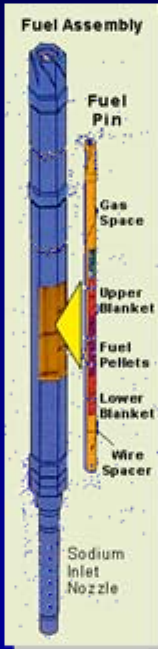
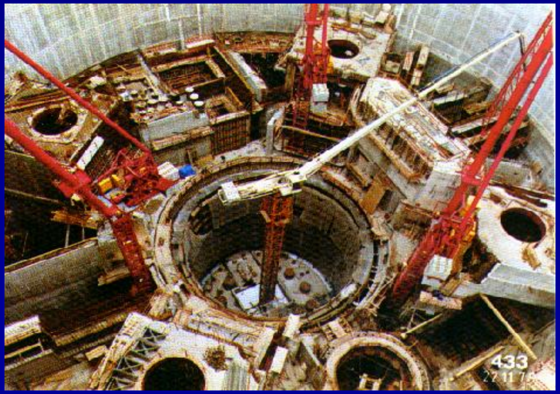


Module 11

Liquid Metal Fast Breeder Reactors

(LMFBR)



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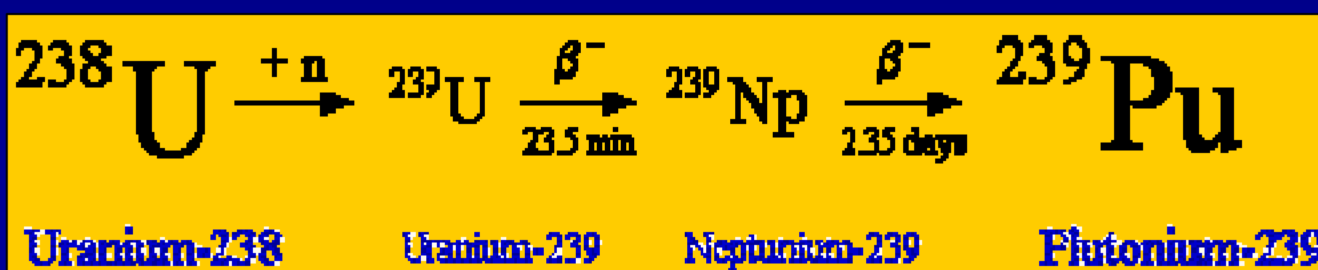
LMFBR Basics

- A fast breeder reactor can convert Uranium-238 into Plutonium-239 at a rate faster than it consumes its fuel (mixture of U-235 plus Pu-239)
- By repeated recycling of the fuel, it should be realistically possible to exploit 50% of the fuel value of the uranium feed
- This means that fast reactors could extend the energy output from the world's uranium fuel reserves about 25 fold

Breeding Process

If a neutron is captured by a Uranium-238, following a short series of decays, it is transformed to Plutonium-239. The process is shown in the figure below: symbol +n indicates a neutron absorption, *β*⁻ represents radioactive decay by beta emission with the half-life shown below the arrow.



Core and Blanket

- The LMFBR core is composed of two parts: core and blanket
- The fission process takes place in the core volume
- Extra neutrons diffusing out from the core are absorbed in a material (depleted U-238) surrounding the core which is called the **radial blanket**.
- In the vertical direction escaping neutrons are absorbed in the **vertical blanket**.
- This material is directly incorporated into each fuel rod above and below the fuel region (depleted U-238)

Physics behind LMFBR 1

- **The average number of neutrons produced in one fission process is around η= 2.5 for thermal fission and increases up to about η =3 at 100 keV neutron energy**
- **Therefore LMFBR has no light nuclei in core (H,D,C,O,Be)**
- **One neutron is necessary to continue chain reaction, some neutrons are lost in reactor materials**
- **Extra neutrons can be captured by U-238 to be converted to Pu-239**
- **Total number of fissile nuclei (Pu-239) in the reactor increase as the reactor operates**

Example

- Assumption: 100 fissions produce 300 fast neutrons
  - **100 neutrons necessary for chain reaction**
  - **100 neutrons convert U-238 to Pu-239 in the core**
  - **40 are lost by parasitic absorption in core**
  - **60 leave the core for the blanket (leakage)**
    - **50 convert U-238 to Pu-239 in the blanket**
    - **10 are lost again by parasitic absorption**

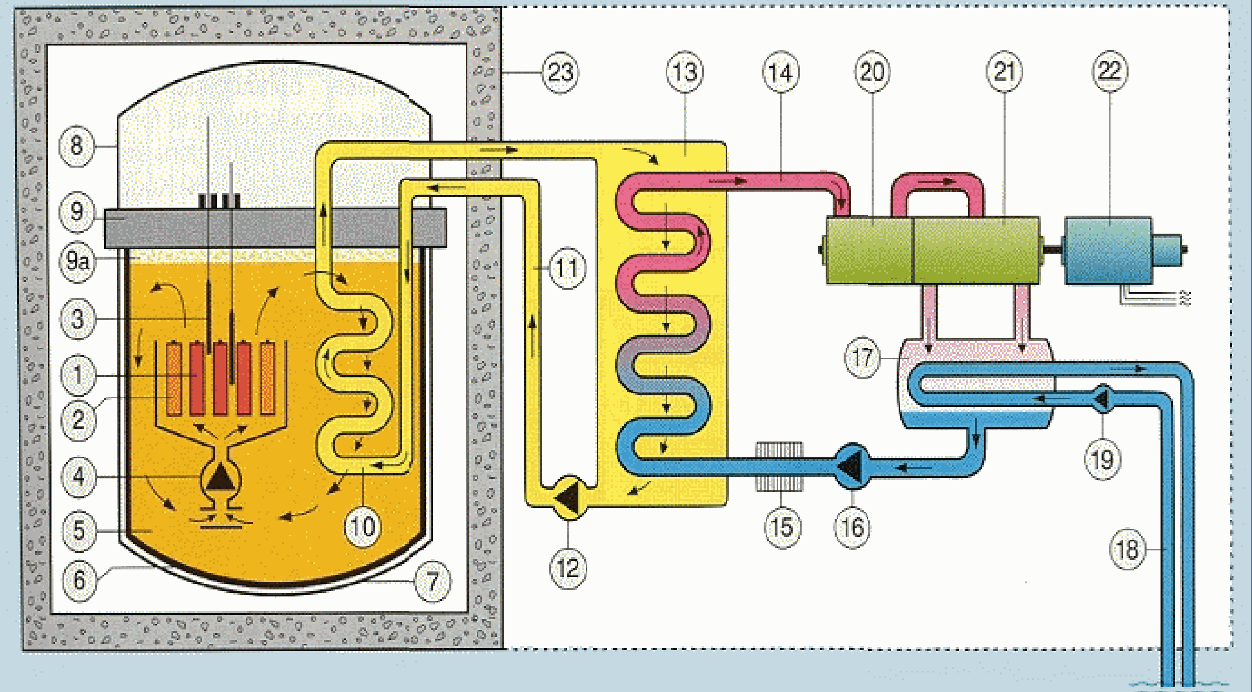
Physics behind LMFBR 2

- Breeding ratio (BR): Number of produced fissile nuclei (Pu-239) by absorption in U-238 to number of consumed nuclei in fuel
- BR in core: 0.8
- BR in blanket: 1.25
- Main Pu-239 production in blanket due to resonance absorption in U-238 (between 5 and 5000 eV)

Coolant for LMFBR

- Liquid metals are the preferred option due to their excellent heat transfer properties
- Possible choices of liquid metal coolant are mercury, lead, sodium and a sodium-potassium (NaK) mixture
- Sodium best choice:
  - High density: 0,85 g/cm3 at 400 °C
  - High specific heat : 1.28 J $°C^{-1}g^{-1}$
  - High boiling point: 883 °C
  - Melting point: 98 °C
  - Strongly activated: Na-24, 15 h half-life
  - Intense gamma emitter: 1,4 MeV

Pool Type Heat Transfer System



1 Brennelemente (Spaltzone)
2 Brennelemente (Brutzone)
3 Steuerstäbe
4 Natriumumwälzpumpe
5 Natrium im Primärkreis
6 Reaktortank (rostfreier Stahl)
7 Sicherheitstank
8 Reaktorkuppel
9 Deckel
9a Schutzgasatmosphäre (Argon)

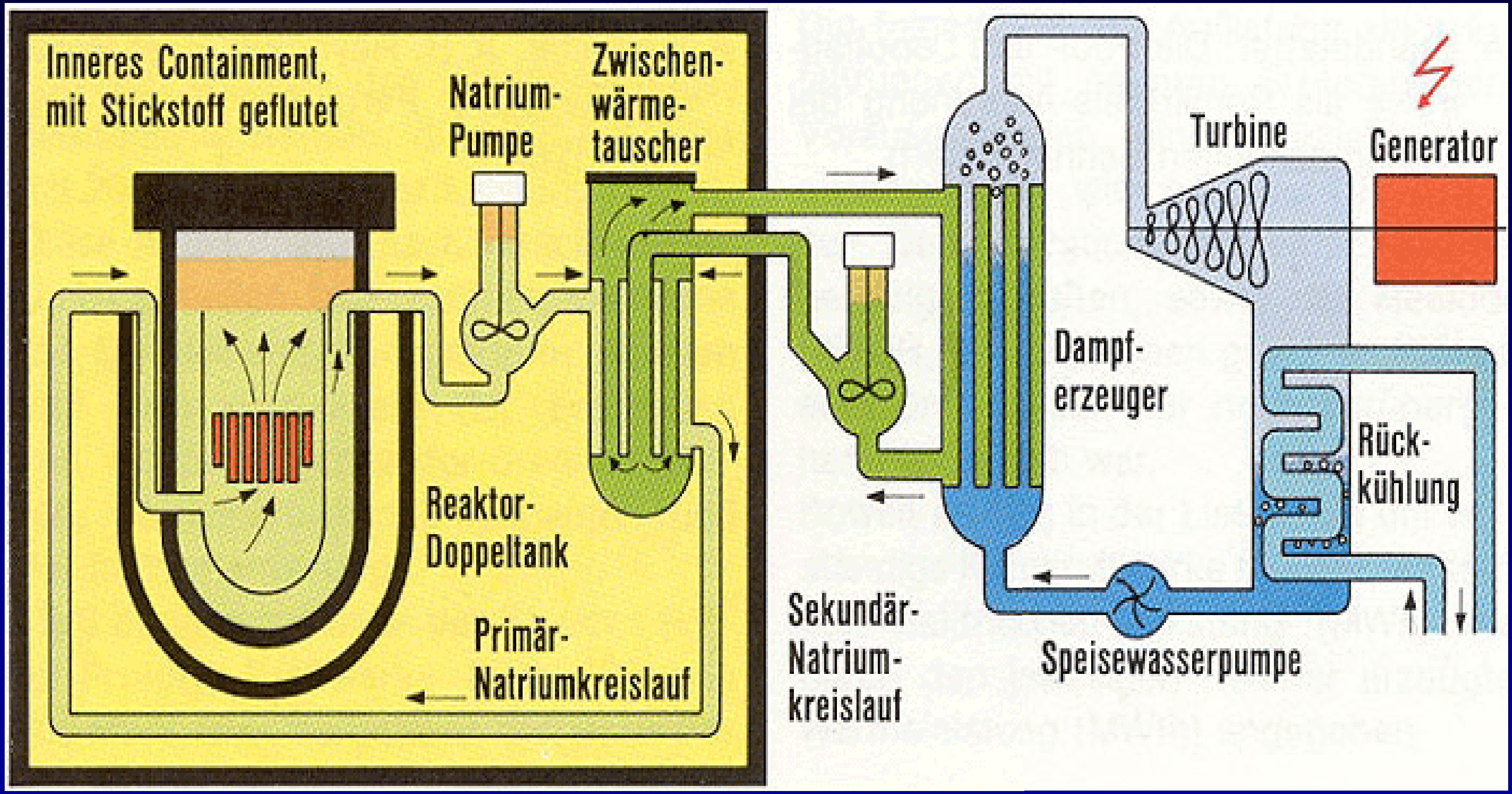
10 Zwischenwärmetauscher (einer von vier)
11 Sekundär-Natriumkreislauf
12 Sekundär-Natriumpumpe
13 Dampferzeuger (einer von vier)
14 Frischdampf
15 Vorwärmanlage
16 Speisewasserpumpe
17 Kondensator

18 Flußwasser zur Kühlung
19 Kühlwasserpumpe
20 Hochdruckteil der Turbine
21 Niederdruckteil der Turbine
22 Generator
23 Reaktorgebäude

Pool Type

- Vessel very simple design with only few pipes
- Disadvantages of the pool: vessel is large, must be fabricated on-site, difficult quality assurance
- In operation internal structures difficult to inspect as they operate under liquid sodium

Loop Type Heat Transfer System



Loop Type

- Vessel much smaller
- Can be built in a factory and transported to the site
- The pipework of the loop reactor may be longer and more complicated but it is easier to inspect

Table of past and present LMFBRs

Reactor Name	Country	Location	Criticality	MWth	MWe	Fuel	Cooling System
EBR-I	USA	Arco - Idaho	1951	1.2	0.2	U	1 loop
BR5	USSR	Obninsk	1958	5.9	-	PuO_2 / UC	2 loops
DFR	UK	Dounreay	1959	60	14	UO_2	24 loops
Enrico Fermi	USA	Detroit	1963	300	61	U	3 loops
EBR-II	USA	Arco - Idaho	1963	62.5	20	U	pool
KNK-II	W.Germany	Karlsruhe	1977	-	20	PuO_2 -UO_2	2 loops
Rapsodie	France	Cadarache	1967	40	-	PuO_2 -UO_2	2 loops
SEFOR	USA	Arkansas	1969	20	-	PuO_2 -UO_2	1 loop

Table of past and present LMFBRs

BN 350	Kazachstan	Chevchenko	1972	1000	150	PuO_2-UO_2	6 loops
Joyo	Japan	Oarai	1977	100	-	PuO_2-UO_2	2 loops
Phenix	France	Marcoule	1973	560	250	PuO_2-UO_2	pool
PFR	UK	Dounreay	1974	600	250	PuO_2-UO_2	pool
FFTF	USA	Hanford	1980	400	-	PuO_2-UO_2	3 loops
BN 600 2 units	USSR	Beloyarsk	1980	1470	600	PuO_2-UO_2	pool
Super-phenix	France	Creys-Malville	1985	2900	1200	PuO_2-UO_2	pool
SNR 300	W.Germany	Kalkar	-----	736	312	PuO_2-UO_2	3 loops
MONJU	Japan	Tsuruga	1994	714	300	PuO_2-UO_2	3 loops

France/Superphenix in Creys-Malville

- Criticality: 9/1985
- Shut down: 12/1998
- 1174 $MW_{e\ net}$
- 3000 MW_{th}
- Efficiency: 41.3%

Technical Data of the Superphenix

- Fuel assemblies:
  - Number of fuel assemblies: 364
  - Total length: 5.4 m
  - Active length: 1.95 m
  - Number of rods per assembly: 271
  - Outer diameter fuel rod: 8.5 mm
  - Fuel: MOX 15%UO_2, 85%PuO_2
  - Maximum burn up: ca. 100 000 MWd/ton
  - Cladding: Stainless steel

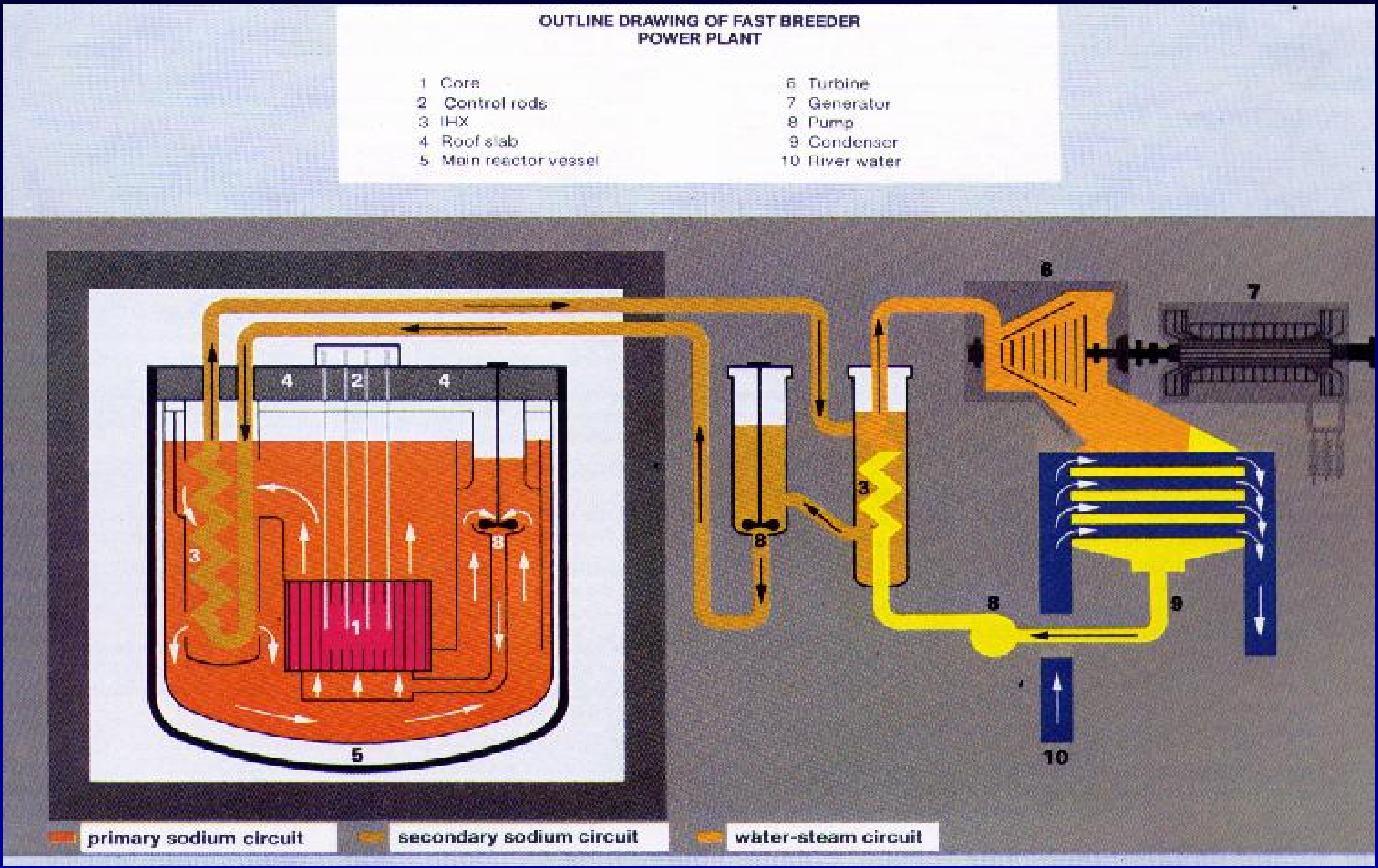
Technical Data of the Superphenix

- Breeding assemblies:
  - Number of fuel assemblies: 233
  - Total length: 5.4 m
  - Active length: 1.95 m
  - Number of rods per assembly: 91
  - Outer diameter fuel rod: 10.5 mm
  - Material: Depleted U-238
  - Cladding: Stainless steel

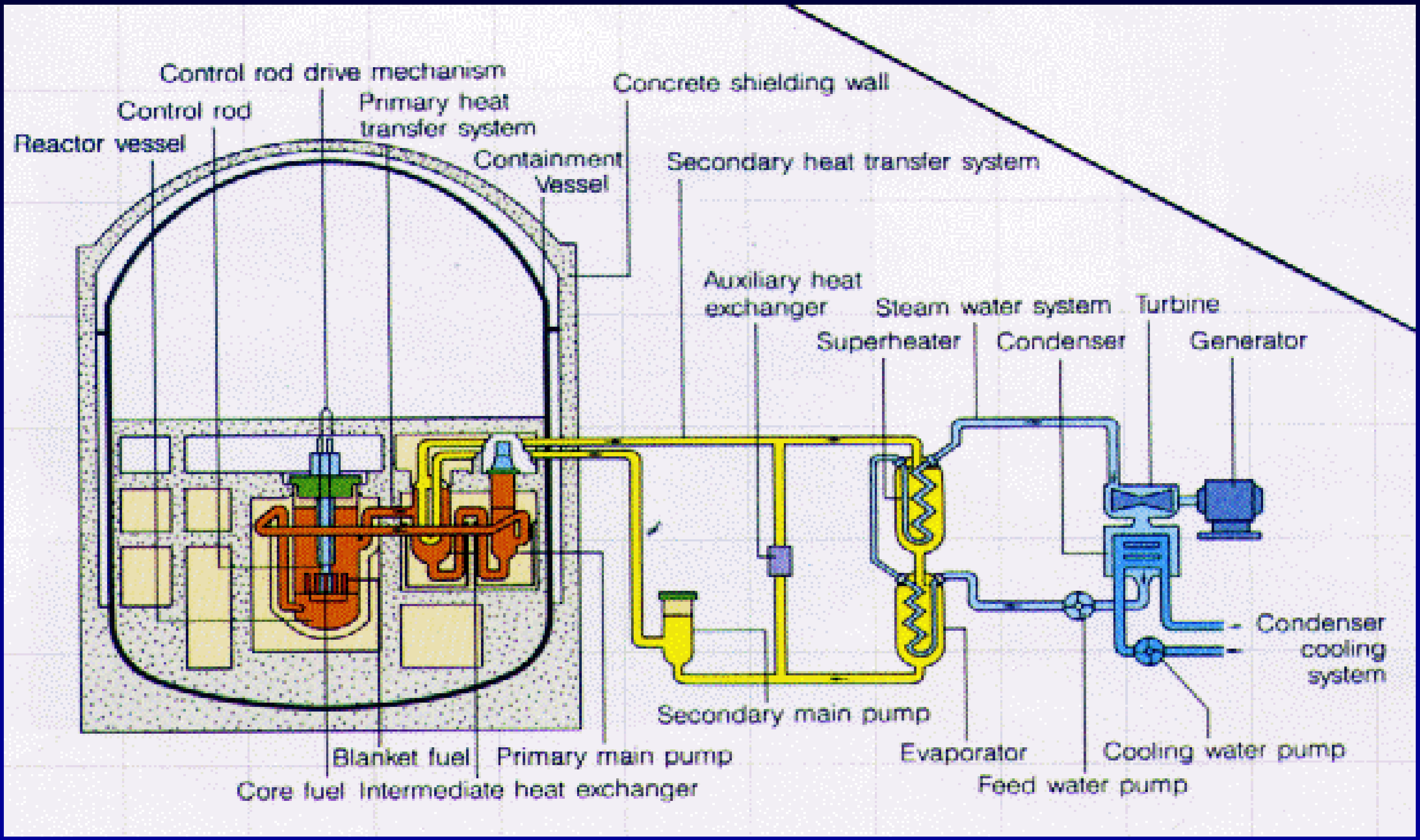
Superphenix Shut Down Systems

- Primary shut down system:
  - **Number of control rods: 21**
  - **Number of absorber fingers per control rod: 31**
  - **Absorber material: Stainless steel**
  - **Absorber length: 1.3 m**
- Secondary shut down system:
  - **Number of absorber segments: 3**
  - **Number of absorber segments per control element: 3**
  - **Absorber material: Boron carbide**

Superphenix Coolant Circuits



Superphenix Heat Transfer System



Superphenix Heat Transfer System

- Number of primary sodium pumps: 4
- Number of intermediate (Na/Na) heat exchangers (IHX): 8
- Number of secondary sodium pumps: 8
- Number of steam generators: 4
- Number of feedwater pumps: 4

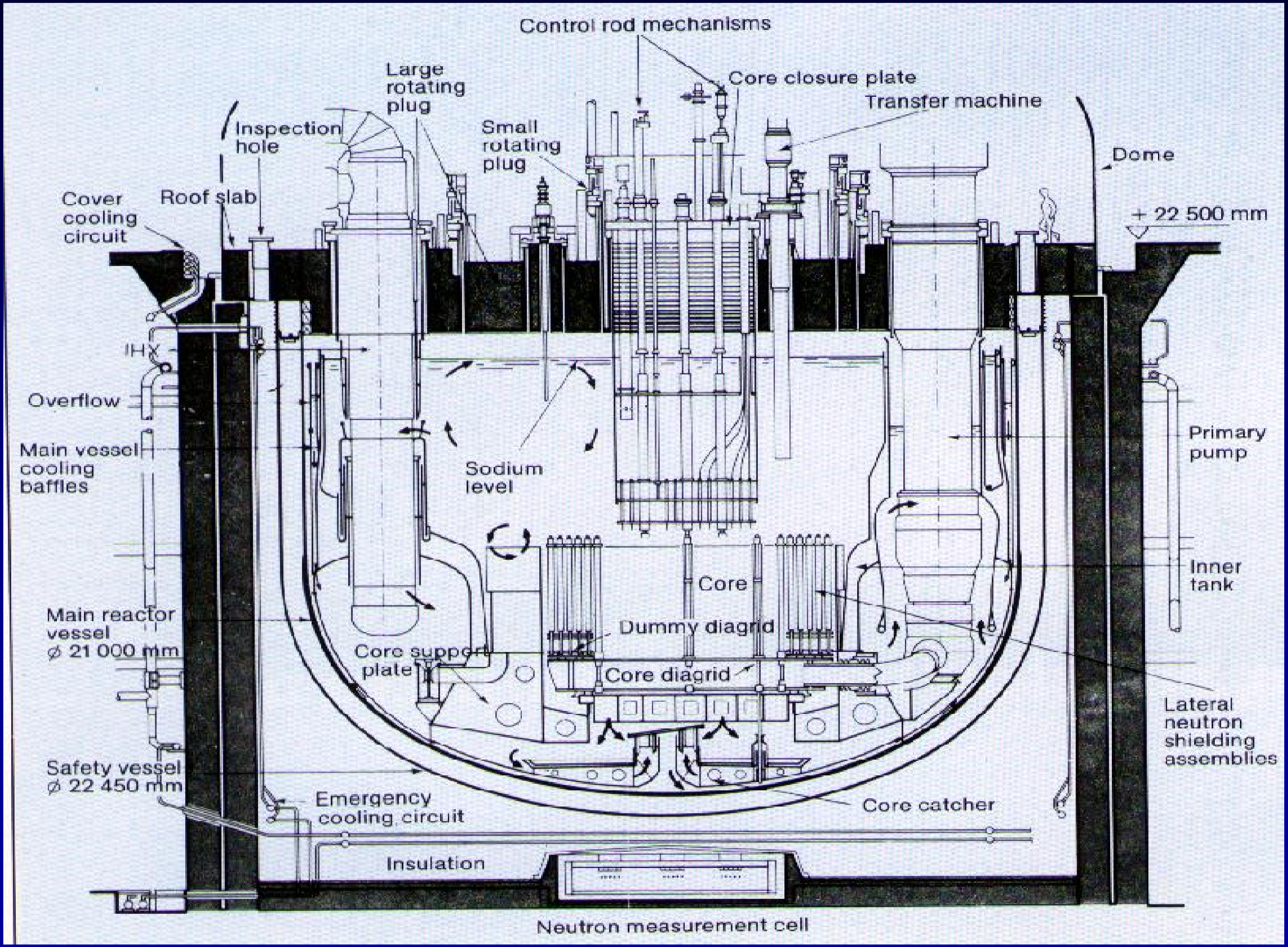
Superphenix Heat Transfer System

- Primary (Na) Coolant Circuit:
  - Total amount: 3250 tons
  - Core inlet temperature: 395 ˚C
  - Core outlet temperature: 545 ˚C
  - Inlet intemediate heat exhanger (IHX): 542 ˚C

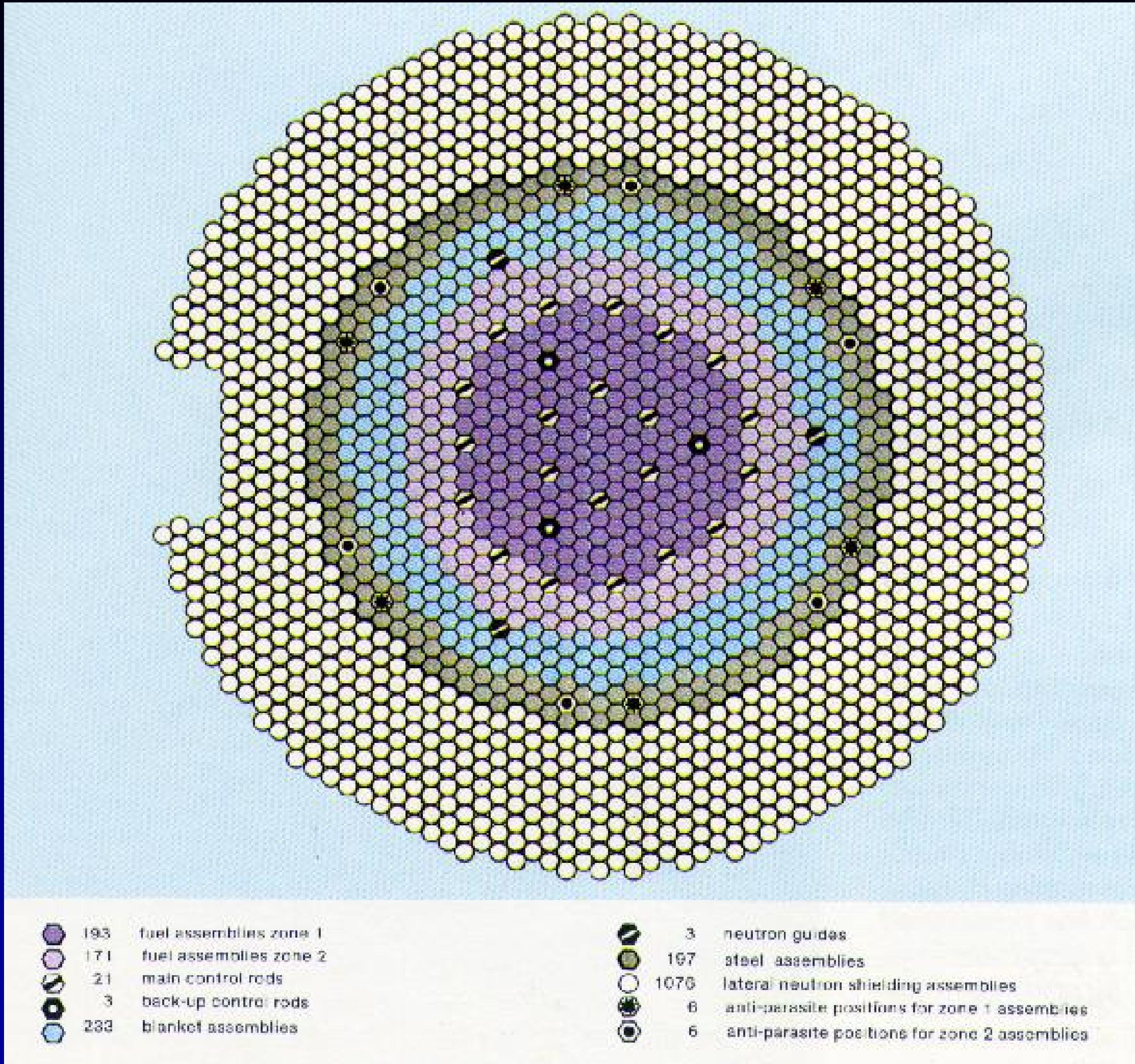
Superphenix Heat Transfer System

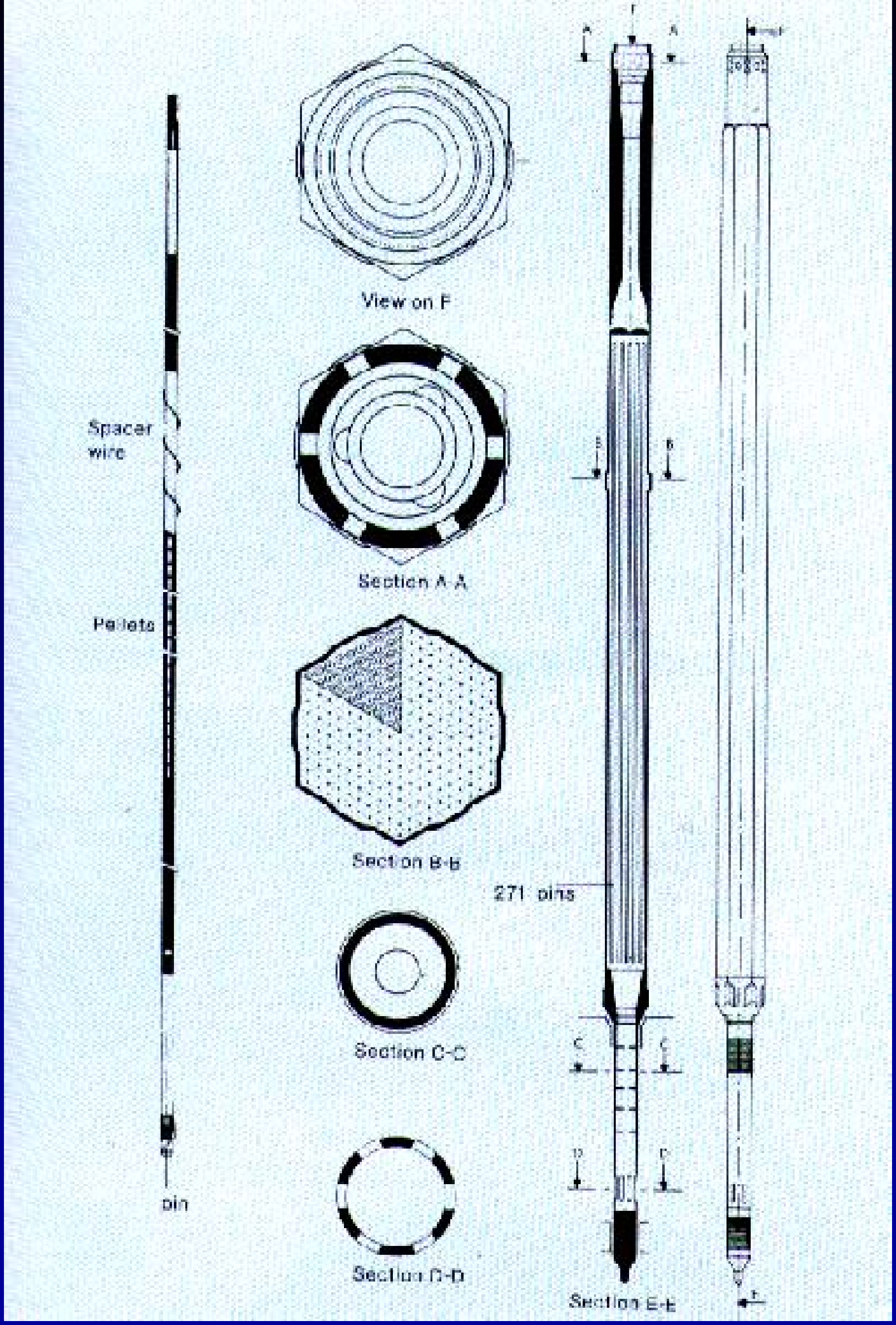
- **Secondary (Na) Coolant Circuit:**
  - Total amount: 1500 t
  - Steam Generator (SG) inlet temperature: 542 ˚C
  - SG outlet temperature: 345 ˚C
  - IHX outlet: 542 ˚C
  - IHX inlet: 345 ˚C
- **Water – Steam Circuit:**
  - SG inlet: 237 ˚C
  - SG outlet: 487 ˚C

Reactor Tank Internals



Reactor Core

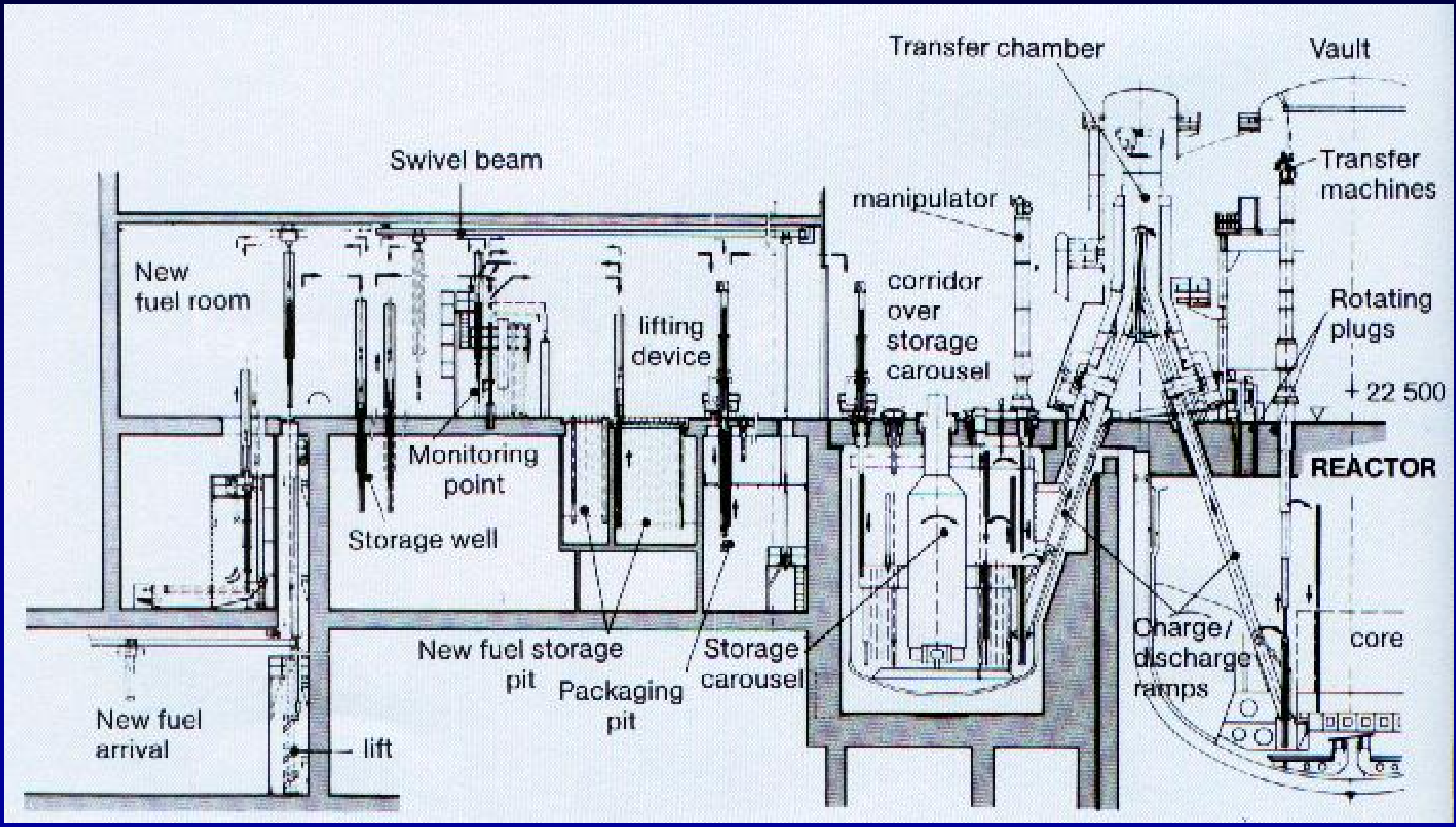




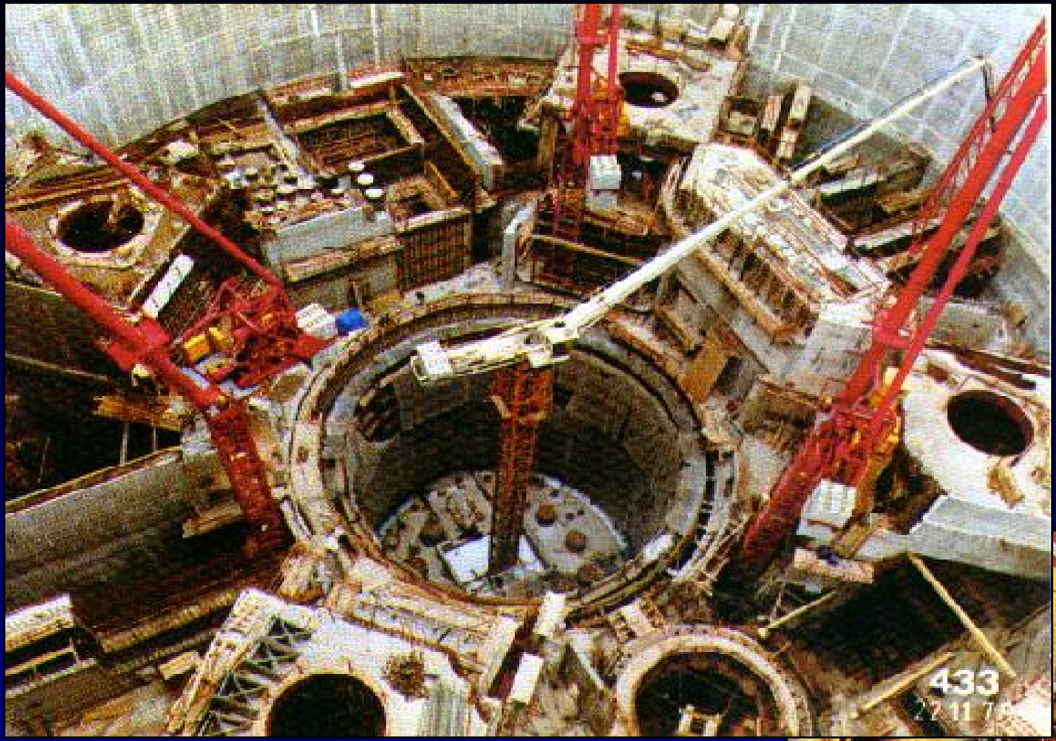
Fuel Assembly

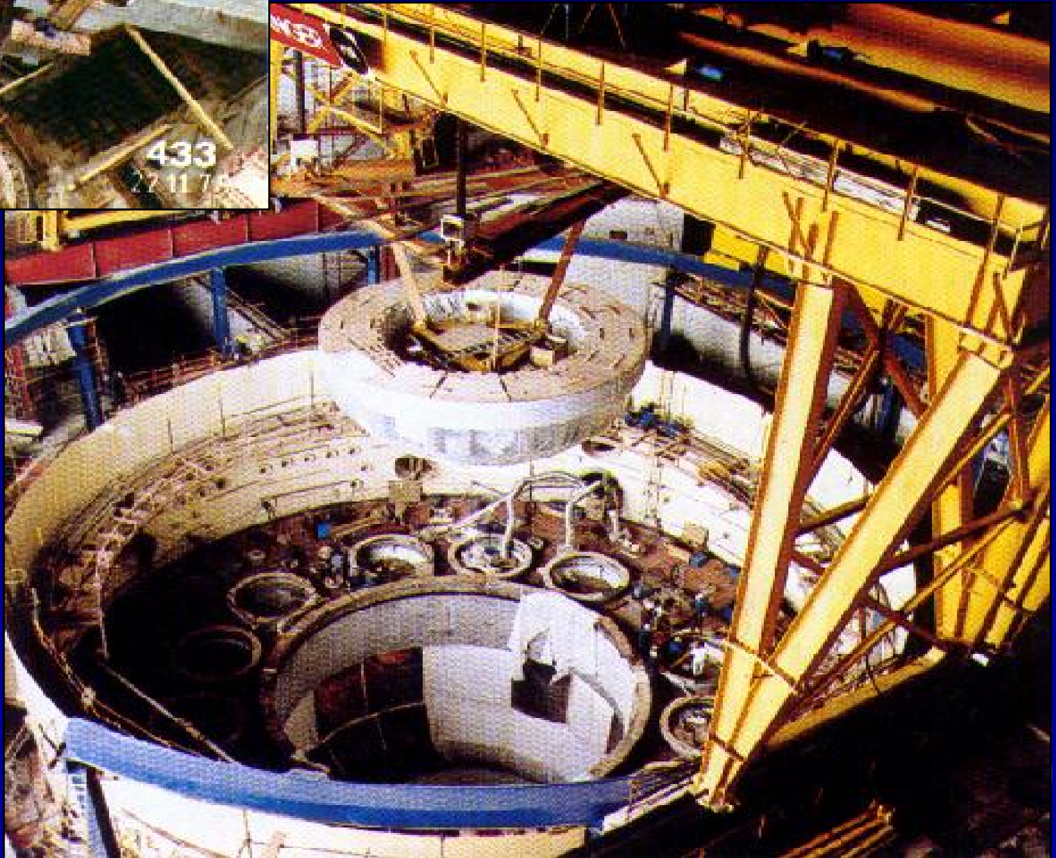
- **Overall length: 5.4 m**
- **Active length: 1.95 m**
- **Total number of assemblies in core:354**
- **Number of rods per assembly: 271**
- **Cladding material: SST**
- **Maximum cladding temperature: 620 °C**

Refuelling Procedure



Reactor Foundation

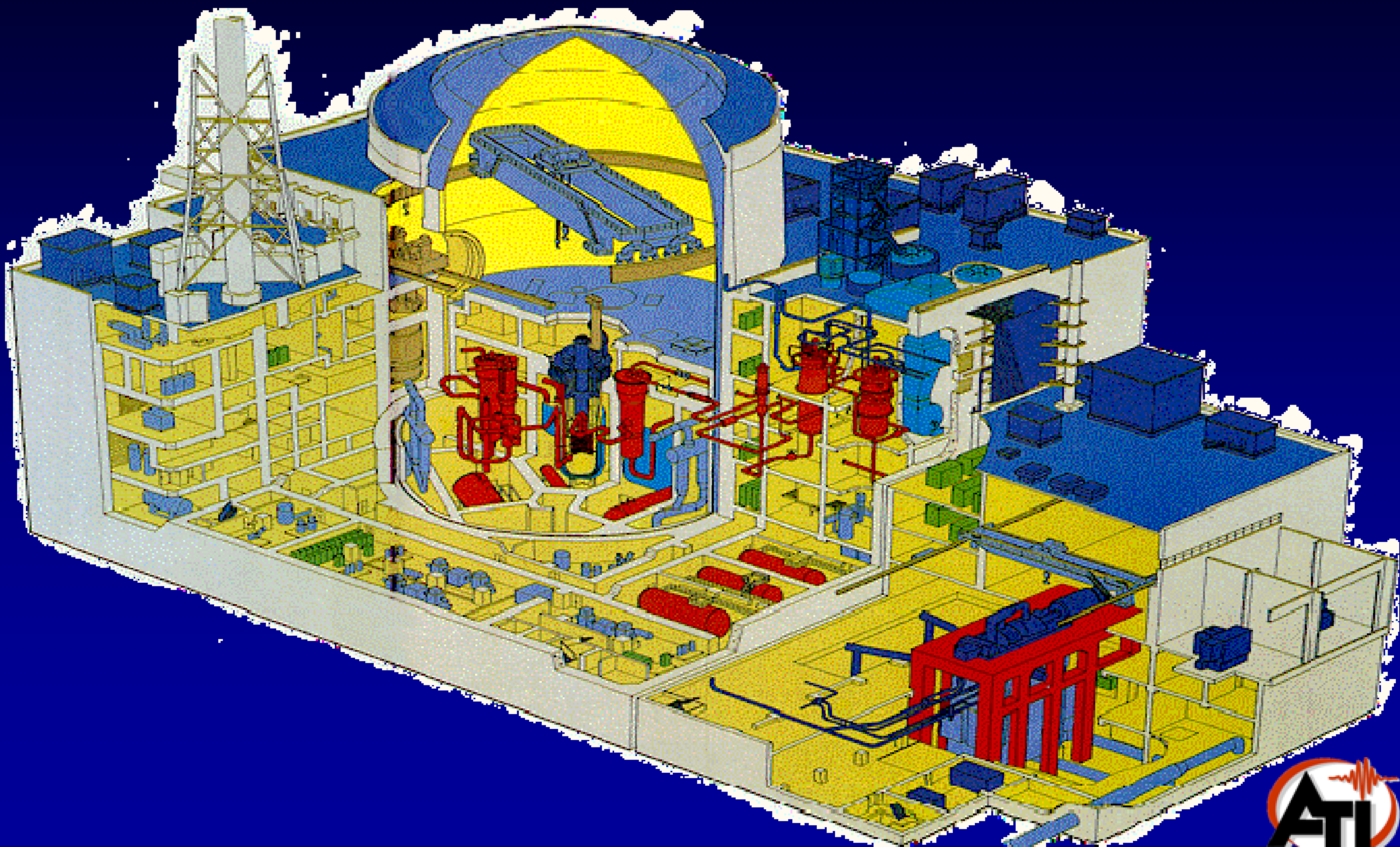




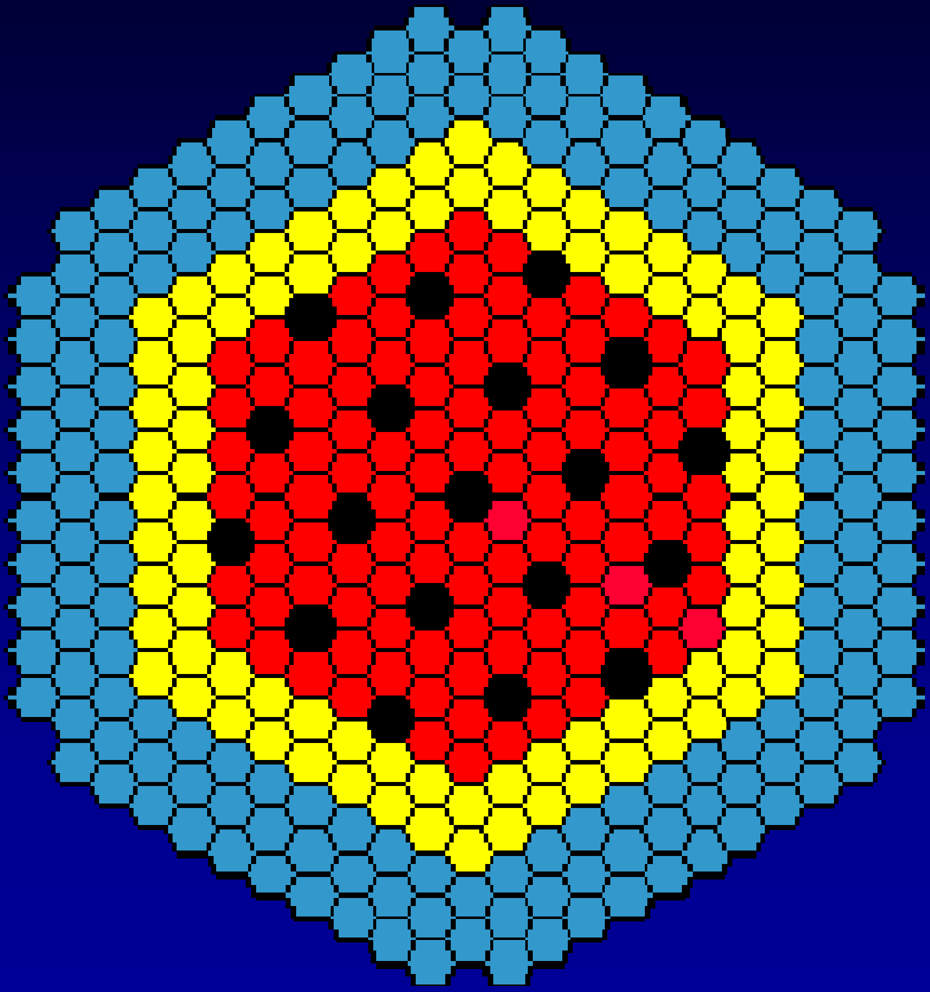
LMFBR Monju/Japan

- First criticality: 8/1994
- Cooling System: Na cooled (loop-type)
- Thermal output: 714 MW_{th}
- Electrical output: 280 MW_e
- Fuel: $PuO_2 + UO_2$
- Plutonium enrichment
- Inner core: 16 % Pu 239
- Outer core: 21% Pu 239
- Core Dimensions:
- Diam./Height: 180/93 cm
- Volume: 2340 liters

Monju General View



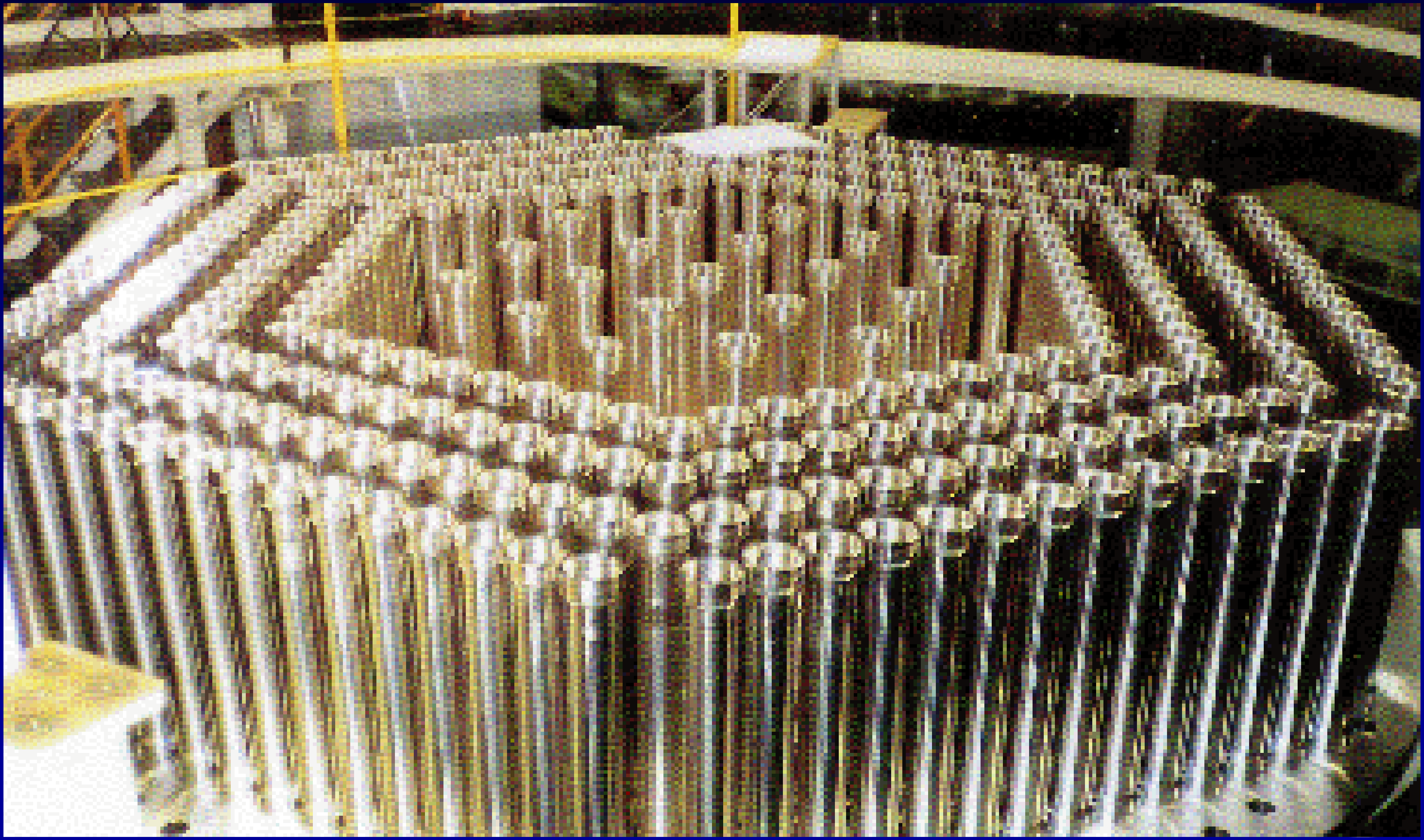
Reactor Core

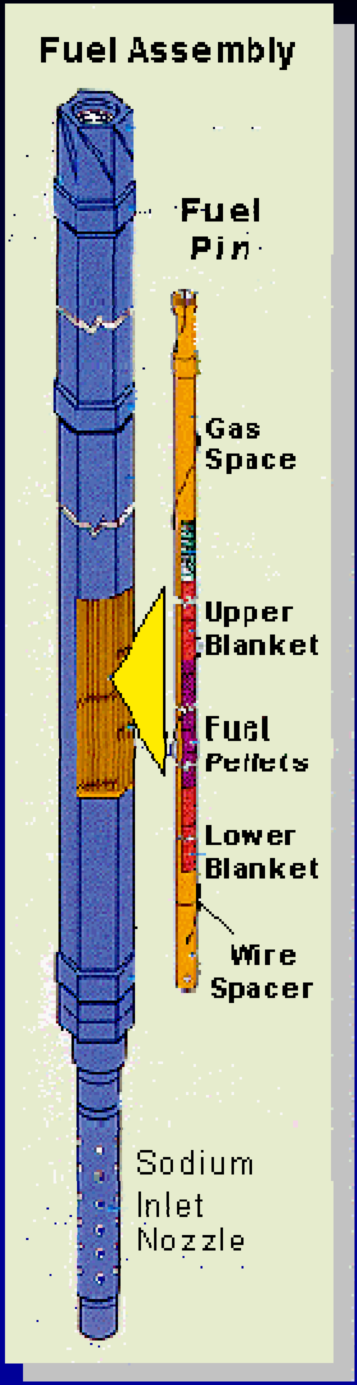


Breeder Core composed of three regions:

1. Inner core: U-238+Pu-239
2. Outer core: U-238+Pu-239 (higher conc)
3. Breeding blanket (U-238)
4. Reflector elements not shown

View on Core Structure





Fuel Assembly

- Hexagonal: 169 rods per assembly, in center 92 cm fuel zone (U-238+Pu239), above and below breeder zone (U-238 only)
- Fuel rod: 2.8 m long, 6.5 mm diameter
- Fuel Mass:
  - Core (U+Pu metal): 5.9 t
  - Blanket (U metal): 17.5 t
- Number of fuel assemblies:
  - Inner core: 108
  - Outer core: 90
- Cladding material: SS 316
- Power density: 275 kW / litre

Breeder Blanket

- Radial breeder assemblies: 172
- Blanket thickness:
  - Upper: 30 cm
  - Lower: 35 cm
  - Radial: 30 cm
- Control rods:
  - Fine: 3
  - Coarse: 10
  - Back-up: 6
- Breeding ratio: 1.2 approx.

Cooling Circuits

- Primary sodium temperature:
  - Reactor inlet / outlet: 397°C / 529°C
- Secondary sodium temperature:
  - IHX inlet / outlet: 325°C / 505°C
- Number of loops: 3
- Reactor vessel dimensions:
  - Height / diameter: 18 / 7 m
- Steam Pressure: 127 kg/cm^2
- Interval between refuelling: 6 months
- Refuelling system: Single rotating plug with fixed arm fuel handling machine

Animated Flow Diagram

- http://www.jnc.go.jp/zmonju/mjweb/schemati.htm

References

- http://www.jnc.go.jp/zmonju/mjweb/index.htm
- http://www.schneller-brueter.de/index2.htm
- http://www.ippe.obninsk.ru/rnpp/rnpp_eng.html
- http://www-frdb.iaea.org/index.html

Feedback from YOU

- Ich hätte gerne von Ihnen ein Feedback zu einigen Fragen:
- Welche Themen wurden zu ausführlich behandelt?
- Welche Themen haben Sie vermisst? (zB. Forschungsreaktoren, Reaktoren für Antriebe, Nuklearbatterien etc.)
- War die Bildqualität OK oder sind manche Bilder zu detailliert?
- Informationen über englische Fachausdrücke ausreichend oder zu wenig?
- Literaturhinweise ausreichend oder zu wenig?
- Bitte geben Sie Ihre Kommentare nach der Vorlesung in die vorbereitete Box

- Danke H.Böck