1)

A Lamont forced circulation boiler is arranged conventionally with an economizer, evaporator, and superheater. When not in use as a steam generator, only a section of the evaporator is used. Dump condensers were designed to fulfill the function of pressurized water coolers, with simple conversion to steam condensers at a later stage. (Ref. 2)

Electric power was first generated in October 1962.

Figure XII.H-1 Dounreay NaK/Water-Steam Heat Exchanger (Ref. 1)

XII.I. REACTOR INSTRUMENTATION AND CONTROL

The reactor control room is located outside of the containment sphere. All controls and measurements are installed on a central desk, and measurements which require only periodic checking are displayed on panels around the room. These panels also contain alarm and reactor trip circuits, with one panel allocated to oscillator controls and instruments for analyzing reactor stability.

Thermal neutron detectors provide information on power level, drift, and doubling time. Three groups of instruments measure neutron flux in three ranges: 50 mW-100W, 2W and 2MW, 1MW and 100MW. The radium-beryllium neutron source in use can be withdrawn from the reactor, with withdrawal and insertion controlled from

the reactor control room. The neutron detectors are installed in 12 holes in an equatorial belt of pure graphite contained within the neutron shield around the reactor vessel. The detectors are gas-cooled. There are three ^{235}U coated fission chambers for low-power channels, two ion chambers for intermediate-power channels, one ion chamber for use with the oscillator, and eight ion chambers for high power channels. All detectors, except the latter, are retractable.

Reactor operating conditions are controlled by moving control rods and by controlling the temperature and flow-rates of the coolant. Control rods are manually operated by switches at the control desk. Primary and secondary flow-rates can be altered by increase or decrease switches. Pumps can be adjusted in pairs or in groups. (Ref. 2)

XII.J. FUEL HANDLING

Fuel-loading is done with the reactor shut down. Access to the core is through holes in the eccentric rotating plugs. Two charge machines, each handling single elements, are used. The machine is positioned over the reactor and sealed in it through an adapter-door valve. A snout is driven into the core by a rack and chain through a rack tube; in the retracted position the fuel element and the snout are completely within the tube in the charge machine body. As the element is being withdrawn from the core it is continuously

cooled. Valves are closed and the machine is moved to the canning station. Maximum heat generated by an irradiated core element is 2.5 MW. Safe temperatures are maintained by forced convection cooling by nitrogen. Fans draw air over the nitrogen heat exchanger, exhausting the heat to the atmosphere. Elements can be inspected and identified by an introscope fitted to the base of the machine, with viewing through a stabilized glass window in the machine casing. The machine can be motor-driven or hand-driven. (Fig. XII.J-1) (Ref. 1)

Figure XII.J-1 Dounreay Core, Vessel and Charge Machine (Ref. 1)

XII.K. CONTAINMENT

The reactor vault containing the primary system is located within the reactor building, which is a 135 ft. diameter steel sphere. The main vault is surrounded by a secondary, 5-ft. thick concrete shield. Air cooling holds the temperature of the concrete to less than 50° C. The reactor control room is outside the sphere.
(Ref. 1)

XIII. PFR

LOCATION: Dounreay, Scotland
OPERATION: March 3, 1974

Construction was started on a site near the Dounreay Fast Reactor in 1967, following completion of the conceptual design. During construction, modifications were made to parts of the design to take into account the latest experimental work.

PFR is a pot-type system using $\text{UO}_2\text{-PuO}_2$ fuel. Nominal output is 250 MWe and 600 MWt. Depleted fuel is stored in the primary vessel for about thirty days.

PFR achieved criticality on the first core loading on March 3, 1974. Contractor for completion of PFR was the Nuclear Power Group, fuel manufacturer is British Nuclear Fuels Ltd., Windscale.

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Table - 1

GENERAL PARAMETERS

Type	Pot-type
No. loops	3
Coolant	Sodium
Core inlet temp.	400°C
Core outlet temp.	600°C
Flow direction	Upward
Driver fuel	UO ₂ -PuO ₂
Blanket fuel	UO ₂ (depleted)
No. enrichment zones in core	2
Output MWe/MWt	250 MWe/600 MWt
Max. can temperature	700°C (hot spot)
Linear power, max.	450 w/cm
Neutron flux, total	8.9×10^{15} n/cm ² sec (center)
No. Driver elements	78
No. Radial blanket elements	52
No. In-core control elements	10 + 1 safety
In-core storage:	Transfer rotor buckets
Goal burnup	7.5%

Table - 2

CORE AND BLANKET

	Driver Zone	Axial blanket	Radial blanket
Fuel material	UO ₂ PuO ₂	UO ₂	UO ₂
Form	Annular pellet	Annular and solid pellet	Pellet
Composition	25% Pu + nat. U		
²⁴⁰ Pu	~18%		
²³⁵ U		Depleted	Depleted
Density	80% TD smear		95% TD smear
Rod cladding	Stainless steel		Stainless steel
od	5.84 mm/5.08 mm	5.84 mm/5.08 mm	13.49 mm/12.50 mm
Wall thickness	~0.38 mm	~0.38 mm	
Bond material	gas		
Column length	914 mm	Lower 458 mm Upper 102 mm	
Gas plenum length	711 mm (bottom)		
Pin length	2.3 m		
Vented/ non-vented	No		No
Assembly material	SS and Nimonic		SS and Nimonic
Shape	Hexagonal		Hexagonal
Across flats (dia.)	142 mm		142 mm
Overall length	3810 mm		3810 mm
No. pins/assembly	325	325	85
	Each assembly has a top crown of 19 wire-wrapped breeder elements		
Pin spacing	Honeycomb grid/egg-crate		Wire wrap
Pin pitch	P/D - 1.26		
Assy. pitch	144.8 mm		
Assy. in core	78		52

XIII.A. CORE AND BLANKET

The subassembly is a hexagonal wrapper, 142.2 mm across the flats, containing a 325-pin bundle. Pins are supported within the wrapper by a honeycomb grid on the fuel section and an egg-crate type grid on the plenum section. A top crown assembly of nineteen wire-wrapped breeder pins is supported between grids. These pins swirl the exiting coolant. The upper tube assembly is cylindrical. The lower end of the assembly terminates in a bending bar which plugs into the support. In the first core loading two wrapper materials are used, a stainless steel and a Nimonic alloy. Overall assembly length is 3.81 mm. (Fig. XIII.A-1)

The fuel pin is a stainless steel tube, 5.84 mm od, wall thickness 0.38 mm. The ends are sealed by swaging and spot-welding. Overall length is 2.3 m. Arrangement from the top down consists of 100 mm of depleted UO_2 solid pellets; 914 mm UO_2 - PuO_2 annular pellets; a 19 mm fuel support platform with a molybdenum wire mesh plug; 457 mm depleted UO_2 annular pellets; a 19 mm fuel support platform; a 711 mm gas plenum, with the pin od in this section reduced to 5.33 mm. Fissile pellet smear density is 80% TD. Pin pitch-to-diameter is 1.26. (Fig. XIII.A-2)

The radial blanket assembly holds 85 wire-wrapped pins 12.5 mm id and 13.49 mm od. Smear density of the depleted UO_2 column is 95%. Pellets are solid. The radial assembly also has the 19-pin mixer-breeder crown unit above the pin bundle.

Neutron shield rods are thick steel tubes with the outer rows containing graphite and the inner steel. The inner three rows are force cooled, and the others cooled by bypass flow from the hot core sodium passing through the shield to the intermediate heat exchangers.

The PFR core contains 78 fuel assemblies plus 13 positions for absorber rods and experiments, surrounded by 126 breeder and reflector assemblies. The core has two enrichment zones. There is one row of radial breeder, except for a 120° sector in which there are three rows. No long-term in-vessel storage is provided. Control rods are located on the boundary of the inner core zone. (Fig. XIII.A-3) (Ref. 3, 4, 8)

Figure XIII.A-1 PFR Subassembly (Ref. 4)

Figure XIII.A-2 PFR Fuel Pin (Ref. 4)

Figure XIII.A-3 PFR Core (Ref. 2)

XIII.B. CORE SUPPORT AND VESSEL INTERNALS

The PFR core is free-standing, the top support point being level with the bottom of the active fuel. The core is divided into modules of six subassemblies, each with an associated control rod or leaning post. The leaning post, in the central position, has pads positioned at the level of the fuel/lower axial breeder boundary. Each of the module positions has a fuel carrier, or pressure chamber, fixed in a hole in the diagrid. In each carrier there are six upper and lower bearings which carry the support spike of the six subassemblies. The leaning post accommodates a tube extending close to the top of the core, which provides guidance for control and shut-down rods. (Fig. XIII.B-1,2)

The diagrid supports the core and forms a high-pressure plenum for feeding sodium to the core, the radial breeder, and the inner rows of the neutron shielding. It transmits the load by means of a support skirt and a strongback to the main diagrid support structure attached to the top of the primary tank. It is a titanium-stabilized stainless steel structure composed of circular top and bottom plates spaced by a circumferential cylindrical part and carrier support tubes. (Fig. XIII.B-3)

Design for a restrained core has been studied as a possible alternative to the free-standing core. This consists of an external ring which would clamp the subassemblies close to their tops. (Ref. 5, 9, 10)

Figure XIII.B-1 PFR Subassembly, Spike Detail (Ref. 5)

Figure XIII.B-2 PFR Subassembly Support (Ref. 5)

1. FUEL ELEMENT CARRIER
2. TOP PLATE (50 MM THICK)
3. LOW PRESSURE PLENUM
4. CIRCUMFERENTIAL WALL MEMBER (38 MM THICK)
5. BOTTOM PLATE (50 MM THICK)
6. SUPPORT SKIRT
7. FUEL ELEMENT CARRIER LOCATION NUT
8. B.P.D. CONNECTOR PLATE
9. B.P.D. CONNECTOR STUBS
10. B.P.D. PIPES
11. B.P.D. CONNECTOR BLOCK
12. FUEL ELEMENT CARRIER LOCATION NUT
13. FUEL ELEMENT CARRIER SUPPORT TUBE (9.5MM THICK)

LEADING DIAGRID DIMENSIONS

OVERALL DIAMETER	3.25 METERS
DEPTH	0.8 METERS
MASS	12 TONNE

Figure XIII.B-3 PFR Diagrid (Ref. 10)

XIII.C. REACTOR VESSEL AND SHIELDING

The whole of the primary circuit is contained in the primary reactor tank, a cylindrical stainless steel vessel suspended from the roof support structure. A low-alloy leak jacket surrounds the vessel. A reinforced concrete vault below ground level contains the vessels. The primary vessel is 12.2 m dia. and 15.2 m deep.

A reactor jacket ducts the sodium from the core to six intermediate heat exchangers. The jacket is stainless steel with 12 mm wall thickness, 12 m high and 16 m across the Intermediate Heat Exchanger (IHX) trays. There are four layers of a quilted stainless steel insulation fitted to all inside surfaces of the jacket, and eight layers in the area around the neutron shield support toroids. This toroid is fitted to the top of the reactor jacket. The reactor jacket sits on the core support structure. (Fig. XIII.C-1, 2)

All primary components are supported from the roof structure of the primary vessel. The roof is a ferritic steel structure composed of an outer ring girder connected by ten spokes to the central section in which the rotating shield operates. The leak jacket is suspended from the outer ring girder and a "tuning fork" forging of the inside member of this ring.

A single rotating shield plug is mounted in the roof structure concentric with the core. The rotating plug is 336 cm dia., mounted on a ball race and provided with a dip seal. Cooling is by a forced convection argon system. Stainless steel plates give thermal insulation, and shielding is provided by concrete. (Ref. 1, 8, 10)

Figure XIII.C-1 PFR Reactor Vessels and Shielding (Ref. 18)

1. STRONGBACK	7. PRIMARY CIRCULATING PUMP
2. DIAGRID	8. HEAT EXCHANGER TRAY
3. INTERMEDIATE HEAT EXCHANGER TUBE BUNDLE	9. BURST PIN DETECTION THIMBLE (BULK)
4. REACTOR JACKET QUILTED THERMAL INSULATION	10. PRIMARY NON-RETURN VALVE
5. BURST PIN DETECTION THIMBLE (BULK & LOCATION)	11. DIAGRID SUPPORT STRUCTURE
6. NEUTRON SHIELD SUPPORT TORROID	12. REACTOR JACKET

Figure XIII.C-2 PFR Vessel Components (Ref. 10)

PFR XIII.D.

XIII.D. CONTROL ELEMENTS

Control is by means of five control rods and six shutoff rods. The control rod is a shell and tube assembly with sodium flowing through the tubes. The shut-off rod is an assembly of stainless steel cans containing enriched B_4C within a stainless steel hexagonal wrapper. Control and shutoff guide tubes are suspended from the rotating shield. They

also house thermocouple conduits, each serving one group of six subassemblies.

A secondary shutdown mechanism or oscillator occupies the center hole in the rotating plug. The concept is entirely different from the other control mechanisms. (Ref. 20)

XIII.E. HEAT TRANSFER SYSTEMS

Each of the three primary loops includes two intermediate heat exchangers mounted in pairs, and a cold-leg pump. Sodium from the cooler outer region of the primary tank is driven by the pumps through twelve separate delivery pipes to the inlet plenum/core support grid. Flow is upward through the core and radial breeder into an upper and inner pool contained within an insulated jacket structure, then into tray extensions of the jacket which house the IHX units. Primary sodium flow is downward through the tubes of the IHX. The IHX pairs are supplied with three sets of sub-critical pressure steam generators. Each secondary loop is independent of the others. Within the reactor hall, secondary pipes are double-jacketed, with nitrogen in the annulus. Each heat exchanger has an associated decay heat removal coil. Cold traps are used in the primary and secondary systems. (Fig. XIII.E-1)

The intermediate heat exchanger consists of a counterflow shell and tube unit, with a decay heat removal coil, a primary isolation sleeve valve, a biological shield plug containing the secondary sodium pipes, and a valve drive unit. The assembly is supported from the primary tank roof. Secondary sodium flows through a central downcomer to the bottom of the IHX shell and then upward through the unbaffled shell. Differential expansion between tube and shell is accommodated by a sine wave in the tubes. The sleeve valve located above the top tube plate can isolate the primary flow to facilitate loop maintenance. (Fig. XIII.E-2)

Decay heat following a reactor trip can be removed by an independent NaK circuit. The heat exchangers for this circuit are coils positioned inside the valve sleeve above the top tube plate. Inlet and outlet pipes to the outside NaK/air heat exchangers pass through the shield plug. There are three independent loops, each capable of removing 5 Mwt of heat. Each loop includes two coils. NaK pipework is jacketed with an inert gas and has a leak-detection system. The system is designed for completely automatic operation, although operator initiation from the control room or from a remote emergency control room is possible. (Fig. XIII.E-3) (Ref. 11, 12)

Primary pump is a vertical shaft, centrifugal unit with double entry. A rubbing face shaft seal seals the primary circuit argon. The bottom bearing is a hydrostatic sodium-fed bearing immersed in the sodium. The top bearing consists of an integral oil-lubricated hydrostatic annular slot-fed sleeve with a hydrodynamic thrust step bearing. One oil system supplies both the seal and the top bearing. Bearing center-line distance is about 15 ft. The shaft incorporates a tubular section welded to two solid end forgings. A flywheel gives minimum rundown time of eight seconds to half-speed. (Fig. XIII.E-4)

The secondary pump is a vertical mechanical unit with a cold flange. Anticonvection baffles are incorporated into the tank structure. There is a conical bottom section. (Fig. XIII.E-5) (Ref. 13)

1. TOROID	13. DIAGRID COOLING PIPES
2. PRIMARY HEAT EXCHANGER SHUT OFF VALVE	14. PRIMARY PUMP MOTOR
3. PROTECTIVE LAYER	15. FLUID COUPLING
4. REACTOR JACKET	16. PONY MOTOR
5. BELLOWS SLEEVE	17. SHIELDING
6. INSULATION	18. FLUX DISTORTION FLOW METER GUIDE TUBE
7. NEUTRON SHIELD SUPPORT STOOLS	19. DISCHARGE PORT
8. BULK MONITORING PIPE	20. SHOCK ABSORBER ASSEMBLY
9. PRIMARY HEAT EXCHANGER	21. PRIMARY TANK
10. B.P.D. PIPEWORK	22. ROTOR PLATE
11. STRONGBACK	23. VALVE
12. DIAGRID SUPPORT STRUCTURE	24. LOW TEMPERATURE PIPEWORK

Figure XIII.E-1 PFR Primary Circuit Excluding Shields and Core (Ref. 7)

Figure XIII.E-2a PFR Intermediate Heat Exchanger (Ref. 12)

Figure XIII.E-2b PFR Inlet Region of IHX (Ref. 22)

Figure XIII.E-3 PFR Decay Heat Removal (Ref. 11)

XIII.E-6

Figure XIII.E-4 PFR Primary Pump (Ref. 13)

Figure XIII.E-5 PFR Secondary Pump (Ref. 13)

XIII.F. SODIUM PURIFICATION AND INSTRUMENTATION

Cold traps are used in both the primary and secondary circuits. In the primary circuit, the cold trap loop includes a regenerative heat exchanger on the forced air flow cooling system. Primary cold traps are housed in shielded, air-cooled concrete vaults adjacent to the reactor. A cold trap pump moves sodium at a rate of 6.5 kg/second from the cooler sodium pool to the cold trap basket via the regenerative heat exchanger. Sodium is returned to cool the debris tray situated below the diagrid. An additional decay heat removal system is provided by valving, which allows by-pass of the regenerative heat exchanger. A 1 MW heat rejection capability is possible by this means. (Ref. 1)

Primary loop monitoring facilities include coolant sampling and distillation, a plugging meter, two carbon meters, a demountable subassembly for the collection of particulate material, specimens for material monitoring, and a blanket gas sampling point. The coolant sampling facility is incorporated in the cold trap loop. (Fig. XIII.F-1)

The plugging meters are installed at the inlet and outlet of the primary cold trap. They are a variant on the servo-controlled continuous reading device, utilizing an NaK filled loop inserted between the orifice region and the air

cooler. Two versions of a carbon meter are installed in the primary loop; they monitor sodium at the inlet of one of the IHX. There is no carbon meter in the secondary circuit.

Four hydrogen meters installed in a heated by-pass at the evaporator outlet serve for detection of small water leaks. (Ref. 16)

Two systems for the detection of cladding failure are utilized in PFR. The Bulk and Location System monitors samples taken directly from the coolant channels. The Bulk Only System monitors samples of the bulk coolant taken from the outlets of the primary loop heat exchangers. The samples are monitored for delayed neutrons. The loops include D.C. electro-magnetic pumps and flowmeters, and a selector valve. The two systems differ somewhat in the operation of the flowmeter and the selector valve. (Fig. XIII.F-2, 3) (Ref. 17)

The boiling noise detection system depends on the measurement and detection of boiling noise against background noise. Detection is by means of above-core wave guides.

Temperature of the sodium coolant is measured by standard instruments mounted at subassembly outlets.

Figure XIII.F-1 PFR Primary Loop Sampling (Ref. 16)

XIII.F-2

Figure XIII.F-2 PFR Bulk and Location Selector Valve Assembly - BPD (Ref. 17)

Figure XIII.F-3 PFR Bulk and Location Monitor Assembly - BPD (Ref. 17)

XIII.G. COVER GAS AND AUXILIARY SYSTEMS

Decay heat removal system:

See Section E

Cold trap systems:

See Section F

Cover gas is argon. There is an argon supply line and a vent line to each gas volume.

Ancillary cooling systems include a system to maintain the vault concrete below 90°C; a reactor vault roof cooling system; the primary cold trap loops; an irradiated fuel cooling system; and a vault emergency cooling coil.

The system to cool the reactor vault consists of three two-stage axial flow fan units. Shut-off dampers prevent air ingress under no-flow conditions. A single fan stage can provide a cooling flow of 850 m³/sec. An emergency flow five times the normal operating value can be obtained by full use of all fan units.

The vault roof cooling system maintains the concrete temperature in the roof below 40°C. Nitrogen gas is fed into the roof via annular ducts in the perimeter of the plant roof. The gas passes downward through penetrations to the lower face of the roof and then radially outwards in a

gap between the main roof structure and a diaphragm plate attached to the lower face, passes down over the outside of the reactor tank top insulation, and discharges through ducts at the top of the leak jacket. The nitrogen system is designed for a pressure of 100 lb ft/in².

In PFR, irradiated assemblies are moved from the reactor core to a buffer storage within the primary tank, with the fuel at all times immersed in sodium. After a period of decay time the assemblies are removed into a transfer flask provided with an argon cooling system, fed by circulating fans. The fuel transfer and subassembly storage tanks are both cooled by similar organic liquid systems. Each tank is divided into three separate sections, containing three, four, and three separate cooling coils connected to three organic liquid/water heat exchangers.

The vault emergency cooling coil is a simple loop of thick-walled stainless steel tube mounted in the vault air-cooling inlet duct, and connected to a header tank fed by the site water supply. Gravity flow through the system can remove 4 MW of heat with a sodium temperature of 450°C. (Ref. 11)

XIII.H. STEAM GENERATORS

The IHX pairs supply three sets of sub-critical pressure steam generators. Each generator unit consists of a superheater and reheater in parallel, with combined sodium outlet flows feeding a recirculating flow evaporator. Each set is located in a separate bay in the turbine hall, and is provided with an individual sodium fire fighting system.

All units are U-tube and shell geometry with water or steam in the tubes. The evaporator employs parallel flow, with water in the tubes and sodium in the shell. The superheater and reheater operate with counterflow. The evaporator tube material is ferritic steel, and 316 stainless for the superheater and reheater. Tubes are single-wall construction.

There is a conventional steam drum and circulating pump piped together to form a forced circulation steam generator system. Blanket gas spaces on the sodium inlet and outlet of each heat exchanger unit are completely independent. Sodium levels are monitored continuously by probes and hydrogen detectors are mounted in all heat exchanger gas spaces, and in the flowing sodium between the evaporator and the pump tank. A sodium dump and blanket gas system serves all three circuits in turn. Plugging meters are located in the line between the pump and the intermediate heat exchanger. Bursting disks are provided which vent to a cleanup system. (Fig. XIII.H-1 to XIII.H-4) (Ref. 11, 15)

Figure XIII.H-1 PFR Heat Removal and Steam Plant (Ref. 12)

Figure XIII.H-2 PFR Steam Generator Heat Exchangers (Ref. 12)

Figure XIII.H-3 PFR Evaporator (Ref. 15)

Figure XIII.H-4 PFR Superheater - Reheater (Ref. 15)

XIII.I. REACTOR INSTRUMENTATION AND CONTROL

The PFR has a sophisticated computerized system for data monitoring, called the Data Reduction Equipment (DRE). The acquisition, processing, display, and recording of data from plant sensors, including detection, display, and recording of alarm conditions, are with few exceptions vested in the DRE. The system also performs several monitoring and analysis functions. It provides a permanent record of plant variables, storing and sorting information which can be printed out, displayed, or played back through the computer system to isolate the record of especially significant variables. The CRT picture can be photographed with an installed polaroid camera. Normal functions are the display of plant operating data, provision of information for the main automatic control loops, programming and control of sequential operations such as fueling and startup. The data system consists of two identical, linked, digital computer subsystems, either of which can sustain plant operation if necessary. A data link

enables the subsystems to update each other. Manual controls for system operation are provided on the operator's desk and by a keyboard at the printout station, but the operator's task is primarily supervisory. Automatic control is based on the use of direct digital control as much as possible.

For core and primary system monitoring standard nucleonic instrumentation is used. Chambers are enclosed in cooled thimbles inserted in the neutron shield. Each subassembly has a thermocouple. Measurements of level and flow use electromagnetic coupling principles so that transducers can operate through pipe walls, or the instruments are contained in thimbles. A boiling noise detector to detect the presence of small obstructions to coolant flow in the core is either through wave guides, or the analysis of power fluctuations arising from the voiding effect. (Ref. 19)

XIII.J. FUEL HANDLING

Fuel handling is done with the reactor shutdown. The single, large rotating plug carries the charge machine, orientation machine, transfer rotor, and other equipment. It rotates on a grease-lubricated wire race ball bearing. Sealing is by a mercury dip seal. An anti-vibration grid below the shield, and attached to it, supports the lower end of the guide tubes in which the control rods and shut-off rods operate and which carry the above-core thermocouples. (Fig. XIII.J-1)

The charge machine is a pantograph type. It provides a facility for the insertion or withdrawal of subassemblies while holding down adjacent ones. Controls and instrumentation are carried on the upper half of the machine. A small CRT in the machine gives the operator access to all data in the DRE. (Fig. XIII.J-2)

An orientation machine above the core operates in conjunction with the charge machine. It provides a facility for rotating the subassemblies to the correct angular position. Three sweep arms interlocked with the charge machine and the rotating shield sweep the space between the bottom of the instrument guide tubes and the top of the core, making certain that nothing is inadvertently left between the stationary and moving parts of the transfer rotor.

The transfer rotor is a magazine type device carrying twenty buckets for storing subassemblies and other components prior to their removal from the reactor, or new assemblies for loading. Irradiated

subassemblies are posted into the rotor through a discharge port valve, which forms a nonhermetic seal between the hot sodium inside the reactor jacket and the cooler sodium outside of it. Storage within the reactor vessel in the transfer rotor is about thirty days.

New fuel is posted to the transfer rotor from the ex-reactor charge machine through a reactor transfer port. This port is provided with a long guide tube spanning the underside of the reactor roof and the top side of the transfer rotor, and is provided with a valve which seals the reactor atmosphere and provides shielding when the reactor is in operation.

The irradiated fuel transfer cask is a shielded and cooled flash used to transfer irradiated assemblies in sodium-filled buckets to the cave, and to bring new assemblies to the transfer rotor. This operation can be carried out with the reactor on-load.

When the reactor is on power, the charge machine is removed and replaced by the charge hole instrument plug. This plug is inserted into the hole vacated by the charge machine. It is opened out in-situ to provide thermocouples within the slot required by the charge machine.

Decontamination and fuel handling buildings and an active work area are in a building in line with the reactor hall. The building also houses facilities for storage of spent fuel. (Ref. 1, 20)

1. TRANSFER FLASK	14. BIOLOGICAL SHIELD
2. CHARGE MACHINE CONSOLE	15. SHOCK ABSORBER
3. CHARGE MACHINE	16. CONTROL RODS
4. PUMPS	17. HEAT EXCHANGER
5. VALVE	18. NEUTRON SHIELD
6. FALSE FLOOR	19. CORE
7. ROTATING SHIELD	20. CORE SUB-ASSEMBLY SUPPORTS
8. ROTATING SHIELD DRIVE	21. CORE SWEEP ARM
9. ROTOR SWEEP ARM	22. DIAGRID
10. ROTOR DRIVE	23. REACTOR JACKET
11. ROTOR	24. DIAGRID SUPPORT STRUCTURE
12. DISCHARGE TUBE	25. PRIMARY VESSEL
13. LOAD/UNLOAD TUBE	26. LEAK JACKET

Figure XIII.J-1 PFR Fuel Handling Equipment (Ref. 7)

Figure XIII.J-2 PFR Change Machine (Ref. 21)

XIII.K. CONTAINMENT

The reactor hall is a low-pressure containment building designed to withstand an internal pressure of 50.8 m.b. with a low leak rate. The whole of the active area is enclosed in the secondary containment building. Construction is of concrete panels bolted and sealed onto supporting steel framework. Joints are sealed with a plastic compound. (Fig. XIII.K-1) (Ref. 21)

Figure XIII.K-1 PFR Containment Systems (Ref. 21)

XIV FERMI

LOCATION: Monroe, Michigan
U.S.A.

OPERATION: August, 1963

The Enrico Fermi Atomic Power Plant is a power demonstration station, designed by Atomic Power Development Associates, Inc. (APDA) and operated by the Power Reactor Development Company (PRDC).

Construction was started at a site near Monroe, Michigan, in 1956. Initial criticality was achieved in August 1963. A three year test period followed. The power test program was initiated in December 1965. Maximum power level was reached in May 1967. Numerous shutdowns were caused by small leaks from water-side to sodium-side in the steam generators. Fermi was shut-down on October 5, 1966, following damage to fuel assemblies. This damage was caused by obstruction of core coolant flow from a broken piece of a zirconium sheet covering the flow guide.

After cleanup, inspection, and addition of improved instrumentation to the reactor, it was relicensed. The reactor was loaded with new fuel and reached criticality on July 18, 1970. A power of 67 MWt was achieved by September 1970.

An oxide core was designed for Fermi, the work supported mainly by the Edison Electric Institute, Belgonucleaire, Central Research Institute of Electric Power (CRIEP) of Japan, and Detroit Edison Company.

However, a decision for permanent shutdown was reached, and Fermi is being dismantled.

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Table - 1

GENERAL PARAMETERS

Reactor type	Pool-type. Demonstration
No. loops	3
Coolant	Sodium
Core inlet temperature	552°F
Core outlet temperature	910°F
Flow direction	Upward
Driver fuel	Enriched U-Mo alloy
Blanket fuel	Depleted U-Mo alloy
Core diameter	30.5 in.
Core height	30.5 in.
Core volume	11.65 ft ³
No. enrichment zones	1
Output	65 MWe, 300 MWt
Neutron lifetime	2×10^{-7}
Delayed neutron fraction	0.0069
Max. can temperature	940°F
Fuel centerline temperature	1134°F
Neutron flux, ave.	0.5×10^{16} n/cm ² sec.
Doppler ($\Delta K/K$)°C	-1.6×10^{-6} (total)
Specific power	605 kw/kg ²³⁵ U
Power density	23,000 kw/ft ³
No. driver elements	91
No. radial blanket elements	548
No. in-core control elements	10
Goal burnup	~1.0%

Table - 2

CORE AND BLANKET

	Driver zone	Axial blanket	Radial blanket
Fuel material	Uranium alloy	Uranium alloy	Uranium alloy
Form	Round pin	Round rod	Round rod
Composition	U-10 Mo	U-2.75 Mo	U-2.75 Mo
^{235}U	25.6%	0.35%	0.35%
Pin od	0.148 in.	0.415 in.	0.415 in.
Rod cladding	Zirconium	Stainless steel	Stainless steel
od	0.158 in.	0.443 in.	0.443 in.
Wall thickness	0.005 in.	0.010 in.	0.010 in.
Fuel-clad gap		Bond 0.004 in.	Bond 0.004 in.
Bond material	Metallurgical bond	Sodium	Sodium
Active length	30.5 in.	14 in. x 2	65 in.
Gas plenum length		(top)	
Pin length	32-1/16 in.	18 in.	71.5 in.
Vented/non-vented	No	No	No
Assembly material	Stainless steel	Stainless steel	Stainless steel
Shape	Square	Square	Square
Side	2.646 in.	2.646 in.	2.646 in.
Wall thickness	0.096 in.	0.096 in.	0.096 in.
Overall length	96-9/16 in.	96-9/16 in.	96-9/16 in.
No. pins/assembly	144	16	25
Pin spacing	Grid-egg crate	Grid-lattice	Wire and grid
Pin pitch	0.200 in.		0.483 in.
Assy. pitch	2.693 in. (square)		2.693 in. (square)
Assy. in core	91	182	548
Volume fraction (Vol.%)			
Fuel	^{235}U 7.1	28.3	44.6
	^{235}U 20.8		
Steel	24.9	18.2	20.7
Sodium	47.2	53.5	37.4

XIV.A. CORE AND BLANKET

In the fuel region of the assembly, 144 rods of 25.6% enriched U-10 Mo alloy are loaded into a square cartridge, maintained on a square pitch of 0.200 in. by a wire and plate arrangement. Fuel pin fabrication is by the coextrusion of the uranium alloy slug in zirconium tubing. The ends are pointed, and zirconium caps are locked on the pin by cold swaging. The upper and lower blanket sections, each containing sixteen depleted U-2.75 Mo pins in stainless steel tubes, are mechanically incorporated into the core subassembly cartridge. Lugged grids hold the top and bottom sections of the pins within the cartridge. Thermal bonding for the axial blanket pins is sodium. There is a gas space above the rod. The central positions within the cartridge contain no rods. (Fig. XIV.A-1)

Radial blanket rods are the same as axial blanket rods except for their length, which is 71.5, and the spacing which is by spiral wire and lugged grids. The inner radial assemblies have a thermal expansion spring like that of the core assemblies in the support structure. Outer radial assemblies have a simple support structure. The lattice consists of twenty-five blanket rods of depleted U-2.75 Mo in stainless steel cladding. Bonding is by sodium. (Fig. XIV.A-2) (Ref. 2)

Preliminary design of the mixed oxide core was initiated in 1965. A single-zone core divided into two regions was selected for the reference design. The inner zone would contain PuO_2 -depleted UO_2 and the outer zone enriched UO_2 . The inner region would represent about 85% of the initial core volume. (Ref. 2.)

Summary of final core design data

Core size	48 in. height	
	37 in. diameter	
	844 l. volume	
Fuel enrichment	Center pins 31.7 w/o Pu/Pu + depleted U	
	305 day pins 28.2 w/o $^{235}\text{U}/\text{U}$	
Breeding ratio	1.08 total	
Neutron flux	$8 \times 10^{15} \text{ n/cm}^2 \text{ sec. total central}$	
Fuel pin	Clad od	0.25 in.
	Clad thickness	0.016 in.
	Clad material	316 or 347 SS
	Overall length	70 in.
	Gas plenum	2 x 9
	Smeared fuel density	83.5% TD
Max. burnup	90,000 MWD/MT	

(Ref. 6)

XIV.B. CORE SUPPORT AND VESSEL INTERNALS

Core and radial blanket assemblies are supported by two plates. These are 2 in. thick and spaced 14 in. apart by ribs welded to them. There are openings to take the subassembly nozzles, which are 18 in. in length. The center section which supports the core assemblies is removable. The support plates rest on a ledge ring and seal rail. (Fig. B XIV.B-1)

The upper section of the vessel contains a hold-down device or plate. Hold-down of the assemblies is accomplished by engaging the handling lug of the assembly with a finger attached to the

hold down plate, compressing a spring in the assembly nozzle to hold it firmly against the finger and provide for thermal expansion. Alignment of the device is maintained by a three arm spider. When the plate is lowered into position, sockets attached to the lower ends of the arms are positioned by the subassembly support plates and at the top of brackets attached to the lower vessel inner shield assembly. (Fig. XIV.B-2)

A thermal shield section of sub-assemblies containing stainless steel rods surrounds the radial blanket. (Ref. 2)

XIV.B-2

Figure XIV.B-1 Fermi Section through Support Plates (Ref. 2)

Figure XIV.B-2a Fermi Hold-Down Device - Plan Section (Ref. 2)

Figure XIV.B-2b Fermi Hold-Down Device - Elevation (Ref. 2)

XIV.C. REACTOR VESSEL AND SHIELDING

The Fermi reactor vessel is an irregularly staged cylinder. The upper vessel houses the core hold-down device and the offset fuel handling mechanism. The lower vessel, 9.5 ft. dia., contains the core, blanket, and thermal shield assemblies and the core support structure. Inlet piping for radial blanket and core coolant are at the lower part, feeding to the core inlet plenum and the radial blanket inlet plenum. A melt-down section is located in the core-flow section inlet plenum. (Fig. XIV.C-1)

The melt-down section consists of a flat 1/8 in. thick zirconium liner bolted to the top of a 1/2 in. thick baffle plate, which is part of the shielding and baffling for the lower head of the vessel. Material from a melt-down would collect as a flat, circular, subcritical slab about 7 ft. diameter. Three vertical baffles and a conical flow guide direct the coolant flow and serve to disperse molten fuel as it enters the plenum. A secondary melt-down section is located immediately below the bottom head of the vessel. This consists of 6 in. cubes of 5% borated graphite bonded together with boron-containing cement, to form a crucible capable of containing molten uranium. (Fig. XIV.C-2)

The rotating shield plug is located at the top of the reactor vessel. The hold-down device and the offset handling mechanism are mounted eccentrically on it. The plug serves as an integral part of the biological shielding and as part of the fuel handling equipment. It consists of a 1-1/32 in. thick stainless

steel shell containing layers of shielding material and insulation composed of stainless steel, borated graphite, and carbon steel. The 12 in. thick cover plate carries the hold-down and offset handling equipment. The weight of the plug is transmitted to the reactor vessel plug container flange through a load-carrying ring and ball-bearing assembly. Sealing is by a liquid NaK dip seal, with a mechanical seal as backup. O-ring gaskets seal all bolted covers and flanges. (Fig. XIV.C-3)

Primary shielding is provided by the two rows of stainless steel elements surrounding the blanket, and several layers of cylindrical plate sections mounted eccentrically with the reactor vessel. Including the vessel wall, the thickness of this part of the shield is 7.5 in. Sodium coolant flows between the inner layers. Outside the vessel, a graphite shield consisting of six inches of borated graphite is placed next to the reactor vessel. This is followed by an insulating layer. The upper and lower vessel shielding systems are similar. A primary shield tank encloses the reactor vessel and shielding. Its primary function is to act as a stand-pipe for secondary containment of molten sodium in the event of a leak. The dense lattice of the neutron shielding around the reactor vessel leaves a small enough void space in the primary tank so that the sodium coolant level will not drop below the centerline of the 30 in. outlet pipe. Void spaces are filled with a low pressure inert gas. The bottom of the tank is a flat reinforced base for the reactor vessel supports. (Fig. XIV.C-4) (Ref. 1,2)

Figure XIV.C-1 Fermi Reactor Vessels (Ref. 3)

Figure XIV.C-2 Fermi Melt-Down Section (Ref. 2)

Figure XIV.C-3 Fermi Reactor Plug Support (Ref. 2)

Figure XIV.C-4 Fermi Reactor Shielding (Ref. 2)

XIV.D. CONTROL ELEMENTS

Eight safety rods and two operating control rods control the Fermi reactor. Poison material is ^{10}B -enriched boron carbide. The rods are spaced uniformly in the core, with the two operating control rods on opposite sides of the vertical center. Each safety and control rod is housed in a cylindrical guide tube, which in turn is mounted inside a square tube. The upper part of the guide tube is permanently attached to the hold-down mechanism and moves with it. The lower part is seated in the support plates and can be removed and replaced. (Fig. XIV.D-1)

The safety rod is made up of four sections, consisting of the dash ram, the poison section, the extension rod, and the handling head. The poison section is ~ 36 in. long and is a 2-1/4 in. od stainless steel tube containing six hermetically sealed stainless steel tubes 5/8 in. dia. Hollow cylinders of boron carbide fill the six tubes. Sodium is admitted to the poison section tube from the guide tube by 3/8 in. dia. holes at the lower end of the rod. Safety-rod stroke is ~ 54 in., with a maximum velocity during scram of 6.5 ft/sec. (Fig. XIV.D-2)

The two operating control rods are identical. Each rod has three sections; the poison section, the extension rod, and the pickup head. The poison section consists of nineteen sealed stainless tubes about 30 in. long, located on a triangular pitch within a 2-1/4 in. od

tube. The boron carbide is located in the lower ten inches of the containment tubes. The poison cylinders are solid. Coolant holes permit sodium circulation around the poison tubes. Total stroke is ~ 20 in.

Safety-rod drive mechanisms are electromechanical devices consisting of a power unit and a drive extension, mounted above the rotating shield plug on the top plate of the hold-down mechanism vertical drive assembly. The rods are raised or lowered through a ball screw and nut. The drive extension penetrates the rotating shield plug through a seal thimble bolted to the shield plug cover. The reciprocating stroke is sealed by a bellows connecting the seal thimble to the drive extension. Loss of current to a latch magnet at the upper end of the drive extension scrams the reactor. Total time to insert the more than eight dollars of negative reactivity in the eight safety rods is approximately 0.9 seconds from scram-signal initiation. Rods can be scrammed from any point in their stroke. (Fig. XIV.D-3)

Operating control rod mechanisms are similar in design, except in the use of a variable-speed drive for the regulating rod, and a special safety-latch arrangement to ensure non-release of the control rods except by operator initiation, and then only when the rods are seated in their guide tubes or are within one inch of being seated. (Fig. XIV.D-4) (Ref.1,2)

Figure XIV.D-1 Fermi Safety and Control Rod Guide Tube (Ref. 5)

Figure XIV.D-2 Fermi Safety Rod Assembly (Ref. 5)

Figure XIV.D-3 Fermi Safety Rod Drive Extension (Ref. 5)

Figure XIV.D-4 Fermi Control Rod Latch Mechanism (Ref. 5)

XIV.E. HEAT TRANSFER SYSTEMS

Fermi is a pool-type, three loop system with sodium as primary and secondary coolant.

Each primary loop includes check and throttle valve, the shell side of the intermediate heat exchanger, and a cold-leg pump. Primary sodium flows by gravity from the free-surface pool of the upper reactor vessel to the Intermediate Heat Exchanger (IHX), then to the pump tank to be sent back to the reactor, entering the core and blanket plenums at the lower end of the reactor vessel. About 90% of the flow is delivered to the core plenum, and 10% to the blanket plenum. Blanket flow is controlled by a throttle valve. Primary piping is stainless steel, 30 in. dia. from reactor to pump, 16 in. at pump discharge, 14 in. piping in flow to core, and for flow to blanket, 6 in. All walls are 3/8 in. thick. All primary components are enclosed by secondary containment.

The secondary loop transfers heat from the primary system to the steam generator. Each loop includes the tube side of the IHX, the shell side of the steam generator, and the secondary coolant pump. There are no check valves. System pressure is higher than in the primary system.

The three intermediate heat exchangers are counter flow shell-and-tube units, with primary sodium on the shell side. Tube bundles are removable. Secondary sodium enters through upper nozzles, flows downward through a central downcomer, and upward through the tubes. The downcomer is shielded inside and outside by stainless steel plates. Leakage of secondary sodium into the primary side is prevented by gaskets. The top shield extends through the operating floor, and the plug is filled with serpentine. Heat transfer surface is 5840 ft². Primary inlet temperature is

900°F, outlet is 600°F. Secondary sodium temperature at the inlet is 520°F, outlet 820°F. Tubes and shell are stainless steel. (Fig. XIV.E-1)

The primary sodium pumps are vertical shaft, centrifugal, sump-type units with oil-lubricated mechanical shaft seals. Each pump is designed to deliver 11,800 gpm at 310 ft. The pump shield plug, shaft, impeller and casing are removable. (Fig. XIV.E-2)

Secondary pumps are vertically mounted units with single suction and single discharge welded to the piping. The sodium-lubricated lower bearing is above the impeller. The upper pump bearing is a combination radial and thrust bearing. (Fig. XIV.E-3)

An overflow tank located in the reactor building collects overflow sodium from the reactor. The sodium can be returned to the system by pumping it to the IHX. Two sump-type pumps are located in the tank. The pump shield plug, shaft, impeller and casing can be removed as a unit.

Primary loop valves include a check valve to prevent sodium back-flow in case of pump failure, and a blanket throttle valve to control coolant flow to the radial blanket. The check valves are a balanced disk type, with the body welded to the pump case discharge nozzle. The blanket throttle valve (Fig. XIV.E-4) is an angle-type, double-bellows seal valve. The whole assembly is contained in a pipe-riser sealed above reactor level.

Secondary loops do not include valving.

Heat energy following a scram will be removed by natural thermal circulation of the primary and secondary coolants. Water is supplied by gravity to the steam generators and steam is vented to the atmosphere. (Ref. 2,5)

XIV.E-2

Figure XIV.E-1 Fermi Intermediate Heat Exchanger (Ref. 2)

Figure XIV.E-2 Fermi Primary Pump (Ref. 2)

XIV.E-3

Figure XIV.E-3 Fermi Secondary Pump (Ref. 2)

Figure XIV.E-4 Fermi Throttle Valve (Ref. 2)

XIV.F. SODIUM PURIFICATION AND INSTRUMENTATION

The primary sodium system receives, stores, and repurifies sodium when it is received. The sodium is filtered as it fills the storage tanks, and is cold-trapped in the storage tanks to remove sodium oxides. Purity is checked by a plugging indicator. The system can purify and monitor the purity of sodium from the primary system, which can be recirculated to the service system when desired. Hydrides as well as oxides are monitored and removed. Sampling is from the cold trap cell. The cell containing the purification equipment is shielded by 6 ft. thick concrete walls. A separate cell holds the storage tanks. A third unshielded cell serves the sodium building ventilation and heater-cooler system for the cold trap and the plugging indicator.

The cold trap is an NaK cooled unit. Sodium passes through the shell side of an economizer to reduce the temperature, then into the trap where the temperature is further reduced. It rises through the center portion packed with stainless steel wire mesh, leaves the cold trap through the tube side of the economizer. (Fig. XIV.F-1)

Sodium enters the plugging indicator past a flowmeter, and into a hairpin-bend Na-NaK heat exchanger to the plugging indicator device. Inlet is at 900°F and outlet at 250°F.

Temperature measurements inside the primary shield tank and inside the reactor vessel are made by means of iron-constantan thermocouples encased in stainless steel sheaths with magnesium oxide insulation. Thermocouples installed on the hold-down plate are used to measure temperatures in the safety system. Outside the primary tank, resistance elements with integral wells are used. Resistance elements used in control are installed in the sodium pipe outlets of the reactor plenum and the outlets of the steam generator. Other standard type thermocouples are used for measurements of pipe and component heating.

NaK-filled high temperature pressure detectors and conventional pressure transmitters are used. Flow measurements in sodium loops and sodium service systems are by means of permanent magnet flowmeters, which require no penetrations of the sodium piping. Submerged pressure detectors in the reactor vessel and primary system measure the sodium head. In some applications, resistance-type level detectors are used.

Leakage of liquid sodium from primary loop components is detected by a double probe type of detector which utilizes the electrical conductivity of sodium to complete a circuit. It has a test and annunciator circuit. (Ref. 2)

MATERIALS OF CONSTRUCTION: TYPE 304 STAINLESS STEEL

Figure XIV.F-1 Fermi Cold Trap (Ref. 2)

XIV.G. COVER GAS AND AUXILIARY SYSTEMS

Cover gas is argon. A recirculating system maintains a gas blanket over all primary system units, furnishes cooling gas to the fuel exit port, and supplies shaft purging gas to the primary sodium and overflow pumps. All spaces are interconnected by piping. The cover gas is held at a slight over-pressure. When the reactor operates at a constant temperature there is no recirculation of the cover gas. Discharge is to a vacuum tank, and makeup gas is taken from a hold-up and surge tank. Gas compressors provide the pressure differential. A vapor trap and a cyclone separator are located downstream

from the vacuum tank. Detector installations monitor the escape of radioactive materials in both components and piping. A secondary inert gas system maintains a gas blanket over sodium in the steam generator, over the secondary pumps, and the auxiliary units. This system exhausts directly to the atmosphere. (Fig. XIV.G-1)

The primary shield tank has an independently controlled nitrogen atmosphere. The primary sodium service building is charged with nitrogen, and the atmosphere is continuously filtered and cooled. It is kept at a slight overpressure. (Ref. 2)

Figure XIV.G-1 Fermi Inert Gas System for Secondary Circuit (Ref. 2)

XIV.H. STEAM GENERATORS

Fermi steam generators are vertical shell, single-wall tube, once-through units with cross-and counter-flow. Tubes are horizontal U-tubes nested in banks of eight, and attached to the stationary head. Each unit includes an economizer, evaporator, and superheater in one integral component. There are no steam drums. Feedwater enters an upper manifold and passes through a down-comer inside a sodium flow shield. Steam leaves from the other manifold at 780°F. Sodium enters the shell side through side nozzles, at 820°F, and leaves by the nozzle at the bottom of the shell at 520°F. There are three steam generator units. Tubes, headers and shell are a Cr-Mo alloy. (Fig. XIV.H-1) (Ref. 2)

When a normal steam flow path is interrupted because of the loss of a turbine generator, an alternate flow path is provided in Fermi. The main condenser

is used as a heat sink by by-passing the turbine. Two large steam dump valves in the de-aerating heater open if turbine stop valves and control valves are closed suddenly. These valves admit steam to the steam space of the de-aerator, reducing steam pressure from the 600 psig operating pressure to 130 psig heater pressure. Increase in the internal pressure in the de-aerator heater causes the condenser dump valve to open, and the heat is dumped to the main condenser. (Fig. H-2) (Ref. 1)

The turbine-generator is a tandem compound, single-flow, 1800 rpm machine with an expected gross output of 156 MWe. The condenser is a single-pass unit with divided water box and hotwell. (Ref. 2)

FERMI XIV.H

Figure XIV.H-1 Fermi Steam Generator (Ref. 2)

Figure XIV.H-2 Fermi Steam Dump System (Ref. 1)

XIV.I. REACTOR INSTRUMENTATION AND CONTROL

Systems are designed for centralized control of the reactor plant and auxiliaries. One operator and assistant in the central control room, and one roving operator, can operate the plant.

Functions of the Reactor Plant Operating Control are automatic/manual control of primary and secondary coolant temperatures; manual control of primary and secondary coolant flows; provision of a signal to control feedwater flow to the steam generators; automatic/manual control of reactor power level, automatic power level set-back by partial insertion of operating control rods.

The Reactor Plant Safety System initiates scram operation by various abnormal conditions.

The Steam Generator Isolation System acts to isolate a steam generator from feedwater and steam headers in case of a sodium-water leak reaction.

Inert Gas Systems Control regulates the gas blanket pressures and flow in the primary systems and monitors pressures in the secondary system. (Ref. 2)

XIV.J. FUEL HANDLING

A single rotating plug with a fixed fuel handling machine is used to insert and remove fuel from the reactor core. The machine, called the offset handling mechanism, rotates around its vertical axis. A transfer rotor is provided to allow decay storage within the reactor vessel. Subassemblies are moved from core positions to the transfer rotor by the handling machine. Transfer from the rotor position to a cask car is also done by the offset handling machine. Spent assemblies are moved in the cask car outside the containment building to the fuel and repair building, and lowered in their pots into the cask car unloading station transfer rotor. After a decay period of one or two weeks the spent assemblies are cleaned and transferred to the water-decay pool.

The offset handling machine consists of four concentric tubes, an elevation drive unit, an azimuth drive unit, seals and shielding. (Fig. XIV.J-1)

The transfer rotor consists of a rotary drive unit with indexing equipment, a vertical drive shaft, and a large rotating disk at the bottom of the drive shaft in which finned pots to contain subassemblies are stored. Eleven spent assemblies can be stored between unloadings. The rotor is contained in a tank attached to the reactor vessel and the tank is

filled with sodium. A low sodium flow is maintained to the transfer rotor through connections in the blanket plenum. (Fig. XIV.J-2)

The cask car, which can handle eleven new assemblies and eleven spent assemblies in each cycle, has three main components: a vertical twelve position cask and rotor, a shielded heat exchanger, and a control cab. The main load is supported in two four-wheel trucks. It is self-propelled by an electric motor drive, has brakes, and hydraulic snubbers fore and aft. The hoisting mechanism is housed in the upper part of the cask and rotor section. The fuel storage rotor of the cask car consists of eleven guide tubes to receive the transfer pot flanges. A twelfth position is for storing the exit-pot shield plug. Argon gas sweeps the finned section of the transfer pots. Thermocouples monitor fuel assembly temperatures. The heat exchanger is an argon-to-air device, and its compartment is lead shielded. Lead and depleted uranium are used for shielding in the cask car storage space and the front end of the cask car. (Fig. XIV.J-3) (Ref. 1, 5)

Figure XIV.J-1 Fermi Offset Handling Machine (Ref. 5)

Figure XIV.J-2 Fermi Transfer Rotor Assembly (Ref. 2)

XIV.J-4

Figure XIV.J-3 Fermi Cask Car Sectional and Plane Views (Ref. 2)

XIV.K. CONTAINMENT

The reactor building is an uninsulated steel pressure vessel, consisting of a vertical cylinder with hemispherical top head and elipsoidal bottom head. Inside diameter is 72 ft., overall height 120 ft., with 51 ft. below grade. Reinforced concrete foundations are in contact with the top and bottom surfaces of the steel, and rest on the underlying rock stratum. Vessel walls are 1.03 in. thick. All penetrations have gas-tight seals located 18 in. beyond the building wall. A rotary crane supported from the vessel

wall is used for equipment handling. A 5 ft. thick operating floor supported on structural steel columns has a stepped radiation seal around the periphery. The seal is bridged with a rubber strip to prevent mixing atmospheres above and below the floor. A secondary shield wall consists of 30 in. concrete, clad on both sides with steel. The area above the operating floor is accessible to personnel. The lower area has a dehumidified nitrogen atmosphere. (Ref. 2)

XV. EBR-2

LOCATION: Idaho Falls, Idaho

OPERATION: 1964

EBR-2 was authorized in 1955, and the first construction contracts awarded in 1957. Power was delivered to the electrical distribution system on August 7, 1964. EBR-2 has since operated as a base-load experimental LMFBR power station, although emphasis has shifted to experimental irradiation of LMFBR fuels and structural materials. A core loading can include 25% or more experimental assemblies, which contribute about 10% of the power output.

EBR-2 is a 20 MWe, 65 MWt pool-type system using uranium alloy fuel. Spent fuel is transferred to an on-site reprocessing and fabrication facility.

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EBR-2 XV (Nominal 1st Core Loading)
MARK-1

Table - 1

GENERAL PARAMETERS

Type	Pool-type
No. loops	1
Coolant	Sodium
Core inlet temp.	700°F
Core outlet temp.	883°F
Flow direction	Upward
Driver fuel	Uranium-fissium alloy (enriched)
Blanket fuel	Uranium (depleted)
Core diameter (equivalent)	19.94 in.
Core volume	72.79 ℓ
No. enrichment zones in core	1
Output MWe/MWt	20 MWe/62 MWt
Breeding ratio	1.2
Neutron lifetime	8×10^{-8} sec.
Neutron flux, total	3.55×10^{15} n/cm ² sec.
Doppler ($\Delta K/K$)/°C (ave)	$< + 0.04 \times 10^{-5}$
Power Density (Max.)	1230 kW/ ℓ
# Driver elements	53
# Radial blanket elements	570 (2 zones)
# In-core control elements	14
In-vessel storage positions	75

EBR-2 XV (Nominal 1st Core Loading)
MARK-1

Table - 2

CORE AND BLANKET

	Driver zone	Axial blanket	Radial blanket	
Fuel material	Uranium alloy	Uranium	Uranium	
Form	Pin	Pin	Pin	
Composition	U-5 fissium	Uranium metal	Uranium metal	
^{235}U	48.4 a%	Depleted	Depleted	
Alloy density	17.95 gm/cc	> 18.7 gm/cc	> 18.7 gm/cc	
Pin od	0.144 in.	0.3165 in.	0.433 in.	
Pin cladding	Stainless steel	Stainless steel	Stainless steel	
od	0.174 in.	0.376 in.	0.493 in.	
Wall thickness	0.009 in.	0.022 in.	0.018 in.	
Fuel-clad gap	0.006 in.	0.008 in.	0.012 in.	
Bond material	Sodium	Sodium	Sodium	
Active length	14.22 in.	18 in. (total)	55.0 in.	
Gas plenum length	2.35 in. (top)			
Vented/non-vented	No	No	No	
Assembly material	Stainless steel		Stainless steel	
Shape	Hexagonal		Hexagonal	
Across flats (dia.)	2.290 in.		2.290 in.	
Wall thickness	0.040 in.		0.040 in.	
Overall length	~7-1/2 ft.		~7-1/2 ft.	
No. pins/assembly	91	18	19	
Pin spacing	Grid	Grid	Wire wrap	
Assy. pitch	2.320 in.			
Assy. in core	53 + 14 as control		60 + 510	
Volume fraction (Vol.%)			Inner	Outer
Fuel	31.8	30.3	60	60
Steel	19.5	18.5	19.6	20.9
Sodium	48.7	51.2	20.4	19.1

XV.A. CORE AND BLANKET

The nominal MARK-1 core had 67 subassemblies, fourteen of these being operated as control and safety rods. Two sections were loaded with 570 radial blanket assemblies. The inner and outer sections differed slightly in flow adapter arrangement. Nominal core size was increased from the original design by adding six core-type subassemblies in the sixth row. (Fig. XV.A-1)

Alterations to the fuel subassembly included a redesign of the cap, and the provision of holes rather than slots in the lower adapter for coolant entry into the subassembly from the high pressure plenum. The central elements of the axial blanket bundles were replaced by a steel tie rod which interconnects the upper and lower blanket support grids. (Fig. XV.A-2)

Lower adapter sections on the radial blanket subassemblies were also modified. The inner and outer blanket subassemblies differ in the method of coolant flow orificing. (Fig. XV.A-3)

Each subassembly has spacer buttons approximately at the midplane of the core. The subassemblies are free-standing, supported only by the lower grid structure. (Ref. 3)

MARK-1A elements, loaded in 1966, have a shorter fuel alloy length, 13.50 in. instead of 14.221 in., and an increase in the size of the gas plenum, the volume being 52.5%. Enrichment was increased to 52.5% ^{235}U . (Ref. 4)

XV.A-2

Figure XV.A-1 EBR-2 Reactor Arrangement (Ref. 3 add)

XV.A-3

Figure XV.A-2 EBR-2 Fuel Subassembly (Ref. 3 add)

EBR-2 XV.A.

XV.A-4

Figure XV.A-3 EBR-2 Inner and Outer Blanket Subassemblies (Ref. 3 add)

XV.B. CORE SUPPORT AND VESSEL INTERNALS

The grid plenum assembly supports and locates the subassemblies and forms the coolant inlet chambers. It consists of two 4-in. thick stainless steel plates, interconnected by tubes welded to each plate in the outer blanket zone. The low-pressure plenum is an annular chamber immediately below the lower grid plate. The plates contain holes for locating the lower adapters of the subassemblies. The subassemblies are supported by a spherical shoulder which

engages a conical seat in the upper grid plate to provide a seal. They extend through the lower plate. The lower end of the subassembly nozzle is closed. The holes for coolant entry are located between the upper and lower grid plates. The outer radial blanket assemblies have coolant inlet orifices at the bottom. The lower grid plate is stepped for flow orificing. (Fig. XV.B-1a-1b, XV.B-2) (Ref. 3-add.)

Figure XV.B-1a EBR-2 Grid Plenum Assembly (Ref. 3 add)

Figure XV.B-1b EBR-2 Bottom Section of Grid Plenum Assembly (Ref. 1)

Figure XV.B-2 EBR-2 Grid Plenum Section (Ref. 3 add)

XV.C. REACTOR VESSELS AND SHIELDING

The reactor vessel assembly is supported at the bottom of the primary tank, on the structural members which reinforce the bottom of the inner primary tank. The grid-plenum assembly is bolted to the reactor vessel. A portion of the radial neutron shield is located inside the reactor vessel, another portion outside the vessel. The shielding consists of canned borated graphite. Retainers and liners provide positive positioning of the shielded cans. Below the reactor vessel, borated stainless steel plates are located between the vertical webs of the beams on the bottom of the primary tank. The reactor cover closes the upper end of the reactor vessel and forms the upper surface of the outlet plenum chamber. It contains the top part of the neutron shield and has two rotating plugs. Pin projections on the underside of the cover are positioned about 1/4 inch above core and inner blanket assemblies, serving as a secondary hold-down device. (Fig. XV.C-1, XV.C-2)

The reactor, primary system equipment, and fuel handling system are immersed in the sodium contained by the primary tank. The tank is a double-walled, stainless

steel cylindrical structure. The inner vessel is 26 ft. od, the outer vessel 26 ft. 11 in. id and has 0.25 in. thick walls. An inert gas fills the annulus. The tank support structure is a system of beams and columns which form a box-like structure. The six radial top beams frame into circular rings with additional stiffening members. The primary tank is hung from this top structure by means of roller-type support hangers. The columns are tied together at the bottom by beams which are anchored to the concrete. The inside of the vertical steel columns is approximately the inner diameter of the 6-ft thick concrete biological shield. Together, the structures form a pressure vessel around the primary tank. (Fig. XV.C-3)

A laminated blast shield formed by alternate layers of 1/2-in carbon steel plate shells and 4-in. thick low-density concrete is located between the primary tank and the biological shield. The biological shield is constructed of ordinary concrete reinforced with hoops of reinforcing rods. It is cooled by a forced circulation of air. (Ref. 3, 3-add.)

Figure XV.C-1 EBR-2 Reactor Vessel Assembly (Ref. 3 add)

Figure XV.C-2 EBR-2 Primary Tank and Internals (Ref. 3 add)

Figure XV.C-3 EBR-2 Primary Tank Support Structure (Ref. 3 add)

XV.D. CONTROL ELEMENTS

EBR-2 has twelve control rods and two safety rods. All are fueled rod assemblies, consisting of a control rod and guide thimble. The guide thimble is hexagonal in cross section and has the same dimensions as the subassembly tube. Rods are modified core assemblies.

The control rod is encased in a hexagonal tube 1.908 in. across the flats. It is smaller than the thimble by the equivalent of one row of fuel elements. There is no axial blanket, but a void section equivalent in height to the reactor core is provided above the fuel section. The void is filled with sodium during operation. Vertical movement of the control rod adjusts the proportion of fuel or void in the reactor core region. A reflector section of steel is located above the void section. The upper end of the rod has an adapter section identical to that of the fuel subassemblies. The lower end is a cylindrical tube with a steel reflector section. The assembly is cooled by the high-pressure sodium which enters through a series of holes in the lower end of the thimble and the lower end of the control rod. A flow-twister device is installed immediately above the core section to minimize bowing of the control rod within the thimble. (Fig. XV.D-1)

The safety subassemblies are essentially identical to the control rod assemblies, except that there is no flow-twister device. They are fully inserted in the reactor at all times during operation and shutdown. They are attached to a common drive unit extending below the reactor structure. (Fig. XV.D-2)

The control rod is actuated by a long shaft extending through the upper biological shield, connecting the control rod to the drive mechanism. The shaft is driven by a rack and pinion at a rate of 5 in./minute by a constant speed, reversible, polyphase motor. A magnetic latch connects the rack tube to the drive shaft. Interlocks insure that all parts are in proper operating position. A scram signal de-energizes the magnetic clutch, releases the shaft from the drive rack and drives the control rod down out of the reactor core. A release time of 0.008 seconds is expected. Deceleration of the stroke is provided by a hydraulic shock absorber connected to an air cylinder. A mechanical stop is built into the system. The twelve control drive mechanisms are mounted on a platform surrounding a central support structure. (Fig. XV.D-3) (Ref. 3,3-add.)

Figure XV.D-1 EBR-2 Control Rod (Ref. 3 add)

Figure XV.D-2 EBR-2 Safety Rod (Ref. 3 add)

Figure XV.D-3 EBR-2 Control Rod Drive Mechanism (Ref. 3 add)

XV.E. HEAT TRANSFER SYSTEMS

EBR-2 has two centrifugal pumps which take sodium from the primary tank and feed it in two streams to the high-pressure and low-pressure plenums of the reactor. Sodium flow is upward through the subassemblies to a common upper plenum with a single 14 in. outlet. The outlet nozzle is located on the opposite side of the vessel from the intermediate heat exchanger, and the connecting piping forms a helix-like spiral which accommodates thermal expansion. An auxiliary pump is located in this line. Primary sodium flows downward through the shell side of the intermediate heat exchanger and back into the primary vessel.

Pumps are vertically mounted, single stage centrifugal units driven by variable speed motors. Each pump delivers 4500 gal/min at full reactor power, with a maximum capacity of 5,000 gpm at 85 psig. An integral shield plug contains about 33 in. of carbon steel balls and 34 in. high density concrete. Direct-coupled pump drives are totally enclosed, gas-tight, 480 volt a.c. motors. Labyrinth shaft seals are used. A radial hydrostatic bearing is located immediately above the impeller, to which sodium is supplied directly from the impeller discharge. The pump has a plug-in capability. (Fig. XV.E-1)

The secondary pump is an a.c. linear induction electromagnetic unit with a capacity of 6500 gpm at 53 psi, and flow control almost down to zero.

The auxiliary pump is a 500 gal/min d.c. electromagnetic pump connected to a rectifier and batteries. Its purpose is to smooth transition from forced convection to natural convection under abnormal circumstances. (Ref. 1,3-add.)

The intermediate heat exchanger is a tube-in-shell unit with a removable tube bundle. Primary sodium flows downward through the shell side. Secondary sodium enters at the top and flows down through a down-comer, upward in the tube side of the heat exchanger. Tubes and shell are stainless steel. Tube od is 0.625 in., wall thickness 0.062 in., and effective tube length is 9.16 ft. Effective surface is 4539 ft². Primary sodium inlet temperature is 880°F, outlet 692°F. (Fig. XV.E-2)

EBR-2 was designed to operate without valves in the primary or secondary systems. Fine flow is achieved in the secondary system by an a.c. electromagnetic pump.

Shut-down cooling is either by forced convection or natural convection. During normal shut-down the primary pumps continue to operate, with assistance from the auxiliary pump, and heat is transferred to the secondary system, following the normal circuit back to the bulk sodium.

If the secondary system is inoperative, and heat is not removed from the primary tank, the gradual increase in temperature of the sodium is relieved by two shut-down coolers, which remove heat entirely by natural circulation. Each cooler system consists of a bayonet-type exchanger immersed in the primary tank, with NaK as the coolant. An NaK/air heat exchanger mounted in a stack outside the containment building exhausts to the atmosphere. Each cooler is designed to remove 250 kW of heat. (Fig. XV.E-3)

Figure XV.E-1 EBR-2 Primary Pump (Ref. 3 add)

Figure XV.E-2 EBR-2 Intermediate Heat Exchanger (Ref. 3 add)

Figure XV.E-3 EBR-2 Shut-Down Cooler and Cooling System (Ref. 1)

XV.F. SODIUM PURIFICATION AND
INSTRUMENTATION

A recirculating cold-trap system is used for continuous primary sodium purification. The trap is a 500 gal. tank filled with stainless steel wire-mesh. A regenerative heat exchanger is incorporated in the main sodium stream to reduce heat losses in the cold-trap system. Operational temperature of 350°F is maintained by a secondary sodium cold-trap loop. For monitoring sodium quality, a plugging indicator is mounted on the cold-trap inlet line, and two vacuum cup samplers remove sodium samples from the cold-trap inlet or discharge line. A single tank is included in the cold-trap line to prevent syphoning of the primary sodium. The cold-trap discharge line empties into a splash sleeve in the gas space of the primary tank. Five remotely controlled valves on the cold-trap line can isolate various sections of the circuit. The cold-trap

inlet and discharge lines are pitched to drain back into the primary tank. An argon blanket is maintained over all free surfaces.

Contact leak detectors are installed in the pump housing and on the floor of the Sodium Purification Cell. A leak monitoring device is included in the ventilation system for this cell. Any one of the devices can shut down the purification system. (Ref. 3,3-add.)

Four permanent magnet flow-meters have been installed in subassembly inlet regions. Chromel-alumel thermocouples are used as active in-core sensors to monitor temperatures of the cladding, coolant, structural specimens, and metal fuel. Tungsten/rhenium couples are used to monitor fuel centerline temperatures of experimental oxide fuels. (Ref. 5)

XV.G. COVER GAS AND AUXILIARY SYSTEMS

Argon cover gas over EBR-2 primary sodium is normally stagnant, except for mixing due to natural convection currents. Fission product activities are monitored by three on-line systems and by periodic sampling. On-line systems withdraw gas from one nozzle, which also feeds the Xenon tag trap system, the cover gas purge system, the gas chromatograph, and several experimental facilities. A floating-head tank controls argon blanket-gas pressure to within $\pm$ in. H₂O pressure differential with respect to the building atmospheric pressure. (Ref. 3-add.)

Shut-down cooling is described in Section XV.E.

The biological shield is cooled by a forced circulation of air. The system is part of the building ventilation system, and the air is exhausted from the building through the shield cooling system, which operates at a pressure slightly below that of the building atmosphere. The top structure and shield plugs, the radial shield and the structure below the primary tank, are cooled primarily by recirculating air. (Ref. 3)

XV.H. STEAM GENERATORS

The steam generator consists of a natural circulation evaporator, a conventional steam drum, and a once-through superheater. Individual units are shell-and-tube design with double tubes and double tube sheets. The evaporator section has eight identical units connected in parallel on the tube side to a horizontal, overhead steam drum with conventional moisture separation internals. Dry and saturated steam flows from the top of the steam drum down through four identical, vertical superheaters and into the turbine generator unit. The steam system is all chrome-moly steel. Two evaporators were modified by coring the evaporator tubes with an 0.812 in. od tube to be used as superheaters, increasing steam velocity in the annulus. (Fig. XV. H-1, H-2)

The secondary sodium system has been provided with a relief system to accommodate a pressure surge in the event of a sodium-water reaction. The system consists of two duplex, 10 in. blow-out diaphragms, one connected to the 10-in. header which interconnects the superheaters and evaporators. Rupture of the diaphragms allows sodium to flow from the header into a 1200 gal. relief tank. The tank communicates with the atmosphere via two 12 in. lines, each supplied with a rupture diaphragm set at 25 psi.

Turbine steam admission valves are controlled as a function of the pressure in the steam system to maintain a constant steam pressure. Electrical energy generated is a direct function of reactor power, and is independent of electrical demands. (Ref. 3-add.)

Figure XV.H-1 EBR-2 Steam Generator (Ref. 3 add)

Figure XV.H-2 Superheater and Evaporator Assemblies (Ref. 3 add)

XV.I. REACTOR INSTRUMENTATION AND CONTROL

Instruments for measuring neutron flux and reactor period include eleven channels. Each channel has detectors, amplifiers, and read-out equipment.

Three fission counter channels indicate reactor period and record log count rate, and provide a startup level interlock which withholds control power for reactor operation or for fuel handling. For reactor operation, period trips are connected in coincidence, with two out of three channel trips causing reactor scram. For fuel handling operation, the period trips, long count rate trips, and counter high-voltage trips are connected in series. Any trip will scram the safety rods.

Three compensated ion chamber channels indicate reactor period and record log N. During operation or fuel handling, two out of three trips will scram the reactor.

One compensated ion chamber covers the linear level range and records reactor power level. Linear indication of reactor power level is given on an expanded scale obtained by manual range switching. Trips may be by-passed by a keyswitch on the console, and will be used only for experimental operations. An interlock requires that the range switch be set at the correct low range.

The high-flux level range is covered by three compensated ion chamber channels which record reactor power level. Trip of two out of three channels scrams the reactor. Channel trips are connected in coincidence.

The automatic flux level control system is designed to maintain reactor power at $\pm 1\%$ of a preselected power level after equilibrium operation at that level has been established manually by the operator. It consists of a comparator circuit and amplifier with a relay output. The system provides automatic flux level control, using only one rod at a time. Any of the twelve control rods may be selected for this purpose. (Ref. 3-add.)

The EBR-2 fuel failure monitor (Fuel Element Rupture Detection Loop) samples coolant at the Intermediate Heat Exchanger (IHX) At a site shielded from core neutrons, a graphite stack surrounds a section of this loop in order to moderate fast neutrons emitted by the delayed neutron emitters down to the region of cross-sections useful for detection. The 20 ft.³ stack has eight BF₃ proportional counters. Signals are processed through electronic circuitry and provide two to four output channels. A mag-tape memory can temporarily store and display data on command. The system disseminates against gamma background. Detection efficiency is nearly 1%. (Ref. 6)

XV.J. FUEL HANDLING

In EBR-2 fuel handling, the first step is a transfer of subassemblies between the reactor and the storage basket, with the reactor shut-down. The second step is a transfer of subassemblies between the storage basket and the fuel-cycle facility via an interbuilding coffin while the reactor is operating.

The fuel-handling system includes the gripper and hold-down mechanisms for removing (and installing) subassemblies from the reactor, the transfer arm for transferring subassemblies between the gripper and the storage rack, and the storage rack. Operation of the rotating plugs and their freeze seals, and certain operations of the control rod and safety rod drives, are included. The gripper mechanism is an electro-mechanical device mounted on the small rotating shield plug and extending into the sodium of the primary tank. The hold-down mechanism is an electro-mechanical device working in conjunction with the gripper mechanism, also mounted on the small rotating shield plug. The transfer arm is a manually operated and electrically controlled device which transports subassemblies between various points in the fuel-handling and unloading systems. The storage rack is an electro-mechanical mechanism to provide temporary storage for new and spent fuel and blanket assemblies. It is suspended from the primary tank cover and fully submerged in sodium at all times. The rack is cylindrical, with a capacity of seventy-five subassemblies. (Fig. XV.J-1)

A subassembly dropped from the transfer arm at any point will drop into a funnel-shaped trough or "subassembly basin" which traverses the area under much of the transfer arm path. It would slide into a retrieving position, standing in a vertical attitude. (Fig. XV.J-2)

The fuel unloading system transfers subassemblies between the primary tank and the interbuilding coffin. Components include the storage rack, transfer arm, transfer port, and fuel unloading machine. The transfer port provides access to the inside of the primary tank, and is basically a large manually operated valve. There are provisions for argon gas during operation.

The fuel unloading machine is an electro-mechanical device which transfers the subassemblies from the transfer arm inside the primary tank to the interbuilding coffin. It is a shielded container carriage assembly mounted on tracks. Mechanisms include a gripping device, an argon gas circulating system, and a drive unit. (Fig. XV.J-3)

Fuel handling is semi-automatic, with the operator initiating instructions relating to the sequence of operations. The system will only respond to correct instructions. (Ref. 3-add.)

Subassemblies decay in the primary tank storage rack for about two weeks, generating about 2300 watts of decay heat at the end of the two week period. Burnup has usually been about 1%.

Figure XV.J-1 EBR-2 Fuel Handling System (Ref. 3 add)

Figure XIV.A-2 Fermi Radial Blanket Assemblies (Ref. 2)

XIV.A-3

Figure XV.J-2 EBR-2 Subassembly Basin (Ref. 3 add)

Figure XV.J-3 EBR-2 Fuel Unloading Machine (Ref. 3 add)

XV.K. CONTAINMENT

The containment shell is a steel cylinder with hemispherical top head, 80 ft. id and ~146 ft. high. 48 ft. are below grade. Thickness of the cylindrical section is 1 in. The shell is gas-tight. Concrete insulation over the inner surface is a minimum of 14 in. thick. The top shell closure is protected by 6 in. thick high temperature insulation lined with sheet steel. (Ref. 3)

XVI. FFTF

LOCATION: Richland, Washington

OPERATION: Target: 1977

The Fast Flux Test Facility (FFTF) under construction near Richland, Washington, will be the primary test installation in the United States LMFBR program.

Prime contractor for the project is the Westinghouse Hanford Company, Hanford Engineering Development Laboratory, under contract to the AEC (now ERDA). Site preparation was started in 1970. Target date for project completion is November 1977.

The Final Safety Analysis Report is being prepared.

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17. Design of the Intermediate Heat Exchanger for the
Main Coolant Loop of the FFTF
W. Wolowodiuk, B. E. Dawson
Joint Power Generation Conf. Sept. 1973
CONF-730918-1 (1973)

Table - 1

GENERAL PARAMETERS

Type	Loop-type
No. loops	3
Coolant	Sodium
Core inlet temp.	316°C (600°F)
Core outlet temp.	482°C (900°F)
Flow direction	Upward
Driver fuel	UO ₂ -PuO ₂
Blanket fuel	No. breeder blanket
Core volume	1040ℓ
No. enrichment zones in core	2 (28 inner elements, 45 outer)
Output MWt	400 MWt
Max. can temperature	670°C (hot spot)
Neutron flux, total	Peak 7×10^{15} n/cm ² sec
Doppler ($\Delta k/k$)/°C total	(-) 0.005
Power Density	0.39 MW/ℓ
No. Driver Elements	73
No. Radial blanket elements	Reflectors: 99
No. In-core control elements	9 (B ₄ C)
Test positions	Open 5, closed loop capability 6
In-vessel storage positions	3 modules
Goal burnup	80,000 MWD/T peak

Table - 2

CORE AND BLANKET

	Driver zone	Axial blanket	Radial blanket
Fuel Material	UO ₂ -PuO ₂	Inconel Reflectors	
Form	Dished pellet		
Enrichment (Pu/U + Pu)	Inner - 22.43 w/o		
	Outer - 27.37 w/o		
Stoichiometry	1.96		
Composition			
Inner zone	21% PuO ₂		
Outer zone	25% PuO ₂		
Density	Smear 85.5% TD		
	90.4% TD		
Pellet od	5 mm		
Rod cladding	Stainless steel		
od	5.84 mm		
Wall thickness	0.38 mm		
Fuel-clad gap	~0.13 mm		
Bond material	Inert gas		
Column length	910 mm	Inconel 144 mm x 2	
Gas plenum length	940 mm (top)		
Pin length	2.38 m		
Vented/non-vented	Sealed		
Assembly material	Stainless steel		
Shape	Hexagonal		
Across flats (dia.)	118 mm		
Wall thickness	3mm		
Overall length	3.7 m		
No. pins/assembly	217		
Pin spacing	Helical wire 1.4 mm dia		
Pin pitch	P/D = 1.24		
Assy. pitch	120 mm		
Assy. in core	73		

XVI.A. CORE AND REFLECTOR ELEMENTS

FFTF has 199 lattice positions making up the core. They are arranged in a hexagonal lattice. The cells are on 4.715 in. centers. Of these positions, 73 are occupied by driver assemblies, and around these, 99 are occupied by reflector assemblies. There is no breeding blanket. There are two fueled zones, PuO_2 content in the inner region is 21% and in the outer region 25%. Three safety rods are located in the inner region, and six shim/scram rods in the outer region. Up to nine movable or fixed shim rods can be located in the reflector zone. General and special purpose test loops, and two closed loops, occupy nine of the available lattice positions. Core volume is 1040 liters. (Fig. XVI.A-1)

The driver assembly is a hexagonal stainless steel can containing a bundle of 271 fueled pins. The hexagonal can is 3.7 m long overall, with a 3mm thick wall and a distance across the flats of 118 mm. Coolant inlet ports in the nozzle assembly provide for radial inlet of the primary sodium. There are wear pads located on the outside of the duct. The top ends in a handling socket. (Fig. XVI.A-2a).

The fuel pin cladding is a stainless steel tube 5.84 mm od, with a wall thickness of 0.38 mm. Overall length is 2.38 m. Spacing of the pins in the bundle is by helically-wrapped, 1.4 mm dia. wire, to give a pitch/diameter ratio of 1.24. The pins are sealed at both ends after loading, and arranged in hexagonal bundles of 217 pins. Each tube contains a 910 mm high stack of dished, UO_2 - PuO_2 pellets. Stoichiometry is 1.96, and smear density is 85.5% TD. The pellet-clad gap is ~ 0.13 mm. Insulator pellets of UO_2 are located above and below the fuel pellet stack, and Inconel reflector elements beyond the insulator pellets in place of the usual axial breeder elements. The fission gas plenum occupies a space 940 mm long at the top of the pin, and a spring is located in this space. The pins are linked together at the bottom with a grid and support assembly. A grid at the top of the bundle provides lateral restraint. (Fig. XVI.A-2b)

Reflector assemblies, supported by the center section of the core support

plate, have the same outer configuration as the fuel assemblies. Reflector assemblies inserted in receptacles in the inner shield segments are about twelve inches shorter, and differ as to inlet nozzles. Each assembly is composed of flat, hexagonal plates, stacked vertically, and fitted over an array of parallel, vertical flow tubes. The active core region of the reflector assembly has Inconel plates. Above and below this region the plates are stainless steel. The assembly nozzle, like the fuel assembly nozzle, provides hydraulic holddown. (Ref. 1, 2)

The Open Test Assembly (OTA) supports and contains irradiation tests to be placed in open test positions in the reactor. It is the same geometrically as the driver fuel assembly, and the nozzle is the same. The top is fitted with a modified driver assembly handling socket. Secondary holddown is by an instrument stalk located above the OTA duct, which consists of an outer holddown tube and an inner instrument tube. Both fuels and materials can be tested. (Fig. XVI.A-3a, XVI.A-3b)

FFTF will provide four Closed Loop In-Reactor Assemblies (CLIRA) for irradiation testing. The components of CLIRA are the pressure tube, flow tube, instrument tube, spool piece, and meltdown cup. The pressure tube is double-walled stainless steel. The flow tube which fits inside the pressure tube is single-walled in the active core region and double-walled above. An annulus between the pressure tube and the flow tube serves as the inlet coolant passage. Inner diameter of the flow tube is 2-1/2 in. A meltdown cup at the bottom of the pressure tube contains any test fuel meltdown that might occur. The instrument tube forms the return flow annulus with the flow tube, and contains instrument leads. The pressure tube, flow tube, and instrument tube are supported from the spool piece attached to the reactor vessel head. The spool assembly directs inlet flow of the test coolant. Seals at the bottom separate the test coolant from the FFTF cover gas, and top seals isolate the test coolant from the containment. Test assemblies for insertion into the system will be supplied by the users. (Fig. XVI.A-4) (Ref. 8)

FFTF CORE MAP

Figure XVI.A-1 FFTF Core Map

XVI.A-2

Figure XVI.A-2a FFTF Driver Fuel Assembly

FFTF XVI.A.

XVI-A.3

Figure XVI.A-2b FFTF Driver Fuel Pin

XVI-A.4

FUELS OPEN TEST ASSEMBLY (FOTA)

Figure XVI.A-3a Fuels Open Test Assembly (Photo No. 750156-2)

HEDL 7409-99.1

FUELS OPEN TEST ASSEMBLY (FOTA) CONTINUED

Figure XVI.A-3b Fuels Open Test Assembly (Photo No. 750156-1)

CLOSED LOOP IN REACTOR ASSEMBLY

HEDL 7312-36.2

Figure XVI.A-4 FFTF Closed Loop In-Reactor Assembly (Photo No. 736943-7)

XVI.B. CORE SUPPORT AND VESSEL INTERNALS

Core support is by means of a welded bridge structure formed by a conical lower surface and a horizontal upper deck. The lower structure is welded to the core barrel. Vertical support is provided by the conical skirt, welded to the outer ring forging of the core support structure and attached to a ring forging on the reactor vessel. The central section consists of a removable core basket containing fuel assemblies, control rods, test positions and inner reflectors. Outside this removable section there is space for in-vessel radial shielding, supported laterally by the core barrel. The region outside the core barrel is used for in-vessel storage positions and vertical components of the core restraint system. The structure is fabricated of stainless steel. In addition to supporting core components, the core support structure provides the pressure barrier between the high pressure inlet plenum and the outlet sodium pool. (Fig. XVI.B-1)

The active core restraint system described in Reference 1 has been changed in favor of a passive mechanical system. The passive concept for core restraint consists of unyielding static restraint rings installed at the core periphery, at the elevations of load pads above the core and below the top of the reactor assemblies. (The active-clamp system consisted of six hydraulic yokes applying load to the top of the core components, and six hydraulic yokes applying load in a plane above the active core region. The peripheral active clamps required in-vessel mechanisms.) (Fig. XVI.B-2) (Ref. 15)

Three instrument trees are located in the space above the tops of the fuel ducts. Each tree consists of a column which penetrates a fixed plug in the reactor vessel head, and an in-reactor structure which includes instrument ducts. The column is mounted on a bearing in the fixed plug and on a bearing on the core barrel at the bottom of the column. The lift and rotation mechanism is installed on the reactor vessel head. The trees provide support and location of instrumentation for each driver fuel assembly, some reflector assemblies, and each movable control rod assembly. They also provide control rod drive shaft guidance and secondary hold-down for driver fuel assemblies and control rod ducts. The instrument assembly is a completely replaceable unit. Each of the three units is within a guard vessel. (Fig. XVI.B-3)

Three In-Vessel Handling Machines (IVHM) are mounted in rotating plugs in the reactor top shield. All contact between sodium and air, or the escape of sodium, fission gases or contamination, is prevented or minimized by double barriers and multiple seals.

Three in-vessel storage modules are supported by the core barrel and the core support structure. They provide in-vessel storage for spent fuel and other core assemblies in the annular region between the core barrel and the reactor vessel thermal liner. (Ref. 1, 2)

Figure XVI.B-1 FFTF Core Support and Internals (Ref. 13)

Figure XVI.B-2 FFTF Core Restraint Modules

INSTRUMENT TREE

Figure XVI.B-3 FFTF Instrument Tree Photo #720425-18

XVI.B-4

XVI.C. REACTOR VESSELS AND SHIELDING

The reactor vessel is a cylindrical stainless steel structure, 6.1 m (20 ft.) id and 13.1 m (43.5 ft) high. Walls are greater than 5 cm (2 in.) in thickness. Three 406 mm (16 in.) diameter inlet nozzles are located near the bottom, and three 710 mm (28 in.) dia. outlet nozzles above core level and below the level of the sodium pool. The reactor vessel head is 7.6 m (25 ft.) in diameter and 550 mm (21.81 in.) thick, formed by welding together two semicircular forgings of carbon steel. The vessel head has penetrations for instrumentation, control, and test devices, and for the in-vessel handling machines. It is attached to a support flange (Z-ring) by bolts. A stack of stainless steel shield plates is mounted under the vessel cover, with crush tubes between the top plate and the vessel head. A stack of thin plate thermal reflectors is suspended below the shielding stack, about 30 cm (1 ft) above the top of the sodium pool. Vortex suppressor plates are located just below the sodium surface. A thermal baffle covers the annular area between the core barrel and the vessel wall. Support for the core support structure is provided by a ring forging on the reactor vessel. (Fig. XVI.C-1)

Radial shielding within the core barrel is furnished by vertical steel plates set in a hexagonal pattern, tangentially to the core. Additional plates fill the corners of the hexagon to conform to the cylindrical core barrel. Coolant channels are maintained by spacers between the plates. The reactor vessel thermal liner is in the form of a 2.5 cm (~1 in.) thick cylinder concentric with the vessel wall. There is a small sodium flow in the annulus. In-vessel fuel storage modules, supported by the core support structure, are surrounded by guard vessels.

The vessel is supported from the Z-ring part of the support structure by steel arms bolted to the ring. The lower ends of the arms are welded to a ring in the vessel wall. The Z-ring is formed on the concrete ledge which is an extension of the reactor cave shield walls.

A guard vessel surrounding the reactor vessel is designed to maintain core decay heat removal in the event of a pipe or vessel rupture. The downcomer for the inlet of primary sodium is installed vertically in this annular space. Guard vessel dimensions are 6.7 m (>22 ft) od and 11.8 m (~38 ft) high. There are no piping penetrations. It is bottom-supported in the reactor cavity, with ties to provide lateral support for the reactor vessel.

The reactor cavity forms part of the inner containment barrier. It is a reinforced concrete cell in the shape of a hollow cylinder, closed at the bottom by a slab. The vessel support ring is located at the top of the cavity, which is 11 m (~36 ft) dia., and 14-1/2 m (~48 ft) high to the top of the support ring. Interior surfaces are lined with steel plate. A pipeway space is located between the reactor cavity and each equipment cell. (Ref. 1,2)

No final decision has been made on the inclusion of a core-catcher device. It is felt that core debris can be contained and cooled within the primary system.

FFTF XVI.C.

Figure XVI.C-1 FFTF Reactor Vessel

XVI.C-2

XVI.D. CONTROL ELEMENTS

Two completely independent sets of control systems are provided. One is a primary shutdown system, and the other system is for control and secondary shutdown. Each system has similar components, consisting of control rod assemblies, drive shafts and drive mechanisms, in-core channel ducts, and drive shaft drive tubes. B_4C is the neutron absorber material. Three types of absorbers will be used:

- Safety rods: Three in row three for shutdown
- Control rods: Six in row five for startup and regulation
- Shim rods: As needed in row seven for reactivity balance

Pin bundle design is basically the same for all three types, consisting of a hexagonal bundle of 61 sealed pins. Spacing is by wire wrap, to give a pitch of 12.65 mm. Cladding tube is stainless steel, 12.07 mm od with a wall thickness of 1.30 mm. Natural B_4C pellets 9.19 mm dia. are stacked in a column 914.4 mm high. Pellet density is 92%. There is an upper and a lower gas plenum. Control rod channels in the core have the same dimensions as the fuel assembly channels. (Fig. XVI.D-1) (Ref. 11)

Vented control rods are being studied.

FFTF FUEL SYSTEM

XVI.D-2

7302-57

Figure XVI.D-1 FFTF Control Rod Absorber System

XVI.E. HEAT TRANSFER SYSTEMS

FFTF has three independent heat transfer loops. Each primary loop includes a hot-leg pump, two isolation valves, a check valve, and the shell side of an intermediate sodium/sodium heat exchanger. The three secondary loops include the tube sides of the intermediate heat exchangers, cold-leg pumps, expansion tanks, valves, and forced draft sodium/air dump heat exchangers. The system removes heat for all modes of operation including emergency cooling and shutdown, except for the closed loops. The Closed Loop In-Reactor Assembly (CLIRA) has its own primary and secondary systems and dump heat exchangers. Each loop can operate independently. Piping and components of each primary loop are contained under an inert atmosphere in separate shielded cells beneath the reactor operating floor. Equipment elevation and low system hydraulic resistance provide natural circulation cooling capability. (Fig. XVI.E-1)

Sodium coolant enters near the bottom of the vessel through three 16 in. nozzles in the high pressure plenum, flows vertically upward through the core, reflector and shield to the upper plenum, where it is mixed. It leaves by way of three 28 in. outlet nozzles to the primary pump.

Primary pumps are single stage, double suction, vertical shaft, free-surface centrifugal units. Design capacity per pump is 14,500 gpm at a head of 500 ft. Sodium is pumped by the impeller at the bottom of the drive shaft, drawn through the double suction impeller inlet, and discharged through the outlet nozzle at the bottom of the pump tank. The free sodium surface in the tank has an argon gas cover, kept at the same pressure as the cover gas in the reactor vessel by connecting, equalizing lines. Thermal baffles in the pump tank and a biological shield are provided. The main shaft has an oil pressure seal. Wound rotors with liquid rheostat controllers provide variable pump speed control. There are auxiliary pony motors for pump operation at about 1/2 of the rated speed at low flow rates. Each pump is within a guard vessel. (Fig. XVI.E-2)

The three intermediate heat exchangers are vertical tube and shell units with bayonet downcomers. Primary sodium enters the unit below the top of the tube sheet and flows downward along the outside of the tubes, around the perimeter of the lower tube sheet, and out through the bottom nozzle. Secondary sodium enters at the top of the unit and flows through the central downcomer into the lower plenum area, through the lower tube sheet, upward through the tubes to the upper plenum, and leaves by an outlet nozzle. The tube bundle is removable. The Intermediate Heat Exchanger (IHX) is 78-3/8 in. dia. and 35 ft. long. Tubing is 7/8 in. od stainless steel, with a minimum wall thickness of 0.047 in. Each tube has a compound bend. There are tube support plates, with orifices for sodium flow, located along the straight parts of the tubes. Inner and outer shrouds direct primary sodium flow over the tubes. A hemispherical head welded to the lower tube sheet provides the boundary between primary and secondary sodium. There is a thermal liner between the shell and the tube bundle. Each IHX is enclosed by a guard vessel. (Fig. XVI.E-3)

There are twelve dump heat exchange modules. The heat exchange bundle is composed of 4-pass serpentine tubes attached to horizontal headers, with finned sections. There is a fan and drive, air control vanes, and an oil-fired pre-heater for each module. (Fig. XVI.E-4) (Ref. 1, 9)

Single isolation valves are installed in the 28 in. dia. hot legs and in the 16 in. dia. cold legs of the primary loops. They are hinged rotating gate valves with rotary motion freeze seals. They have no safety function, but are associated with maintenance and loop isolation. (Fig. XVI.E-5)

Each primary loop has a check valve installed in the 16 in. dia. cold leg piping to limit flow reversal in a loop with pump failure or loss of power. These are tilting disk type valves with dashpot pistons. (Fig. XVI.E-6)

Each secondary loop has eight angle-globe type set/isolation valves, installed at inlet and outlet connections of the DHX modules to isolate the module and to balance flow for uniform heat exchange performance. (Fig. XVI.E-7)

Guard vessels around the IHX and the primary pumps are supported from the floors of the equipment vaults. They are not concentric with the components, but located to accommodate vertical downcomers. The annular free volumes are $\sim 1000 \text{ ft}^3$ for the IHX and 2000 ft^3 for the primary pump. They are fabricated of stainless steel. (Ref. 1, 4)

Each CLIRA has its own primary and secondary heat removal system. Primary flow is driven by a helical induction electromagnetic pump located in the cold leg, directly upstream of the CLIRA.

Immediately downstream of CLIRA, the sodium enters the tube side of an intermediate heat exchanger, and then a surge tank. The primary pump takes its suction head from the surge tank and returns the flow to the CLIRA. Hot and cold leg connecting piping runs from branch arm piping traversing the top of the reactor vessel head, through pipeways to the primary closed loop cell. A small electromagnetic booster pump provides sample flow. The secondary loop is located mainly outside the FFTF containment. The DHX is outside the building. The secondary pump is an electromagnetic unit located in a cold leg. A side stream is removed ahead of the pump for sampling and returned to the main loop through a secondary surge tank. Cold traps are located in by-pass lines. Flow is measured by electromagnetic flow-meters. (Fig. XVI.E-8) (Ref. 8)

Figure XVI.E-1 FFTF Heat Transport System

PRIMARY PUMP WITH GUARD VESSEL

Figure XVI.E-2 FFTF Primary Pump

INTERMEDIATE HEAT EXCHANGER (IHx)

Figure XVI.E-3 Intermediate Heat Exchanger (IHx)

HTS DHX MODULE

Figure XVI.E-4 FFTF Dump Heat Exchanger

ISOLATION VALVE

28 INCH HOT LEG

16 INCH COLD LEG

XVI.E-6

Figure XVI.E-5 FFTF Primary System Isolation Valves

Figure XVI.E-6 Primary System 16 Inch Cold Leg Check Valve .

Figure XVI.E-7 FFTF Secondary Set/Isolation Valve

CLOSED LOOP SYSTEM

FOR TESTING OF FAST REACTOR FUELS AND MATERIALS IN FFTF

XVI.E-9

Figure XVI.E-8 FFTF CLIRA Closed Loop System

FFTF XVI.E.

FFTF XVI.F

XVI.F. SODIUM PURIFICATION AND
INSTRUMENTATION

Planned system for sodium purification is by cold-trapping. Sampling and monitoring devices in test operation include on-line oxygen meters, hydrogen meter, carbon activity meter, plugging meters, sodium sampling devices and flow meters. Chromel-Alumel thermocouples and platinum wire resistance temperature detectors measure reactor outlet and inlet temperatures. Flow and outlet temperature are measured for each fuel channel. Coolant inlet and outlet temperature and flow are monitored for each CLIRA. (Ref.2)

FFTF will use one NaK-cooled cold trap for the primary system (two are installed); one gas-cooled unit for each secondary system; and a gas-cooled unit for the interim decay storage facility. A gas-cooled prototype is being developed.

Two types of vapor traps will be used: a controlled temperature profile condenser, and aerosol filter units. (Ref. 14)

XVI.G. COVER GAS AND AUXILIARY SYSTEMS

Argon cover gas is provided for the reactor vessel and the primary pumps at a controlled pressure by the argon receiving and distribution system. Secondary pumps and expansion tanks are supplied with argon gas to maintain a positive pressure differential with respect to the primary sodium in the IHX. Argon cover gas is maintained over all free sodium surfaces. Exhaust from the gas spaces is discharged to the radioactive gas decay system or to the heating and ventilating system according to its radioactivity. Argon gas can be pumped directly to a radioactive sampling area. Nonradioactive gas is manually sampled from vent lines. Argon cover gas of the CLIRA system and of the reactor is continuously monitored. Supply is not automatically isolated in the event of containment isolation. Check valves and shutoff valves are operated from the control room, and there are overpressure relief valves on the cover gas systems. Liquid argon is stored outside the containment system. The distribution system has feed-and-bleed components.

A nitrogen atmosphere is maintained in cells handling radioactive sodium, and the circulation of nitrogen through cooling coils cools cell atmospheres. Exhaust gas from the cells is discharged to the radioactive gas decay system or to the heating and ventilating system. Liquid nitrogen is stored outside the containment building.

Two independent NaK loops are provided, for the decay storage tanks ($\sim 400^{\circ}\text{F}$) and for the sodium cold traps ($125^{\circ}\text{--}200^{\circ}\text{F}$).

Primary sodium can be pumped directly to the radioactive sampling area and returned to the loop. There are no cross-connections or shared components between loops. The primary sodium is monitored continuously for oxygen and carbon. Secondary sodium can be circulated through plugging meters located in purification loops, and samples removed with removable section samplers in by-pass loops in the secondary circuits.

A preheat system for sodium piping and components uses electrical resistance heaters. Oil and/or gas-fired preheaters are provided for the DHX modules.

Primary sodium level is maintained by continuous feed and bleed from the reactor vessel through the sodium receiving and processing system. Expansion tanks in the secondary loop account for thermal expansion requirements, with a small bleed taken to the secondary sodium processing system. (Ref. 1)

XVI.I. INSTRUMENTATION AND CONTROL

Three low-level flux monitors located in the reactor vessel monitor the core neutron activity during refueling, shutdown, and startup operations. The monitor consists of a fission chamber, in-vessel thimble, in-line drive assembly, and a common nitrogen cooling system. The fission chambers are withdrawn from the maximum flux zone for power operation.

Three fission counters and three compensated ion chambers are located outside the reactor vessel to measure flux beyond the startup range.

Chromel-Alumel thermocouples and platinum wire resistance temperature detectors measure reactor outlet and inlet temperatures. Flow and exit temperature are measured for each fuel channel. The sodium flowmeter is a probe type operating on the eddy current principle. Coolant inlet and outlet temperature and flow are instrumented for each CLIRA. Open test loops have the same type of flow and temperature instrumentation as the driver fuel channels, except that one open test loop is instrumented by sensors in near-proximity to the channel.

The fuel failure monitoring system detects fuel failure by sensing the presence of released xenon or other fission gases. A high resolution Ge (Li) spectrometer system monitors the cover gas for Xenon isotopes. Sodium is continually monitored for soluble fission products. Delayed neutron monitors detect iodine and bromine neutron precursors and characterize the severity of a failure. Grab samples of sodium and cover gas can be taken for laboratory analysis.

Techniques under study for failed fuel location are gas tagging and eddy current flowmeter monitoring for released gases. With gas tagging, small amounts of mixed lighter isotopes of Xenon or krypton are incorporated into the gas plenum of each fuel pin, a specific isotope ratio being placed in each pin of a fuel assembly. With failure, part of the tagged gas is released to the sodium coolant and thence to the cover gas.

The plant protection system provides automatic monitoring of variables, and initiates protective action when necessary. The system includes all active equipment required for protective functions from sensors through final devices such as valves, poison rods, etc. There are two totally independent systems for reactor shutdown.

During startup, the reactor is brought up to 40 MWt on manual control. At or above 40 MWt one of the row five rods can be placed in automatic control, with the operator manually shimming the remaining five rods one at a time. Manual control can be resumed at any time. There are overpower limiters to prevent manual or automatic rod withdrawal if the power level exceeds a set value.

Primary pumps have automatic flow feedback control, with set points adjusted manually by the operator. Flow control is by varying pump speed. Control for the secondary pumps is identical. (Ref. 2)

XVI.J. FUEL HANDLING

On completion of irradiation, driver fuel assemblies are transferred by the In-Vessel Handling Machine (IVHM) to in-vessel storage positions for decay during the next operating cycle. From the in-vessel storage station, core components, in finned pots, are transferred by the Closed Loop Ex-Vessel Machine (CLEM) to the Interim Decay Storage (IDS) system, and then transferred by CLEM into the Core Component Transfer Cask (CCTC). This cask is lifted by the containment polar crane from the cask loading pit and transferred through the containment transfer air lock on a transfer cart. Outside, the cask is lifted by crane from the transfer cart for loading and shipment from FFTF.

Fresh core components are transferred into the containment building on a transfer cart to an inerting/heating/storage station where air atmosphere and surface films are removed by vacuum heating and back-filling with argon, and the temperature is conditioned. CLEM lifts the component and transports it to a position in the IDS system, where it is lowered into a finned pot for storage before transfer to the reactor vessel. Finned pots with core components are transferred to in-vessel storage positions by CLEM, and then the core component is lifted from the finned pot by the IVHM and transferred to its designated core position. (Fig. XVI.J-1)

There are three identical In-Vessel Handling Machines (IVHM) mounted in refueling plugs in the reactor top shield. Each machine services a 120° sector of the reactor and can transport core components under sodium to and from the core, in-vessel storage positions, and the in-vessel transfer station. The IVHM consists of a grapple system which engages a handling socket at the top of the core component. A rising stem and offset arm provide vertical grapple operation. Each IVHM weighs ~50 ton and is 33 ft. high. The part below the vessel head extends into the sodium pool to a depth of 16.125 ft. The rotating plug is positioned in an opening in the reactor vessel head. The IVHMs are operated during reactor shutdown. Operation and control is by a console located on the operating floor. (Fig. XVI.J-2) (Ref. 12)

CLEM is a single-barrel, shielded fuel handling machine, permanently mounted on a transporter consisting of a gantry and a trolley. Overall height is 61.25 ft. above the operating floor. Its weight is 217 ton. CLEM handles fuel assemblies in a sodium-filled core component pot and performs transfer of irradiated and non-irradiated components between the reactor and various fuel-handling stations in the containment building. Control is semi-automatic and is accomplished from a control panel. Components of CLEM include a grapple, dual grapple chain drives and drive units, a shielded cask body, cold wall assembly, drip pan, bottom and closure valve, movable shielded skirt assembly, a NaK cooling system, and an argon gas purge system. Normal cooling mode is by internal radiation of decay heat to the cold wall, externally cooled by NaK. The NaK is circulated by two electromagnetic pumps in a closed system, with heat dumped to an air blast heat exchanger mounted on the CLEM. (Fig. XVI.J-3)

The Interim Decay Storage (IDS) comprises three separate facilities: Reactor Core Decay Storage Tank (CCDT); the Test Assembly Decay Tank (TADT); and the All Component Inerting/Heating/Storage (ACIHS). Its functions are to store irradiated and unirradiated core components (in sodium-filled pots), test assemblies, test sections, and closed-loop in-reactor tubes, and to establish an inert gas coverage and to preheat new core components. The IDS is located within the containment vessel, below floor level, in steel-lined cavities. There are 110 storage positions for core components in the CCDT. Full-length test assemblies are stored in four sodium-cooled storage positions in the TADT. Sodium-filled tanks in CCDT and TADT are connected to a normal and to an alternate cooling system.

The Core Component Transfer Cask has six fuel positions. It provides the capability of handling one test assembly after thirty days decay with an initial rating of 100 MWd/Kgm, and five driver assemblies at ninety days decay with an initial rating of 45 MWd/Kgm. (Ref. 1)

FUEL HANDLING CYCLE

FFTF XVI.J.

XVI.J-2

* ITEM DEFERRED

Figure XVI.J-1 FFTF Fuel Handling Cycle

Figure XVI.J-2 FFTF In-Vessel Handling Machine (IVHM)

CLOSED LOOP EX-VESSEL MACHINE (CLEM) AND TRANSPORTER

Figure XVI.J-3 Closed Loop Ex-Vessel Machine (CLEM)

XVI.K. CONTAINMENT AND STRUCTURES

Major structures are the reactor containment building, reactor service building, control building, auxiliary buildings and dump heat exchanger enclosures. The reactor containment building is a carbon steel shell 41.1 m (135 ft.) dia. and 55.5 m (182 ft.) high. 24.4 m (80 ft.) of the structure is below grade. The cylindrical shell has 3.5 cm ($\sim 1\frac{1}{2}$ in.) thick walls and hemispherical heads. The bottom head is embedded in concrete. Maximum design leak rate is 0.1% of total volume per day. All penetrations are leak-tight. All radioactive components and systems are within the containment structure, housed in reinforced and shielded concrete cells below the operating floor. The shielded cells have carbon steel liners. The structure has a 200-ton capacity polar gantry crane.

The reactor service building contains facilities for transfer of assemblies and radioactive components to shipping containers for off-site disposal. Rail and truck access is provided to the adjacent containment structure through an equipment air lock. Below grade there are concrete shielded cells for some auxiliary systems, including cryogenic systems for storage and processing of radioactive waste gases.

The control building is located with a portion of the building adjacent to the containment structure, with access through an air lock and monitored areas. Auxiliary buildings housing ancillary systems and equipment are of steel superstructure. The DHX structures are steel, and provided with insulation to reduce noise levels. (Fig. XVI.K-1) (Ref. 2)

FFTF PLANT ARRANGEMENT

Figure XVI.K-1 FFTF Plant Arrangement

XVII. CLINCH RIVER BREEDER REACTOR
(CRBR)

LOCATION: Clinch River
Oak Ridge, Tennessee
(TVA site)

OPERATION: Construction
1976-1980 target

The objective of the Clinch River Breeder Reactor (CRBR) project is the design and construction of a 350 MWe demonstration fast breeder reactor. A joint proposal for the design, construction, and operation of CRBR by Commonwealth Edison Co. of Chicago and Tennessee Valley Authority was accepted by the AEC in January 1972. In March 1972, two non-profit groups were formed to implement the CWE-TVA proposal. The Project Management Corporation (PMC) was to provide centralized management of the Project and the demonstration program. The Breeder Reactor Corporation (BRC) served as liaison between project participants and the utility industry. BRC represents 350 utilities which have contributed to the project. In November 1972, AEC and PMC announced the selection of Westinghouse Advanced Reactors Division as prime contractor, with responsibility for designing and supplying the Nuclear Steam Supply System, and assisting PMC in overall planning. Burns and Roe was retained as architect-engineer in December 1972, with Holmes and Narver, Inc. assisting in selected phases. Contract between Westinghouse and PMC was signed on November 14, 1973, and the contract between AEC and Westinghouse for supporting technology was signed January 30, 1974. General Electric Co. Breeder Reactor Department and Atomics International are subcontractors to Westinghouse.

The schedule announced by PMC in January 1974 was for filing the environmental report by December, 1974, construction permit expected about 14 months later, and a construction period from 1976 to 1980. The first application was rejected because of lack of detailed information on site meteorology, seismology, and aquatic environment.

Under a realignment of industry-government relationships in the Liquid Metal Fast Breeder Reactor (LMFBR) program in 1975, the Energy Research and Development Administration (ERDA) will now assume direct management of the CRBR Project, with PMC assuming an advisory role along with the TVA group and a three member Project Steering Committee.

The Nuclear Regulatory Commission docketed the Clinch River application in April 1975. Debates over the requirement for a core-catcher are still progressing.

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Table - 1

GENERAL PARAMETERS

Type	Loop
No. Loops	3 (+ Overflow Heat Removal System)
Coolant	Sodium
Core inlet temp.	730°F
Core outlet temp.	995°F
Flow direction	Upward
Driver fuel	Mixed oxide
Blanket fuel	oxide
Core diameter	6.2 ft.
Core volume	2400ℓ
Enrichment zones	2
Output MWe/MWt	350/975
Breeding ratio	1.2
Max. can temperature	1215°F
Linear power	14.5 kw/ft. max. (7 kw/ft. ave)
Doppler ($-\lambda \frac{dk}{dt}$)	.0073 (Beginning of first cycle)
Driver elements	198
Rad. blanket elements	150
In-core control elements	15/4 Primary/secondary
In-vessel storage	None
Goal Burnup	80,000 peak

Table - 2

CORE AND BLANKET

	Driver Zone	Axial Blanket	Radial Blanket
Fuel material	UO ₂ -PuO ₂	UO ₂	UO ₂
Form	Pellet	Pellet	Pellet
Stoichiometry	Substoichiometric		
Enrichment Pu(U + Pu)		Depleted	Depleted
Inner	22%		
Outer	32%		
Rod cladding material	Stainless steel 316		Stainless steel
od	0.23 in.	0.23 in.	0.52 in.
Wall thickness	0.015 in.	0.015 in.	0.015 in.
Column length	36 in.	14 in. x 2	64 in.
Gas plenum length	48 in. (top)		36 in. (top)
Vented-non-vented	No		
Assembly material	Stainless steel	Blanket pins integral with fuel pins in can	Stainless steel
Shape	Hexagonal		Hexagonal
Across flats	4-1/2 in.		4-1/2 in.
Overall length	180 in.		180 in.
Pins/assembly	217		61
Pin spacing	Spiral wire		Spiral wire
Pin pitch	1.26 P/D		
Assembly pitch	4.76 in.		
Assemblies in core	198		150
Fuel	.325		

XVII.A. CORE AND BLANKET

CRBR fuel assemblies are similar to the Fast Flux Test Facility (FFTF) assemblies. The driver core consists of 198 assemblies in a triangular pitch of 4.76 in. Feed enrichments are 22% Pu/U+Pu for the inner core zone and 32% for the outer zone for the equilibrium cycle. First core enrichments are 18.7% and 27.1%. Surrounding the core are 150 radial blanket assemblies. The reflector and restraint assemblies quoted in the General Parameters have been replaced by 174 removable radial shield assemblies to protect the two core restraint former

rings and the core barrel. Overall lengths of all reactor assemblies and the reactor vessel have been shortened. Inlet and outlet nozzles of the assemblies have been modified to improve handling and location in the core lattice. Coolant flow distributions in the ducts and rod bundles have been improved by reducing the space between the outer rods or pins and the hexagonal can. Smaller spacer wires are used on the outer row rods, while maintaining the same spacings. (Fig. XVII.A-1, A-2) (Ref. 4)

		Sym.	Component Name	Quan.
1.	77.50 R			
2.	75.50 R			
3.	75.00 R			
4.	70.00 R			
5.	SURVEILLANCE SPECIMENS			
6.	FUEL TRANSFER/STORAGE 8.625 O.D., 7.981 I.D. (4 PLACES)			
7.	5.00 FIXED SHIELDING			
8.	.50 GAP			
9.	2.00 CORE BARREL			
10.	85.70 R			
		IC	INNER ZONE FUEL ASSEMBLY	108
		OC	OUTER ZONE FUEL ASSEMBLY	90
		RB	RADIAL BLANKET ASSEMBLY	150
		RS	RADIAL SHIELD ASSEMBLY	324
		PC	PRIMARY SYSTEM CONTROL ASSEMBLY	15
		SC	SECONDARY SYSTEM CONTROL ASSEMBLY	4

Figure XVII.A-1 Reactor Cross Section (Ref. 4)

Figure XVII.A-2a Core Fuel Assembly (Ref. 1)

Figure XVII.A-2b Radial Blanket Assembly

XVII.B. CORE SUPPORT AND VESSEL INTERNALS

The lower internal structure consists of the core support plate and core support skirt, core barrel, horizontal baffles, core restraint former rings, fixed radial shielding, and inlet and by-pass flow modules.

The core support structure is composed of a 24 in. thick core support plate with holes into which liners are inserted. The inlet nozzles fit into the liners. Each module holds the nozzle for a group of reactor assemblies, and most modules have flow orifices to assist flow distribution. The orifices also establish pressure zones upon which hydraulic balance of the fuel, control, and radial blanket assemblies is based. With the hydraulic balance arrangement, the upper core plate is not required.

The skirt of the bottom support plate attaches to the reactor vessel wall at a ring forging. The core barrel is a welded structure of 2 in. thick plate, 151 in. dia. It is supported on the support plate and is external to the radial shielding. The core barrel rings provide lateral restraint for the reactor assemblies. Constraint former rings apply against load pads, above the core zone. The upper internals structure utilizes transverse plates connecting four jack-operated lift columns used to raise the structure during refueling. (Fig. XVII.B-1, B-2, B-3)

Outlet modules above the assembly outlet nozzles guide the flow into the outlet plenum. Each outlet module collects the flow from a group of reactor assemblies. (Fig. XVII.B-4)

Figure XVII.B-1 CRBR Core Support Structure (Ref. 5)

Figure XVII.B-2 CRBR Modular Core Support System Assembly Flow Paths (Ref. 1)

Figure XVII.B-3 CRBR Core Restraint (Ref. 1)

Figure XVII.B-4 CRBR Upper Package Outlet Module (Ref. 1)

XVII.C. REACTOR VESSELS AND SHIELDING

The reactor vessel is a vertical cylindrical shell with a torospherical bottom head and an upper flange. Inside diameter is 243 in., overall length 658.35 in. Material is stainless steel, with alloy steel used for the flange and stationary outer ring, and a transition shell of Inconel between the low alloy and the stainless steel. The vessel flange is bolted to the stationary outer ring, and the ring is supported by the concrete ledge of the reactor cave. (Fig. XVII.C-1)

The closure head assembly is a 21-1/2 in. thick forging of low alloy steel. It has radiation shielding, thermal insulation plates, and a suspended vortex-suppressor plate. The head is composed of three independent rotating plugs, contained one inside the other. The ex-vessel transfer machine is located in the largest plug, and the in-vessel transfer machine in the smallest plug. (Fig. XVII.C-2, C-3)

The guard vessel provides secondary containment and limits total leakage in the event of a leak from the primary vessel or piping. The cylinder has an id of 262.5 in. and is 570.5 in. high. A skirt bolted to the floor of the reactor cavity supports the guard vessel. Leakage sensors and in-service inspection equipment can be located in the space between the two vessels. The inlet piping downcomer is protected by an extension of the guard vessel. (Fig. XVII.C-4)

The reactor vessel cavity is sealed and filled with an inert gas. Below the cavity there is an area which will house an ex-vessel core retention device if required.

Individual cells house the heat transport system loops. All primary system components are surrounded by guard vessels. (Ref. 4)

1. PLUG RISER	6. VESSEL FLANGE
2. REACTOR CAVITY SEAL	7. CONCRETE LEDGE
3. CLOSURE HEAD VESSEL HOLDDOWN BOLT	8. INCONEL 600 TRANSITION
4. STATIONARY OUTER RING	9. HEAD TO VESSEL BOLT
5. OMEGA SEAL	10. VESSEL WALL

Figure XVII.C-1 CRBR Vessel Support System (Ref. 4)

1. COVER GAS	8. RADIAL SHIELD ASSEMBLIES
2. SODIUM LEVEL	9. FUEL TRANSFER AND STORAGE POSITIONS
3. VORTEX SUPPRESSOR PLATE	10. REACTOR CORE
4. OUTLET PLENUM	11. CORE SUPPORT STRUCTURE
5. UPPER INTERNALS STRUCTURE	12. INLET MODULE
6. OUTLET NOZZLE	13. INLET NOZZLE
7. CORE RESTRAINT FORMER RINGS	14. INLET PLENUM

Figure XVII.C-2 CRBR Reactor System (Ref. 4)

1. EX-VESSEL TRANSFER MACHINE PORT	5. IN-VESSEL TRANSFER MACHINE PORT
2. INTERMEDIATE ROTATING PLUG	6. SHIELDING
3. CONTROL ROD DRIVE MECHANISM	7. SUPPRESSOR PLATE
4. SMALL ROTATING PLUG	8. LARGE ROTATING PLUG
	9. STATIONARY RING

Figure XVII.C-3 CRBR Closure Head Assembly (Ref. 4)

1. REACTOR CORE	10. CONTROL RODS
2. INLET NOZZLES (3)	11. HEAD HEATING AND COOLING SYSTEM
3. STATIONARY OUTER RING	12. CABLE HANDLING
4. PLUG DRIVE AND CONTROL	13. EVTM PORT
5. SEAL HEAD ACCESS AREA	14. BEARINGS
6. SEALS	15. HEAD ACCESS AREA
7. IVTM PORT	16. OUTLET NOZZLES (3)
8. ROTATING PLUG (3)	17. GUARD VESSEL
9. THERMAL INSULATION AND SHIELDING	18. REACTOR CAVITY

Figure XVII.C-4 CRBR Reactor Enclosure (Ref. 4)

XVII.D. CONTROL ELEMENTS

There are fifteen primary and four secondary control assemblies. Each primary system control rod has 37 absorber pins. Secondary assemblies each have 19 absorber pins. The secondary system utilizes a hydraulic scram assist, the primary system a spring assist. Primary and secondary reactivity control systems

are independent. Pin bundles consist of SS tubes containing B_4C pellets. The rods are wire-wrapped and include a gas plenum. The outer duct remains in the core. The inner duct is connected to the control rod drive and moves relative to the outer duct. (Fig. XVII.D-1) (Ref. 1, 4)

Figure XVII.D-1 CRBR Control Assembly (Ref. 1)

XVII.E. HEAT TRANSFER SYSTEMS

There are three secondary independent loops. The primary system includes a hot-leg pump, the shell side of an intermediate heat exchanger, and a check valve. No isolation valves are used. Piping between the reactor and the primary pump is 36 in., between the pump and the heat exchanger 24 in. All primary loop piping is either elevated or contained within guard vessels, and there are guard vessels around the pumps and the Intermediate Heat Exchanger (IHx). Reactor vessel outlet nozzles are ~16 ft. below the normal sodium level in the reactor vessel.

The intermediate system includes a cold leg pump, the tube side of the IHx, and incorporates an expansion tank in each loop. The system is arranged to accommodate "hockey stick" steam generator modules (evaporator and super heater).

Preliminary design for the primary and secondary pumps is being done by Byron Jackson and Westinghouse-EMD. Vertical centrifugal units are proposed. The primary pump operates in the hot leg of the loop at 995°F. Intent at the present time is to make the primary and secondary pumps hydraulically identical. (Fig. XVII.E-1)

The design concept for the Intermediate Heat Exchanger is a straight tube component, with a flexible downcomer. (Fig. XVII.C-2) (Ref. 5)

The check valve concept under consideration uses a tilting disc housed within a cylindrical body with conical end

closures. The tilting disc seats against a free-standing seat. A dashpot controls the rate of disc closure upon flow reversal and limits pressure surges in the loop. A flanged access opening is provided at the top of the valve. (Fig. XVII.E-3)

The reference design provides for forced convection decay heat removal and heat removal by natural circulation, under normal or off-normal conditions. Elevation of piping and the provision of guard vessels assure continued decay heat removal, with primary pumps operating at pony motor speed. The steam generator auxiliary heat removal system functions by first venting steam to the atmosphere. In the event of loss of normal feedwater, steam is generated from water from a protected storage tank. Steam from the steam drum is naturally circulated to the tube-side of an air-cooled condenser, condensed, and returned to the steam drum. A major change made recently is the addition of a system to allow decay heat removal without the use of the main coolant loops and the steam generators. This system, the Overflow Heat Removal System (OHRS), was created by adding a heat exchanger to the existing overflow loop and adding two small air-blast heat exchangers. The OHRS is rated at 5.6 MWt. (Fig. XVII.E-4) (Ref. 4)

All loop vaults are independent and shielded from one another. All main components are supported by their flanges at the operating floor level in the containment building. Vault atmosphere is nitrogen. (Ref. 5)

1. OPERATING FLOOR	6. PONY MOTOR 75 HP/85 RPM
2. GUARD VESSEL	7. PRIMARY SUCTION NOZZLE
3. ALTERNATE DISCHARGE 90° FROM SUCTION	8. MAIN MOTOR 5000 HP/1170 RPM
4. RADIATION SHIELD PLUG	9. PRIMARY DISCHARGE NOZZLE
5. SHAFT SEAL	10. STANDPIPE BUBBLER

Figure XVII.E-1 CRBR Primary Sodium Pump Concept (Ref. 4)

Figure XVII.E-2 CRBR Intermediate Heat Exchanger (Ref. 4)

1. OUTLET
2. SWING DISC
3. VENT AND MAINTENANCE OPENING
4. DASHPOT
5. FREE STANDING SEAT
6. INLET

Figure XVII.E-3 CRBR Cold Leg Check Valve Concept (Ref. 4)

Figure XVII.E-4a CRBR Overflow Heat Removal System (Ref. 5)

Figure XVII.E-4b CRBR Operation During Decay Heat Removal (Ref. 5)

CRBR XVII.F.

XVII.F. SODIUM PURIFICATION AND
INSTRUMENTATION

The auxiliary liquid metal system provides for receipt, storage, and purification of liquid metal, and provides the capability for reactor sodium level control, accommodates primary sodium volume changes, and provides cooling for core components stored in the ex-vessel storage tank. There are three 60 gpm cold traps for purification, one active trap in the primary sodium processing subsystem and one in each of the intermediate sodium processing subsystem. Cold traps have NaK cooling, with heat rejected to

the auxiliary coolant fluid system consisting of an electromagnetic pump, diffusion-type cold traps, heat exchangers, a storage tank and an expansion tank.

Hydrogen and oxygen meters monitor sodium after exit from each unit, the bulk sodium in the intermediate loop cold leg, and the argon cover gas in the expansion tank. Each monitoring location has an electromagnetic pump, flow-meter, heat exchanger and heater.

XVII.G. COVER GAS AND AUXILIARY SYSTEMS

Liquid metal coolant cover gas is argon. An impurity monitoring and analysis system samples plant liquid metal and argon systems. Equipment is cooled by an auxiliary system using an organic fluid. A recirculating gas cooling system provides cooling to inert cells and equipment.

The auxiliary liquid metal system provides for receipt, storage, handling and purification of sodium and NaK. The rad-waste system collects, stores, monitors, and packages and transfers liquid and solid radioactive waste materials. (Ref. 2)

XVII.H. STEAM GENERATORS

There are three steam generator loops, one for each intermediate loop. The steam generator module chosen for the reference design consists of two evaporators and superheater per loop, utilizing the hockey-stick concept. Evaporators and superheaters are identical and interchangeable, except that inlet water orifice inserts will be added to the evaporators. Overall height of the evaporator or superheater is 65 ft, shell od. 52 in. There are 757 heat transfer tubes 0.625 in. od with single 0.109 in. thick walls. Active tube length is 46 ft. Tube triangular pitch is 1.22 in. Sodium flows in the shell side and water/steam in the tubes. A hydrogen diffusion tube detector was selected as the steam generator leak detector. (Fig. XVII.H-1)

The sodium/water reaction pressure relief subsystem protects the sodium side of the evaporators and superheaters and the intermediate loop by the use of rupture disks in the main sodium piping close to the superheater and evaporator nozzles. There are three rupture disks per loop. Pressure-relief system piping routes the reaction products to a separation tank. Gaseous products are vented to the atmosphere, liquid and solid wastes remain in the separation

tank or the storage tank of a centrifugal separator. There is a sodium leak detector at each rupture disk location. (Ref. 4)

A sodium dump subsystem is provided to remove sodium from an affected loop of the intermediate sodium system in case of a sodium/water reaction, before the IHX has been excessively contaminated. Drain lines located at low points include pairs of dump valves in series. Drain lines route the sodium to a dump tank located below the appropriate superheater/evaporator cell of the steam generator building. (Ref. 4)

The steam generator auxiliary heat removal system removes decay heat and/or sensible heat from the reactor and heat transport system in the event the main heat sink is unavailable. It can be activated when desirable. The concept incorporates two subsystems; a long-term system and a short-term system. The short-term system uses a direct steam dump to the atmosphere through power relief valves in the steam lines. The long-term system uses three protected air-cooled condensers on the roof of the steam generator building to condense steam from the steam drums. (Ref. 4)

Figure XVII.H-1 CRBR Steam Generator Module (Ref. 4)

XVII.I. REACTOR INSTRUMENTATION AND CONTROL

The overall plant control system is designed to provide load-following capacity at a maximum of 3% per minute over a load range from 40% to 100% of full power. Basic control is from a central supervisory control system, providing for either automatic load dispatch or operator load control capability. Main areas of control are the reactor, primary and intermediate sodium flows, primary and intermediate sodium pumps, and feedwater flow. Two out of three logic is maintained throughout the plant. Twelve functions are projected to cover the entire shutdown system. (Fig. XVII.I-1) (Ref. 5)

Fuel failure monitoring is similar to the FFTF system, with three subsystems. The cover Gas monitoring subsystem includes a charcoal chromatograph column, a germanium detector, a fixed-channel spectrometer, a multi-channel spectrometer-computer and printer, gas sampling equipment and associated control panels. The delayed neutron monitoring system includes BF_3 neutron detectors and the shielding moderator assembly, adjacent to each of the three primary loops. The failed fuel location system includes gas tag sampling traps, mass spectrometer, minicomputer and printer. (Ref. 4)

Figure XVII.I-1 CRBR Protective Subsystems (Ref. 5)

XVII.J. FUEL HANDLING

A new core component is received as a fully assembled element in a single-assembly shipping container, with twelve containers per shipment, and transferred in the containers to the new fuel storage cell. It is removed from the container inside the cell and stored in separate thimbles. About a month before scheduled refueling the assembly is removed from storage by a new component transfer machine to the ex-vessel storage tank, a large two tier sodium tank with 650 positions. Reactor port plugs are removed and the In-Vessel Transfer Machine (IVTM) is installed. The Ex-Vessel Transfer Machine (EVTM) moves a new fuel assembly from the ex-vessel tank while the IVTM and rotating plugs remove a spent assembly from the core and place it in an in-vessel transfer position. The EVTM places the new fuel in another in-vessel transfer position and removes the spent fuel assembly, transferring it to the tank. The IVTM and the rotating plugs install the new fuel in the core open lattice position. All fuel handled by the EVTVM is in a sodium-filled core component pot. Heat is dissipated from the machine by forced air cooling on the outside of the cold wall. On completion of refueling the IVTM is removed from the reactor. Spent fuel decays for one hundred days in the ex-vessel tank before being shipped off-site. Maximum use of FFTF technology has been used in design and development of the equipment.

The IVTM conceptual design employs a rising-stem grapple drive. Seals and bushings, drive components, grapple alignment, and IVTM prototype programs are under way. (Fig. XVII.J-1)

The EVTVM reference concept is essentially identical to the FFTF CLEM. Changes include the deletion of almost all in-vessel storage, requiring removal of spent fuel during the same refueling shutdown during which it is removed from the core. Decay heat removal capability required is ~20 kw. Alternate approaches to cold-wall heat removal system are being studied, for example forced convection of argon, although it is concluded that the cold wall EVTVM will be capable of handling fuel with 20 kw decay heat. The height has been reduced from 61 ft. to about 34 ft. (Fig. XVII.J-2)

A two-tier, rotatable storage rack was selected for the ex-vessel storage tank, where 650 core assemblies can be stored in ten circular rows. A fuel transfer port for each circular row is accessible to the EVTVM. Storage positions are cylindrical tubes restrained and supported by a stainless steel grid in the rotatable rack. Each tube can hold two core component pots, one above the other. There are 24 argon-filled positions where new assemblies will be placed for radiant pre-heating before immersion in sodium. Two independent and redundant heat removal systems are provided, each capable of removing the maximum design decay heat and holding sodium outlet temperatures below 600°F. (Fig. XVII.J-3)

Spent fuel is transferred from EVST storage, after a suitable decay period, by the EVTVM to the Fuel Handling Cell. The pot containing the spent assembly is lowered into a sodium-filled storage tank in the floor of the cell. An in-cell crane will lower the assembly through a port in the cell floor into the spent fuel shipping cask. (Fig. XVII.J-4) (Ref. 4)

1. GRAPPLE ROTATION DRIVE	7. IDENTIFICATION/ORIENTATION SYSTEM COMPONENTS
2. PNEUMATIC LOAD CONTROL SYSTEM	8. SMALL ROTATING PLUG
3. GRAPPLE STEM	9. IVTM SUPPORT COLUMN
4. GRAPPLE VERTICAL DRIVE	10. IDENTIFICATION/ORIENTATION SHAFT
5. HOLDDOWN ACTUATORS (3 PLACES)	11. HOLDDOWN SLEEVE
6. IVTM SERVICE EQUIPMENT BAY	12. GRAPPLE

Figure XVII.J-1 CRBR In-Vessel Transfer Machine (Ref. 4)

1. GRAPPLE DRIVE ASSY	7. COLD WALL
2. GRAPPLE FINGER ACTUATOR	8. VIEW PORT
3. GRAPPLE	9. DRIP PAN
4. BODY MOUNT	10. CLOSURE VALVE
5. LEVELING JACKS	11. FLOOR VALVE
6. COLD WALL	12. FLOOR VALVE CONTROL PANEL

Figure XVII.J-2 CRBR Ex-Vessel Transfer Machine (Ref. 4)

1. RSB OPERATING FLOOR	7. ROTATING STORAGE RACK
2. FUEL TRANSFER PORT	8. INSULATION AND HEATER
3. CRUSH CYLINDERS	9. PRIMARY VESSEL
4. TOP SHIELD	10. SEISMIC RESTRAINT
5. SODIUM LEVEL	11. SODIUM INLET PIPE
6. CORE COMPONENT POTS	12. GUARD JACKET

Figure XVII.J-3 CRBR Ex-Vessel Storage Tank (Ref. 4)

1. CC POT DRY STORAGE	8. HOT GAS CLEANING STATION IN FLOOR
2. SPENT FUEL STORAGE TANK	9. IN CELL CRANE
3. OPERATING ROOF PLUG	10. CASK LOADING ROOF ACCESS PORT PLUG
4. SPENT FUEL TRANSFER PORT PLUG	11. FLOOR-CASK LOADING PORT
5. POWERED MANIPULATOR	12. FLOOR VALVE CONTROL PANEL
6. MAINTENANCE AND SERVICE STATION	13. MASTER/SLAVE MANIPULATORS
7. FUEL EXAMINATION STATION	14. OPERATING GALLERY FLOOR

Figure XVII.J-4 CRBR Fuel Handling Cell (Ref. 4)

1. GENERATOR	7. STEAM DRUM	12. REACTOR VESSEL	19. FUEL HANDLING CELL
2. LOW-PRESSURE TURBINES	8. STEAM GENERATOR BUILDING	13. REACTOR GUARD VESSEL	20. NEW CORE COMPONENT STORAGE
3. HIGH-PRESSURE TURBINE	9. GANTRY CRANE	14. PRIMARY PUMP	21. EX-VESSEL STORAGE TANK
4. STEAM GENERATOR	10. REACTION PRODUCTS TANK	15. REACTOR BUILDING POLAR CRANE	22. SPENT FUEL SHIPPING CASK ON RAILROAD CAR
5. AUXILIARY HEAT REMOVAL	11. INTERMEDIATE PUMP	16. INTERMEDIATE HEAT EXCHANGER	
6. SUPERHEATER	12. LARGE COMPONENT CLEANING AND INSPECTION VESSEL	17. PRIMARY CHECK VALVE	
7. EVAPORATORS		18. EX-VESSEL TRANSPORT MACHINE	

Figure XVII.K-1 CRBR Reactor Plant (Ref. 4) (Photo No. 755315-1)

XVII.K. CONTAINMENT

The containment building concept is for a cylindrical steel vessel embedded in concrete up to the operating floor, with a hemispherical head and a flat bottom. Inner diameter is 186 ft. and height is 159 ft. to the spring line. The operating floor is one foot above finished grade and 76 ft. below the spring line. Below the top floor, the free-standing steel containment vessel is bounded by inner and outer, 3 ft. thick concrete walls. Above the operating floor the vessel is of 1-1/2 in. thick steel, internally reinforced by steel stiffener rings. A polar crane is located near the spring line. Vessel centerline is 6 ft. off the containment

centerline. A 7 ft. thick hollow cylinder extending from the base mat to 14 ft. below the operating floor supports the reactor vessel. The reactor vessel cavity is sealed and inerted, and the guard vessel is supported in the cavity from below. The head access area has an air atmosphere, but can be sealed and inerted. Within containment, individual cells house the sodium heat transfer loops, radioactive component cleaning facilities, sodium cold traps, sodium storage tank and major support equipment. Services and auxiliaries are housed in support buildings adjoining the Containment Building. (Fig. XVII.K-1) (Ref. 4)

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