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OVERVIEW OF THE THORIUM FUEL CYCLE

DR. MAGDI RAGHEB
Department of Nuclear, Plasma and Radiological Engineering,
University of Illinois at Urbana-Champaign,
216 Talbot Laboratory, 104 South Wright Street, Urbana, Illinois 61801, USA.
mragheb@illinois.edu,
http://www.mragheb.com

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Summary

An overview of the thorium fission fuel cycle is presented. The global and local Th resources are assessed, and its ability to provide a practically unlimited energy supply through the breeding process is discussed. Two approaches to the use of thorium are identified using either solid or liquid fuel.

The solid fuel approach is exemplified in the pilot Shippingport fission reactor plant using the seed and blanket approach, in the High Temperature Gas Cooled Reactor (HTGR) in a pebble bed and a prismatic moderator and fuel configurations. The General Atomics (GA) Company built two thorium reactors over the 1960-1970 period. The first was a 40 MWe prototype at Peach Bottom, Pennsylvania operated by Philadelphia Electric. The second was the 330 MWe Fort St. Vrain reactor for Public service of Colorado which operated between 1971 and 1975. The AVR, TFTR-300 pebble-bed reactor was built and operated in Germany. Existing research reactor installations are centered around solid fuel. This approach is characterized by marginal breeding capabilities requiring sometimes the use of neutron multiplication features such as the use of beryllium.

The liquid fuel approach was pursued on an experimental basis in the Molten Salt Breeder Experiment (MSBR) over the period 1950-1976 at the Oak Ridge National Laboratory (ORNL). The Molten Salt Breeder Reactor is also understudy as a Generation IV reactor concept.

A comparison between the solid and liquid fuels approaches identifies concrete safety and breeding advantages, making the liquid fuel approach worthy of serious consideration for a long-term nuclear non-carbon energy option.

THORIUM

Thorium (Th) is named after Thor, the Scandinavian god of lightning.

It occurs in nature in the form of a single isotope: Th^{232}.

It occurs in Thorite ($ThSiO_4$) and Thorianite ($ThO_2 + UO_2$).

It is 3 times as abundant as uranium and as abundant as lead and molybdenum.

It is commercially obtained from the monazite mineral containing 3-9 percent ThO_2 with other rare-earths minerals.

Its large abundance would make it in the future valuable for electrical energy generation with supplies exceeding both coal and uranium combined.

This would depend on breeding of the fissile isotope U^{233} from thorium according to the breeding reactions:

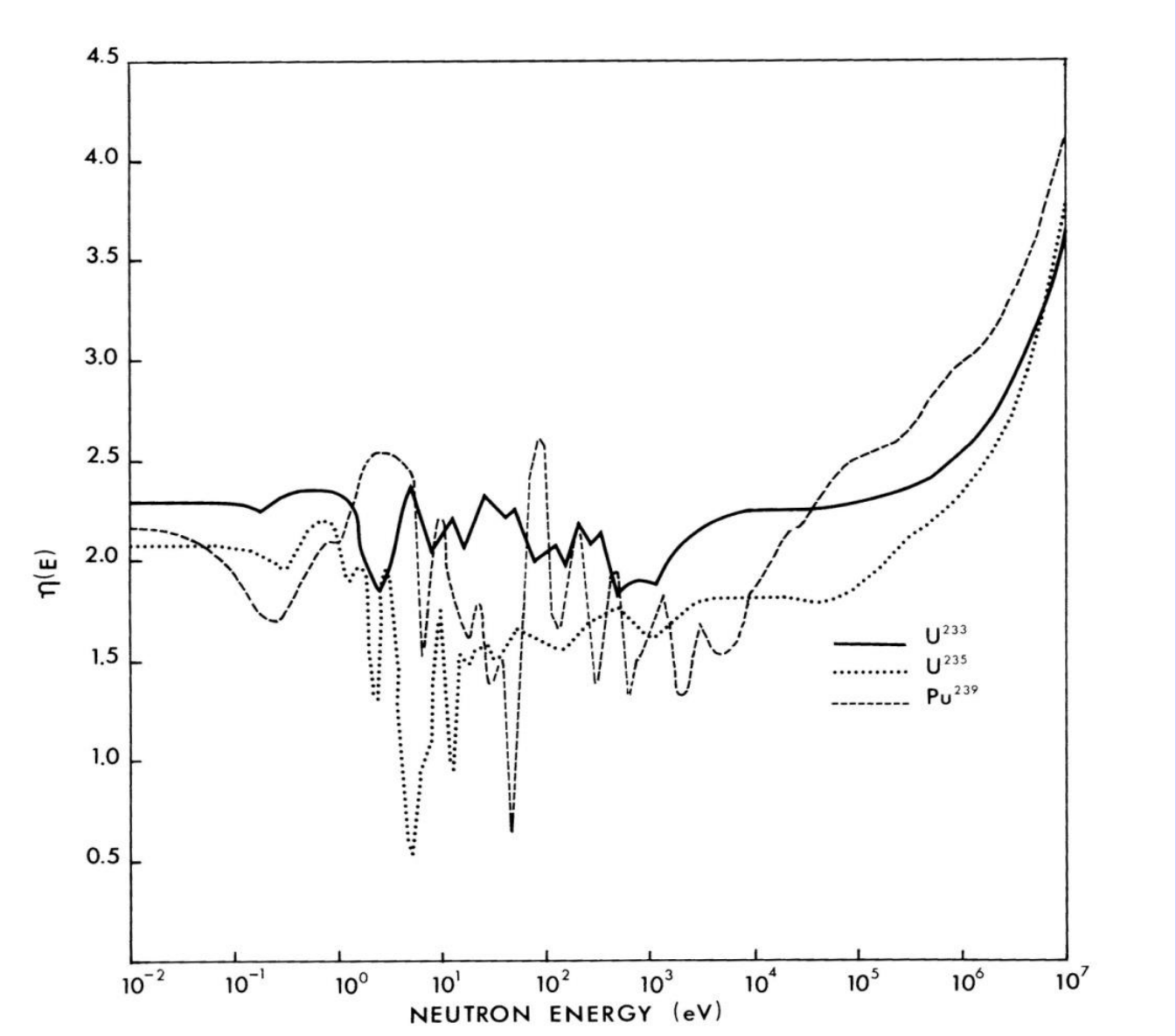
$$ {}_0n^1 + {}_{90}Th^{232} \rightarrow {}_{90}Th^{233} \ (t_{1/2} = 22.2 \text{ min}) + \gamma $$

$$ {}_{90}Th^{233} \rightarrow {}_{91}Pa^{233} \ (t_{1/2} = 27.0 \text{ days}) + {}_{-1}e^0 + \nu^* + \gamma $$

$$ {}_{91}Pa^{233} \rightarrow {}_{92}U^{233} (t_{1/2} = 1.592 \times 10^5 \text{ years}) + {}_{-1}e^0 + \nu^* + \gamma $$

$$ {}_0n^1 + {}_{90}Th^{232} \rightarrow {}_{92}U^{233} + 2\,{}_{-1}e^0 + 2\nu^* + 3\gamma $$

Regeneration factor η(E) as a function of neutron energy for the different fissile isotopes.
Breeding in the Thorium-U^{233} fuel cycle can be achieved with thermal or fast neutrons.



CONVERSION OR BREEDING RATIO

The conversion ratio C is defined as:

$$C = \frac{\text{average number of fissile nuclides produced}}{\text{average number of fissile nuclides consumed}}$$

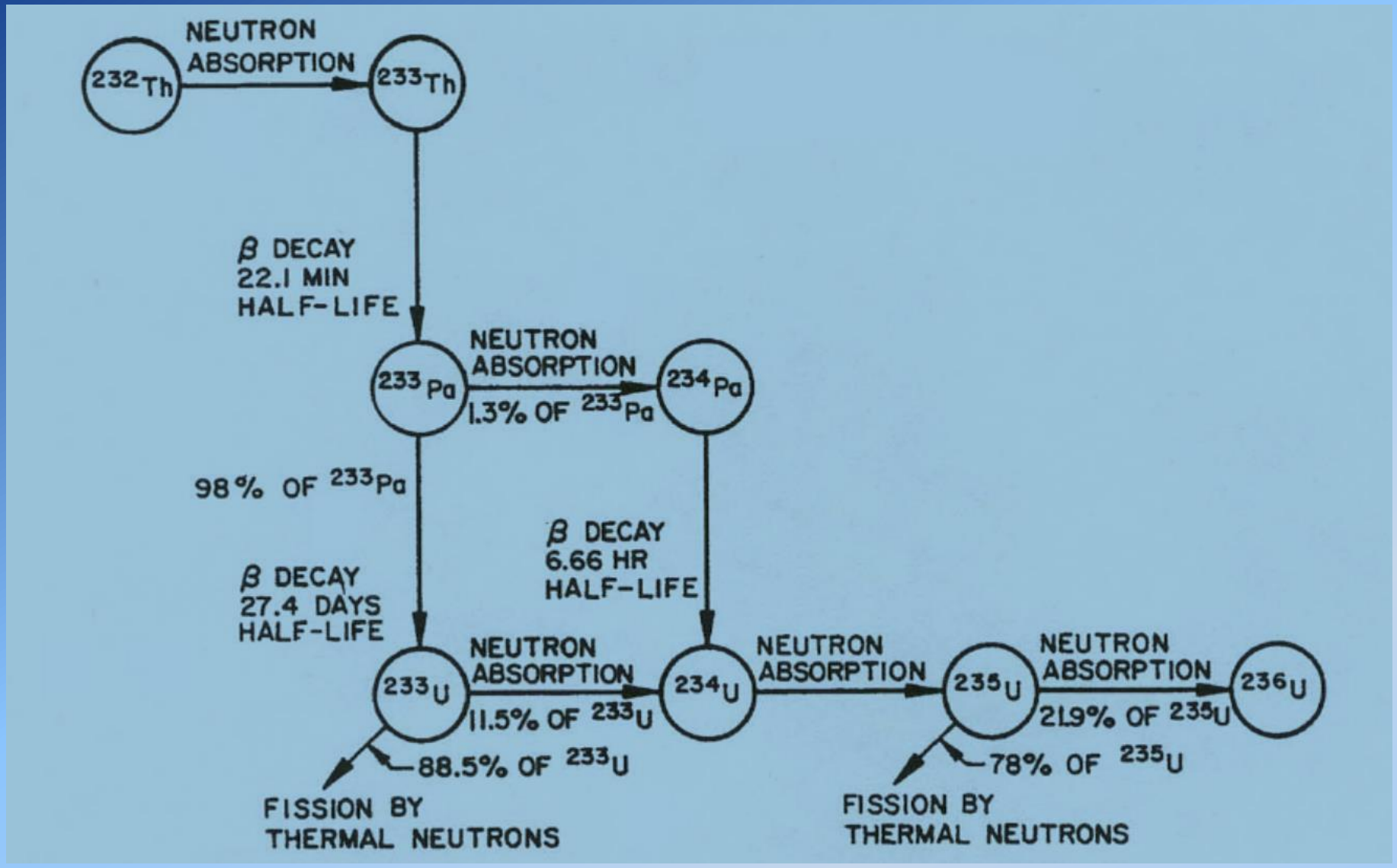
When N nuclei of fissile fuel are consumed, NC nuclei of fertile fuel are converted into fissile nuclei. If the process is repeated, the consumption of N fuel nuclei results in the conversion of a total number of fissile nuclei as:

$$N_{total} = N + NC + NC^2 + NC^3 + NC^4 + \ldots$$

$$= N(1 + C + C^2 + C^3 + C^4 + \ldots)$$

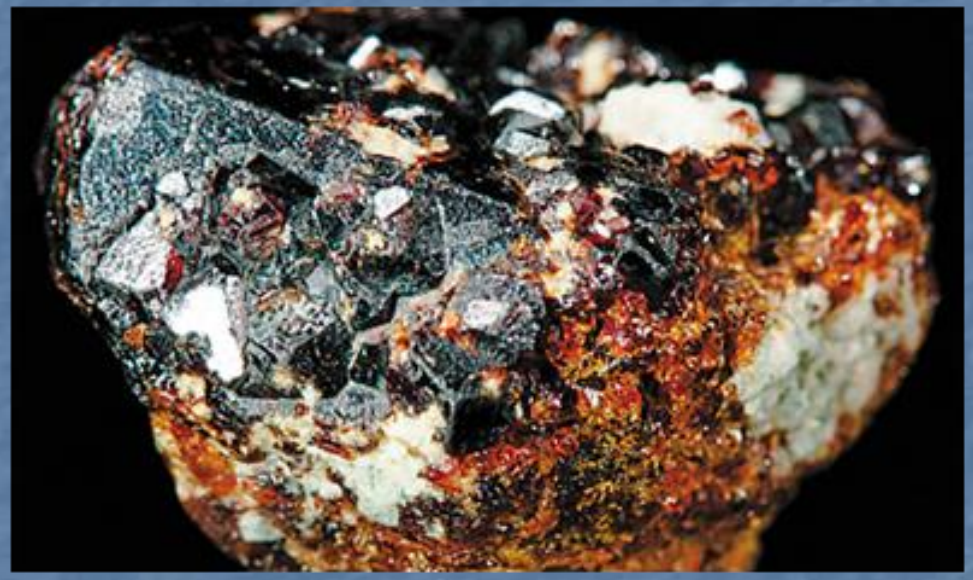
$$= N\frac{1}{1-C}, \forall\ 0 < C < 1.$$

When C = 1, an infinite amount of fissile fuel can be converted from a starting amount of fertile fuel. When C > 1 the sequence diverges since more than a fissile nucleus is created from a fertile nucleus and cannot be summed mathematically. In this case C is designated as B, the breeding ratio.


NEUTRON ABSORPTION
232Th
233Th
β DECAY 22.1 MIN HALF-LIFE
NEUTRON ABSORPTION
233Pa
234Pa
1.3% OF 233Pa
98% OF 233Pa
β DECAY 6.66 HR HALF-LIFE
β DECAY 27.4 DAYS HALF-LIFE
NEUTRON ABSORPTION
NEUTRON ABSORPTION
NEUTRON ABSORPTION
233U
234U
235U
236U
11.5% OF 233U
21.9% OF 235U
88.5% OF 233U
78% OF 235U
FISSION BY THERMAL NEUTRONS
FISSION BY THERMAL NEUTRONS

Thorium dioxide

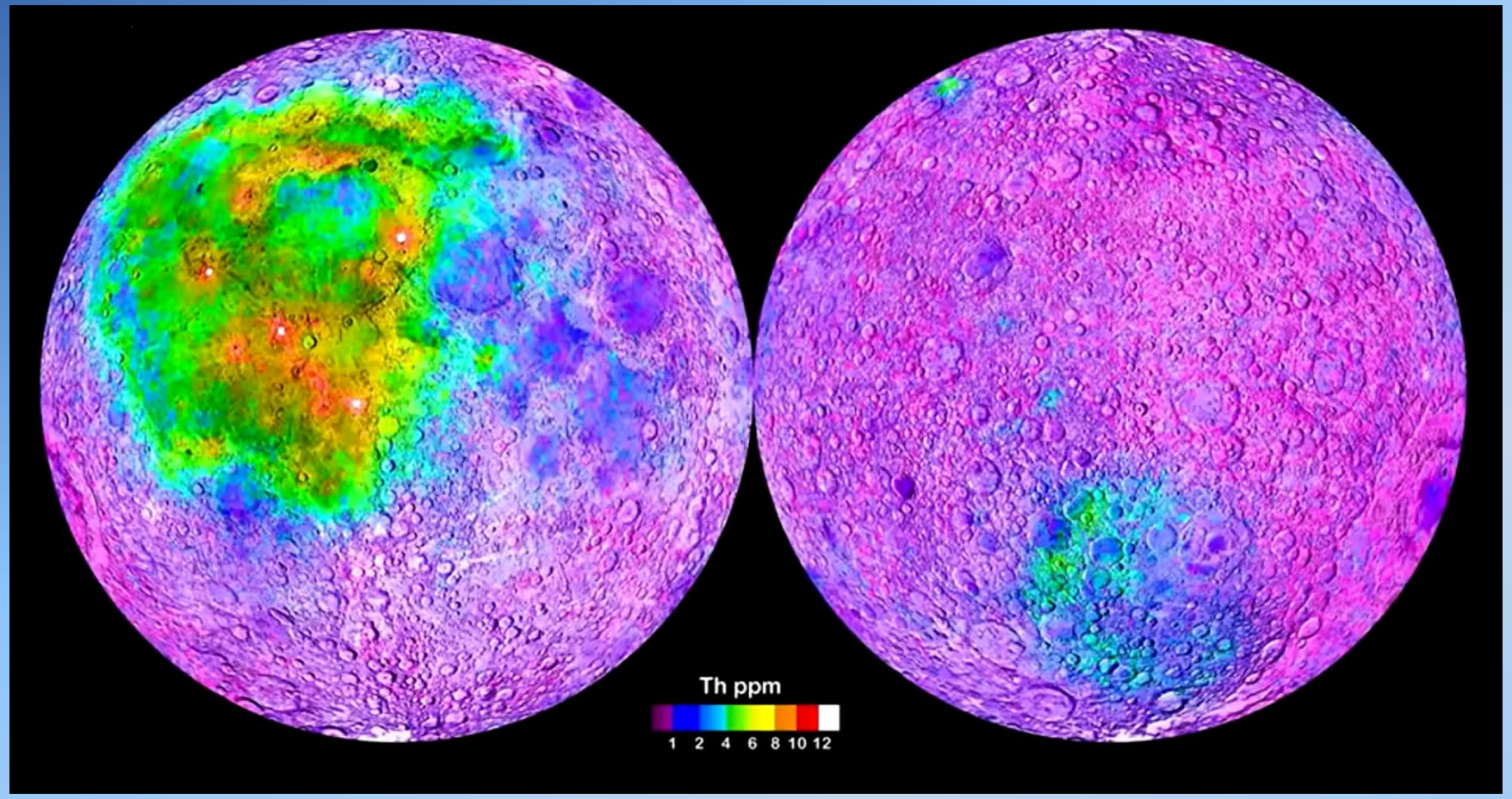
Monazite and Thorite Thorium ores



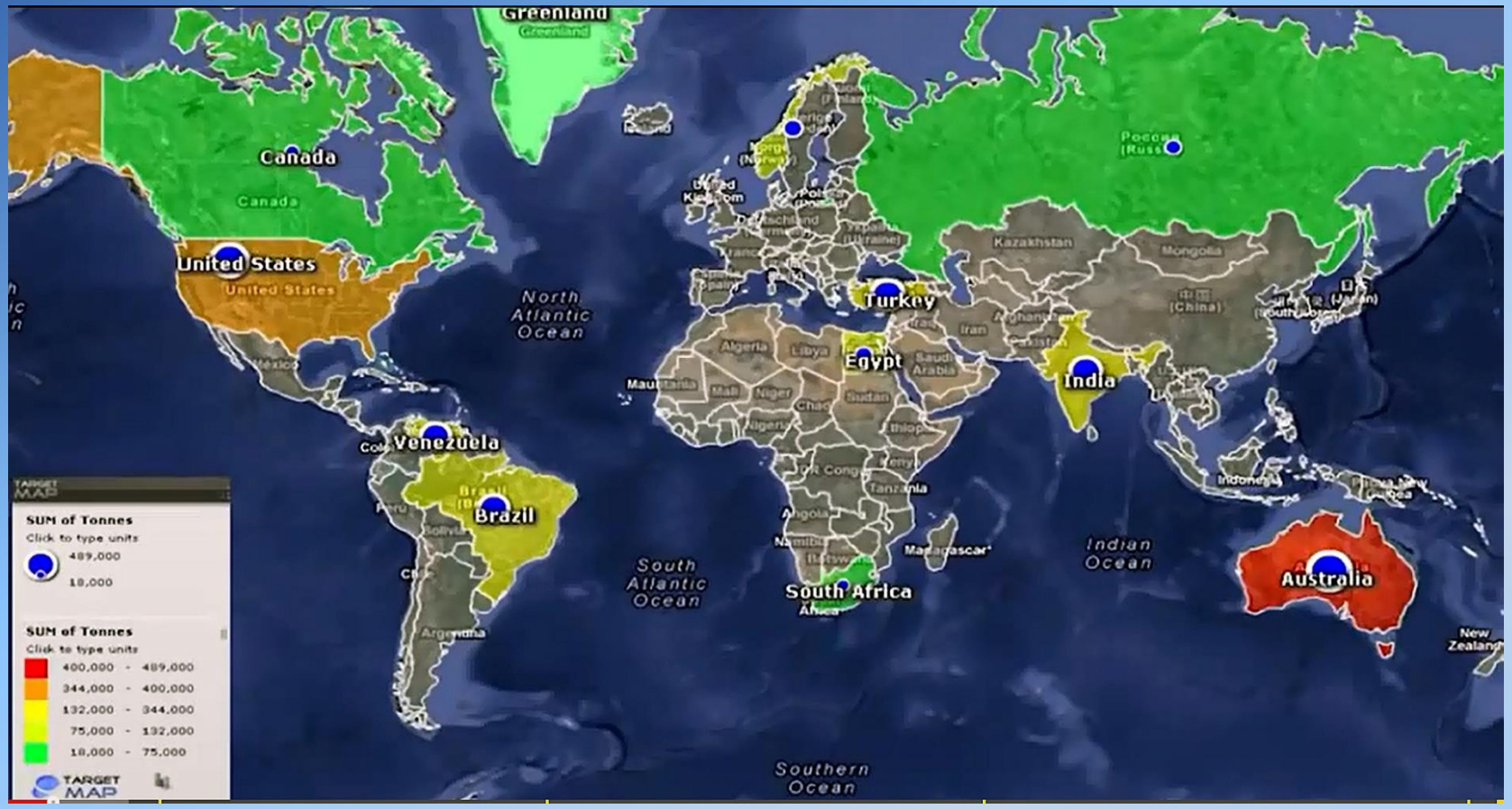
Thorium is more Abundant than Uranium in the Earth's Crust

Element	Symbol	Abundance [gms/ton]
Lead	Pb	16
Gallium	Ga	15
Thorium	**Th**	**10**
Samarium	Sm	7
Gadolinium	Gd	6
Praseodymium	Pr	6
Boron	B	3
Bromine	Br	3
Uranium	**U**	**2.5**
Beryllium	Be	2
Tin	Sn	1.5
Tungsten	W	1
Molybdenum	Mo	1
Mercury	Hg	0.2
Silver	Ag	0.1
Uranium^{235}	**U^{235}**	**0.018**
Platinum	Pt	0.005
Gold	Au	0.02

Thorium Abundance on the moon's surface



Global Thorium resources



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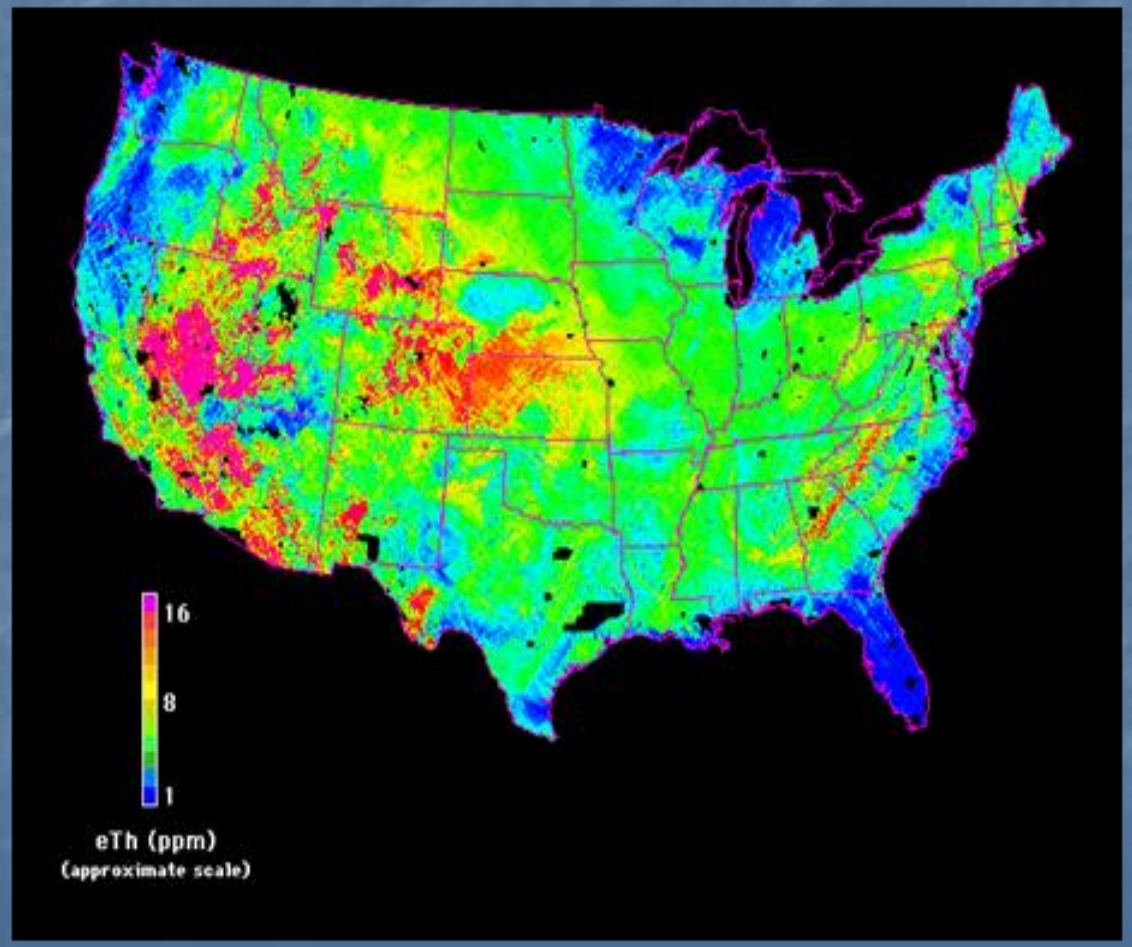
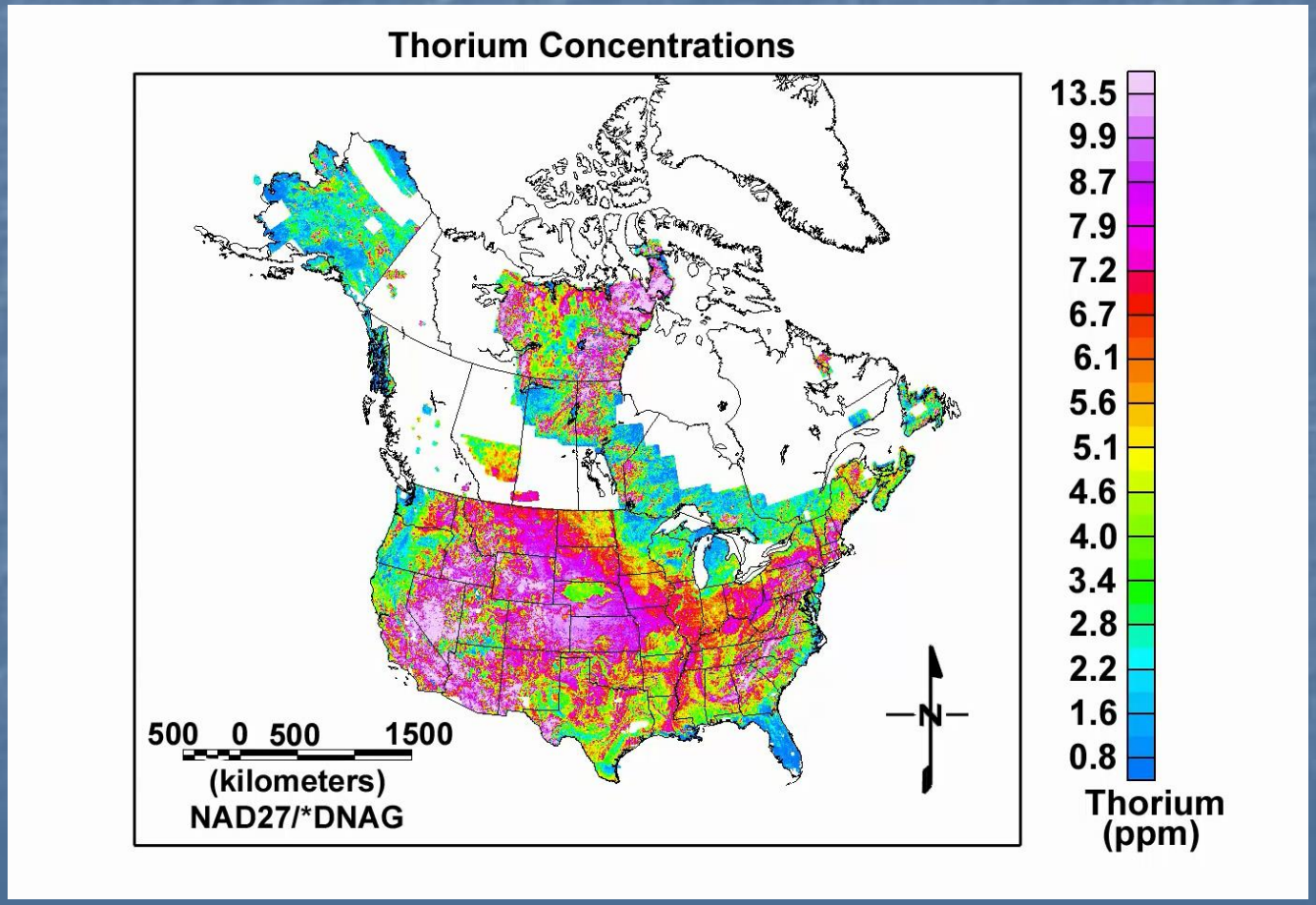
Th concentrations in ppm and occurrences in the USA and Canada. Source: USA Geological Survey Digital Data Series DDS-9, 1993.





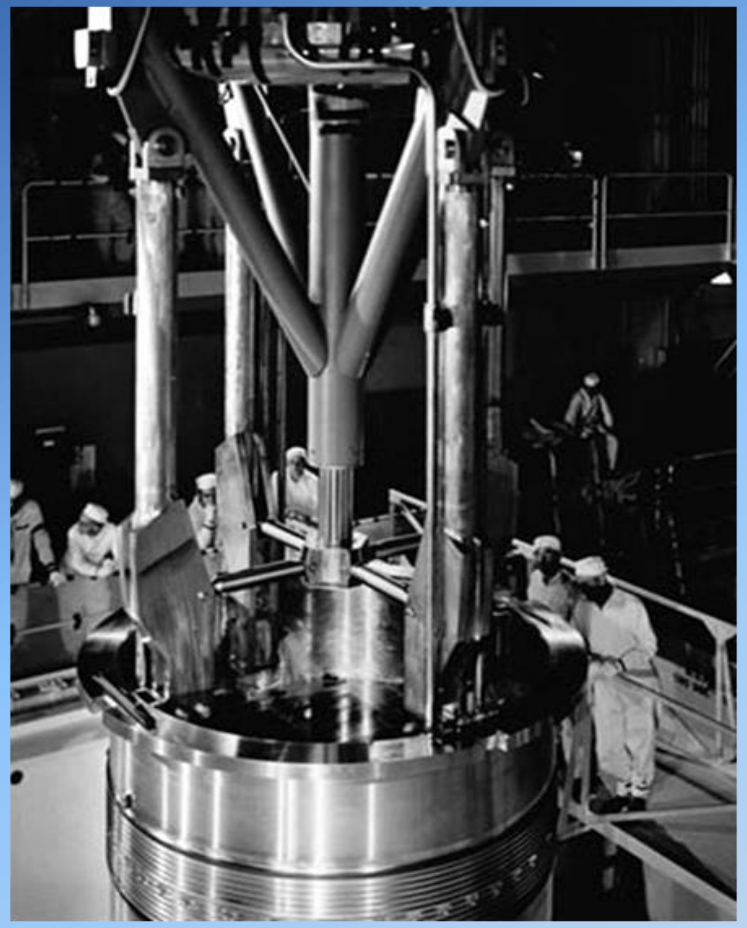
Estimated Global Thorium Resources

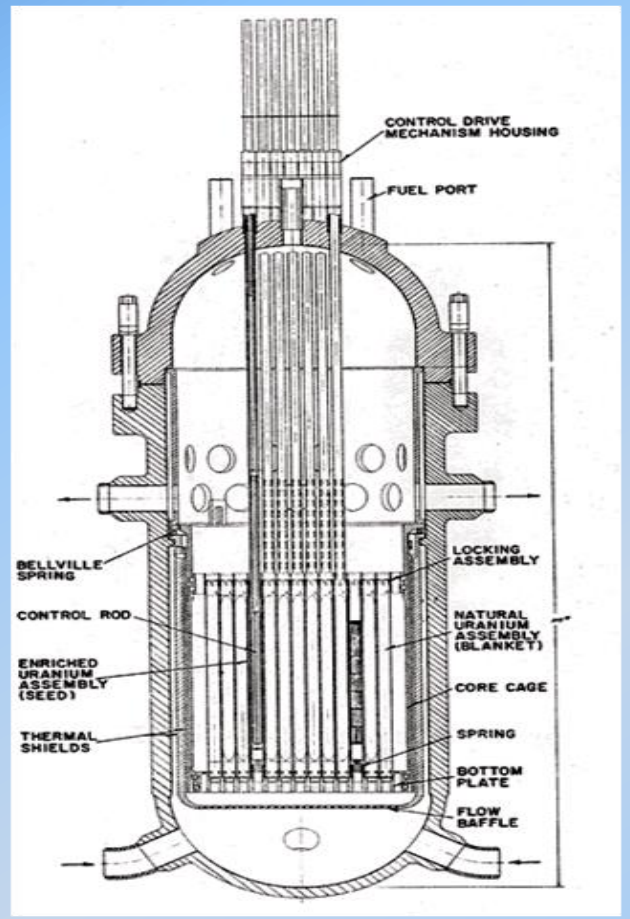
Country	ThO_2 Reserves [metric tonnes] USGS estimate 2010	ThO_2 Reserves [metric tonnes] NEA estimate	Mined amounts 2007 [metric tonnes]
USA	440,000	400,000	-
Australia	300,000	489,000	-
Turkey		344,000	
India	290,000	319,000	5,000
Venezuela		300,000	
Canada	100,000	44,000	-
South Africa	35,000	18,000	-
Brazil	16,000	302,000	1,173
Norway		132,000	
Egypt		100,000	
Russia		75,000	
Greenland		54,000	
Canada		44,000	
Malaysia	4,500		800
Other countries	90,000	33,000	-
Total	1,300,000	2,610,000	6,970

Lehmi Pass is a part of Beaverhead Mountains along the continental divide on the Montana-Idaho border, USA.
Its Th veins contain rare earth elements, particularly Neodymium.

Thorium stockpile in Nevada

The Shippingport reactor was the first commercial and experimental nuclear power plant in the USA and second in the world after Calder Hall in the UK.





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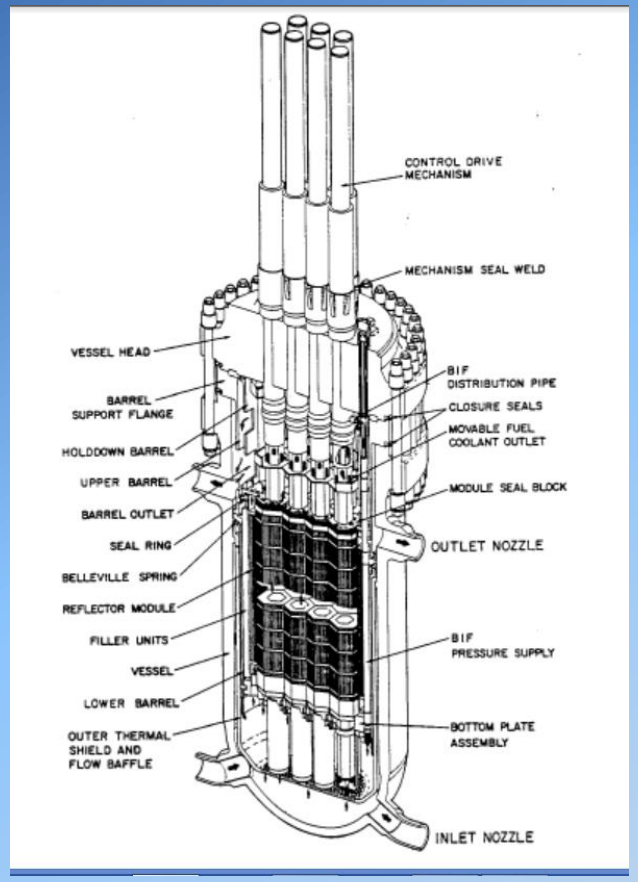
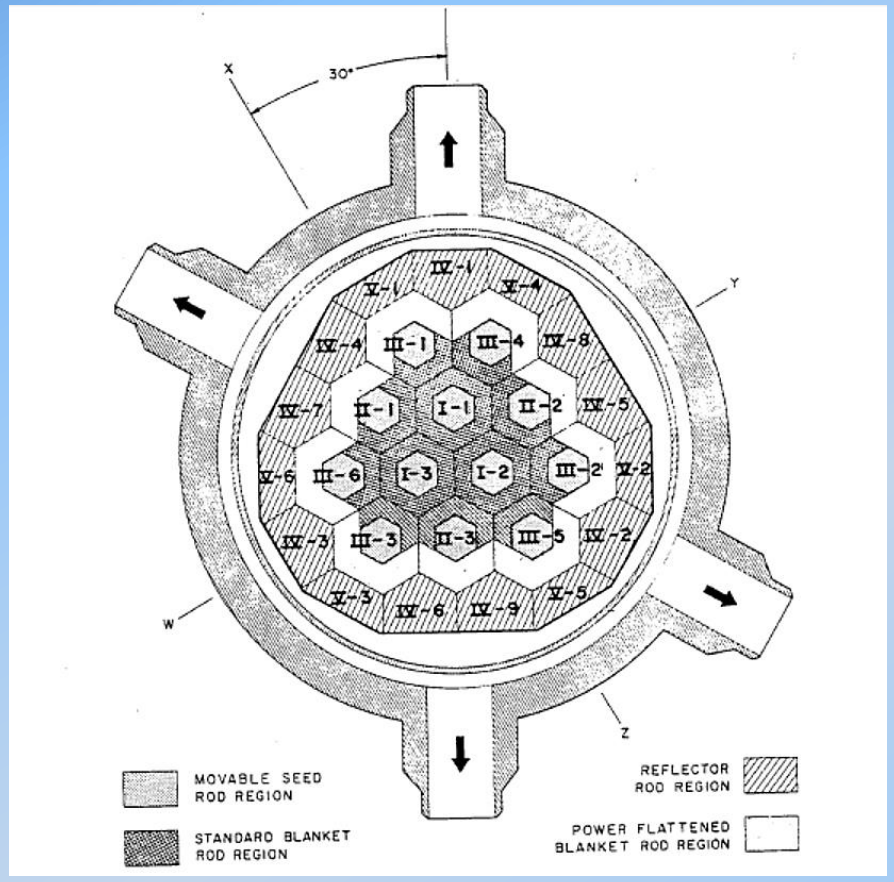
Seed and Blanket solid fuel core in the Shippingport design





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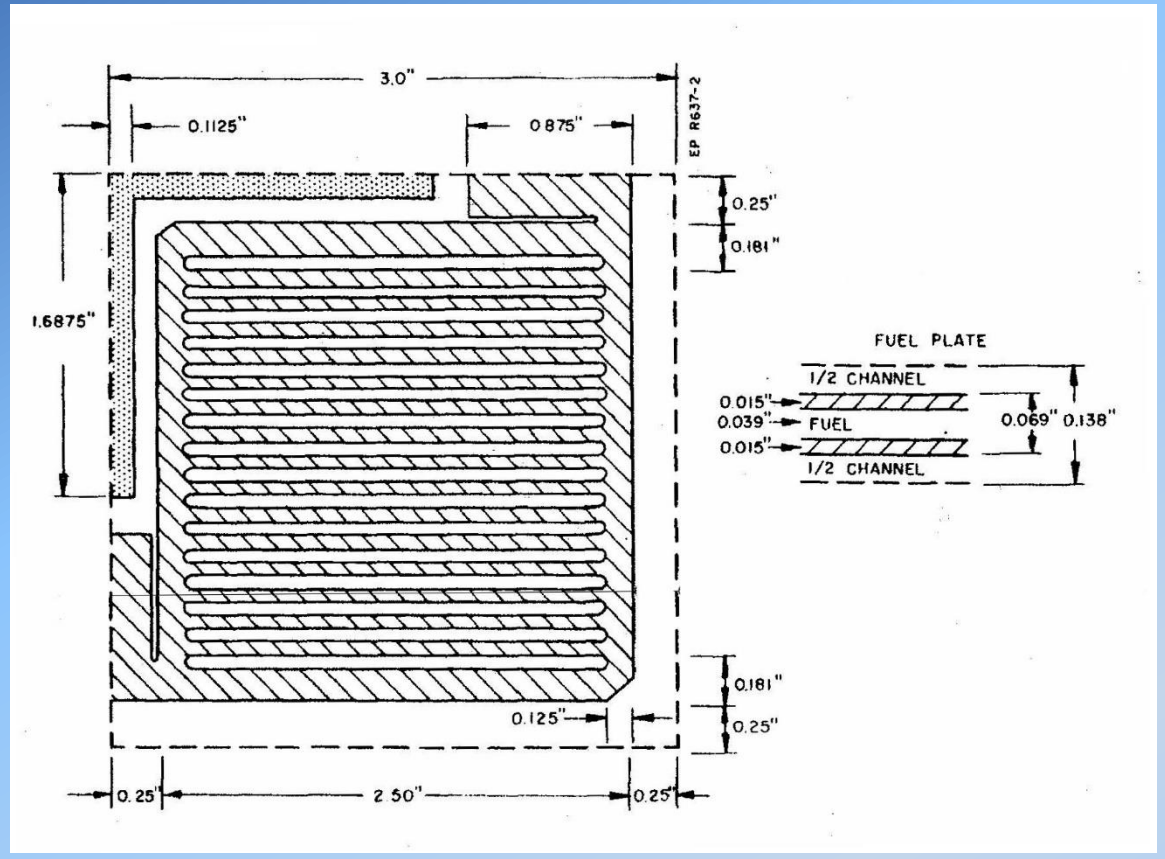
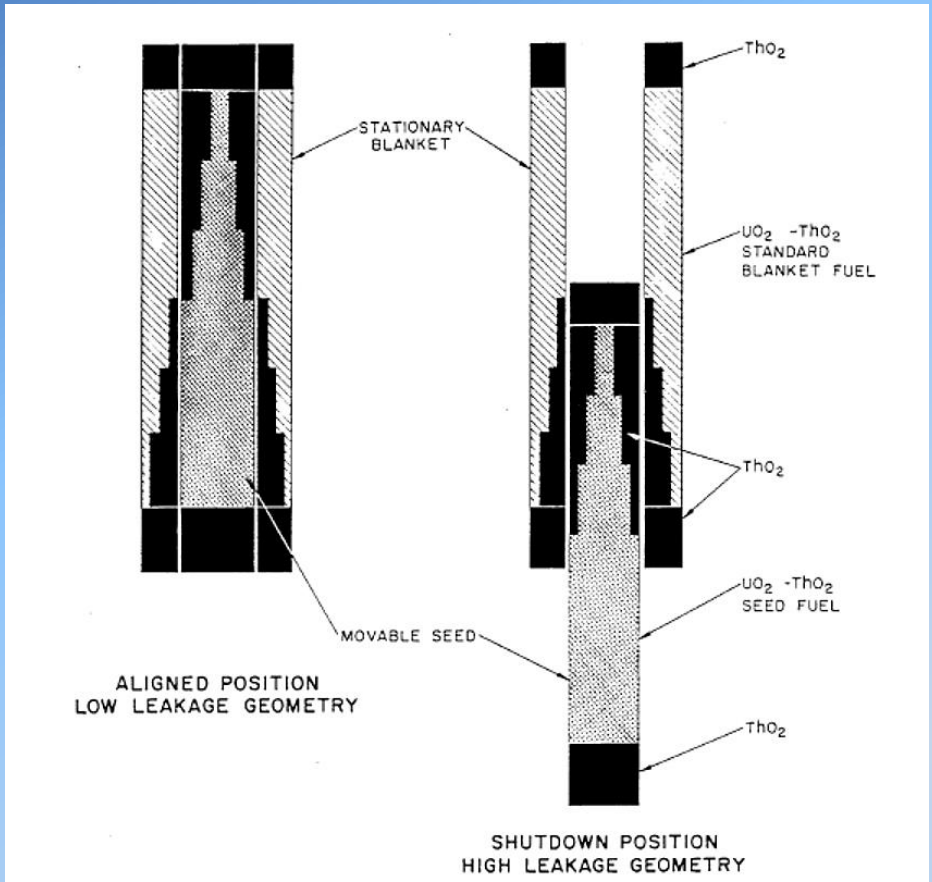
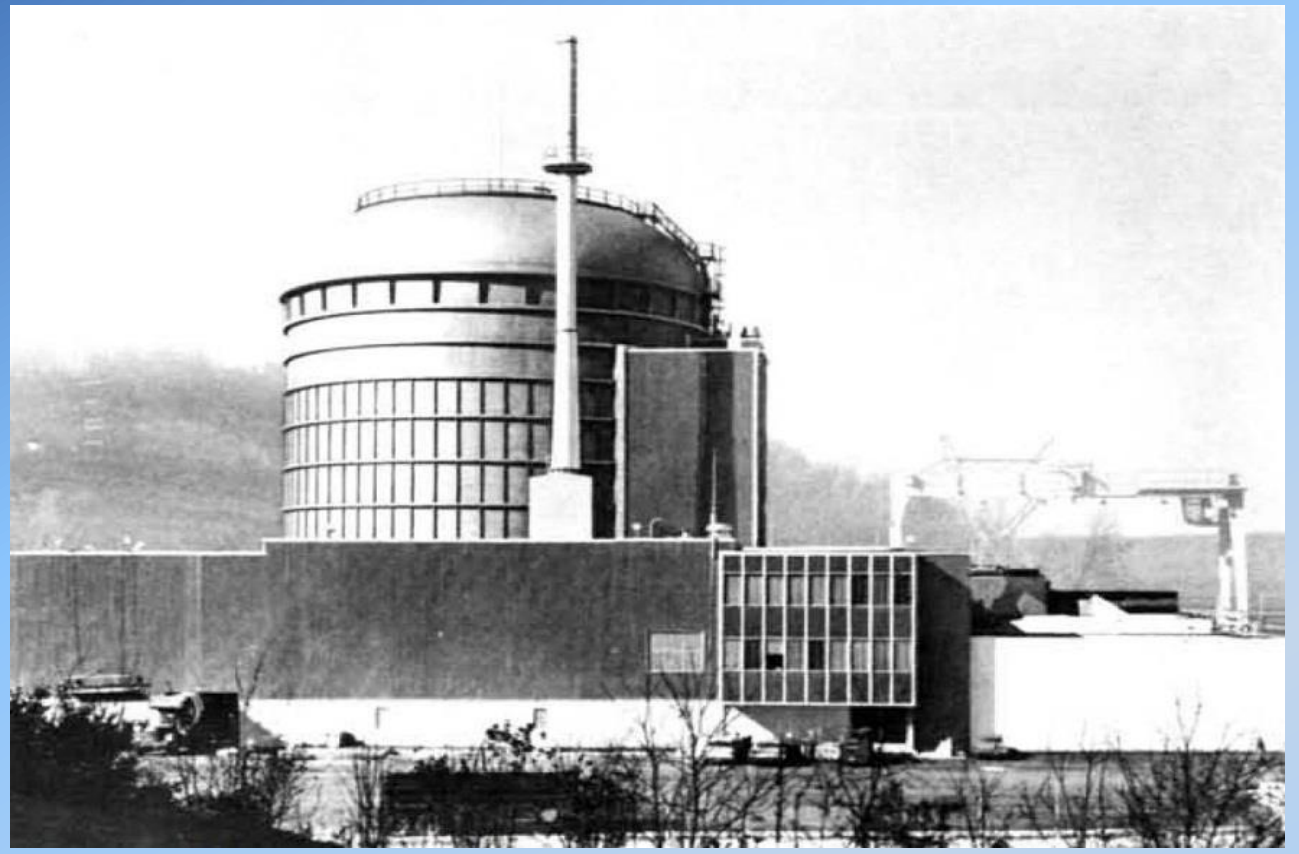
Shippingport reactor plate fuel elements



Seed and Blanket operational and shutdown configurations



Peach Bottom 40 MWe HTGR. Photo: General Dynamics.

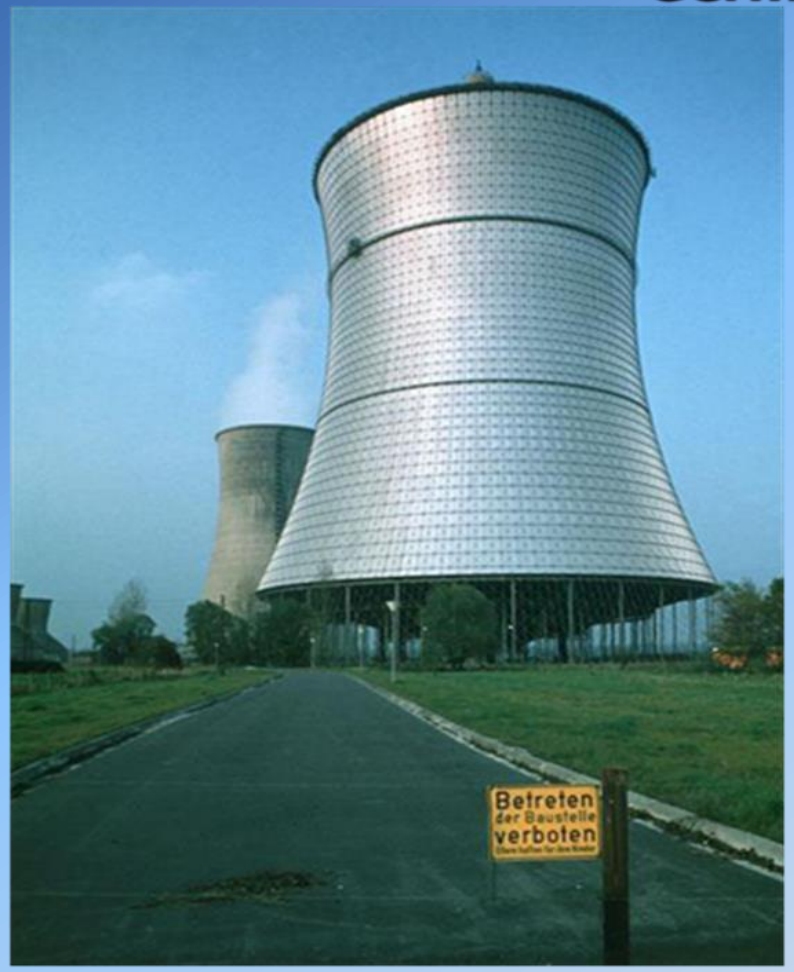


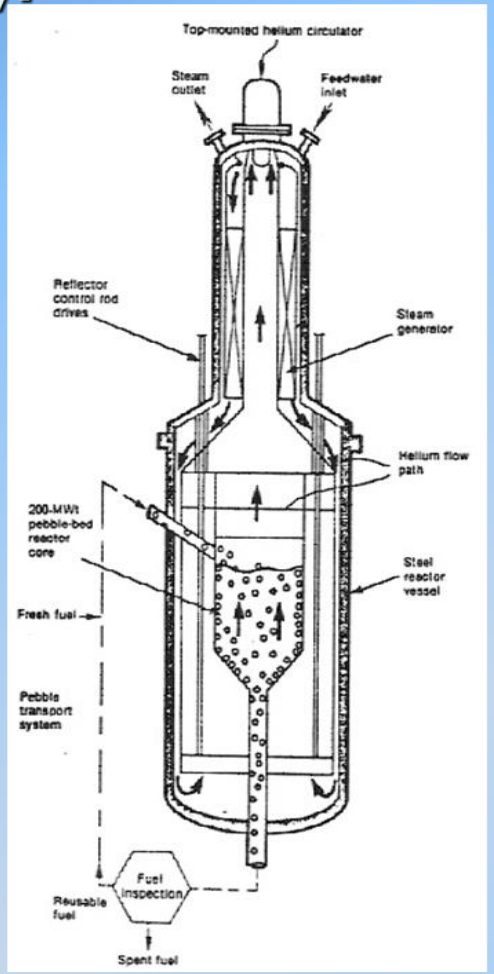
Dragon reactor at Winfrith Heath, UK.

Fort Saint Vrain He cooled graphite moderated reactor, Colorado.

One of 1,482 prismatic graphite blocks lowered into the core of the Fort Saint-Vrain HTGR. Photo: General Atomics (GA).

The TFTR-300 U235-Th232 high temperature pebble bed reactor used a 180 m high dry cooling tower. AVR reactor, Germany.

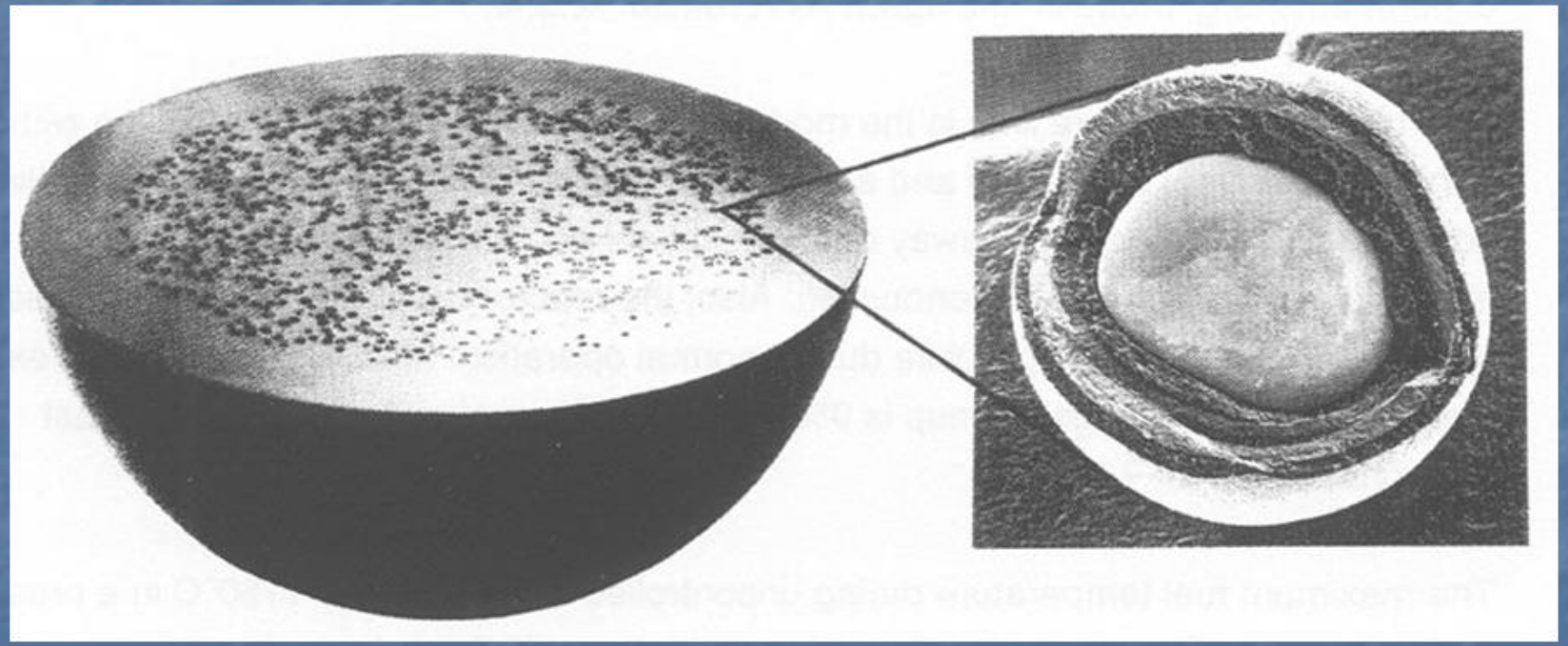




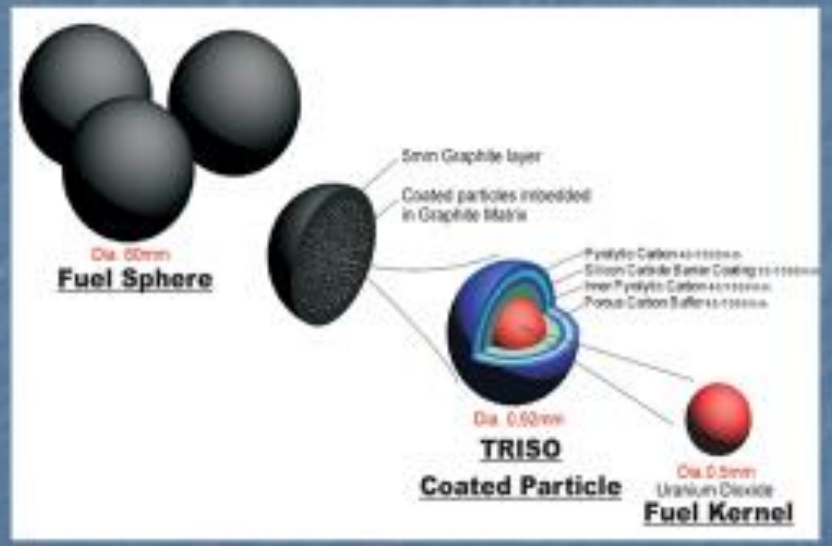
THTR pebbles inside core.

Pebble bed reactor top

Fuel particles used in the pebble bed and the prismatic fuel designs.



Fuel kernel, coated triso fuel particle and pebble fuel sphere design.

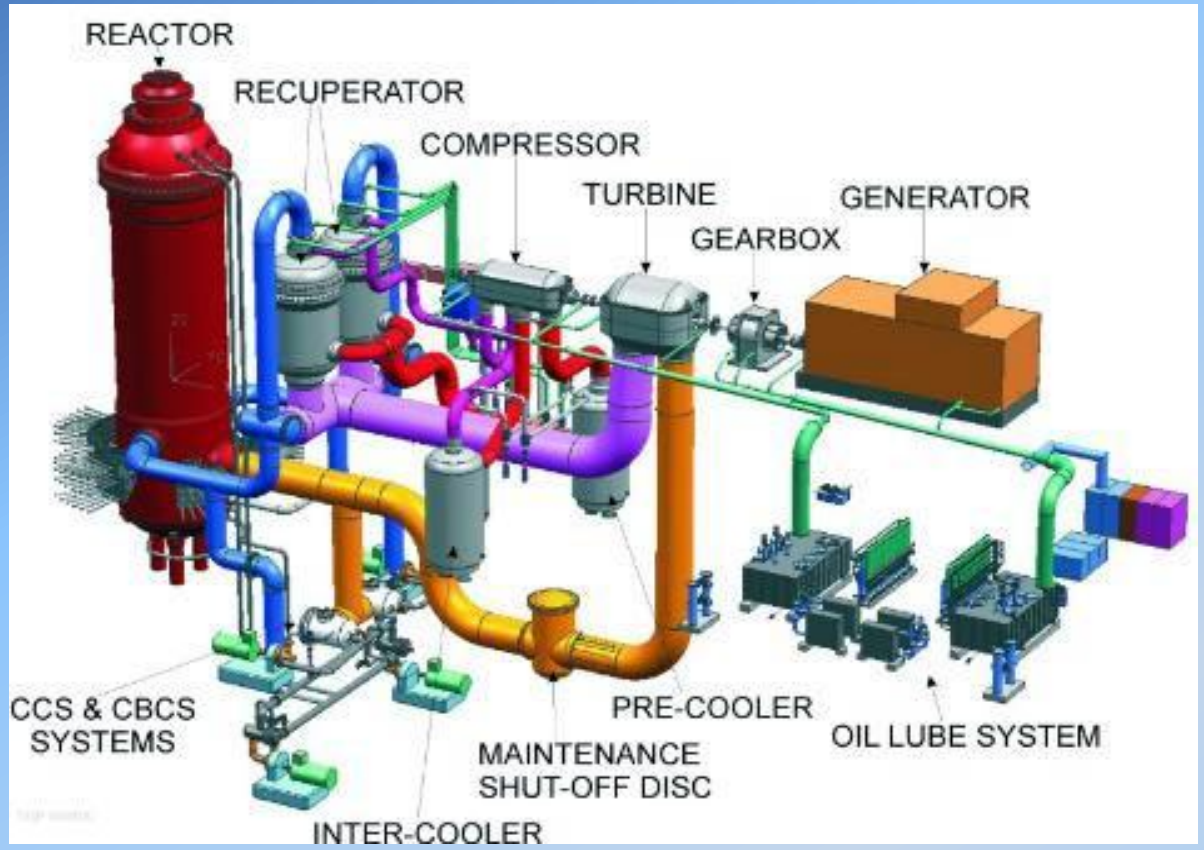


Comparison of the technical characteristics of different HTGR designs.

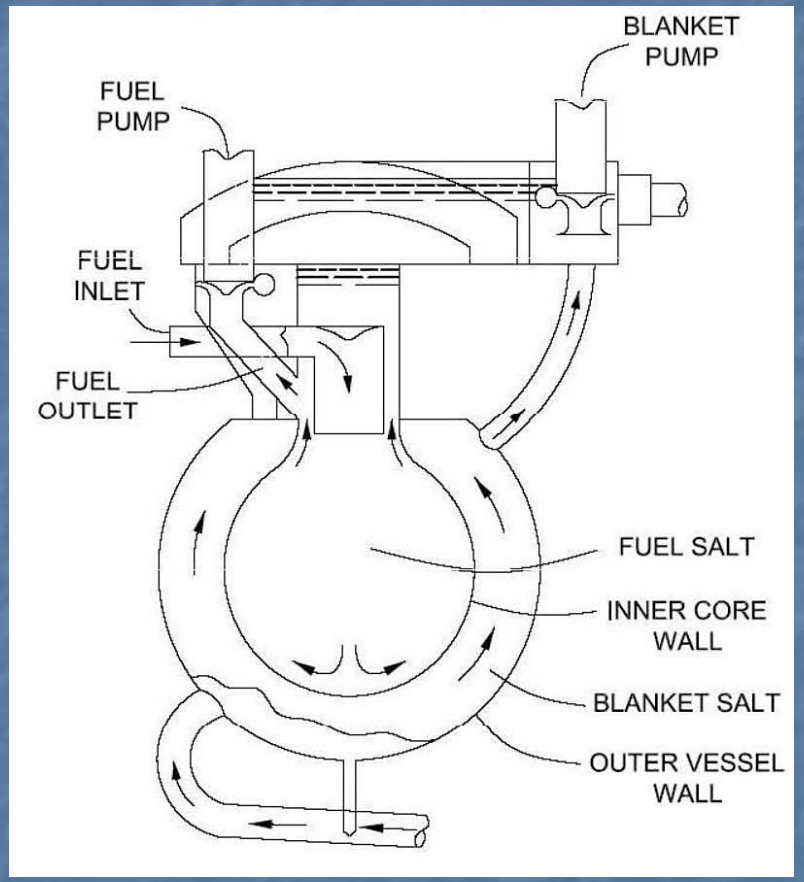
	Peach Bottom USA	Dragon UK	AVR Germany	THTR Germany	Fort Saint-Vrain USA
Power generation	1967-1974	1966-1975	1968	1985	1976
Power MWth/MWe	115/40	20/-	46/15	750/300	837/330
Fuel type	cylinders	cylinders	Pebble bed, spheres	Pebble bed, spheres	Hexagonal blocks
He outlet temperature ^{o}C	750	750	950	750	785
He coolant pressure bar	25	20	11	40	48
Fuel composition	Th, uranium carbide	Th, uranium carbide	Th, uranium oxides	Th, uranium oxides	Th, uranium carbides
Reactor vessel	Steel	Steel	Steel	PCRV	PCRV

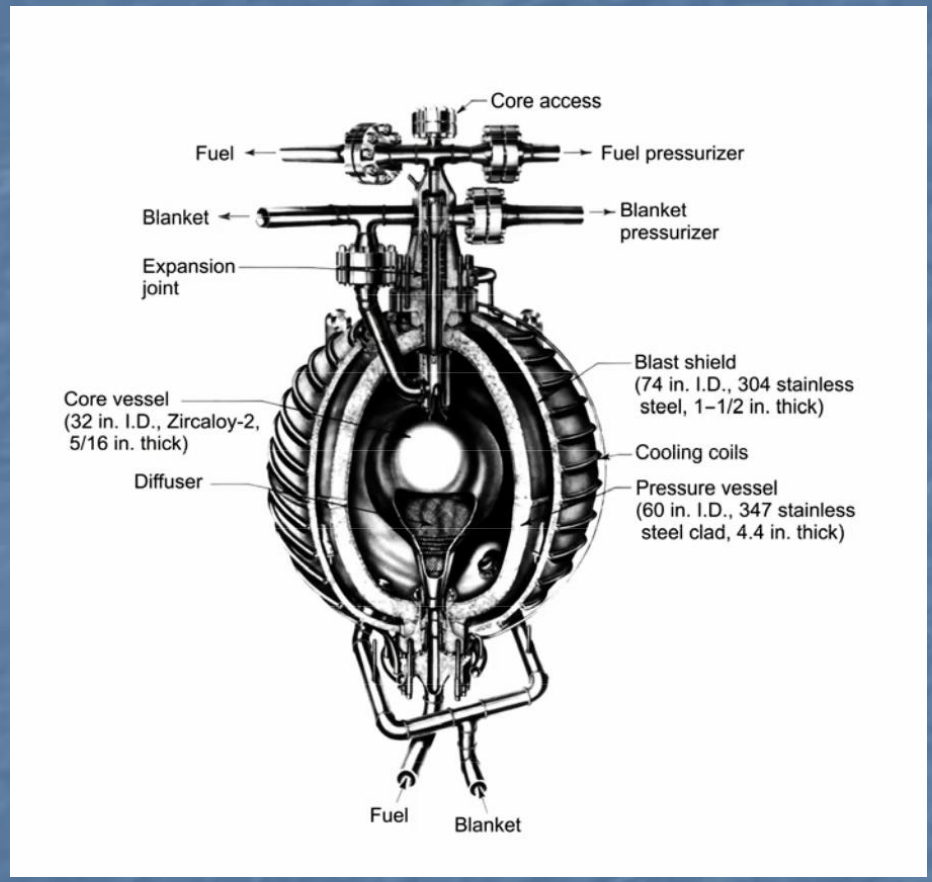
PCRV = Prestressed Concrete Pressure Vessel

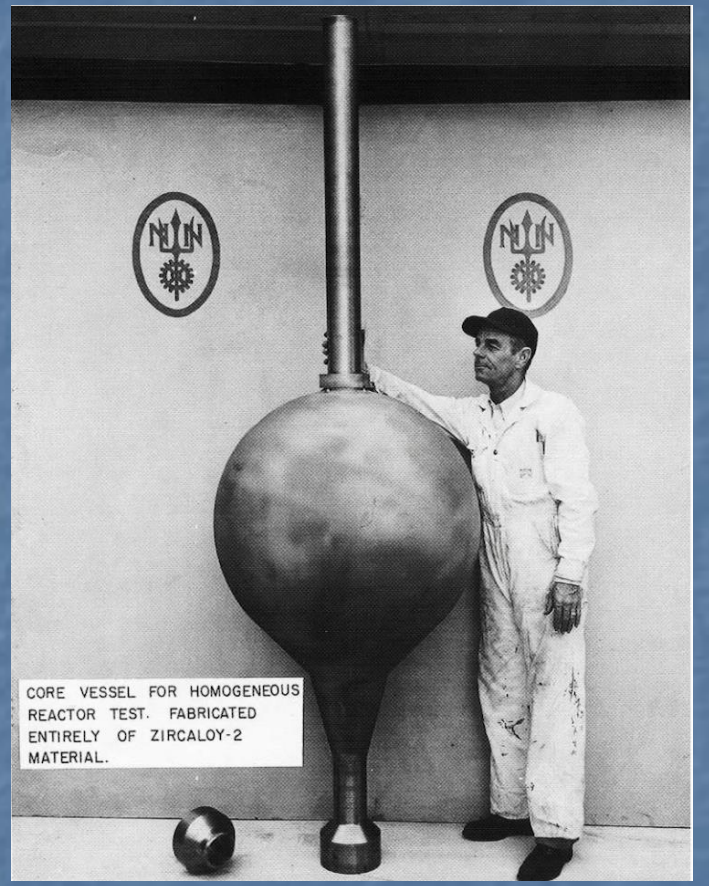
Single reactor unit arrangement of the Pebble Bed Modular Design PBMR design using the gas turbine or Brayton thermodynamic cycle.



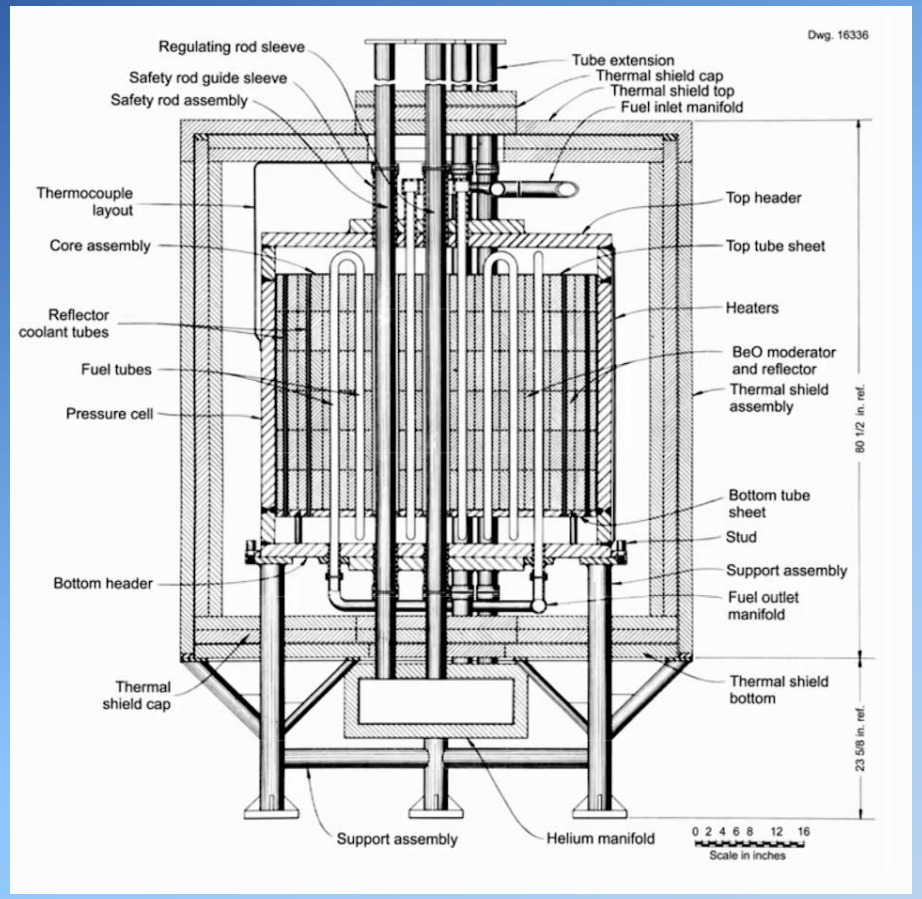
Homogeneous Molten Salt Reactor

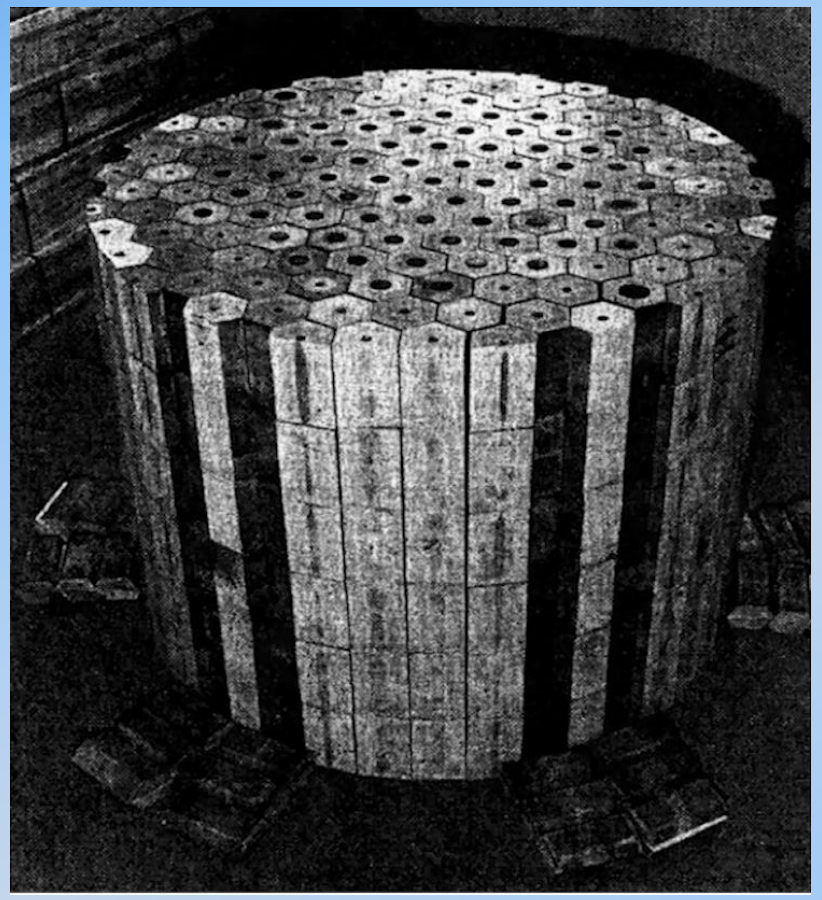




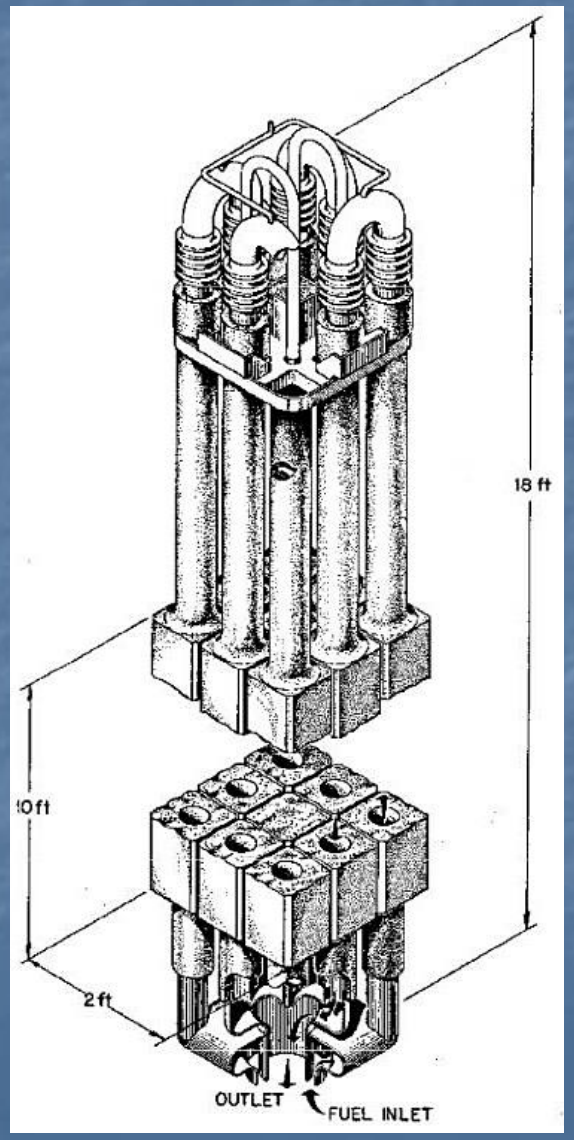


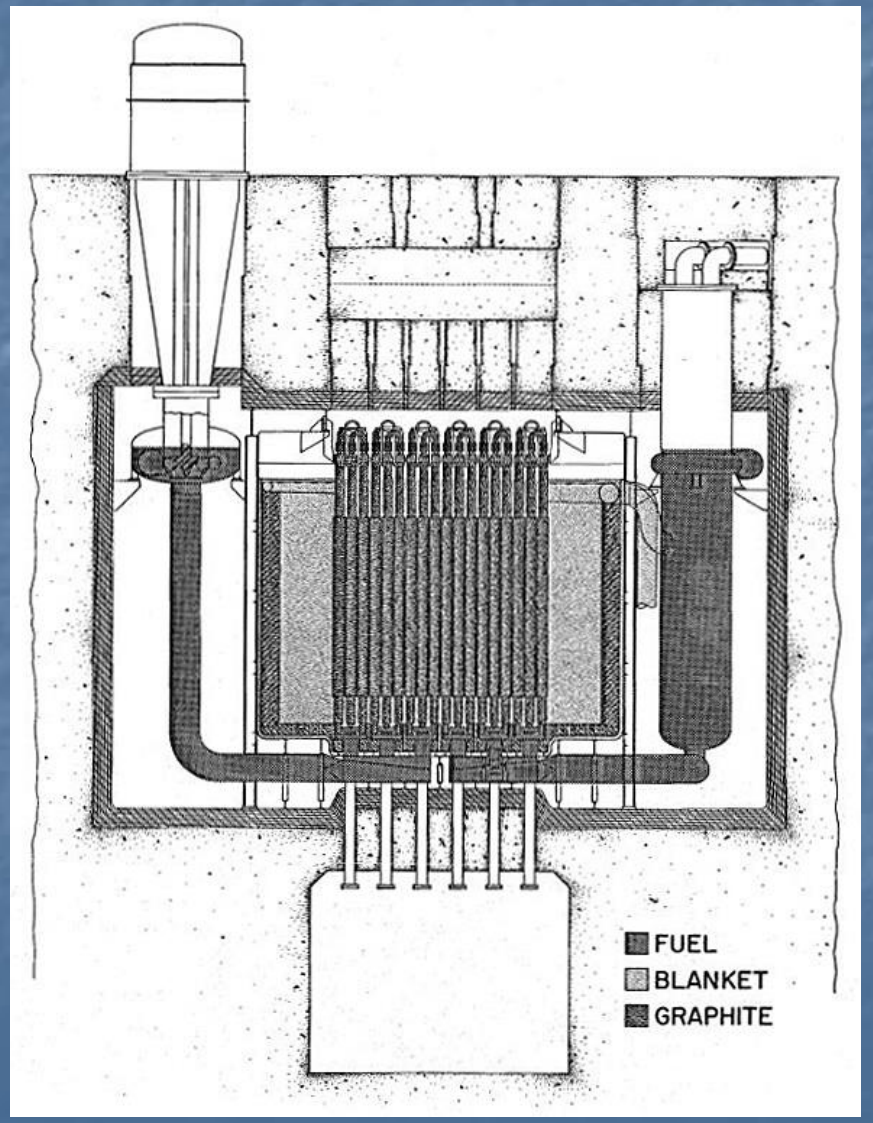
Beryllium Oxide BeO moderator and reflector , He-cooled Core



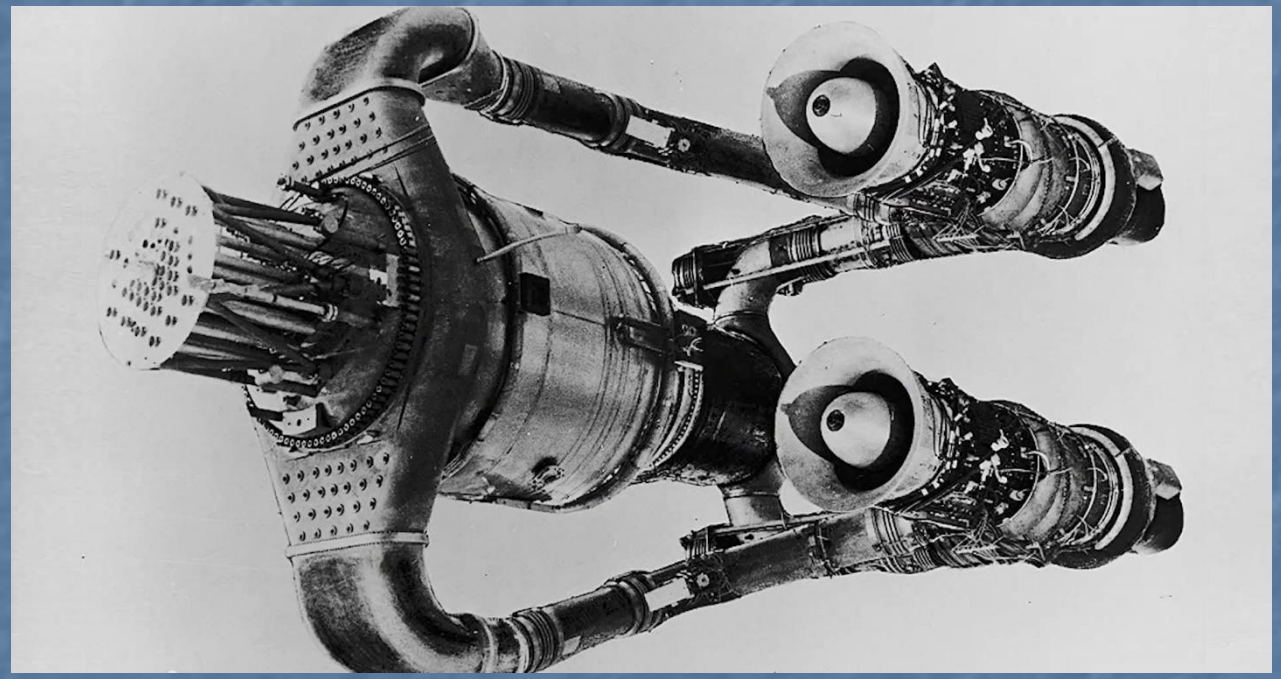


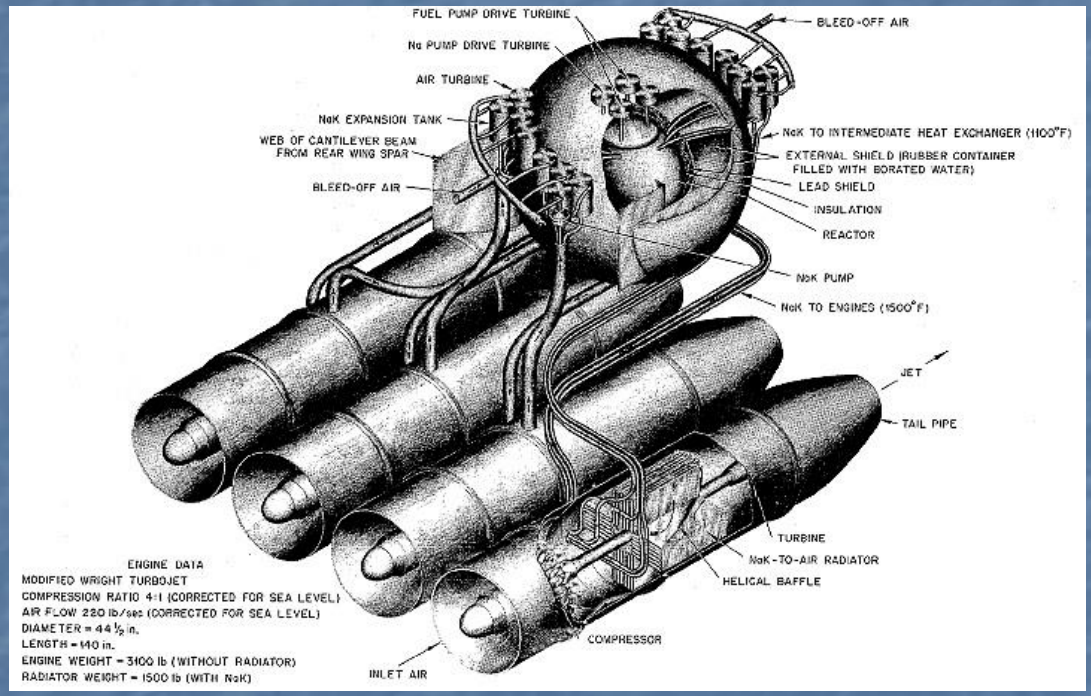
Two region Salt-Graphite Molten Salt Breeder



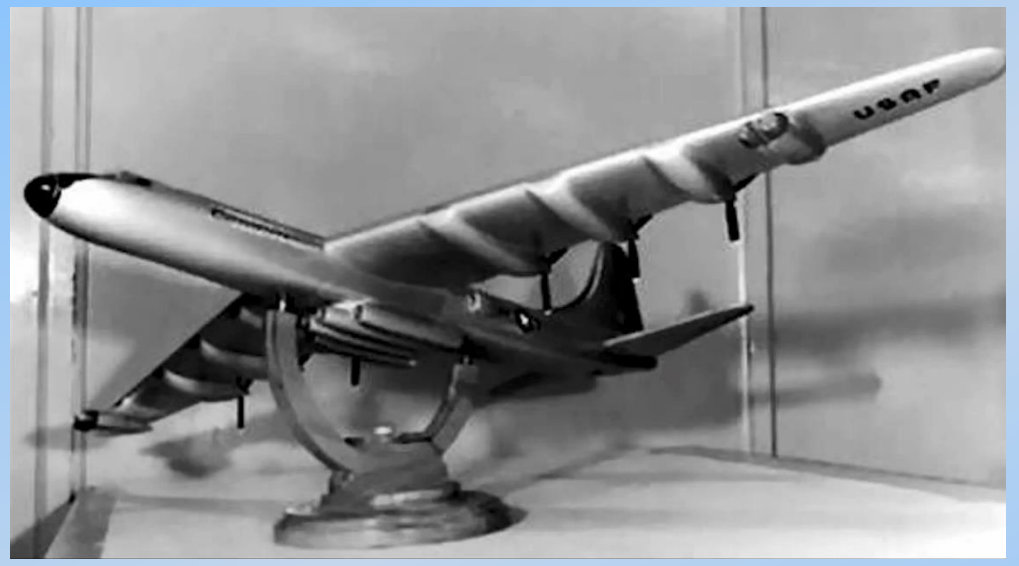


Convair B36 X6 200 MW Wright turbojet engine using Na-K as a coolant





Thorium strategic bomber designs

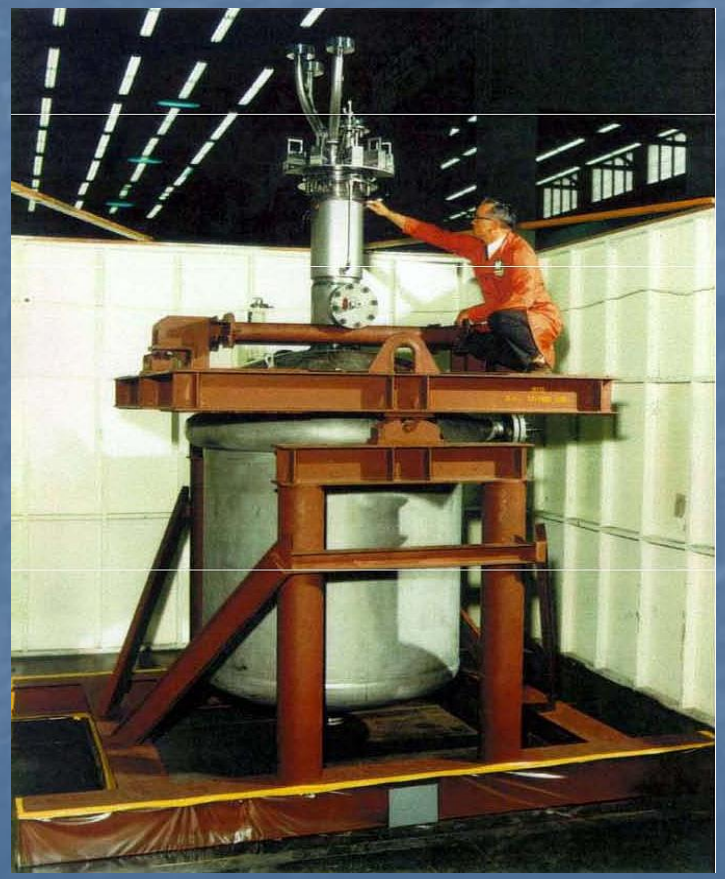


Molten Salt Reactor Experiment, MSRE, ORNL

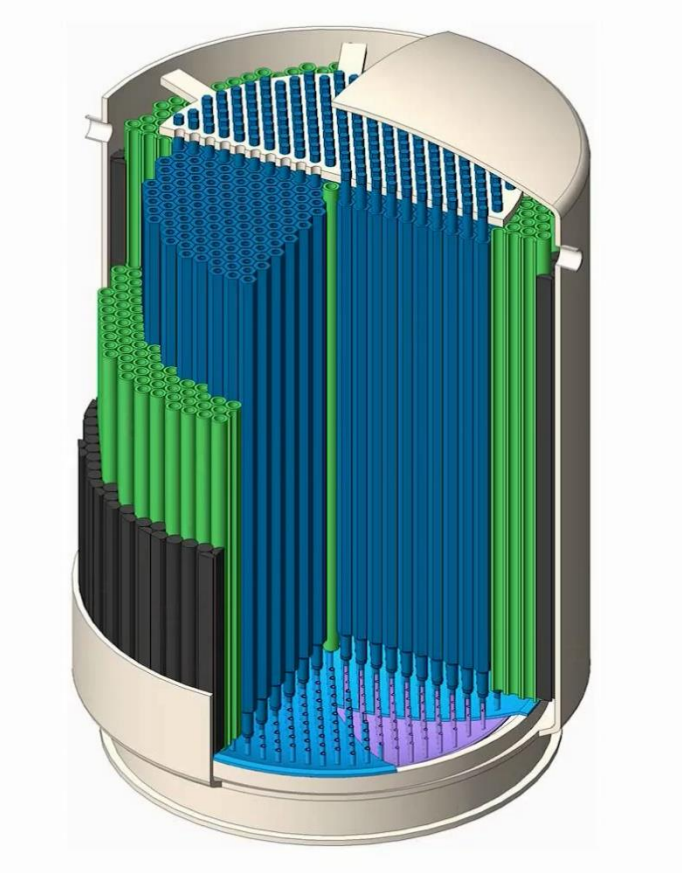
History of the MSBR Experiment

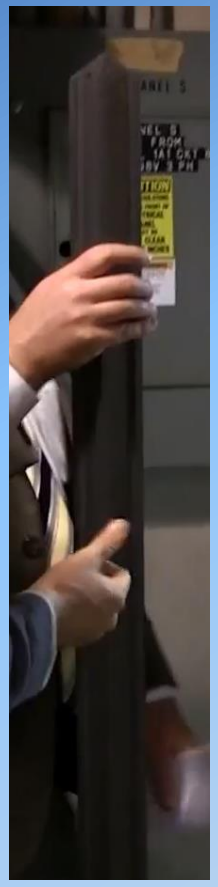
- Operated from June 1965 to December 1969.
- Nominal power level: 8 MWth.
- Initial fuel loading in 1965: 227 kg U235+U238.
- Fuel mix changed in 1968: U233+U235+Pu239.
- Metal fluoride salts: Liythium+Beryllium+Zirconium.

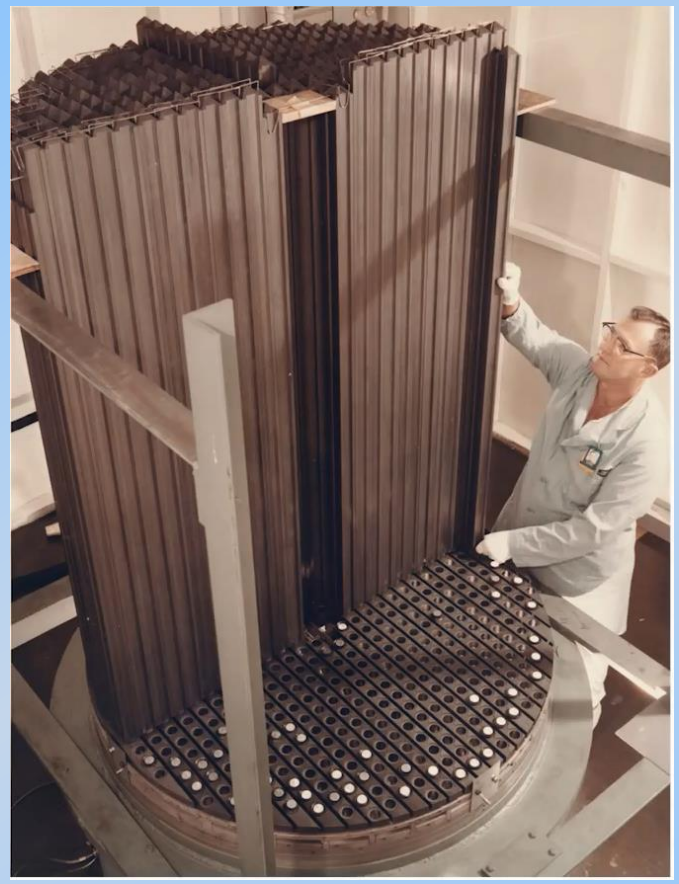
Molten Salt Reactor Experiment, Oak Ridge National Laboratory, ORNL 8MWth



MSRE core configuration and graphite moderator element

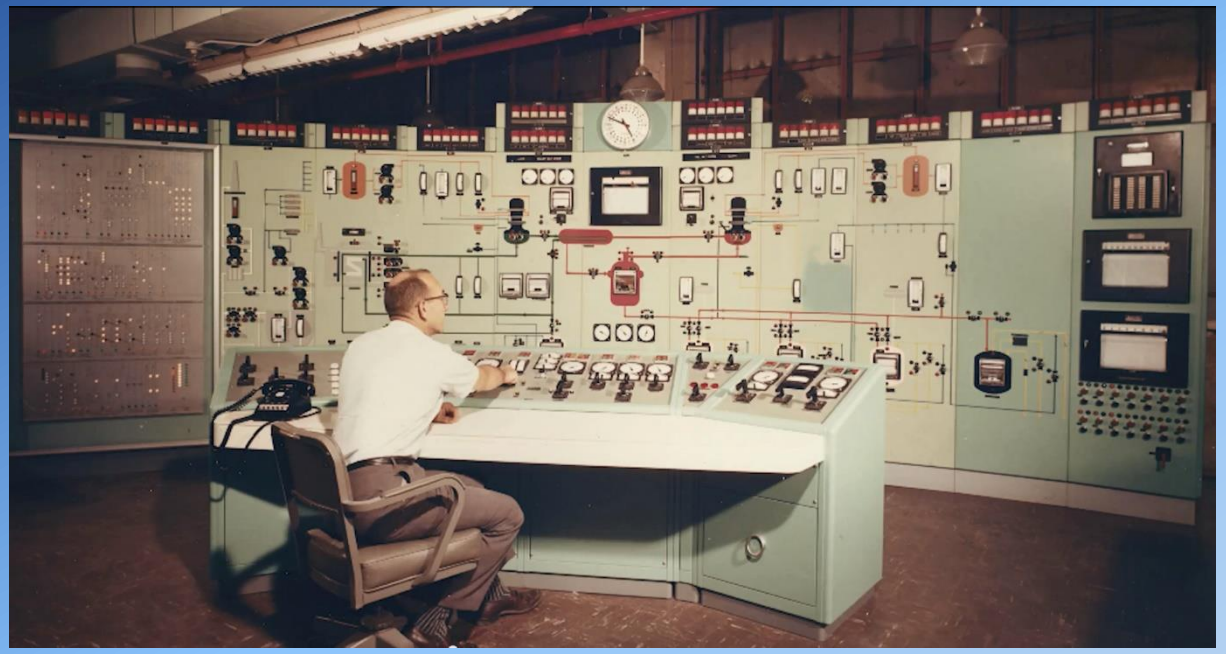






MSRE heat exchanger

MSRE Control Room and 6,000 hours of full-power operation milestone



MSRE Schematic

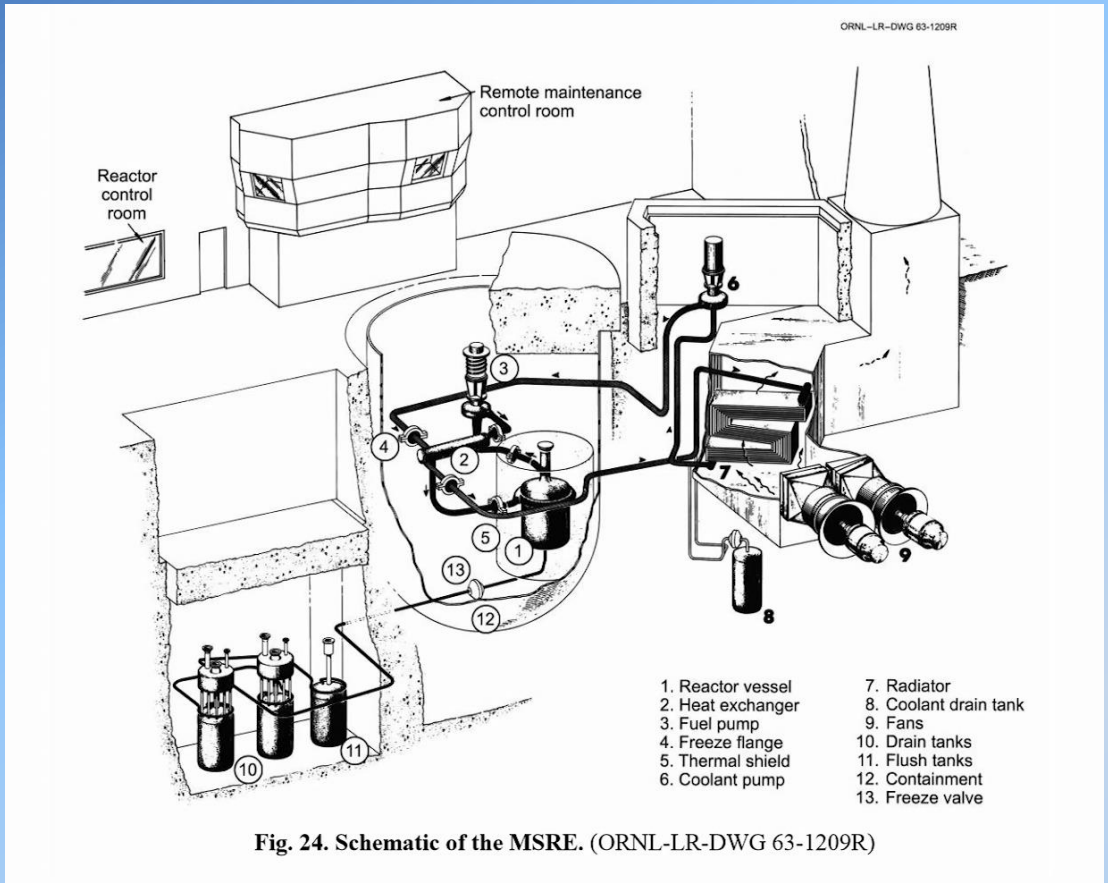
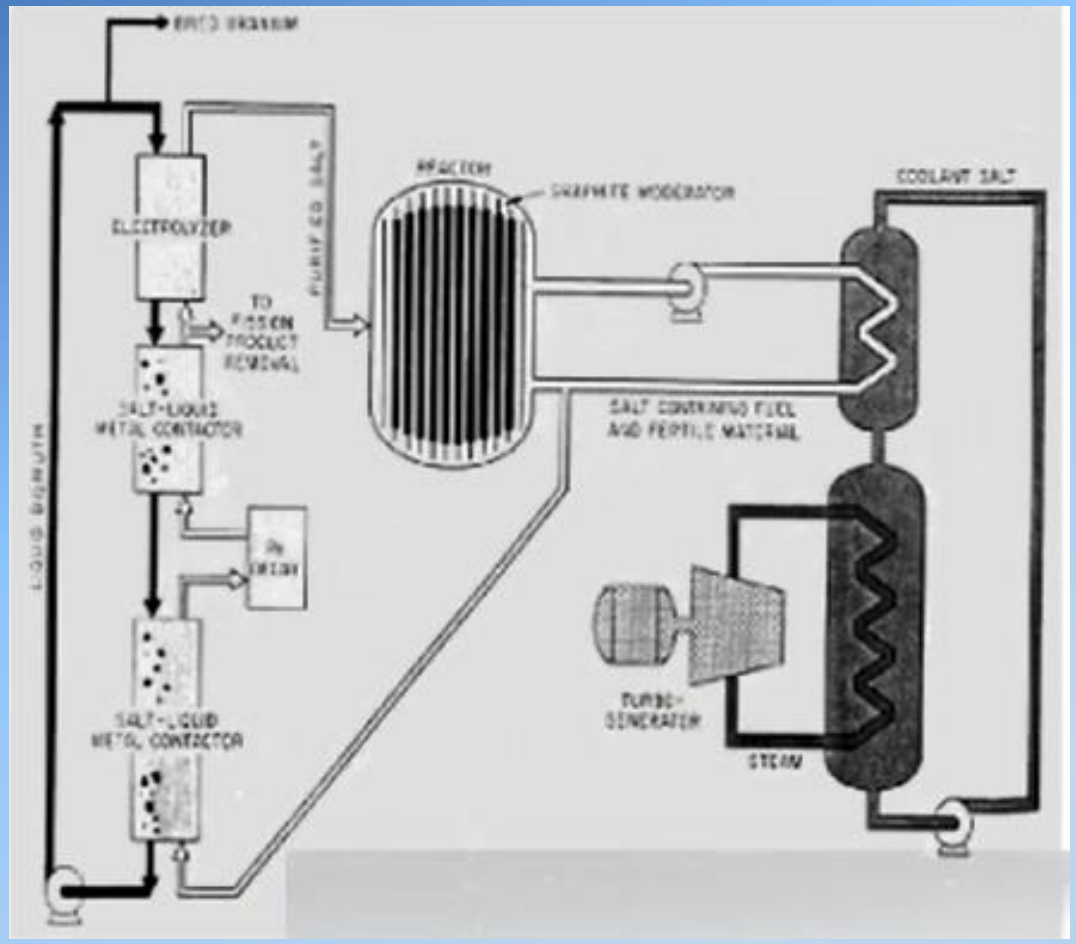
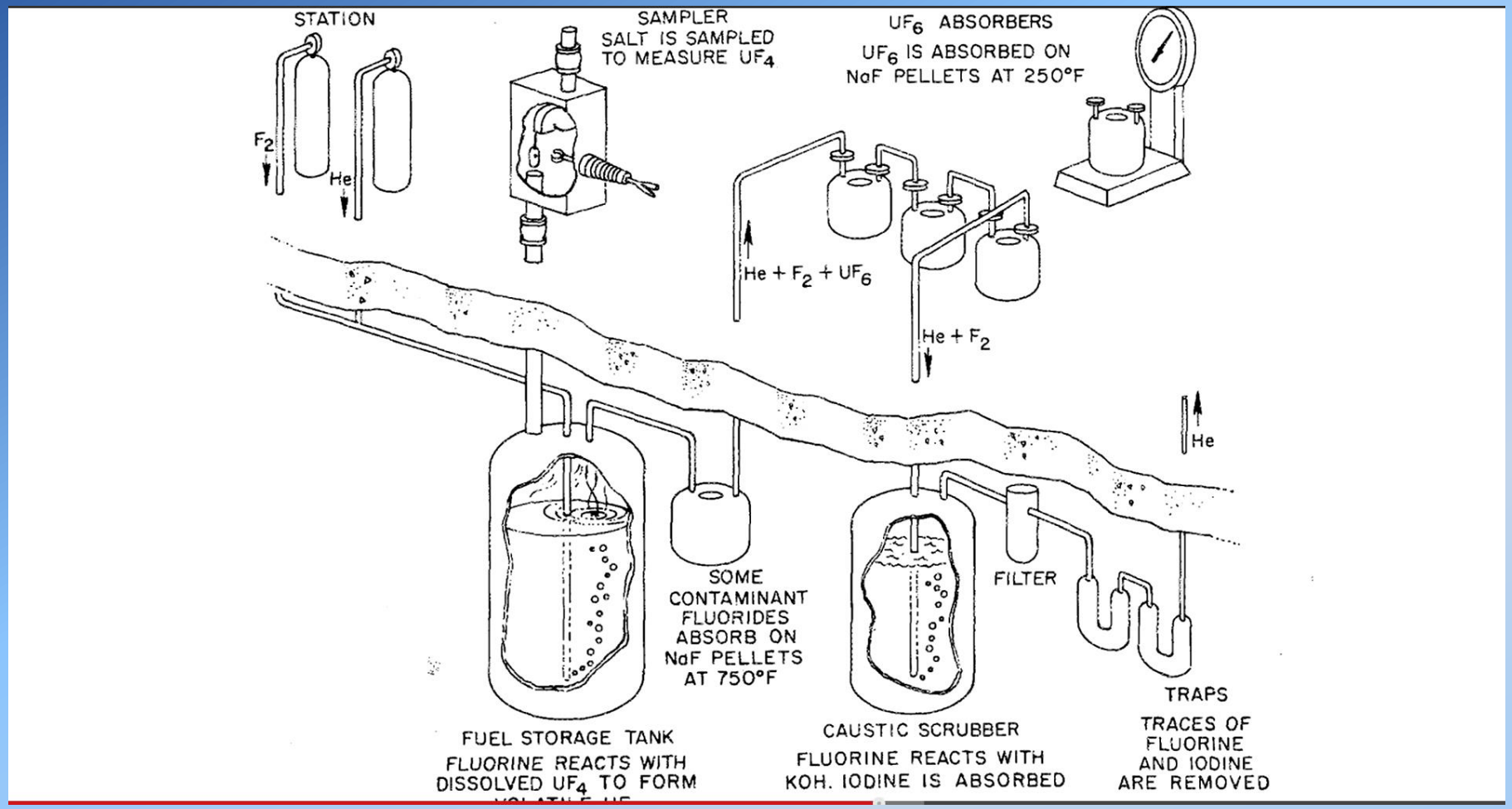


Fig. 24. Schematic of the MSRE. (ORNL-LR-DWG 63-1209R)

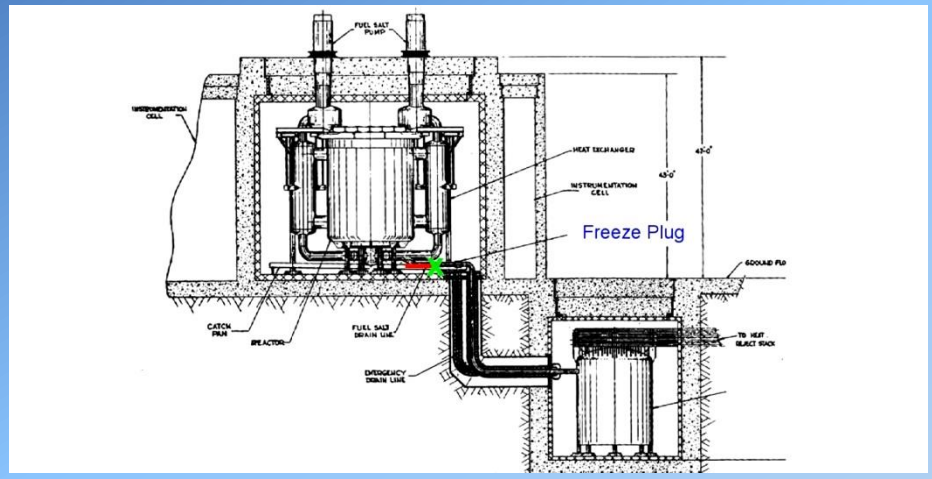
MSRE Flow Diagram

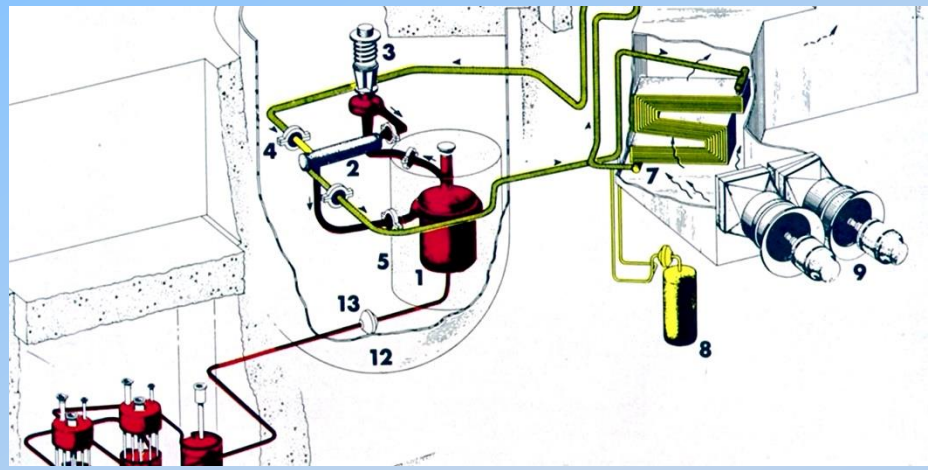


MSRE Chemical flow diagram

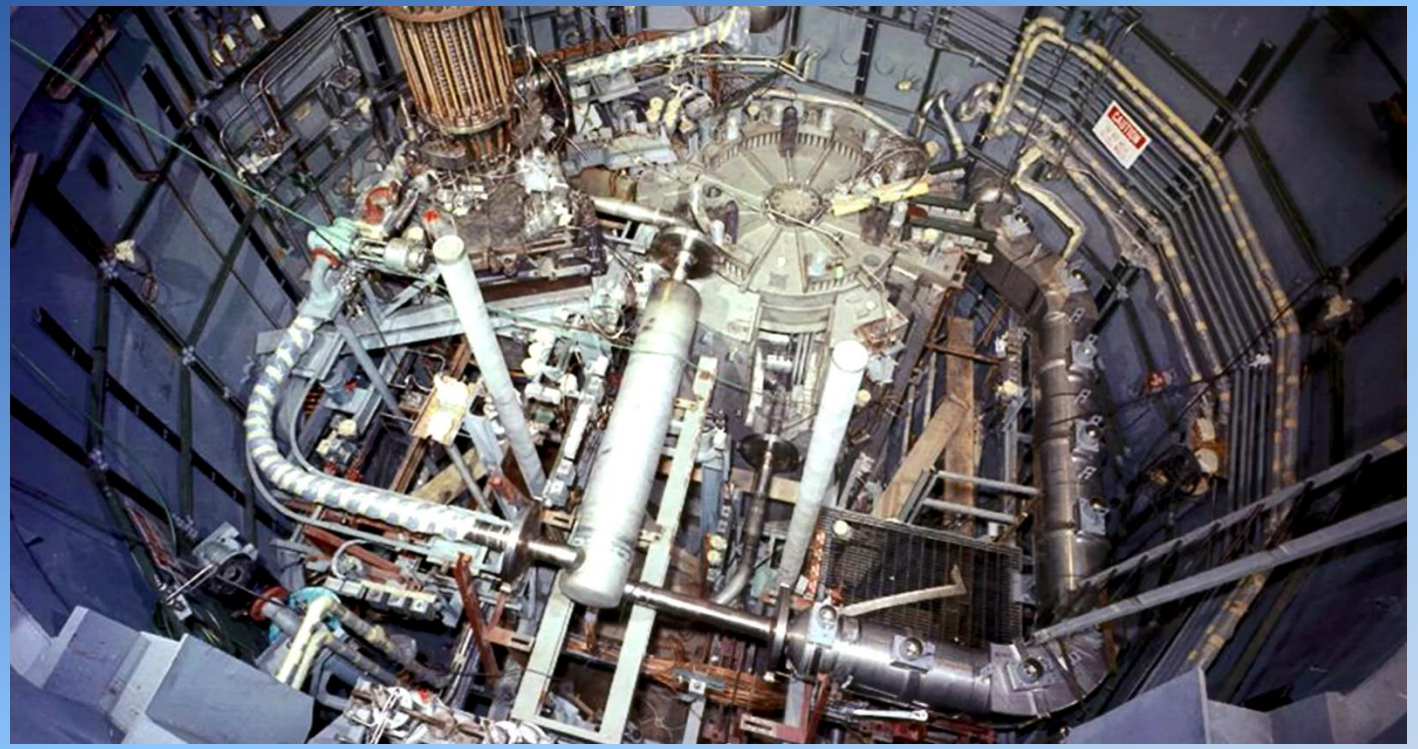


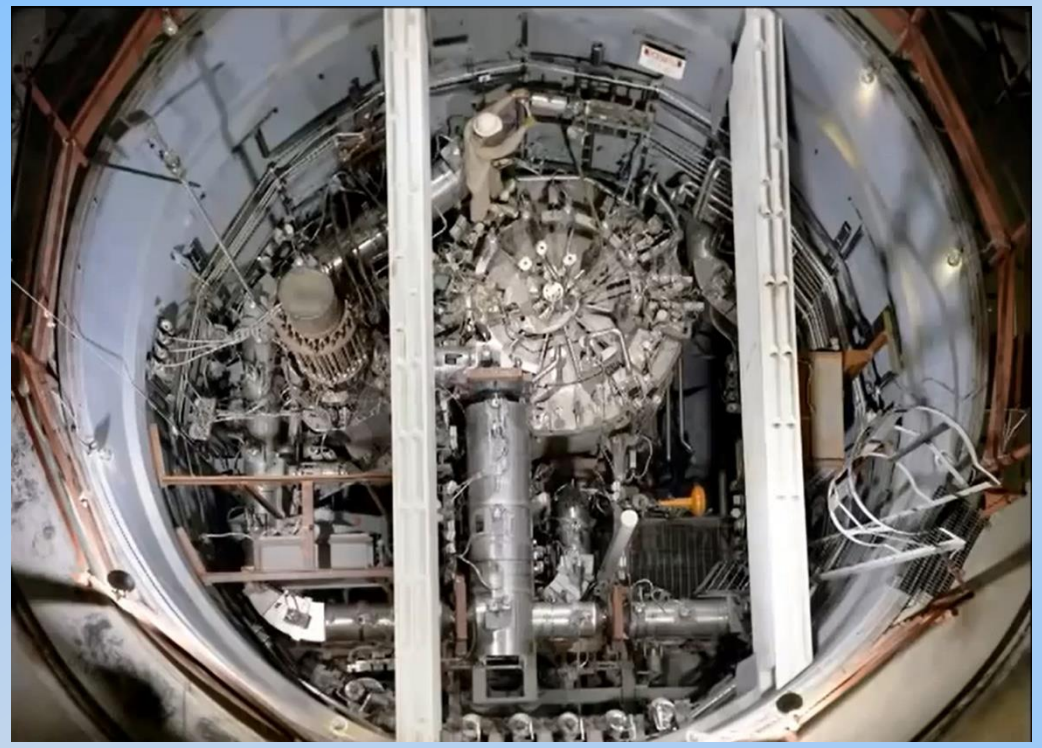
MSRE Freeze-plug safety feature



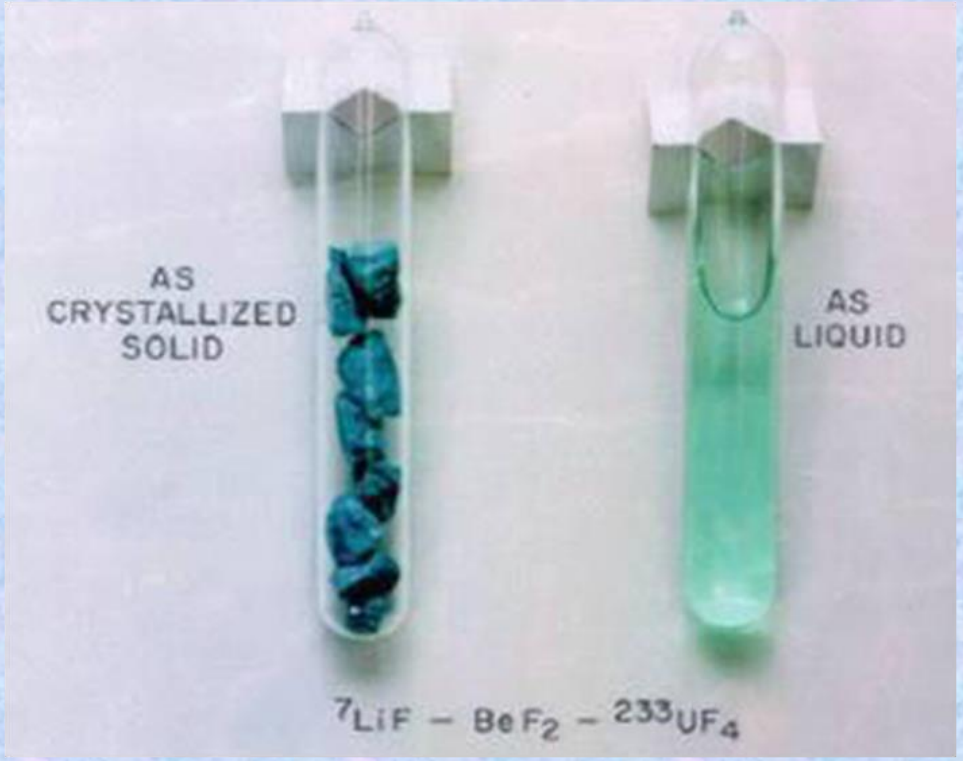


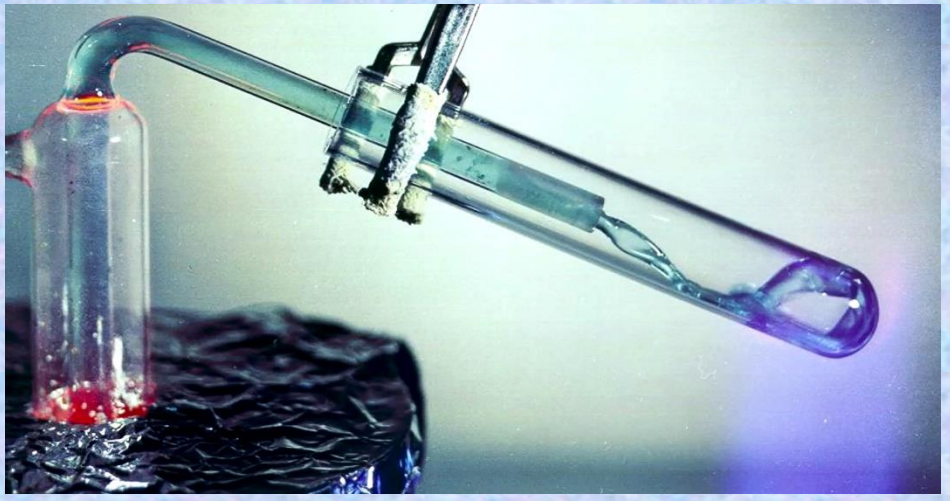
Interior views of MSRE, ORNL

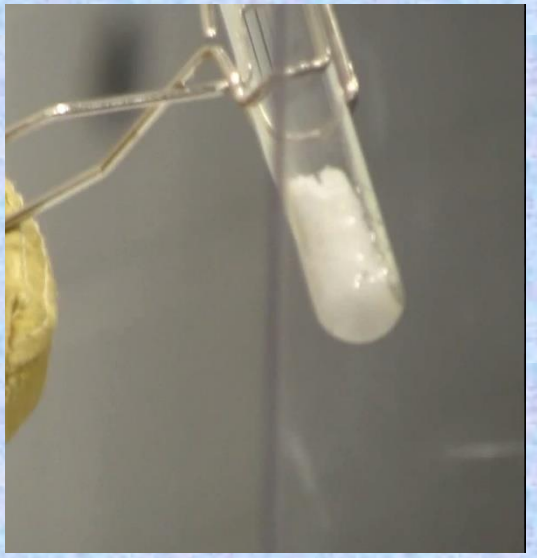




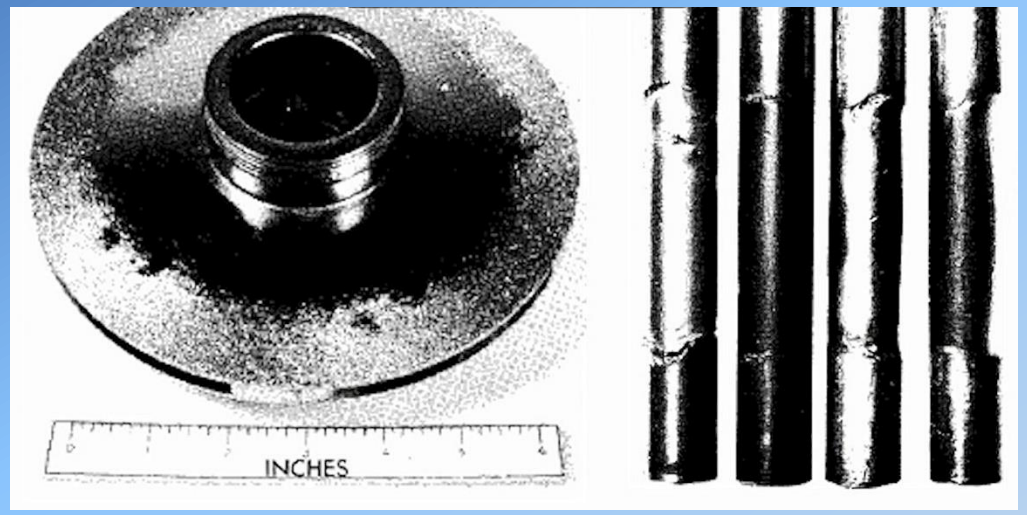
3Li7F-BeF2-92U233F4 salt in the cold solid and hot liquid states.



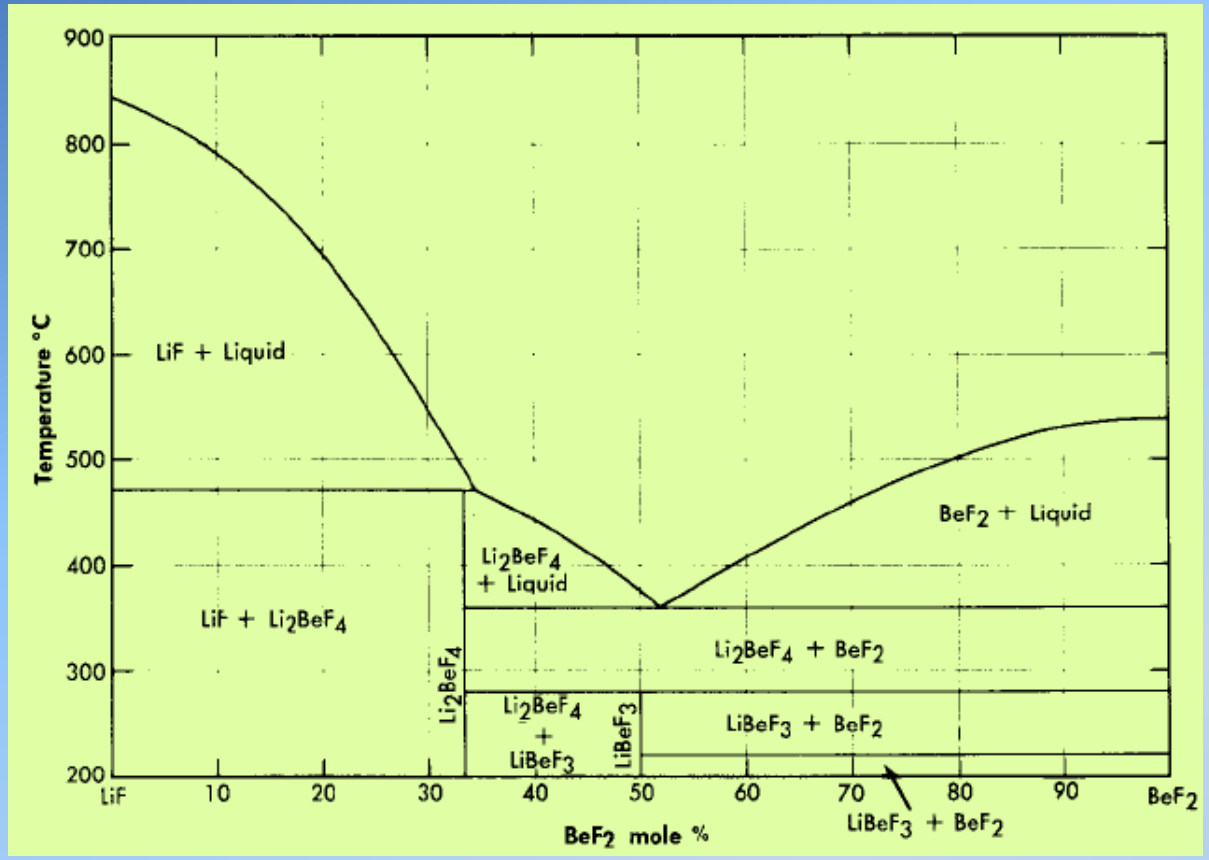




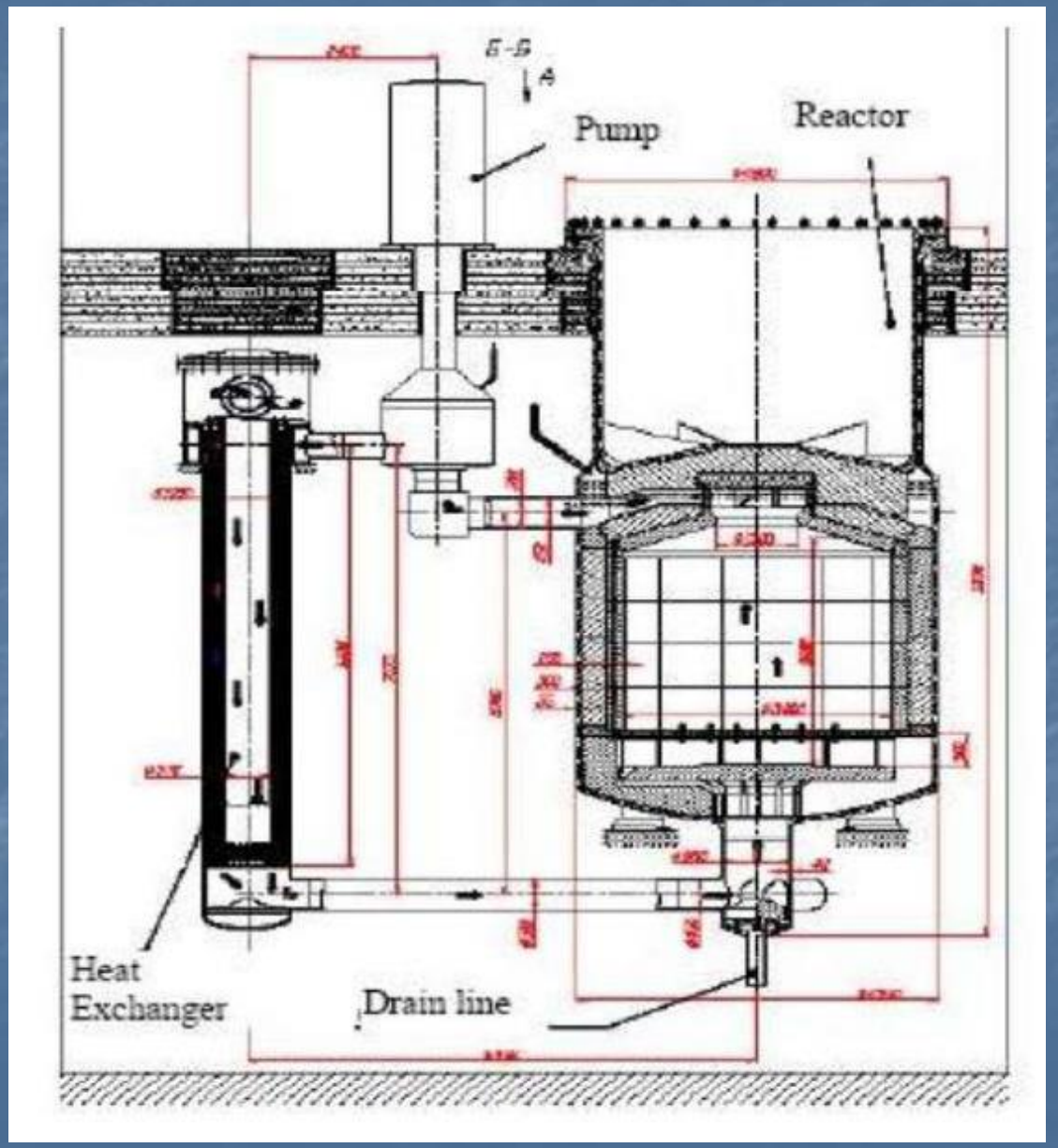
Metal corrosion and etching of glass by molten salt. Be is added to enhance corrosion resistance



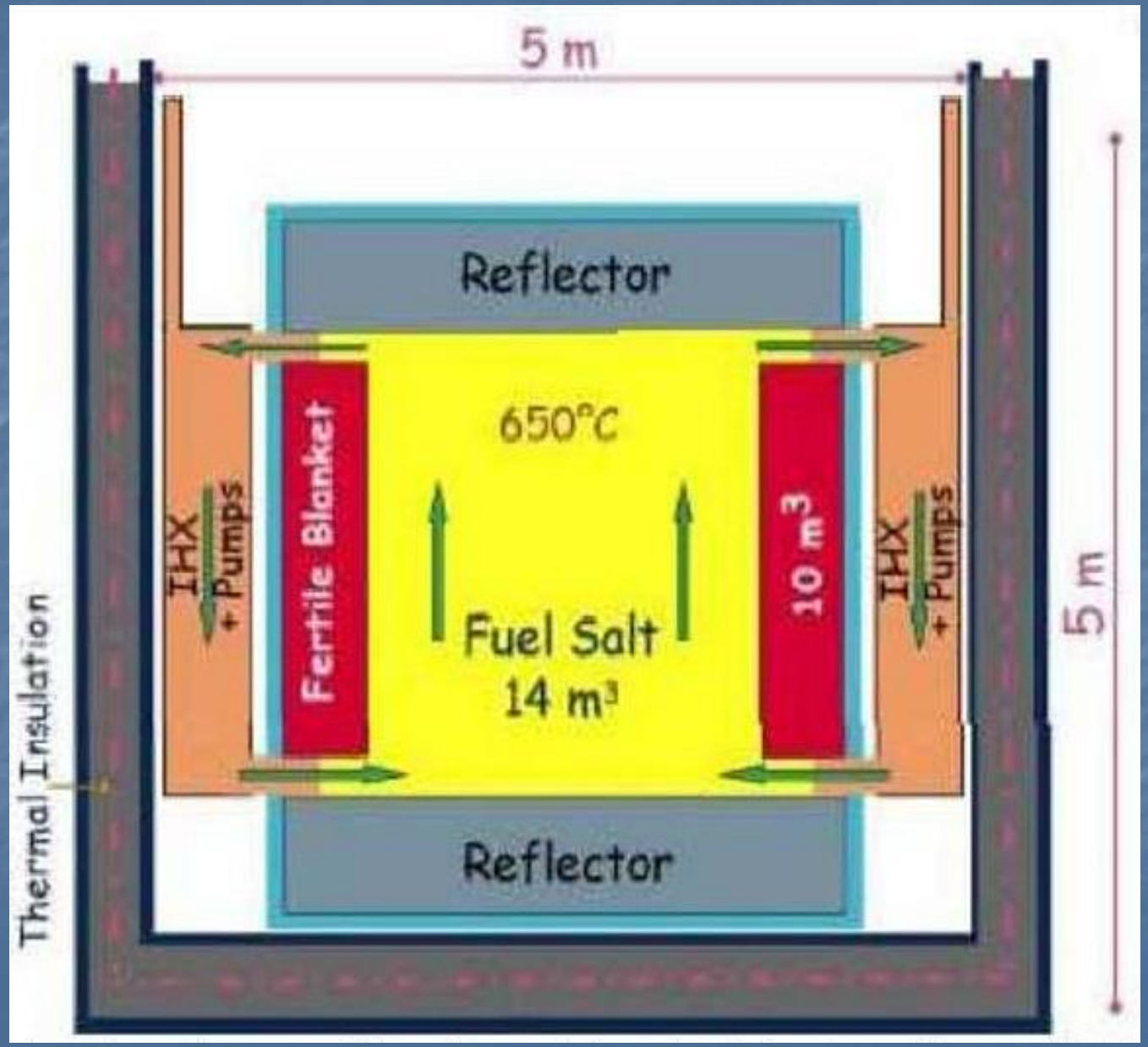
Phase diagram of LiF and BeF2 salt



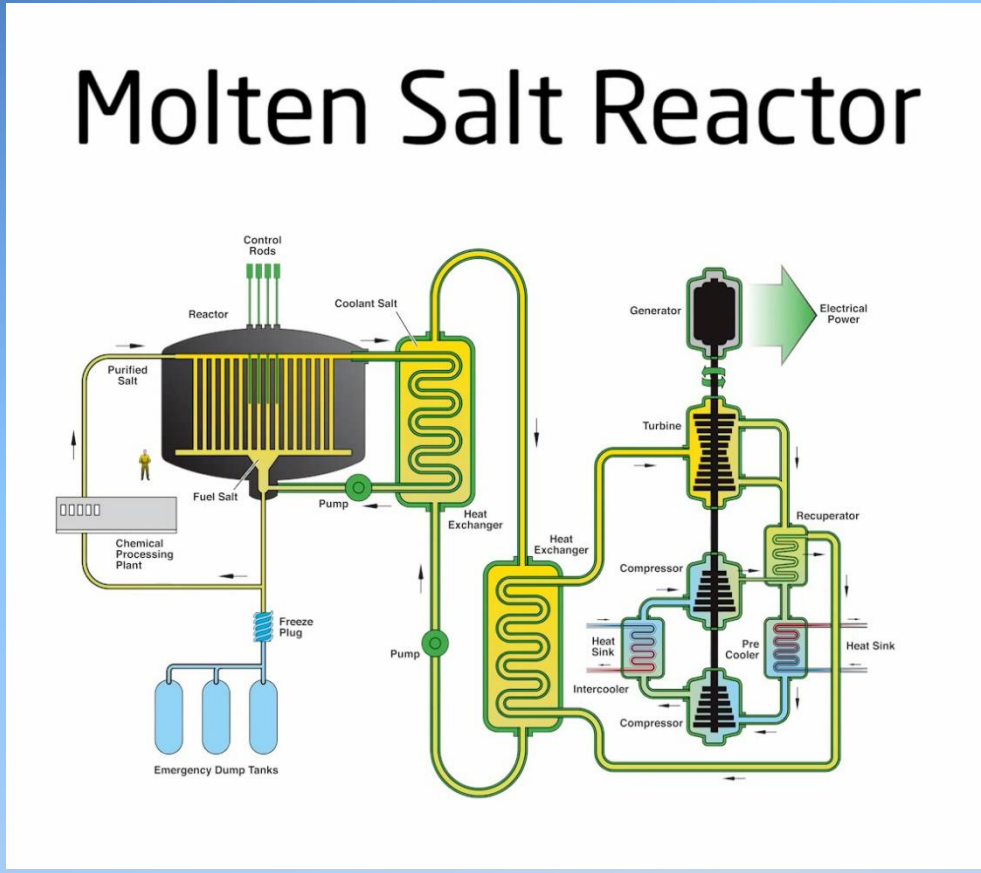
Russian Molten Salt Actinide Recycler and Transmuter, MOSART



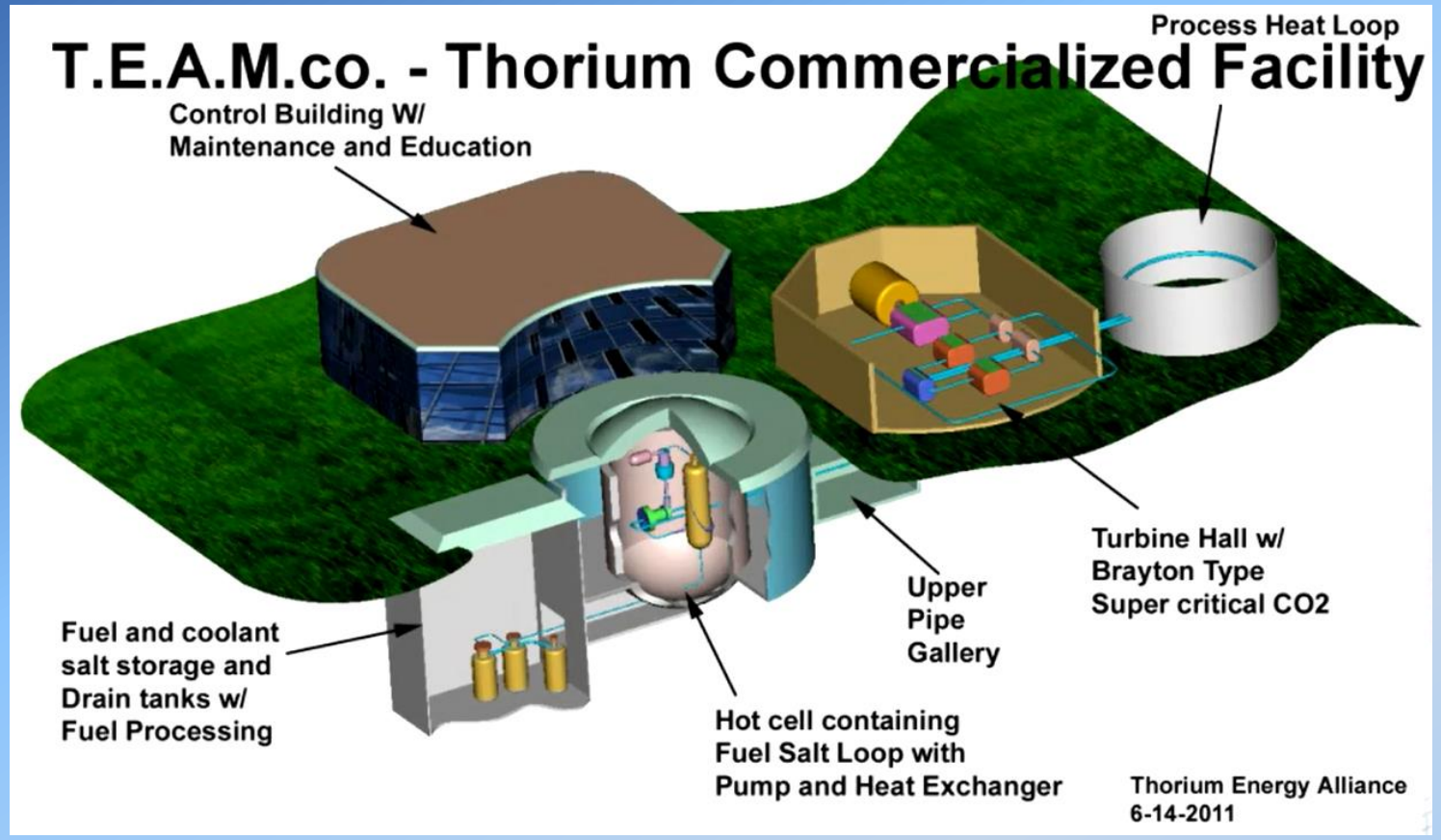
French Thorium Molten Salt Reactor, TMSR

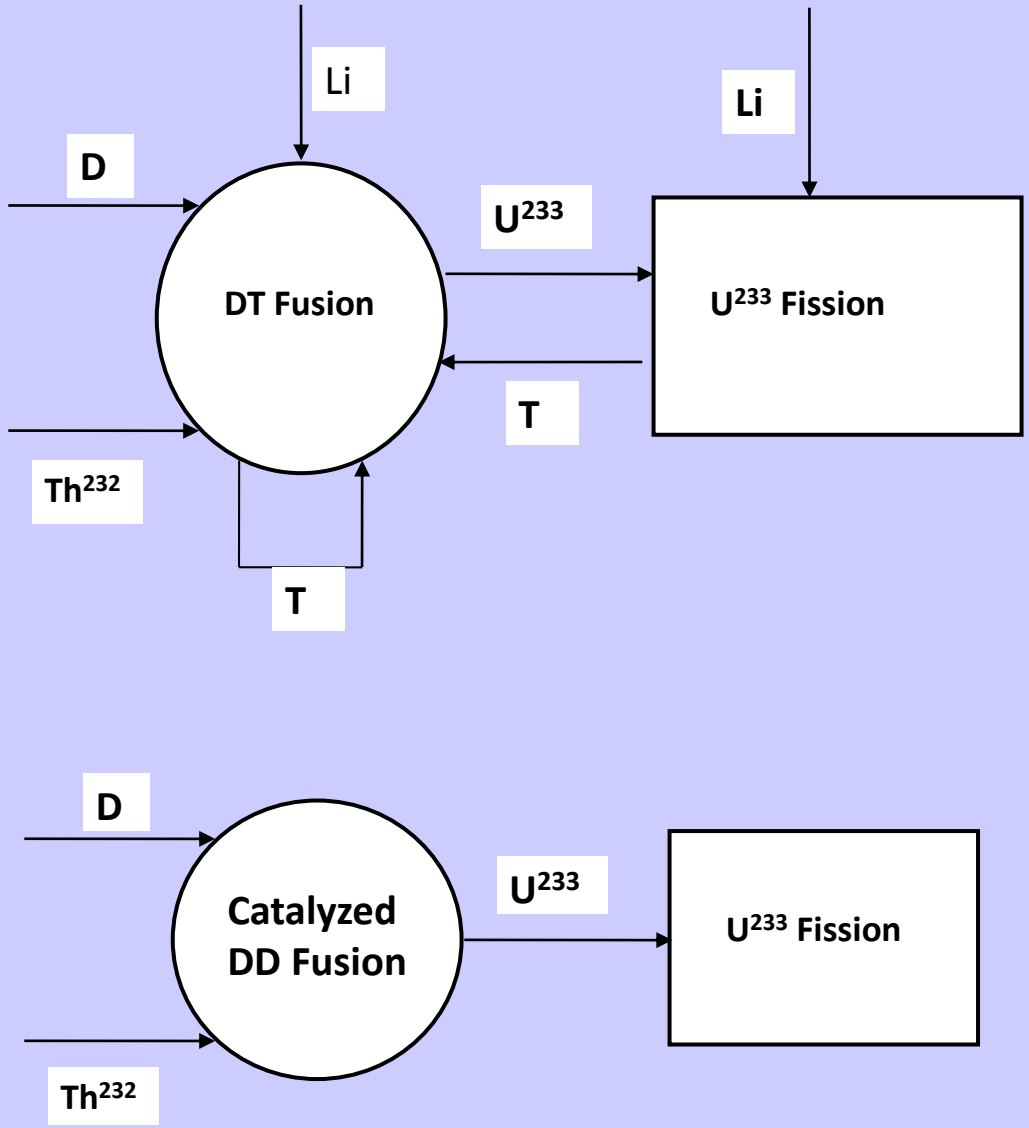


The Molten Salt Breeder Reactor is considered as a Generation IV reactor concept alternative.



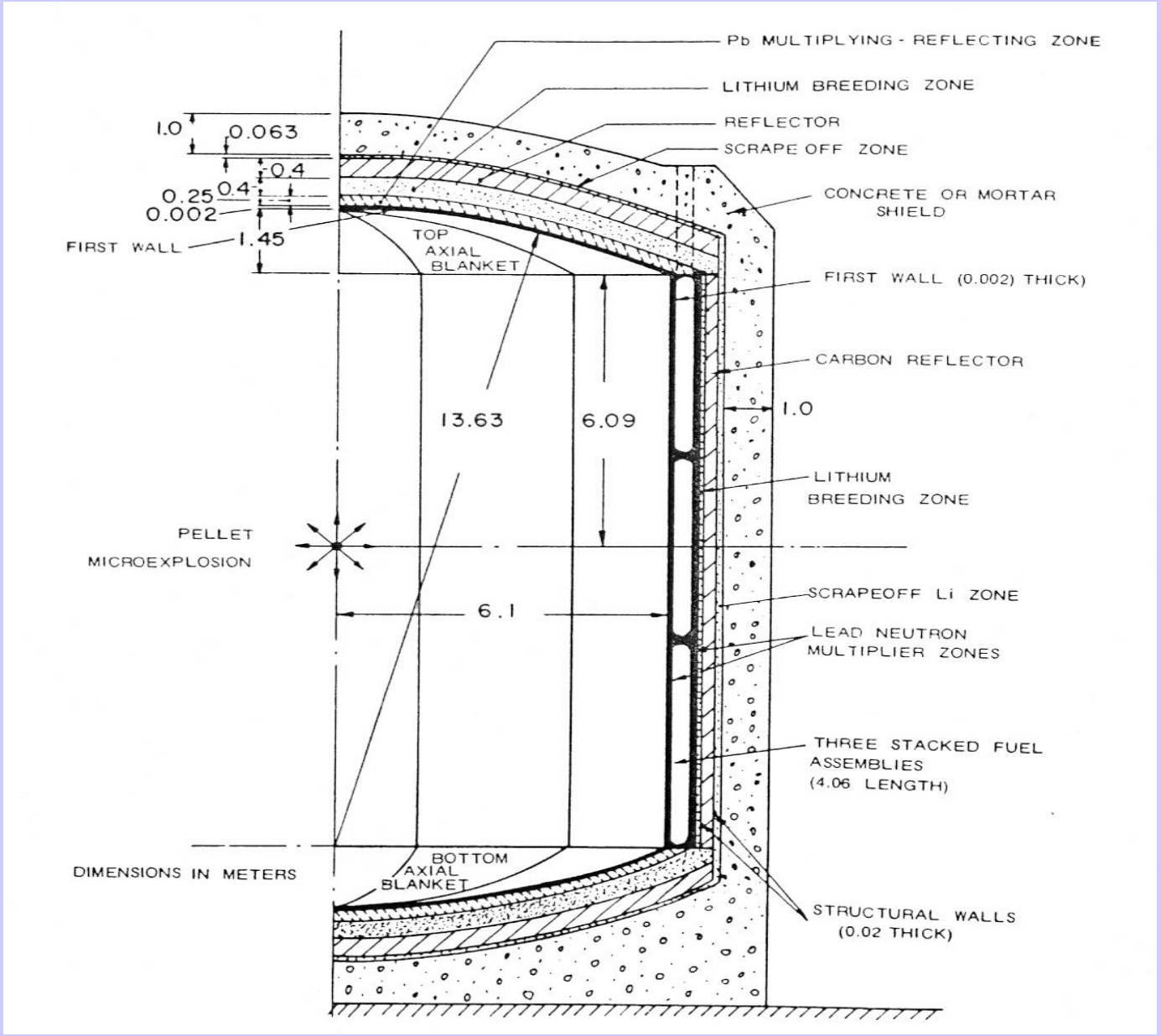
Conceptual design of a Molten Salt Reactor



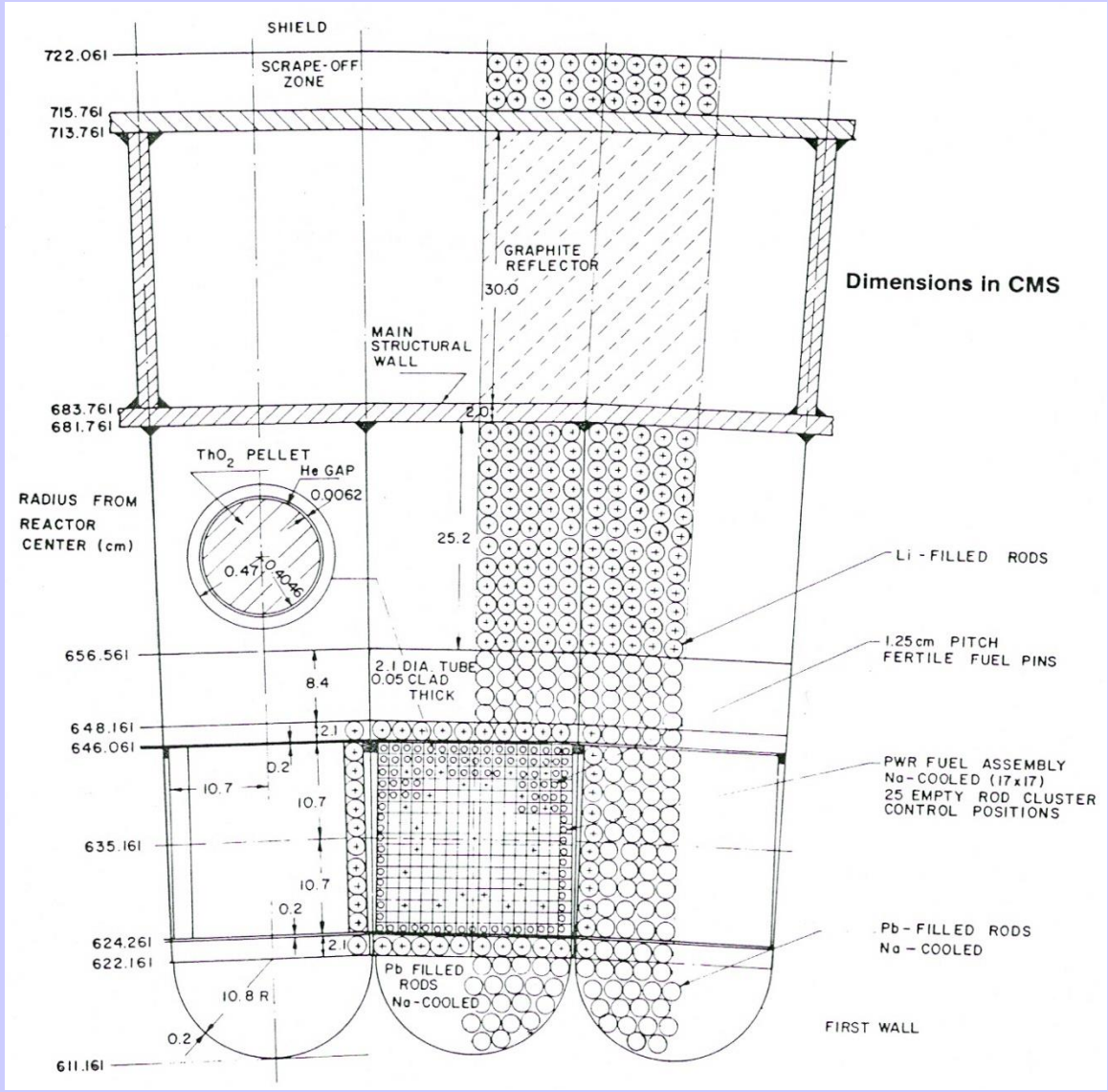


Material flows in the DT (top) and Catalyzed DD fusion-fission hybrid (bottom) Fuel Factory alternatives with U^{233} breeding from Th^{232}.

Laser fusion fissile generator plant with U^{233} breeding.

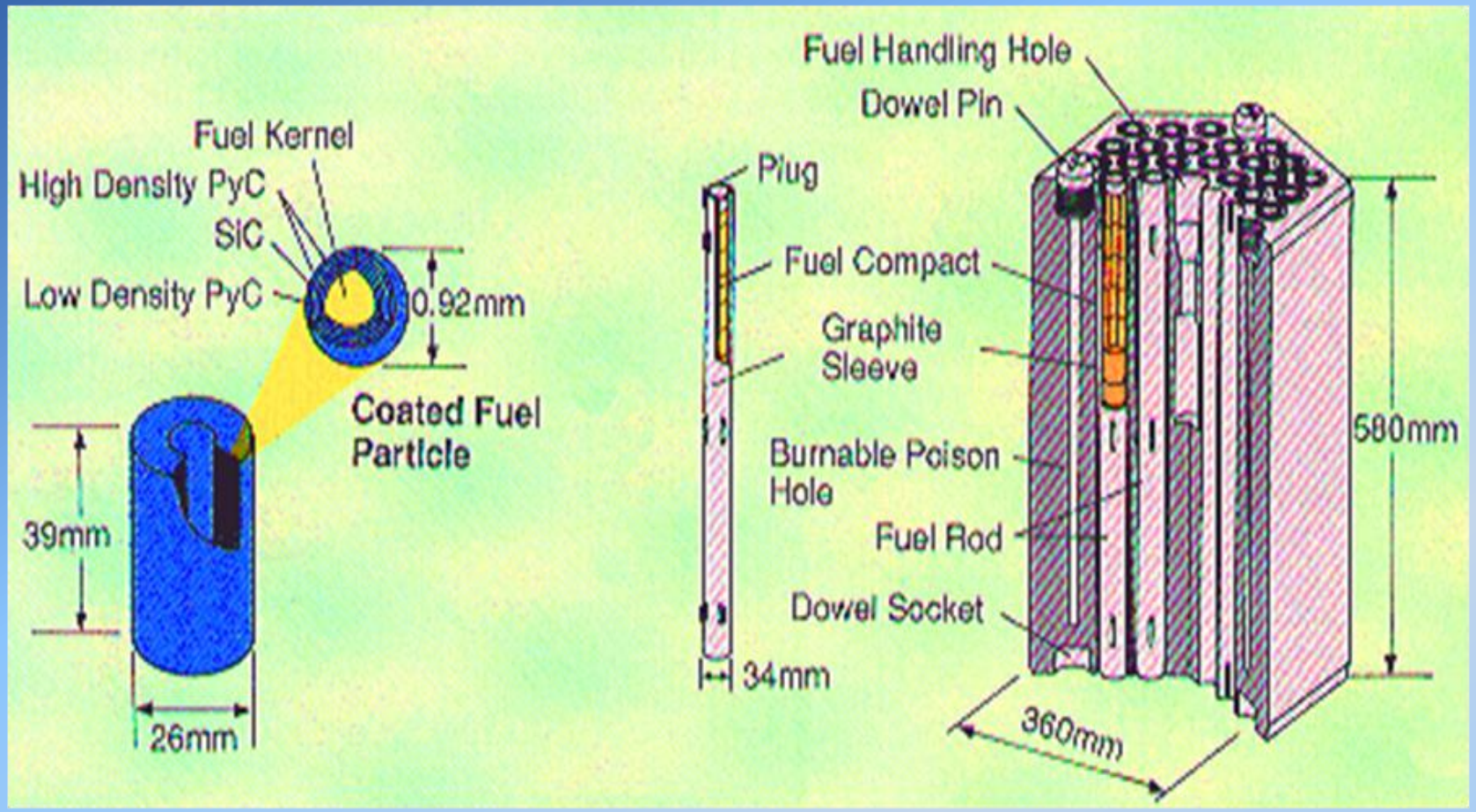


ThO_2 Pressurized Water Reactor fuel elements within a flux trap neutron multiplication zone, followed by a tritium breeding zone and a graphite reflector.



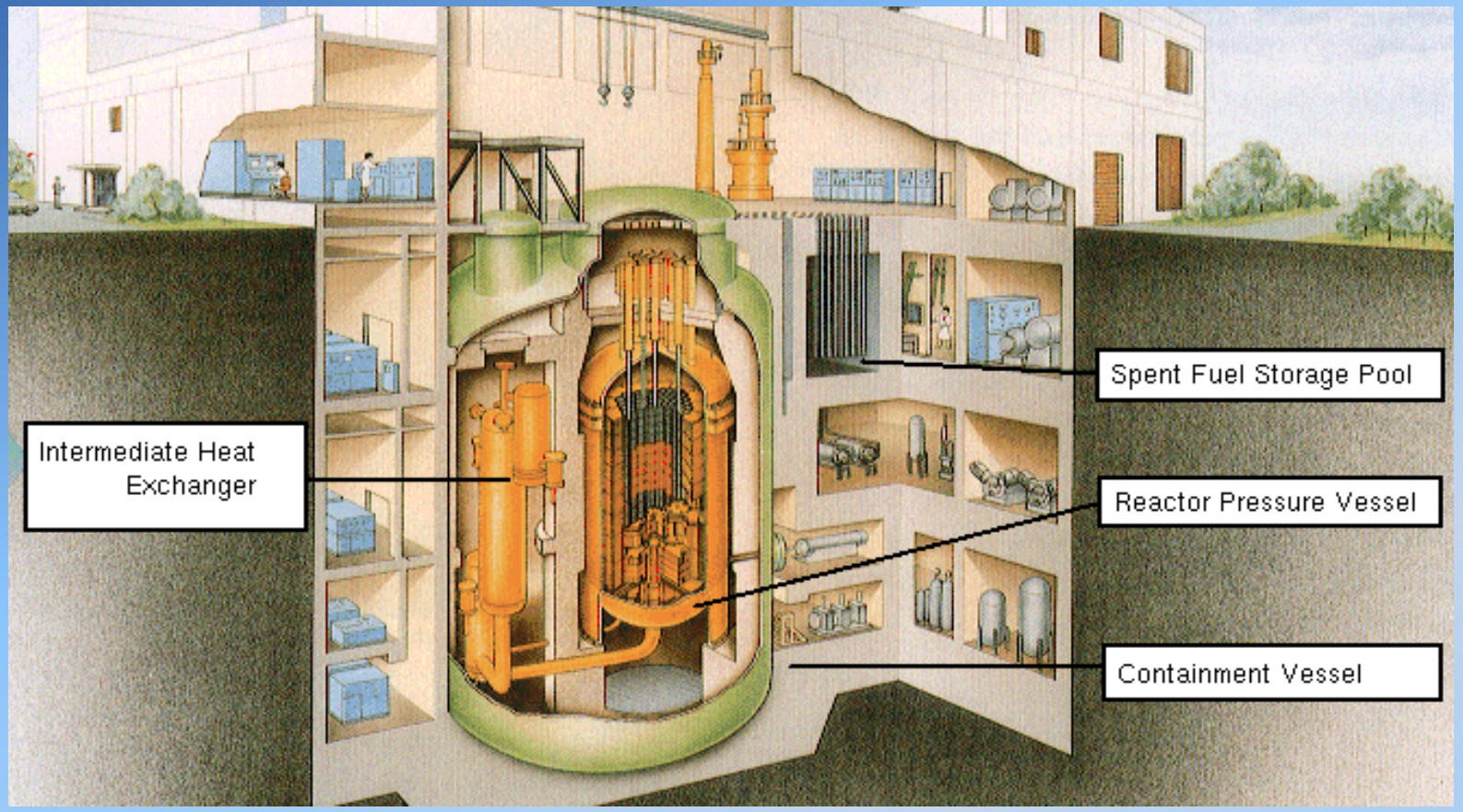
Prismatic hexagonal graphite fuel block.

High Temperature Engineering Test Reactor (HTTR) is a 30 MW(th) prismatic core HTGR designed, constructed and operated by the Japan Atomic Energy Research Institute (JAERI).



Solid fuel pellets

High Temperature Engineering Test Reactor, HTTR is sited underground.

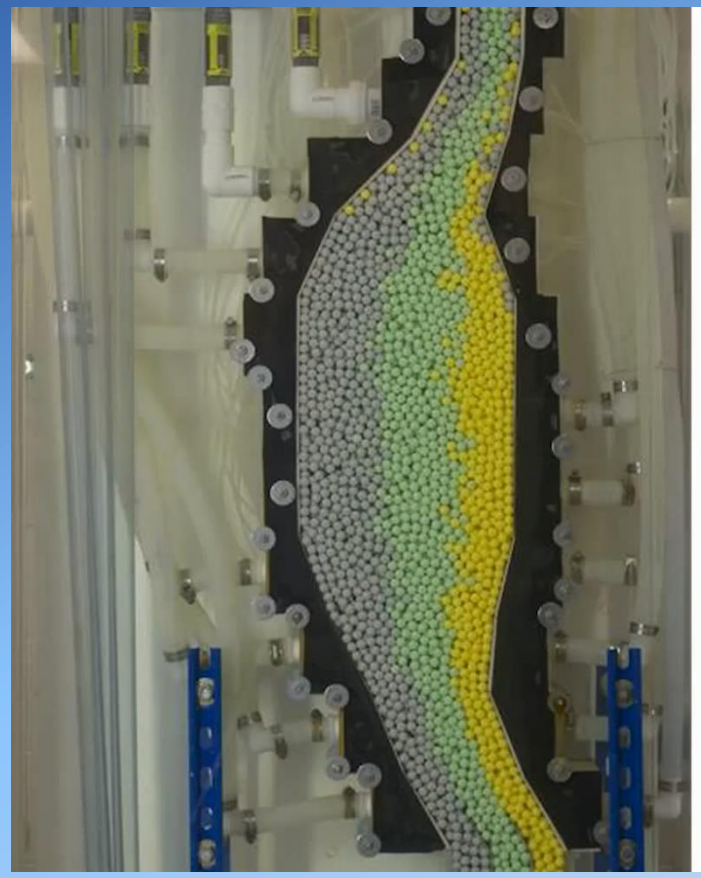


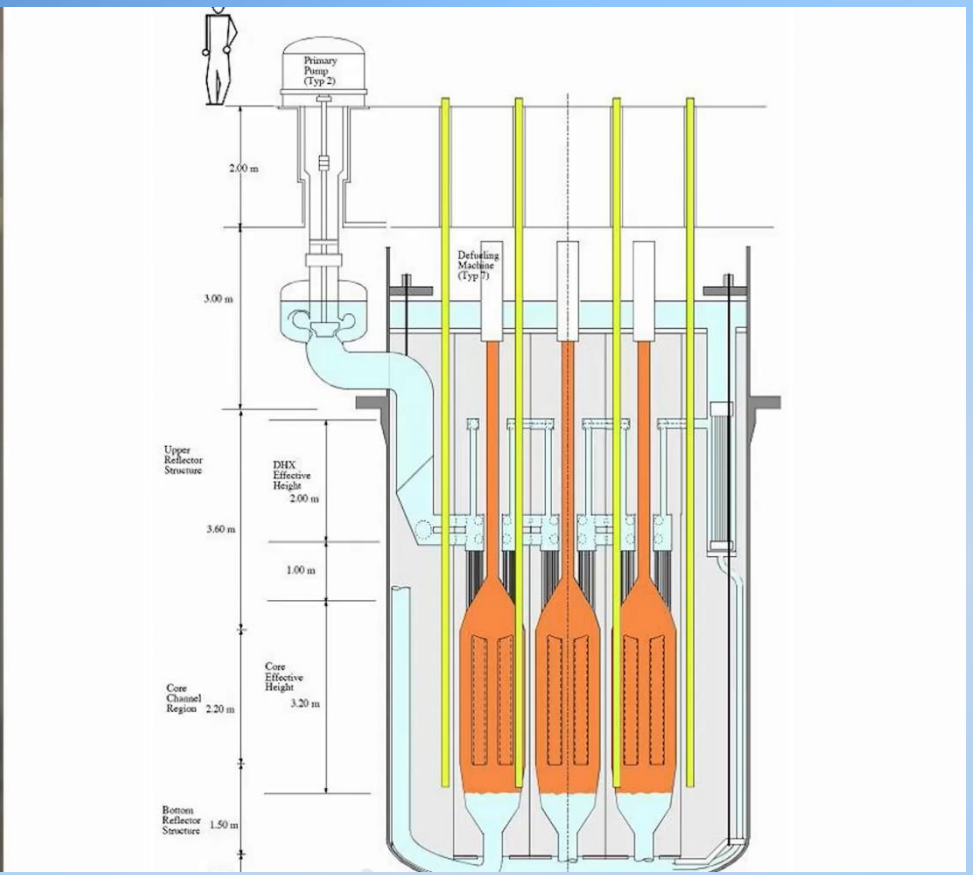
HTR-10 is a 10 MWth pebble bed core HTGR designed, constructed and operated by the Institute for Nuclear Energy Technology (INET) at Tsinghua University in China.

Fluoride Salt Cooled High temperature Reactor, FHR, ORNL

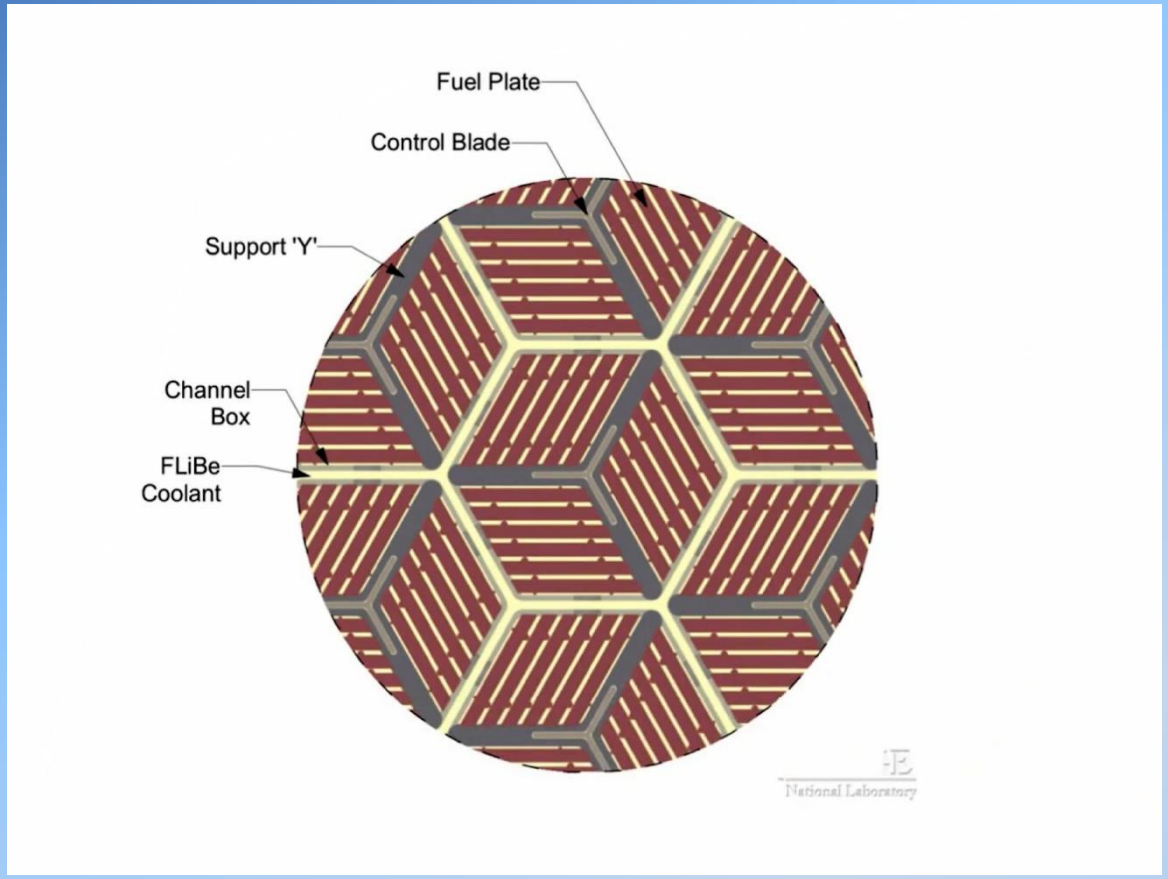
- Uses solid fuel: coated-particle ceramic fuel.
- Fluoride salt is used as primary coolant.
- Low pressure pool-type primary system configuration.
- Can deliver high temperature in the range of 600 oC.
- Strong safety features. No requirement for active response to avoid core damage or large off-site release from postulated severe accidents.

Pebble bed high temperature molten salt cooled reactor, ORNL





Solid fuel Flibe-salt cooled fuel plates



Safety Advantages of Liquid Fueled Systems

- Decay heat generation can be eliminated by continuous extraction of the fission products.
- Need to store solid fuel elements in storage pools eliminated.

- Core meltdown accidents are not applicable since fuel is in liquid form.
- In the case of fuel spillage, secondary criticality is not a problem, since a thermal reactor requires a moderator for criticality.

OTHER ADVANTAGES OF THE THORIUM FUEL CYCLE

1. Breeding is possible in both the thermal and fast parts of the neutron spectrum with a regeneration factor of $\eta > 2$.

2. Expanded nuclear fuel resources due to the higher abundance of the fertile Th232 than U238. The USA proven resources in the state of Idaho amount to 600,000 tons of 30 percent of Th oxides. The probable reserves amount to 1.5 million tons. There exists about 3,000 tons of already milled thorium in a USA strategic stockpile stored in Nevada.

3. Lower nuclear proliferation concerns due to the reduced limited needs for enrichment of the U235 isotope that is needed for starting up the fission cycle and can then be later replaced by the bred U233. The fusion fission hybrid totally eliminates that need. An attempted U233 weapon test was reported as a fizzle because the U232 contaminant concentration and its daughter products could not be reduced enough.

4. A superior system of handling fission products wastes than other nuclear technologies and a much lower production of the long lived transuranic elements as waste. One ton of natural Th232, not requiring enrichment, is needed to power a 1,000 MWe reactor per year compared with about 33 tons of uranium solid fuel to produce the same amount of power. The thorium just needs to be purified then converted into a fluoride. The same initial fuel loading of one ton per year is discharged primarily as fission products to be disposed of for the fission thorium cycle.

ADVANTAGES OF THE THORIUM FUEL CYCLE

5. Ease of separation of the lower volume and short lived fission products for eventual disposal.

6. Higher fuel burnup and fuel utilization than the U235-Pu239 cycle.

7. Enhanced nuclear safety associated with better temperature and void reactivity coefficients and lower excess reactivity in the core. Upon being drained from its reactor vessel, a thorium molten salt would solidify shutting down the chain reaction,

8. With a tailored breeding ratio of unity, a fission thorium fuelled reactor can generate its own fuel, after a small amount of fissile fuel is used as an initial loading.

9. The operation at high temperature implies higher thermal efficiency with a Brayton gas turbine cycle (thermal efficiency around 40-50 percent) instead of a Joule or Rankine steam cycle (thermal efficiency around 33 percent), and lower waste heat that can be used for desalination or space heating. An open air cooled cycle can be contemplated eliminating the need for cooling water and the associated heat exchange equipment in arid areas of the world.

10. A thorium cycle for base-load electrical operation would provide a perfect match to peak-load cycle wind turbines generation. The produced wind energy can be stored as compressed air which can be used to cool a thorium open cycle reactor, substantially increasing its thermal efficiency, yet not requiring a water supply for cooling.

ADVANTAGES OF THE THORIUM FUEL CYCLE

11. The unit powers are scalable over a wide range for different applications such as process heat or electrical production. Units of 100 MWe each can be designed, built and combined for larger power needs.

12. Operation at atmospheric pressure without pressurization implies the use of standard equipment with a lower cost than the equipment operated at high pressure in the LWRs cycle.

13. In uranium-fuelled thermal reactors, without breeding, only 0.72 percent or 1/139 of the uranium is burned as U235. If we assume that about 40 percent of the thorium can be converted into U233 then fissioned, this would lead to an energy efficiency ratio of 139 x 0.40 = 55.6 or 5560 percent more efficient use of the available resource.

14. Operational experience exists from the Molten Salt reactor experiment (MSRE) at oak Ridge National Laboratory (ORNL) at Oak Ridge, Tennessee. A thorium fluoride salt was not corrosive to nickel alloy: Hastelloy-N. Corrosion was caused only from tellurium, a fission product.

Summary

An overview of the thorium fission fuel cycle is presented. The global and local Th resources are assessed, and its ability to provide a practically unlimited energy supply through the breeding process is discussed. Two approaches to the use of thorium are identified using either solid or liquid fuel.

The solid fuel approach is exemplified in the pilot Shippingport fission reactor plant using the seed and blanket approach, in the High Temperature Gas Cooled Reactor (HTGR) in a pebble bed and a prismatic moderator and fuel configurations. The General Atomics (GA) Company built two thorium reactors over the 1960-1970 period. The first was a 40 MWe prototype at Peach Bottom, Pennsylvania operated by Philadelphia Electric. The second was the 330 MWe Fort St. Vrain reactor for Public service of Colorado which operated between 1971 and 1975. The AVR, TFTR-300 pebble-bed reactor was built and operated in Germany. Existing research reactor installations are centered around solid fuel. This approach is characterized by marginal breeding capabilities requiring sometimes the use of neutron multiplication features such as the use of beryllium.

The liquid fuel approach was pursued on an experimental basis in the Molten Salt Breeder Experiment (MSBR) over the period 1950-1976 at the Oak Ridge National Laboratory (ORNL). The Molten Salt Breeder Reactor is also understudy as a Generation IV reactor concept.

A comparison between the solid and liquid fuels approaches identifies concrete safety and breeding advantages, making the liquid fuel approach worthy of serious consideration for a long-term nuclear non-carbon energy option.

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