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EUROPEAN ATOMIC ENERGY COMMUNITY - EURATOM

CHARACTERISTICS OF FAST NEUTRON POWER REACTORS

by

M.-Th. BEYENS-HENRY

1966

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Brussels, April 1966 - 168 Pages - 64 Figures - FB 210

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-:-:-:-

CHARACTERISTICS OF FAST NEUTRON POWER REACTORS *

After publication of the report EUR 549 f. " Quelques caractéristiques de piles à neutrons rapides et piles assimilées " various people, and in particular members of the staff of the Gesellschaft für Kernforschung m. b. H. Karlsruhe and of the Centre d'Etudes Nucléaires de Cadarache have suggested that it would be desirable to develop this report, setting out in detail the characteristics of some reactors. Fast neutron power reactors were chosen at the request of a large number of engineers at these centres.

This report lists the most important features of each of 19 reactors or reactor projects complete with a short bibliography and diagrams of essential parts. These diagrams have been taken from the various reports consulted.

The aim is to give, as far as possible, exhaustive data. This means that those projects for which too little information is available or which have been abandoned are not included.

This report has been prepared with the help of the Department for Fast Reactors of the Directorate-General for Research and Training ; the Gesellschaft für Kernforschung m. b. H. Karlsruhe and the Centre d'Etudes Nucléaires de Cadarache.

* Manuscript received on February 18, 1966

BN - 350

1. Location : near Shevchenko on the North-east coast of the Caspian Sea, USSR.

2. Owner :

3. Main contractors :

4. Present status and construction schedule :

   Excavation work is nearly complete. The plant is to be completed and begin operation in 1968 - 1969.

5. Reactor type : Fast, UO_2 and PuO_2 fuel, sodium cooled depleted uranium blanket.

   The USSR's first full-scale fast breeder, the world's first nuclear desalting reactor.

6. Purpose :

7. Power :

   - thermal : 1000 MW
     av. power density : 480 KW/liter

   - electrical : 350 MWe if a standard condensate turbine were used, but a back-pressure turbine will be used to produce an output of 150 MWe of electricity and 1200 tons/hour of process steam, which in turn will yield 120,000 m^3 of fresh water daily.

8. Fast flux :

9. Fuel :

   a) Core :

   - composition : The inner zone will have 15% PuO_2, the outer 18% PuO_2 in mixed oxide of plutonium and uranium.

   - shape and dimensions : rods, diameter : 6.1 mm
     rods are in a triangular lattice on a 7 mm pitch.
     Total length of each element with its tip and bottom and fitting : 3.6 m.

- number : 211 hexagonal fuel elements
  169 rods per element

- critical mass :

- cladding : stainless steel , 0. 4 mm thick

b) Blanket : above and below the core is an axial blanket

- composition : depleted uranium

- shape and dimensions :
  - axial blanket: diam. of element : 12 mm
  - radial blanket: diam. of rods : 14.2 mm

- number :
  - radial blanket: 440 elements (inner zone : 120 elements; (outer zone : 320 "
    rods per element : 37
  - axial blanket: 37 elements

- critical mass :

- cladding :
  - radial blanket : stainless steel : 0.5 mm thick
  - axial blanket : stainless steel : 0.4 mm thick.

10. Control :

- 12 control rods, enriched boron carbide is the control material
- 2 safety systems, a scram and a slow setback
- 3 independent scram mechanisms are provided
- scram time is 0.7 sec.

11. Reflector :

12. Shielding :

13. Geometric dimensions :

a) Core : diameter : 1.5 m

high : 1.06 m

volume : 1.87 m^3

percent of core volume : (fuel : 44. 7
(coolant : 31.1
(steel : 14.3

b) Blanket : height of axial blanket : 0.6 m

height of radial blanket : 2.4 m

c) Pressure vessel :

roughly conical in shape

diameter : 6 m at the top

2.2 m at the bottom

wall thickness : 30 mm

14. Temperatures :

a) Core : max. clad temperature : 675 °C

b) Blanket :

15. Coolant : sodium
max. coolant flow rate : 8 m/sec
coolant inlet temperature : 300 °C
outlet temperature : 500 °C
max. heat flux : 1.86 x 10^6 kcal/m^2/ hr
sodium coolant enters the elements through side holes.

15. bis Thermal systems and turbine plant :

The core and inner radial blanket coolant flow goes to one header of the plenum collector. That of the outer radial blanket, with significantly lower heat release, to a separate header.

Of six primary coolant loops, five are intended for use at one time at full power, with the sixth in reserve.

The secondary circuit also uses sodium as system fluid. Steam and water are separated from sodium by 2 mm thick tubing.

Steam temperature : 435 °C
Steam pressure : 750 psi

16. Physical Data :

Breeding coefficient, per cent :

core : 0.7
total : 1.5

Max. burnup life (85% plant factor) : 300 days

Time of operation between refuelings : 2 months.

BIBLIOGRAPHY :

- Nucleonics Week, vol. 6, n° 17, April 29, 1965

CEA - EURATOM PROJECT (1000 MWe)

1. Location :

2. Owner :

3. Main contractors :

CEA-EURATOM association does study design only.

4. Present status and construction schedule :

- from now to July 1966 : study on the 1000 MWe concepts with sodium cooling
- July 1966 - end of 1968 : detailed study of the prototype (Phénix)
- 1969 - 1972 : construction of Phénix
- 1974 - 1978 : construction of the demonstration power plant 1000 MWe

5. Reactor type : Fast Power Reactor , 1000 MWe, UO_2-PuO_2 fuel, sodium coolant, independant loops in primary system with centrifugal pumps for coolant circulation, power flattering by radial zoning.

6. Purpose : This reference core is taken as a starting point for a refined dynamic analysis. As it is indicated in the planning mentioned above, France intends to study the 1000 MWe fast breeder design by July 1966.

7. Power :

- thermal : 2300 MW
(max. specific power/mean specific power)
radial : 1.3
mean specific power : 1 MW/kg $Pu^{239+241}$

8. Fast flux :

9. Fuel :

a) Core : Two concentric core zones of different enrichment

- Composition : UO_2 -PuO_2, pellets of 75% T.D.
  Enrichment (PuO_2/PuO_2+UO_2) :
  central zone : 12.69
  external zone : 18.23
  Pu-composition : Pu^{239} : 76.7% Pu^{240} : 20.1%
  Pu^{241} : 2.8% Pu^{242} : 0.4%

- Shape and dimensions : pellets
  pellets diameter : 6 mm
  length of pellets column : 1000 mm
  fission gas plenum : 730 mm
  subassemblies : distance across flats : 155.5 mm
  hexagonal can thickness : 2.5 mm
  overall length : 3650 mm

- Number : number of pins per assembly : 217
  number of subassemblies : internal zone : 227
  external zone : 193

- Critical mass : 2980 kg (Pu total)

- Cladding : stainless steel type 316, tube with 1 helical fin
  cladding thickness : O.35 mm

b) Blanket :

- Composition :

- Shape and dimensions :

- Number : Number of pins per assembly :
  axial blanket : 2 x 37
  radial blanket : 37

  Number of subassemblies :
  radial blanket: 305

- Critical Mass :

- Cladding :

10. Control :

11. Reflector :

12. Shielding :

13. Geometric Dimensions :

a) Core : flat cylinder

height : 1 m
diameter : 2.86
volume : 5220 liters

		inner	outer
composition : v/o	fuel + void	30	48
	sodium	60.	40
	structure + clad	10	12

ratio v_1/v_2 (internal zone/total core volume)0.54

b) Blanket : thickness of the blankets : 400 mm

c) Pressure vessel :
material : SS
OD. : 7.85 m
height : 10 m

14. Temperatures :

a) Core :
cladding hot spot temperature : 650°C
max. fuel temperature : 2300°C

b) Blanket :

15. Coolant :
sodium flows from the bottom to the top
- mean outlet temperature : 530°C
- mean inlet temperature : 330°C
- pressure drop : 12 kg/cm^2
- max. coolant velocity : 15 m/sec

15 bis Thermal systems and turbine plant :

The sodium circuits are outside the vessel containing the reactor. There are primary and secondary sodium circuits. The present choice is 4 primary circuits with 8 heat exchangers and 4 pumps.

Primary System:

total flow : 3.56×10^7 kg/hr
sodium loops : 4
system material : SS
pumps (centrifugal
(flow/hr : $4 \times 10{,}500$ m^3/hr

16. Physical data :

- ratio (q_1 max/q_2 max) : 0.77
- ratio (fertile atoms/fissile atoms) : 7.24
- internal breeding ratio : 0.98
- total breeding ratio : 1.36
- β eff. : 328×10^{-5}
- Doppler coefficient (at 1500°K) : -0.6×10^{-5} $\frac{\Delta k}{k}$ /°C
- sodium coefficient : total core $+ 0.14 \times 10^{-5}$ $\frac{\Delta k}{k}$ /°C

  total reactor : $- 0.02 \times 10^{-5}$ $\frac{\Delta k}{k}$ /°C
- doubling time: ~8 years
- subassembly life : 1.5 years

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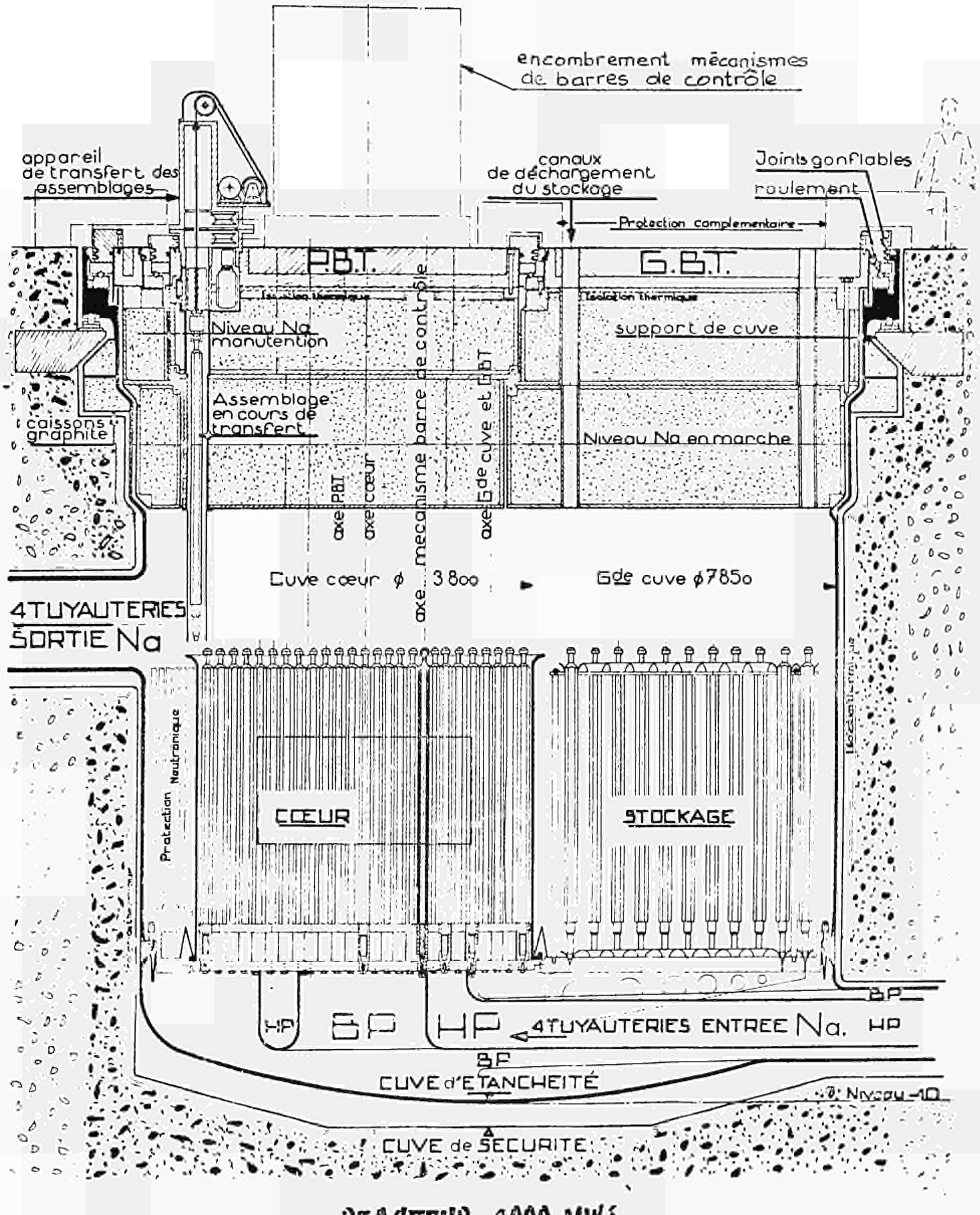
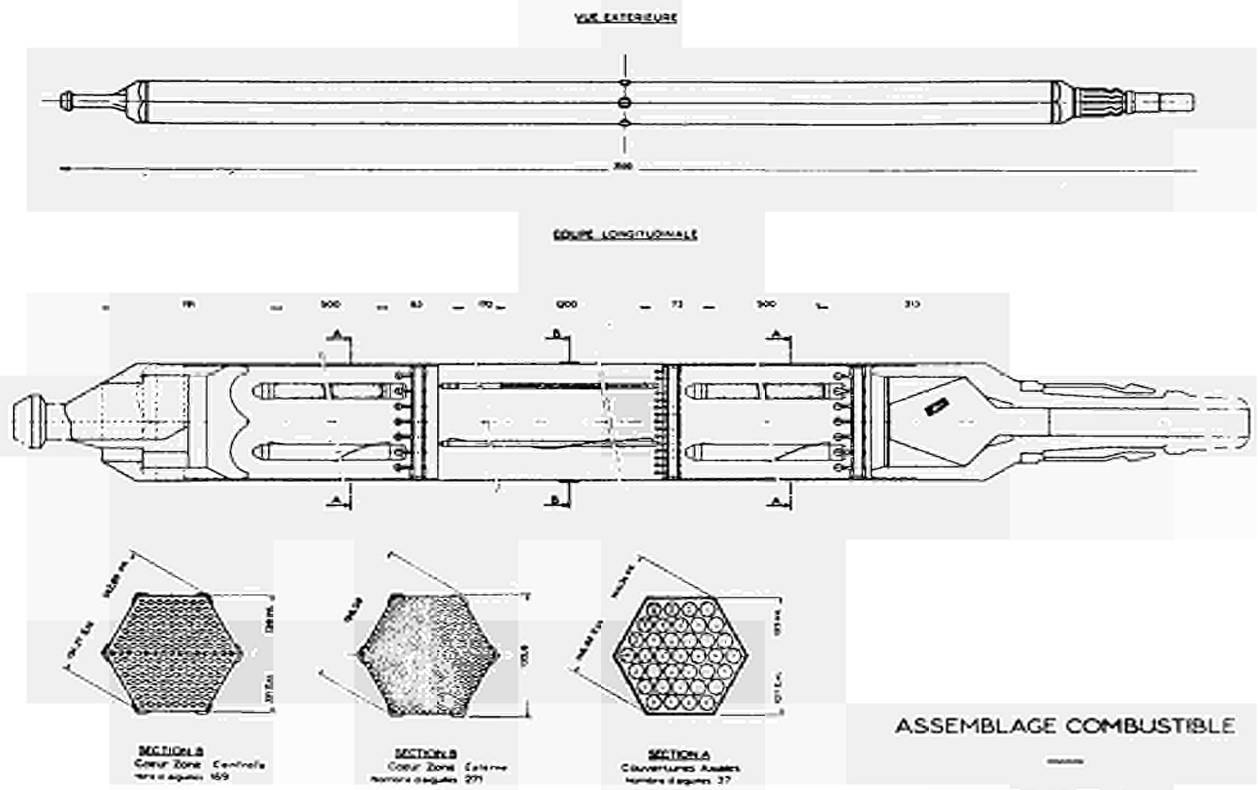


REACTEUR 1000 MWé

SCHEMA du BLOC-PILE Echelle : 0 0,5 1 2 3m

FIGURE : VI. 8



ASSEMBLAGE COMBUSTIBLE

Figure VI. 5

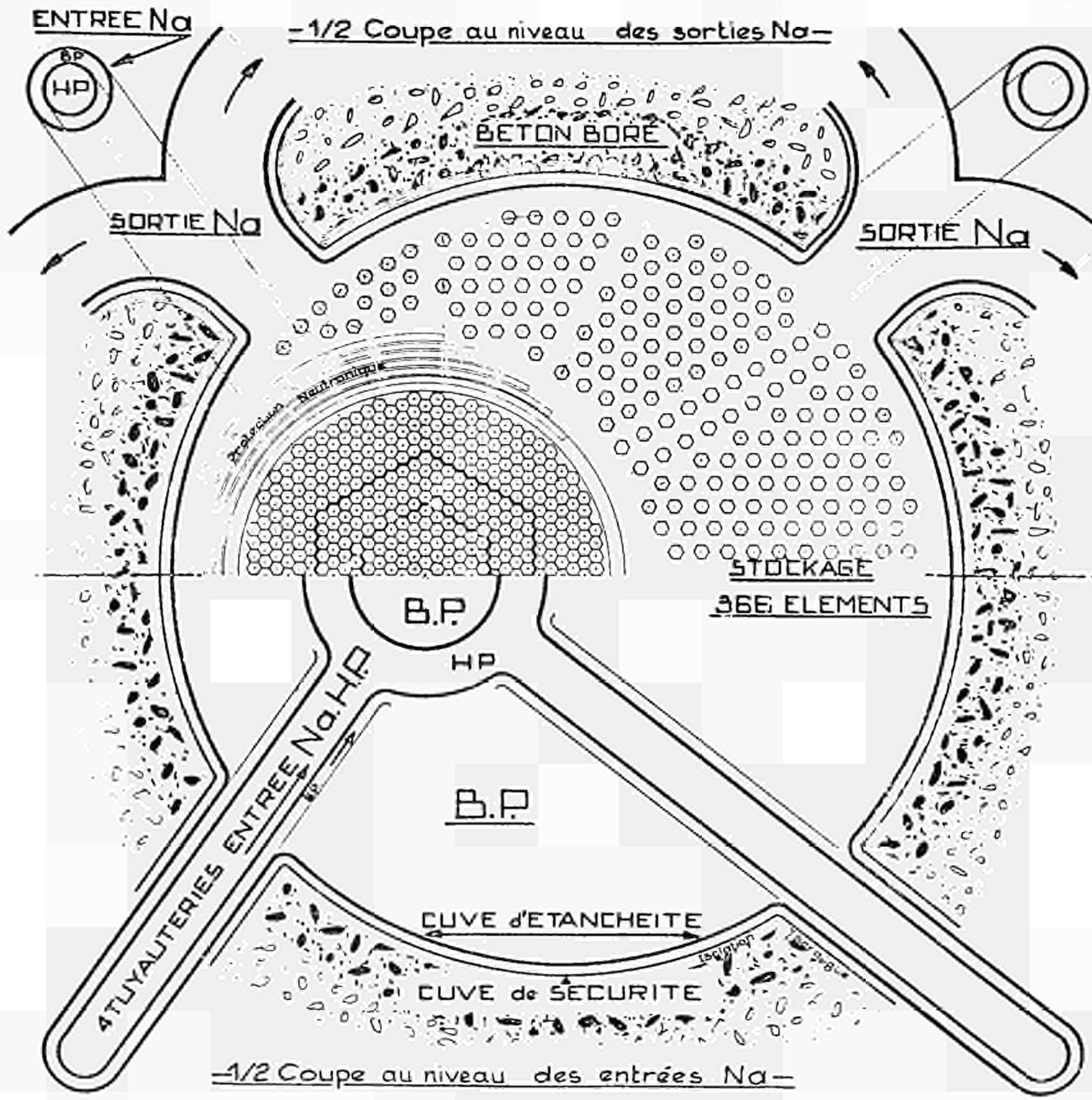


Fig. VI 9

REACTEUR 1000 MWE

COUPE de la CUVE d'ETANCHEITE Echelle :

D F R

DOUNREAY FAST REACTOR

1. **Location** : Dounreay, Caithness, Scotland

2. **Owner** : United Kingdom Atomic Energy Authority
   Operator : U.K.A.E.A.

3. **Main contractors** :

   Messrs. John THOMPSON

4. **Present status and construction schedule** :

   Start of construction : March 1955
   Reactor critical : November 1959
   electrical power was first produced in October 1962.

5. **Reactor type** : Highly enriched (45.5%) uranium core, natural uranium blanket, sodium potassium (70/30) cooled, fast breeder type.

6. **Purpose** : The reactor and its associated fuel plant were planned as a large scale experiment to study the operating and safety characteristics of the system, including the performance of fast reactor fuels and the problems encountered in the use of liquid metal coolant.

7. **Power** :

   - thermal :

     gross heat : 72 MW)
     core : 60 MW)
     blanket : 12 MW)

     average density in core: 460 kw/liter
     average specific power in fuel : 286 kw/kg U^{235}

   - electrical :

     gross electricity : 15 MW
     self consumption : 3 MW (generated by diesel generator set)

     The total electricity production up to March 1964 was 36,275,600 kwh of which 23,548,000 kwh were exported to the North of Scotland Hydro - Electric Board.

8. Fast flux : fast av. : 2.3×10^{15} n/cm^2 sec.
fast max. : 3.8×10^{15} n/cm^2 sec.

9. Fuel :

a) Core :

- Composition : Uranium metal enriched to 46% in U^{235}, alloyed with 20 at. % Mo

- shape and dimensions : hollow rods : id. 0.26 in.
od. : 0.75 in.
long : 3 in.

- number : 7 rods per element
345 core fuel elements of which 120 are contained in 12 regulating, safety and shut down rods and 21 in a central section which is removable to allow irradiation of experimental fuel element. 250 elements contain enriched Uranium, 95 natural Uranium.

- critical mass : 210 kg U^{235}

- cladding : outside 0.02 in. niobium
inside 0.02 in. vanadium
sodium bonded to fuel

b) Blanket :

- Composition : natural U

- Shape and dimensions : solid rods : 1.36 in. diam., 6 in. long, overall length : 7 ft

- number : 14 rods per element
1872 blanket elements surrounding core

- cladding : 0.036 in. stainless steel

10. Control :

The control is achieved by moving 12 groups of 10 fuel elements each, which are situated around the edge of the core. These groups are split up into 2 safety rods, 6 control rods and 4 shut off rods.

- 6 regulating groups, total worth 4.0% $\frac{\Delta k}{k}$

- 4 shut-down rods, total worth 2.7 $\frac{\Delta k}{k}$

- 2 safety rods, total worth 1.34 % $\frac{\Delta k}{k}$

- speed of rods O.O3 in./sec. :

$$8 \times 10^{-5} \% \frac{\Delta k}{k} \text{ /sec. per rod}$$

3 B^{10} shut-down rods, 0.9 in. diam. , 27.8 in. long between core and blanket region.

scram time and mechanism :

Relays operate in 0.17 sec. to break down supply to magnets ; rods drop out of core in approx. 1 sec. , B^{10} rods drop in after 1 sec.

fuel failure detection :

Monitoring of primary coolant for delayed neutrons.

11 Reflector :

The core is surrounded at the sides and top by natural uranium (blanket region) which acts as a reflector in which plutonium is produced.

12. Shielding :

- Sides : 4 ft borated graphite, 5 ft reinforced concrete
- Bottom : B_4C and anhydron rasorite, 5 ft reinforced concrete
- Top : 54 in. borated graphite, 16 in. mild steel, 3 in. Al-foil in rotating plugs ; 5 ft reinforced concrete on sides of plugs, on top removablecover of 11 in. compressed wood and mild steel.

13. Geometric dimensions :

a) Core : Hexagonal prism
approximately 21 in. high by 21 in. diameter

b) Blanket :

c) Vessel : cylinder, stainless steel
diameter : 16 ft 6 in.
high : 20 ft 9 in.
double wall, inner 0.5 in. thick, outer 0.25 in.

14. Temperatures :

a) Core : max. fuel : 1202 °F
max. cladding : 1112 °F

b) Blanket :

15. Coolant :

nature : sodium-potassium (70/30)
channel velocity : av. : 16.4 ft/sec
max. : 24.6 ft/sec
heat transfer coefficient : 10.000 $BTU/ft^2/hr\,°F$
flow rate : 59,000 lb/sec
heat flux : av. : 1.6×10^6 $BTU/ft^2/hr$
max. : 3.3×10^6 $BTU/ft^2/hr$
temperatures : inlet : 392 °F
outlet : 662 °F

15. bis Thermal systems and turbine plant :

There are 24 primary circuits, each containing an electromagnetic pump, a main heat exchanger, a flow meter, and either a hot trap, cold trap, or one of several types of meters for checking the oxide content in the coolant. Each circuit handles 3 MW of heat.

Heat exchangers :

24 primary in 24 loops, NaK/NaK, concentric tube type, counter flow, stainless steel ; 20 loops for core, 4 for blanket region.

12 secondary in 12 loops, NaK/water, stainless steel pipes bonded into common copper matrix.

coolant losses and purification :

removal of oxides by cold trapping and hot trapping (using zirconium as gettering agent).

cooling system safety :

all primary circuits are double-walled with interspace connected to leak detectors ; primary and secondary pumps are fed by 12 diesel generator sets.

turbine :

1 multi-stage impulse type, GEC, 15000 kw, 3000 rpm

generator :

1, GEC, 17650 kvA, 3 phase, 11 kv, power factor 0.85, 50 cycles per sec., 3000 rpm.

16. Physical data :

- prompt neutron lifetime : 8.2×10^{-8} sec.
- mean neutron energy : 0.82×10^{6} ev.
- temperature coefficients isothermal :

  $$-3.6 \times 10^{-3}\% \ \frac{\Delta k}{k} \ /°C$$

- conversion ratio : 1.2
- reactivity addition rate (max.) $2 \times 10^{-3}\% \ \frac{\Delta k}{k}$ /sec

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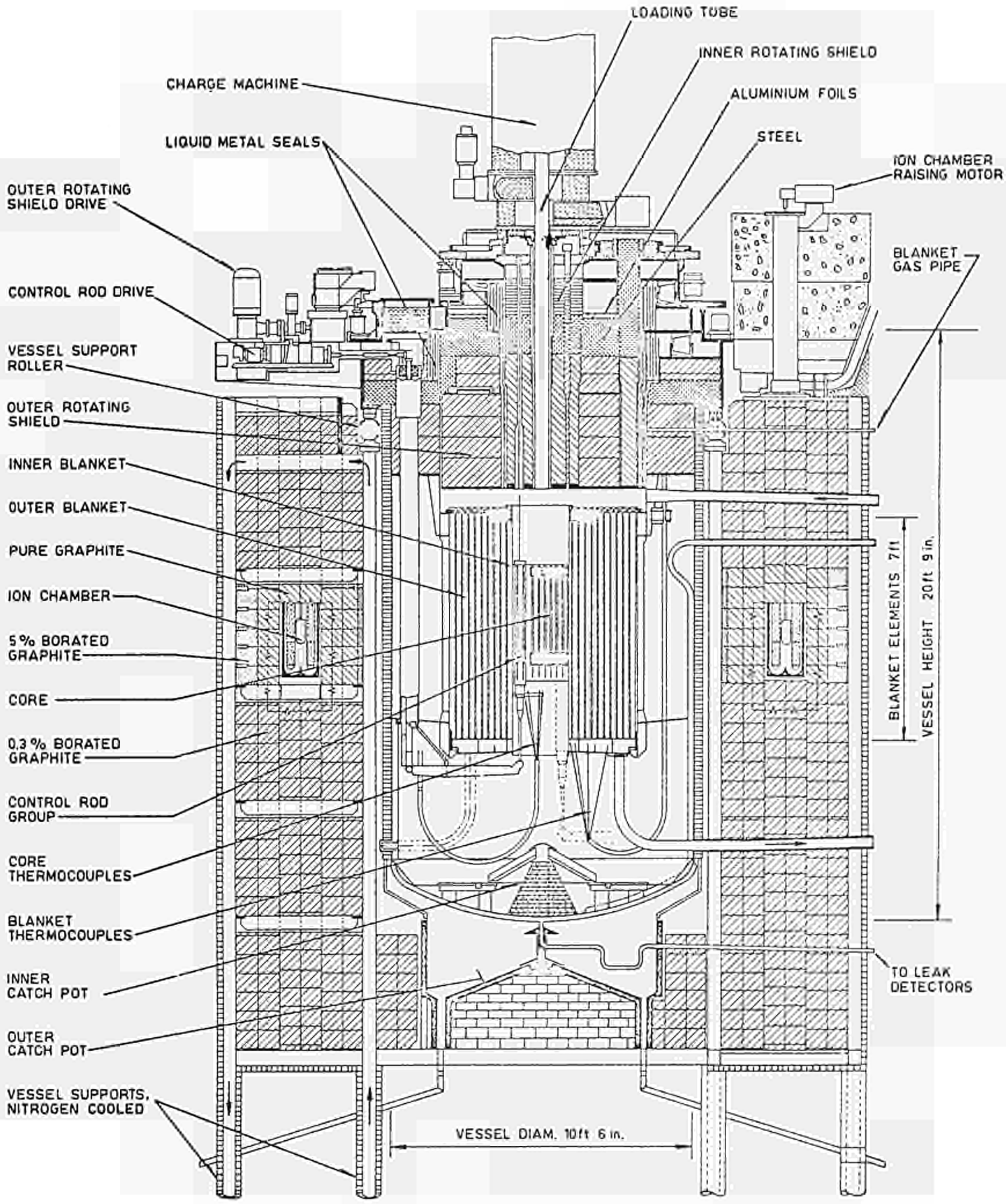
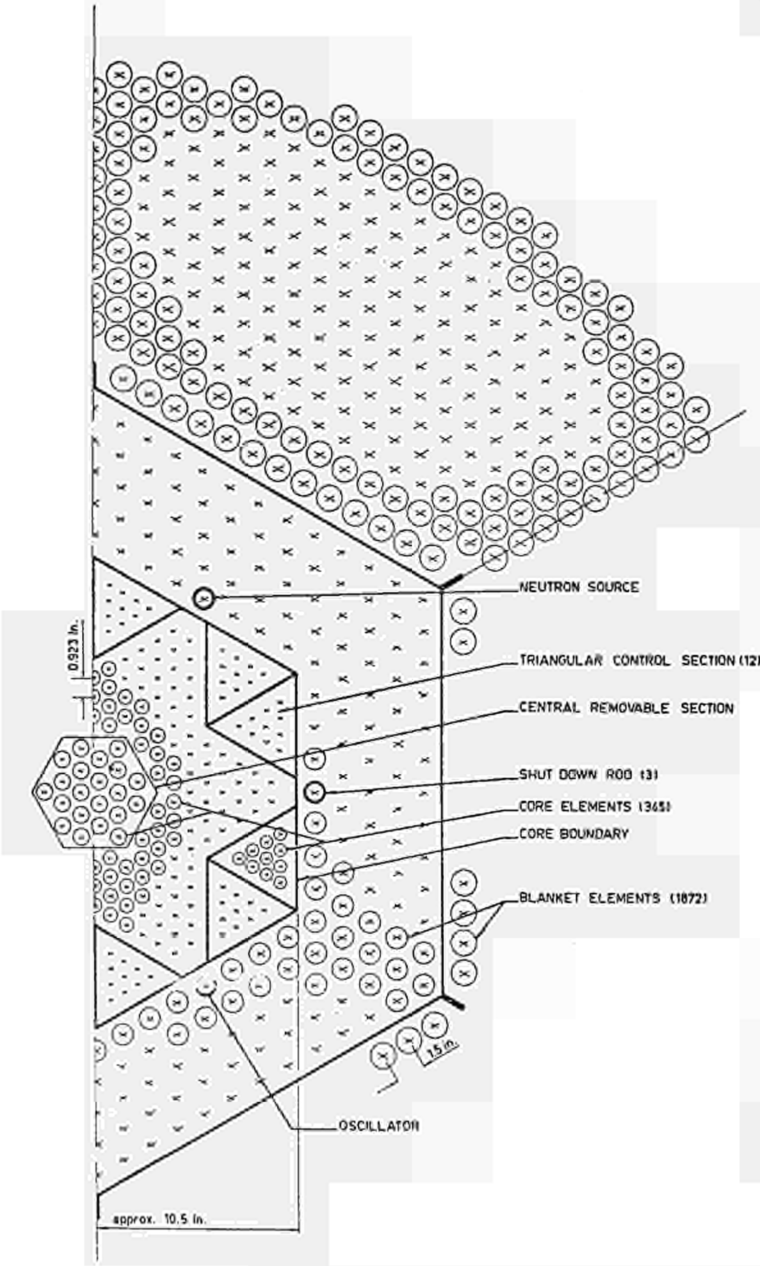
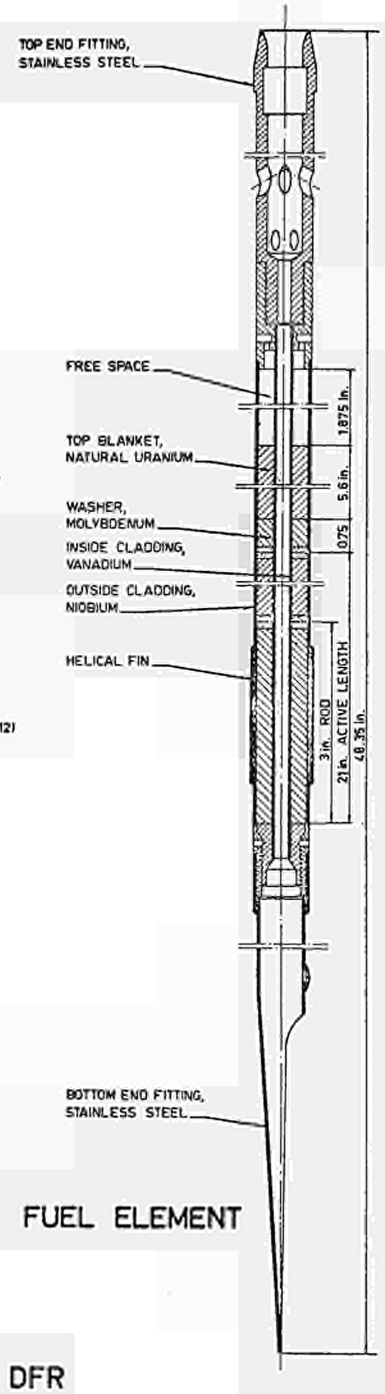


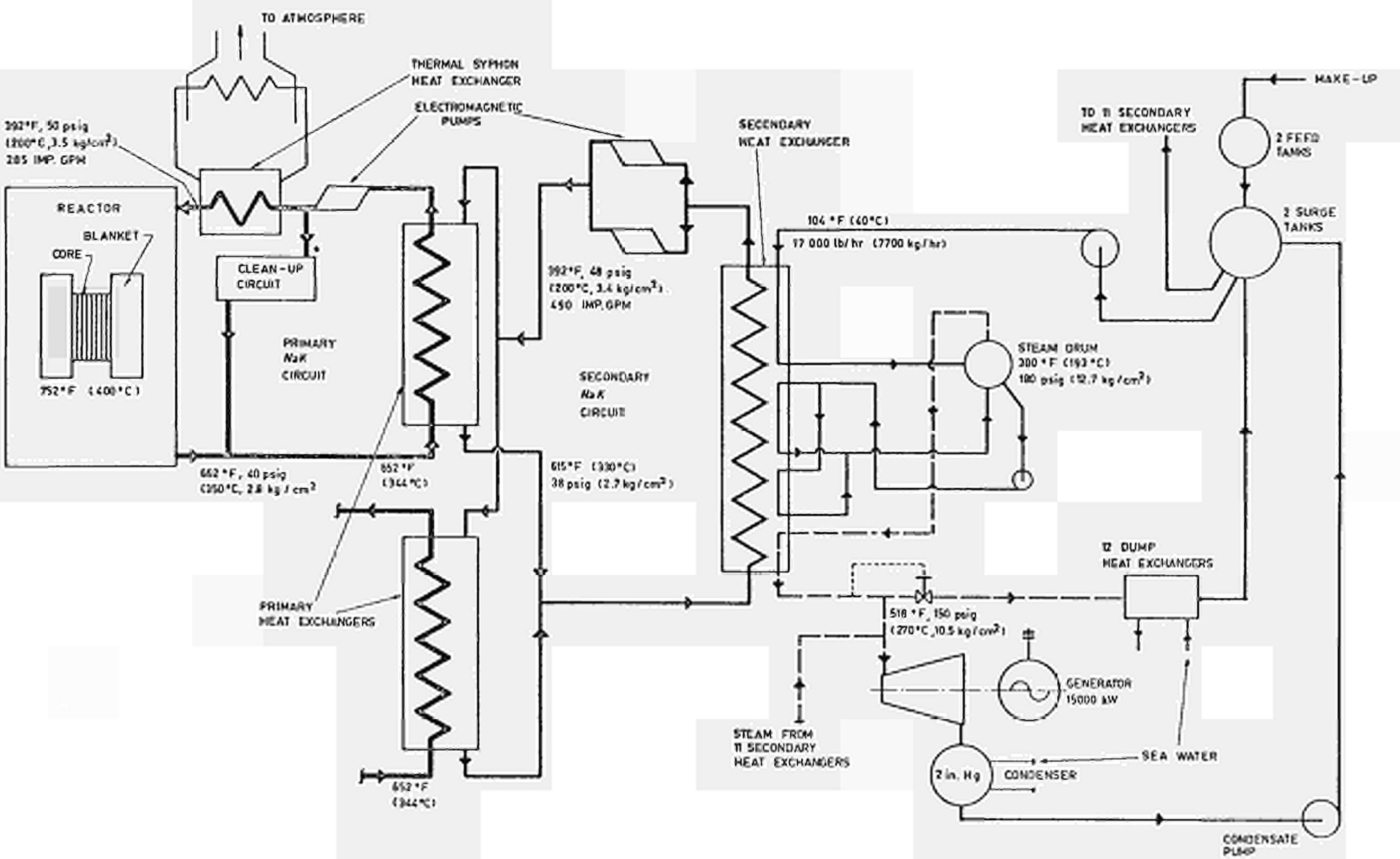
VERTICAL SECTION REACTOR DFR



HORIZONTAL SECTION REACTOR DFR



FUEL ELEMENT



24 PRIMARY CIRCUITS, 2 SHOWN
12 SECONDARY CIRCUITS, 1 SHOWN

FLOW DIAGRAM REACTOR DFR

IAEA-Power 8 — DFR

E B R - 1

EXPERIMENTAL BREEDER REACTOR 1

1. Location : National Reactor Testing Station, Idaho, USA

2. Owner : United States Atomic Energy Commission

   Operator : Argonne National Laboratory

   Reactor Designer : Argonne National Laboratory

3. Main Contractors :

   Austin Co. , Bechtel Corp.

4. Present status and construction schedule :

   - start of construction : 1950
   - reactor critical : August 1951
   - full power operation : December 1951
   - reactor critical with 4th core (Mark IV): Nov. 62
   - reactor shut-down : 1963

5. Reactor type : Fast breeder type, U^{235} and U^{238} fuel, natural uranium blanket, graphite reflected, eutectic sodium potassium alloy cooled.

6. Purpose : Establishment of parameters and economic factors of fast reactors ; engineering and physics studies, study of the feasibility of this reactor type and of the coolant system ; safety studies of fast reactors.

7. Power :

   - thermal : 1.2 MW (1.054 MW in core
(0.149 MW in blanket

     specific power in fuel : av. 33.5 KW/kg of Pu
max . 45.3 KW/kg of Pu
maximum core specific power : 245 KW/liter

   - electrical :

8. Fast flux : Fast 1.3×10^{14} n/cm^2 sec.

9. Fuel :

a) Core — Mark IV

- Composition : Plutonium (95 at. % Pu^{239}, 4.5 at. % Pu^{240}, 0.5 at. % Pu^{241}), alloyed with 1.25 wt % aluminium.
  This material has a stable delta structure up to 700 °C and a melting point about 100 °C higher.

- shape and dimensions : rods
  diam. : 0.232 in.
  long : 8.50 in.

  - above fuel rods, 3.56 in. below and 7.75 in. consists of nat. uranium blanket

  - triangular lattice : pitch of fuel rods : 0.348 in.
    pitch of fuel assemblies : 2.9 in.

- number : 7 hexagonal fuel assemblies
  60 rods per fuel assembly

- critical mass : 30.4 kg of Pu (calculated)
  core loading at rated power : 31.4 kg of Pu calculated

- cladding : zircaloy-2, 0.02 in. thick; NaK bonded (0.0125 in. thick)

b) Blanket :

- Composition : natural Uranium

- shape and dimensions :

- number : 12 hexagonal blanket assemblies
  36 rods par blanket assembly

- critical mass :

- cladding :

10. <u>Control</u> :

8 safety rods
4 regulating rods

All rods are 2 in. diam. nat. Uranium clad in stainless steel, operating in outer reflector.

1 safety plug nat. Uranium

- <u>total worth of safety rods</u> : 0.18% $\frac{\Delta k}{k}$

  worth of safety plug 0.06 % $\frac{\Delta k}{k}$

- <u>speed of safety and regulating rods</u> :

  0.64 in./sec : 1.1×10^{-3}% $\frac{\Delta k}{k}$ /sec. per rod

- <u>speed of safety plug</u> :

  5.0 in./sec : 4.9×10^{-2}% $\frac{\Delta k}{k}$ / sec

- <u>scram time and mechanism</u> :

  magnetic clutch, rods moved by a gear motor
  (safety rods : 0.085 sec.
  (safety plug : 0.15 sec.
  (outer blanket :0.10 sec.

- The entire outer blanket may be raised or lowered, resulting in a reactivity change of 5% $\frac{\Delta k}{k}$

11. <u>Reflector</u> :

Natural Uranium, 6.5 in., 27 in. high, 0.02 in. stainless steel clad, air cooled, inlet temp. 20°C, outlet temp. 108°C, flow rate 5800 cfm.

12. <u>Shielding</u> :

- <u>sides</u> : graphite cylinder, 18 in. thick, 35 in. high (air cooled) ;
  4 in. cast iron, 8.75 ft concrete

- <u>bottom</u> : 4.5 ft steel

- <u>top</u> : 88 in. steel and coolant above core, 2 ft concrete, 8 in. laminated masonite and iron above reactor tank top.

13. Geometric dimensions

a) Core : diam. : 7.5 in.
long : 8.5 in.
volume : 5.8 liters

b) Blanket :

c) Pressure vessel : cylinder, stainless steel
i.d. : 15.87 in.
long : 28 in.
wall thickness : 0.3125 in.
surrounded by a second tank made of Inconel, 0.0625 in. thick
reactor vessel increases to 23.5 in. above central region.

14. Temperatures :

a) Core : max. fuel : 495°C
max. cladding : 420°C
film drop : av. 8.9 °C, max. 12°C

b) Blanket :

15. Coolant : eutectic sodium potassium alloy
coolant flow area : 90.3 cm^2 (0.0972 ft^2)
coolant velocity : 1.706 m/sec (5.6 fps)
coolant mass flow rate : 1.504 kg/sec (244 gpm) through core and blanket
coolant temperatures : inlet : 230°C (446°F)
outlet : 322°C (610°F)
coolant pressures : inlet : 0.68 kg/cm^2 (9.65 psig)

15. bis Thermal systems and turbine plant :

Dissipation of reactor power was through a primary and secondary NaK cooling system, a NaK-to-water steam generator, and finally a turbine-generator. The output of generator was sufficient to supply the entire electrical requirement of the EBR-1- facility.

The primary coolant system contains two pumps, one a dc electromagnetic and the other a motor driven centrifugal.

The secondary NaK system has one pump which is similar to the primary mechanical pump. A shell-and-tube-type heat exchanger is used to transfer heat from the primary to the secondary system, and a specially designed and constructed heat exchanger is used to transfer heat from the secondary system to water and generate steam for the operation of the turbine-generator.

Heat exchangers :

1 primary shell and tube type exchanger
1 steam generator (economizer, boiler, super heater)
1 air cooler
1 shut down air cooler.

16. Physical data : Effective delayed neutron fraction : 0.00304 (calculated)
prompt neutron lifetime : 4×10^{-8} sec.
breeding ratio : $1.250 + 0.008^{6}$ (calculated)
neutron energy : 0.2 MeV
reactivity balance :
max. built in (clear, cold) 0.8 %
to compensate for
temperature and power : 0.769%
burnup : 0.023%
burnup of core : 0.3%
temperature coefficients :
Isothermal $-3.01 \times 10^{-4} \% \frac{\Delta k}{k}$ /°C (calculated)

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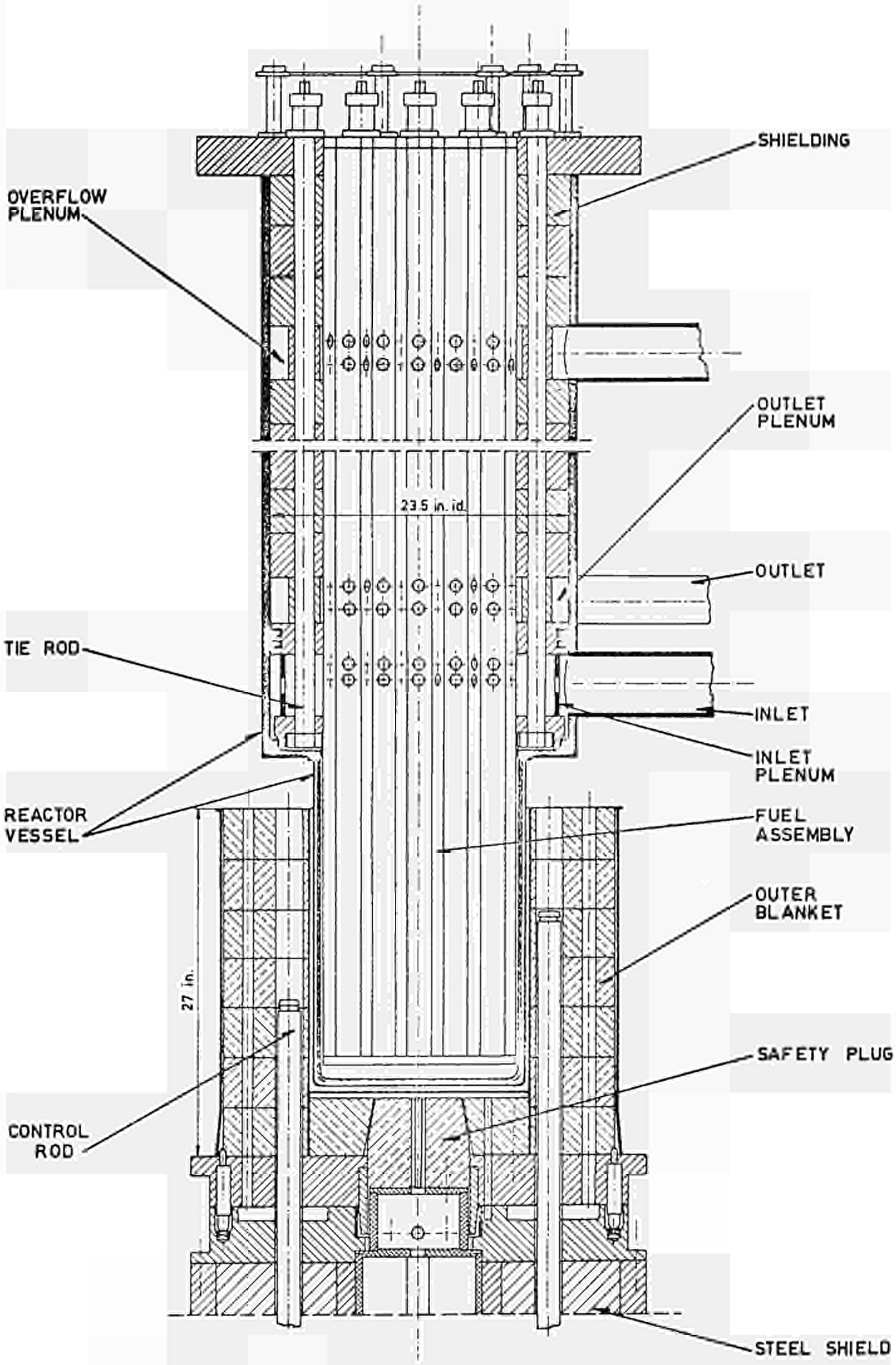
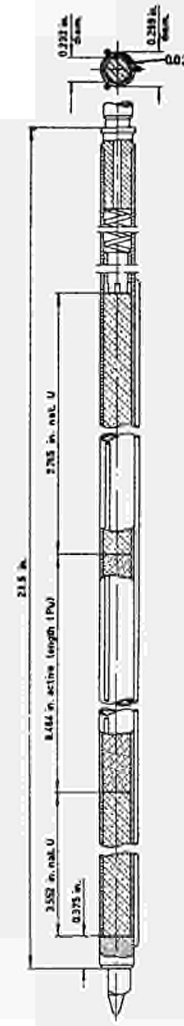
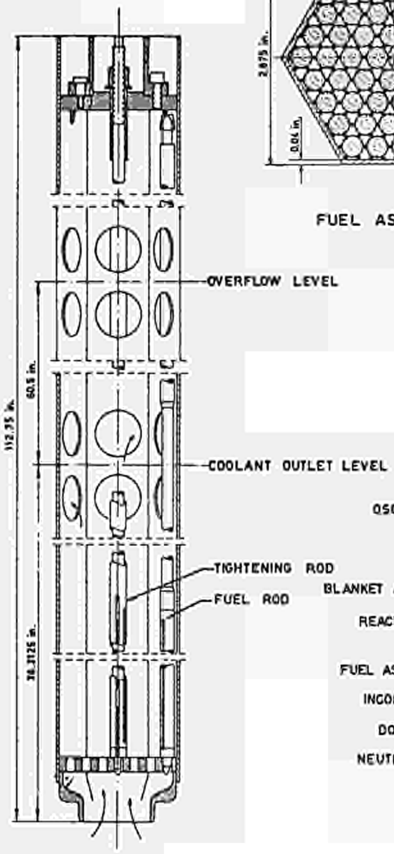


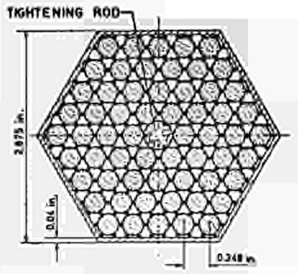
VERTICAL SECTION REACTOR EBR-1



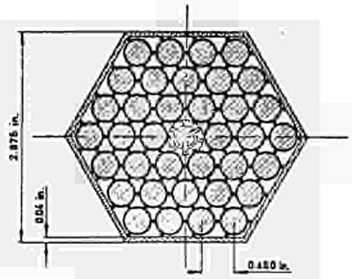
FUEL ROD



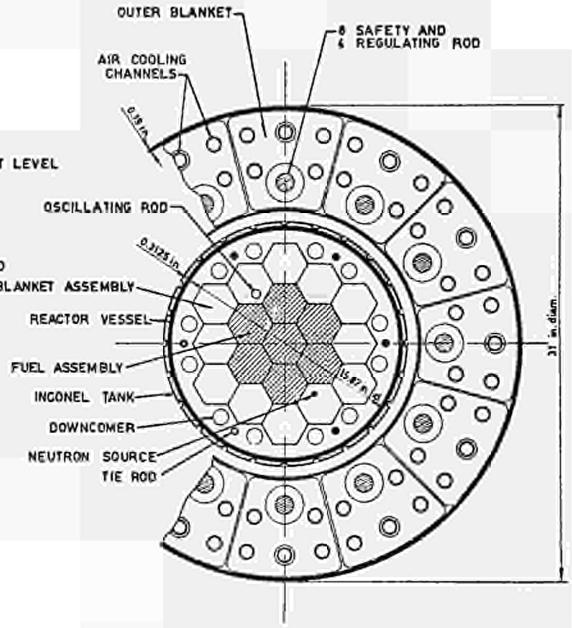
FUEL ASSEMBLY



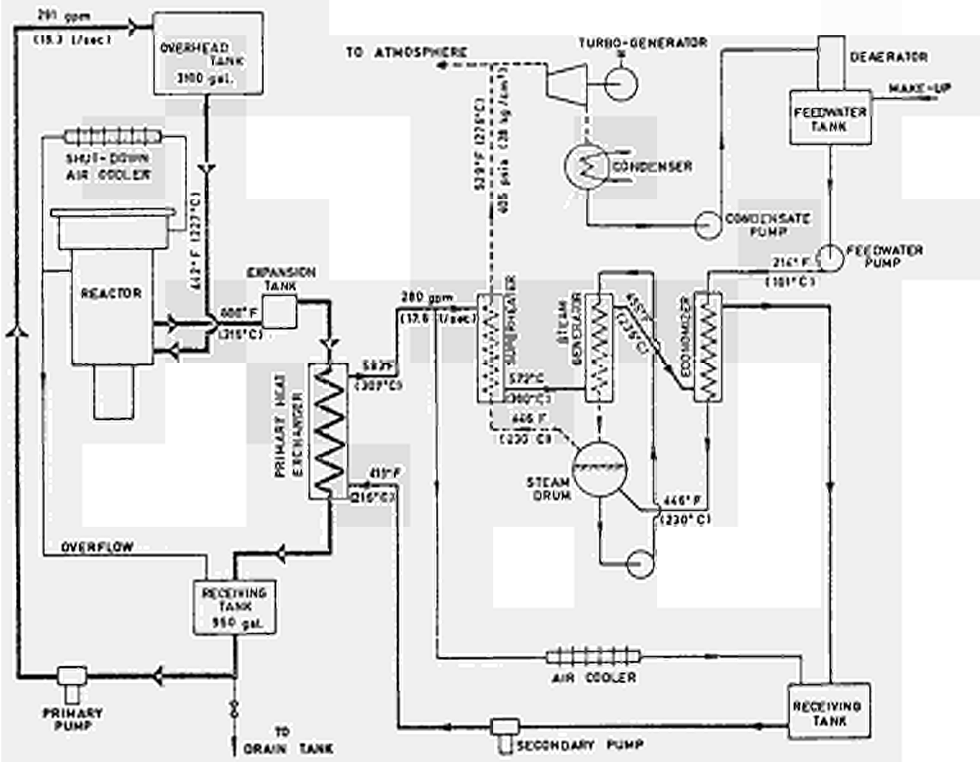
FUEL ASSEMBLY



BLANKET, ASSEMBLY



HORIZONTAL SECTION REACTOR EBR-1



FLOW DIAGRAM REACTOR EBR-1

E B R - 2

EXPERIMENTAL BREEDER REACTOR - 2

1. Location : National Reactor Testing Station, Idaho, USA

2. Owner : United States Atomic Energy Commission

   Operator : Argonne National Laboratory

   Designer : Argonne National Laboratory

3. Main contractors :

   Diversified Builders Inc., J. F. Pritchard Co.

4. Present status and construction schedule :

   Start of construction : December 1957
   Reactor critical : April 1962

5. Reactor Type : Highly enriched (49%) Uranium core, depleted Uranium blanket, sodium cooled, fast breeder.

6. Purpose : The E B R -2 is an experimental fast power reactor directed primarily to establish the technical feasibility of fast reactor for central-station power plants. An other purpose is to study and develop complete fuel cycle operations.

7. Power :

   - thermal : gross heat : 62.5 MW (core : 53.3 MW
     (blankets : 9.0 MW
     (shield : 0.2 MW

     average power density in core : 890 kw/liter
     average specific power in fuel : 355 kw/kg U^{235}

   - electrical : gross elect. : 20.0 MW
     net elect. : 16.5 MW
     sel consumption : 17.5 %

8. Fast flux : Total neutron flux (core center) : 3.7×10^{15} n/cm^2 sec.

9. Fuel :

a) Core :

- Composition : Uranium enrichment : 49% fuel is fissium
  fuel alloy composition : U 95% wt, Zr 0.02% wt
  Mo 2.5% wt, Ru 1.5 % wt, Rh 0.3% wt, Pd 0.5%wt

- shape and dimensions : pin type, sodium bonded

  pins : diameter : 0.144 in.
  length : 14.22 in.

  tubes : O.D. : 0.174 in.
  wall thickness : 0.009 in.

  sodium bond annulus : thickness : 0.006 in.

- number : subassemblies : 53
  elements per assembly : 91

- total mass of U^{235} in core : 176 kg

- total core loading (enriched uranium fissium) : 385 kg

- critical mass : U^{235} (clean, full power) : 172 kg

- cladding : type 304 SS, thickness : 0.009 in.

b) Blanket :

- Composition : depleted Uranium, enrichment : 0.2%

- shape and dimensions : pin type, sodium bonded

  upper and lower blanket elements
  pin diameter : 0.3165 in.
  pin length : 18.0 in.
  tube O.D. 0.376 in.
  tube wall thickness : 0.022 in.

  inner and outer blanket elements

  pin diameter : 0.433 in.
  pin length : 55.0 in.
  tube O.D. : 0.493 in.
  tube wall thickness : 0.018 in.

- number : inner blanket subassemblies : 510
outer blanket subassemblies : 637
upper and lower blanket elements per subassembly : (each end) : 18
inner and outer blanket elements per subassembly : 19

- critical mass : total blanket loading : 28, 100 kg (depleted Uranium)

- cladding : type 304 SS

10. Control : Reactor control is provided by 12 stainless-steel-jacketed U^{238} control rods (one is each outer reflector stack) which move vertically to change neutron leakage from the core. Each control rod has 61 fuel rods identical to those in core elements plus a void (sodium filled). Eight of these rods can be removed rapidly to act as safety rods. In addition, the entire outer blanket can be lowered on a hydraulic elevator and a safety block is provided below the core which can be driven out of the core region pneumatically.

- control rods :

total : 12
operating drive (each rod) : rack and pinion
velocity : 5 in./min.
total movement : 14.0 in.
scram drive : pneumatic

- safety rods :

total : 2
operating drive : rack and pinion
velocity : 2.0 in./min.
total movement : 14.0 in.
scram drive : gravity

- total reactivity worth :

12 normal control rods : 0.048 Δ K/K
2 safety rods : 0.013 Δ K/K

11. Reflector : Breeder blankets of depleted Uranium

12. Shielding :

- Sides : 16 in. graphite + 12 in. of 3% borated graphite + 1 in. steel reactor vessel + various steel retainers and liners + 26 in. blast shield (8.75 in. vermiculite concrete + 8.75 in. aerated concrete + 8 in. celotex + 0.5 in. steel liners) + 72 in. concrete biological shield.

- Top : 16 to 24 in. of 3% borated graphite or 28 in. steel balls, 2 in. steel, 36 in. heavy concrete in tank cover.

- Bottom : Vessel is supported on a series of steel plates within primary tank above a concrete foundation.

The graphite blocks are canned in 0.094 in. type 347 SS cooled by sodium $\sim$720 °F. Entire reactor vessel is immersed in sodium within primary tank (inner liner of blast shield).

13. Geometric dimensions :

a) Core :
equivalent diameter : 19.94 in.
height : 14.22 in.
total volume : 72.79 liters
fuel - alloy : 31.8%-vol.
stainless steel : 19.5%-vol.
sodium : 48.7%-vol.

b) Blanket :
upper and lower :
equivalent diameter : 19.94 in.
length (each end) : 18. in.

	inner	outer
equivalent O.D. :	27.46 in.	61.5 in.
length :	55.0 in.	55 in.
radial thickness :	3. 76 in.	17.02 in.

c) Pressure vessel :
material : 304 SS
diameter : 7.7 ft ; height : 16 ft
wall thickness : 1.0 in.

14. Temperatures :

a) Core : max. fuel : 1200°F
max. cladding : 1083°F

b) Blanket :

15. Coolant : sodium

- flow rate : 3.5×10^6 lb/hr
- flow velocity : 18.3 ft/sec. (average)
- pressure : 47 psig (inlet) ; 10 psig (outlet)
- inlet temperature : 700°F
- outlet temperature : 884°F
- average heat flux : 680,000 BTU/hr ft^2
- coolant flow area : 0.0131 ft^2 per core element
  0.618 ft^2 total core.

15. bis Thermal systems and turbine plant :

The coolant is circulated to a single shell and tube heat exchanger where the heat is transferred to a secondary sodium circuit. The secondary sodium passes to 8 evaporators and 4 superheaters where steam at 850°F and 1250 psia is generated. The steam is used to operate a turbine generator which produces 20 MWe gross.

heat exchangers :

one shell and tube type between primary and secondary sodium coolant systems.
8 evaporators and 4 superheaters between secondary sodium and steam system (all have double walled tubes either mechanically or metallurgically bonded).

steam generator :
output : 250,000 lb/hr
steam temperature : 837°F
steam pressure : 1,300 psig
feed water temperature : 550°F

turbine : one GE unit, 20 MW, 3600 Rpm

turbine throttle conditions :

steam flow : 195, 300 lb/hr
steam temperature : 837°F
steam pressure : 1,250 psig

generator : one GE hydrogen-cooled unit, 20, MW 13.8 KV, 3 phase, 60 cycles/ sec, 0.85 power factor, 3600 rpm.

16. <u>Physical data</u> : - prompt neutron lifetime : 8×10^{-8} sec (mean)

- core neutron energy : 0.409 MeV (mean)
- conversion ratio : 1.1 to 1.2 for initial U^{235} loading

  1.4 to 1.6 for future Pu^{239} loading
- temperature coefficients :

  core fuel : $- 0.40 \times 10^{-3}\% \ \Delta K/K/°C$

  core coolant : $-0.87 \times 10^{-3}\% \ \Delta K/K/°C$

  other : $- 2.23 \times 10^{-3}\% \ \Delta K/K/°C$
- power coefficients : -3.2×10^{-5} $(\Delta K/K)$ MW
- doppler effect-average : $+ 0.04 \times 10^{-5}$ $(\Delta K/K)C$
- plant life : 20 years.

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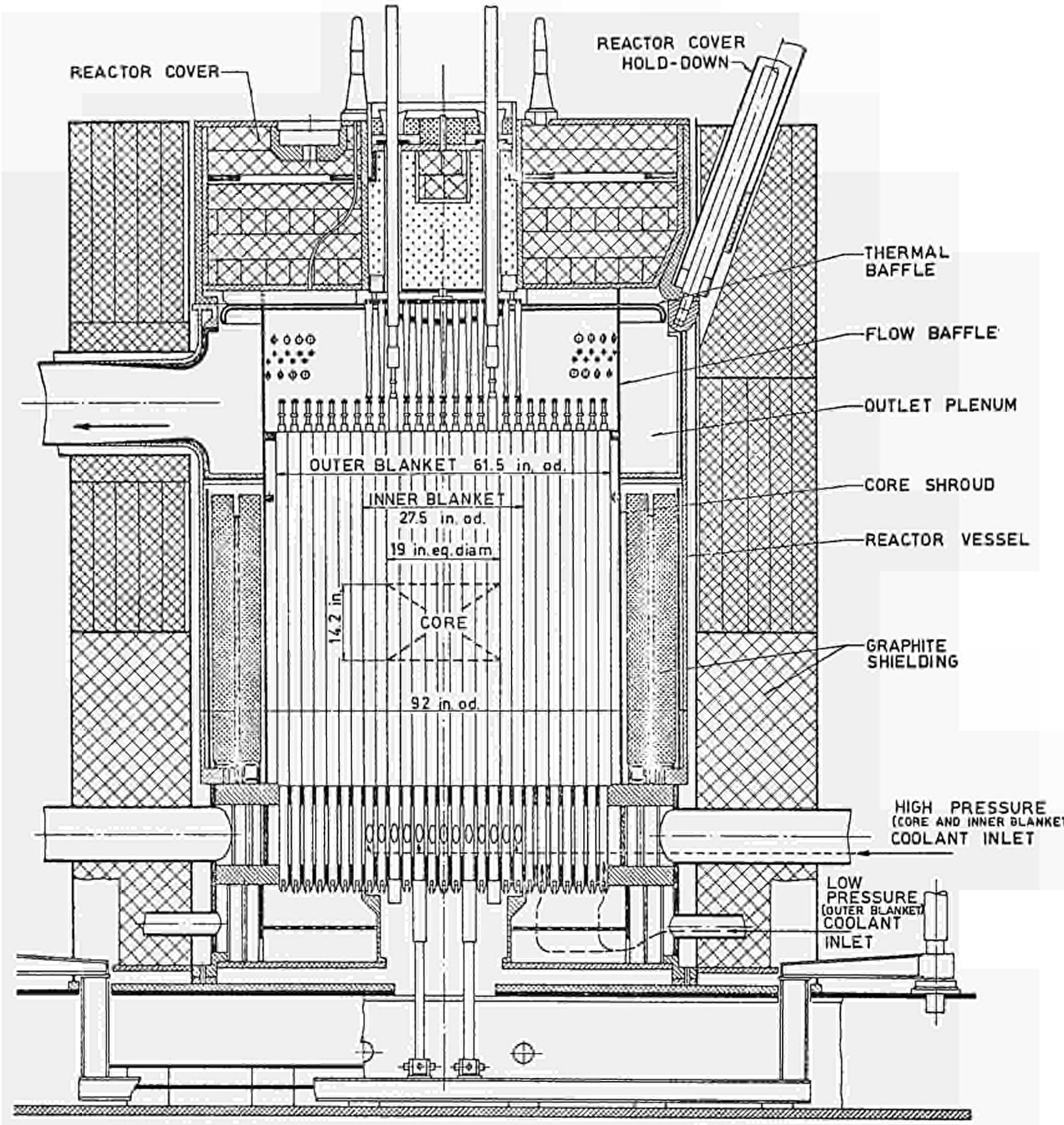
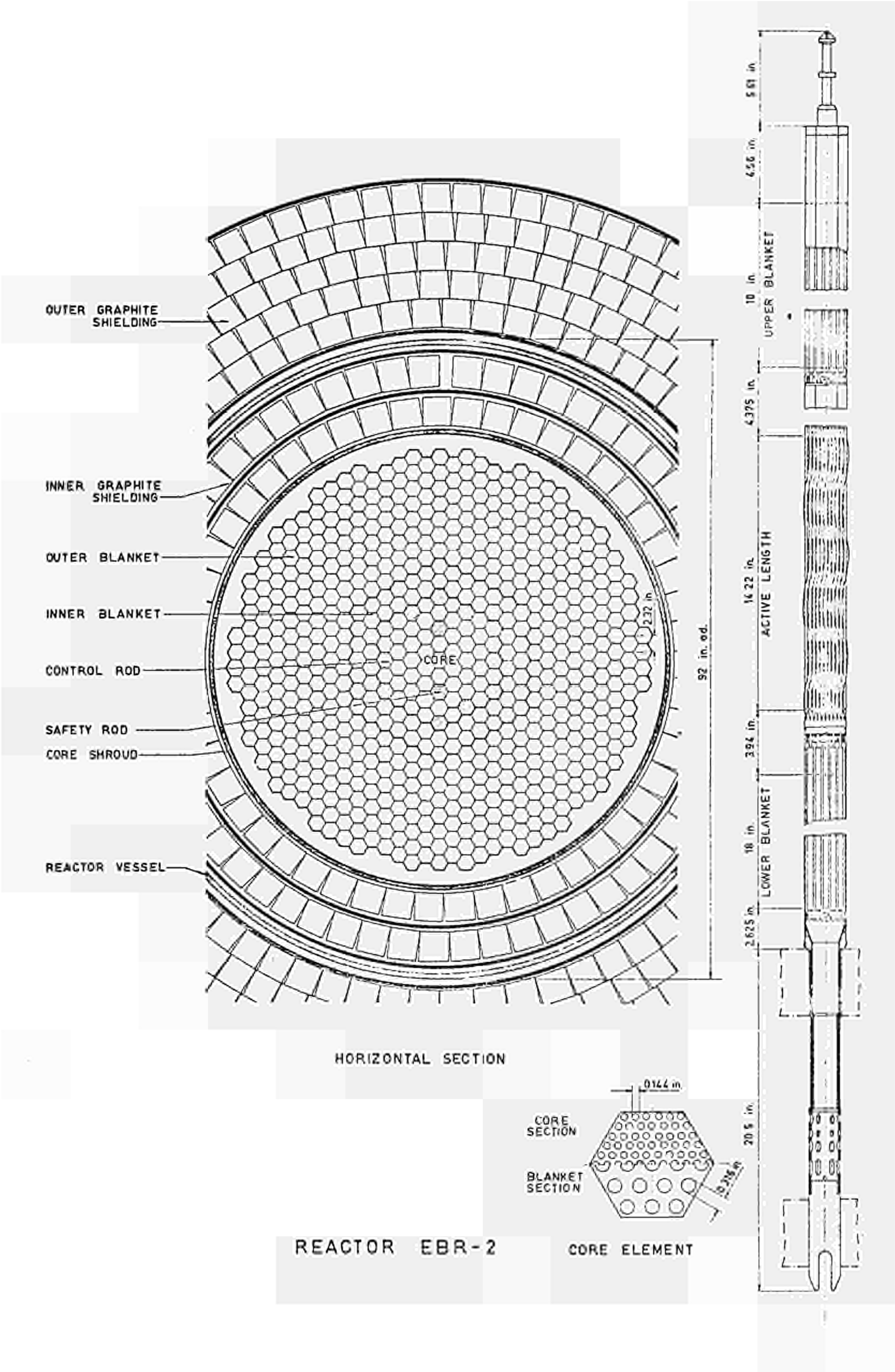
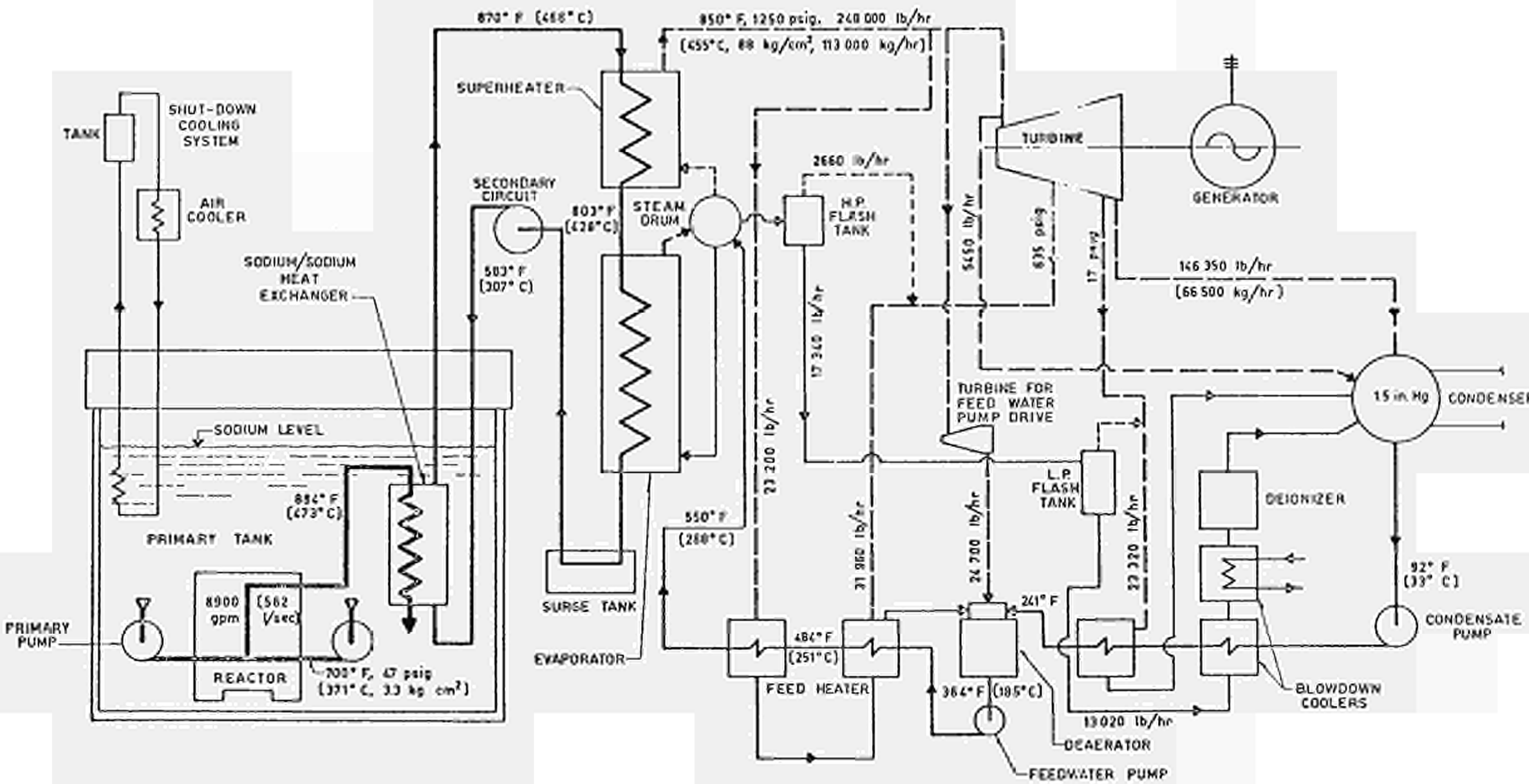


VERTICAL SECTION

REACTOR EBR-2



REACTOR EBR-2



FLOW DIAGRAM REACTOR EBR-2

IAEA-Power R. — EBR-2

E F F B R

(ENRICO FERMI ATOMIC POWER PLANT)

1. **Location** : Lagoona Beach, Michigan, USA

2. **Owner** : Power Reactor Development Co. (PRDC) for reactor plant

   Detroit Edison Co. for conventional plant.

   Operator : Power Reactor Development Co. (PRDC) for reactor plant.

   Detroit Edison Co. for conventional plant.

   Designers : Atomic Power Development Associate, Inc. (APDA)

3. **Main contractors** :

   United Engineers and Constructors
   Commonwealth Associates Inc.

4. **Present status and construction schedule** :

   Start of construction : August, 1956
   Reactor critical : August 23, 1963

5. **Reactor type** : The Enrico Fermi is an unmoderated, heterogeneous sodium cooled fast breeder reactor and power plant, highly enriched (25.6%) uranium seed, depleted (0.35%) uranium blanket.

6. **Purpose** : This plant is a developmental, full size power breeder reactor being built as an essential step in the commercial development of economical nuclear power.

7. **Power** : (first core)

   - **thermal** ; gross heat : 200 MW
     in core : 174 MW
     average power density in core : 13.000 kw/ft^3
     average power density in blanket : 152 kw/ft^3
     average specific power in fuel : core : 250 kw/kg U^{235}
     blanket : 230 kw/kg U^{235}

- electrical : gross elec. : 65.9 MW
  net elec.: 60.0 MW

8. Fast flux : average core at 200 MW : 3 x 10^{15} n/cm^2 sec.

9. Fuel :

a) Core :

- Composition : Enrichment 25.6 %
  Uranium metal alloyed with 10 wt% molybdenum

- shape and dimensions : core (seed) element : 0.148 in. diam.
  30.5 in. length of U-alloy
  rod overall : 0.158 in. diam.
  32.78 in. total length

- number : 105 core elements, 140 rods per core element

- critical mass : 105 fuel elements (496 kg U^{235})

- core loading at rated power : 4270 lb (1940 kg) uranium

- cladding : 0.005 in. zirconium, metallurgical bond.

b) Blanket :

- Composition : Enrichment 0.36%
  Uranium metal alloyed with 3 wt % molybdenum

- shape and dimensions : axial blanket : rod overall 0.443 in., 17 in. length
  radial blanket : rod overall 0.433 in., 65 in. length

- number : 210 axial blanket elements (16 rods per axial blanket element)

  532 radial blanket elements (25 rods per radial blanket element).

- blanket loading at rated power : 67,780 lb (30.800 kg) Uranium

- cladding : 0.010 in. type 304 stainless steel, Na bond.

- blanket gas : Argon

10. <u>Control</u> :

8 safety rods each of which is a bundle of 6 annular tubes containing B_4C with 59 wt. % B^{10}. Tubes are 36.3 in. long. Rod is 68.125 in. long with 2.25 in. od.

2 regulating rods each of which is a bundle of 19 tubes containing B_4C with 34 wt. % B^{10}. Tubes are 30 in. long. Rod is 42.266 in. long with 2.25 od. One rod is used as a fixed-speed shim rod, the other as a variable-speed regulating rod.

Total worth of 8 safety rods : 6.7% $\frac{\Delta k}{k}$

(each at least 0.66% $\frac{\Delta k}{k}$)

Worth of 2 regulating rods : 0.69% $\frac{\Delta k}{k}$

Speed of shim rod 0.017% $\frac{\Delta k}{k}$ / sec.

Speed of regulating rod : 0.04 to 0.4% $\frac{\Delta k}{k}$ /sec.

<u>Scram time mechanism</u> :

Av. scram speed : 11% K/K/ sec.
scram time : 0.75 sec. after signal
spring loaded electro-magnetic release mechanism.

<u>Reactivity addition rate</u> :

max. for 8 safety rods : 0.7×10^{-2}% $\frac{\Delta k}{k}$ /sec.

<u>Other control features</u> :

none

<u>Fuel failure detection</u> :

reactor blanket gas is monitored

<u>Shut down heat removal</u> :

natural circulation possible

11. <u>Reflector</u> : blanket of depleted Uranium

12. Shielding :

- Sides : approx. 5 in SS thermal shield rods + approx. 5.5 in. SS thermal shield shells + 2 in. SS reactor vessel + 6 in. 5% borated graphite + 2.5 ft pure graphite + 6 in. 1% borated graphite + 2.5 ft concrete secondary shield with 0.5 in. steel liners + 7 ft concrete biological shield.
- Top : shield plug with 66 in. graphite, 11 in. 1.5% borated graphite + 12 in. SS insulating material + 2 ft carbon steel.
- Operating floor : 5 ft of steel and concrete.

13. Geometric dimensions :

a) Core : cylindrical
diam. : 32.7 in.
length : 30.5 in. of U-alloy
active volume : 13.4 ft^3

b) Blanket : 32.7 in. id. , 79.9 in. od. , 61.75 in. length of U-alloy, 65 in. overall length
volume of radial blanket ; 156 ft^3
volume of axial blanket : 7.5 ft^3 (each section)

c) Vessel : two connected parts
lower shell diam. : 9.5 ft
upper shell diam. : 14.5 ft
overall height : 36.5 ft
type : 304 stainless steel
maximum thickness : 2 in.

14. Temperatures :

a) Core : average :
max. nominal U temperature : 1115°F
max. nominal clad temperature : 1051°F

b) Blanket :

15. <u>Coolant</u> :

<u>nature</u> : sodium

<u>coolant flow area</u> : core 1.99 ft^2

<u>channel velocity</u> : core 15.7 ft/sec.

<u>coolant mass flow rate</u> : core : 7.10×10^6 lb/hr
radial blanket : 1.47×10^6 lb/hr

<u>heat transfer coefficient</u> : av. 96, 500 BTU/ft^2/hr°F
(Na to SS)

<u>temperatures</u> : inlet : 550°F
outlet : 800°F

<u>coolant pressures</u> : plenum inlet : 120 psia
reactor outlet : 20 psia

15. bis <u>Thermal systems and turbine plant</u> :

<u>Heat exchangers</u> :

3 intermediate Na/Na, vertical shell-and-tube type ; type 304 stainless steel ; surface area : 6320 ft^2
3 steam generators, shell (Na) and tube (water), once-through, cross-counterflow type, low-chrome steel ; surface area 10,800 ft^2 each, with 965 ft^2 for economizer, 2165 ft^2 for evaporator, 7670 ft^2 for superheater.

<u>Turbine</u> :

1 single-flow, tandem-compound unit 157 MW, 1800 rpm.

<u>Generator</u> :

1 Allis-Chalmers, hydrogen-cooled unit, 189.9 kVA, 18 kV, 0.85 power factor, 60 cycles/sec., 1800 rpm.

17. <u>Physical data</u> :

- prompt neutron lifetime, sec. : 1.4×10^{-7} sec. (mean)
- neutron energy : 0.32 MeV (mean core)
- conversion ratio : core : 0.29) total 1.16
  blanket : 0.87)

- maximum excess reactivity : 0.644%
- temperature coefficients isothermal :
  core : 14×10^{-4} % $\frac{\Delta k}{k}$ /°C

  blanket : 4.1×10^{-4}% $\frac{\Delta k}{k}$ / °C

  total : 18.1×10^{-4}% $\frac{\Delta k}{k}$ / °C

- load factor (first 2 years) : 40%
  (after 2 years) : 70%

- plant life : 10 years

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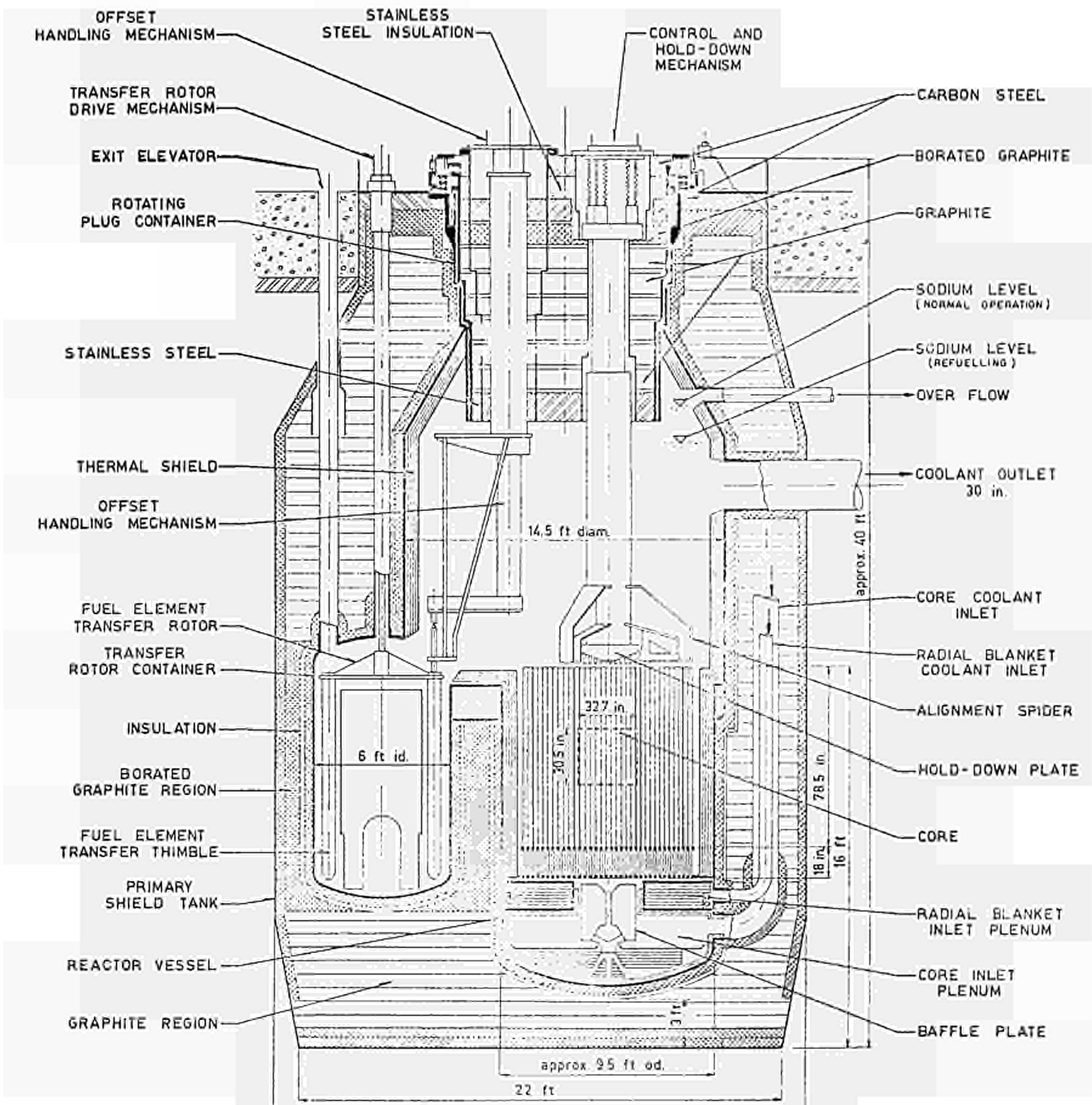
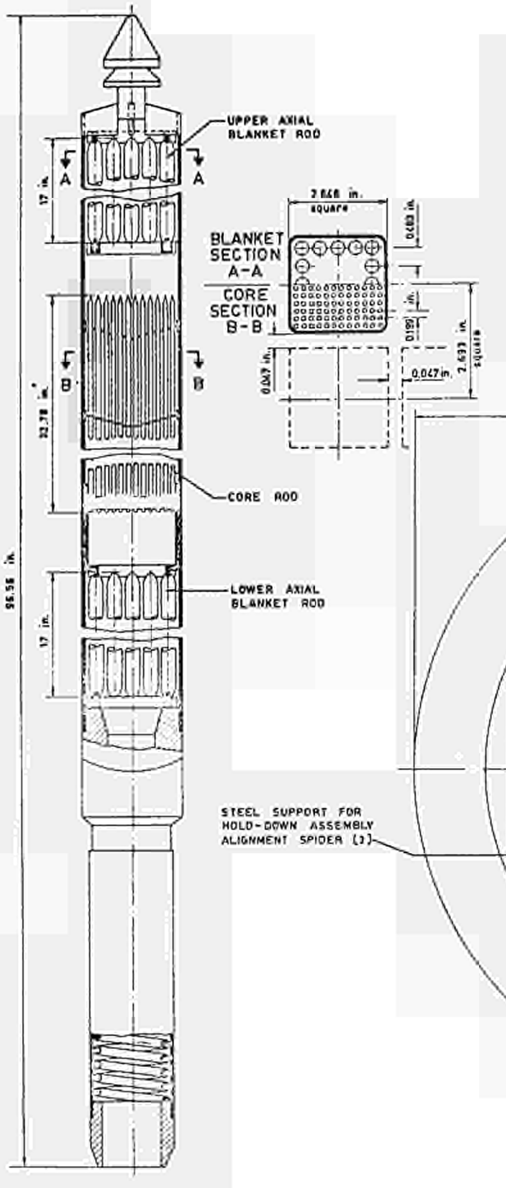
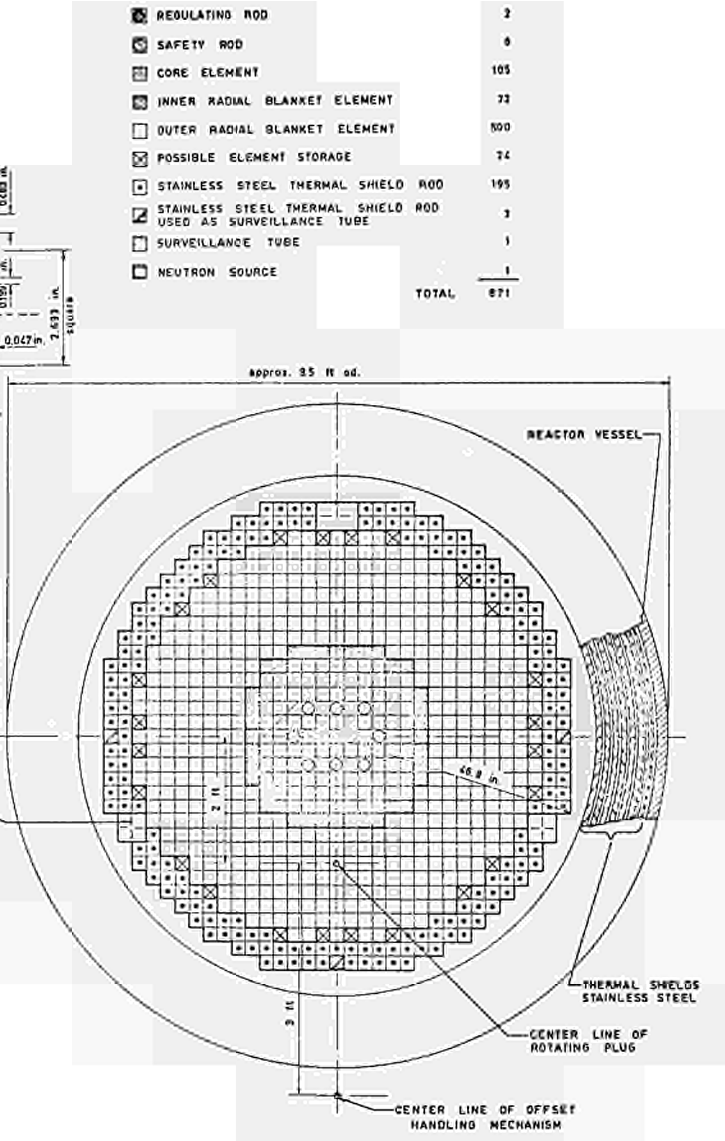


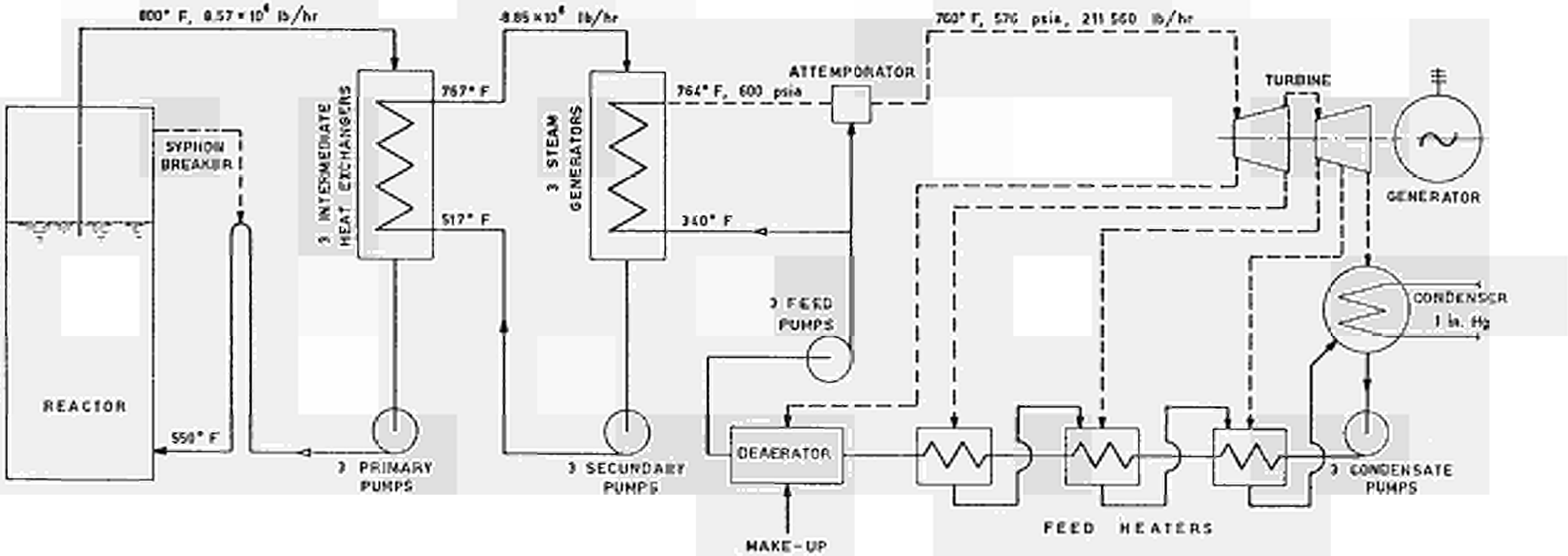
VERTICAL SECTION REACTOR ENRICO FERMI



CORE ELEMENT



HORIZONTAL SECTION
REACTOR ENRICO FERMI



FLOW DIAGRAM REACTOR ENRICO FERMI

IAEA-Power R. — ENRICO FERMI

F C R

FAST CERAMIC REACTOR

1. Location : U. S. A.

2. Owner :

3. Main contractors :

   Atomic Power Equipment Department General Electric

4. Present status and construction schedule :

   Design

5. Reactor type : A 565 MWe (net) reactor design based on the Fast Ceramic Reactor fuel concept, cooled by sodium with a 738°F inlet and 1050°F outlet temperature. The core is surrounded by a blanket region in which approximately half of the new fissile material is bred.

6. Purpose : Major objectives are :

   - development of a reliable, high performance fast reactor having nuclear characteristics which provide stable and safe operation ;

   - demonstration of low fuel cycle cost capability for such a reactor, primarily through achieving high burnup of Uranium fuels operating at high specific power.

7. Power :

   - thermal : 1395 MW (core : 1200 MW
     (axial blanket : 113 MW
     (radial blanket : 82 MW

     thermal efficiency : 40%
     specific power, average : 1,000 KW/kg fiss. Pu
     specific power, average : 128 KW/kg Pu + U
     core power density : 395 KW/liters

   - electrical : net : 565 MW

8. Fast flux :

9. Fuel :

a) Core :

- Composition : UO_2-PuO_2 mixed Plutonium-Uranium oxides (20 weight percent Plutonium oxide).
  Core fuel isotopic composition :
  - Pu^{239} : 10.9 a/o
  - Pu^{240} : 5.6 a/o
  - Pu^{241} : 1.9 a/o
  - Pu^{242} : 0.7 a/o
  - U^{238} : 75.1 a/o

- shape and dimensions : rods : rod diameter : 0.220 in.
  rod spacing center to center : 0.350 in.
  total fuel element length, core and axial blanket + reservoir : 8.65 ft

  assembly : width of hexagonal channel : 4.16 in.
  channel wall thickness : 0.040 in.
  space between subassembly : 0.050 in.

- number : rods per assembly : 127
  number of core assemblies : 314

- critical mass : 1100 kg Pu (239 + 241)

- cladding : stainless steel, thickness : 0.015 in.
  clad. O.D. : 0.25 in.

b) Blanket : axial blanket:
  composition : depleted UO_2
  shape and dimensions : length : 2 x 1.25 ft
  cladding : same as respective core

  radial blanket :
  composition : depleted UO_2
  shape and dimensions : rods-rod diameter :0.42 in.
  rod spacing center to center : 0.500 in.
  total fuel element length, radial blanket + reservoir : 5.0 ft.

assembly : width of hexagonal channel : 4.16 in.
channel wall + thickness : 0.040 in.
space between subassembly : 0.50 in.

number : rods per assembly : 61
number of radial blanket assemblies : 336

cladding : stainless steel, thickness : 0.015 in.
clad. I.D. : 0.45 in.

10. Control : 16 control rods are arranged in the core on one-foot centers : 8 shim-rods + 8 safety rods.

- 8 shim rods, each worth 75 cents, will be used to control the reactivity. The shim rods are specified to consist of stainless steel cans, 2 inches in diam. filled with boron carbide that is enriched in the B-10 isotope. The composition is as follows :

$$45\ ^{v}/o\ B_4^{10}C\ ;\ 25^{v}/o\ Na\ \text{and}\ 30^{v}/o\ \text{steel.}$$

- 8 safety rods, each worth one dollar, are employed for shutdown margin and to cover the emergency requirements due to loss of shim rod control or fuel motion. They consist of

$$25^{v}/o\ B_4^{10}C\ ;\ 25^{v}/o\ Na\ \text{and}\ 50^{v}/o\ \text{steel.}$$

The rods are scrammed by gravity fall with initial spring acceleration. Scram occurs when current to a magnet is interrupted, thus releasing an actuator which opens the scram latch.

11. Reflector :

12. Shielding :

13. Geometric dimensions :

a) Core : height : 325 ft
diameter : 6.50 ft

composition : core and axial blanket : fuel : 33 v/o
structure : 17 v/o
sodium : 50 v/o

b) Blanket : thickness : 1.25 ft

Composition : radial blanket : fuel : 63 v/o
structure : 25 v/o
sodium : 12 v/o

c) Pressure vessel : height : 28 ft
diameter : 12 ft

14. Temperatures :

a) Core :

b) Blanket :

15. Coolant : sodium

- sodium flow : 60×10^6 lb/hr
- sodium velocity : 34 ft/sec (max) ;
  20 ft/sec (average)
- sodium heat transfer coefficient : 15,000 BTU/hr ft^2 °F
- inlet temperature : 785°F
- outlet temperature : 1050°F

15. bis Thermal systems and turbine plant :

The primary sodium system consists of 4 loops without stop valves, but with check valves in the pump discharge. The sodium in the tank is the loop connection between the heat exchanger outlet and pump inlets, and also serves as a dump tank and surge tank.

The 4 heat exchangers, 4 pumps and check valves are grouped around the reactor vessel. The ducting plenum takes the place of the usual piping system and consists of 3 large diameter disks welded to the reactor vessel one above the other, spaced about two feet apart.

Primary pump are of the vertically mounted 37,000 gpm mechanical drive type. Maximum dimensions are 5 feet in diameter over the diffuser and a length of 18 feet including the shield plug for the floor penetration.

Heat exchangers are U-tube design similar to the Fermi plant, and are 8 feet in diameter by 40 feet long including the shield plug for the floor penetration.

There are four secondary loops, independent except for common connections through their dump tanks. The steam generators and re-heaters are once - through design of single-wall ferritic steel.

16. Physical data : - breeding ratio : 1.08 (core : 0.66
(axial blanket : 0.24
(radial blanket : 0.18

- delayed neutron fraction : 0.0036
- prompt neutron lifetime : $\sim 5 \times 10^{-7}$ sec.
- operating reactivity for burn-up at 0.8 load factor :

  - Δ K per 4 months at 1000 KW/kg Pu (239+241): -0.011

  - \$ per 4 months at 1000 KW/kg Pu (239+241): -3.1

- refueling interval : 10 weeks
- sodium coefficient : $+ 1.0 \times 10^{-6}$ Δ K/K°C
- Doppler coefficient : -9.2×10^{-6} Δ K/K°C.

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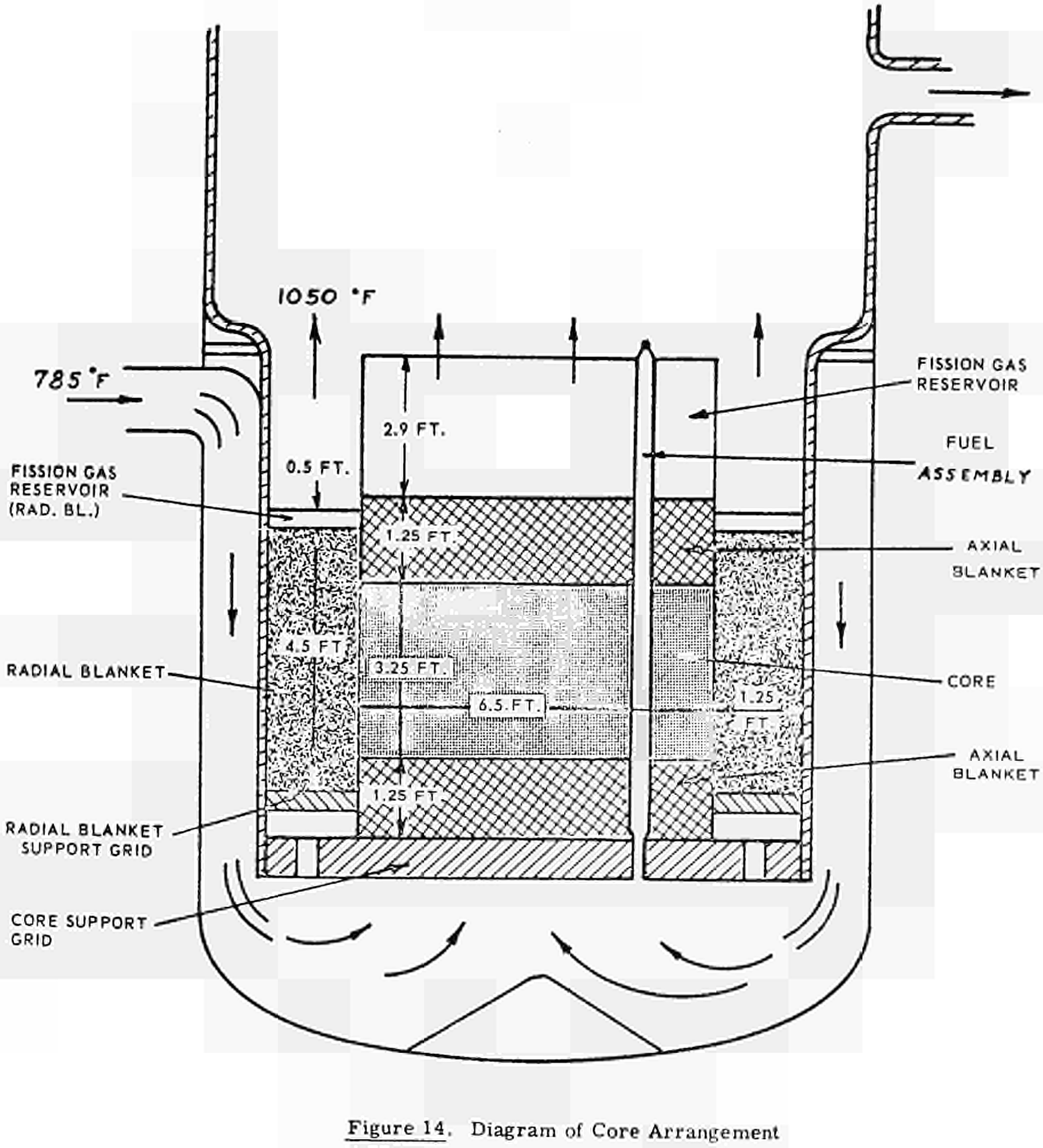

Figure 14. Diagram of Core Arrangement

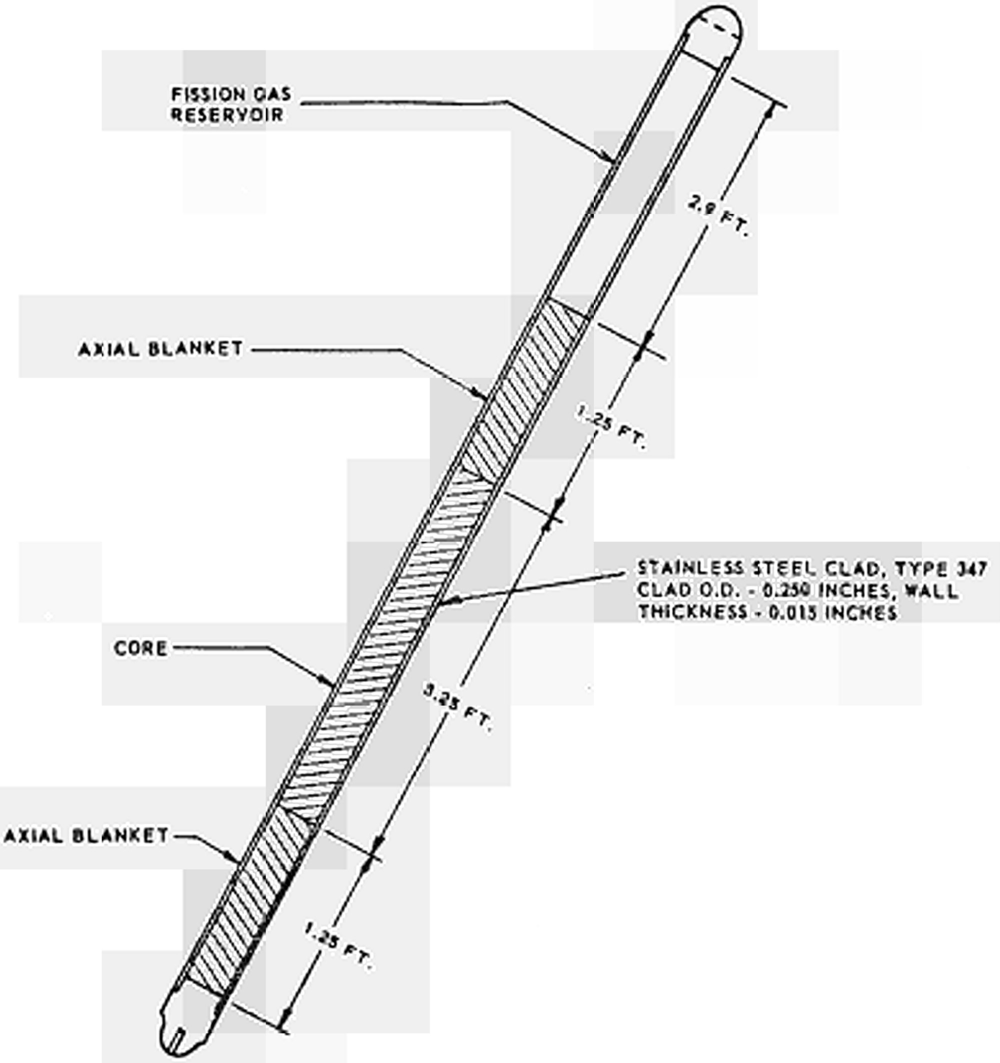

Figure 15. Diagram of Fuel Rod (Not to Scale)

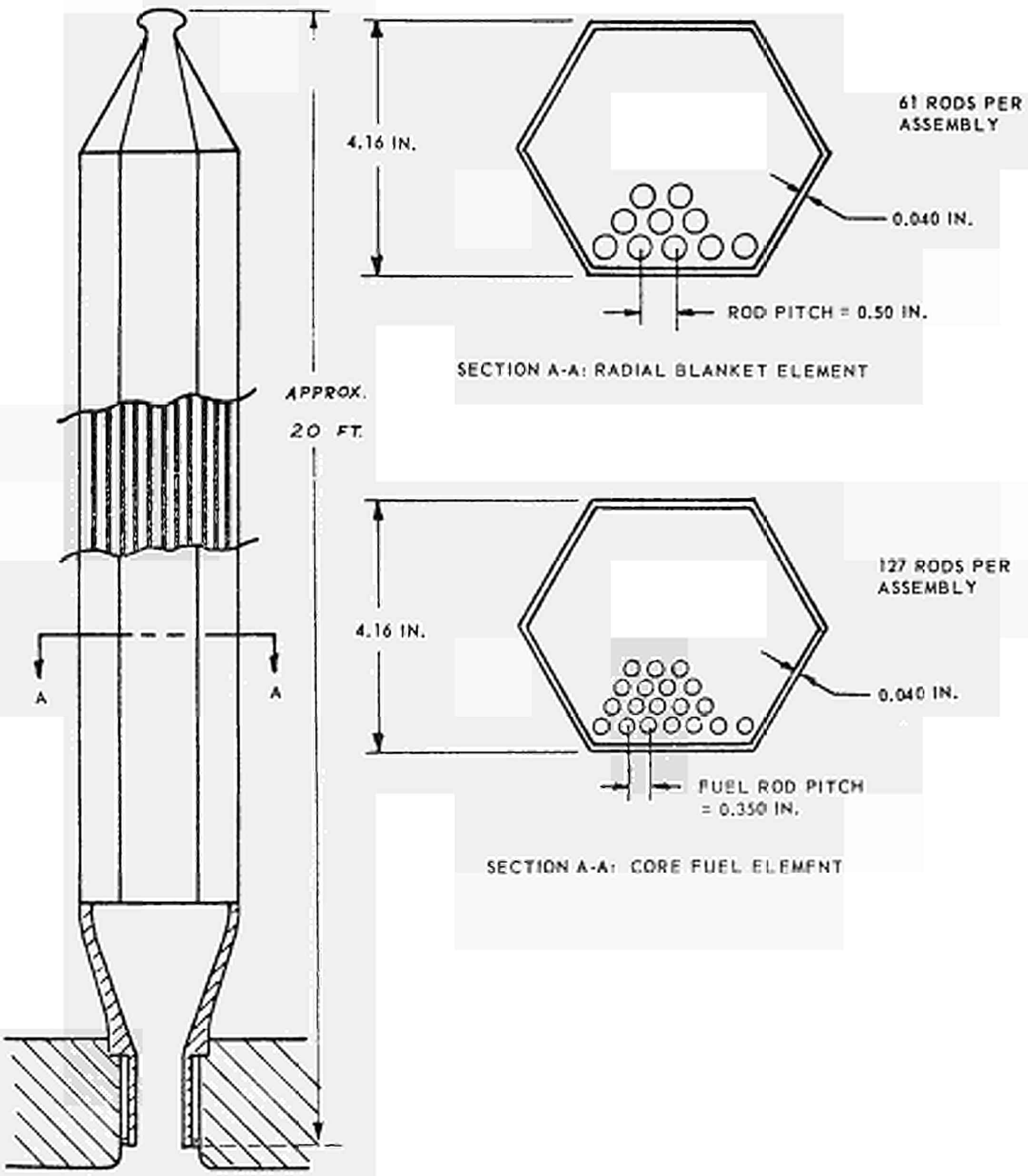

Figure 16. Diagram of Fuel Element Assembly (Not to Scale)

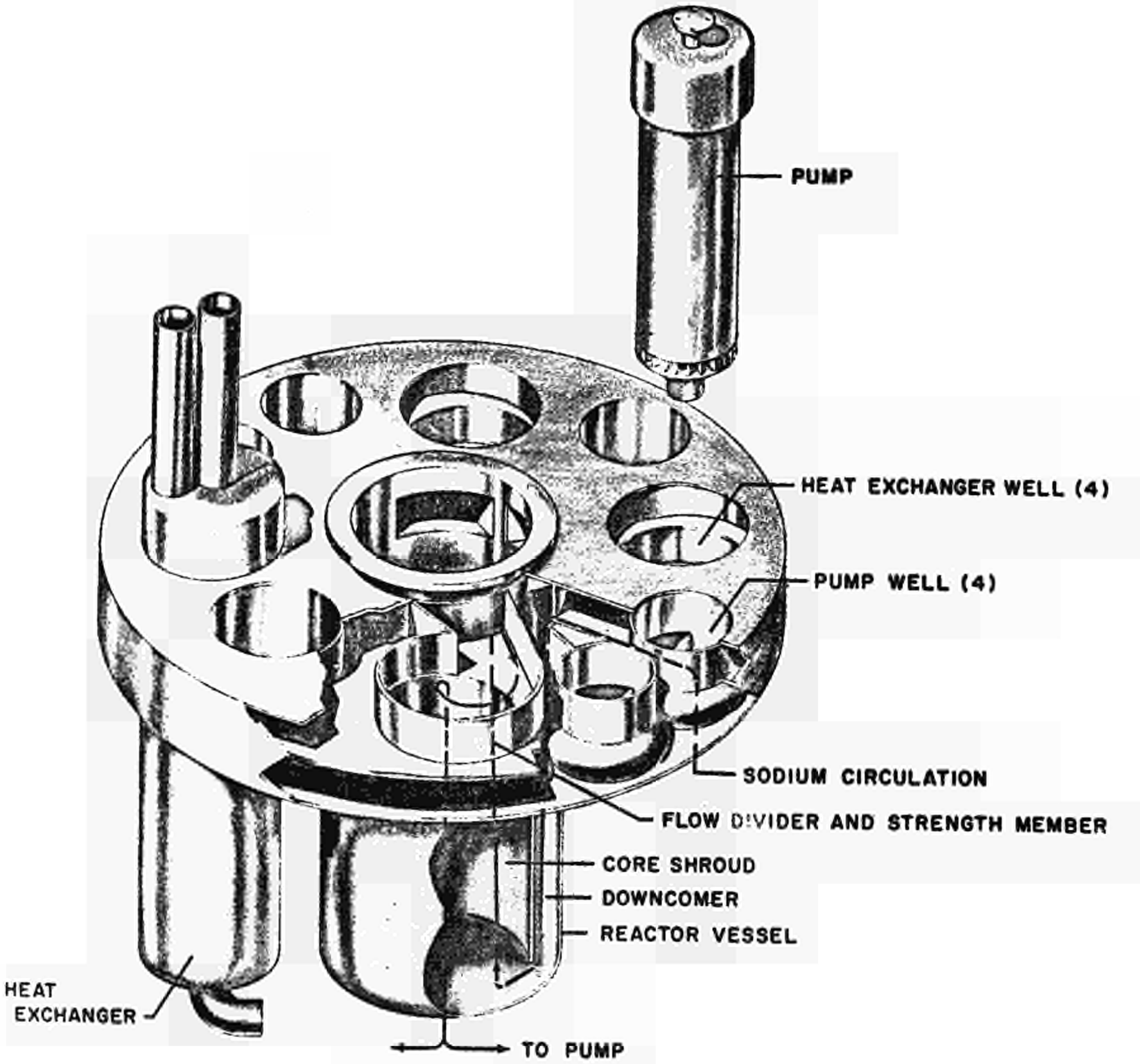

Figure 4. Cut Away of Primary Loop Arrangement

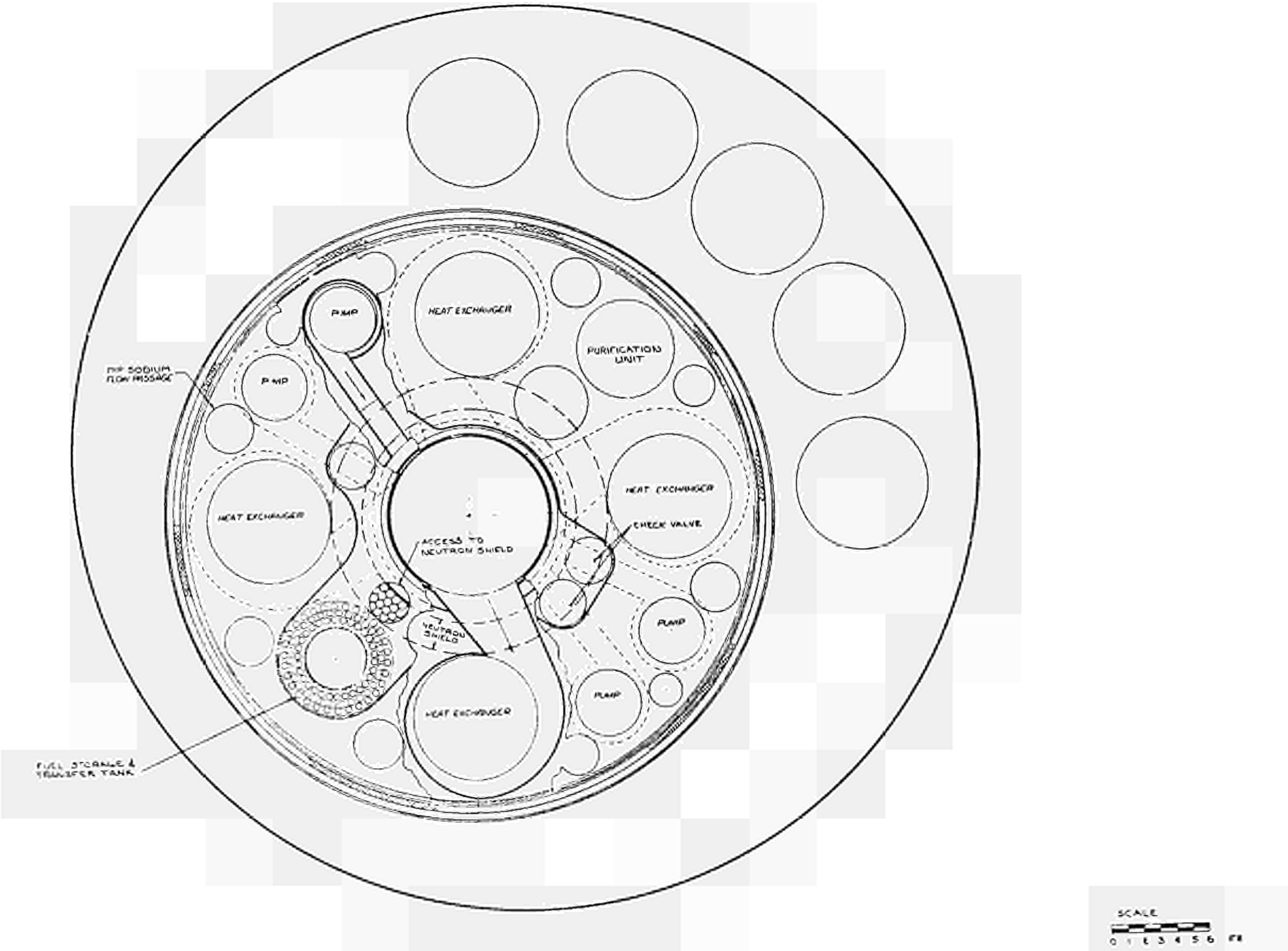

Figure 5. Plan View of Primary Loop

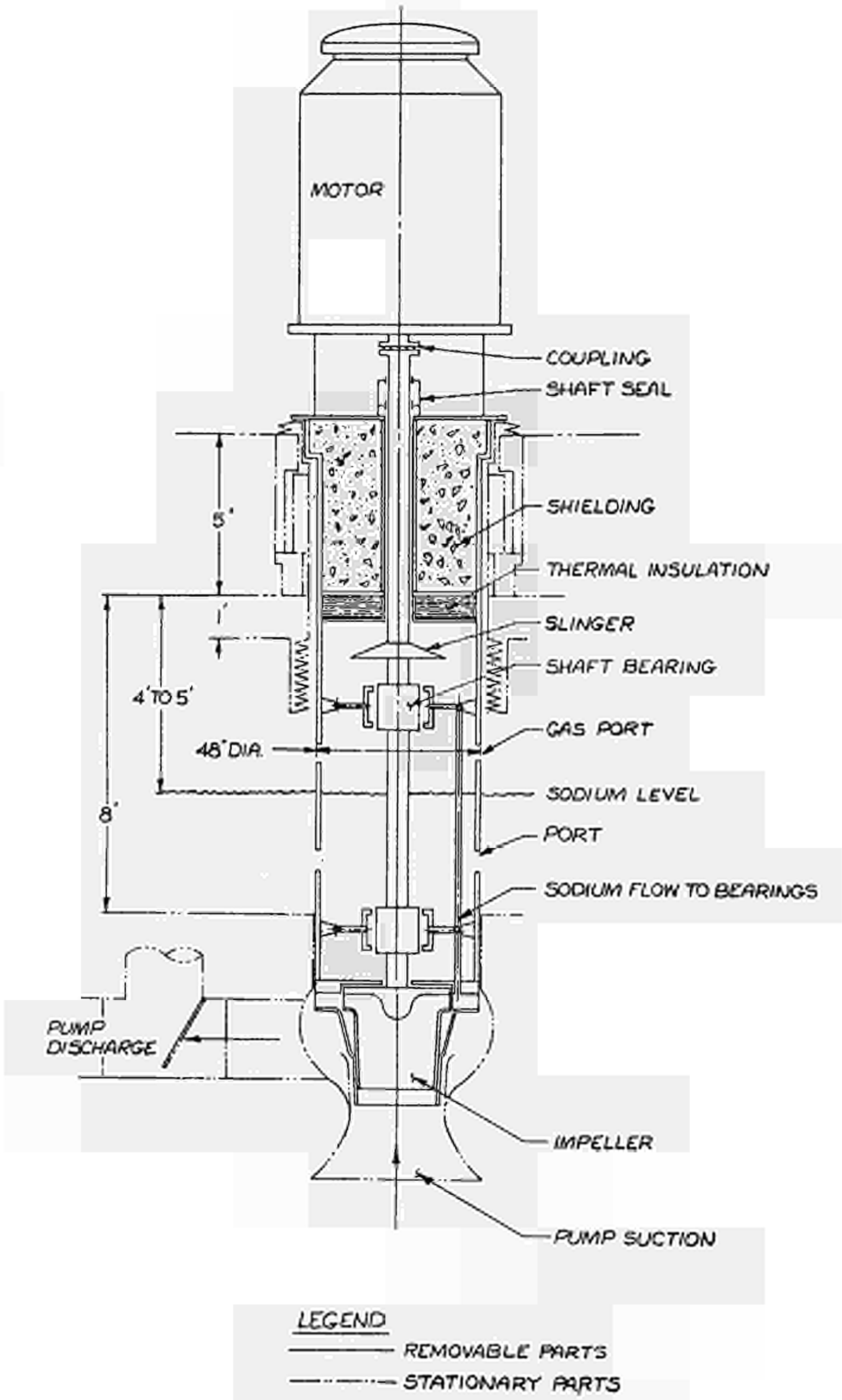

Figure 6. Primary Pump

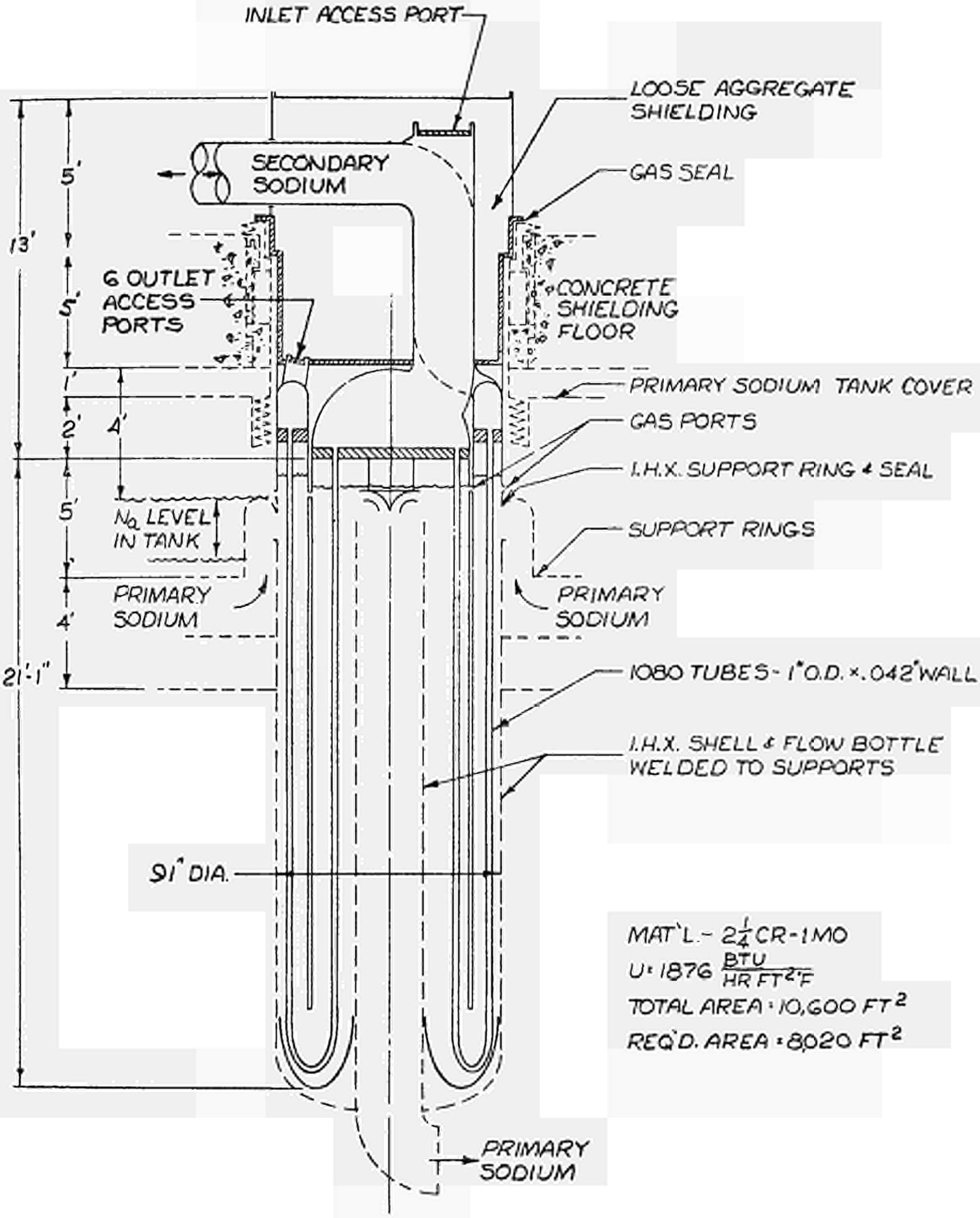

Figure 7. Primary Heat Exchanger

F R C T F

FAST REACTOR CORE TEST FACILITY

1. Location : The FRCTF will be located at the Los Alamos Scientific Laboratory, Los Alamos, New Mexico, U.S.A.

2. Owner : United States Atomic Energy Commission

3. Main contractors :

   Los Alamos Scientific Laboratory

4. Present status and construction schedule :

   under construction

5. Reactor type : The Facility will comprise a reactor tank, primary and secondary sodium systems, steam generator and auxiliaries having a total heat dump capacity of about 20 MW.

6. Purpose : The FRCTF is designed for testing and evaluating a sequence of plutonium fueled, sodium cooled reactor core concepts. It is intended to use the Facility to extend the knowledge of molten plutonium fueled reactor gained by operation of Lampre I.

7. Power :

   - thermal : 20 MW (core : 15 MW
     (blanket : 5 MW

     power density : 8280 KW/liter of fuel
     2540 KW/liter of core

     specific power : 517 Watts/g of plutonium

   - electrical :

8. Fast flux :

9. Fuel : molten plutonium

a) Core capsule :

The core capsule is a 10 in. stainless steel tube approximately 25 ft long containing the following components :

1. fuel reservoir
2. lower axial breeding blanket
3. core structure
4. upper axial blanket
5. fuel circulation system
6. capsule shield plug.

b) Blanket and control assembly :

The blanket consists of three portions : the radial blanket, the control blanket and the axial blanket.

Radial blanket :

uranium, average U density : 80 v/o. The uranium of the radial blanket forms a cylinder :
O.D. : 48 in.
i.d. : 24 in.
high : 48 in.

The full sodium coolant flow passes down-ward through the radial blanket before entering the core and the control blanket.

Control blanket :

uranium, density 65 v/o

The control blanket assembly is mounted in a supporting fixture which can be inserted into the 24 in. sleeve of the core tank. The entire assembly can be removed as a unit. The U pins are mounted in several stainless steel frames which can be indepently moved. When fully assembled, the uranium of the control blanket forms a cylinder about

O.D. : 23 in.
i.d. : 11 in.
height : 48 in.

The control assembly surrounds a central sleeve about 10.5 in. i.d. into which the core capsule is inserted. Cooled sodium flows upward between the inner and outer walls of the control assembly in parallel with the flow through the core capsule.

Axial blanket :

The upper and lower axial blankets are made up of pins similar to those in the control blanket. The axial blankets form part of the core capsule and are renewed with each new core tested.

10. Control :

11. Reflector :

12. Shielding and reactor tank :

The reactor tank consists of a circular stainless steel vessel about 25 ft deep suspended from the top in a concrete lined pit. A circular steel box girder filled with shielding materials. transmits the vessel load to the pit walls. Besides the shielding formed by about 18 tons of uranium in the blanket, laminated iron shields about 1 ft thick are located in the outer angular region of the reactor tank. Biological shielding for the pit consists of earth filling surrounding the pit with a floor of heavy concrete over the complete installation.

13. Geometric dimensions :

a) Core : 8 in. O.D. x 8 in. long

volume : 5.91 liters (Pu-Fe alloy : 30.6 v/o
(container materials : 20.9 v/o
(sodium : 48.5 v/o

b) Blanket : axial blanket : 10 in. diam. x 20 in. long
control blanket : 23 in. O.D. x 10.5 in. i.d. x 48 in. long
radial blanket : 47 in. O.D. x 23 in. i.d. x 48 in. long

composition :

axial and control blanket : 65 v/o U-Mo alloy
35 v/o Na and Fe

radial blanket : 80 v/o U-Mo alloy
20 v/o Na and Fe

c) Pressure vessel : a circular stainless steel about 25 ft deep, 7 ft in. diameter in the lower position and 4 ft in diameter at the top.

14. Temperatures :

a) Core : average fuel temperature : 1200°F

maximum fuel temperature : 1400°F

b) Blanket :

15. Coolant : core sodium flow rate : 6.8×10^5 lb/hr
coolant flow area : 0.155 ft^2
sodium velocity : 23.5 ft/sec
average temperature rise in coolant : 250°F
maximum coolant temperature : 1200°F

15. bis Thermal systems and turbine plant :

I. Primary sodium system :

- coolant : sodium
- heat removal capacity : 20 MW
- system sodium flow rate : 910,000 lb/hr
- pump type : centrifugal , variable speed
- maximum pump capacity (at 850°F):2300 gpm
- sodium temperatures : IHX sodium inlet (shell side):1100°F
  IHX sodium outlet (shell side) : 850°F

2. Secondary sodium system :

- coolant : sodium
- heat removal capacity : 20 MW
- system sodium flow rate : 910,000 lb/hr
- pump type : centrifugal, variable speed
- maximum pump capacity (at 550°F) : 2300 gpm
- sodium temperatures : IHX inlet (-tube side): 750°F
  IHX outlet (-tube side): 1000°F

3. Steam generator :

The steam generator will be made up of three separate heat exchanger sections : an evaporator, a sodium-t-sodium tempering heater and a superheater. The shells of all three heat exchange sections will be welded in series to form one continous U-bend unit.

- Design capacity : 20 MW
- Steam flow rate : 900 psig
- Outlet steam pressure : 900 psig
- Steam and water temperatures :
  - superheater outlet steam : 925°F
  - evaporator outlet steam : 535°F
  - evaporator inlet water : 400°F
- Construction materials :
  - superheater : 315 stainless steel
  - evaporator : 2.25% Cr - 1% Mo steel
  - tempering sodium heater : 2.25% Cr-1% Mo steel

16. Physical data :

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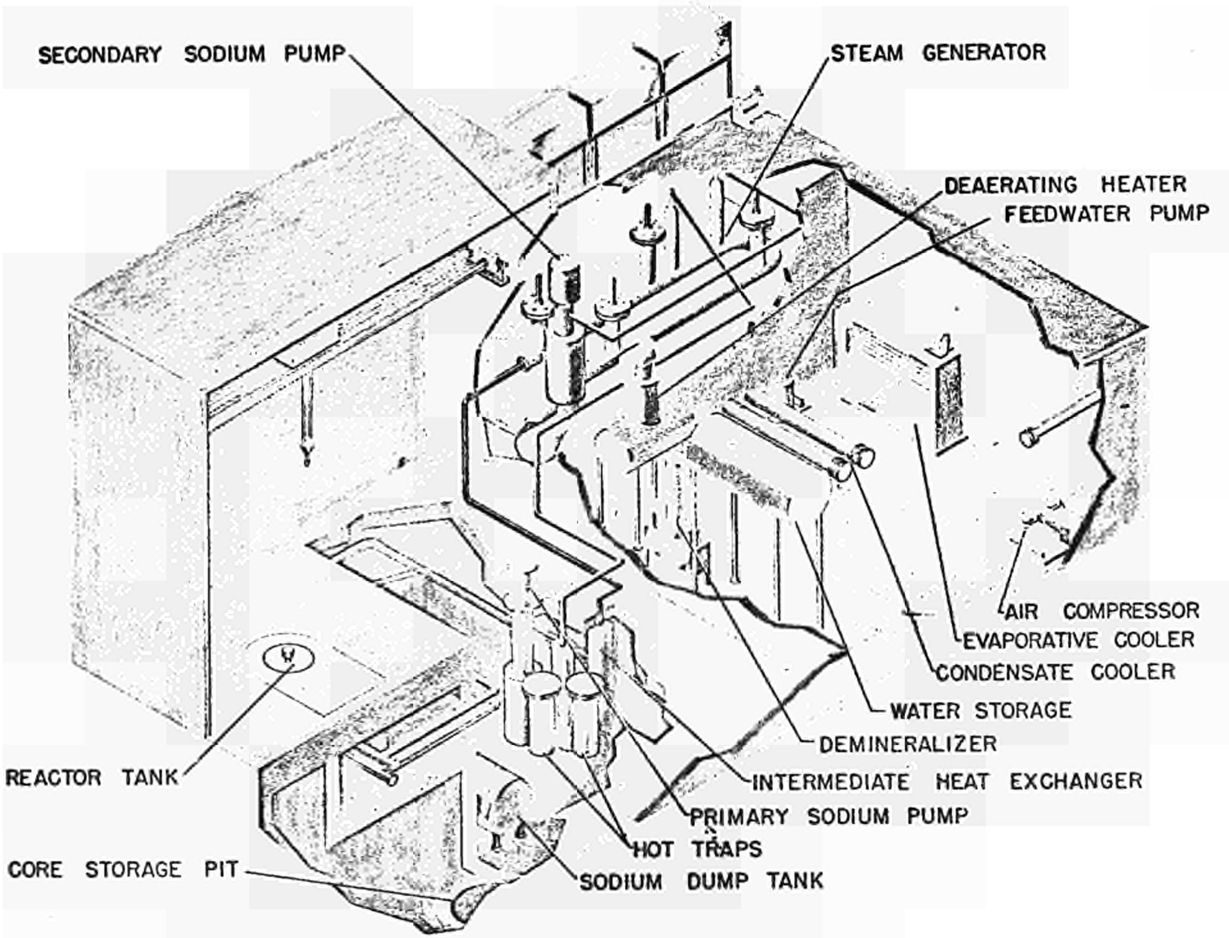

Fig. 10 Cutaway View of Fast Reactor Core Test Facility

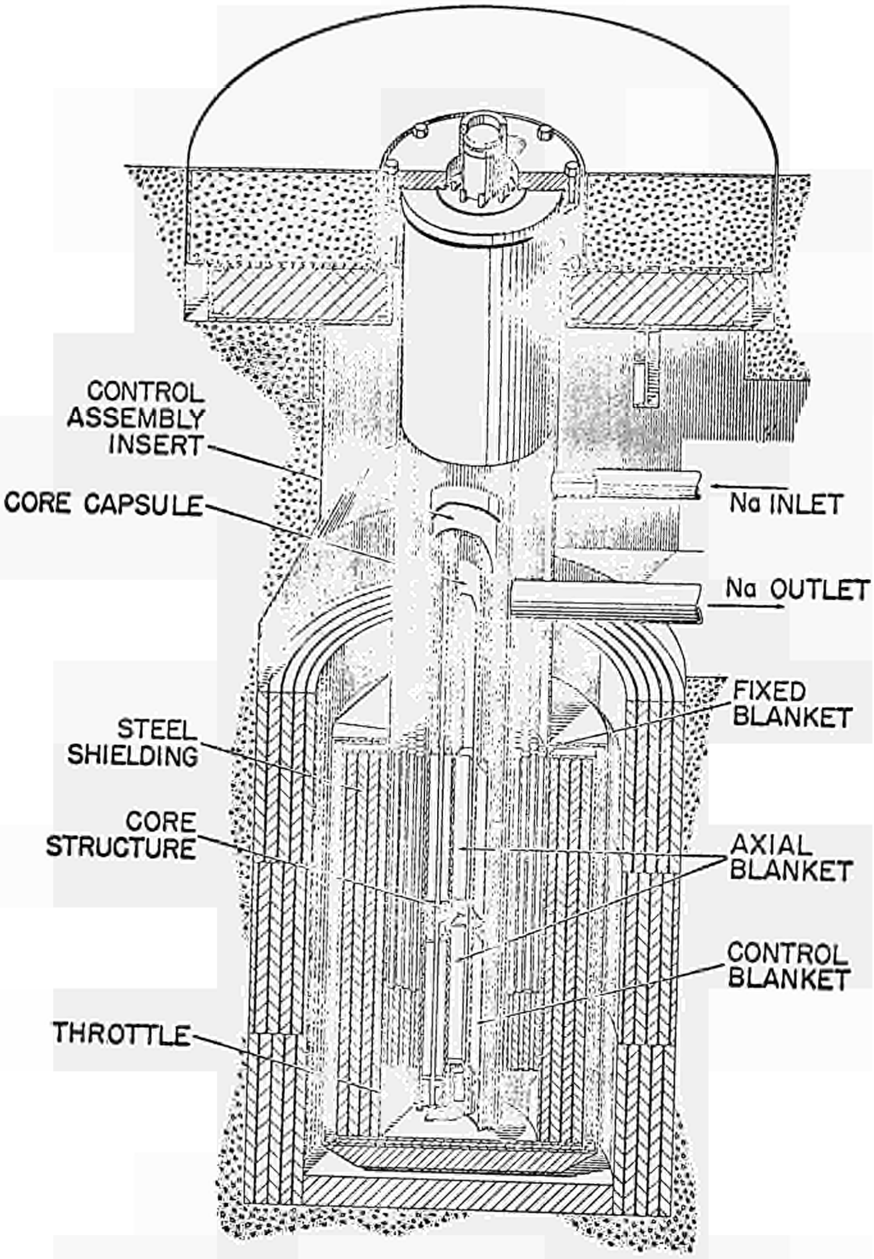

Fig. 2 Cutaway View of Reactor Tank and Core Capsule

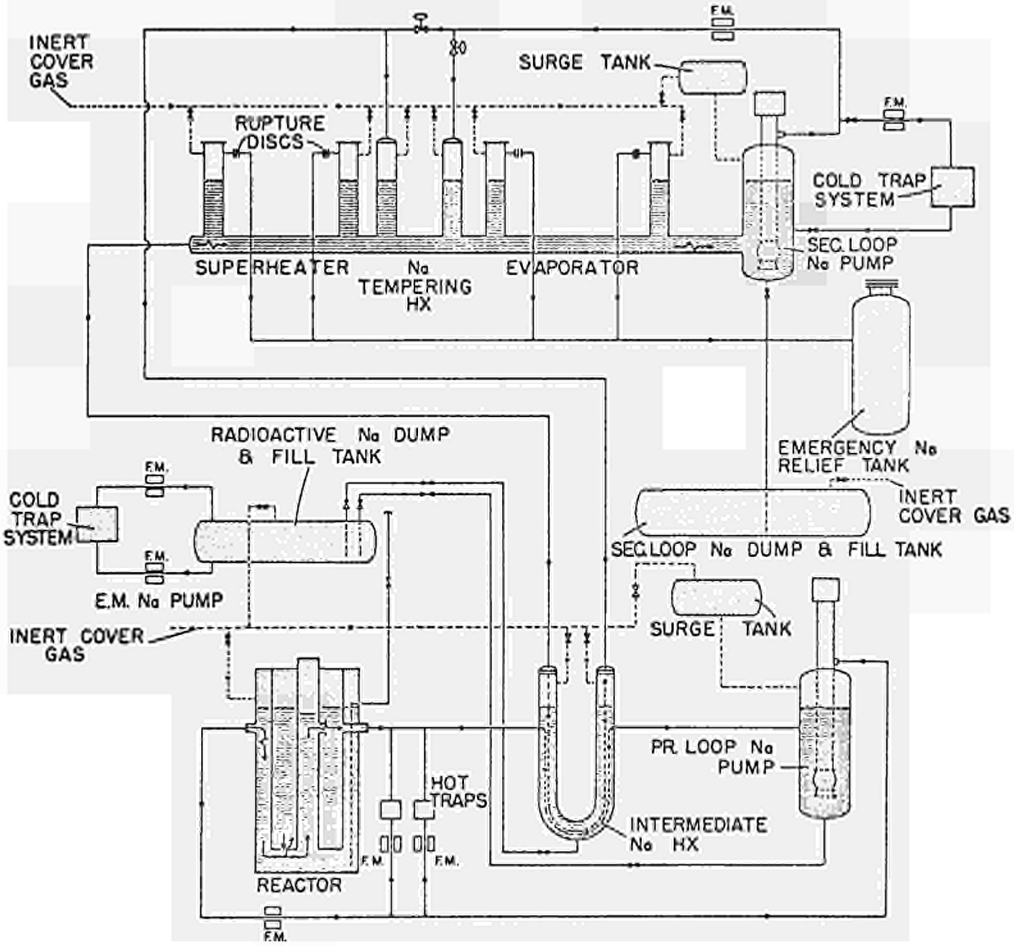

Fig. 3 Schematic Diagram of Primary and Secondary Sodium Systems

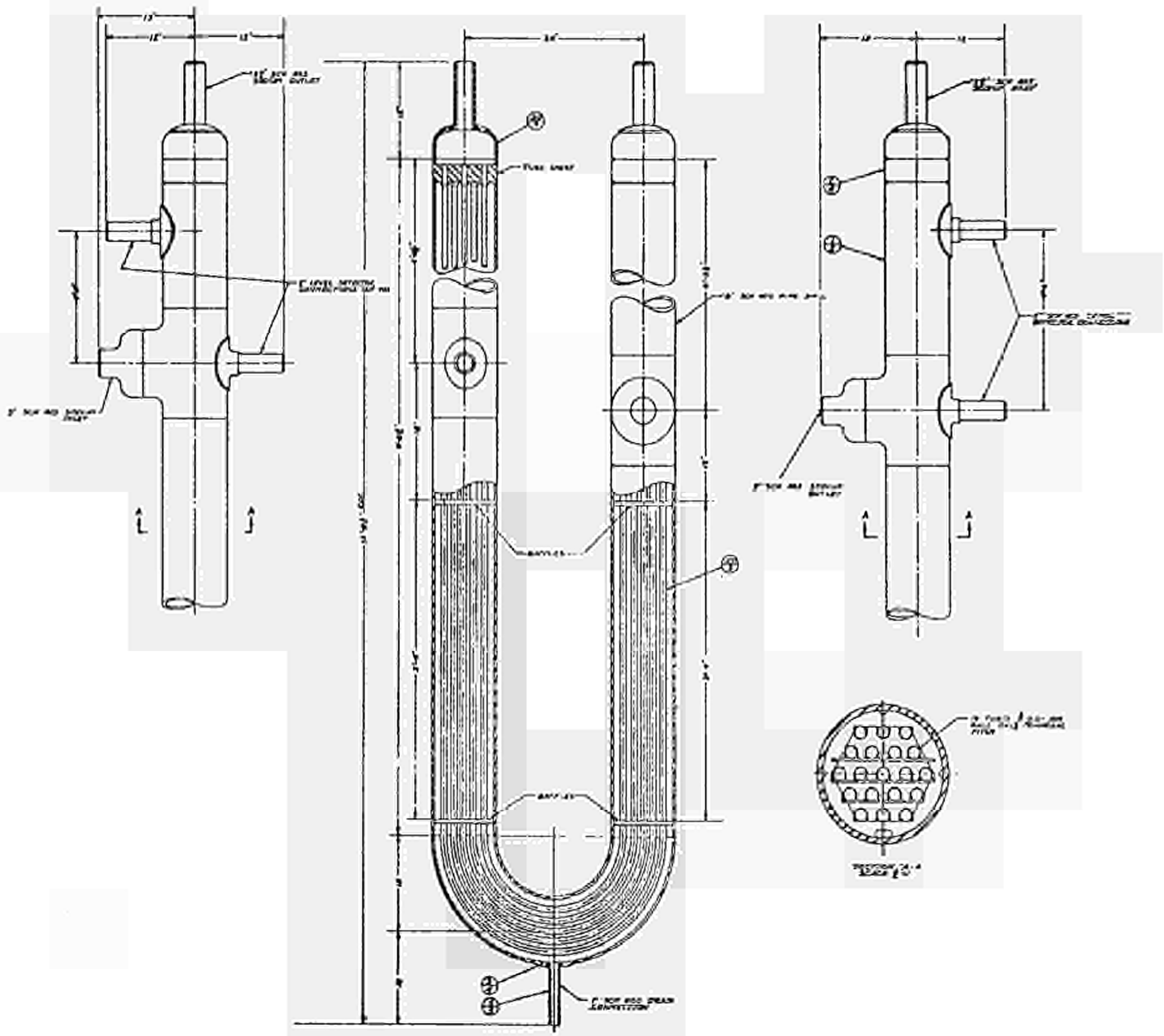

Fig. 4 Intermediate Heat Exchanger, 2 Mw Test Unit

GFK - EURATOM PROJECT (1000 MWe)

1. Location :

2. Owner :

3. Main contractors : GFK-EURATOM Association does study design only

4. Present status and construction schedule :

   - by the end of 1967 : study of the 1000 MWe concepts with sodium or steam cooling
   - end of 1967 : choice of coolant
   - beginning 1968 - 1973 : study and construction of a prototype (200 MWe)
   - 1980 : end of construction of the 1000 MWe demonstration power plant.

5. Reactor type : Fast power reactor ; 1000 MWe, UO_2-PuO_2 fuel, sodium or steam coolant, independent loops in primary system with centrifugal pumps for coolant circulation, power flattening by radial zoning.

6. Purpose : This reference core is taken as a starting point for a refined dynamic analysis. As it is indicated in the planning mentioned above, Germany intends to study the 1000 MWe fast breeder design by the end of 1967.

7. Power :

   - thermal : 2500 MW (2410 in core)
     (max. specific power/mean specific power)
     radial : 1.22
     max. rod power : 566 w/cm
     max. fuel specific power : 2.15 MW/kg
     mean specific power : 1.2 MW/kg Pu

   - electrical : 1000 MWe

8. Fast flux :

9. Fuel :

a) Core : two enrichment zones

- Composition : UO_2-PuO_2 - vibrational compacted 87% th. d.
enrichment ($PuO_2/PuO_2 + UO_2$)
zone 1 : 10.66 a/o (inner zone)
zone 2 : 13.93 a/o
Pu - composition : Pu^{239}; 63% ; Pu^{240} : 30%
Pu^{241} : 5% ; Pu^{242} : 2%

- shape and dimensions : fuel pin
fuel pin diameter : 6 mm
length of fuel zone : 955 mm
fission gas plenum : 800 mm (below)
assembly : (distance across flats : 178.5 mm
(hexagonal can thick : 4 mm
(overall length : 3790 mm

- number : number of pins per assembly : 331
number of assemblies : inner core zone : 118
outer core zone : 111

- critical mass : 2015 kg Pu

- cladding : Incoloy 800, thickness : 0.35 mm

b) Blanket :

- Composition : Two radial blanket zones

- number : number of subassemblies : inner blanket zone : 60
outer blanket zone : 108

- shape and dimensions : upper and lower blanket : 400 mm (each)

- critical mass :

- cladding :

10. Control :

11. Reflector :

12. Shielding :

13. Geometric dimensions :

a) Core : flat cylinder
diameter : 2.86 m
height : 955 mm
height / diameter : 0.33
core volume : 6100 liters (oxide mixture : 30.4%
(structural material : 19.6%
(sodium : 50%

b) Blanket : Thickness of the blankets : 400 mm

c) Pressure vessel : material : 10 CR MoN 910
O.D. : 7.9 m
height : 16.9 m

14. Temperatures :

a) Core : max. fuel temperature : 2,412°C

b) Blanket :

15. Coolant : sodium

max. coolant velocity : 6.6 m/sec
mean outlet temperature : 580°C
mean inlet temperature : 430°C
pressure drop of total primary circuit : 5 kg/cm^2
total flow : 4.75 x 10^7 kg/hr

15. bis Thermal systems and turbine plant :

The primary circuit is of the loop type. This seemed to be advantageous with respect to fabrication and decoupling between core and heat exchangers. There are 2 loops with 2 intermediate heat exchangers but 4 pumps.

Primary system :

number of sodium loops : 2
system material : 10 CR MoN 910
pumps : centrifugal
flow : 4 x 14,000 m^3/hr

16. Physical data : ratio fertile atoms/fissile atoms : zone 1 : 8.71
zone 2 : 6.41

(q_1 max/q_2 max.) initial : - 0.89
zone 1 : 0.556
zone 2 : 0.332

breeding ratio-internal : 0.89
total breeding ratio : 1.38
doubling time : 8.2 years
Doppler coefficient : - 8.5 x 10^{-6}/°C
sodium coefficient (total core) : -3.9 x 10^{-6}/°C

BIBLIOGRAPHY :

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American Nuclear Society, National Topical Meeting
Detroit Michigan , April 26-28, 1965

H E R M E S

1. Location : Concept in Belgium

2. Owner : BELGONUCLEAIRE S.A., Brussels, Belgium

3. Main contractors :

4. Present status and construction schedule :
   Concept

5. Reactor type : A fast neutron superheater reactor, dry-steam cooled.
   Fuel : mixed UO_2-PuO_2, austenitic steel as basis structural material. To feed the reactor with dry-steam, the Loeffler System is used.

6. Purpose : This reactor can be used as heat source for a self-reliant nuclear power station operating according to a Loeffler cycle.

7. Power :
   - thermal : 870 MW
     specific power : 428 KW th/kg of fissionable material
     power fiction between core and blanket :(90% in core
     (10% in blanket
   - electrical : net power : 300 MW
     gross power : 309 MW
     specific power : 150 KW/kg of fissionable material

8. Fast flux :

9. Fuel :
   a) Core : two active core assemblies per modulus
   - Composition : mixed oxides UO_2-PuO_2
     enrichment of fissionable material Pu^{239} : 20%
     specific weight of fuel : 9 g/cc

- shape and dimensions : A great number of small diameter tubes. The active assembly would have the following characteristics :
  - length : 550 mm
  - outside pin diameter : 5.8 mm
  - wall thickness : 0.4 mm
  - pitch : triangular : 6.8 mm

- number : number of pins per assembly : 151

- critical mass :

- cladding : The Hermes concept is at present based on the use of Inconel X, Hastelloy and Nimonic are also attractive.

b) Blanket : two blanket assemblies per modulus

- Composition :

- shape and dimensions :

- number :

- critical mass :

- cladding :

10. Control : The power station operation is simple and safe, owing to inherent and favourable reactivity coefficients of the reactor and excellent properties of the Loeffler cycle in this respect.

The modular structure allows to locate quickly any defect and gives an effective confinement in case of accident.

11. Reflector :

12. Shielding :

13. Geometric dimensions :

a) Core : active length : 1 m
volume : 500 to 10,000 liters

volume fraction in core and blanket :

b) Blanket :

- stainless steel : 0.5
- steam : 0.25
- fuel : 0.25

c) Pressure vessel :

14. Temperatures :

a) Core : maximum cladding temperature : 720°C

b) Blanket :

15. Coolant : steam

- reactor inlet steam velocity : 25 m/s
- reactor outlet steam velocity : 50 m/s
- weight flow rate through the reactor : 4285 T/h
- reactor inlet steam temperature : 315°C
- reactor outlet steam temperature : 540°C
- steam pressure : 100 atu

15. bis Thermal systems and turbine plant :

See fig. 1 Thermodynamic cycle

- turbine throttle pressure : 100 at
- superheat temperature : 540°C
- feedwater temperature : 227°C
- turbine inlet weight flow rate : 1220 T/h

The advantages of this Loeffler cycle are the following :

- the superheater is passed through by a gas (dry-steam)
- the steam drum is acting as a purifier, operating by water distillation
- the superheat temperature is easily controlled by acting on the steam circulator steam.

The working flexibility is great.

16. Physical data :

- net breeding ratio equals unity (simplifying and really pessimistic assumption)
- burn-up in the core : 30,000 MW d/T
- burn-up in the blanket : 5,000 MW d/T
- out of pile immobilization time : 1 year

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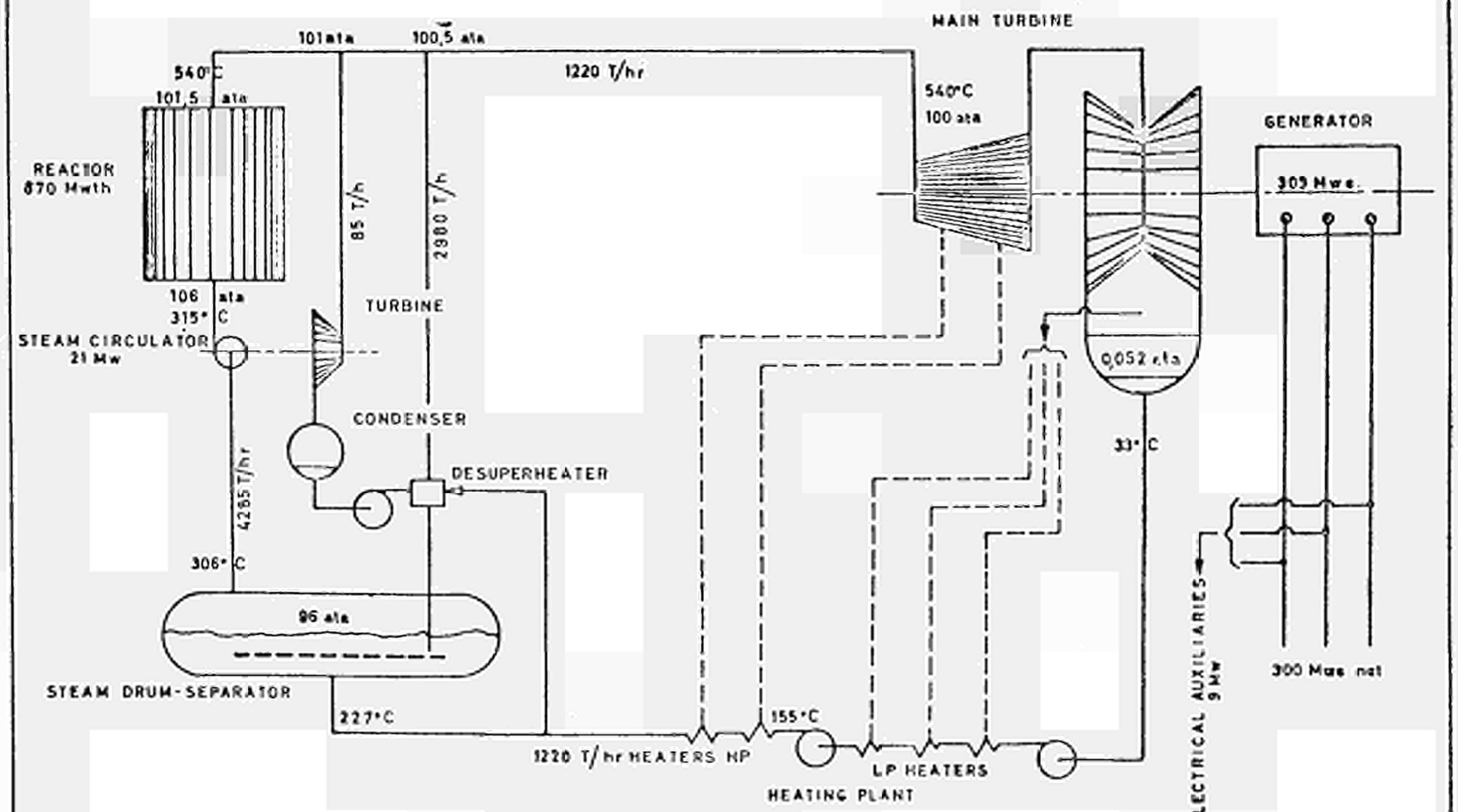

Fig. 1.

THERMODYNAMIC CYCLE

LAMPRE

LOS ALAMOS MOLTEN PLUTONIUM REACTOR

1. Location : Los Alamos, N. Mex., USA

2. Owner : United States Atomic Energy Commission

   Operator : Los Alamos Scientific Laboratory

3. Main contractors : Los Alamos Scientific Laboratory

4. Present status and construction schedule :

   - start of construction : July 1956
   - reactor critical (cold) : Nov. 1959
   - reactor critical (hot) : April 1961
   - full power operation : June 1961
   - reactor shut-down : Feb. 1964

5. Reactor type : Fast, Plutonium, sodium cooled, stainless steel reflected.

6. Purpose : Power experiment
   Investigations of the use of Plutonium alloys as reactor fuels and of the containment of such alloys. The reactor was shut down after completion of the test program, having proven the feasibility of a fast breeder power reactor using molten metallic plutonium as fuel.

7. Power:

   - thermal : 1 MW
     average specific power in fuel : approx. 44 KW/kg Pu
     average power density in core : approx. 155 KW/liter of core

   - electrical :

8. Fast flux : 2.4×10^{14} n/cm^2 sec.

9. Fuel :

a) Core :

- Composition : Plutonium-iron eutectic, 90 at.% Pu, 10 at.% Fe-melting point about 410°C ; under operating conditions fuel is molten.

- shape and dimensions : none subassemblies
lattice triangular, pitch : 0.495 in.
fuel is contained in tubes of tantalum, nominal 0.375 in. id. , 0.027 in. wall thickness, 8.3 in. long

- number : room for 199 fuel elements

- critical mass : at zero power, 470°C : 21.4 kg Pu

- cladding : tantalum, thickness : 0.027 in.

b) Blanket :

- Composition :

- shape and dimensions :

- number :

- critical mass :

- cladding :

10. Control : 1 shim cylinder, operating vertically
made of type 430 stainless steel
o.d. : 20 in.
i.d. : 10.75 in.
long : 16 in.
travel : 16 in.

it may be raised to a position surrounding the core
- 4 control rods, operating vertically inside the shim cylinder, 3.8 diam. x 16 in. long, 14.85 in. travel. They consist of high-purity nickel cylinders.

- worth of shim cylinder : 7.6% $\frac{\Delta k}{k}$
- worth of control rods : 0.5% $\frac{\Delta k}{k}$ each
- speed of shim cylinder : 0.05% $\frac{\Delta k}{k}$ /sec
- speed of control rods : 0.01% $\frac{\Delta k}{k}$ /sec

Scram time and mechanism :

release of hydraulic pressure in rod drives allows rods to drop ; droptime approx. 0.9 sec.

automatic shim run-down is initiated by scram signal

fuel failure detection : monitoring of blanket gas (purified helium) for radiation.

11. Reflector : The shim cylinder may be lowered to a position where its effectiveness as a reflector for neutrons escaping from the core is negligible. Control rods act also as reflector.

12. Shielding :

- Sides : 3.5 ft borated graphite, 5.5 ft ordinary concrete, 8 in. lead
- Bottom : floor shield plug of 5 ft magnetite concrete, density 230 lb/ft^3 , and 2 ft lead shot.
- Top : 9 ft iron (fuel capsules handles) next to vessel ceiling shield plug, 50 in. long, of ferrophosphorus concrete and SS shot

13. Geometric dimensions :

a) Core : cylinder
diameter : 7.5 in.

high : 8 in.
core volume : 3.06 liters (fuel alloy : 50% v/o
(tantalum : α 15% v/o
(sodium : 35% v/o

b) Blanket :

c) Pressure vessel : cylinder, type 304 stainless steel
i.d. : 10 in.
long : 12 ft
thickness : 0.375 in.

14. Temperatures :

a) Core : max. fuel : 870°C
av. fuel : 637°C
film drop : 27°C

b) Blanket :

15. Coolant : sodium

coolant flow area : 14.4 in^2
av. velocity : 39.4 in/sec
coolant mass flow rate : 15.3 lb/sec
temperatures : inlet : 450°C
outlet : average : 563°C
max. 597°C

15. bis Thermal systems and turbine plant :

The system which contains the sodium coolant is, in general, fabricated from type 316 ELC stainless steel. The coolant system has been operating since October 1960, at temperatures from 160° to 500°C and with flows from 15 to 200 gpm.

piping :

The loop is designed to maintain an internal stress level not greater than 14,000 psi at 650°C. For the most part, the loop is insulated with a two-layer construction. The inner part is Superex for high temperatures and the outer layer is 85% magnesia. The overall thickness is between 3.5 and 4 in.

pumps :

2 Callary AC electromagnetic conduction pumps in parallel, each rated at 100 gpm at 20 psi head.

heat exchanger :

One finned tube type sodium to air exchanger, built by Griscom-Russell.

coolant purification :

by cold and hot traps.

16. Physical data :
- neutron energy : 1 Mev
- neutron lifetime : 9×10^{-9} sec.
- reactivity balance : mx. built in (cold, clean) 1.3%
- temperature coefficients : $- 0.7 \times 10^{-2}\% \frac{\Delta k}{k} / {}^\circ C$

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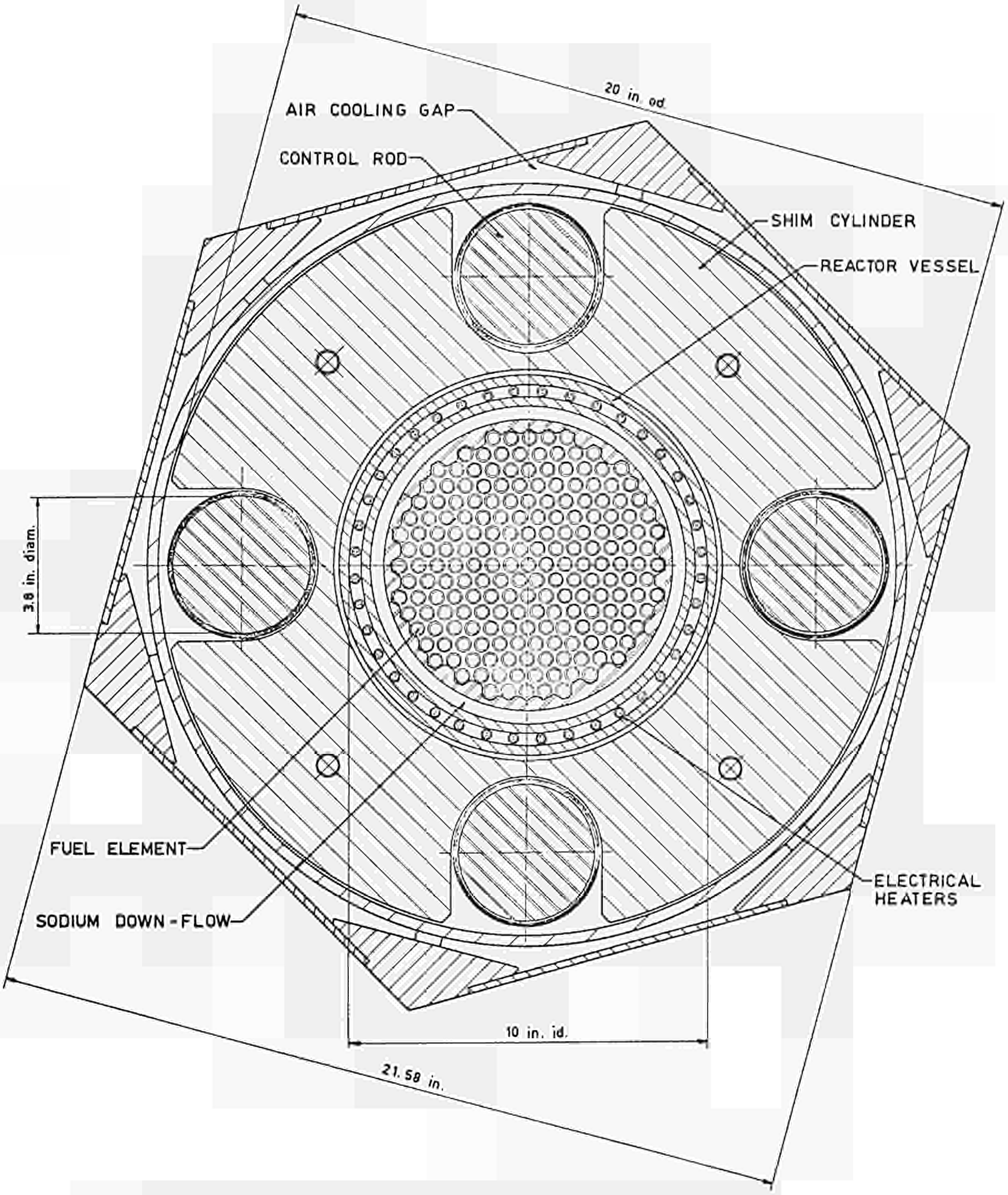
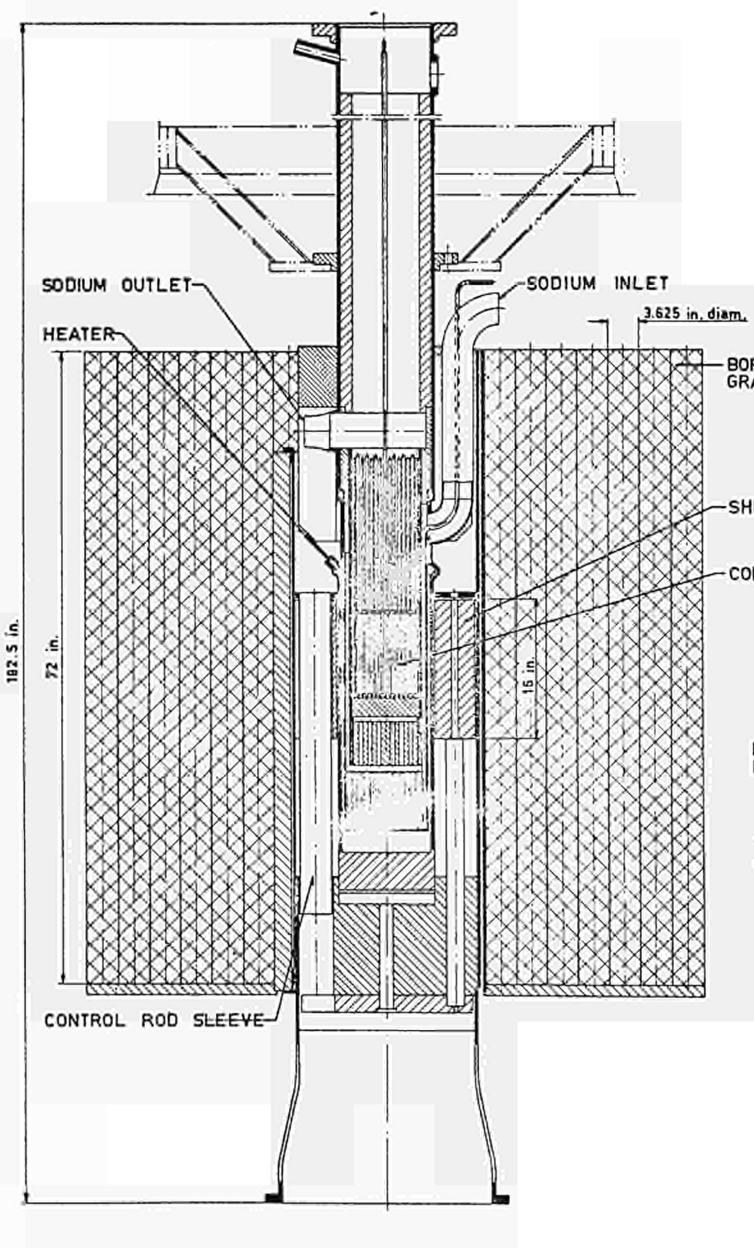
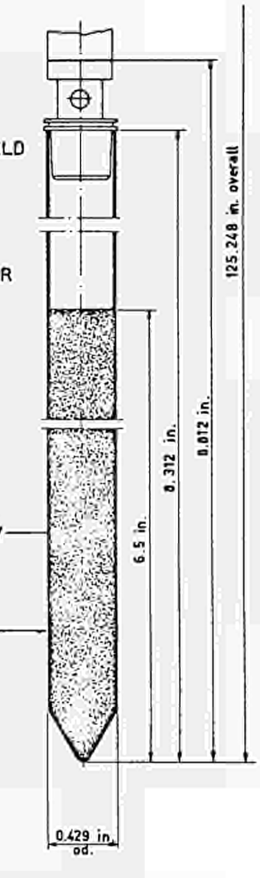


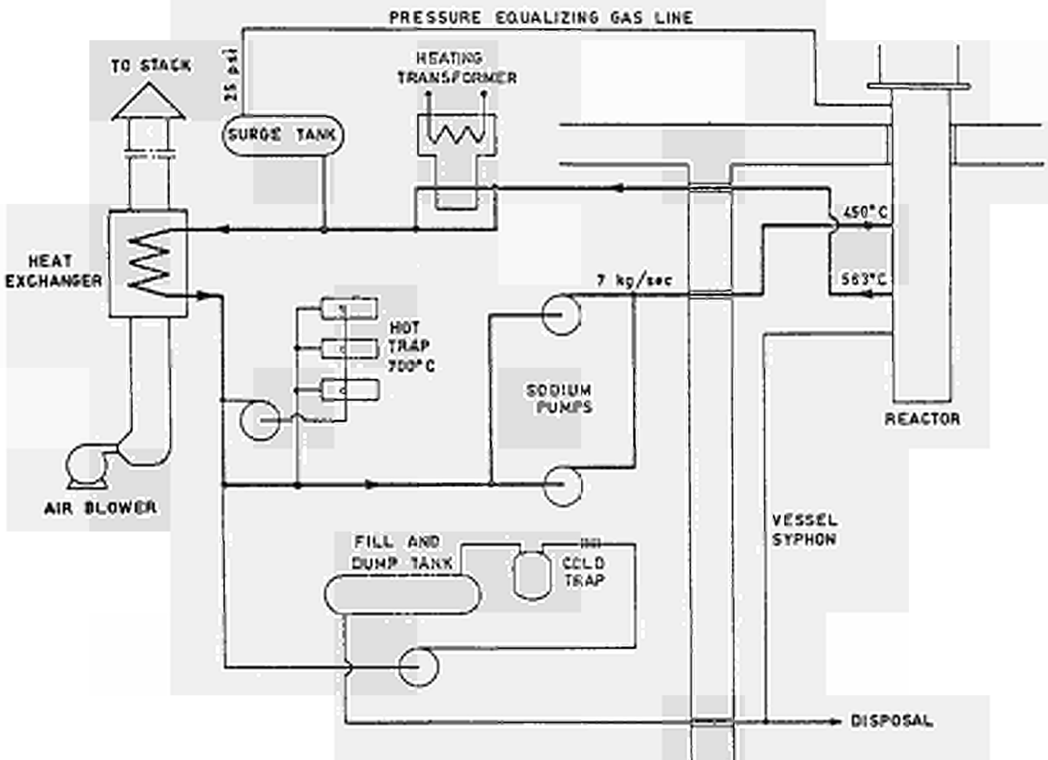
HORIZONTAL SECTION REACTOR LAMPRE





FUEL ELEMENT

VERTICAL SECTION REACTOR LAMPRE



FLOW DIAGRAM REACTOR LAMPRE

L M F R - ALLIS - CHALMERS

LIQUID METAL FAST BREEDER REACTOR DESIGN STUDY

1. Location : U.S.A.

2. Owner : United States Atomic Energy Commission

3. Main contractors :

   ALLIS-CHALMERS and Babcock and Wilcox Co.

4. Present status and construction schedule :

   Study

5. Reactor Type : A high leakage, thin annular core with a sodium reflector directly above the core to enhance the reactivity loss on boiling, with thick radial blankets inside and outside the annulus. The reactor concept studied employs stainless steel clad plutonium-uranium oxide fuel and is cooled by sodium.

6. Purpose : This study was undertaken as part of the Atomic Energy Commission long-range planning program. Its object was to establish the preliminary characteristics of a 1000-MWe sodium-cooled fast breeder reactor. Design goals of a breeding ratio of 1.2 and a sodium outlet temperature of 1200°F were set.

7. Power :

   - thermal : 2500 MW (core : 2125 MW
     (inner radial blanket : 185 MW
     (outer radial blanket : 190 MW

     power density : 282 KW/liter
     specific power : 733 KW/kg Pu

   - electrical : 1000 MW

8. Fast flux :

9. Fuel :

a) Core :

- Composition : (pellet material) mixture PuO_2-UO_2
pellet density : 95% of theoretical

- shape and dimensions : (fuel pellets) : (inner diam. : 0.11 in.
(outer diam. : 0.24 in.

length of pin : (core fuel portion : 4.0 ft
(axial blanket portion : 0.5 ft
(fission gas reservoir : 0.5 ft
(total : 5 ft

pin outside diameter : 0.300 in.
width of hexagonal assembly (flats) : 4.45 in.

- number : fuel assemblies : 498
pins per assembly : 123

- critical mass : Kg of (Pu-239 + Pu-241) : 2910

$$\frac{\text{Kg U-238 + Pu-240}}{\text{Kg Pu-239 + Pu-241}} : \quad 4.57$$

- cladding : material : 316 SS
thickness : 0.028 in.

b) Blanket :

- Composition : depleted UO_2, pellet density : 95% of theoretical

- shape and dimensions : (pellet)
length of pins : 6 ft
pin outside diameter : 0.607 in.
width of hexagonal assembly (flats) : 4.45 in.

- number : pins per assembly : 37
blanket assemblies : inner radial blanket : 276
outer radial blanket : 582
total : 858

- cladding : 316 SS ; thickness : 0.015 in.

10. Control : The safety, shim and regulating assemblies are composed of 85 pins of natural B_4C at 90 percent of theoretical density with a depleted UO_2 follower section.

Control assemblies :

- safety, number : 12
  total worth : 2.4% K/K
- temperature override and regulating, number : 6
  total worth : 1.2% K/K
- fuel depletion, number : 30
  total worth : 6% K/K

The shim and regulating assemblies are similar in construction to the fuel assemblies, they consist of a hexagonal support can containing 85 pins. Each pin consists of two 4-ft-long type-316 stainless steel tubes, 0.300 in. in OD. The upper tube is a poison section containing natural boron carbide pellets. The lower - tube is a follower section containing depleted UO_2 pellets.

The safety assemblies are identical except that the bottom of the boron carbide poison section is located 4 in. above the upper end of the depleted UO_2 follower section.

11. Reflector : A 1 - 1/2 - ft-thick sodium reflector is located on the upper core boundary.

12. Shielding :

13. Geometric dimensions :

a) Core : height : 4 ft
mean outside diameter : 13 ft
mean inside diameter : 9 ft
volume : 7720 liters (% fuel : 29.4
(% sodium : 40.0
(% structure : 30.6

b) Blanket : volume total : core + blanket : 29.320 liters

	inner radial blanket	outer radial blanket	axial blanket
height :	6 ft	6 ft	0.5 ft
mean outside diam. :	9 ft	16 ft	13 ft
mean inside diam. :	6 ft	13 ft	9 ft

c) Vessel : material : 316 SS

outside diameter : 20 ft
overall height : 25 ft

14. Temperatures :

a) Core : fuel max. 4,615°F
clad max. : 1,330°F

b) Blanket :

15. Coolant : nature : sodium

the reactor vessel has been designed for single - passparallel-flow of core and blanket coolant.

total coolant flow rate (including 5% by-pass flow):
1.14×10^8 lb/hr (2.8×10^5 gpm)

coolant velocity (max.) : 10 ft/sec.

temperatures :
coolant inlet temperature : 950°F
coolant outlet temperature : 1200°F

overall core pressure drop : app. 45 psi

15. bis Thermal systems and turbine plant :

Primary system :

number of coolant loops : 6
number of primary heat exchangers : 6
number of primary pumps : 6
material of primary system : 316 SS

16. <u>Physical data</u> : - K, burnup between reloading (1/3 of core) : 0.06
- mean neutron lifetime : 4.1×10^{-7} sec.
- average delayed neutron fraction in core, beta core : 0.0036
effective delayed neutron fraction in core , beta eff. core : 0.0032
- power coefficient (at full power) :

$$- 0.87 \times 10^{-6} \Delta K/K/MW$$

- temperature coefficient (isothermal)

Doppler (at 1000°F)	$-3.2 \times 10^{-6} \Delta K/K/°C$
pin radial expansion :	+ 0.4
sodium expansion core :	+3.0
reflector :	-1.6
radial blanket :	-0.4
axial expansion core :	-4.1
radial blanket :	+0.3
radial expansion core :	-6.8
radial blanket :	+0.3
total	$-12.1 \times 10^{-6} \Delta K/K/°C$

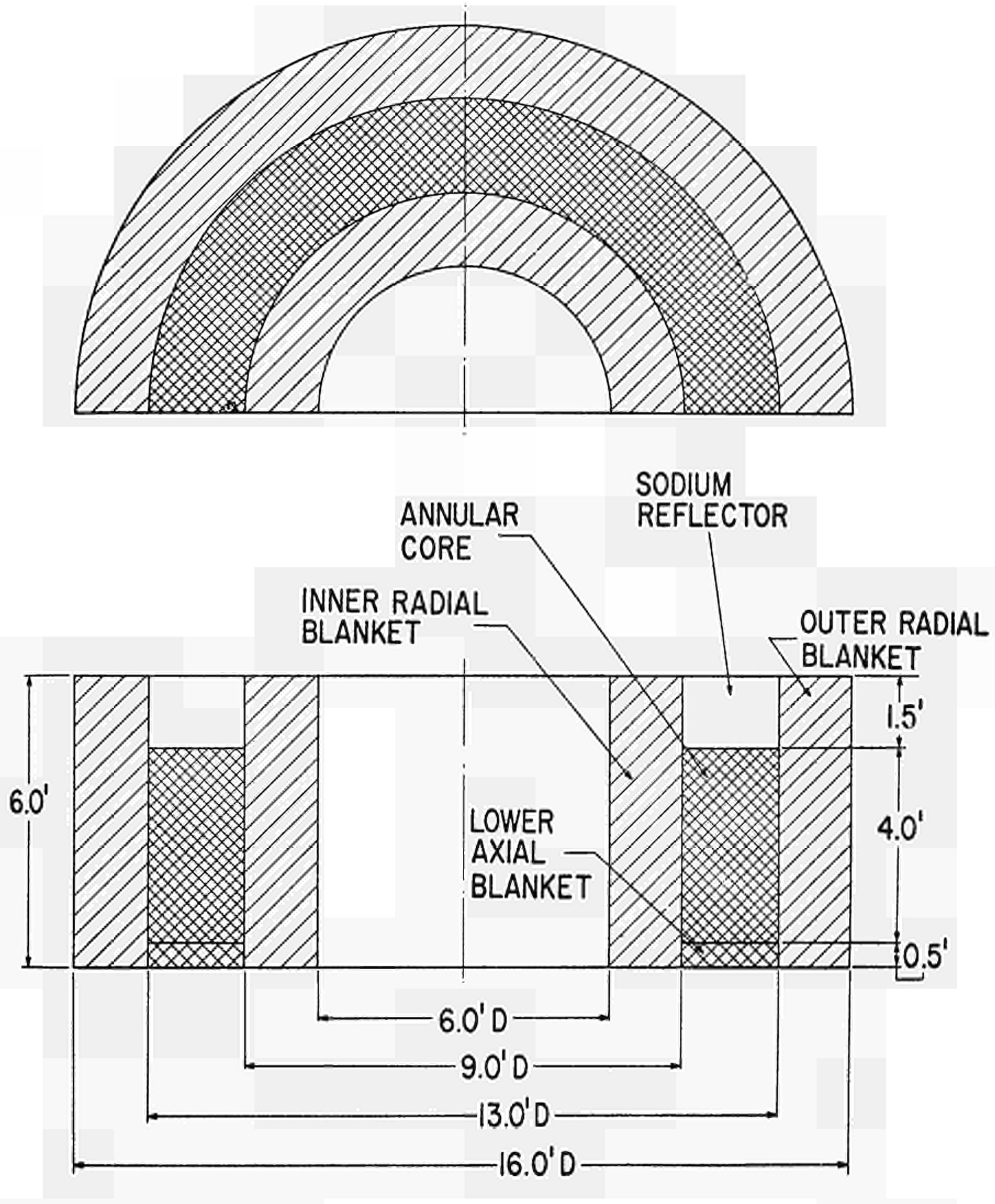
- doubling time : operating years : 18.4
- breeding ratio-core : 0.52)
radial blanket : 0.76)total 1.32
axial blanket : 0.04)

- fuel life, full power days : 836

<u>BIBLIOGRAPHY</u> :

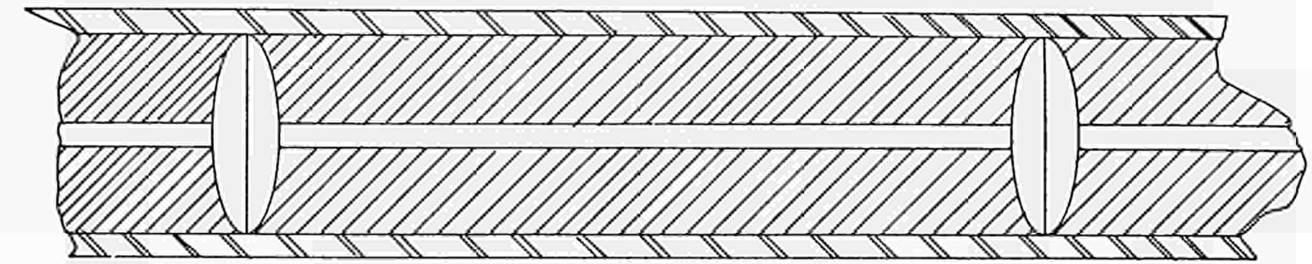
- Large Fast Reactor Design Study
AC NP - 64503
Allis-Chalmers, Atomic Power Development Associates
Babcock and Wilcox, Co. - January 1964

- Sodium Cooled Fast Breeder Reactors
L. J. Koch, F.S. Kirn et al - May 1964
A/ Conf. 28 / P/ 207

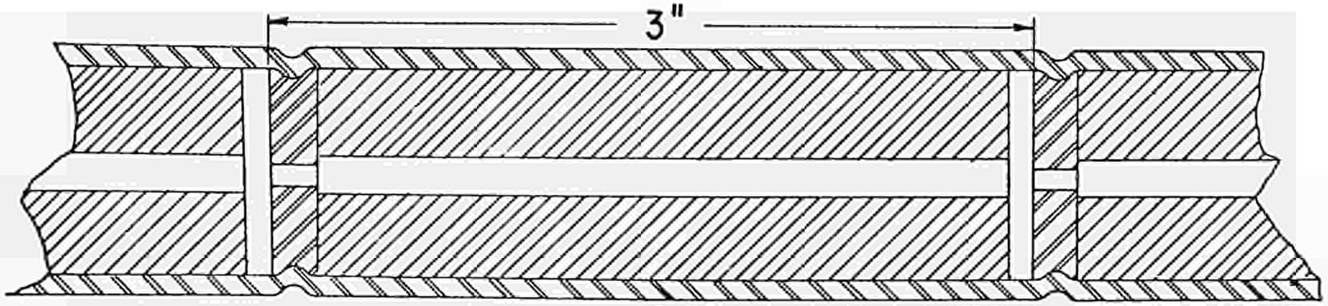


SIMPLIFIED CORE SECTION

FIG. 1.1



TYPICAL OXIDE FUEL CONSTRUCTION



COMPARTMENTED FUEL PIN (Reference)

FUEL-PIN CONSTRUCTION

FIG. 3.4

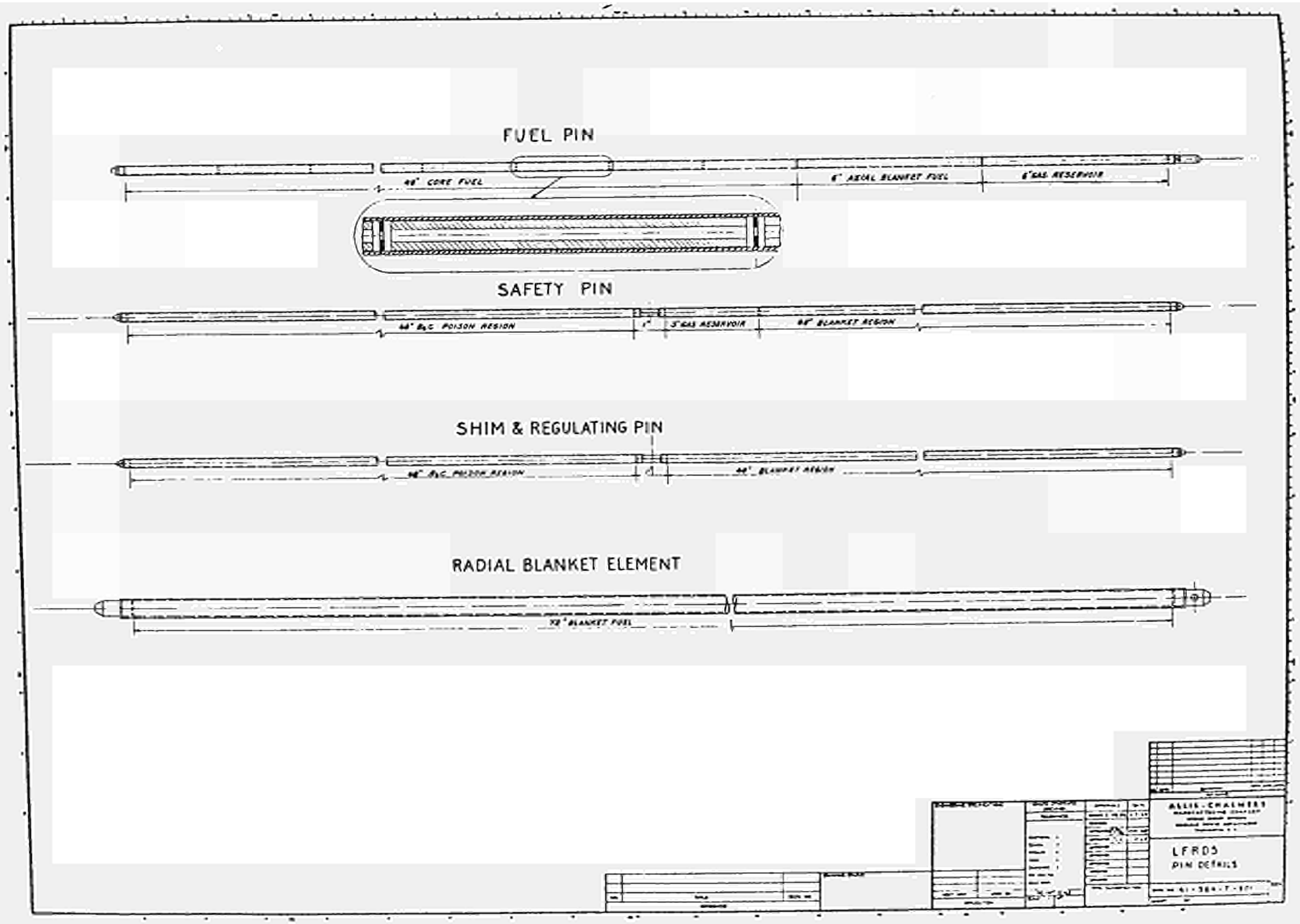

FUEL PIN
SAFETY PIN
SHIM & REGULATING PIN
RADIAL BLANKET ELEMENT
LFRDS
PIN DETAILS

FIG. 5.5

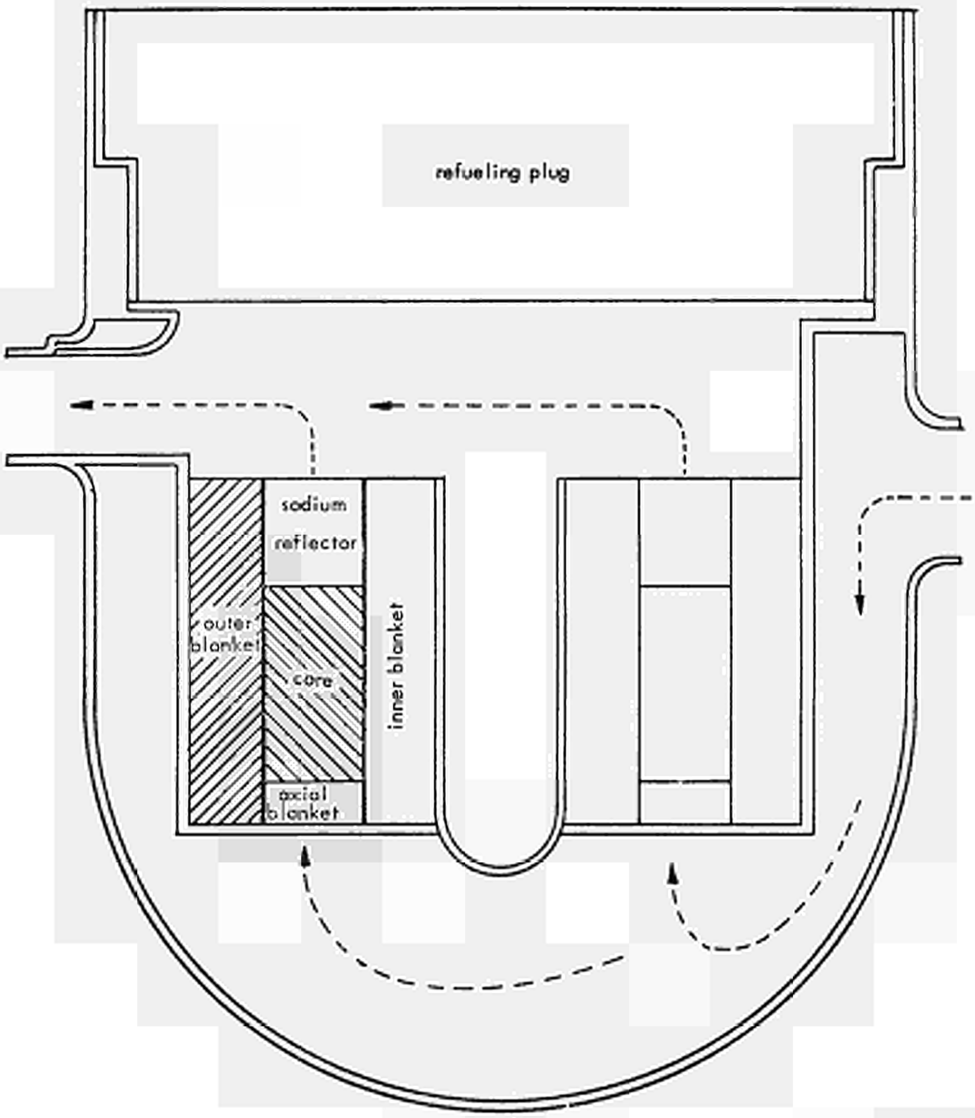


FIG. 1.3

REACTOR FLOW DIAGRAM

L M F R - COMBUSTION ENGINEERING

LIQUID METAL FAST BREEDER REACTOR DESIGN STUDY

1. Location : U.S.A.

2. Owner : United States Atomic Energy Commission

3. Main contractors :

   Combustion Engineering, Inc.

4. Present status and construction schedule :

   Study

5. Reactor type : A sodium-cooled fast reactor which operates at 2500 MW thermal power generation, 1060 MW net electrical power with a net efficiency of 42.4 percent.
   Fuel : UC-PuC.
   The sodium outlet temperature is 1100°F, to produce steam at a temperature of 1000°F.

6. Purpose : The primary objective of the present study was to develop a conceptual design of a large sodium cooled fast breeder reactor of a nominal electrical rating of 1000 MW operating on the Uranium-Plutonium cycle.

7. Power :

   - thermal : 2500 MW (core : 1,868 MW
     (control assemblies : 65 MW
     (axial blanket : 210 MW
     (radial blanket : 358 MW

     average specific : power , KW/kg (U + Pu) :
     - core : 210
     - control assemblies : 95
     - axial blanket : 19
     - radial blanket : 13

   - electrical : 1060 MW net

8. Fast flux :

9. Fuel :

a) Core :

- Composition : A solution of 15 w/o PuC in UC.
The hyperstoichiometric UC contains 4.8 w/o carbon (fuel density : 13.46 gm/cm^3).

- shape and dimensions : rod : length of rod : 82-1/4 in.) 0.301 in.) cylindrical rods

pellet : diam. : 0.259 in.

The pellet column is comprised of 3 main sections. The upper and lower 18 in. long axial blankets are of depleted UC. The 30 in. long central core section is of PuC-UC.

- number : number of fuel rods per assembly : 169

number of fuel bundles : 157

- critical mass :

- cladding : clad thickness : 0.011 in.
type : 19-9 DL stainless steel

b) Blanket :

- Composition : UC

- shape and dimensions :

	axial blanket	radial blanket
rod diameter :	0.259 in.	0.396 in.
clad i.d. :	0.279 in.	0.418 in.
clad thickness :	0.011 in.	0.016 in.
number of rod per assembly :	169	127

10. Control : The 12 control assemblies provide the required shim and shutdown control of the reactor. Each assembly is comprised of 127 rods. The rods consist of depleted UC pellet topped with a 20 in. column of B_4C-pellets, all inside a stainless steel clad. Sodium provides a thermal bond between the pellets and cladding.

type : Boron carbide followed by blanket material
shape : hexagonal
length of poison section : 20 in.
length of blanket section : 50 in.
control rod life at 0.8 power factor : 2 years.

The drive mechanisms (number : 12) are electrically driven and mowe the control assemblies through a total distance of 25 in.

- control rod worth : all rods : 4.0% Δ K/K
  maximum worth, any one rod :0.36% ΔK/K

11. Reflector :

12. Shielding : The radial portion of the shield is composed of :

- steel members, internal to the reactor vessel wall which are cooled by sodium
- borated graphite which is cooled by conduction to the vessel wall
- graphite and borated graphite
- concrete

The blanket of the reactor itself acts as a very effective shield.

13. Geometric dimensions :

a) Core : A right circular cylinder, 30 in. high and 86-1/2 in. in diameter.

volume : 2,900 liters (% fuel : 25.6
(% sodium : 66.5
(% structure : 7.9

b) Blanket : The axial blanket extends 18 in. above and below the core. The radial blanket surrounds the core and is essentially cylindrical in shape, 54 in. high and 120 in. in outer diameter.

c) Vessel : The reactor vessel is fabricated of relatively thin type 316 stainless steel.

i.d. : 16 ft 6 in.
height : 40 ft 7 in.
max. thickness : 3 in.

14. Temperatures :

a) Core : max. clad temperature : 1400 °F
allowable clad temperature : 1400 °F
max. fuel temperature : 2600 °F

b) Blanket :

15. Coolant : nature : sodium
total flow rate : 113.6 x 10^6 lb/hr
total pressure drop : 60 psi
coolant velocity (max.) : 23.4 ft/sec.
temperatures : sodium outlet : 1,100 °F
sodium inlet : 850 °F

15. bis Thermal system and turbine plant :

Primary sodium system :

number of loops : 6
number of pumps : 6
number of cold traps : 3
Piping size : 30 in. and 36 in.
system material : SS

Intermediate sodium system :

number of loops : 6
number of pumps : 6
number of cold traps : 3
piping size : 28 in.
total flow rate : 94.2 x 10^6 lb/hr
total pressure drop : 60 psi

Primary sodium pumps :

type : centrifugal , free surface, with variable speed drive
flow : 6 x 8,500 m^3/hr

Primary coldtraps :

type : forced circulation with economizer

Intermediate heat exchangers :

type : shell and tube, single pass, hotter fluid in shell.
number : 6
capacity : 416.7 MW each
number of tubes : 3440 each
heat transfer area : 12, 110 ft^2 each

Steam generator :

type : Multi-shell, V-bend, once through, hotter fluid in shell
number : 2
capacity : 1,059 MW each
number of tubes by shell : 7
number of shells : 980
heat transfer area : 52, 184 ft^2 each

Reheater :

type : multi-shell, V-bend, single pass, hotter fluid in shell
number : 2
capacity : 190.5 MW each
number of tube per shell : 7
number of shells : 473
heat transfer area : 33, 364 ft^2 each

Turbine plant :

Steam is brought to the turbine throttle at 1000°F and 2400 psig and reheated to 1000°F after partial expansion. The turbine-generator is a cross-compound quadruple flow machine with 50 in. final blading.

condenser pressure : 1.5 in. Hg Abs.
stages of feedwater heating : 6
final feedwater temperature : 575°F
gross turbine output : 1 122 MW
gross heat rate : 7600 BTU/ KWH (449%)
net heat output : 1061 MW
net heat rate : 8050 BTU/KWH (42.4%)

16. Physical data :

- effective delayed neutron fraction : 0.0040

- maximum fresh fuel element worth, reactivity : 0.33% Δ K/K
- Doppler effect :

  Doppler coefficient at operating temperature : $- 2.5 \times 10^{-6} \Delta K/^\circ F$

  Doppler reactivity between operating temperature and impending damage : 0.17% ΔK/K

- temperature coefficient , core only : $3.8 \times 10^{-6} \Delta K/^\circ F$
- breeding ratio (equilibrium reactor)
  total reactor : 1.421
  total core : 0.648
- doubling time : 6.9 years
- subassembly life : 1.8 years
- refuelling interval : 0.22 years

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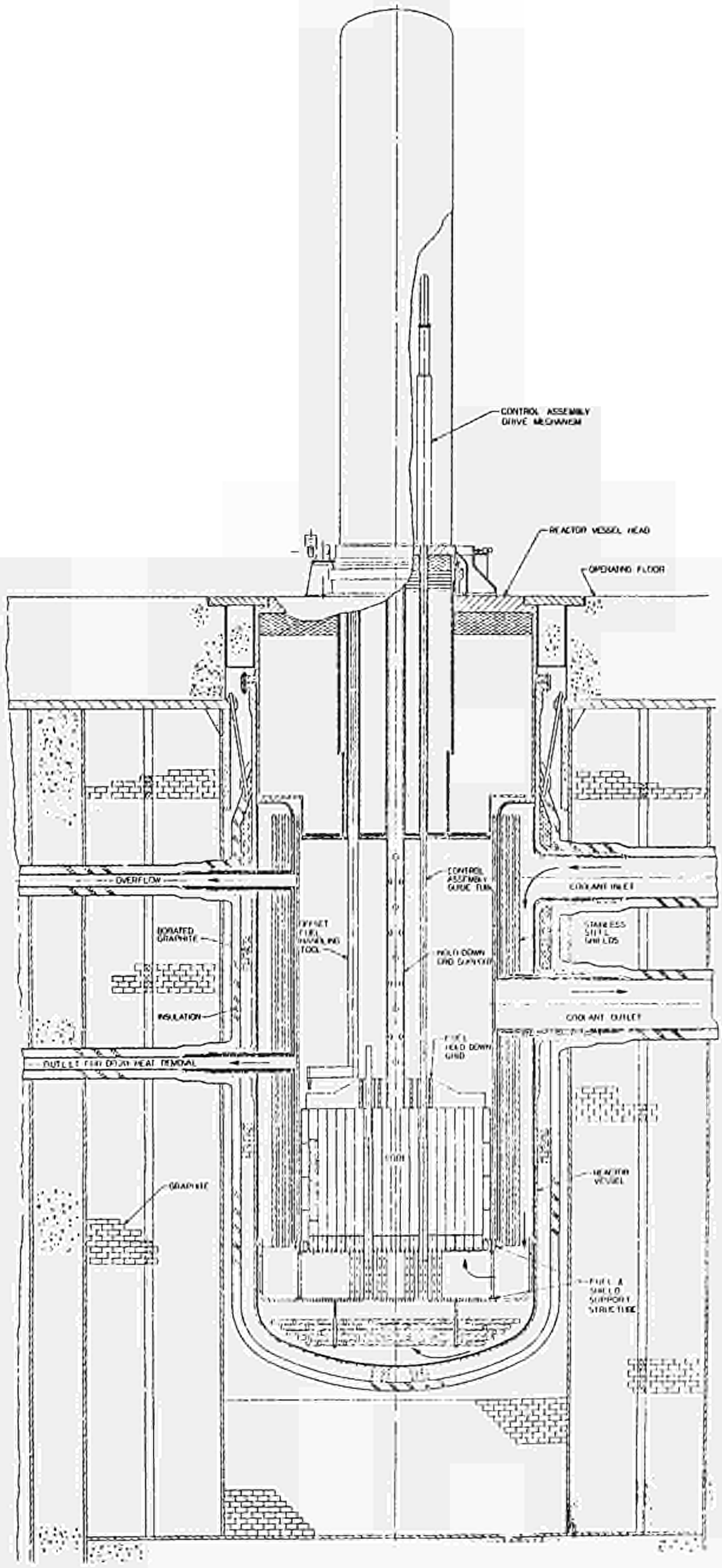
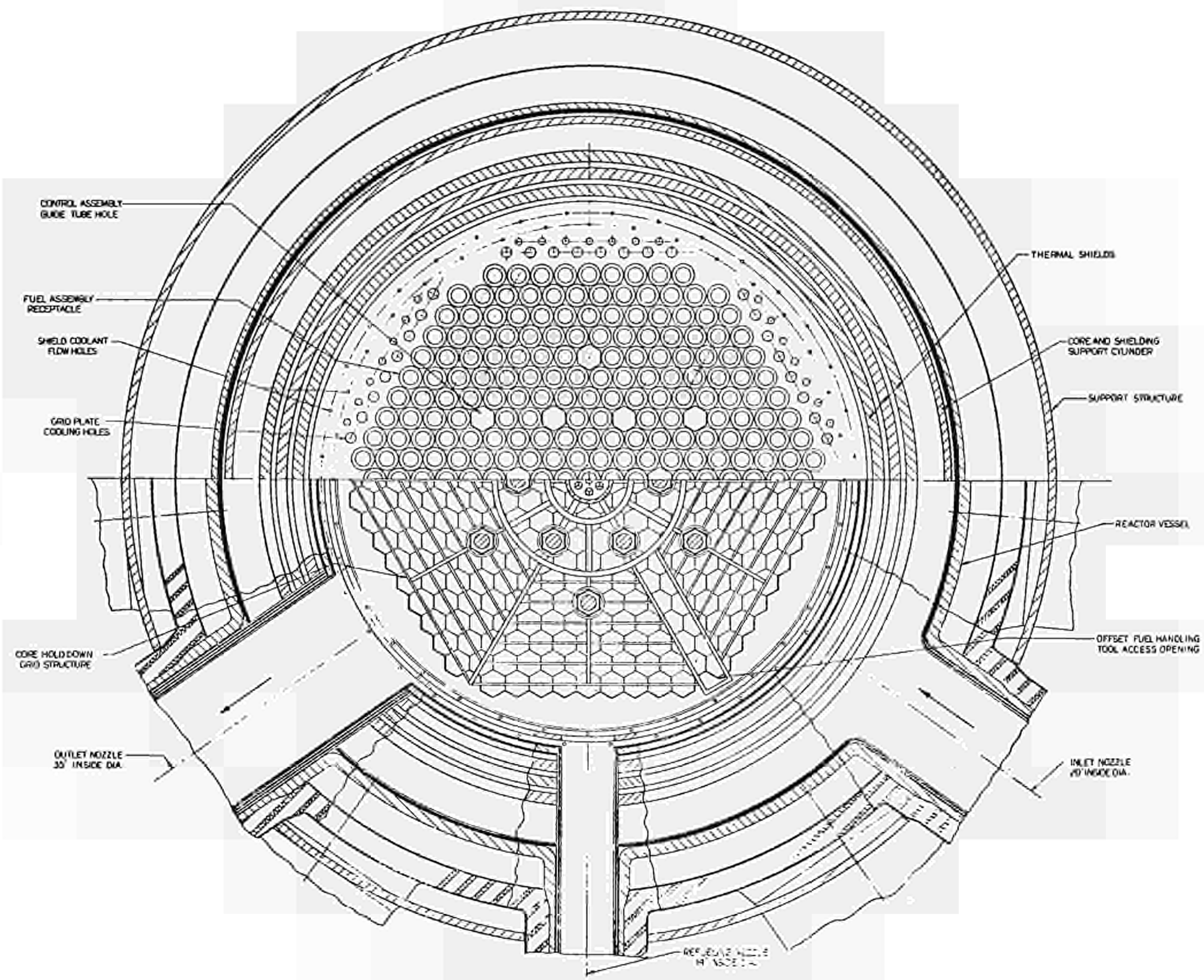
  Liquid metal fast breeder reactor design study
  Combustion Engineering - Janurary 1964

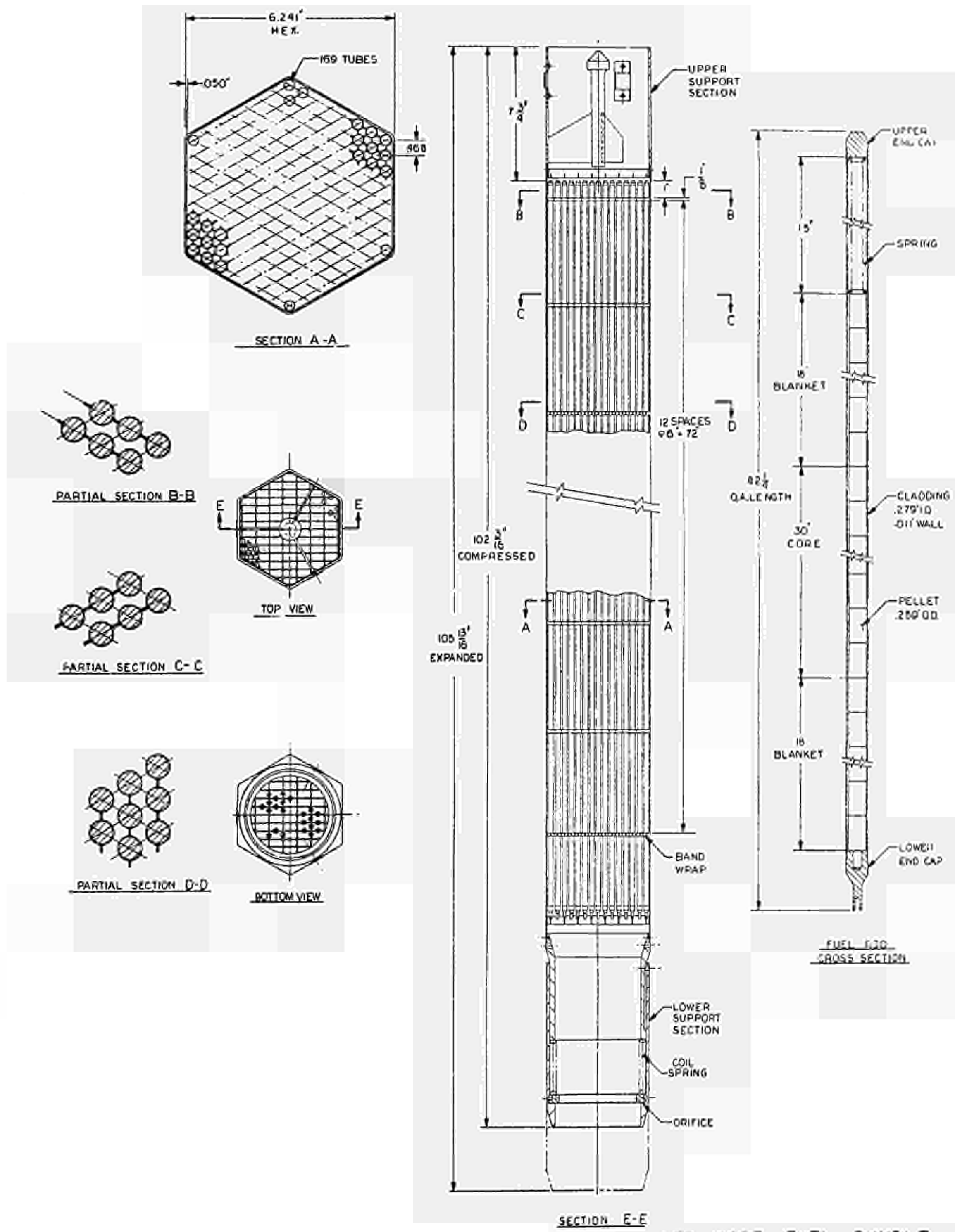
- A/Conf. 28/ P/ 207
  Sodium cooled fast breeder reactors
  L.J. Koch, F.S. Kirn et al - May 1964



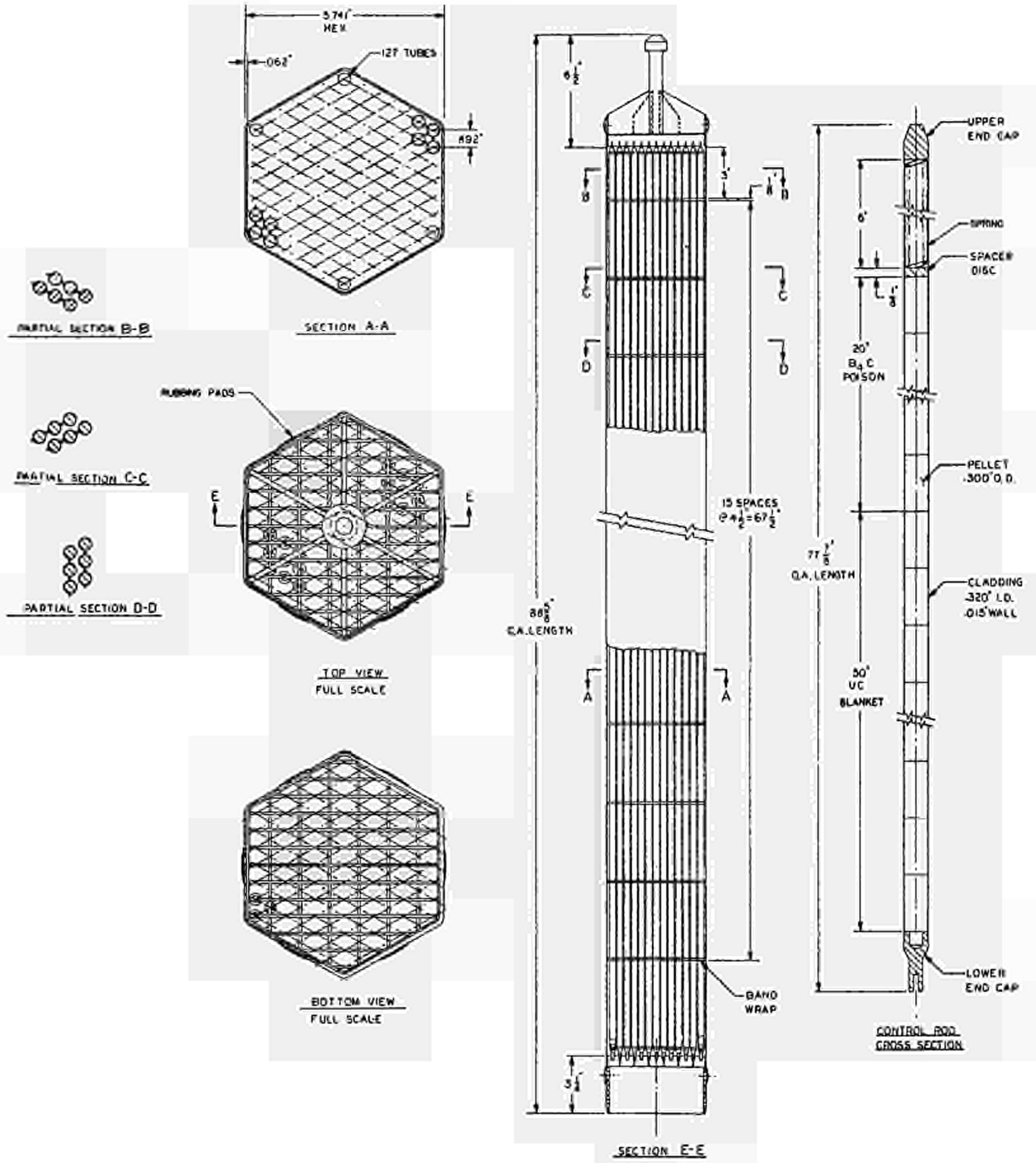
CONTROL ASSEMBLY DRIVE MECHANISM
REACTOR VESSEL HEAD
OPERATING FLOOR
OVERFLOW
CONTROL ASSEMBLY GUIDE TUBE
COOLANT INLET
STAINLESS STEEL SHIELDS
BORATED GRAPHITE
OFFSET FUEL HANDLING TOOL
HOLD DOWN GRID SUPPORT
INSULATION
COOLANT OUTLET
FUEL HOLD DOWN GRID
OUTLET FOR DECAY HEAT REMOVAL
CORE
GRAPHITE
REACTOR VESSEL
FUEL & SHIELD SUPPORT STRUCTURE



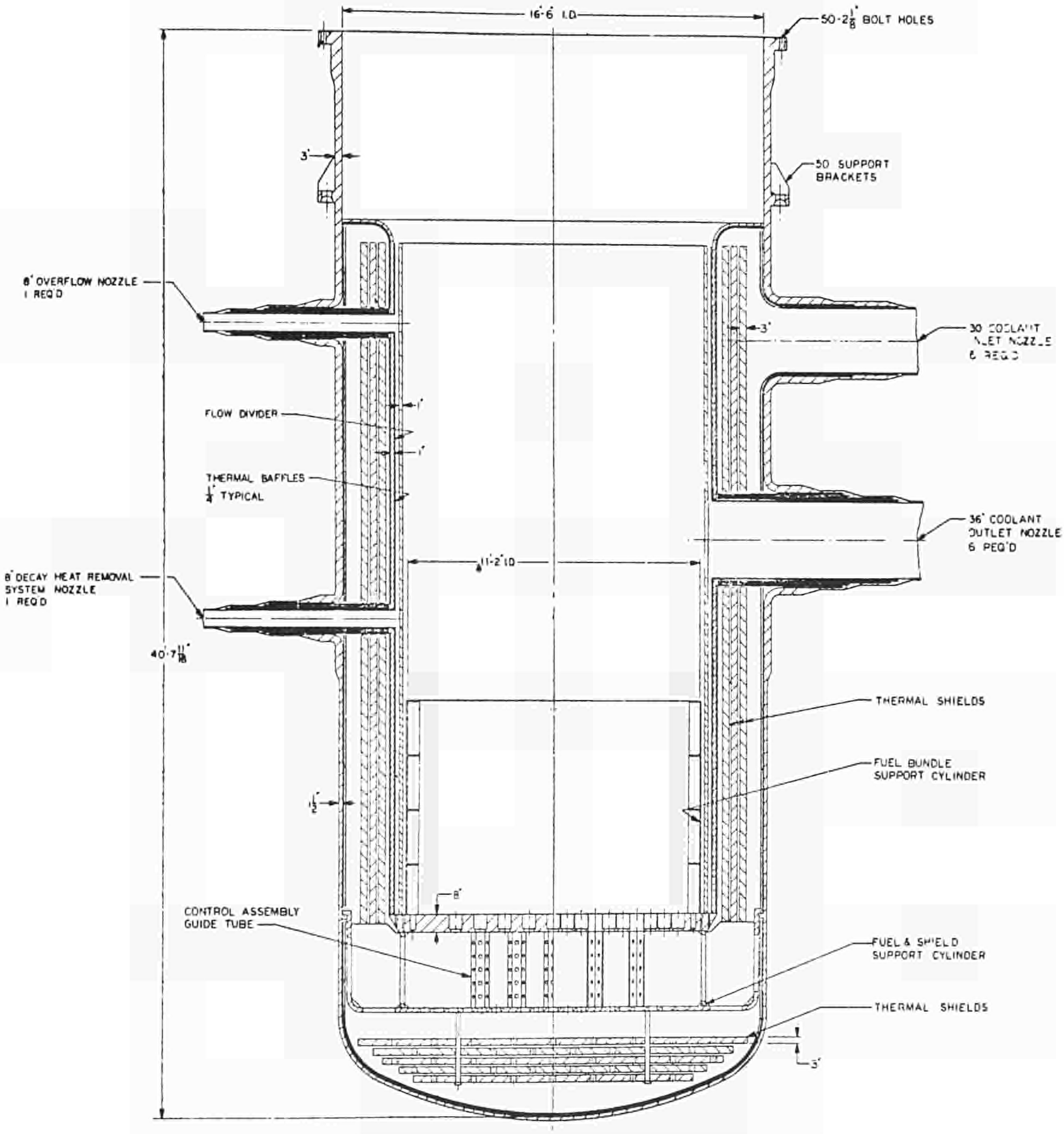
LFR REACTOR ARRANGEMENT - CROSS SECTION
Figure III-3



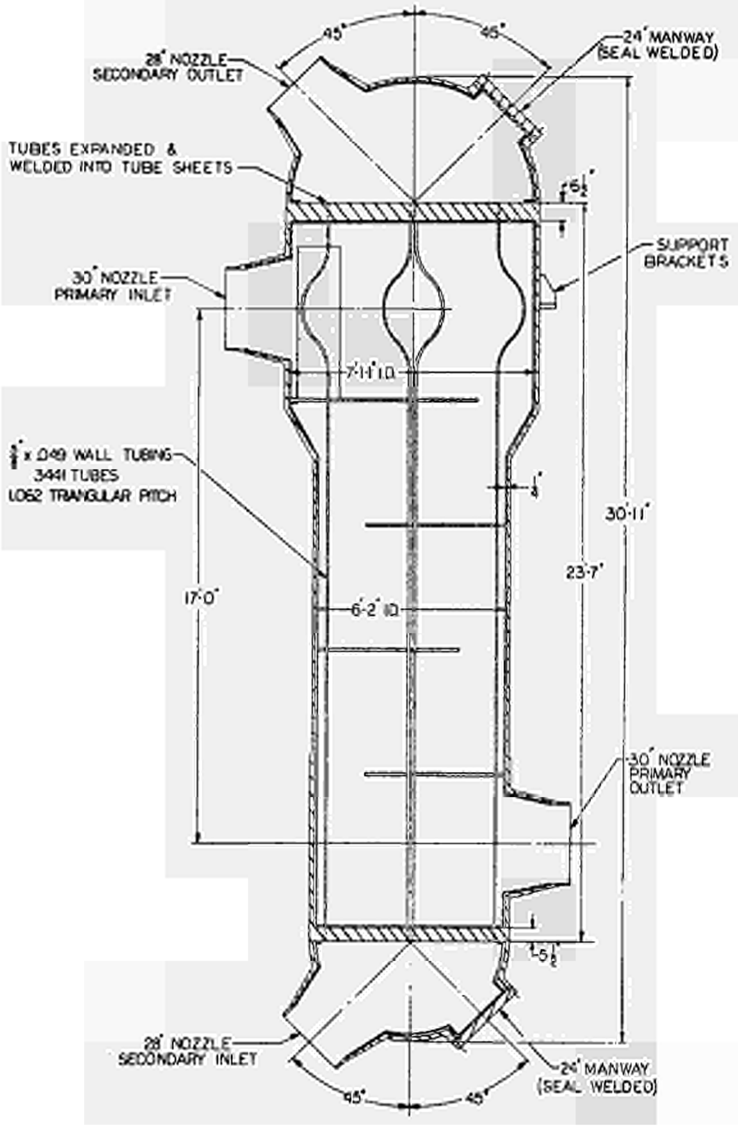
LFR CORE FUEL BUNDLE
Figure III-5



LFR CONTROL ASSEMBLY
Figure III-9



LFR REACTOR PRESSURE VESSEL ASSEMBLY
Figure III-7



LFR INTERMEDIATE HEAT EXCHANGER
Figure III-19

L M F R - GENERAL ELECTRIC

LIQUID METAL FAST BREEDER REACTOR DESIGN STUDY

1. Location : U.S.A.

2. Owner : United States Atomic Energy Commission

3. Main contractors :

   General Electric

4. Present status and construction schedule :

   Study

5. Reactor type : A single sodium cooled reactor unit of 2500 MWt rating. Sodium leaving the reactor core at a mean exit temperature of 1100°F transfers heat to nonradioactive sodium in 6 secondary coolant loops. The reactor is fueled with stainless steel clad mixed uranium, plutonium oxide in the form of fuel pins.

6. Purpose : The purpose of the study by General Electric for the AEC has been to do conceptual design work on a mixed plutonium-uranium oxide fueled reactor consistent with the latest research and development information and to evaluate its potential performance in the 1000 MWe size range.

7. Power :

   - thermal : 2500 MW (core : 2200
     (blanket axial : 250
     (blanket radial : 50

     average core power density : 365 KW/liter
     specific power for fuel cycle : ~ 900 KW/kg fissile Pu

   - electrical : net 1100 MW

8. Fast flux :

9. Fuel :

a) Core :

- Composition : Each fuel assembly consists of a fuel region (UO_2 + PuO_2), upper axial blanket (UO_2), lower axial blanket (UO_2), fission gas reservoir and neutron shielding.

- shape, dimensions and number :

  number of core fuel assemblies : 225
  number of fuel rods per assembly : 478
  number of BeO rods per assembly : 138
  number of filler rods per assembly : 7
  number of neutron shield rods : 17

  over-all assembly length : 23 ft
  fuel length : 24 in.
  blanket length : 2 x 18 in.
  fission gas reservoir : 36 in.
  fuel extension and shield : 12 ft

- cladding : 316 stainless steel
  fuel clad O. D. : 0.25 in.
  clad thickness : 15 mils
  over-all clad length : 8 ft

b) Radial Blanket :

- Composition : Uranium Oxide (depleted)

- shape, number and dimensions :

  number of blanket assemblies : 108
  number of fuel rods per blanket assembly : 208
  active length of rods : 30 in.
  Uranium oxide diameter : 0.45 in.

- cladding : 316 stainless steel
  clad O.D. : 0.5 in.
  clad thickness : 20 mils

10. Control : Each of the 85 control rods consists of a 2-foot-long annular boron carbide poison section, a 2-foot-long plenum and a 35-foot-long connecting rod.

The drives are connected to the control rods by grippers-A-Rack-and-pinion drive is the prime mover of the control rod.

- control rod pitch : 15.4 in.
- guide tube O.D. : 2.34 in.
- I.D. : 2.10 in.
- control rod O.D. : 2.00 in.
- clad thickness : 0.050 in. (316 stainless steel)
- control material - B_4C -smeared density : 75%
  B_{10} - enrichment : natural
- active B_4C length : 2 ft
- normal control travel : 3.5 ft

11. Reflector :

12. Shielding : Personnel dose rate on the operating floor above the primary tank and during refueling and fuel handling is limited to 2.5 mrem/hr. This requires the following :

	steel	concrete
operating floor (at full power)	5 in.	3 ft (high density)
refueling room walls :	12 in.	3.5 ft (high density)
fuel transfer room walls :	12 in.	2 ft (high density)
radial neutron shield thickness :	2 ft	

13. Geometric dimensions :

a) Core : active core height : 2 ft
active core diameter : 11.65 ft
core volume : 213 ft^3

b) Blanket : axial blanket thickness (upper and lower) : 1.5 ft
axial blanket volume : 319 ft^3
radial blanket height : 2.5 ft
radial blanket thickness : 1.26 ft
radial blanket volume : 148 ft^3

c) Vessel : diameter of reactor vessel : 18 ft
height of reactor vessel : 33 ft
thickness : 2 in.
material : stainless steel (type 304)

14. Temperatures :

a) Core : maximum fuel temperature : 4700°F
fuel surface temperature point of max. rating : 2165°F
average clad temperature : 1030°F
average structure temperature : 950°F

b) Blanket :

15. Coolant : nature : sodium : reactor grade

Na_2O : 5 ppm

carbon < 10 ppm

coolant inlet temperature : 800°F
outlet temperature : 1100°F
coolant flow : 95.4×10^6 lb/hr

core inlet pressure : 50 psia
core outlet pressure : 25 psia
max. coolant velocity in core : 13.6 ft/sec

15. bis Thermal systems and turbine plant :

The 6 outlet ducts at the top end of the reactor vessel lead to 6 intermediate heat exchangers operating in parallel. Coolant discharge from the exchangers at approximately 800°F flows to the inlets to the 6 centrifugal pumps also operating in parallel.

Steam is raised at 3500 psia, 1000°F in six parallel units and flows to a single cross compound reheat turbine unit.

Heat removal equipment :

number of circuits : 6

total surface area intermediate heat exchanger :	91 ft^2 $\times 10^3$
pumping power - primary circuit	6.8 MW
- intermediate circuit	4.2 MW

steam - pressure (turbine stop valve) : 3500 psia
- temperature : 1000°F
- heat : 1000°F
- feed temperature : 500°F

mean Δ T-intermediate heat exchanger : 63.8°F
- steam generator : 150°F
- reheater : 115°F

heat loads - intermediate heat exchanger : 86×10^3 BTU/hr
- boiler : 71.8×10^3 BTU/hr
- reheater : 14.2×10^3 BTU/hr

Power plant :

Turbine heat rate : 7570 BTU/KW/hr
steam flow : 7.64×10^6 lb/hr
condenser pressure : 1.5 in. hg
heat rejection : 5.0 BTU/hr 10^9
auxiliary power required (excludes boiler feed pump) : 6 MW

boiler feed pumps (turbine driver) : 32 MW
plant net efficiency : 44%

16. Physical data :

Neutron lifetime ; sec. : 5.7×10^{-7}
β eff. (effective fraction of delayed neutron): 3.3×10^{-3}
over-all temperature coefficient :

$$-7.2 \times 10^{-6} \frac{\Delta k}{k} /°F$$

over-all power coefficient : $-0.0073 \frac{\Delta k}{k}$ per $\frac{\Delta P}{P}$

breeding ratio : 1.257
doubling time for fuel cycle : 13.5 years
mean lifetime of core fuel : 943 days
radial blanket lifetime : 4.6 years

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- GEAP - 4418
  Liquid metal fast breeder reactor design study
  General Electric Co. - January 1964

- A/Conf. 28/ P/ 207
  Sodium cooled fast breeder reactors
  L.J. Koch, F.S. Kirn et al - May 1964

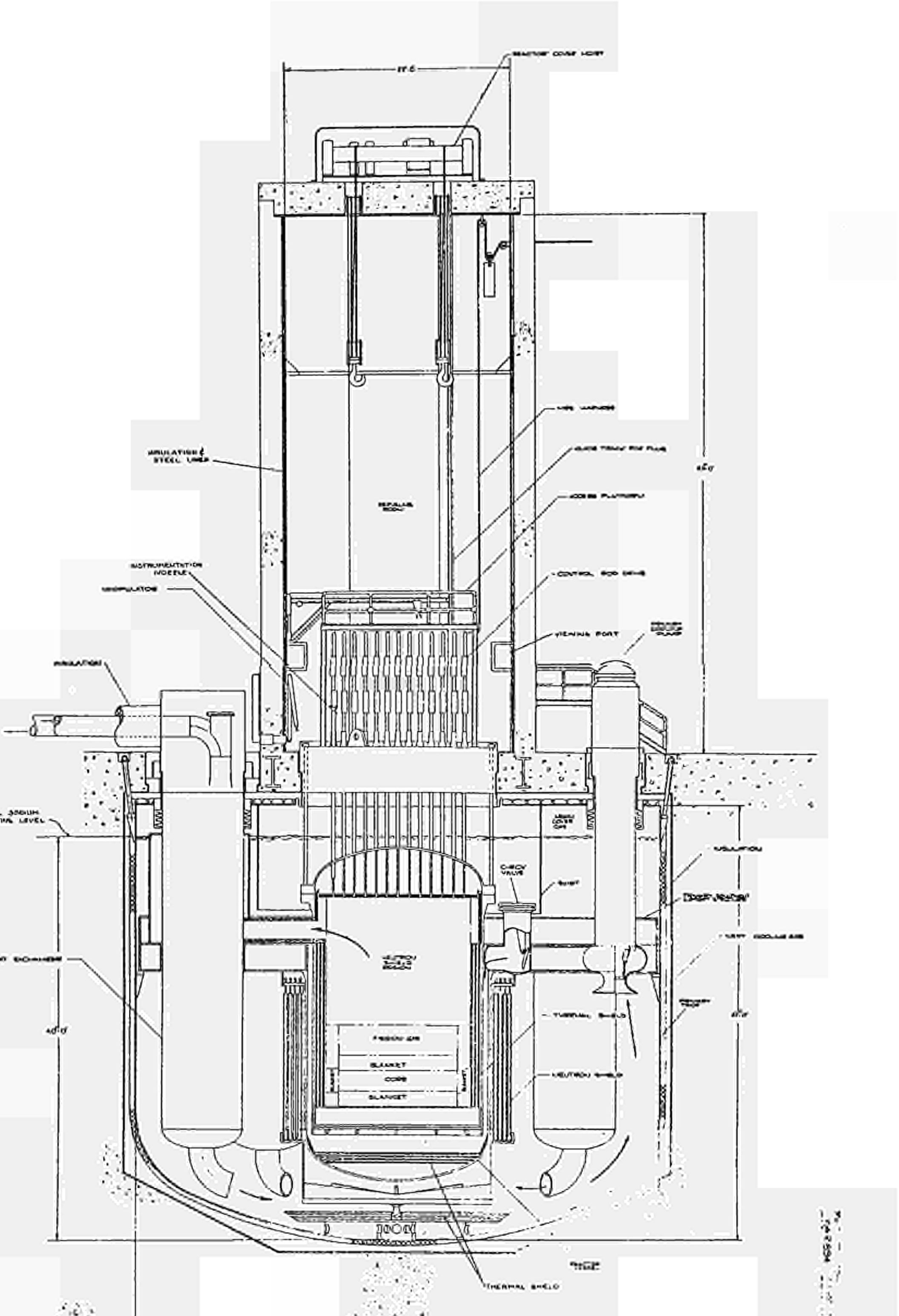

Figure 2.1. Elevation of Reactor System

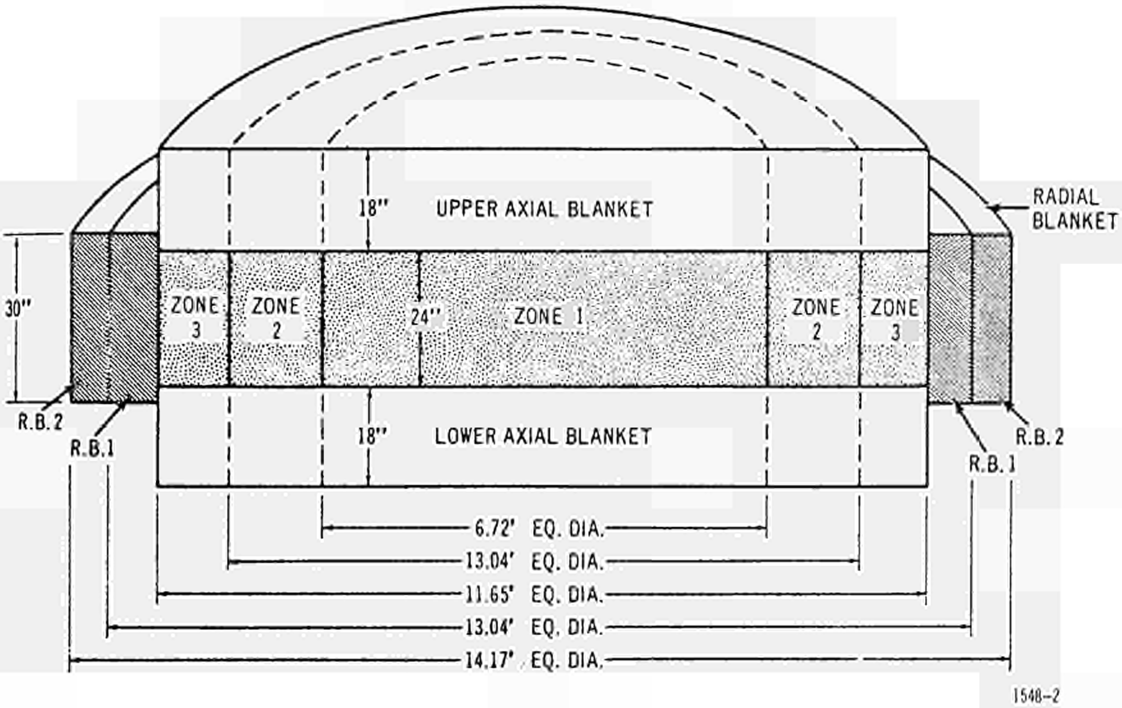

Figure 2.2.1.1. Core and Blanket Arrangement

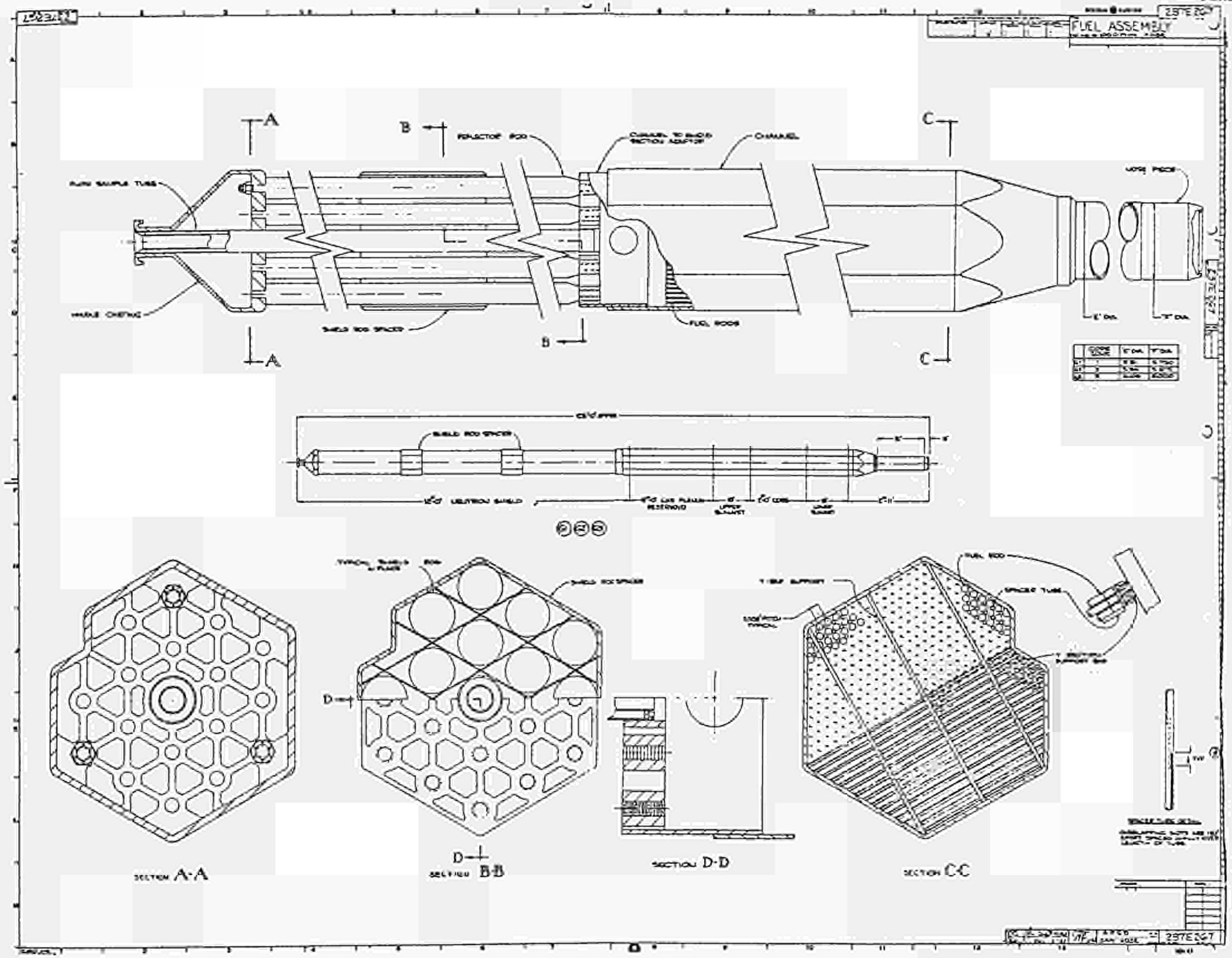

Figure 2.2.2. Fuel Assembly

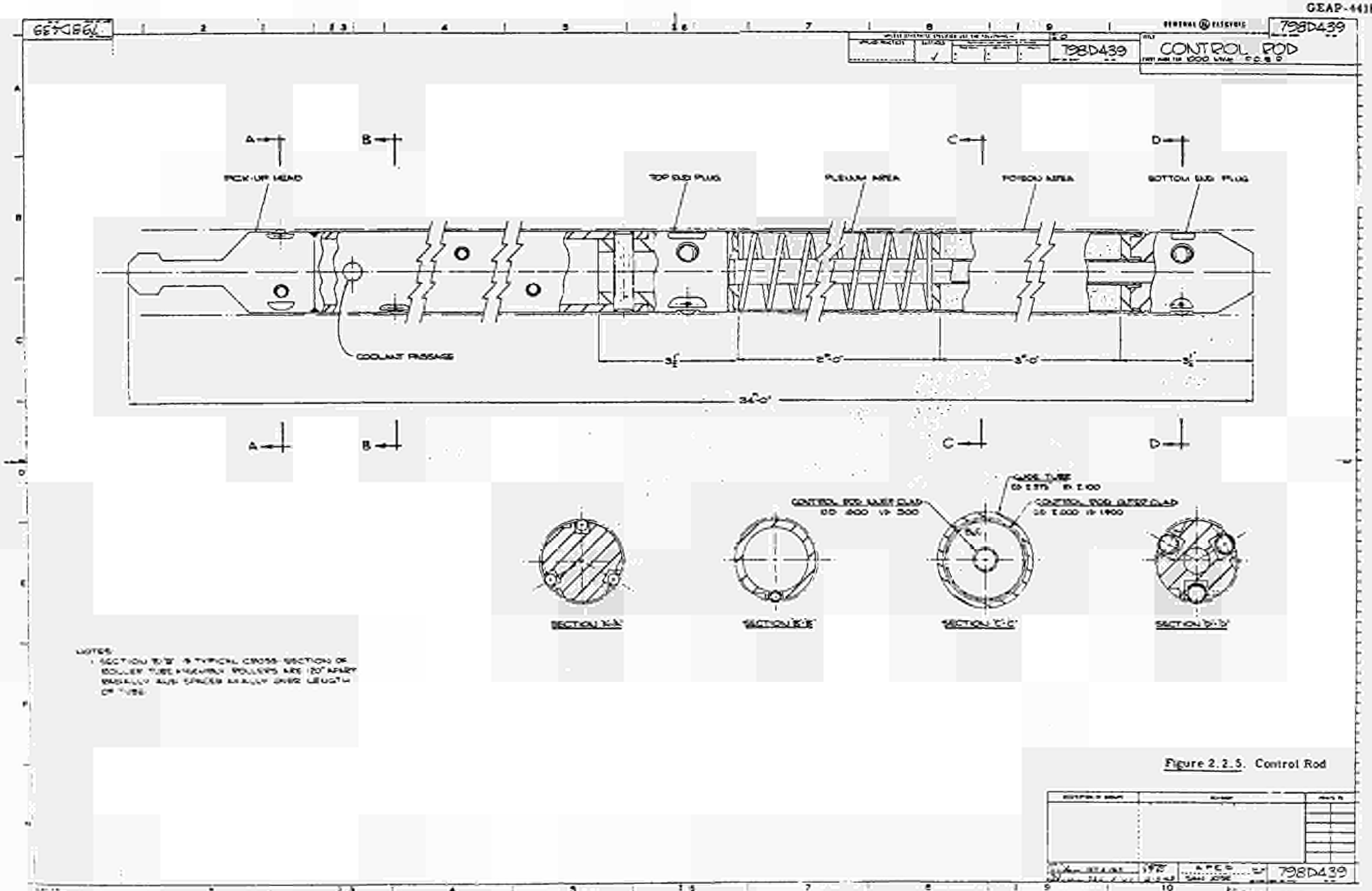

Figure 2.2.5. Control Rod

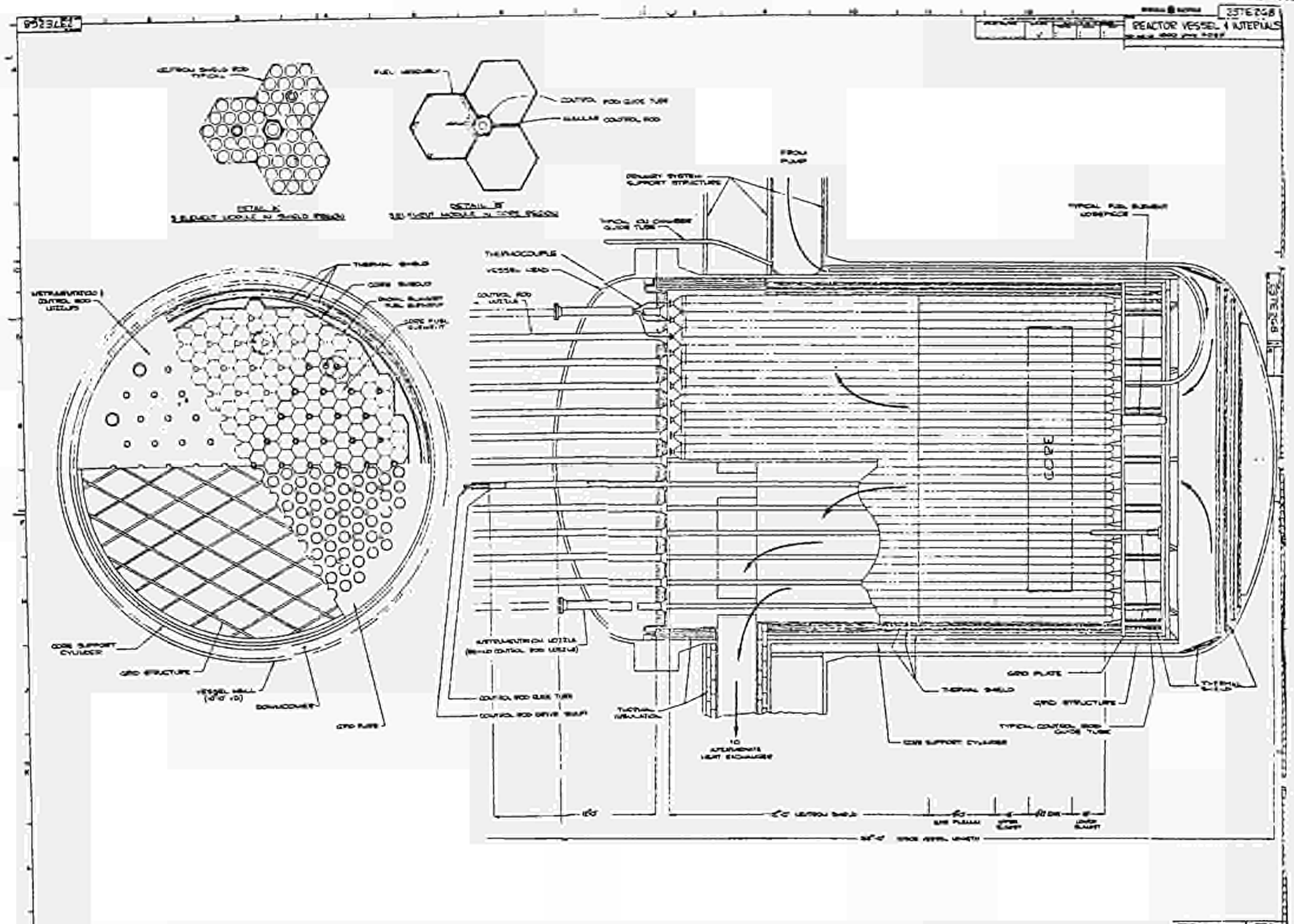

Figure 2.3.2. Reactor Vessel and Intervals

L M F R - WESTINGHOUSE ELECTRIC CORPORATION

LIQUID METAL FAST BREEDER REACTOR DESIGN STUDY

1. Location : U. S. A.
2. Owner : United States Atomic Energy Commission
3. Main contractors :
   Westinghouse Electric Corporation
4. Present status and construction schedule :
   Study
5. Reactor Type : This fast breeder reactor conceptual design is based on plutonium-uranium carbide fuel with a breeding ratio of 1.57 and a doubling time of 10.5 full power years, coolant : sodium.
6. Purpose : The first objective of this study is to develop the technology necessary to produce economic electric power and to conserve the supply of nuclear material.
7. Power :
   - thermal : Total thermal : 2500 MW (core regions : 2170
     (blanket regions : 330
     power density , KW/liter (core) : 308
     specific power , KW/kg contained fuel (Pu, U)C :86.2
   - electrical : 1000 MW
     net electrical efficiency (40%)
8. Fast flux :
9. Fuel :
   a) Core :
   - Composition : UC, 22.2% PuC
     Fraction fissile material (fissile /U+Pu) : 0.1557

- shape and dimensions : shape of fuel assembly : hexagonal
  fuel rod O.D. : 0.300 in.
  fuel pellet diameter : 0.268 in.

- number : number of modules : 7
  number of fuel assemblies per module : 36
  fuel rods per assembly : 120
  cermet rods per assembly : 7

- cladding : clad material : 316 L SS
  type of fuel clad bond : sodium
  clad thickness : 0.010 in.
  clad O.D. : 0.300 in.

- weight of fuel (carbide) : 25,200 kg

b) Blanket :

- Composition : (axial blanket UC (depleted)
  (radial blanket UO_2 (depleted)

- shape, dimensions and number :

  shape of fuel assembly : hexagonal
  pellet diameter : 0.460 in.
  number of fuel assemblies (radial blanket): 357
  rods per fuel assembly : (axial blanket): 120
  (radial blanket): 91

- cladding : clad material : 316 L SS
  clad thickness (radial blanket) : 0.020 in.
  clad O.D. : 0.465 in.

10. Control : The control rod element consists of an array of 61 tubes occupying one full-sized flow channel in the core. The control channel consists of a heavy walled hexagonal tube 0.093 in. thick and approximately two core lengths long, resting in the lower core plate.

A 61-rod array 6 feet long contains about 54 lb of absorber (material B_4C powder) at 64% density.

11. Reflector : Radial graphite reflector (material): Na, SS, C)
radial and axial reflector (material : Na, SS)

12. Shielding :

Secondary shield :

57 in. of ordinary concrete surrounding the reactor coolant loop components.

Radial shield and shield tank :

borated graphite, thickness : 3 ft
carbon steel, thickness : 1/4 in.
outside diameter : 26 ft
nominal height : 35 ft

Shield plug :

borated graphite, carbon and stainless steels
maximum diameter : 15 - 1/2 ft
minimum diameter : 14 - 1/2 ft
thickness : 3 ft

13. Geometric dimensions :

a) Core :

active core height : 6.25 ft
number of modules : 7
module height : 8.5 ft
module diameter (across flats) : 4.5 ft

composition :

sodium : 55.1 %
fuel : 29.4 %
steel : 15.5 %

Core volume : 7,050 liters

b) Blanket :

axial blanket thickness (upper and lower) : 12 in.
activeradial blanket length : 84 in.
radial blanket composition : (fuel : 54.5 %
(sodium : 25.8%
(steel : 19.6%
(void : 0.1%

c) Vessel :

height : 33 1/2 ft
diameter outer : 18 ft
diameter inner : 15 ft
basic wall thickness : 1 1/2 in.
material : type 304 SS

14. Temperatures :

a) Core : core inlet : 979 °F
core average rise : 221 °F
maximum clad (outside) : 1400 °F
maximum fuel center line : 2184 °F) (100% power)
maximum cermet surface : 1325 °F)
maximum cermet center : 1450 °F)

b) Blanket : (radial)

blanket inlet : 979 °F
blanket average rise : 221 °F
maximum clad (outside) : 1400 °F
maximum fuel center line : 2519 °F

15. Coolant : nature : sodium
primary sodium flow : 128 x 10^5 lbs/hr
average velocity : 26.5 ft/sec
coolant velocity (max) : 31.8 ft/sec

coolant mass flow rate :

temperatures : sodium inlet : 979 °F
sodium outlet : 1200 °F
sodium outlet, hot channel : 1372 °F

15. Thermal systems and turbine plant :
BIS

The systems consists of two identical loops connected in parallel to the reactor vessel. Each loop contains two circulating pumps, an intermediate heat exchanger, the connecting piping.

Intermediate heat exchanger design data are :

heat duty : 4.265 x 10^9 BTU/hr
primary sodium flow/unit : 6.4 x 10^7 lb/hr
pressure drop (shell side) : 10 psi max.
design pressure : 150 psig
design temperature : 1250 °F
material : Austenitic stainless steel

Primary sodium circulating pumps design data are :
pump type : vertical centrifugal free surface
design flow : 80,000 gpm
drive : variable speed motor
fluid pumped : 1200°F sodium
volute material : Austenitic stainless steel
impeller material : Austenitic stainless steel

16. Physical data :

neutron lifetime : sec. : 1×10^{-7}
breeding ratio : 1.57
effective fraction of delayed neutrons : β eff : 0.04
core burnup : 100 MWD/kg
core inventory doubling time (85% load factor w/losses) : 9 years
total doubling time (14 months recycletime w/losses) : 12 years
fuel cycle days : 180

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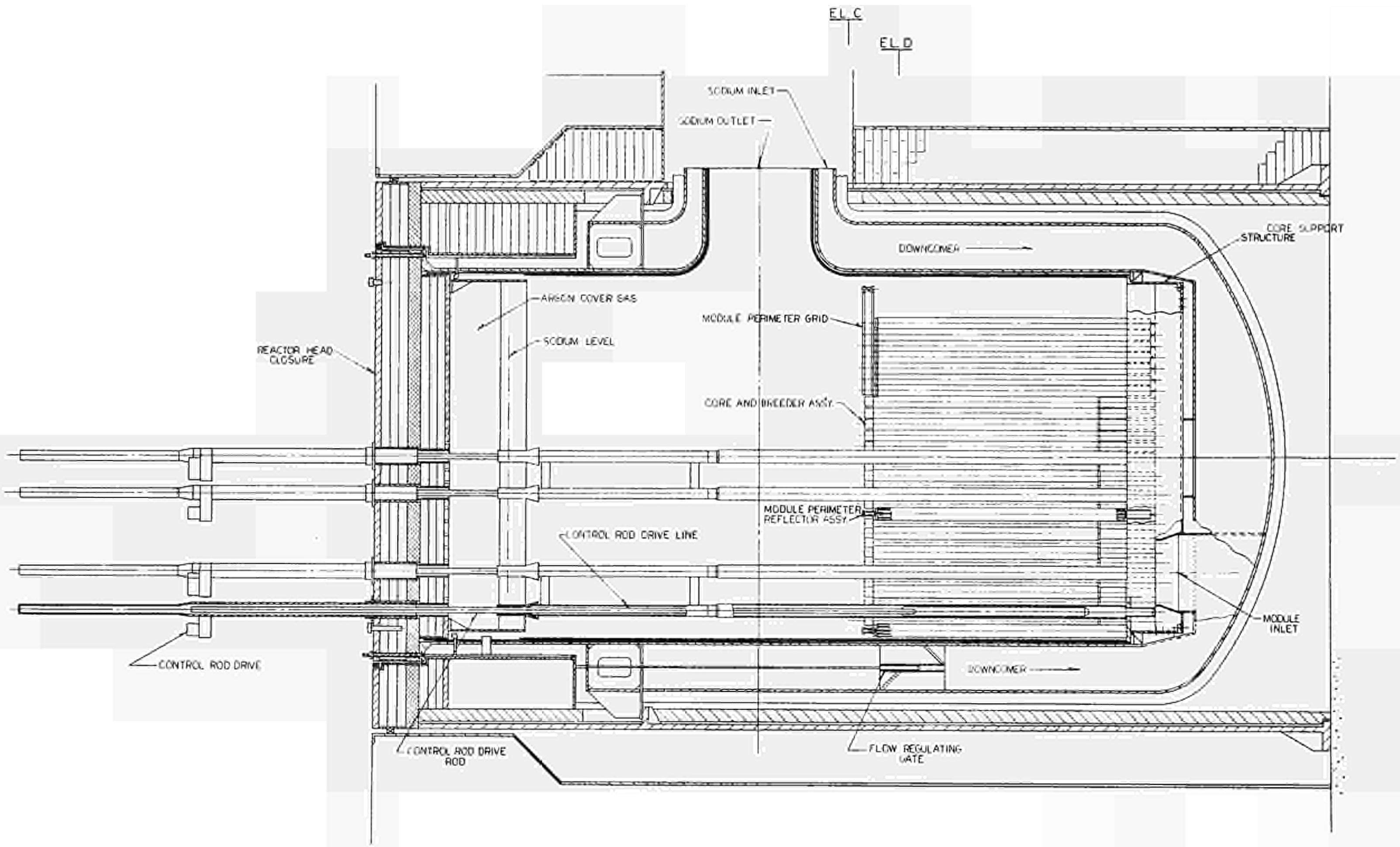
EL C
EL D
SODIUM INLET
SODIUM OUTLET
CORE SUPPORT STRUCTURE
DOWNCOMER
ARGON COVER GAS
MODULE PERIMETER GRID
REACTOR HEAD CLOSURE
SODIUM LEVEL
CORE AND BREEDER ASSY.
MODULE PERIMETER REFLECTOR ASSY.
CONTROL ROD DRIVE LINE
MODULE INLET
CONTROL ROD DRIVE
DOWNCOMER
CONTROL ROD DRIVE ROD
FLOW REGULATING GATE

SECTION A-A

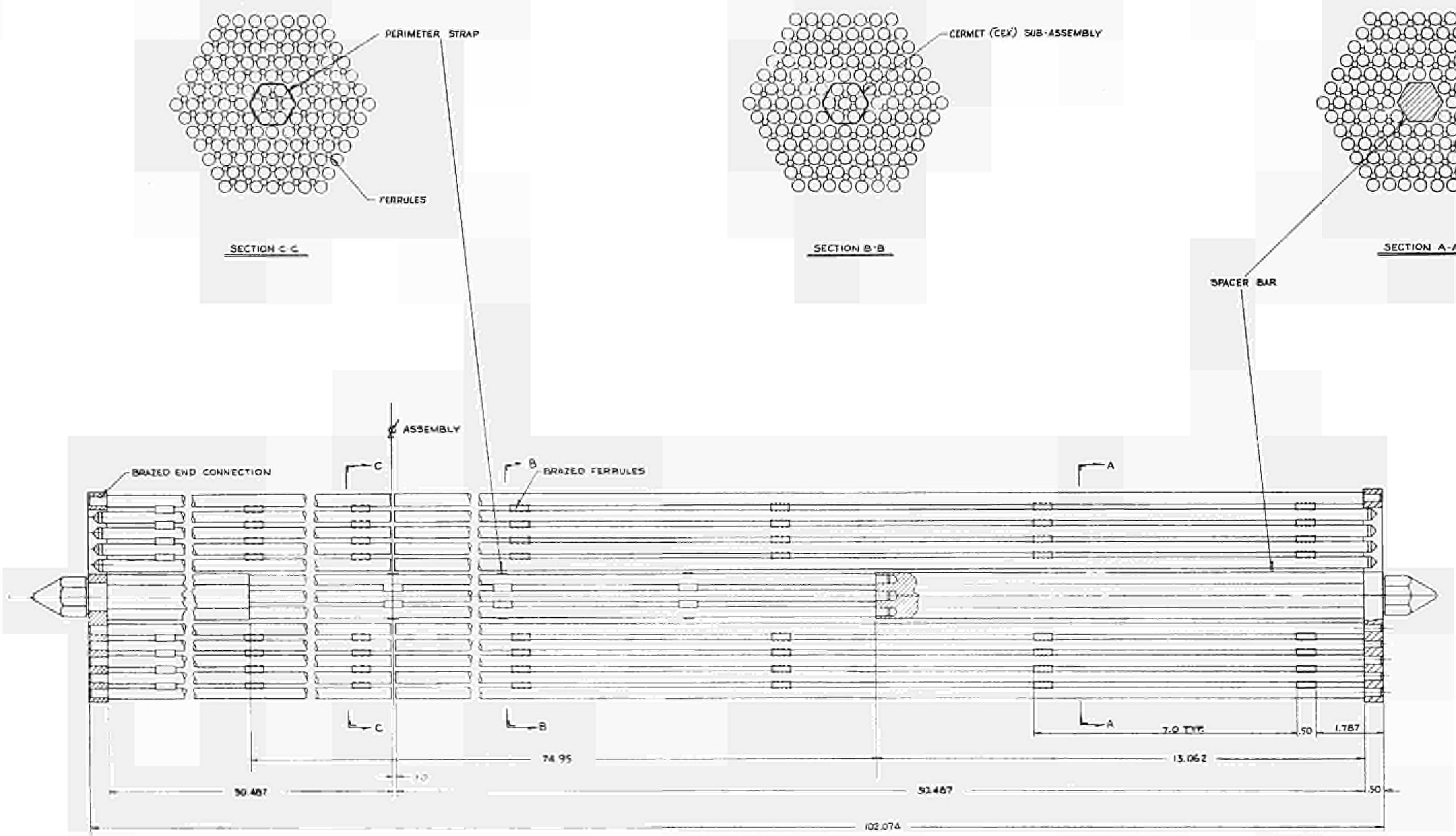

Figure II.2.3-4 Fuel Bundle Assembly

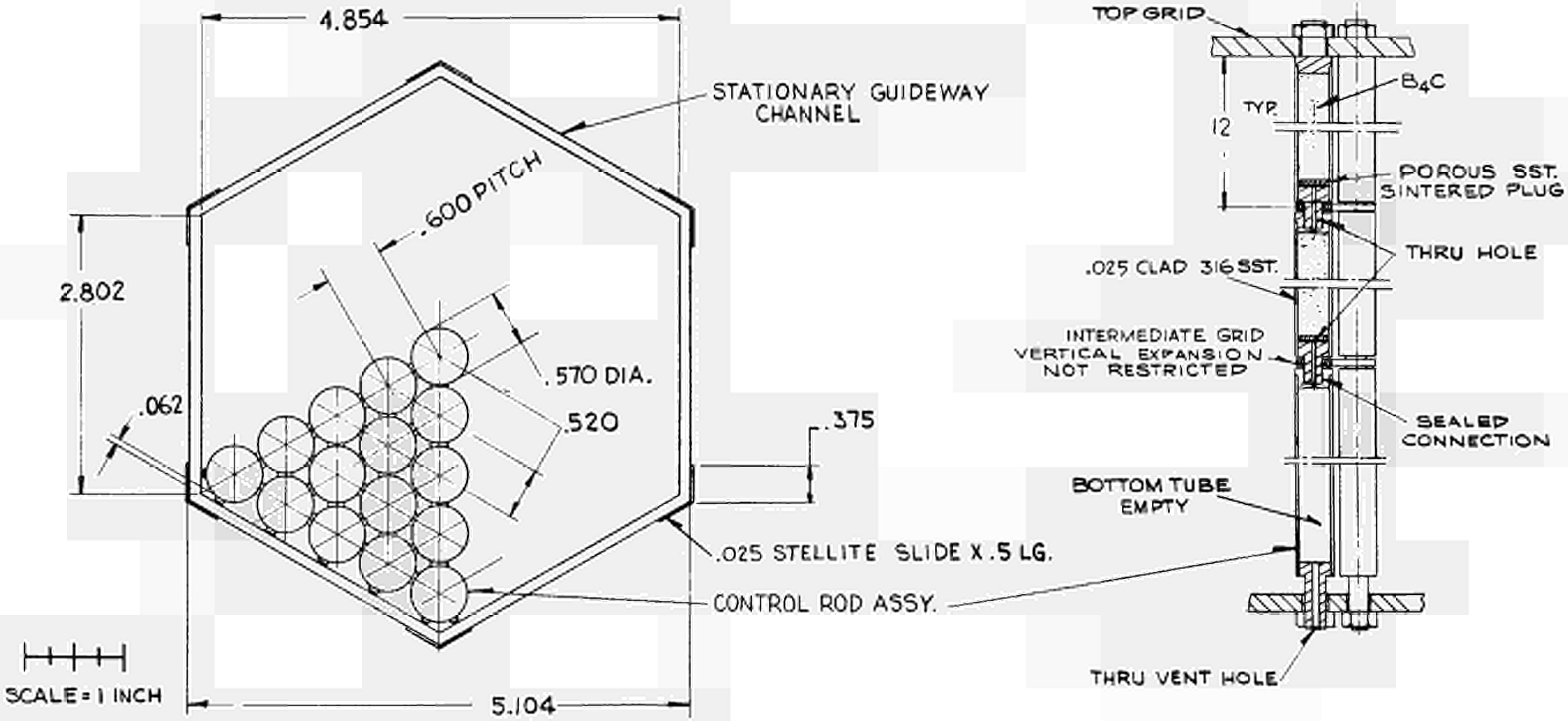

Figure II.2.3-8 Control Rod Element - 61 Rod Element

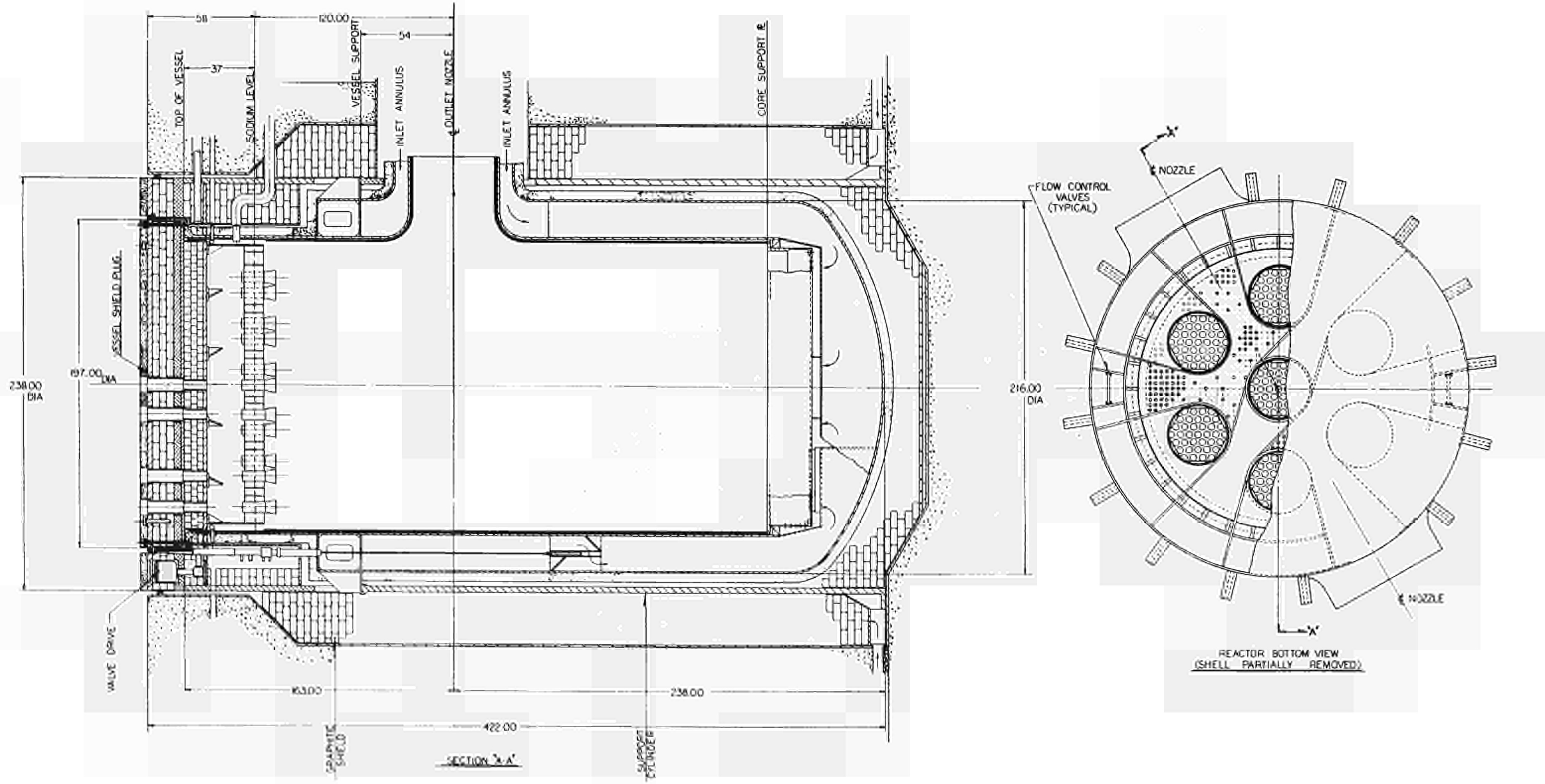

Figure II.3.1-5 Reactor Vessel Assembly

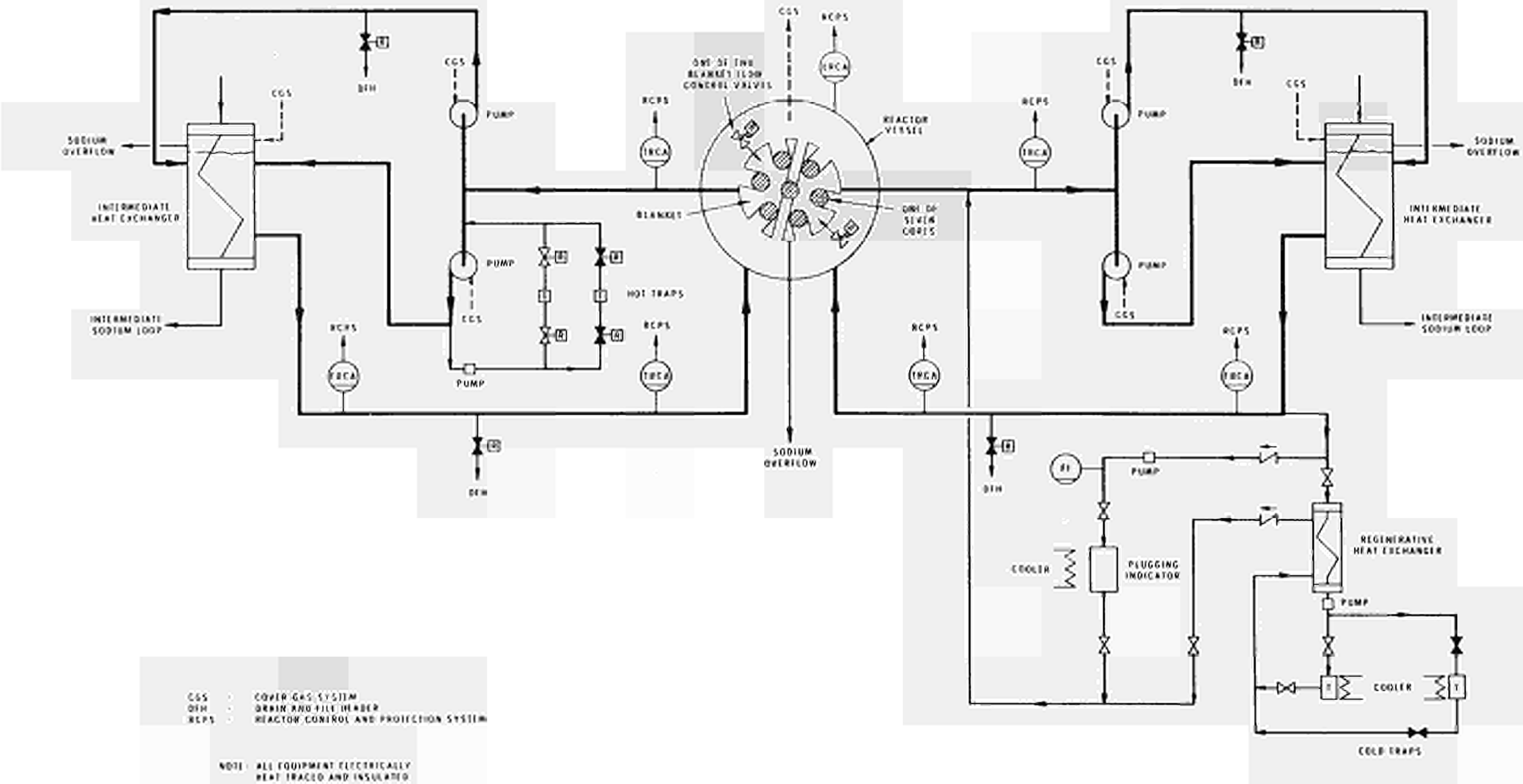

Figure II.3.1-1 Primary Sodium System Flow Diagram

P F F B R

PLUTONIUM - FUELED FAST BREEDER REACTOR

1. Location : U. S. A.

2. Owner : Project undertaken by Atomic Power Development Associates, Inc.

3. Main contractors :

   In cooperation with Allis-Chalmers Manufacturing Company, The Babcock and Wilcox Company, Commonwealth Associates, Inc., The Detroit Edison Company and United Engineering and Constructors Inc.

4. Present status and construction schedule :

   Project

5. Reactor type :

   An unmoderated, heterogeneous, sodium cooled fast reactor with a power output of 775 MW thermal and 300 MW electrical fueled with plutonium.

6. Purpose : PFFBR is another essential step in the commercial development of economical nuclear power utilizing a full scale power breeder reactor, designed to operate at substantially less cost than Fermi utilizing Fermi knowledge and experience and new technology available from research and development programs for Fermi, EBR -1, EBR-2 and Dounreay.

7. Power :

   - thermal : 775 MW
     core power : 705 MW
     specific power : 1, 150 KWt/kg Pu^{239}
     thermal efficiency, percent : (gross : 37.7
     (net : 36.5

   - electrical :

     gross electric output : 300 MW
     net electric output : 238 MW

8. Fast flux :

9. Fuel : The three active regions of a core subassembly are the fuel containing region, the upper and lower axial blanket regions and an inactive gas storage region above the upper axial blanket. The fuel section, upper axial blanket and gas storage space are contained in the pin element.

a) Core :

- Composition : PuO_2-UO_2

enrichment (initial) : 26% Pu^{239}

- shape and dimensions : element shape : round
subassembly shape : hexagonal

subassembly dimensions :

outside dimensions : 3.950 in.
wall thickness : 0.077 in.
space between subassemblies : 0.050 in.

element dimensions :

outside diameter : 0.122 in.
mean diameter : 0.104 in.
mean length : 36.0 in.
pitch (triangular) : 0.187 in.

- number : 188 core subassemblies

397 elements per assembly

- critical mass : 674 kg of Pu^{239}

- cladding : thickness : 0.009 in. (for elements)

b) Blanket : axial blanket :

- Composition :

The lower axial blanket section is composed of depleted uranium 10 v/o molybdenum alloy and the upper axial blanket is composed of depleted uranium dioxide.

- enrichment (lower axial blanket) : 0.35% U^{235}
- enrichment (upper axial blanket) : 0.35% U^{235}

radial blanket :

design is generally similar to that used for the Fermi reactor. The elements are rods of depleted uranium alloyed with 2-3/4 v/o molybdenum enclosed in stainless steel tubes.

- shape and dimensions :

1. subassembly dimensions

   the same dimensions and shape than fuel sub - assemblies

2. element dimensions

   lower axial blanket section

   - shape : trapezoidal plate
   - outside diameter : 0.200 in
   - mean length : 9.80 in.

   upper axial blanket section

   - shape : round
   - outside diameter : 0.122 in.
   - mean length : 14 in.

- number :

248 radial blanket subassemblies
number of subassemblies : 188
number of elements per subassembly :
- lower axial blanket : 18
- upper axial blanket : 397

- critical mass :

- cladding : for lower axial blanket : zirconium (0.250 in. thick)

10. Control :

Reactor control is maintained by ten control elements located near the center of reactor. 6 control elements are safety rods, while the remaining 4 are operating control rods.

Two of the operating control rods are for burnup control, one is a startup rod and the other is a fast rod for adjustment of transient effects.

The poisoning material is hot pressed boron carbide, enriched in boron -10.

	Fast rod	Startup rod	Burnup rod	safety rod
Number	1	1	2	6
Reactivity per rod-dollars	0.7	1.8	8.0	4.5
Control rod O.D. in.	3.44	3.44	3.44	3.19
Length of poisoning rods in.	14	14	18	36
Weight of B_4C kg	0.96	0.92	3.15	7.25
B-10 enrichment %	38	90	90	90
Max. reactivity addition rate -cents/min.	60	1	0.0168	1

11. Reflector :

12. Shielding : The basic design of the shielding is similar to that of the Enrico Fermi. For more details, see Figures.

13. Geometric dimensions :

a) Core : diameter : 5 ft
length : 3 ft
volume : 54.2 ft^3

core composition v/o : (PuO_2-UO_2 : 23.4
(
(structure and clad : 26.0
(Na coolant : 50.5

b) Blanket : The core is completely surrounded by blanket material
radial blanket thickness : 18 in.
top axial blanket thickness : 14 in.
bottom axial blanket thickness : 10 in.

c) Pressure vessel : A cylindrical stainless steel tank
diameter : 9 feet
height : 37 feet
having 3/4 inch-thick walls

14. Temperatures :

a) Core : maximum fuel temperature : 4,250°F
average outer clad temperature : 854°F
maximum outer clad temperature : 1,373°F

b) Blanket : average outer clad temperature : lower axial blanket : 668°F

upper axial blanket : 1000°F

15. Coolant : sodium as primary and secondary coolant
core sodium flow rate : 22.3 x 10^6 lb/hr (core)
sodium velocity : 13.5 ft/sec. (core)
maximum nominal coolant temperature : 1242°F(core)
temperatures : inlet : 650°F (core)
outlet : 1018°F (core)

15. bis Thermal systems and turbine plant :

Heat is removed from the core and the blanket by the circulation of sodium coolant slightly pressurized in three coolant loops. Each loop contains a sodium loop, check value, and the shell side of an

intermediate heat exchanger.
The secondary system is composed of three independant coolant loops, each containing a sodium pump, the tube side of an intermediate heat exchanger and the shell side of a steam generator.

Performance data for coolant systems

1. Primary :

sodium flow per loop : 8.3×10^6 lb/hr
design temperature : 1050°F
design pressure : 125 psig
material in system : type 304 SS
pressure drop in system : 223 ft of Na

2. Secondary :

sodium flow : 8.25×10^6 lb/hr
design temperature : 1000°F
design pressure : 150 psig
material in system : (2-1/4% Cr-1% Mo) and type 304 SS low carbon ferritic
pressure shop in system : 106 ft

Sodium pumps :

	primary system	secondary system
number	3	3
capacity each gpm	20,300	20,100
temperature normal operating °F	650	570
pumping rate normal operating hp	1240	595
drive type	wound rotor motor	wound rotor motor

Intermediate heat exchangers :

- primary side :

inlet sodium temperature : 1000°F
outlet sodium temperature : 650°F
sodium flow, each heat exchanger : 8.3×10^6 lb/hr

- secondary side :

inlet sodium temperature : 570 °F
outlet sodium temperature : 920 °F

- design data :

heat transferred : 8.83×10^8 BTU/hr
tube size : 1 " " OD x 0.42 " " wall
number : 1200

Steam generators :

- design temperatures : shell : 1000 °F
  tubes : 1000 °F
- design pressure : shell : 150 psig
  tubes : 1550 psig
- steam conditions : temperature : 870 °F
  pressure : 1450 psig
- flow, each steam generator : 833,000 lb/hr
- sodium inlet temperature : 920 °F
  outlet temperature : 570 °F
- tube data : outside diameter : 5/8 in.
  minimum wall thickness : 0.068 in.
  pitch : involute
  effective length : 82.5 ft
  number, per steam generator : 1200
  effective heat transfer area per steam generator :
  16.200 sq. ft

16. Physical data :

- breeding ratio : core 0.3
- blanket : 0.95 total (including Pu^{241} formed 7:1.34)
  total : 1.25
- core life : 580 days
- fraction of fissions in core : 0.88
- doubling time : 18 years

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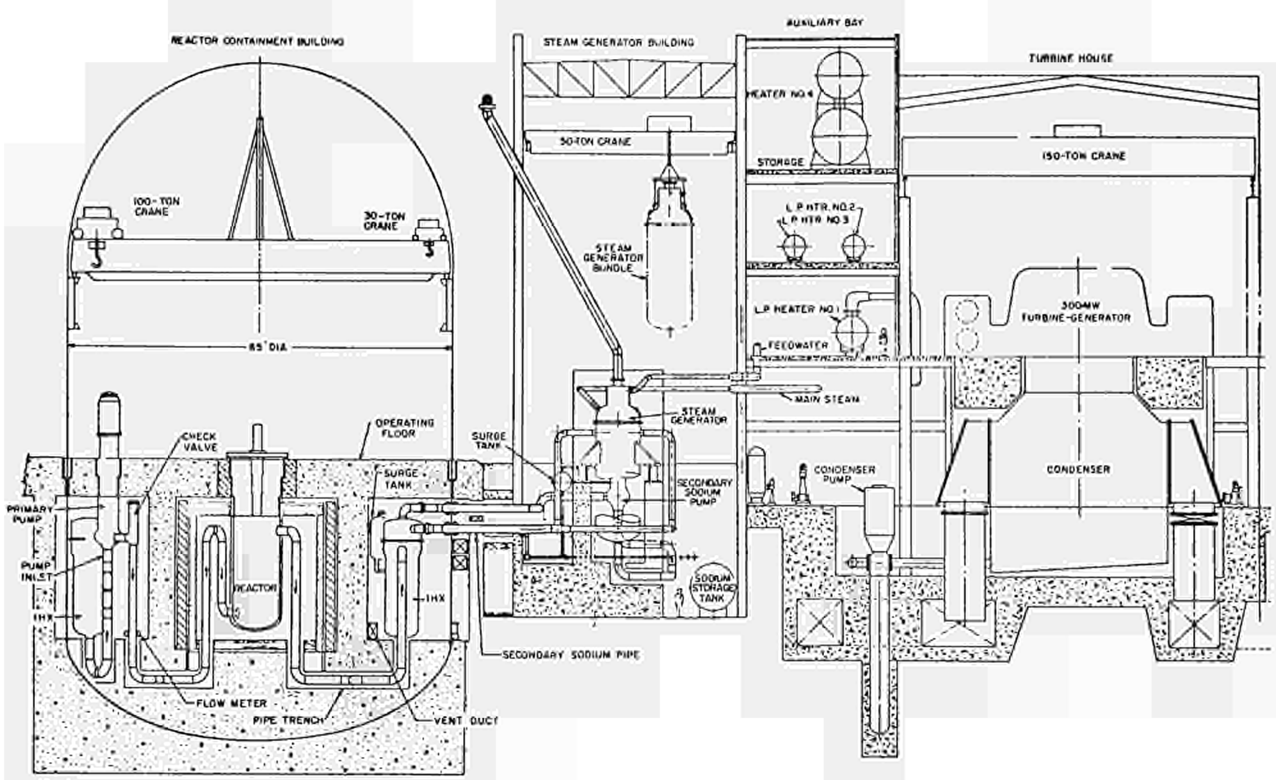

FIGURE 27.—PFFBR plant layout.

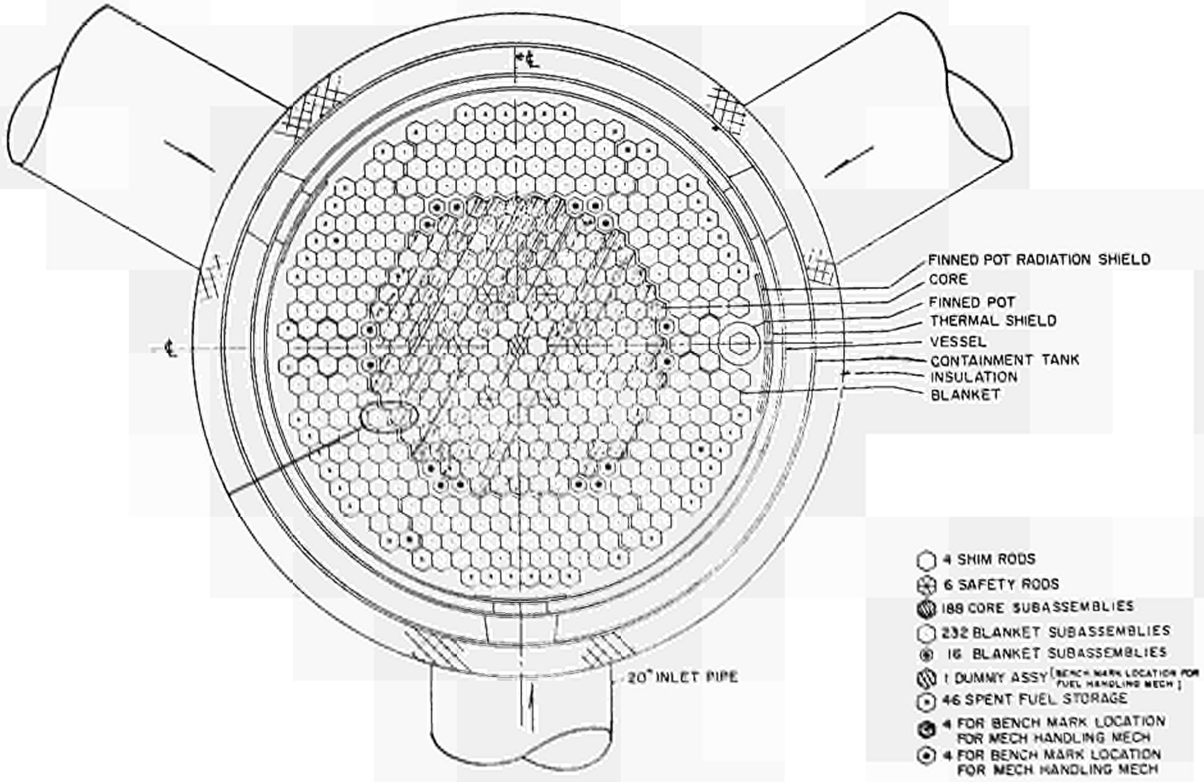

FIGURE 30.—PFFBR reactor cross section.

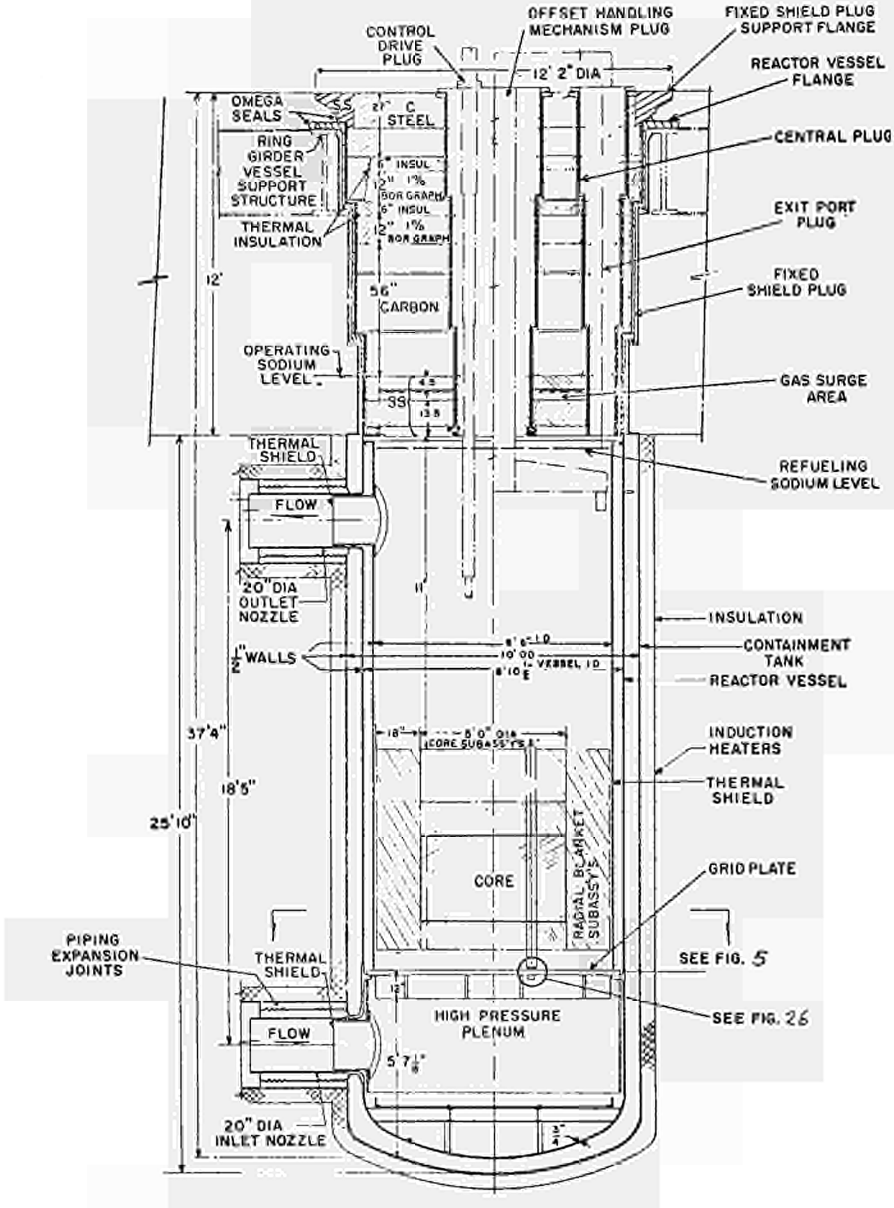

FIGURE 29.—PFFBR reactor vessel.

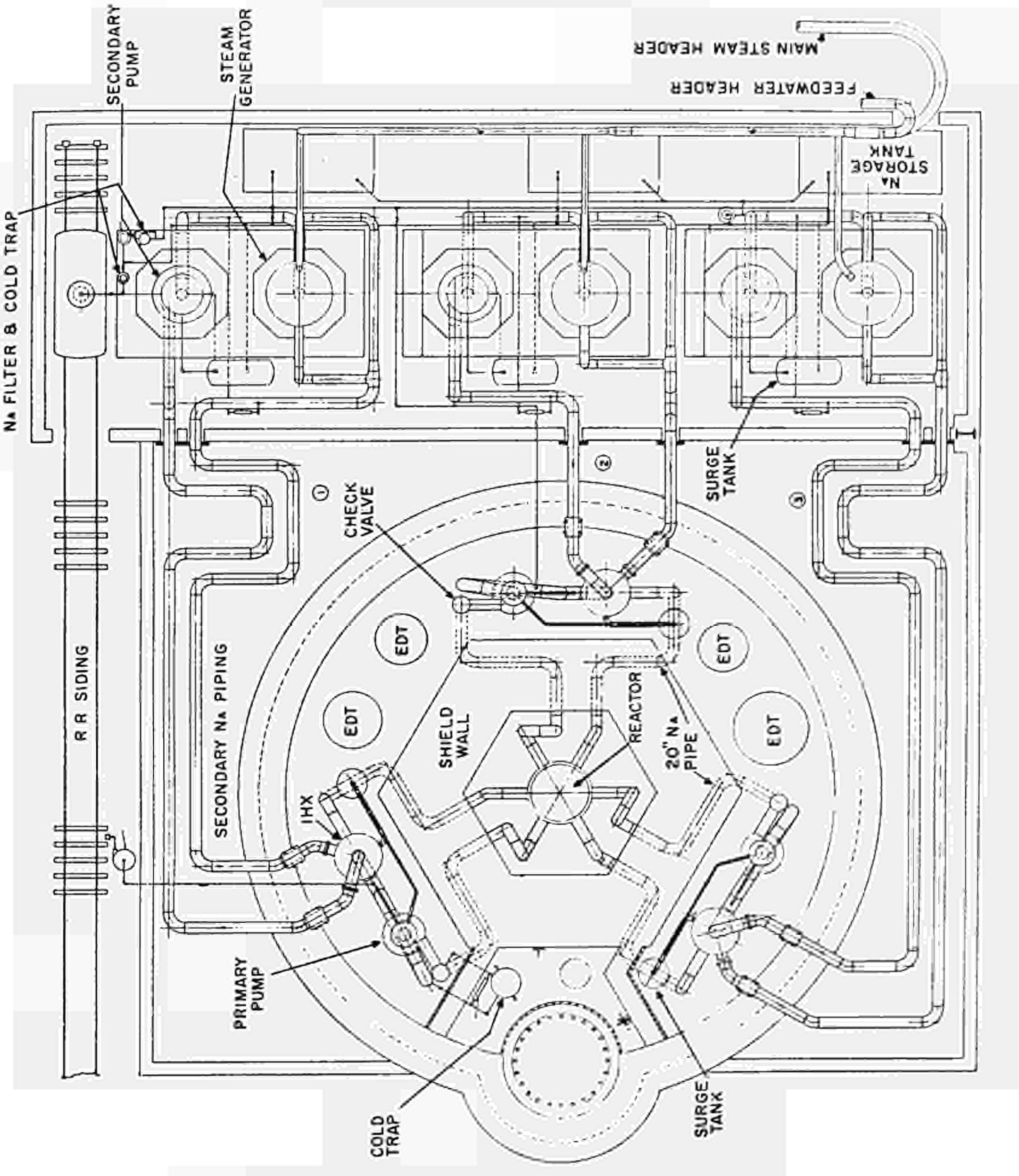

FIGURE 28.—PFFBR plan view of primary and secondary systems.

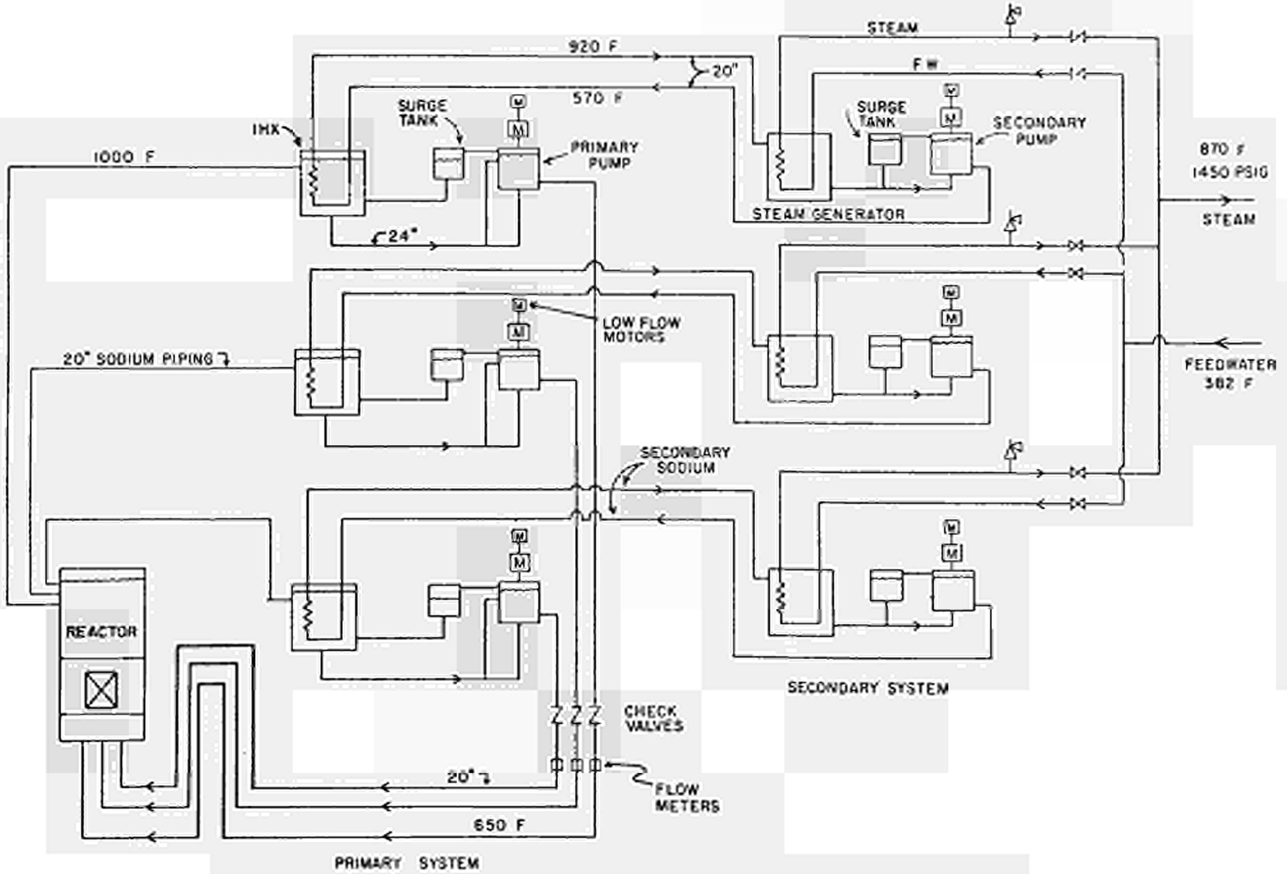

FIGURE 31.—PFFBR flow diagram for primary and secondary sodium systems.

R A P S O D I E

1. Location : Cadarache, France

2. Owner : EURATOM-C.E.A. Association contract

3. Main contractors :

4. Present status and construction schedule :

   Construction

5. Reactor type : A sodium-cooled fast reactor, using plutonium in its fuel.

6. Purpose :
   1) to provide a facility for the physical study of a fast reactor in the steady-state and during transients, at various power levels.

   2) to provide industrial experience in the construction and operation of such a reactor

   3) to provide fast neutron flux sufficient for the testing of fuel intended for future reactors of the same type.

7. Power :

   - thermal : total 20 MW (core : 17 MW
     (axial blanket : 0.2 MW
     (radial blanket : 2.8 MW
     max. specific power : 1.52 KW/cm^3 fuel
     ratio of max. specific power : (core : 1.59
     (axial blanket : 6.5
     (radial blanket : 25

   - electrical :

8. Fast flux : max. neutron flux : 1.70×10^{15} n/cm^2 S
   mean neutron flux : 10^{15} n/cm^2 S

9. Fuel :

a) Core :

- Composition : $UO_2 + PuO_2$

PuO_2 volumetric composition :(24.94 ± 0.25)%

- shape and dimensions : Fuel pins are made up of 34 mixed oxide pellets
pellet (10 mm in thickness
(5.7 mm in diameter

pin length : 485 mm
hexagonal fuel assembly, overall length : 1.664 mm
width between flats : 49.8 mm

- number : 53 fuel assemblies in core
number of pins per assembly : 37
number of pellets per pin : 34

- critical mass :

Pu^{239} : 35.7 kg
Pu^{240} : 3.9 kg
U^{235} : 67.3 kg
U^{238} : 45.4 kg

- cladding : pellets are stacked in 316 L stainless steel cans 0.45 mm thick.

b) Blanket :

- Composition : UO_2 (0.65% U^{235} for axial blanket)
(0.40% U^{235} for radial blanket)

- shape and dimensions : pin length (axial blanket : 302 mm
(radial blanket : 1 153 mm

diameter of pellets (axial blanket : 13.4 mm
(radial blanket : 15.4 mm

- number : 53 fuel assemblies in axial blanket
  500 fuel assemblies in radial blanket

  number of pins per assembly in axial blanket : 2 x 7
  number of pins per assembly in radial blanket : 7

- critical mass :

  weight of UO_2 in radial blanket : 8,040 kg

- cladding : Inox Z3CND, thickness : 0.5 $\pm$ 0.05 mm

10. Control : 6 control rods are arranged in the core
one regulating rod + five safety rods

1 regulating rod : containing B_4C (natural) Boron
rod is 450 mm long

nominal speed : 10 Mn/sec.

5 safety rods : containing B_4C with 90 wt. % B 10
boron rod is 450 mm long.

Each of those rods moves up and down inside a hexagonal casing having the same dimensions as those of the fuel elements. Each rod consists of a cylindrical seath filled with boron 10 and fitted with a gripping head similar to those of the fuel elements.

11. Reflector : A reflector designed to reduce the escape of neutrons.

12. Shielding : The lateral shields consist of a 23 in. layer of graphite completely surrounding the reactor vessel and located inside a cylindrical sleeve of reinforced concrete with a total thickness of 55 in.

13. Geometric dimensions :

a) Core : Volume : 50 liters
active volume in the loop : 40 x 27 liters

(fuel or fertile material : 42.2 v/o
(structural material : 22.8 v/o
(helium : 1.5 v/o
(sodium : 33.5 v/o

hexagonal prism. (length : 1664.5 mm
(side : 49.8 mm

b) Blanket :

	axial blanket	radial blanket
	active volume : 63.95 liters	active vol.:1218.05 l.
fuel material :	44.2 v/o	58.3 v/o
structural material :	19.8 v/o	15.6 v/o
helium :	0.6 v/o	0.7 v/o
sodium :	35.4 v/o	25.4 v/o

c) Pressure vessel : in thick stainless steel
diameter : 7 ft - in.
thickness : 0.6 in.

14. Temperatures :

a) Core : max. nominal can temperature : 635 °C

max. temp. at center of fuel pins : 2000 °C

b) Blanket : max. nominal can temperature :
- axial blanket : 595 °C
- radial blanket : 595 °C

max. temp. at center of blanket pin :
- axial blanket : 650 °C
- radial blanket : 1000 °C

15. Coolant : Sodium

- total sodium flow : 211 liters/s
- max. sodium flow rate : 5.4 m/s in core

- sodium inlet temperature : 410°C
- mean sodium outlet temperature : 500°C
- max. nominal sodium temperature : 585°C in core

15. bis **Thermal systems and turbine plant** :

Two primary circuits and two secondary circuits. Each of the primary and secondary circuit incorporates a mechanical pump of the centrifugal type. Each of the primary circuits transfers its heat to the secondary circuit in an intermediate heat exchanger. The two secondary circuits are identical with each other and each terminates in an air exchanger where the power is passed to atmosphere. The coolant used is sodium, both in the primary and secondary circuits. Each of the circuits can dissipate 10 MW thermal power with a rated flow of approximately 370 m^3 /h.

Primary pumps :

centrifugal, submerged : vertical shaft type
flow rate : 370 m^3h, temperature : 410°C
speed : 860 rpm

intermediate heat exchangers :

number : 2, tube nest type
diameter tube : 12/14 mm
number of tubes per exchanger : 888
exchange length : 2095 mm
exchange surface : 81.8 m^2
exchange coefficient : 5280 K cal/h m^2 °C

secondary pumps :

centrifugal, submerged, vertical shaft type
flow rate : 375 m^3 /h
speed : 875 tours/minute
temperature : 470°C

terminal exchangers :

nests of finned tubes, air cooled type.
number of tubes : 960 (16 nests of 60 tubes)
tube diameter : 21.4/25.4 mm
exchange surface : 1 145 m^2
exchange coefficient : 53.5 K cal/h m^2 °C

16. Physical data :

- breeding ratio : internal : 0.049 external : 1.070 total : 1.118
- lifetime of prompt neutrons : 11.1×10^{-8} δ
- effective fraction of delayed neutrons β eff. : 0.00532
- fraction of fissions in core :
  - above 400 KeV : 50%
  - below 20 KeV : 90%
  - % of neutrons leaving the core : 54%
- Plutonium generation in blanket (in one full year at 20 MW) : 8 kg

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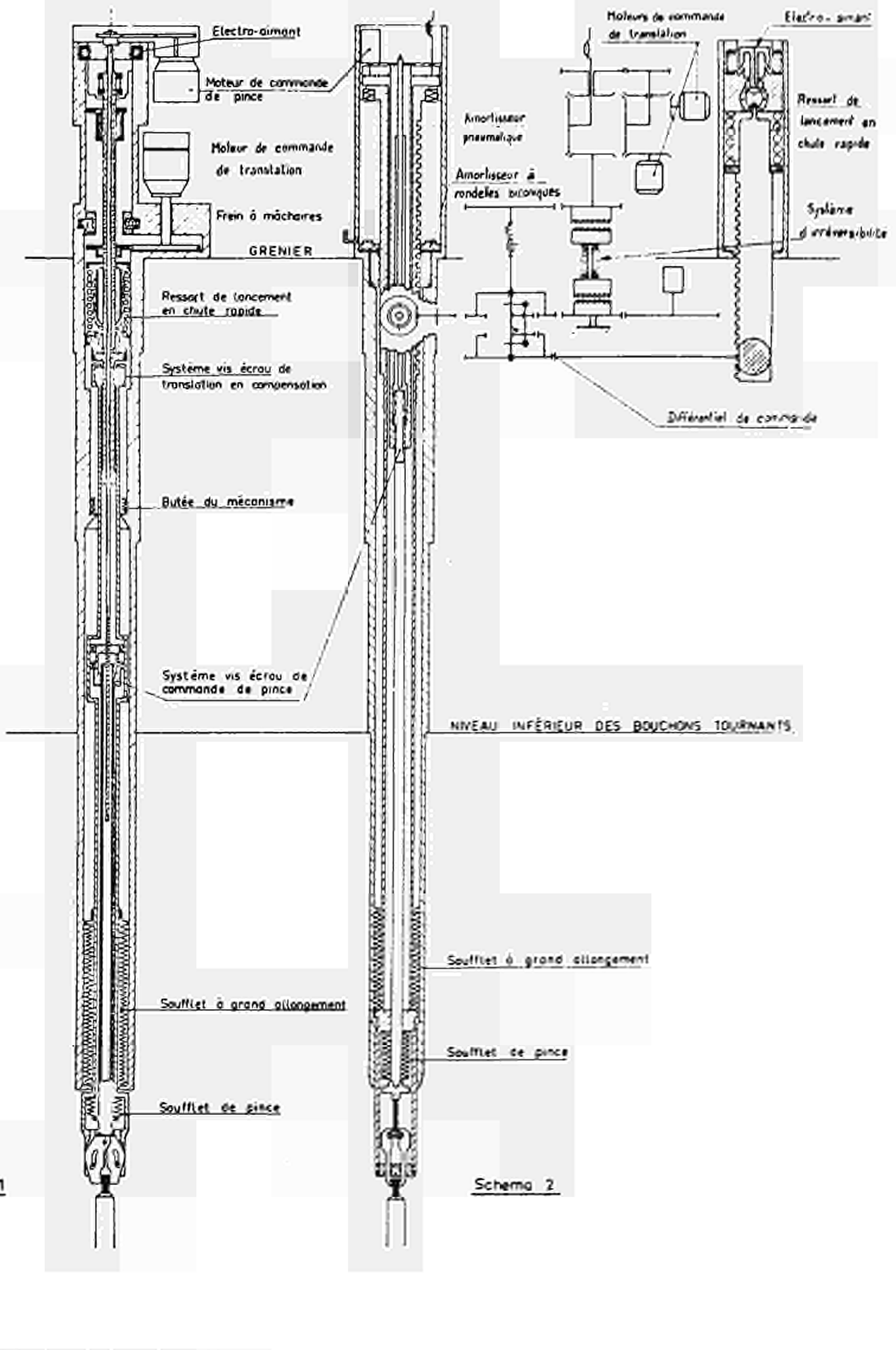

Figure 8. Mécanismes des barres de contrôle

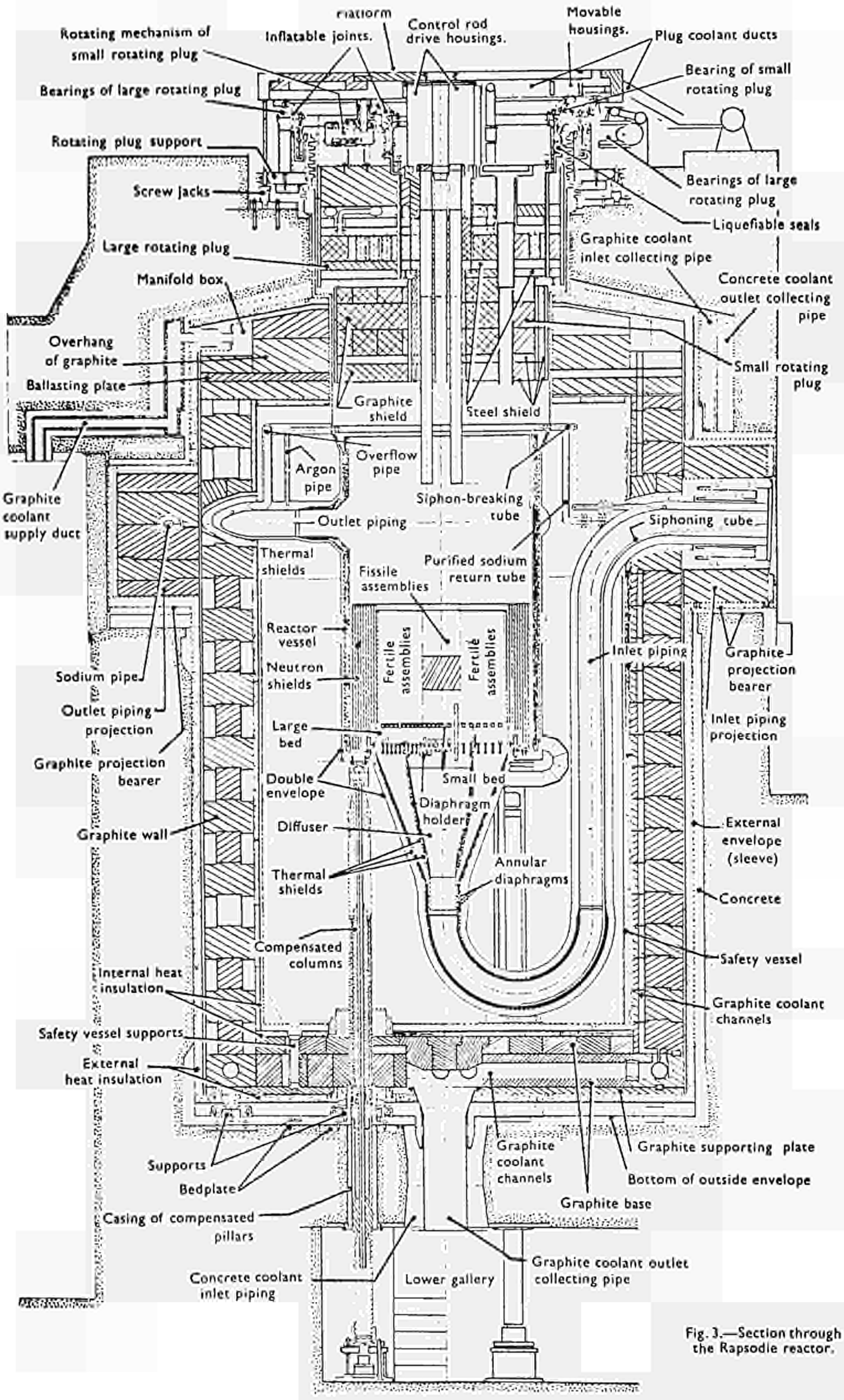

Fig. 3.—Section through the Rapsodie reactor.

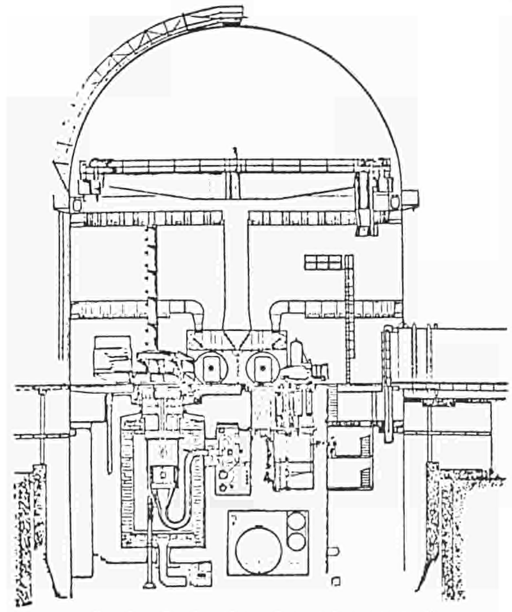

Fig. 1.— Section through containment vessel.

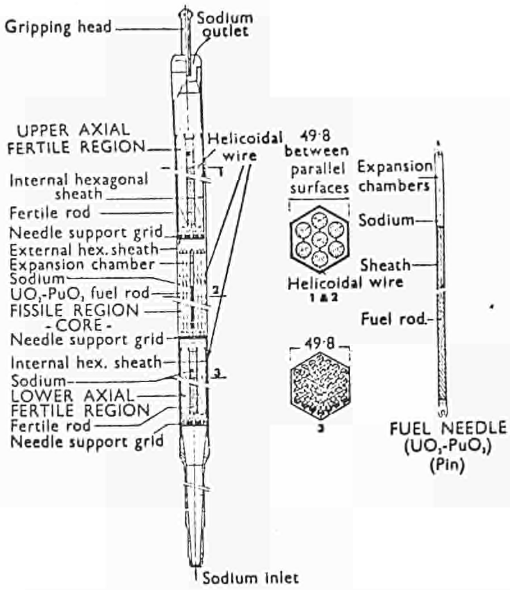

Fig. 2.—Sections showing Rapsodie fuel assemblies.

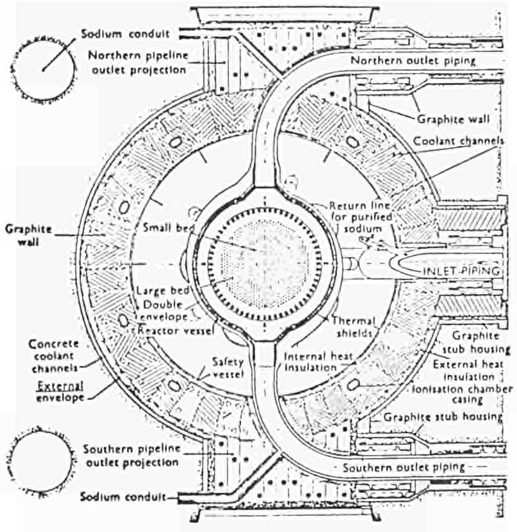

Fig. 4.— Plan section of reactor.

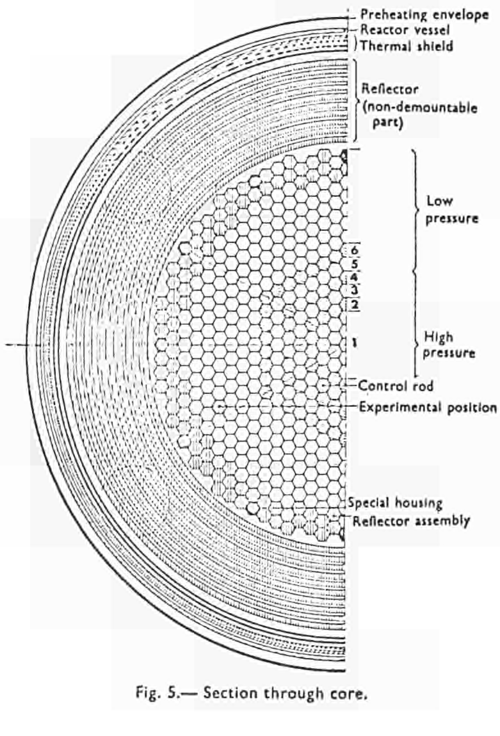

Fig. 5.— Section through core.

S B R - 5

1. Location : Obninsk near Moscow in USSR

2. Owner : Institute of Physics, State Commission for Atomic Energy.

3. Main contractors :

4. Present status and construction schedule :

   In operation
   Reactor critical : June 1958

5. Reactor type : SBR-5 is a 5.000 KWt, 10^{15} flux, sodium cooled reactor operating at 932 °F outlet temperature, fueled with UO_2, two loops, one sodium-to-air, the other sodium -to-water with heat dumped to a condenser.

6. Purpose :
   1. Testing of fuel and shield elements for the reactor BN-50 which has been abandoned.
   2. Testing of individual units of equipment and instruments and getting experimental experience with radioactive sodium heat transfer fluid.
   3. Carrying out of nuclear and material - testing investigations in intensive fast neutron fluxes.

7. Power :

   - thermal : 5 MW in the core
     0.8 MW in the uranium reflector,
     0.13 MW in the nickel reflector,
     average power density in core : 460 KW/liter
     average specific power in fuel : 100 KW/kg Pu

   - electrical :

8. Fast flux : max. : 1×10^{15} n/cm^2 sec.

9. Fuel :

a) Core :

- Composition : plutonium oxide

- shape, dimensions and number :

  - 80 fuel assemblies, placed in a grid plate at the bottom end
  - triangular lattice - Pitch of fuel rods : 0.55 cm
  - 19 fuel rods from a hexagonal fuel assembly . Distance between opposite sides of the hexagonal tube : 2.6 cm
  - cylindrical plutonium oxide pellets, o.d. 0.5 cm active length : 28 cm

- critical mass : 44.7 kg Pu

- cladding : 0. 4 mm thick steel " IX 18 H 9 T "

b) Blanket :

- Composition :

- shape and dimensions :

- number :

- critical mass :

- cladding :

- blanket gas : Argon at a pressure of 2.0 atm in the fuel tubes

10. Control : The reactor SBR-5 is controlled by changing the reactivity by moving inner layers of the nickel shield.

1. The cylindrical reflector layer 50 mm thick (the compensating cylinder : CC) placed just behind the casing of the central tube. The compensating cylinder weights : 187 kg

2. The shield compensator (SC) behind the CC, 10 cm thick, 705 kg

3. Two automatic regulators (AR) moving in slots of the SC-cross-sectionnal area of rods is 140 x 30 mm.

Material : nickel, cooled by air passing through gaps between stationary and moving parts

worth of CC : 3.6% $\frac{\Delta k}{k}$; SC : 2.8 $\frac{\Delta k}{k}$;
2 AR : 0.18% $\frac{\Delta k}{k}$

scram time and mechanism : magnetic clutch, gravity fall

11. Reflector : - 1 internal sodium cooled annular part of uranium elements similar to the fuel assemblies, but each containing 7 elements, consisting of 2 rods : 0.76 cm diam. , 14 cm height each, canned in SS 0.4 mm thick, o.d. 0.9 cm.

- 1 external air cooled part of nickel, behind the nickel control elements.

12. Shielding : Side : 50 cm water, 40 cm cast iron, 110 cm limonite concrete density 4.2

Top : 80 cm boron carbide, 120 cm rotating steel plugs ; 40 cm paraffin and cast iron layers

Bottom : 20 cm water, 140 cm cast iron

13. Geometric dimensions :

a) Core : cylindrical
diameter : 28 cm
height : 28 cm

b) Blanket :

c) Pressure vessel : cylindrical steel shell
reactor with shielding approx. : 5 x 6.2 x 6 m height

14. Temperatures :

a) Core : fuel element temperatures : av. 500°C

b) Blanket :

15. Coolant :

nature : sodium
coolant flow area : 1 50 cm^2
coolant velocity : 450 cm/sec
coolant mass flow rate : 67 l/sec
temperatures : sodium inlet : 375°C
outlet : 450°C

coolant pressure : 2.5 atm. (average)

15. BIS Thermal systems and turbine plant :

The heat removal scheme from the core and uranium reflector is accomplished by sodium passing from bottom to top along the central tube of the reactor. At the exit, sodium flow splits into two equal parts passing through tubes of 1 1 0 mm diam. to two similar circuits.

Each circuit comprises a Na-NaK heat exchanger and a circulation pump returning the sodium to the central tube. After the flow had been split and prior to its junction, non return valves are mounted.

Heat of the secondary is removed by two different methods. In one of the NaK circuits an air heat exchanger is installed and heat is removed by a flow of ambient air from a fan. In the other circuit an evaporato is installed and heat from NaK is used for steam generation. The evaporator contains distilled water. The steam is condensed in a cooler with flowing water. Liquid-metal circuits of the apparatus are provided with oxide traps for cleaning heat-transfer fluid. Steam at 230 psig and 570°F is produced.

Basic Parameters of the cooling system for the Central Part at Normal Working Power

Heat removal system	Circuit	Parameter	Value
Air cooling circuit transferring 50% power	Sodium circuit	Consumption	130m^3/hr
		Temperature at central tube input	375°C
		Average temperature at central tube output	450°C
		Pressure of central tube gas cushion	0.08 atmos (gauge)
	Sodium-potassium circuit	Consumption	130 m^3/hr
		Temperature at metal-metal heat exchanger input	300°C
		Temperature at metal-metal heat exchanger output	430°C
	Air-circuit	Consumption	40,000 m^3/hr
		Temperature at metal-air heat exchanger input	5 to 20°C
Circuit with water cooling transferring 50% power	Sodium circuit	see parameters of sodium circuit with air cooling	
	Sodium-potassium circuit	see parameters of sodium-potassium circuit with air cooling	
	Evaporation - condensation system	Pressure on evaporator	16 atmos
		Consumption of tap water in condenser	70 m^3/hr

16. <u>Physical data</u> :

- burnup ~ 2%

The other data are not avalaible

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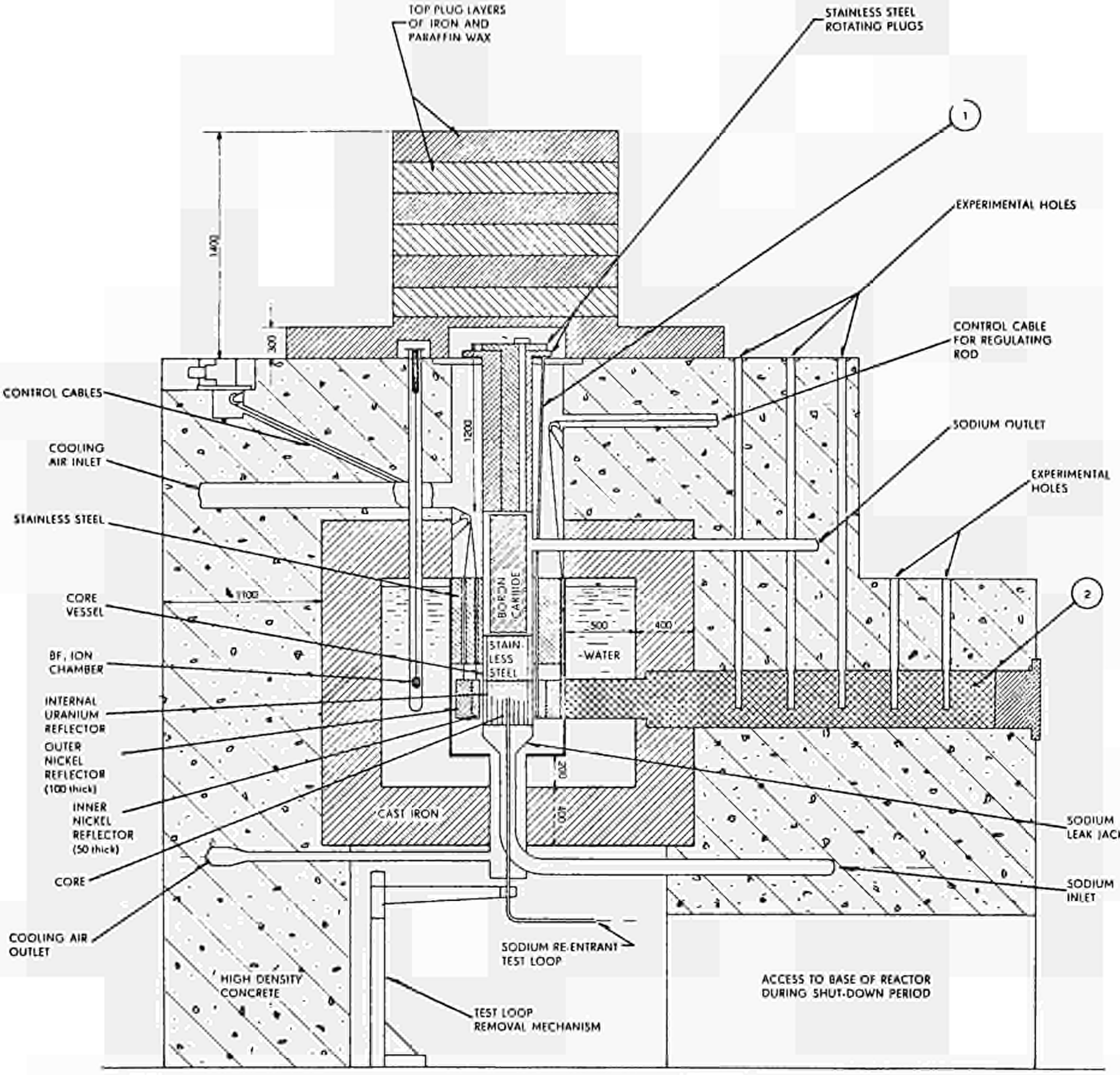
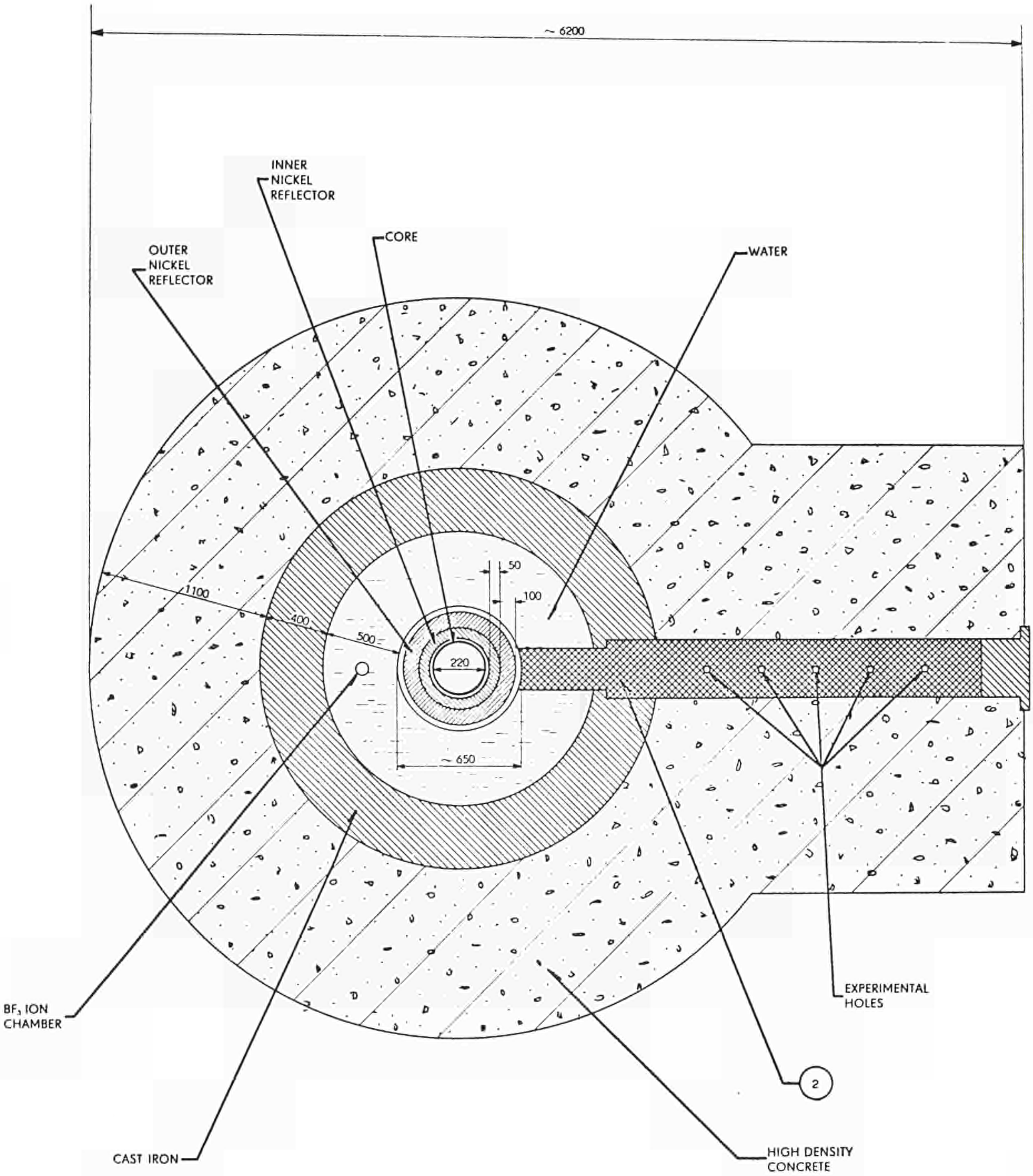


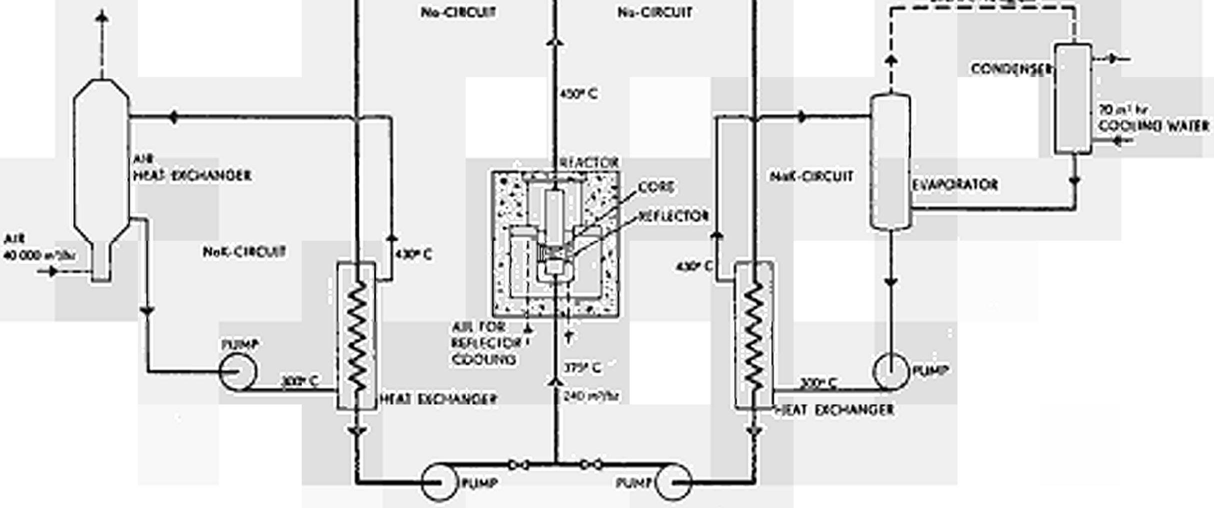
VERTICAL SECTION SBR-5

all dimensions in mm



HORIZONTAL SECTION SBR-5

all dimensions in mm



FLOW DIAGRAM SBR-5

S E F O R

SOUTHWEST EXPERIMENTAL FAST OXIDE REACTOR

1. Location : SEFOR, will be located in the northwest corner of the States of Arkansas - USA

2. Owner : SAEA

3. Main contractors :

4. Present status and construction schedule :

   Design

5. Reactor type : Experimental fast reactor , thermal power 20 MW
   fuel : mixture of PuO_2-UO_2
   coolant : sodium

6. Purpose : This reactor is designed to be representative of a new family of large, soft spectrum fast reactors fueled with mixed PuO_2 - $U^{238}O_2$.

   The SEFOR reactor is intended to :

   1. investigate operating characteristics of large PuO_2-UO_2 fast reactors
   2. measure and investigate the Doppler effect during normal operating operations
   3. measure the Doppler shut down effect under transient conditions and establish engineering design safety criteria for large economic units.

7. Power :

   - thermal : 20 MWt
     fuel linear power generation, max. : 24.2 KW/ft
     average : 12.1 KW/ft

   - electrical :

8. Fast flux :

9. Fuel :

a) Core :

- Composition : 14 percent PuO_2

  86 percent UO_2

- shape and dimensions : The PuO_2-UO_2 is loaded into stainless steel tubes in the form of pellets.

  Fuel rod diameter : 1 in.
  active fuel length : 33 in.

- number : 660 fuel rods

- critical mass : (Pu 239) : 277 kg (approximately 280 kg of plutonium are contained in the 2200 kg of PuO_2-UO_2 mixture)

- cladding : stainless steel

  clad thickness : 60 mil

b) Blanket :

- Composition :

- shape and dimensions :

- number :

- critical mass :

- cladding :

10. Control : The reactor will be controlled by 18 movable radial reflector segments plus three internal poison rods and one special reactivity insertion device.

The primary reactor shutdown control is provided in the reflector. The reflector controls are outside the reactor vessel and will provide positive shutdown even if gross core distortion prevents operation of the in-core control elements.

11. Reflector : The radial reflector is constructed of the nickel alloy, Inconel. The reflector design consists of an annular assembly, 6 nickels thick, surrounding the core on the outside of the reactor vessel.

The reflector contains 18 movable cylinders. The stationary segments support and guide the cylinders. Cooling gas is supplied to the reflector region to remove the internal heat.

12. Shielding :

13. Geometric dimensions :

a) Core : Height : 33 in.
diameter : 33 in.

composition : fuel : 50 v/o
structure : 24 v/o
coolant : 14 v/o
Beryllia : 12 v/o

b) Blanket :

c) Pressure vessel : consists of a core region and mixing plenum approximately 3 feet and 8 feet in diameter respectively. The vessel is double-contained with a second vessel.

14. Temperatures :

a) Core : fuel central temperature steady state max. : 4250°F
fuel central temperature steady state average : 2650°F

b) Blanket :

15. Coolant : nature : sodium in both the primary and secondary system

coolant velocity (average fuel channel): 11.5 ft/sec.

coolant flow rate : 4500 gpm

temperatures (steady state): reactor inlet : 700°F
reactor outlet : 820°F

15. bis Thermal systems and turbine plant

The main coolant system consists of two loops in series : a primary and a secondary loop. The radioactive primary loop is shielded and enclosed within the containment building. The secondary system is maintained at a higher pressure than the primary system.

Heat exchangers :

1. The intermediate heat exchanger is a tube-in-shell design with a single tube wall between the primary and secondary coolant. Type 304 stainless steel is used throughout the exchanger.

- pressure : 200 psi
- temperature : 1100 °F
- heat transfer coefficient : 1000 BTU/hr/ft^2 °F

2. The sodium-to-air heat exchanger is a farcast draft design with finned heat transfer surface. The tubing is constructed of type 304 stainless steel. Three fans with two-speed motors provide temperature control. In addition, louvers are provided for trim control of temperature.

- mean temperature difference : 450 °F
- heat transfer coefficient : 9 BTU/hr/ft^2 °F

Pumps :

Linear a-c electromagnetic pumps as manufactured by the General Electric Co. are proposed to circulate sodium coolant. The pumps have a specified capacity of 5000 gpm at 75 psi. The pump widings are air cooled.

Piping and valves :

Pipes 10 inches in diameter are used in the main coolant system. The sodium purification system is constructed of 2-inch. piping. Valves are of the bellows seal type with secondary shaft packing.

Auxiliary coolant system :

A 3-inch. auxiliary coolant system is provided to remove reactor decay heating in the event that the main loop is out of the service. The system is designed much like the main loop except for the smaller thermal capacity of 1.0 MW.

16. Physical data :

- Neutron lifetime : 5×10^{-7} sec
- Doppler coefficient : 8.9×10^{-6} K/°C
  (mean fuel temp. : -1320 K)
- fission occuring below 9 KeV : 22 per cent
- maximum positive reactivity change due to loss of sodium : + 0.03 $
- reactivity change due to total loss of sodium from the core : - 0.75 $

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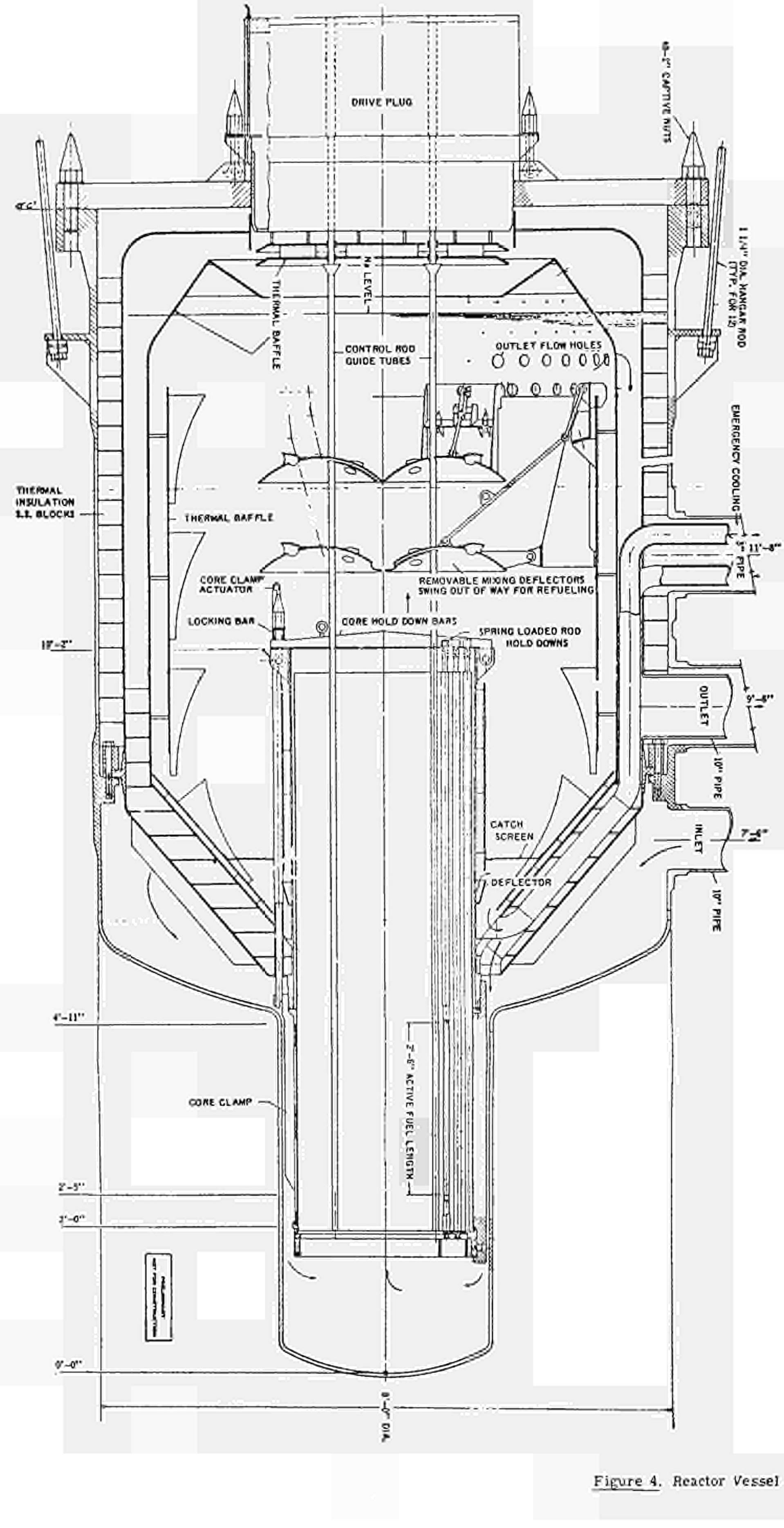

Figure 4. Reactor Vessel

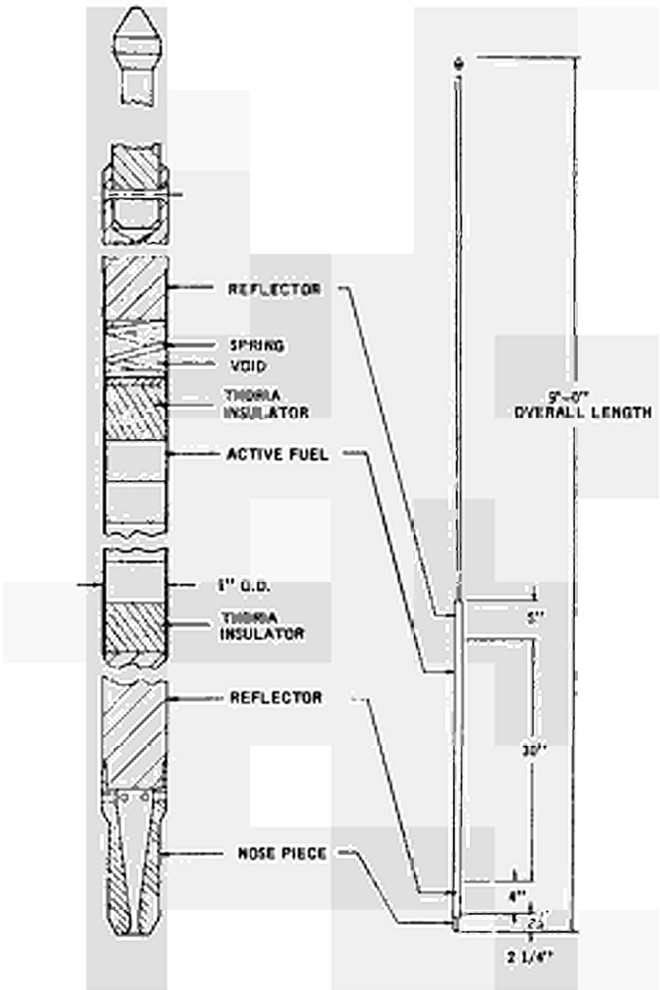

Figure 5. Fuel Rod

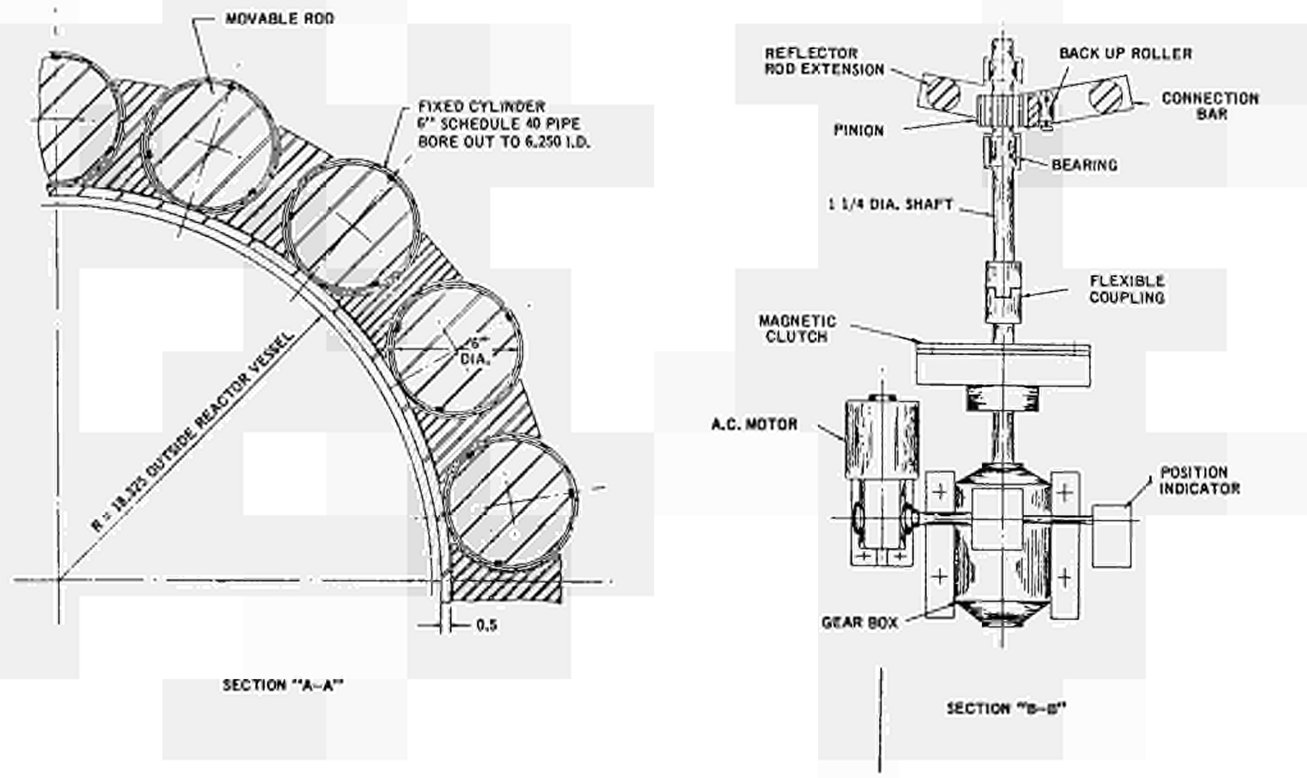

Figure 9. Reflector Control

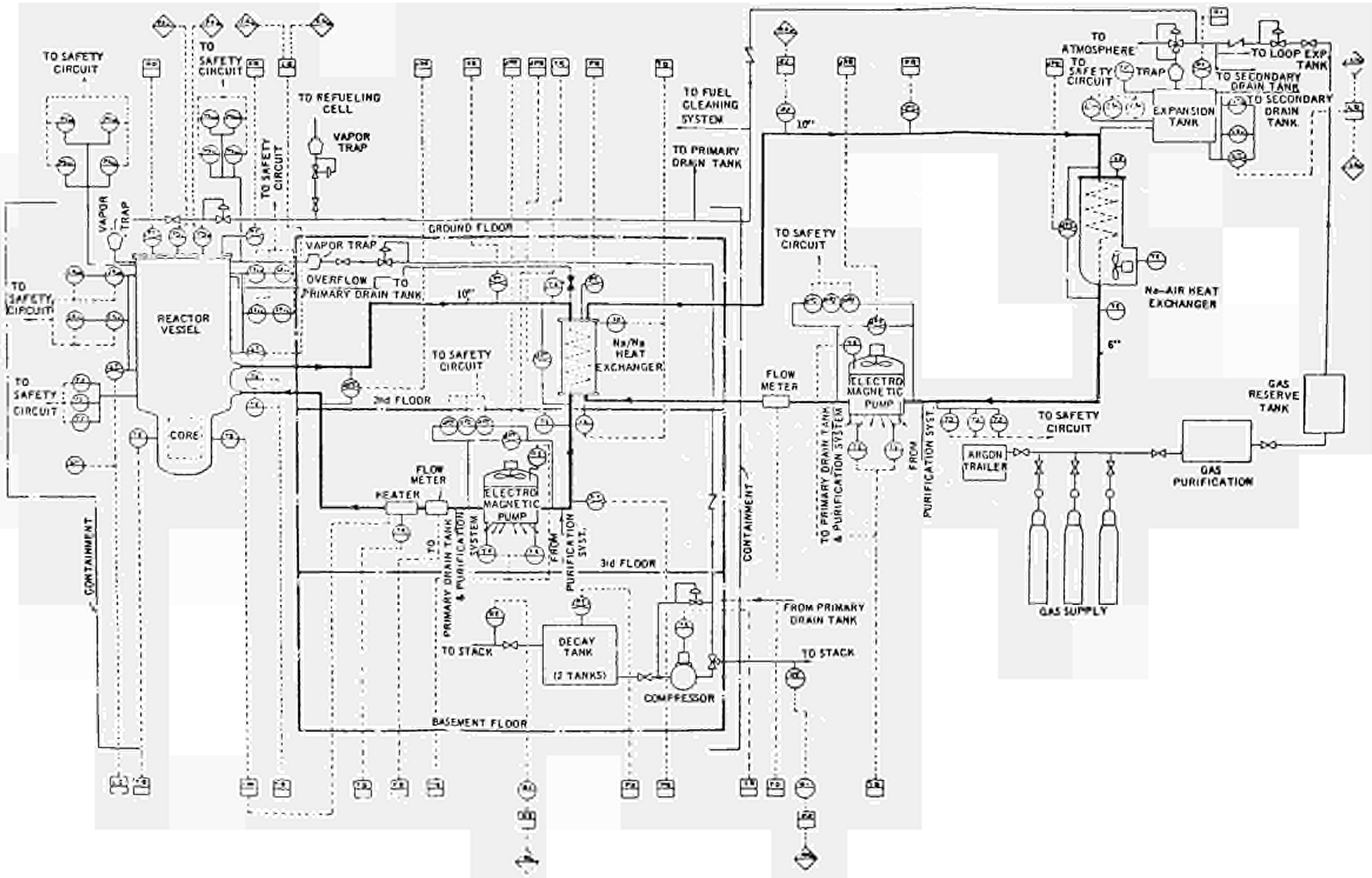

Figure 11. Coolant System

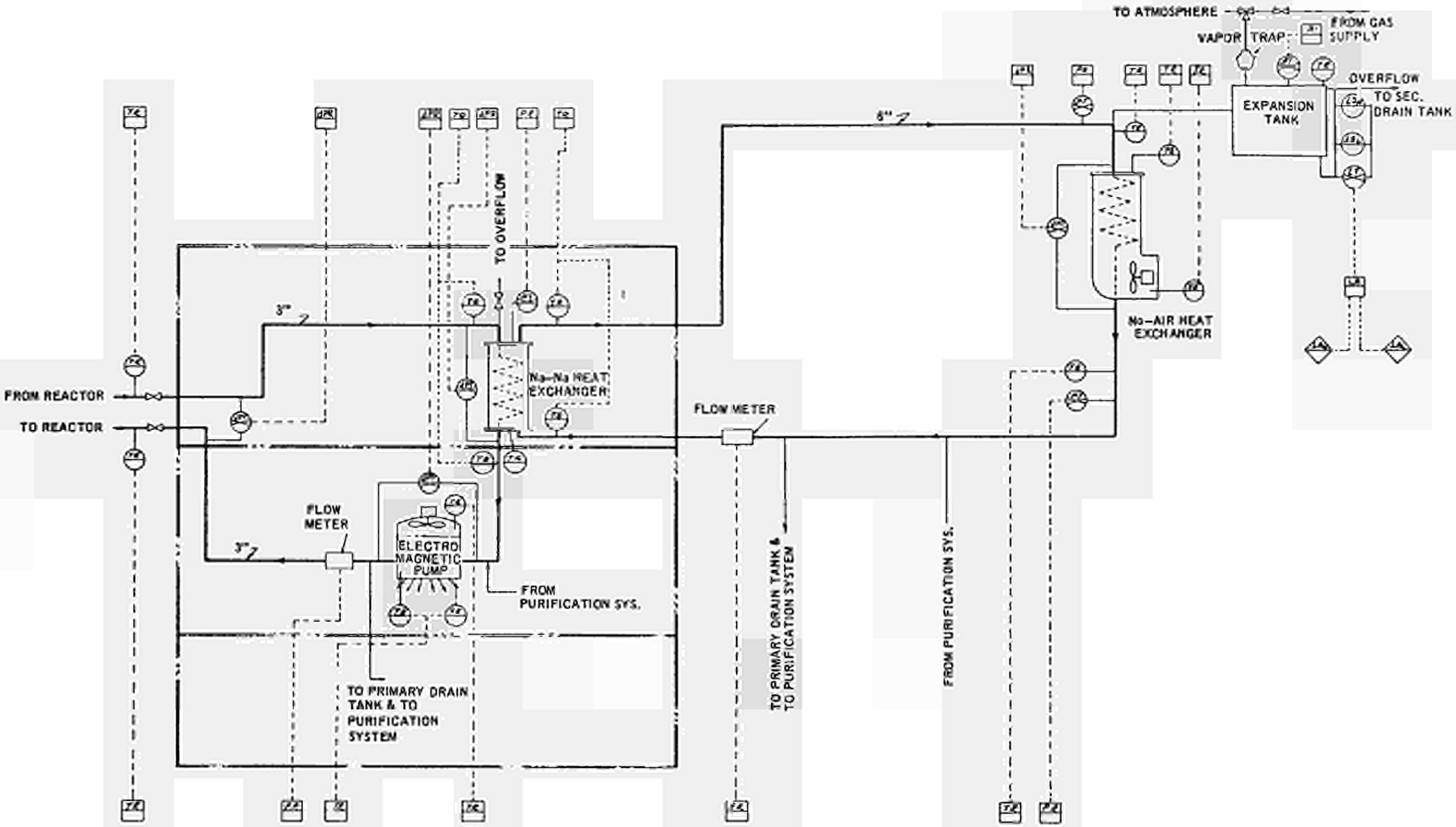

Figure 12. Auxiliary Coolant System

To disseminate knowledge is to disseminate prosperity — I mean general prosperity and not individual riches — and with prosperity disappears the greater part of the evil which is our heritage from darker times.

Alfred Nobel

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