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The Fusion Fission Hybrid Thorium Fuel Cycle Alternative

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ABSTRACT

The thorium fusion fission hybrid is discussed as a sustainable longer term larger resource base to the fast breeder fission reactor concept. In addition, it offers a manageable waste disposal process, burning of the produced actinides and serious nonproliferation characteristics.

With the present day availability of fissile U235 and Pu239, and available fusion and accelerator neutron sources, a fresh look at the thorium-U233 fuel cycle is warranted. The use of the thorium cycle in a fusion fission hybrid could bypass the stage of fourth generation breeder reactors in that the energy multiplication in the fission part allows the satisfaction of energy breakeven and the Lawson condition in magnetic and inertial fusion reactor designs. This allows for the incremental development of the technology for the eventual introduction of a pure fusion technology.

The nuclear performance of a fusion-fission hybrid reactor having a molten salt composed of Na-Th-F-Be as the blanket fertile material and operating with a catalyzed Deuterium-Deuterium (DD) plasma is compared to a system with a Li-Th-F-Be salt operating with a Deuterium-Tritium (DT) plasma. In a reactor with a 42-cm thick salt blanket followed by a 40-cm thick graphite reflector, the catalyzed DD system exhibits a fissile nuclide production rate of 0.88 Th(n,γ) reactions per fusion source neutron. The DT system, in addition to breeding tritium from lithium for the DT reaction yields 0.74 Th(n,γ) breeding reactions per fusion source neutron. Both approaches provide substantial energy amplification through the fusion-fission coupling process.

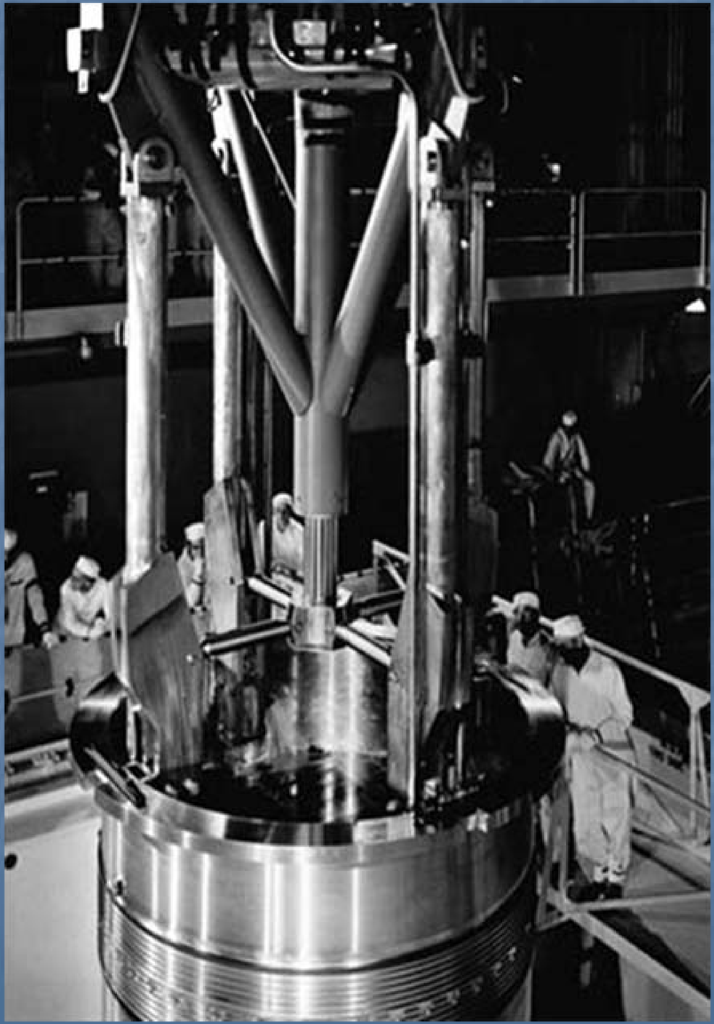
Such an alternative sustainable paradigm or architecture would provide the possibility of a well optimized fusion-fission thorium hybrid using a molten salt coolant for sustainable long term fuel availability with the added advantages of higher temperatures thermal efficiency for process heat production, proliferation resistance and minimized waste disposal characteristics.

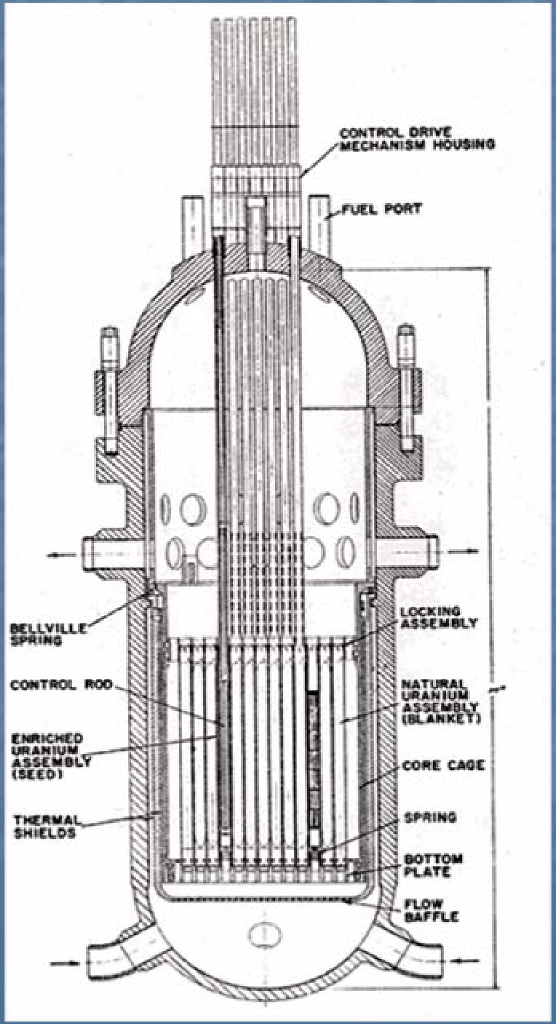
Historical Perspective

Historically, the thorium fission fuel cycle was investigated over the period 1950-1976 in the Molten Salt Breeder Reactor (MSBR) at the Oak Ridge National Laboratory (ORNL) as well as in the pilot Shippingport fission reactor plant.

It has also been used 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.

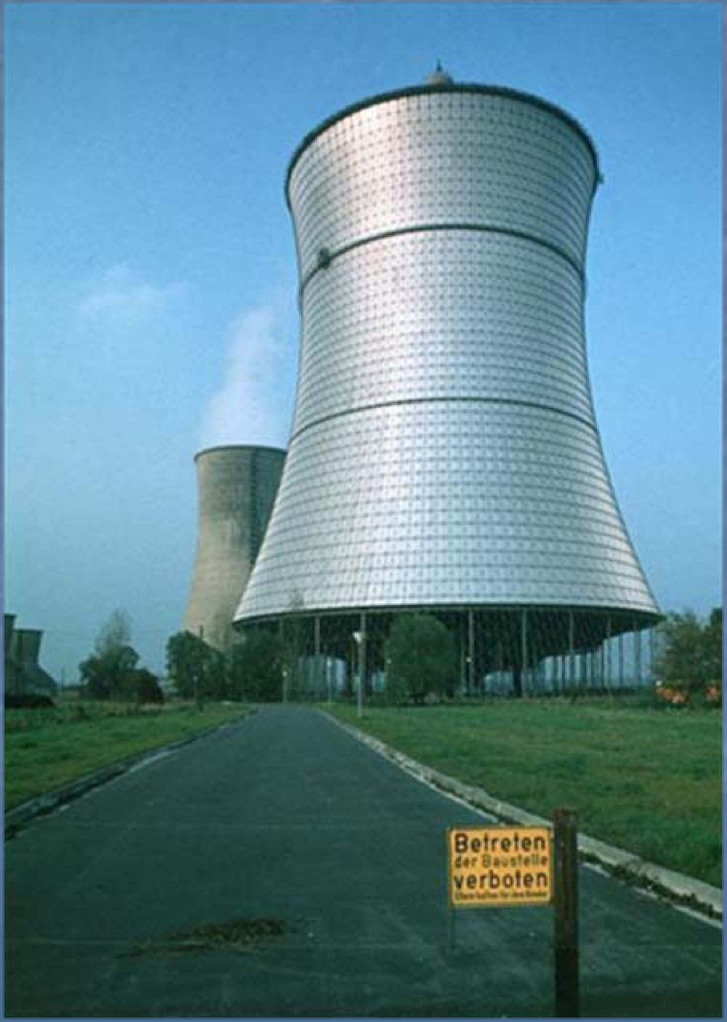
The Shippingport reactor was the first commercial and experimental nuclear power plant in the USA and second in the world after Calder Hall in the UK.

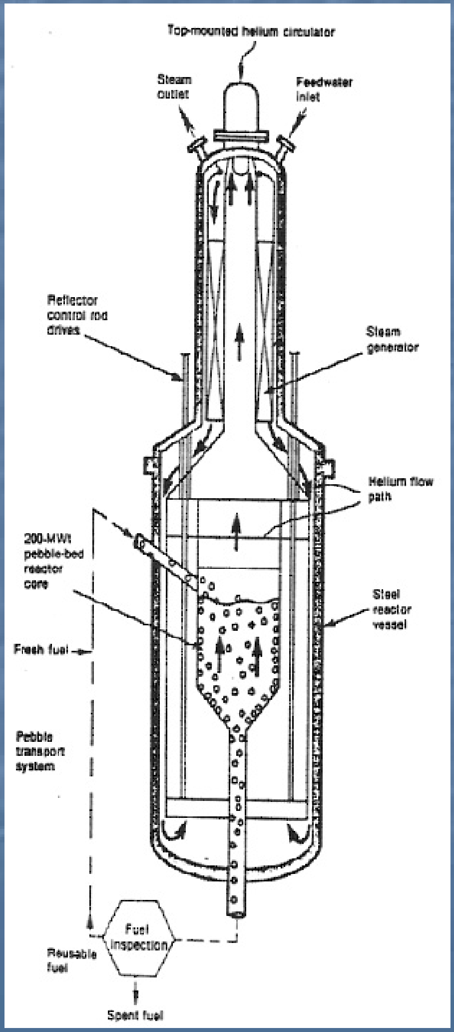




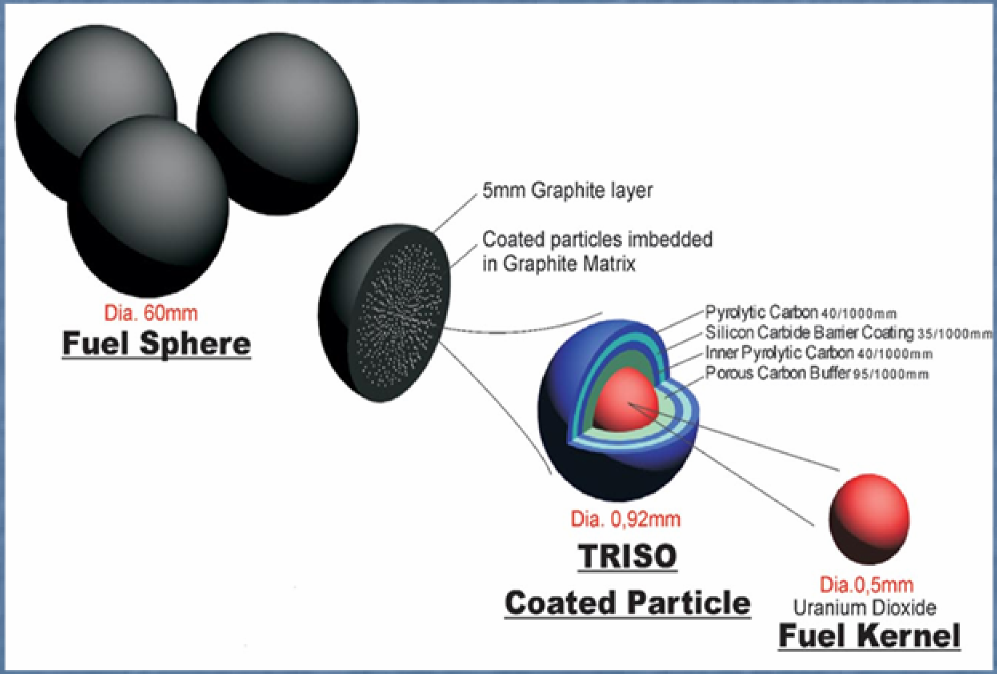
Fort Saint Vrain He cooled graphite moderated reactor, Colorado.

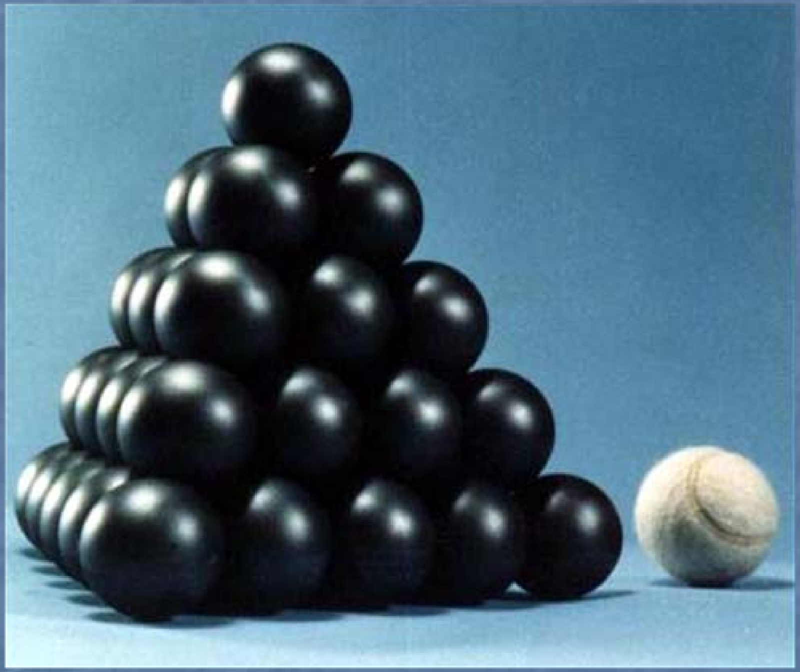
The TFTR-300 U235-Th232 high temperature pebble bed reactor used a 180 m high dry cooling tower. AVR reactor, Germany.



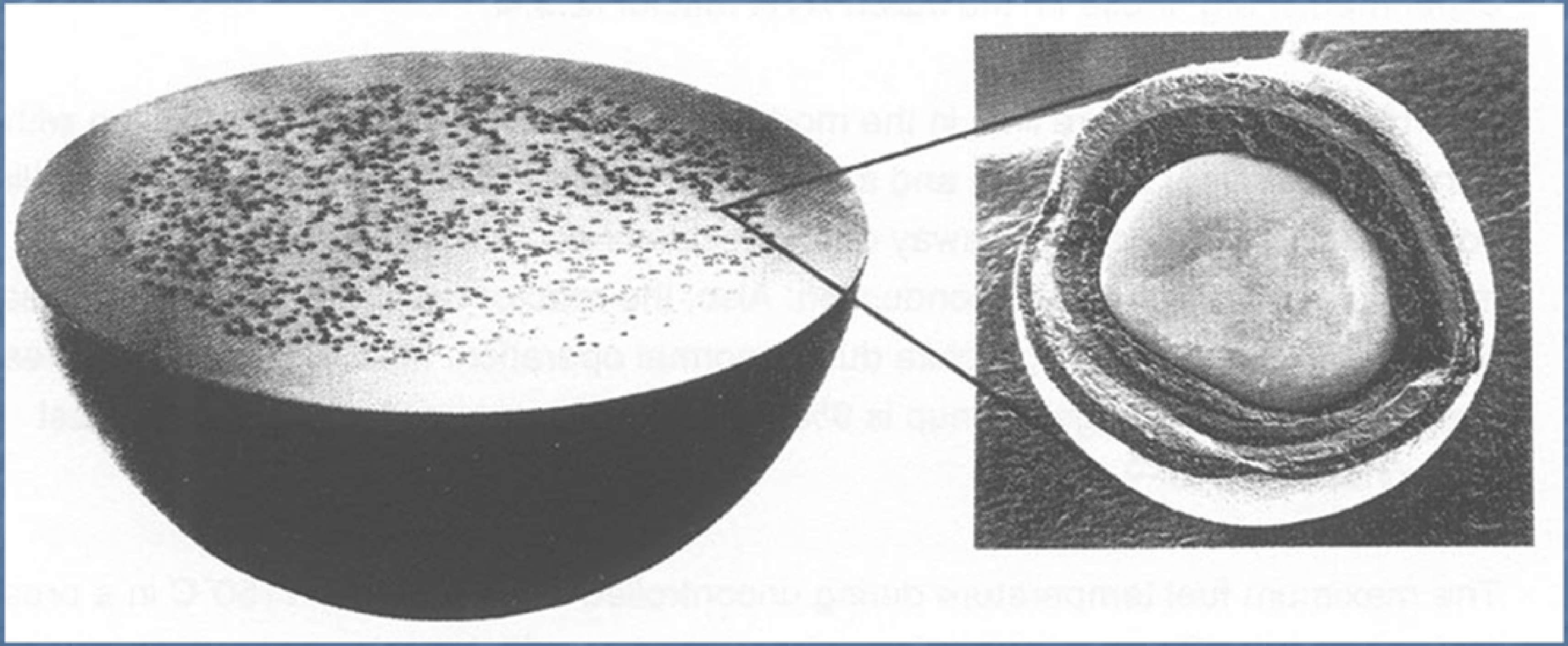


Fuel kernel, coated triso fuel particle and pebble fuel sphere design.



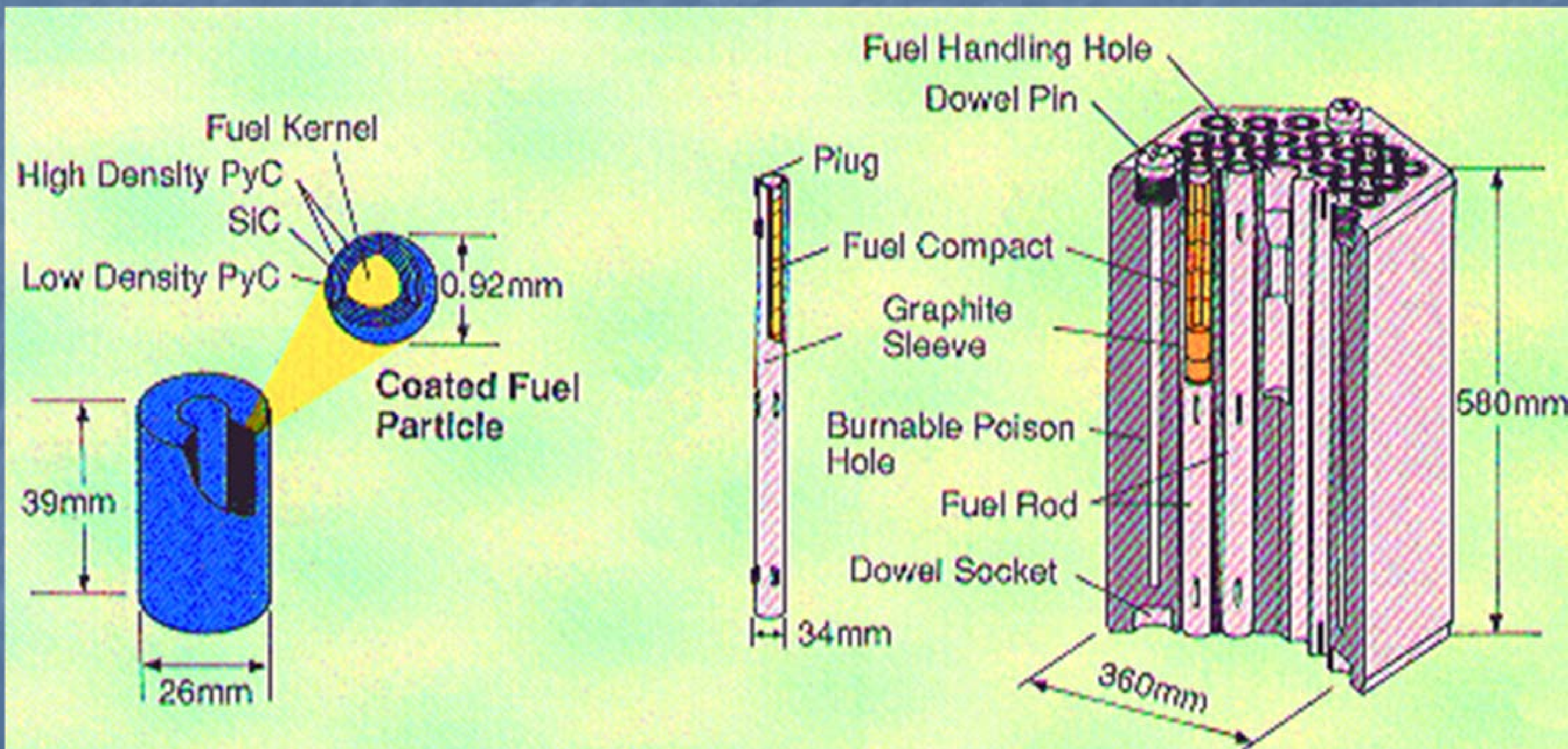


Fuel particles used in the pebble bed and the prismatic fuel designs.

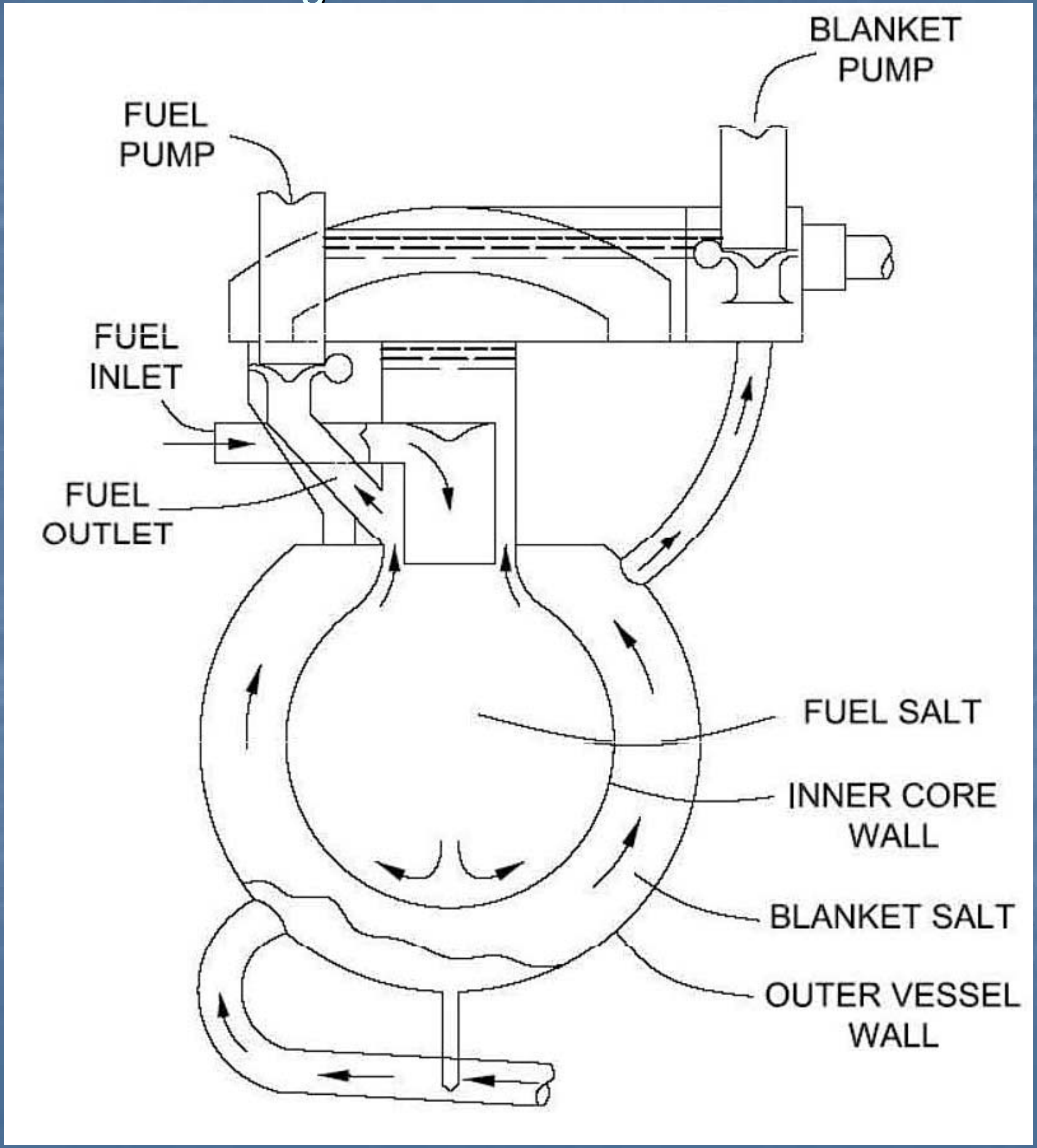


Prismatic hexagonal graphite fuel block.

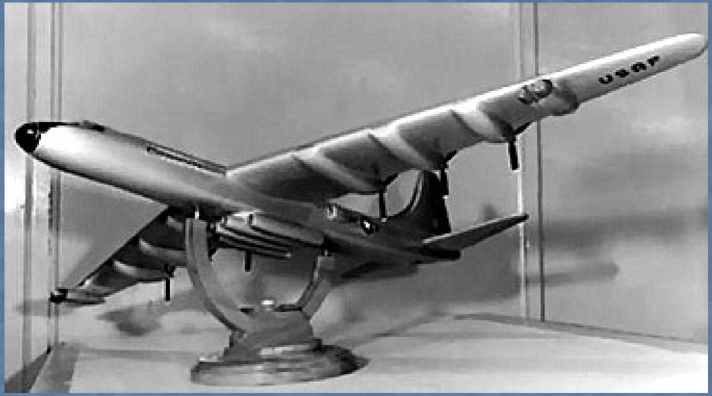
High Temperature Engineering Test Reactor (HTTR) is a 30 MW(th) prismatic core HTGR designed, constructed and operated by the Japan Atomic Energy Research Institute (JAERI).

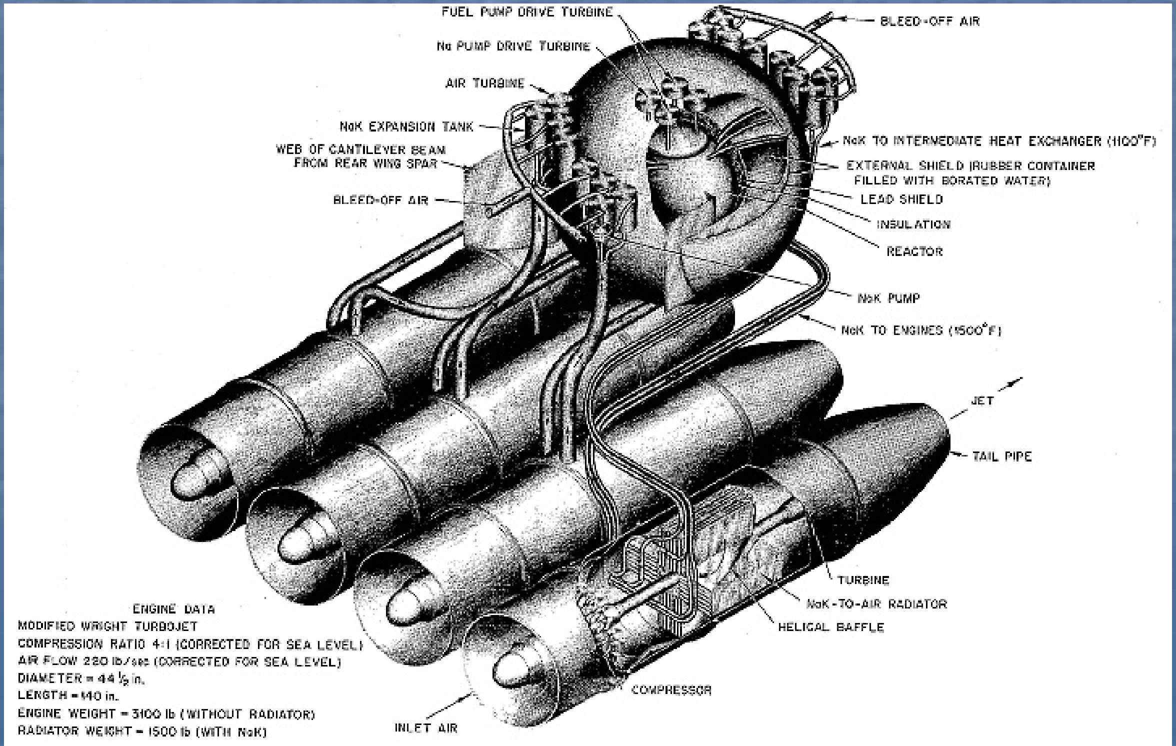


Homogeneous Molten Salt Reactor

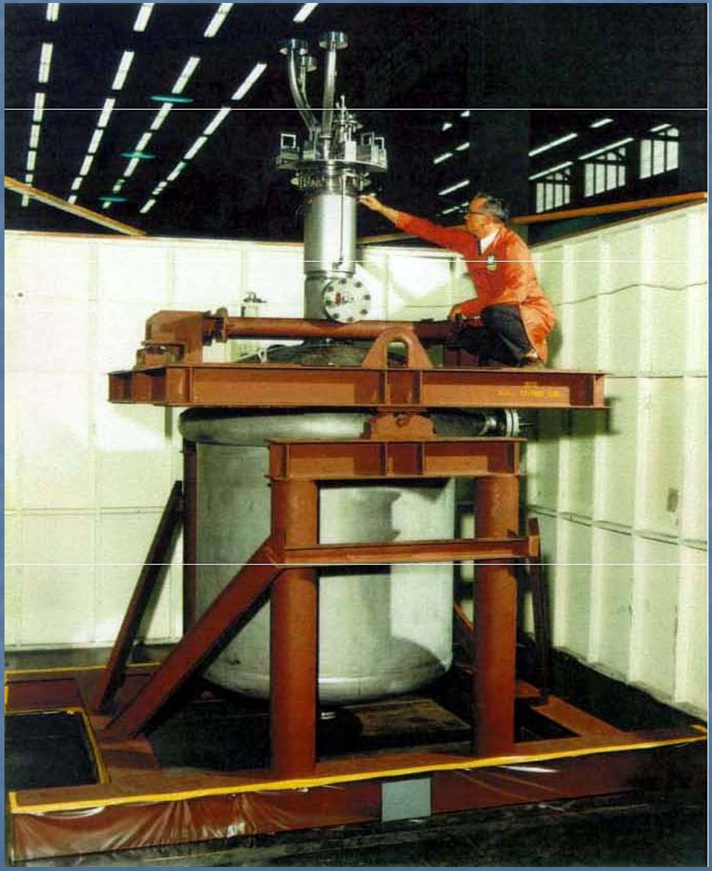


Convair B36 X6 200 MW Wright turbojet engine

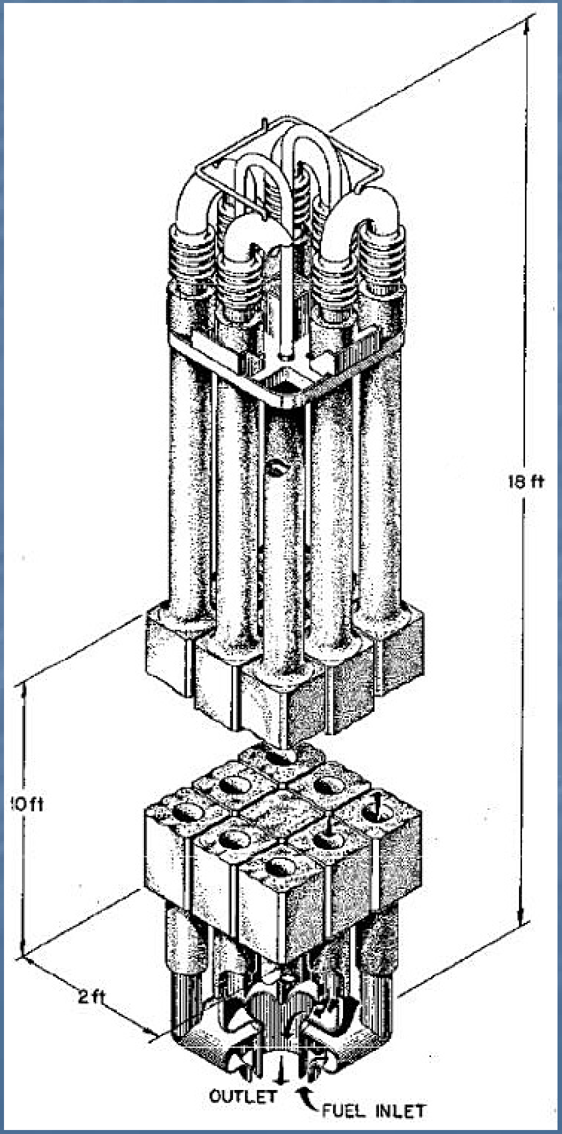


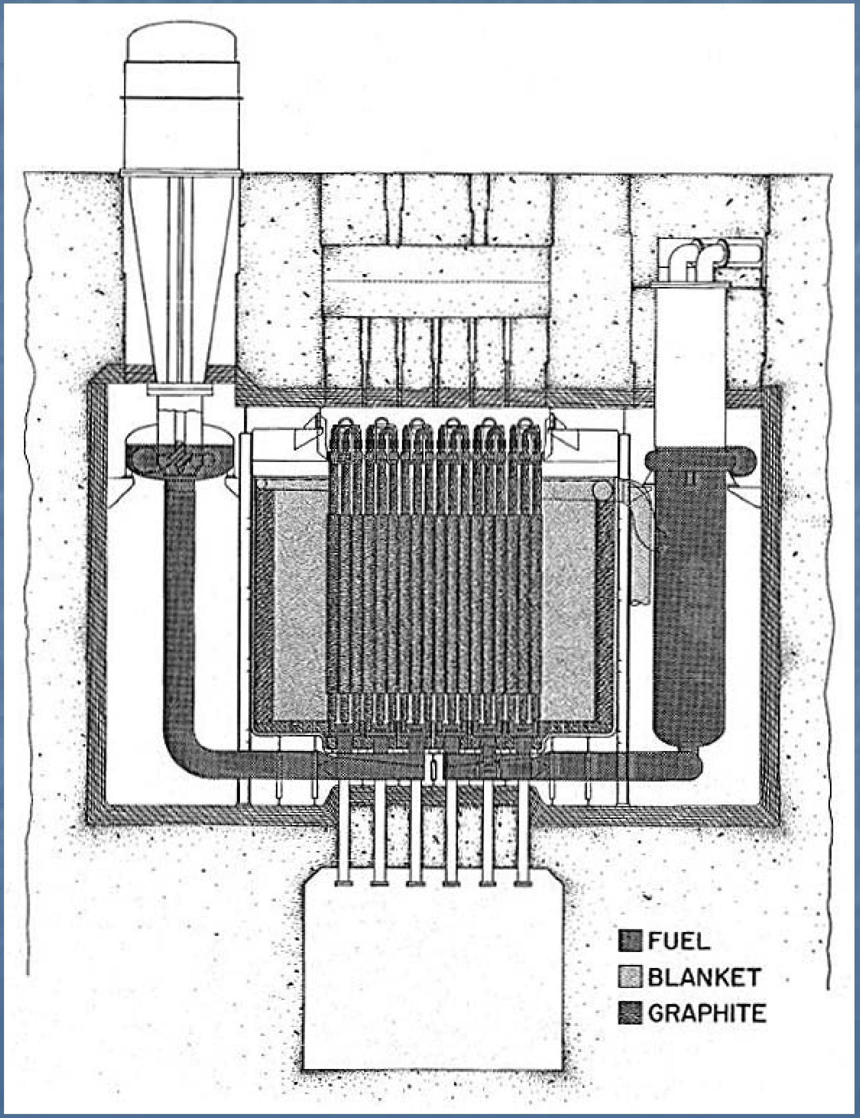


Molten Salt Reactor Experiment, 8MWth

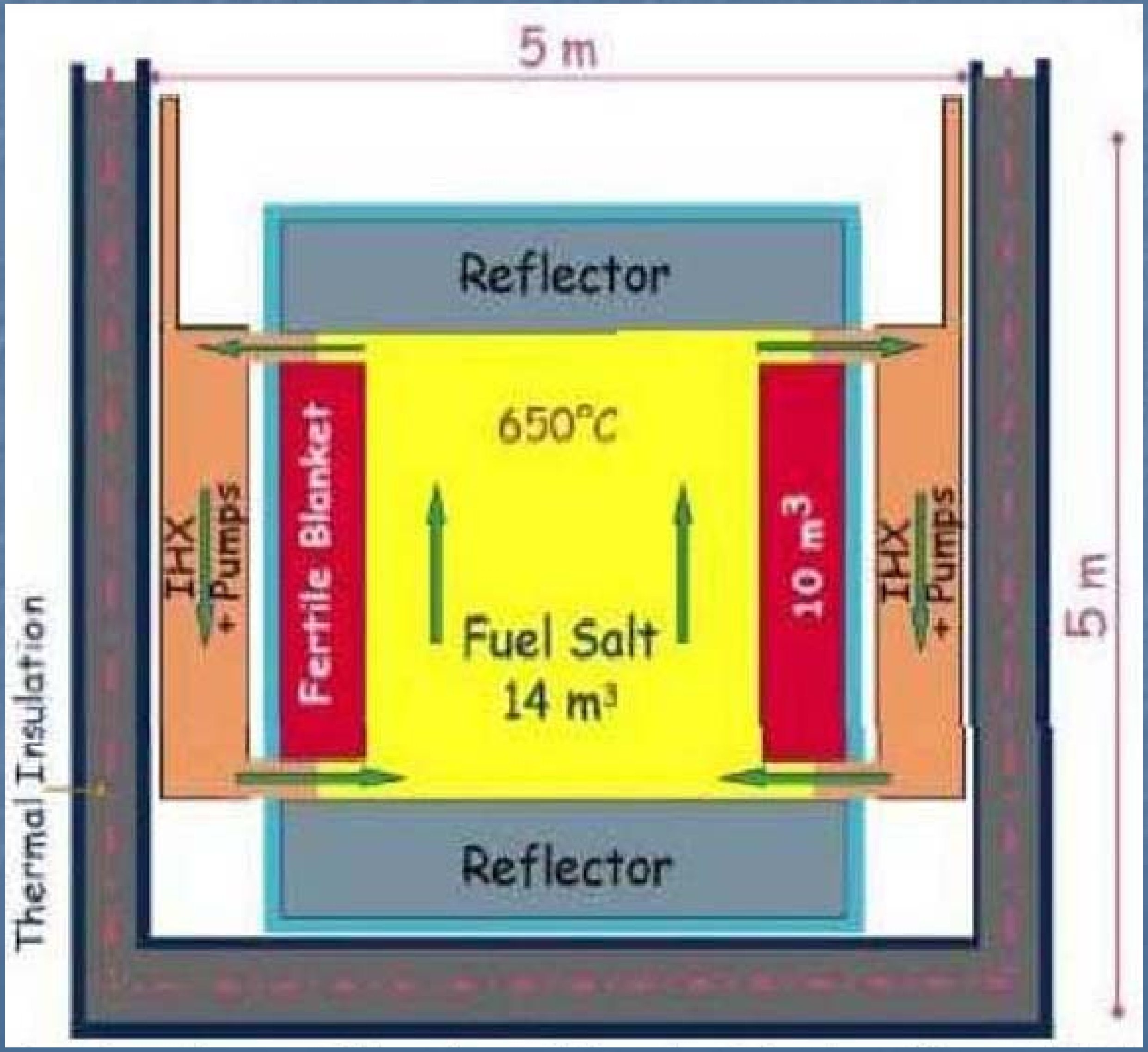


Two region Molten Salt Breeder

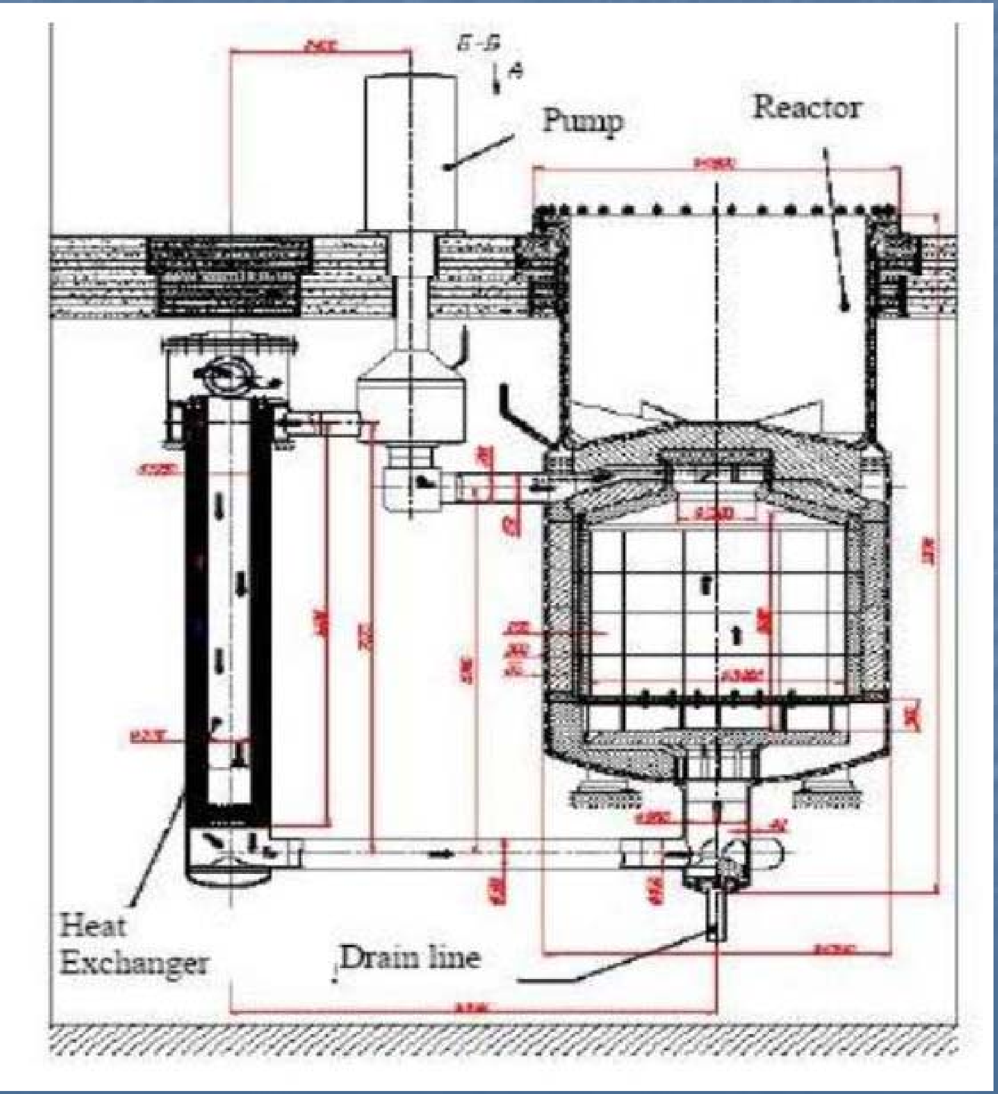




French Thorium Molten Salt Reactor, TMSR



Russian Molten Salt Actinide Recycler and Transmuter, MOSART



Goal

- With the present day availability of fissile U235 and Pu239, and available fusion and accelerator neutron sources, a fresh look at the thorium cycle is ongoing.
- Whereas the U233-Th232 fuel cycle is undergoing a revival as a replacement of the existing Light Water Reactors (LWRs) system, a highly promising approach is its use in fusion-fission hybrid reactors as an eventual bridge and technology development for future pure fusion reactors, bypassing the intermediate stage of the fast fission breeder reactors.
- We discuss the possibility of taking advantage of the Th cycle benefits in the form of an optimized fission-fusion thorium hybrid.

Monazite and Thorite Thorium ores

Thorium is more Abundant than Uranium

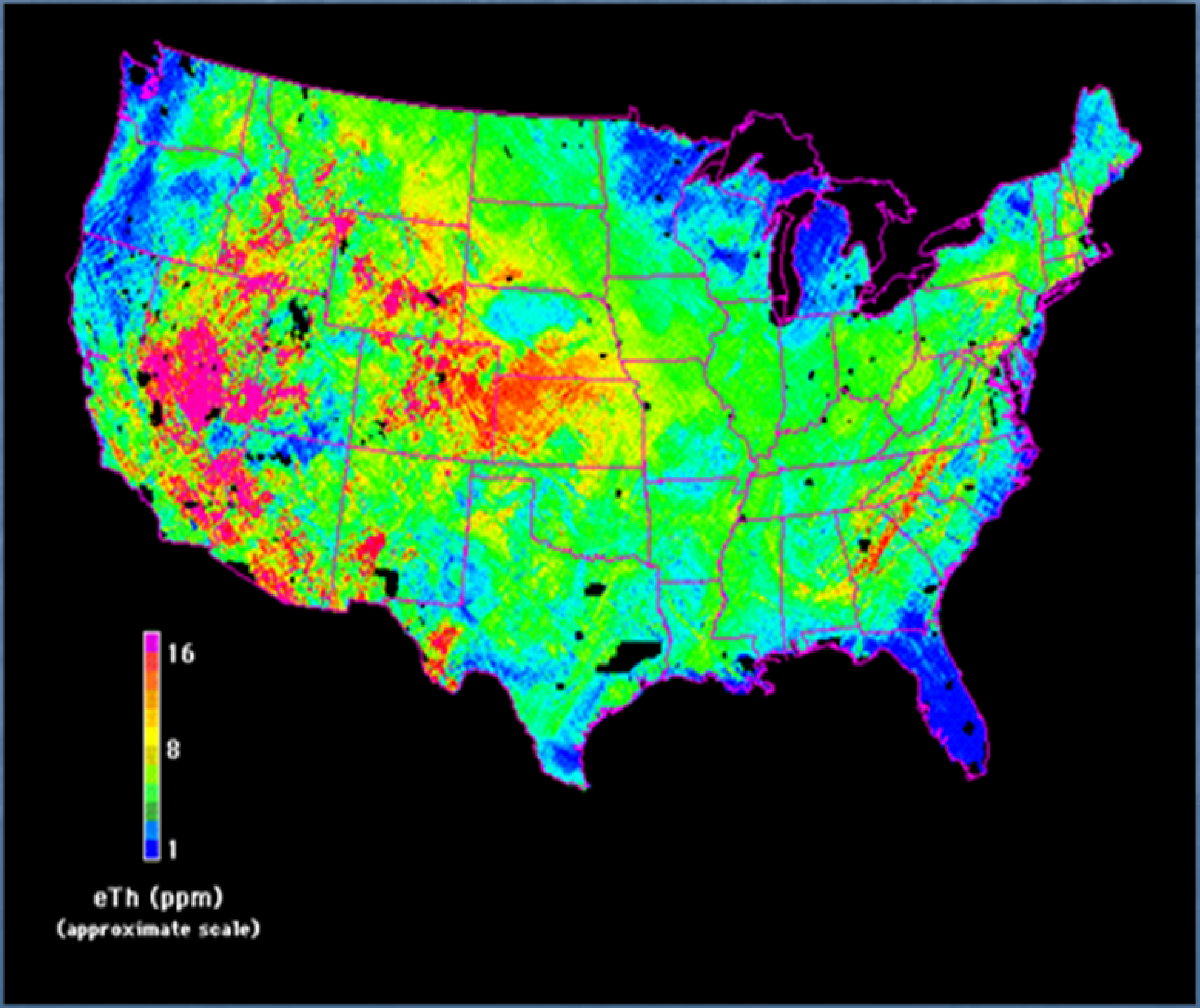
Element	Symbol	Abundance [gms/ton]
Lead	Pb	16
Gallium	Ga	15
Thorium	**Th**	**10**
Samarium	Sm	7
Gadolinium	Gd	6
Praseodymium	Pr	6
Boron	B	3
Bromine	Br	3
Uranium	**U**	**2.5**
Beryllium	Be	2
Tin	Sn	1.5
Tungsten	W	1
Molybdenum	Mo	1
Mercury	Hg	0.2
Silver	Ag	0.1
Uranium^{235}	**U^{235}**	**0.018**
Platinum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

Estimated Global Thorium Resources

Country	ThO_2 Reserves [metric tonnes] USGS estimate 2010 [16]	ThO_2 Reserves [metric tonnes] NEA estimate [22]***	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

Thorium dioxide

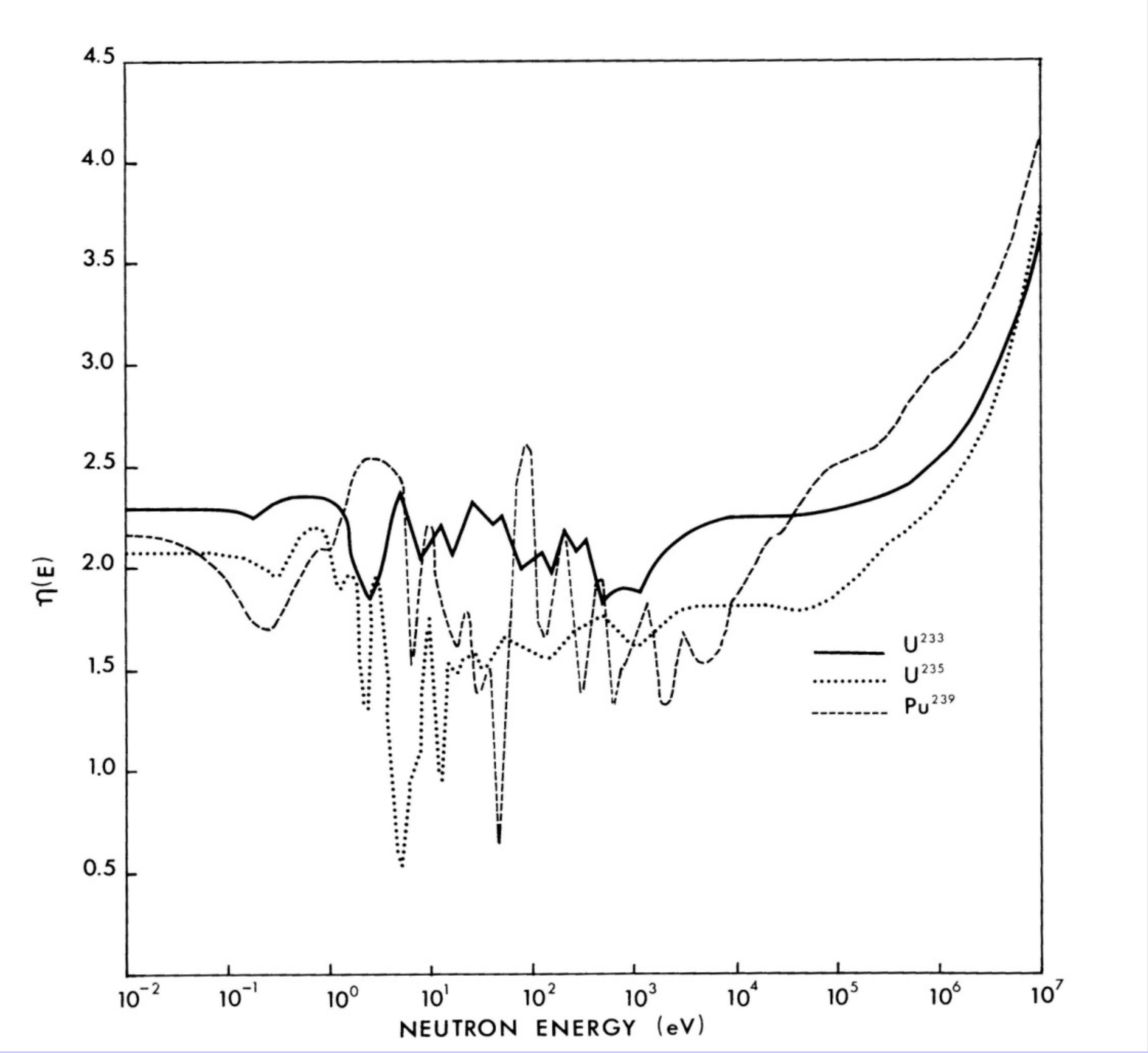
Th concentrations in ppm and occurrences in the USA. Source: USA Geological Survey Digital Data Series DDS-9, 1993.

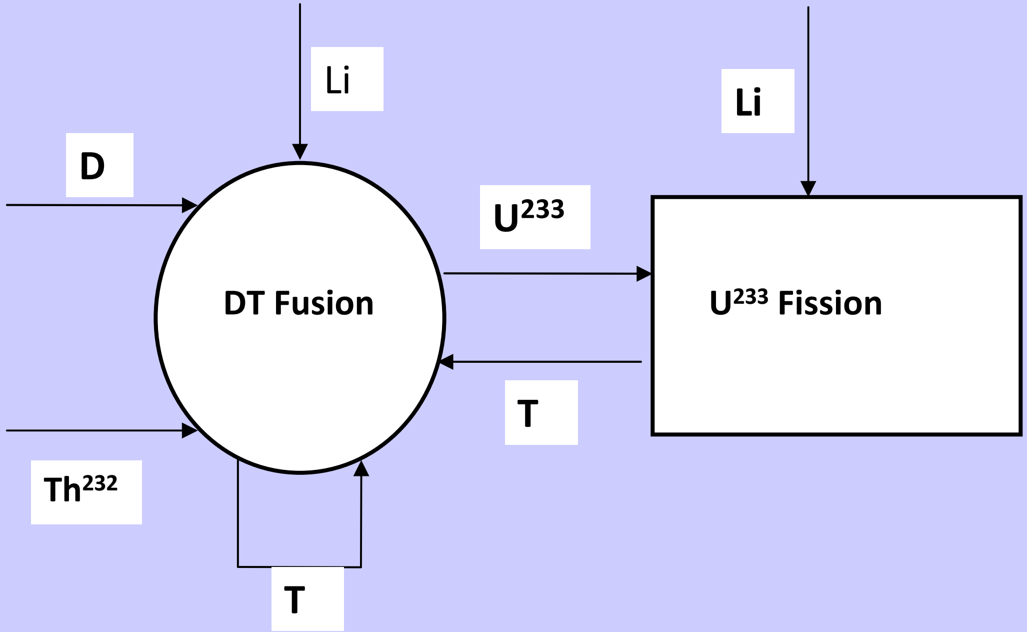


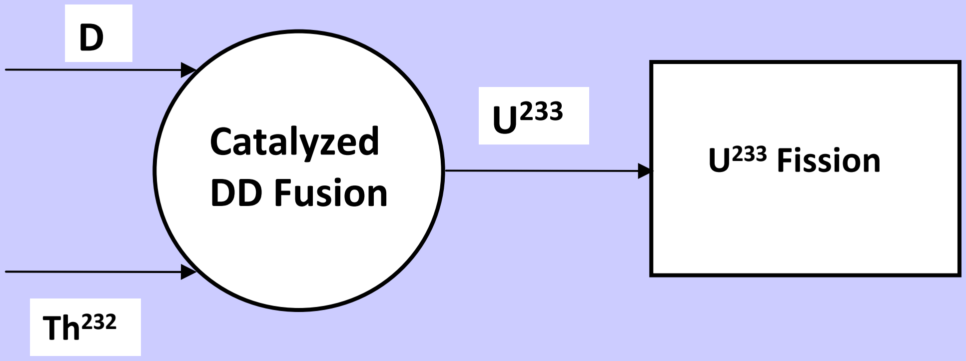
Lehmi Pass is a part of Beaverhead Mountains along the continental divide on the Montana-Idaho border, USA.

Its Th veins contain rare earth elements, particularly Neodymium.

Regeneration factor 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.







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

For a first generation application of the fusion hybrid using the Th cycle, the DT fusion fuel cycle can be used

$$_1D^2 + _1T^3 \rightarrow _2He^4(3.52\text{ MeV}) + _0n^1(14.06\text{ MeV}) + 17.58\text{ MeV}$$

Deuterium can be obtained from heavy water D_2O separated from ordinary water H_2O.
Tritium (T) must be bred from abundant supplies of lithium as feed to the DT fusion reaction.

$$_3Li^6 + _0n^1(\text{thermal}) \rightarrow _2He^4(2.05\text{ MeV}) + _1T^3(2.73\text{ MeV}) + 4.78\text{ MeV}$$

$$_3Li^7 + _0n^1(\text{fast}) \rightarrow _2He^4 + _0n^1 + _1T^3 - 2.47\text{ MeV}$$

For a practically unlimited supply of deuterium from water at a deuterium to hydrogen ratio of D/H = 150 ppm in the world oceans, one can envision the use of the catalyzed DD reaction in the fusion island

:

$$ {}_1D^2 + {}_1D^2 \rightarrow {}_1T^3(1.01) + {}_1H^1(3.03) + 4.04\ MeV $$

$$ {}_1D^2 + {}_1D^2 \rightarrow {}_2He^3(0.82) + {}_0n^1(2.45) + 3.27\ MeV $$

$$ {}_1D^2 + {}_1T^3 \rightarrow {}_2He^4(3.52) + {}_0n^1(14.06)\ +\ 17.58\ MeV $$

$$ {}_1D^2 + {}_2He^3 \rightarrow {}_2He^4(3.67) + {}_1H^1(14.67) + 18.34\ MeV $$

$$ 6\,{}_1D^2 \rightarrow 2\,{}_1H^1 + 2\,{}_2He^4 + 2\,{}_0n^1 + 43.23 MeV $$

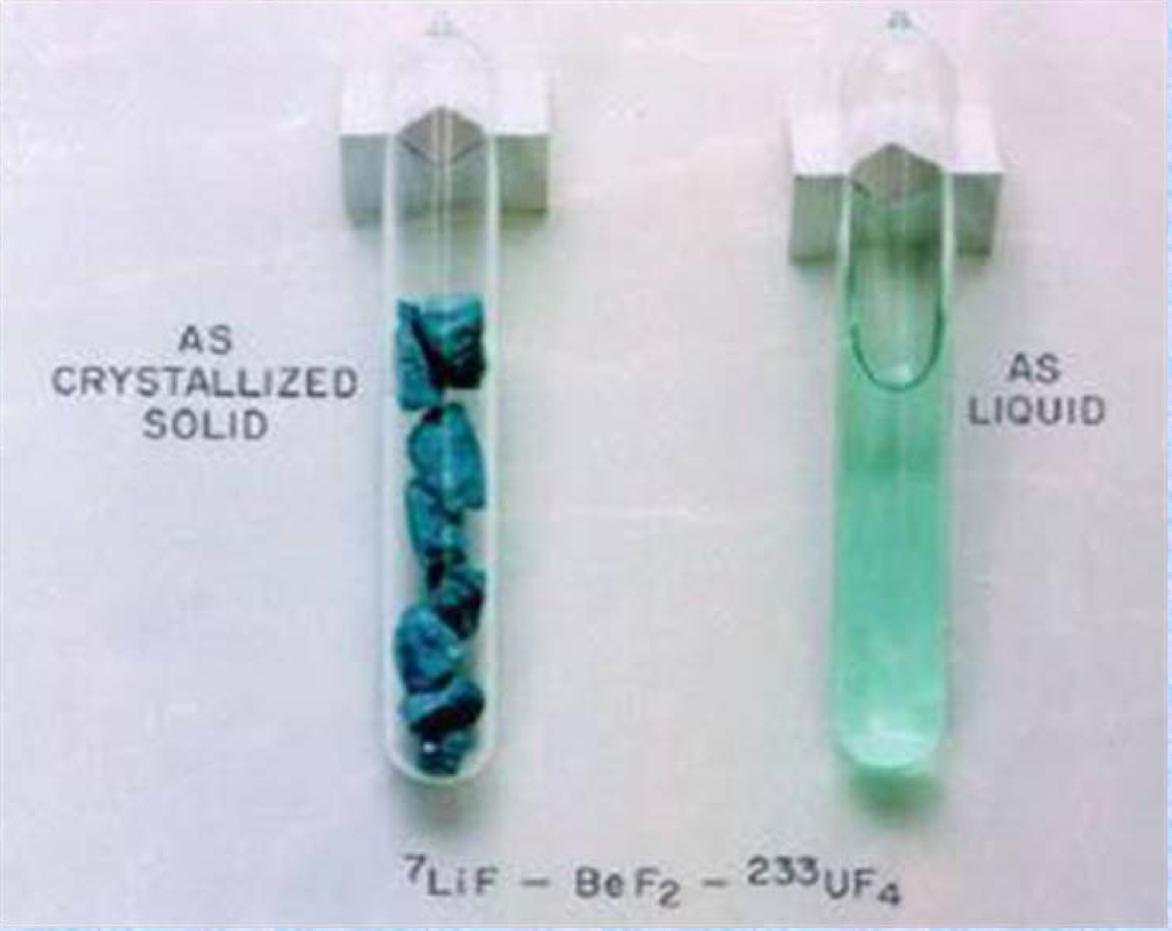
Fusion-fission reactor geometrical model

Material	Zone	Outer Radius (cm)	Thickness (cm	Remarks
Plasma	1	100.0	100.0	DT(14.06 MeV) or, Catalyzed DD (50 % 2.45 MeV + 50 % 14.06 MeV)
Void	2	150.0	50.0	Vacuum zone
First wall	3	151.0	1.0	Type 316 stainless steel
Water coolant	4	151.5	0.5	H_2O cooling channel
Structure	5	152.5	1.0	
Molten salt	6	194.5	42.0	$NaF.BeF_2.ThF_4$ or: $LiF.BeF_2.ThF_4$ ρ =4.52 gm/cm^3 (71-2-27 mol %)
Structure	7	195.5	1.0	Type 316 stainless steel
Neutron reflector	8	235.5	40.0	Graphite as C^{12}
Structure	9	236.5	1.0	Type 316 stainless steel
Albedo	10	-	-	20 percent albedo surface to simulate neutron and gamma ray reflection

Fusion-fission material compositions

Material	Composition	Nuclide Density [nuclei/(b.cm)]
1. $LiF.BeF_2.ThF_4$ salt ρ = 4.52 gm/cm^3 71-2-27 mol %	${}_3Li^6$ ${}_3Li^7$ ${}_4Be^9$ ${}_{90}Th^{230}$ ${}_9F^{19}$	1.414×10^{-3} 1.744×10^{-2} 5.310×10^{-4} 7.169×10^{-3} 4.859×10^{-2}
2. $NaF.BeF_2.ThF_4$ salt ρ =4.52 gm/cm^3 71-2-27 mol %	${}_{11}Na^{23}$ ${}_4Be^9$ ${}_{90}Th^{230}$ ${}_9F^{19}$	1.697×10^{-2} 4.799×10^{-4} 6.452×10^{-3} 4.373×10^{-2}
3. Type 316 stainless steel 63.6 wt% Fe, 18 wt% Cr, 13 wt% Ni, 2.6 wt% Mo, 1.9 wt% Mn, 0.9 wt% (Si+Ti+C) ρ = 7.98 gm/cm^3	C Si Ti Cr Mn Fe Ni Mo	1.990×10^{-4} 1.360×10^{-3} 4.980×10^{-5} 1.150×10^{-2} 1.650×10^{-3} 5.430×10^{-2} 1.060×10^{-2} 1.290×10^{-3}
4. Graphite ρ =2.25 gm/cm^3	C	1.128×10^{-1}
5. H_2O ρ = 1.0 gm/cm^3	H O	6.687×10^{-2} 3.343×10^{-2}

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

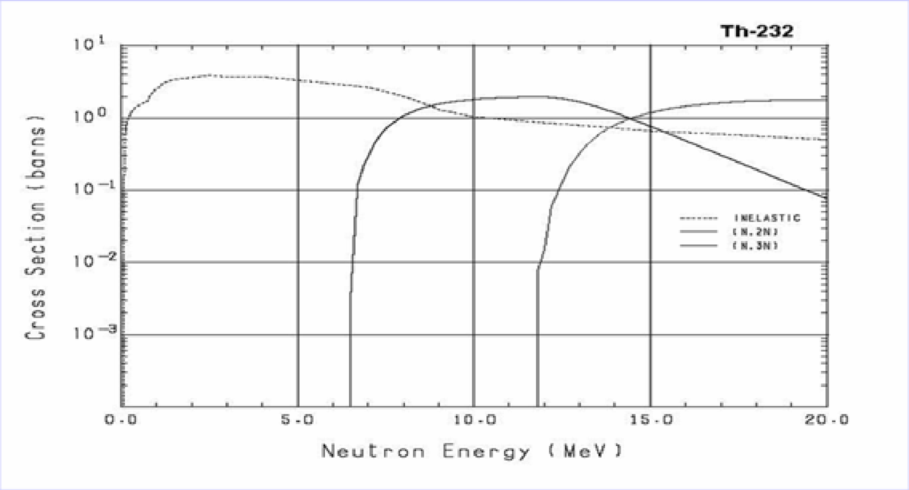


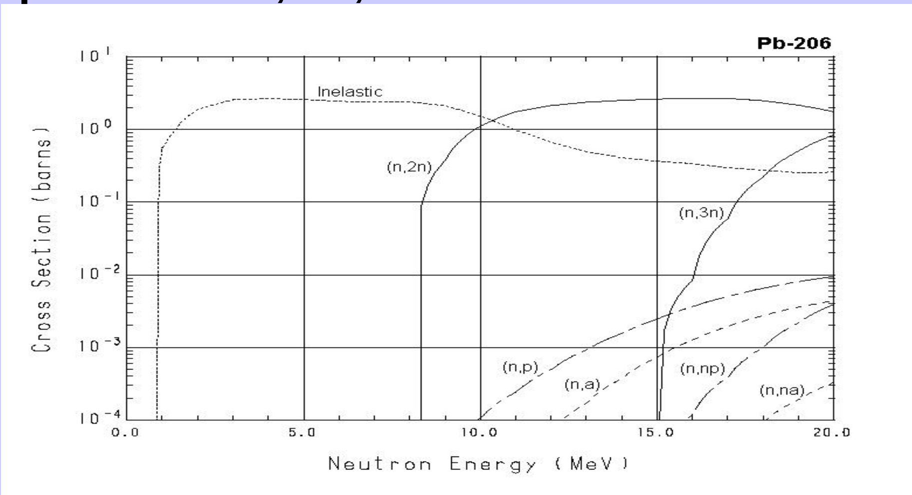
Fissile and fusile breeding for sodium and lithium salts in DT and DD symbiotic fusion-fission fuel factories. Blanket thickness = 42 cm, reflector thickness =40 cm; no structure in the salt region.

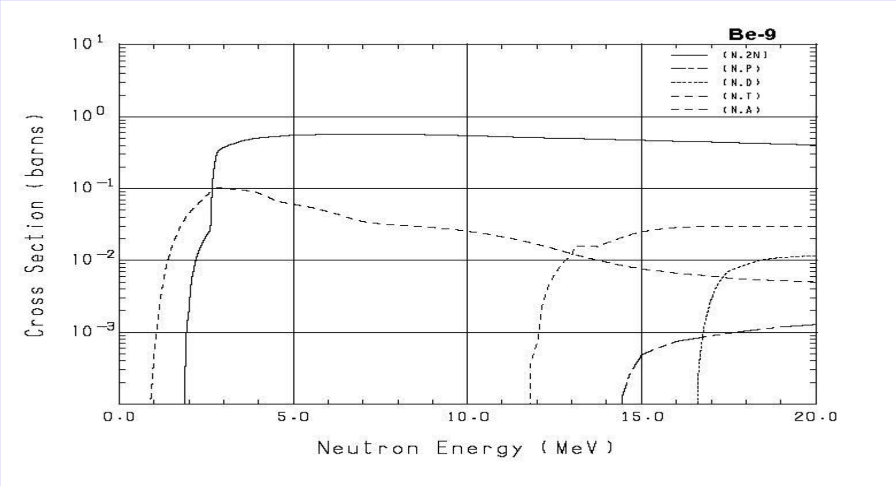
Source	Li-Be-Th-F Salt						Na-Be-Th-F Salt			
	$Li^6(n,\alpha)T$	$Li^7(n,n'\alpha)T$	$Be^9(n,T)$	F(n,T)	Total T	$Th(n,\gamma)$	$Be^9(n,T)$	F(n,T)	Total T	$Th(n,\gamma)$
	(Nuclei / fusion source neutron)									
DD 100% 2.45 MeV	0.311	0.001	4.03×10^{-10}	1.01×10^{-7}	0.312	0.579	4.18×10^{-10}	1.04×10^{-7}	1.04×10^{-7}	0.794
DT 100% 14.06 MeV	0.391	0.073	1.08×10^{-4}	3.33×10^{-3}	0.467	0.737	1.04×10^{-4}	3.08×10^{-3}	3.18×10^{-3}	0.966
Catalyzed DD 50% 2.45 MeV 50% 14.06 MeV	0.351	0.037	5.40×10^{-5}	1.67×10^{-3}	0.390	0.658	5.20×10^{-5}	1.54×10^{-3}	1.59×10^{-3}	0.880

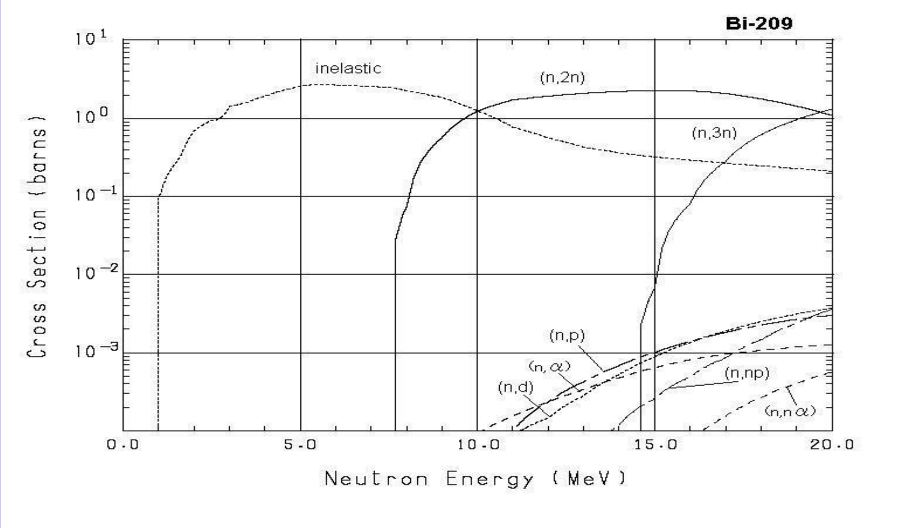
Neutron Multiplication

The cross section distribution for the (n, 2n) and n(3n) neutron multiplication reactions in Th^{232} shows energy thresholds at 6.465 and 11.61 MeV.
Other candidate neutron multipliers are Pb, Be, Bi and U.

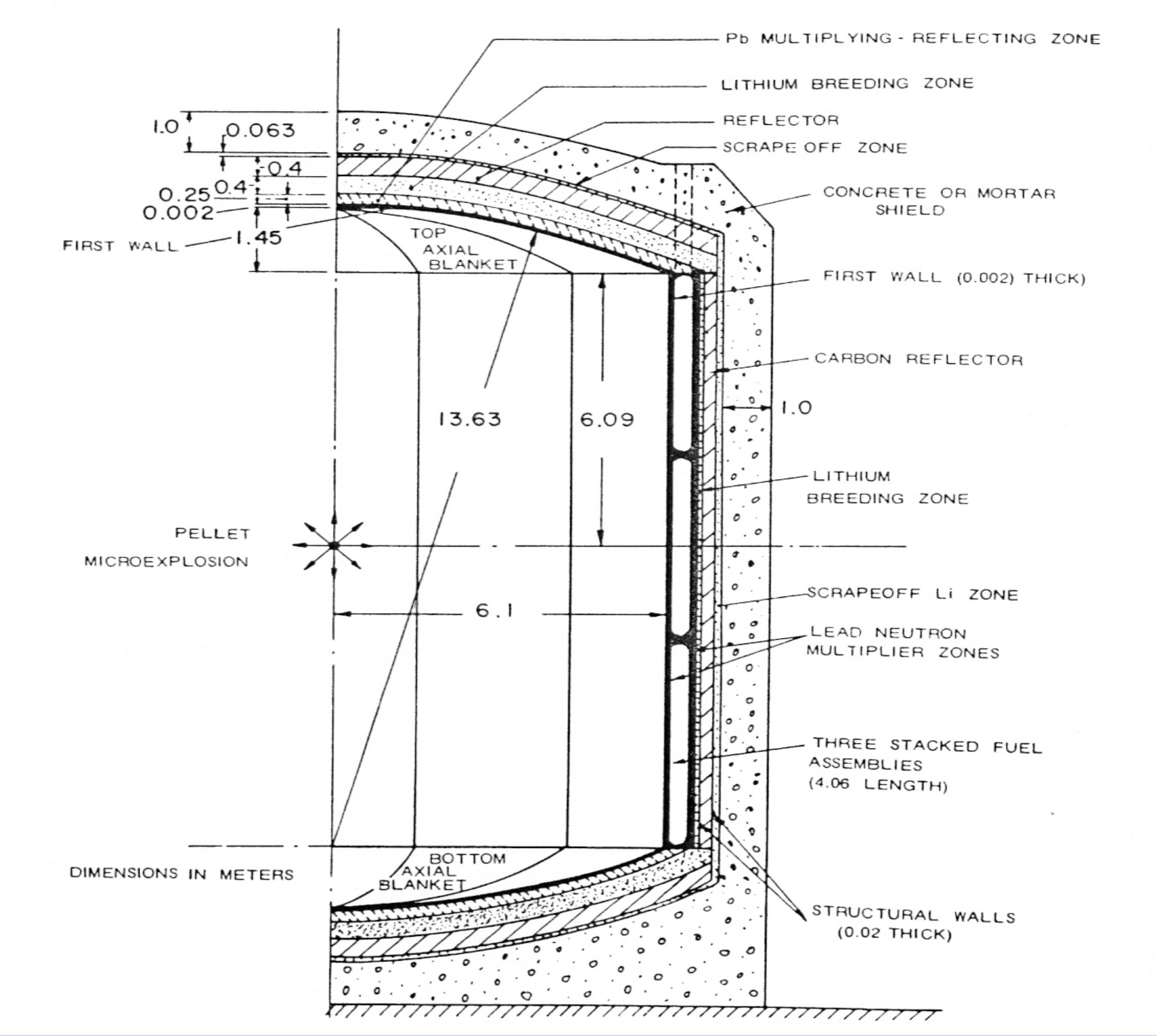




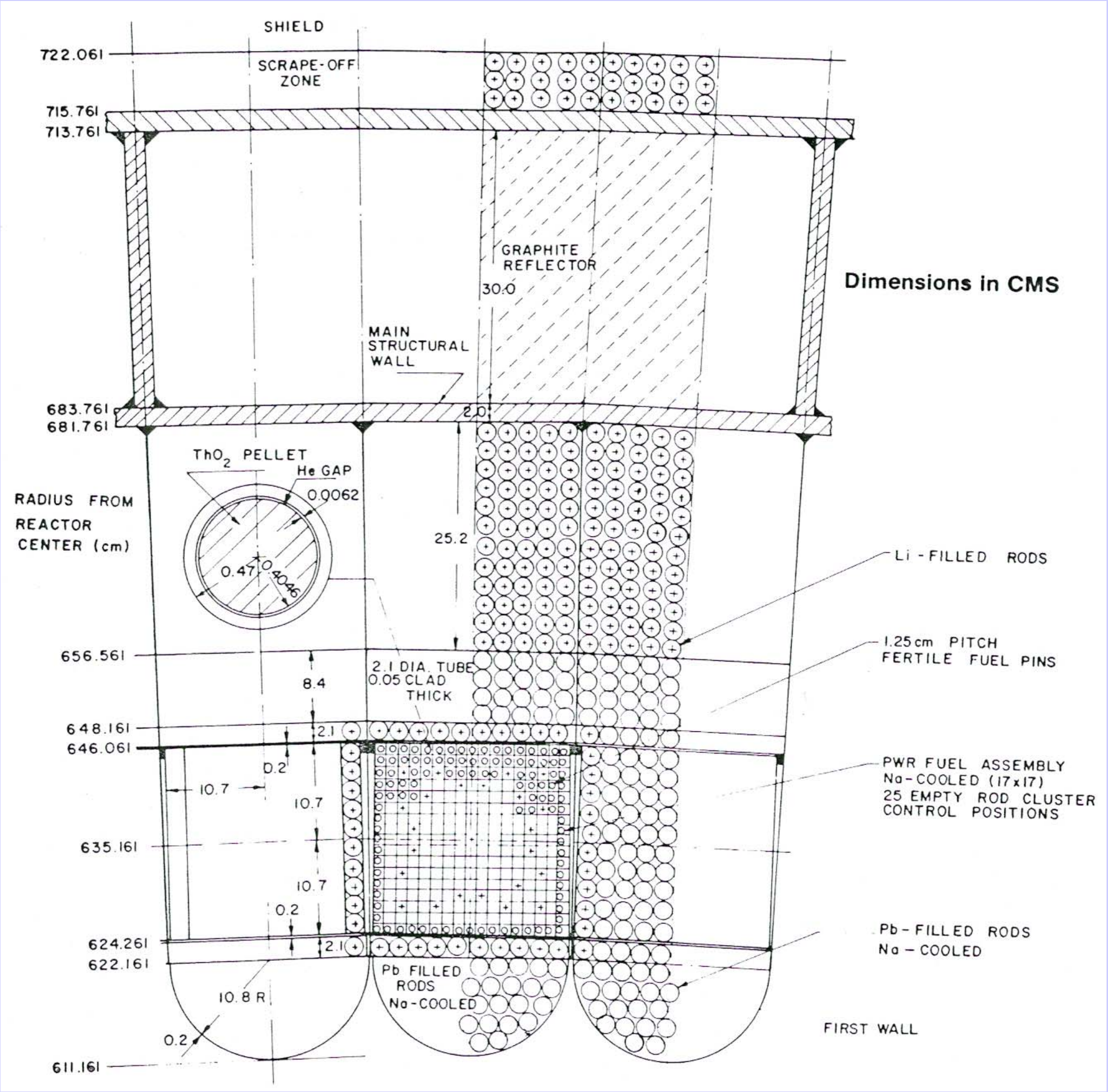




Laser fusion fissile generator plant with U^{233} breeding.



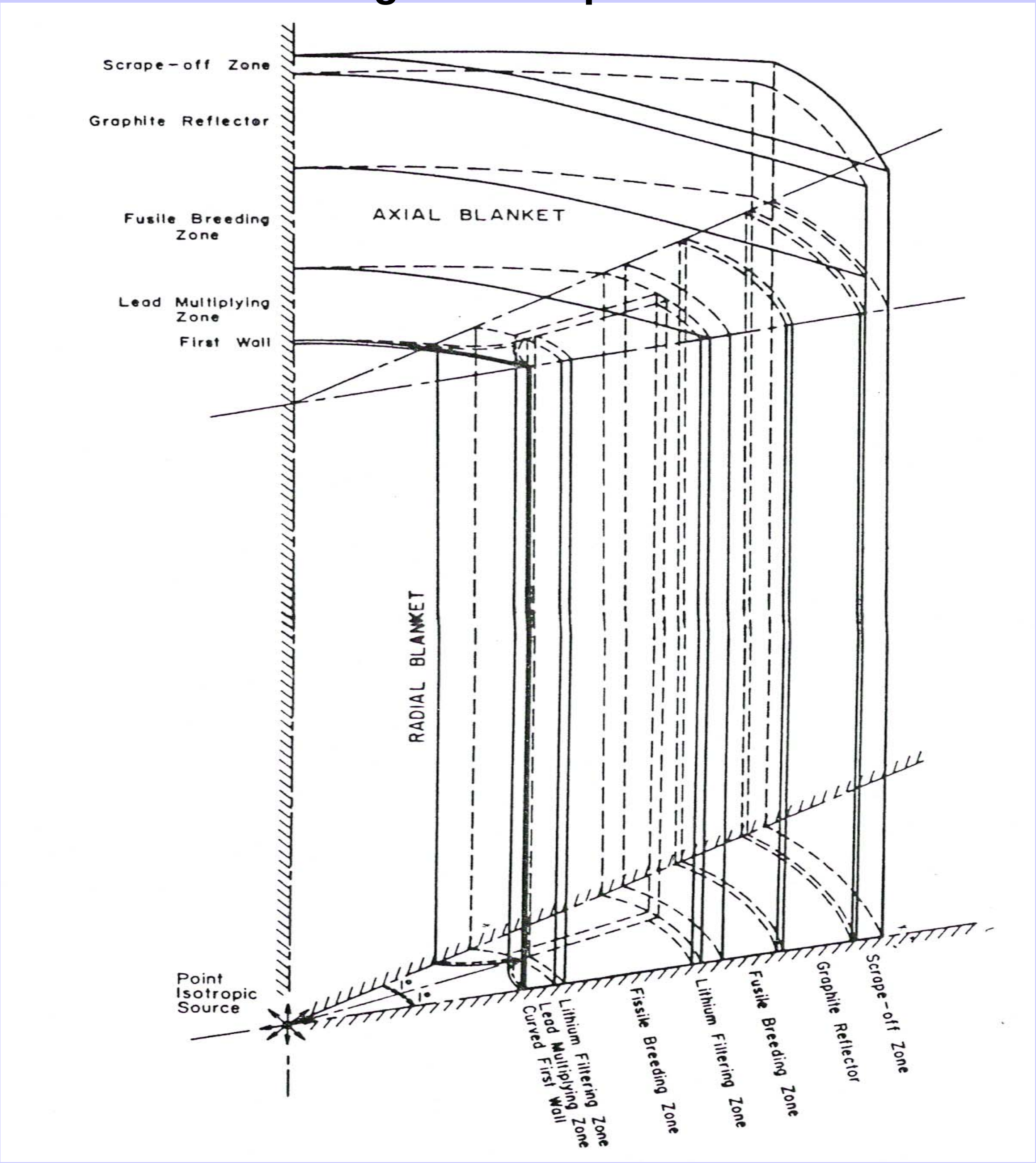
ThO_2 Pressurized Water Reactor fuel elements within a flux trap neutron multiplication zone, followed by a tritium breeding zone and a graphite reflector.



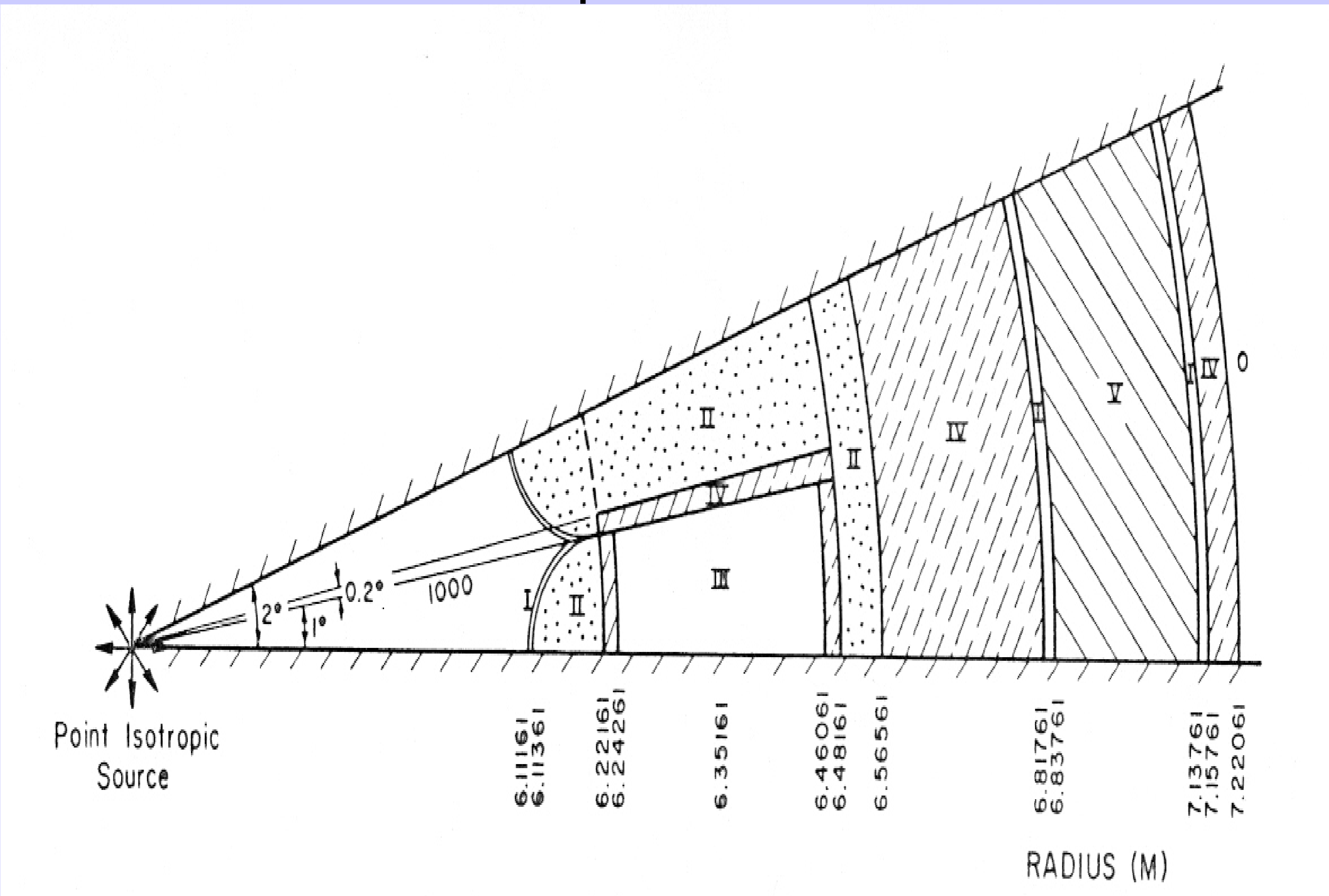
Fusion fissile generator plant with U^{233} breeding. Material compositions.

Material composition	Element	Atomic densities [atoms/(barn·m)]
1. First wall and structural wall		
100 v/o Zircaloy-4	Zr	4.374+0
98.24 w/o Zr+1.5 w/o Sn	Sn	4.962−2
+0.21 w/o Fe	Cr	7.812−3
+0.10 w/o Cr	Fe	1.527−2
ρ(Zircaloy-4)$=6.745\times10^3$ kg/m^3		
2. Reflector	^{12}C	8.373+0
100% Reactor-grade graphite		
ρ(graphite)$=1.67\times10^3$ kg/m^3		
3. Neutron multiplication zones	Pb	2.145+0
65.03 v/o Pb+844 v/o	Zr	3.692−1
Zircaloy-4+26.53 v/o	Sn	4.188−3
Na coolant.	Cr	6.593−4
ρ(Pb)$=11.35\times10^3$ kg/m^3	Fe	1.289−3
ρ(Na)$=9.71\times10^2$ kg/m^3	Na	6.748−1
4. Fusile breeding zones	^6Li	2.364−1
68.78 v/o natural lithium	^7Li	2.950+0
+7.97 v/o Zircaloy-4	Zr	3.486−1
+23.25 v/o Na Coolant	Sn	3.955−3
ρ(Li)$=0.534\times10^3$ kg/m^3,	Cr	6.226−4
7.22 a/o ^{6}Li+92.58 a/o	Fe	1.217−3
^{7}Li	Na	5.914−1
5. Fissile breeding zone	Th	6.415−1
28.10 v/o ThO_2 + 10.47 v/o	^{16}O	1.283+0
Zircaloy-4	Zr	4.580−1
+60.98 v/o Na Coolant	Sn	5.195−3
+1.15 v/o He Fill Gas	Cr	8.179−4
$\rho(ThO_2)=10.01\times10^3$ kg/m^3	Fe	1.599−3
	Na	1.533+0

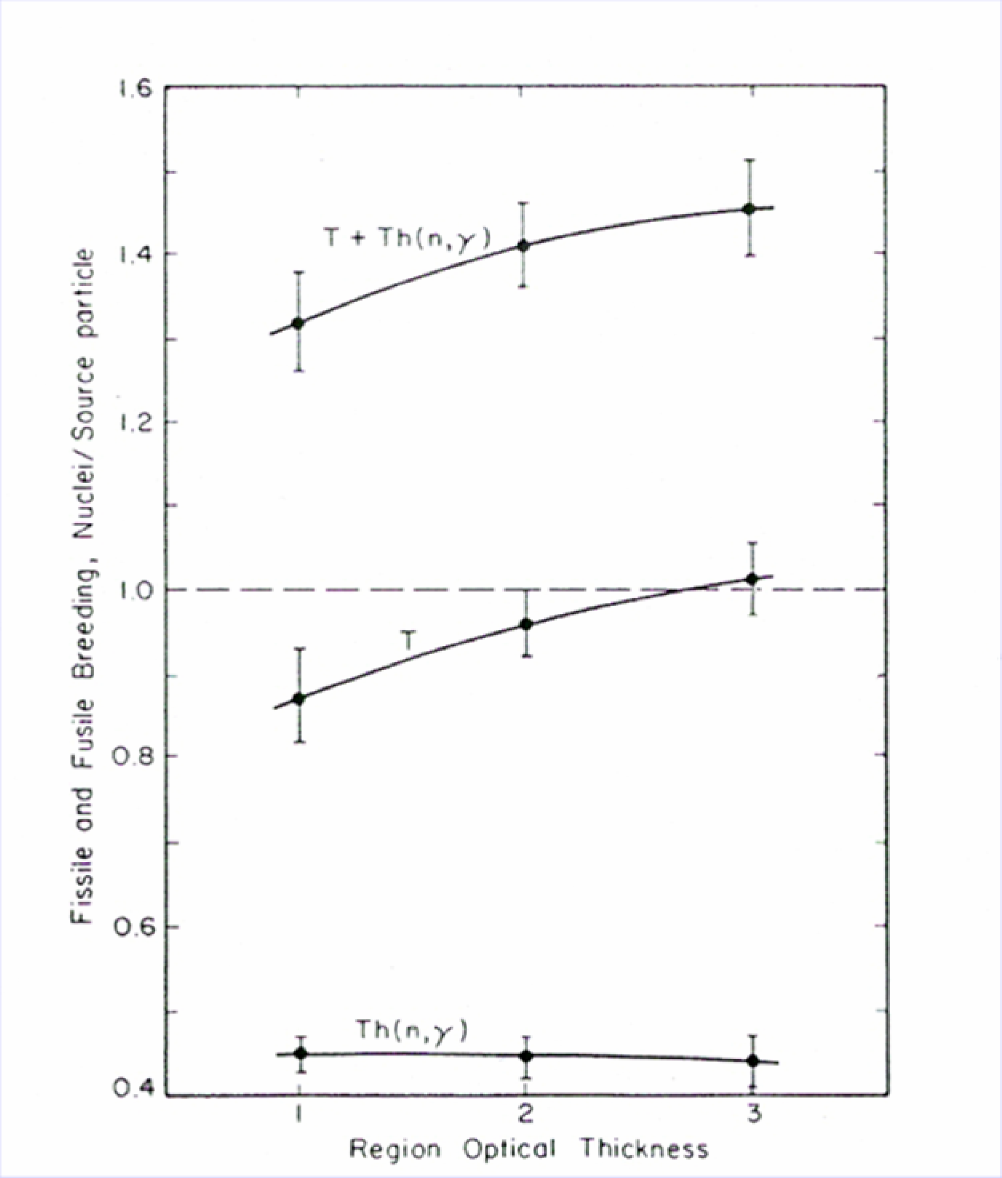
Laser fusion fissile generator plant with U^{233} breeding.



Horizontal cut through unit cell of three dimensional lead flux trap computational model.

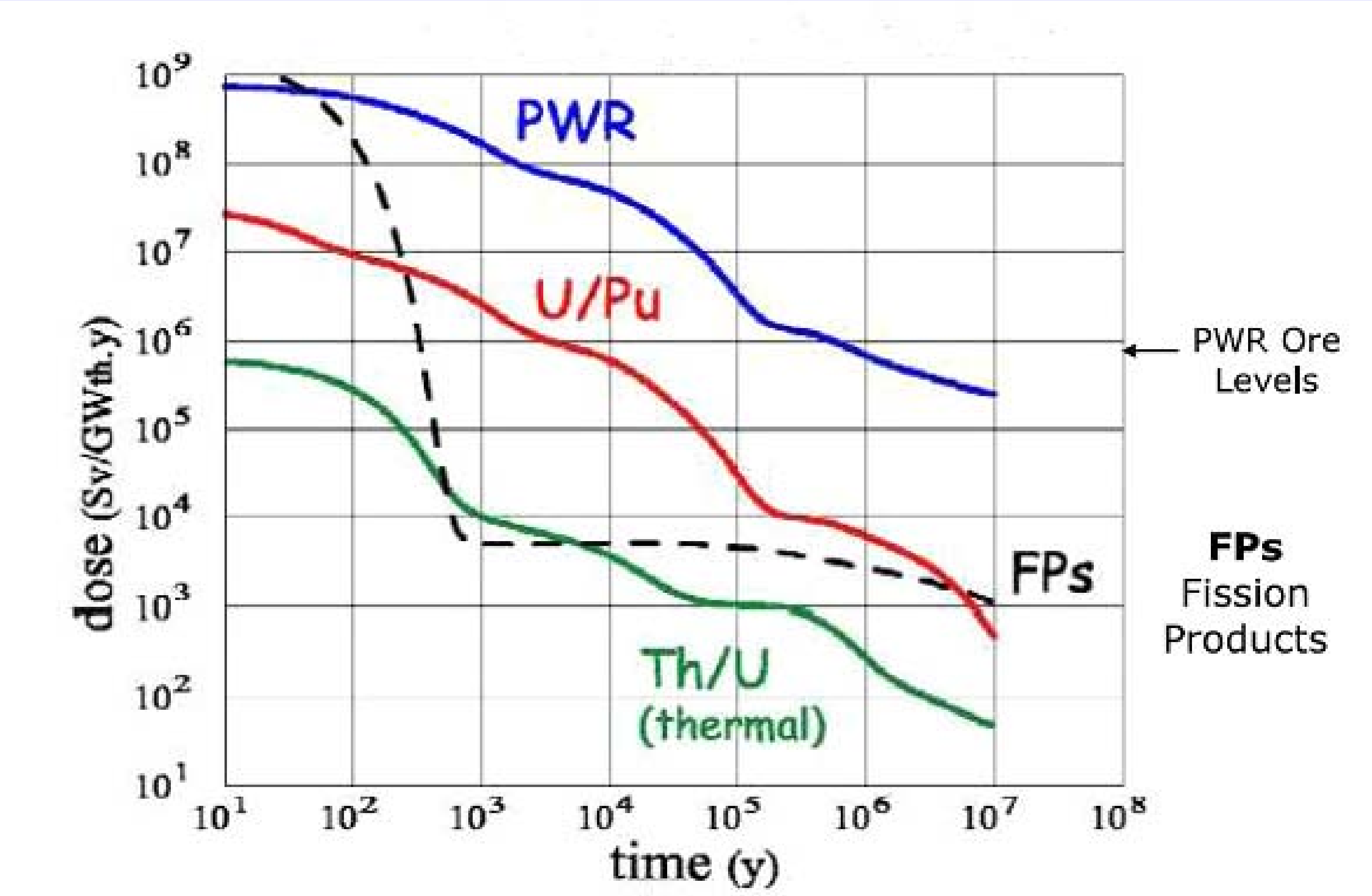


Optimization of fissile U^{233} and fusile tritium (T) breeding.



Actinides and Fission products radiotoxicity

Source: Sylvain David, Institut de Physique Nucleaire d'Orsay



DISCUSSION

The use of the thorium cycle in a fusion fission hybrid could bypass the stage of fourth generation breeder reactors in that the energy multiplication in the fission part allows the satisfaction of energy breakeven and the Lawson condition in magnetic and inertial fusion reactor designs. This allows for the incremental development of the technology for the eventual introduction of a pure fusion system.

As a proof of principle, a compact experimental device can be built using inertial electrostatic confinement with DD or DT fusion with a cusped configuration or a grid diode, and coupled to a molten salt breeding blanket at a university or a national laboratory site.

Such an alternative sustainable paradigm or architecture would provide the possibility of a well optimized fusion-fission thorium hybrid for sustainable long term fuel availability with the added advantages of higher temperatures thermal efficiency for process heat production, proliferation resistance and minimized waste disposal characteristics.

SUMMARY

The thorium fission fusion hybrid is discussed as a sustainable longer term larger resource base alternative to the fast breeder fission reactor concept. In addition, it offers a manageable waste disposal process, burning of the produced actinides and inherent nonproliferation properties.

With the present day availability of fissile U^{235} and Pu^{239}, and available fusion and accelerator neutron sources, a fresh look at the thorium cycle is ongoing. Whereas the U^{233}-Th^{232} fuel cycle is undergoing a revival as a replacement of the existing Light Water Reactors (LWRs) system, a highly promising approach is its use in fusion-fission hybrid reactors as an eventual bridge and technology development for future pure fusion reactors, bypassing the intermediate stage of the fast fission breeder reactors. We discuss the possibility of taking advantage of the Th cycle benefits in the form of an optimized fission-fusion thorium hybrid.

The nuclear performance of a fusion-fission hybrid reactor having a molten salt composed of Na-Th-F-Be as the blanket fertile material and operating with a catalyzed Deuterium-Deuterium (DD) plasma is compared to a system with a Li-Th-F-Be salt operating with a Deuterium-Tritium (DT) plasma. In a reactor with a 42-cm thick salt blanket followed by a 40-cm thick graphite reflector, the catalyzed DD system exhibits a fissile nuclide production rate of 0.88 Th(n,γ) reactions per fusion source neutron. The DT system, in addition to breeding tritium from lithium for the DT reaction yields 0.74 Th(n,γ) breeding reactions per fusion source neutron. Both approaches provide substantial energy amplification through the fusion-fission coupling process.

In a fuel factory concept using a DT fusion source, a tritium yield per source neutron of 1.08 and a Th (n, γ) reaction yield of 0.43 can be obtained whereas ThO_2 Zircaloy-clad fuel assemblies for Light Water Reactors (LWRs) are enriched in the U233 isotope by irradiating them in a Pb flux trap. This corresponds to 0.77kg/[MW(th).year] of fissile fuel production, and 1.94 years of irradiation in the fusion reactor to attain an average 3 w/o fissile enrichment in the fuel assemblies. For a once through LWR cycle, a support ratio of 2-3 is estimated. However, with fuel recycling, more attractive support ratios of 4-6 may be attainable for a conversion ratio conversratio of 0.55, and 5-8 for a conversion ratio of 0.70.

Such an alternative sustainable paradigm would provide the possibility of an optimized fusion-fission thorium hybrid using for long term fuel availability with the added advantages of higher temperatures thermal efficiency for process heat production, proliferation resistance and minimized waste disposal characteristics.

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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.