Flibe Energy Perspective on LFTR and Graphite

Graphite-Molten Salt Interactions Workshop
Virtual

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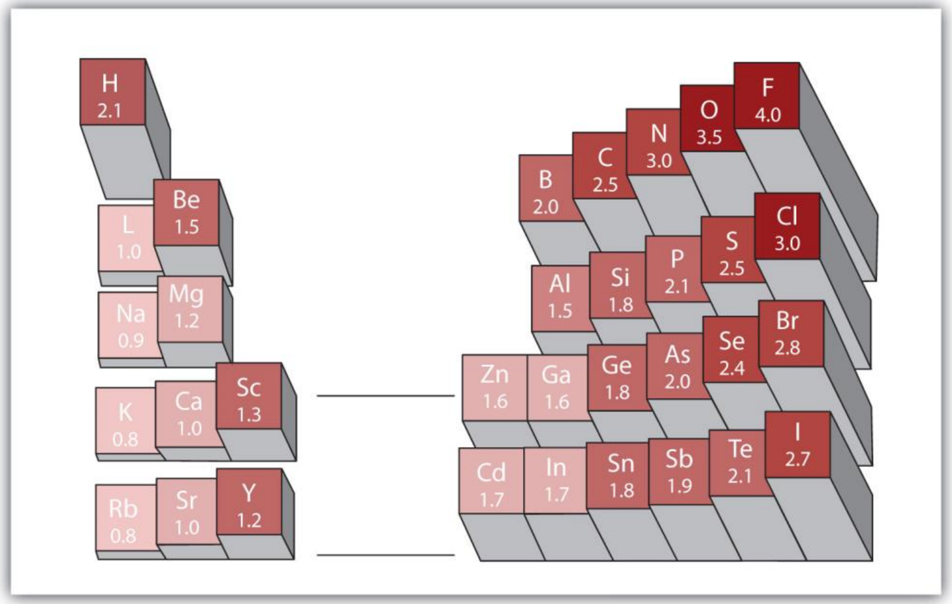
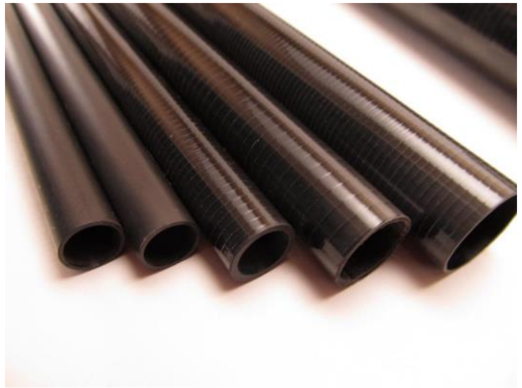
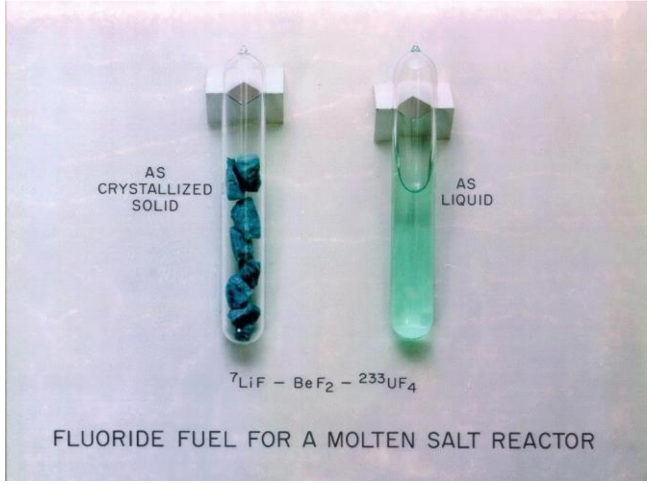
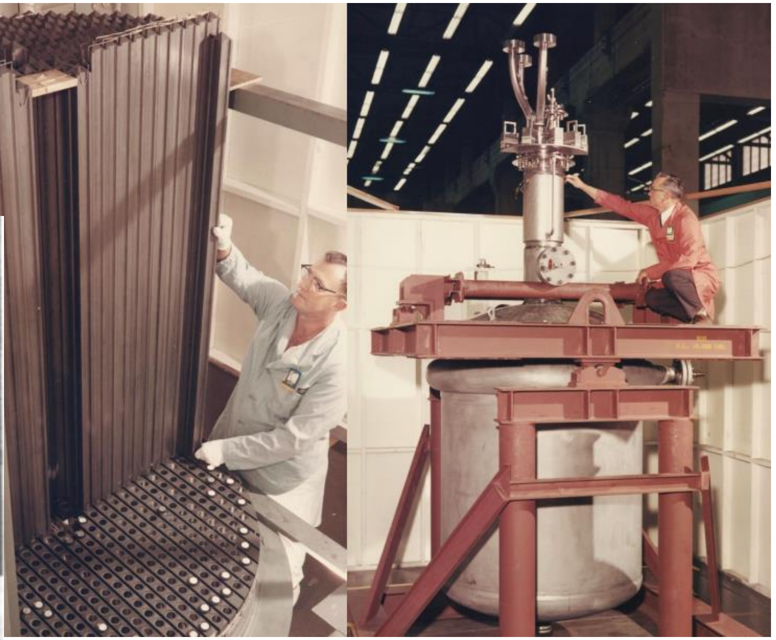
MSRs


H 2.1
L 1.0
Be 1.5
Na 0.9
Mg 1.2
K 0.8
Ca 1.0
Sc 1.3
Rb 0.8
Sr 1.0
Y 1.2
B 2.0
C 2.5
N 3.0
O 3.5
F 4.0
Al 1.5
Si 1.8
P 2.1
S 2.5
Cl 3.0
Zn 1.6
Ga 1.6
Ge 1.8
As 2.0
Se 2.4
Br 2.8
Cd 1.7
In 1.7
Sn 1.8
Sb 1.9
Te 2.1
I 2.7

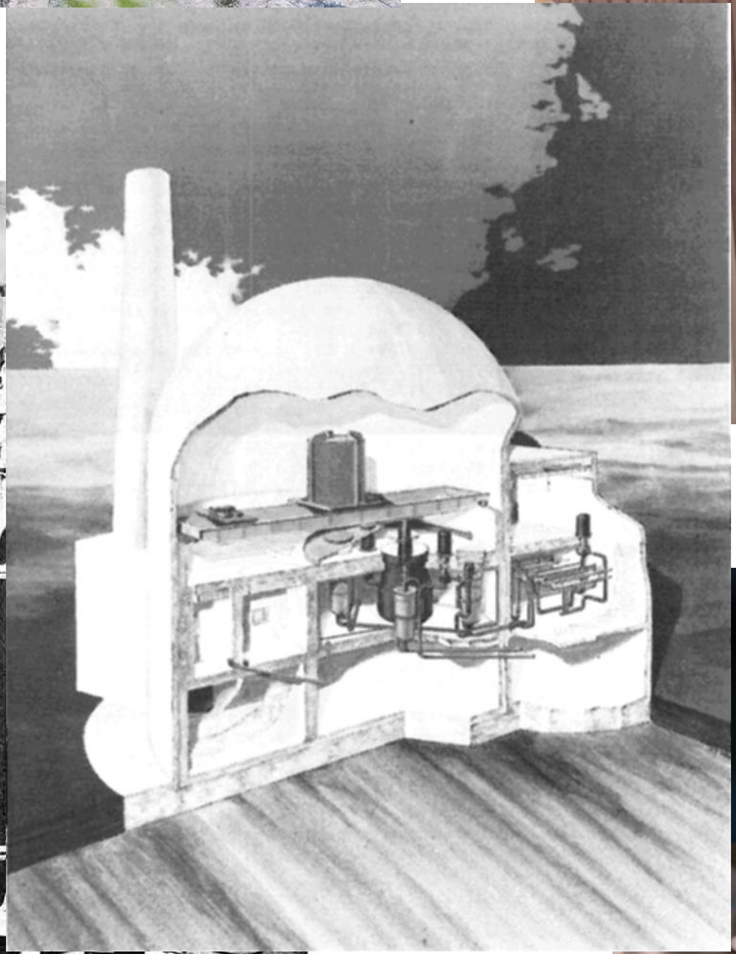



AS CRYSTALLIZED SOLID
AS LIQUID
$^{7}LiF - BeF_2 - {}^{233}UF_4$
FLUORIDE FUEL FOR A MOLTEN SALT REACTOR

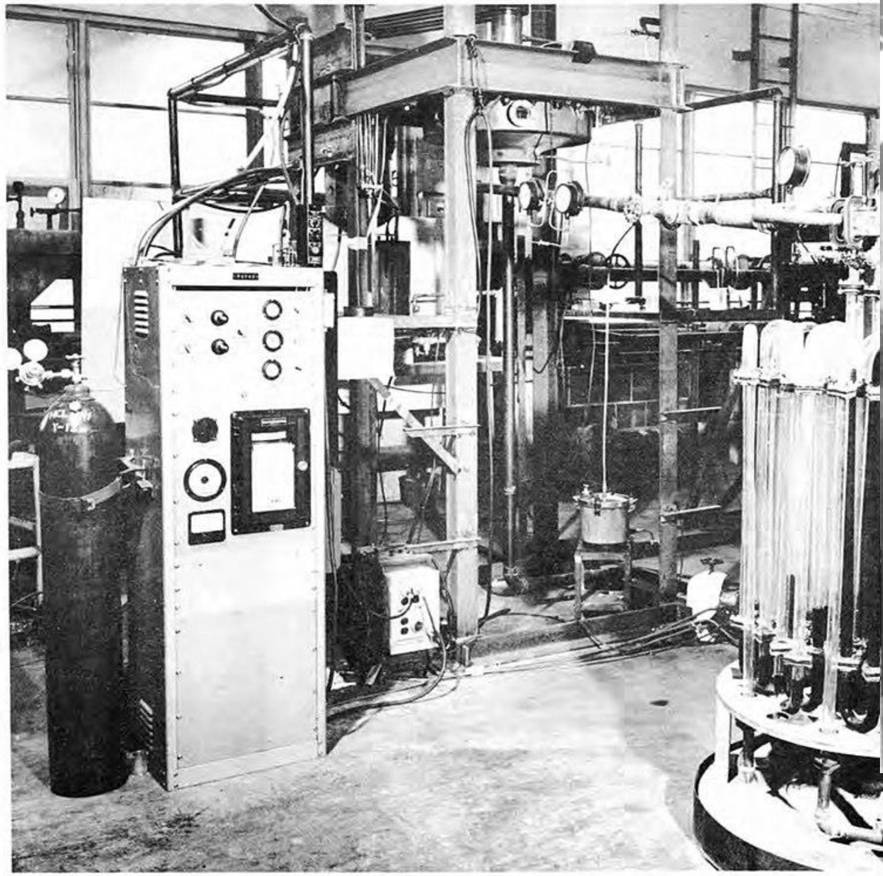
History at ORNL



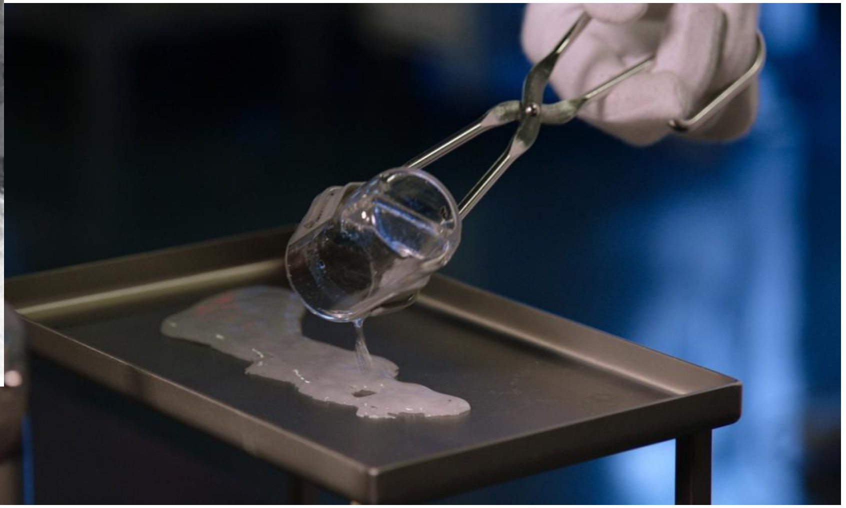
MSRE, 1965-1969



MSBR, 1971



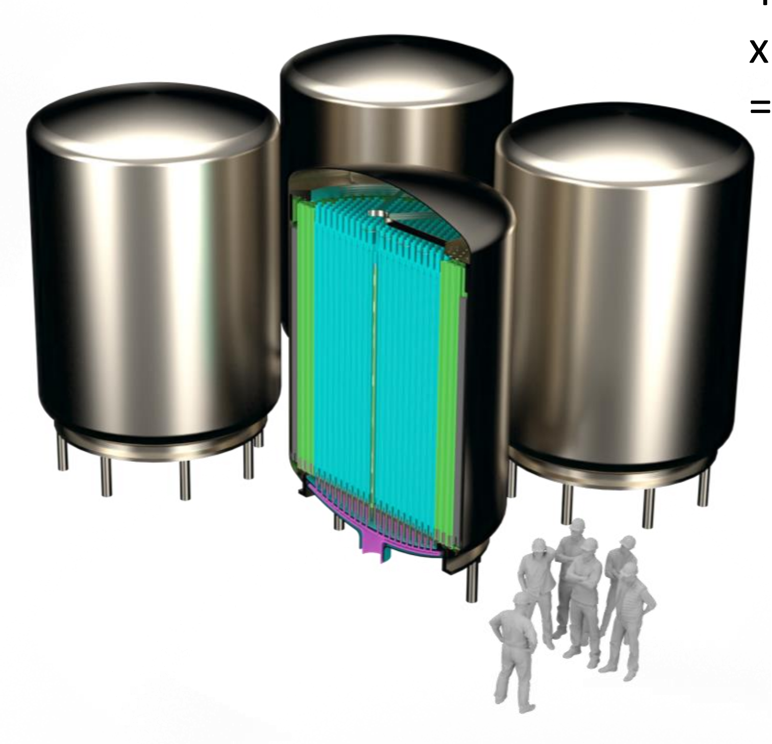
ARE, 1954

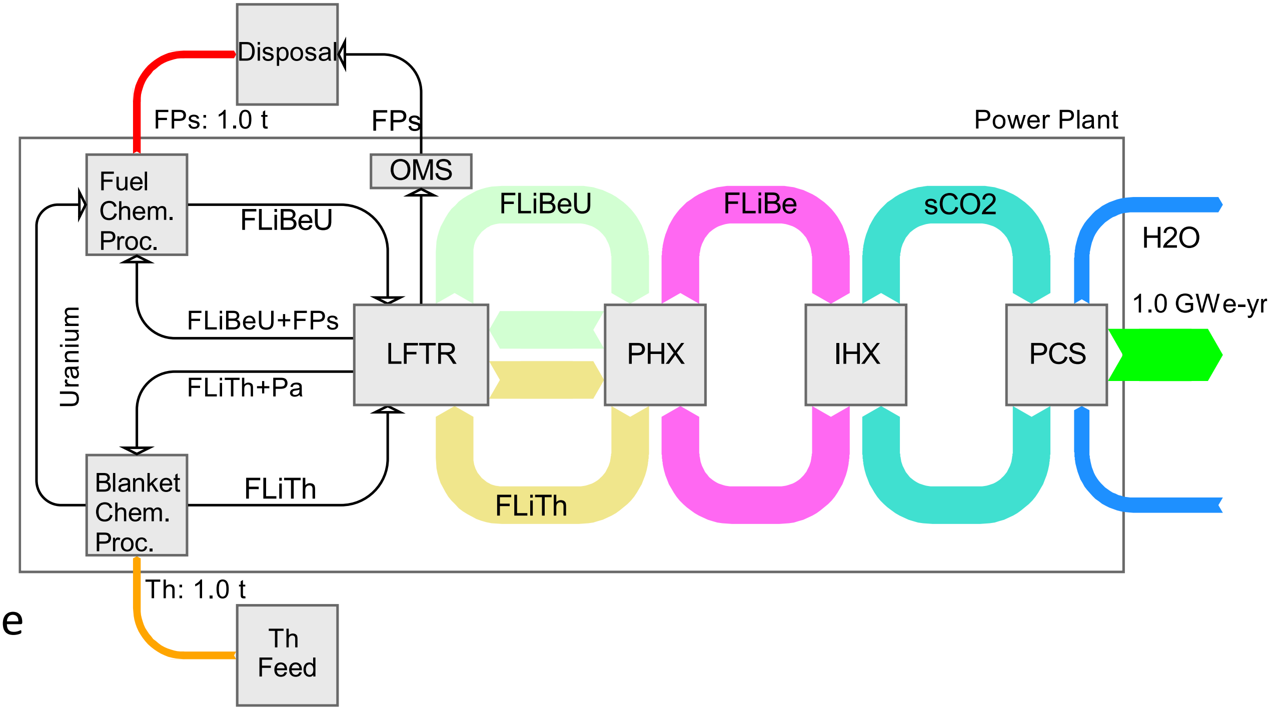


safe

MSBR → LFTR

4 modules
x250 MWe (600 MWth)
=1 GWe (2400 MWth)





80% of core is graphite

Program on Technology Innovation: Technology Assessment of a Molten Salt Reactor Design -- The *Lithium* Fluoride Thorium Reactor (LFTR)
https://www.epri.com/research/products/000000003002005460

Category	Fuel Salt	Blanket Salt	Coolant Salt
Nickname	FLiBeU	FLiTh	FLiBe
System	LiF-BeF2-UF4	LiF-ThF4	LiF-BeF2
Composition mol%	66-33-1	73-27	66.7-33.3
Melting T (°C)	452	558	456
Operating T (°C) range	500-650	600-650	480-570
Operating P (psi) range	50-150 (0.3-1.0 MPa)	50-150 (0.3-1.0 MPa)	50-250 (0.3-1.7MPa)
Density @ 600°C (g/cc)	2.0	4.5	1.9
Contacting materials	Hastelloy N, Graphite	Hastelloy N, Graphite	Hastelloy N

- 10 ft/s flow rate targeted in small pipes and graphite channels
- Chemical controls to keep the salt in a reducing state
- Chemical separations to reduce fission product and other contamination

Graphite Size

250 MWe module
ORNL MSBR

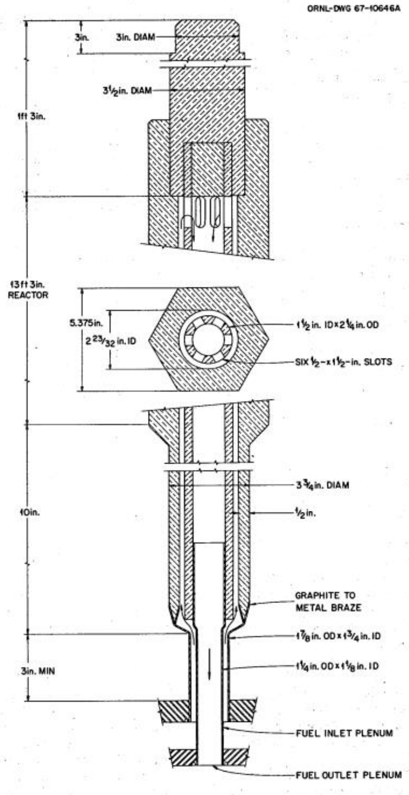


Fig. 5.3. Sectional Drawing of Graphite Fuel Cell.

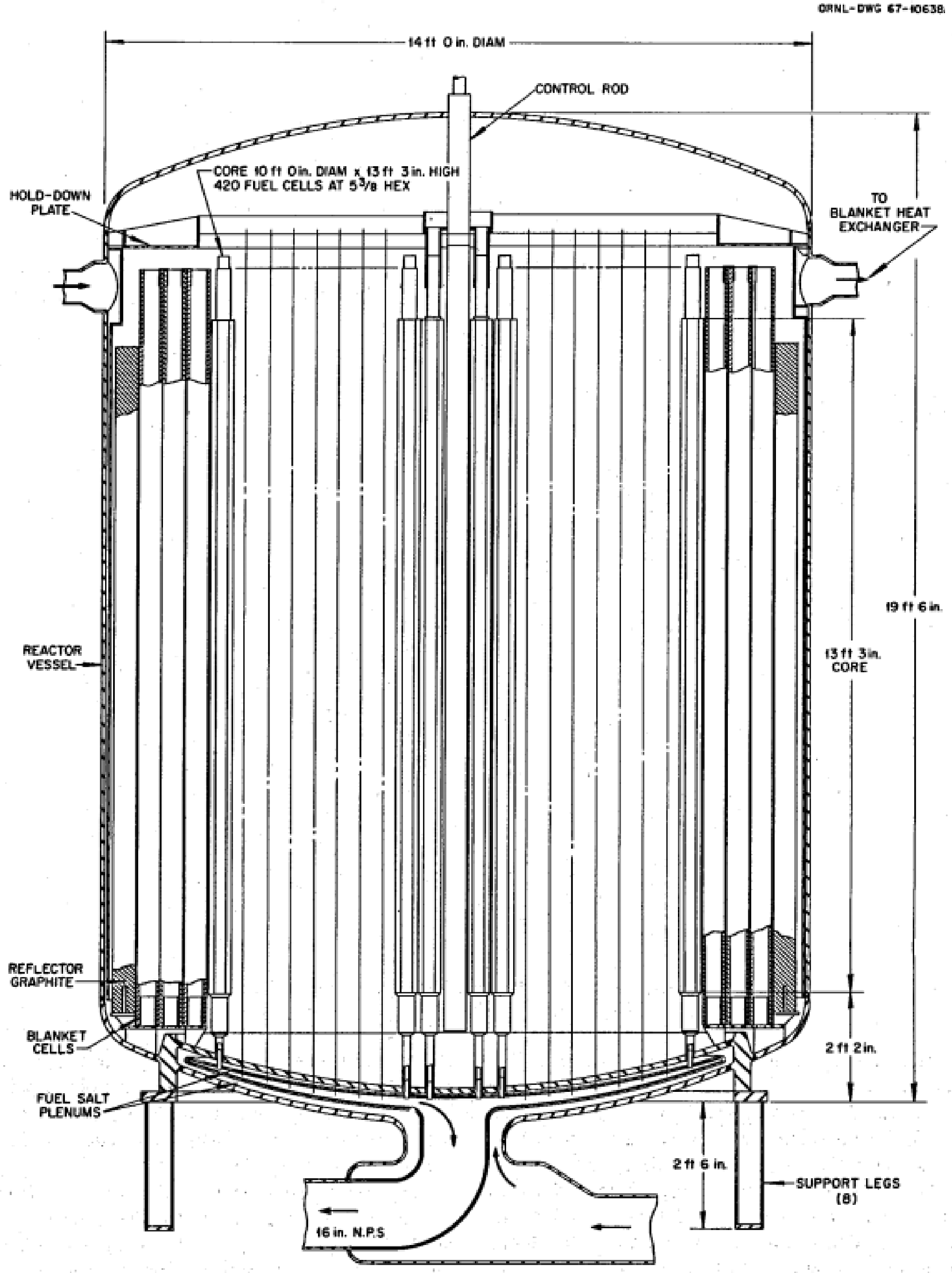


Fig. 5.1. Vertical Section Through Center of Reactor Vessel for One Module of 1000-Mw(e) Plant.

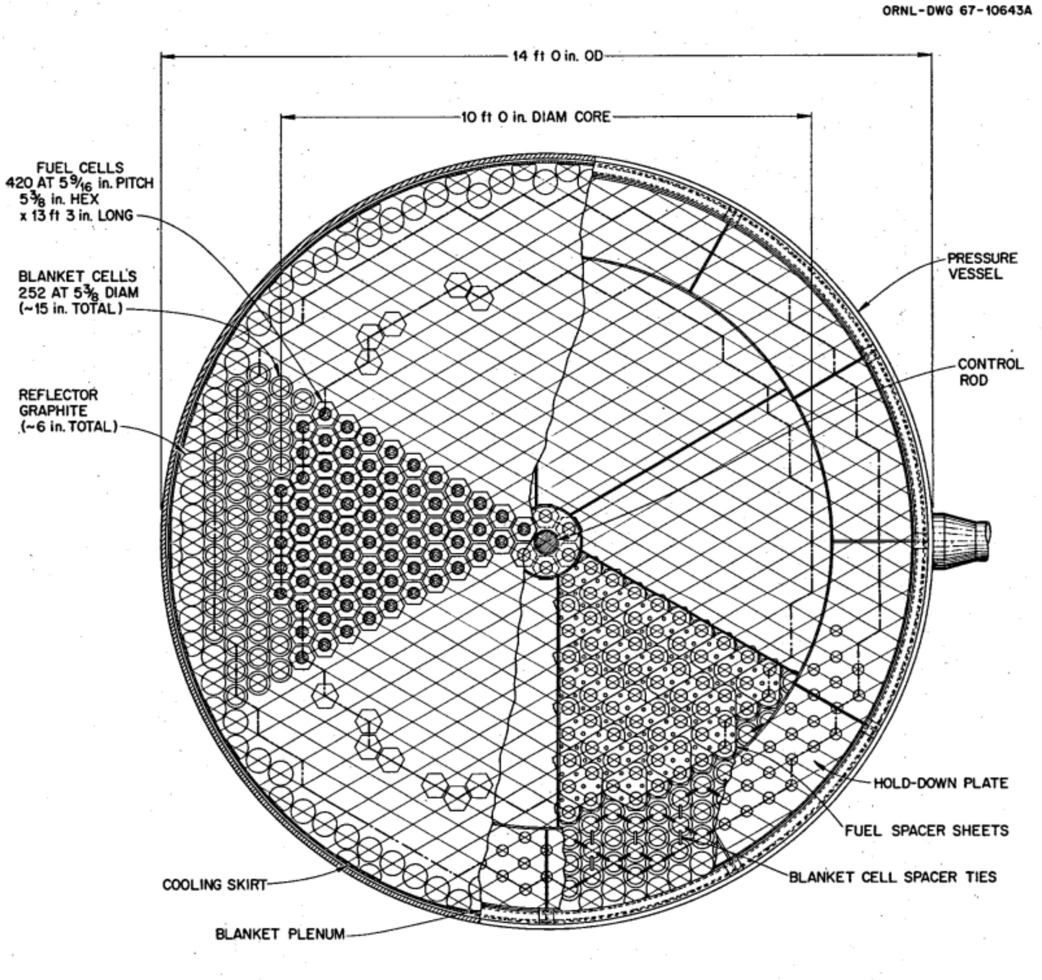


Fig. 5.2. Horizontal Section Through Center of Reactor Vessel.

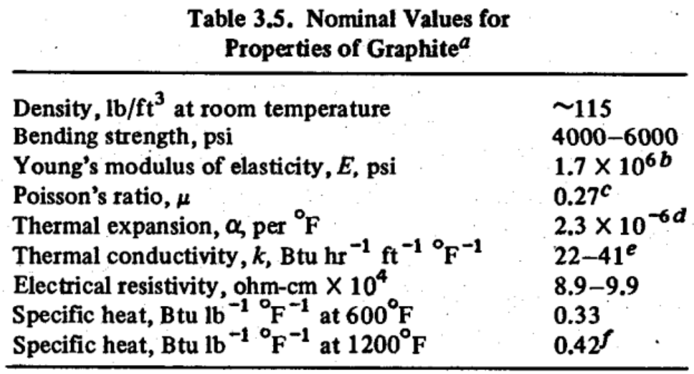
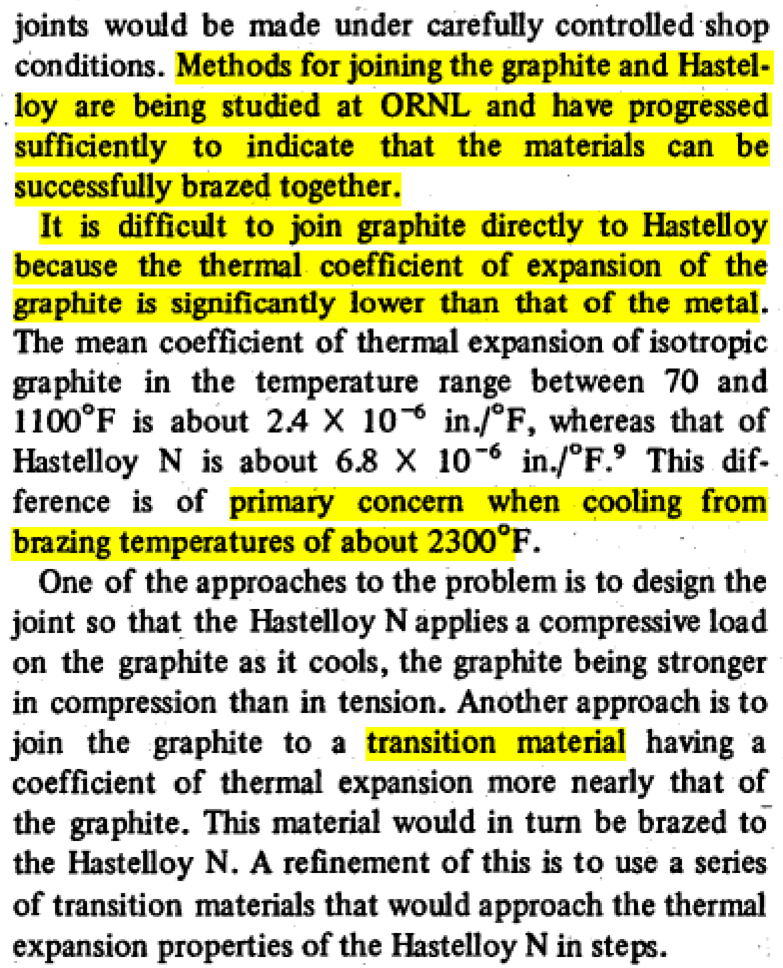


Table 3.5. Nominal Values for Properties of Graphite[a]

Density, lb/ft^3 at room temperature	~115
Bending strength, psi	4000–6000
Young's modulus of elasticity, *E*, psi	1.7×10^6[b]
Poisson's ratio, μ	0.27[c]
Thermal expansion, α, per °F	2.3×10^{-6}[d]
Thermal conductivity, *k*, Btu hr^{-1} ft^{-1} °F^{-1}	22–41[e]
Electrical resistivity, ohm-cm × 10^4	8.9–9.9
Specific heat, Btu lb^{-1} °F^{-1} at 600°F	0.33
Specific heat, Btu lb^{-1} °F^{-1} at 1200°F	0.42[f]

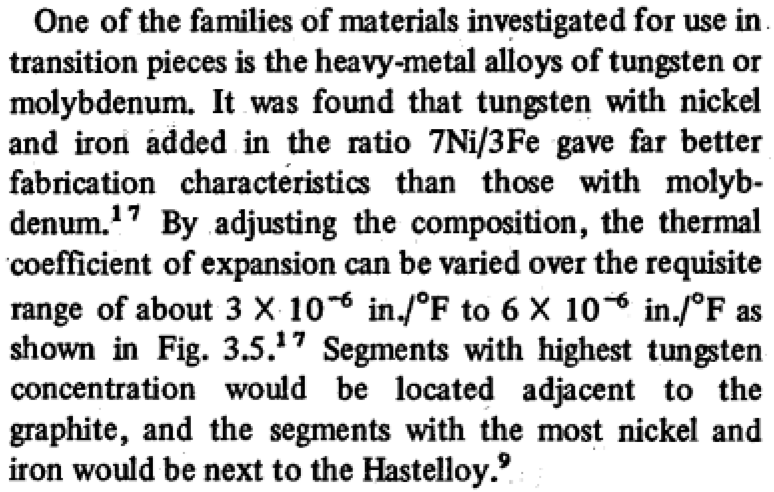
Graphite-to-Metal Joints



joints would be made under carefully controlled shop conditions. Methods for joining the graphite and Hastelloy are being studied at ORNL and have progressed sufficiently to indicate that the materials can be successfully brazed together.

It is difficult to join graphite directly to Hastelloy because the thermal coefficient of expansion of the graphite is significantly lower than that of the metal. The mean coefficient of thermal expansion of isotropic graphite in the temperature range between 70 and 1100°F is about 2.4×10^{-6} in./°F, whereas that of Hastelloy N is about 6.8×10^{-6} in./°F.[9] This difference is of primary concern when cooling from brazing temperatures of about 2300°F.

One of the approaches to the problem is to design the joint so that the Hastelloy N applies a compressive load on the graphite as it cools, the graphite being stronger in compression than in tension. Another approach is to join the graphite to a transition material having a coefficient of thermal expansion more nearly that of the graphite. This material would in turn be brazed to the Hastelloy N. A refinement of this is to use a series of transition materials that would approach the thermal expansion properties of the Hastelloy N in steps.



One of the families of materials investigated for use in transition pieces is the heavy-metal alloys of tungsten or molybdenum. It was found that tungsten with nickel and iron added in the ratio 7Ni/3Fe gave far better fabrication characteristics than those with molybdenum.[17] By adjusting the composition, the thermal coefficient of expansion can be varied over the requisite range of about 3×10^{-6} in./°F to 6×10^{-6} in./°F as shown in Fig. 3.5.[17] Segments with highest tungsten concentration would be located adjacent to the graphite, and the segments with the most nickel and iron would be next to the Hastelloy.[9]

Graphite I

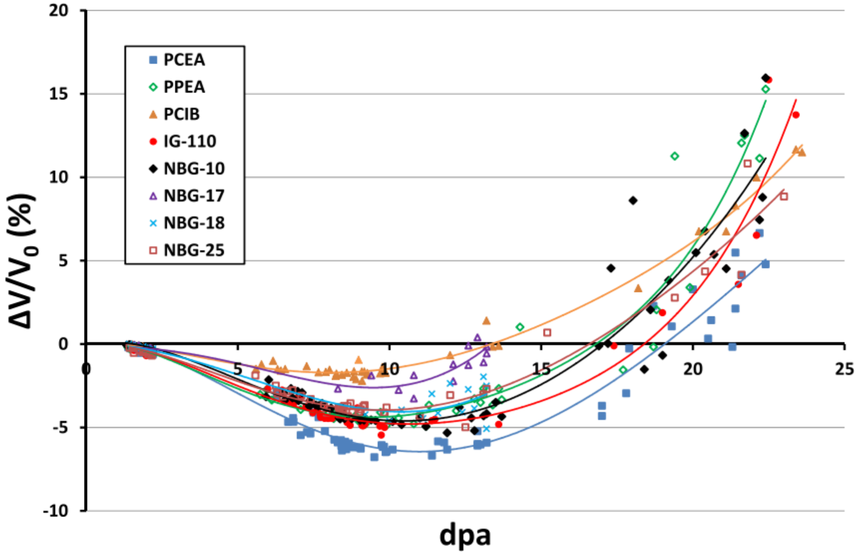


Fig. 2. Dimensional change as function of dpa at 750 °C.

$$\frac{\Delta \ell}{\ell} = \frac{1}{3}\,(0.11 - 0.7 \times 10^{-4} T)(x^2 - 2x)$$

where

$x \approx \dfrac{10^{-22}\,\Phi t}{5.7 - 0.006T}$

T = temperature, °C,

Φ = fast neutron flux, neutrons $cm^{-2}\ sec^{-1}$ ($E > 50$ kev)

t = time, second,

and

$\frac{\Delta \ell}{\ell}$ = fractional length change of graphite.

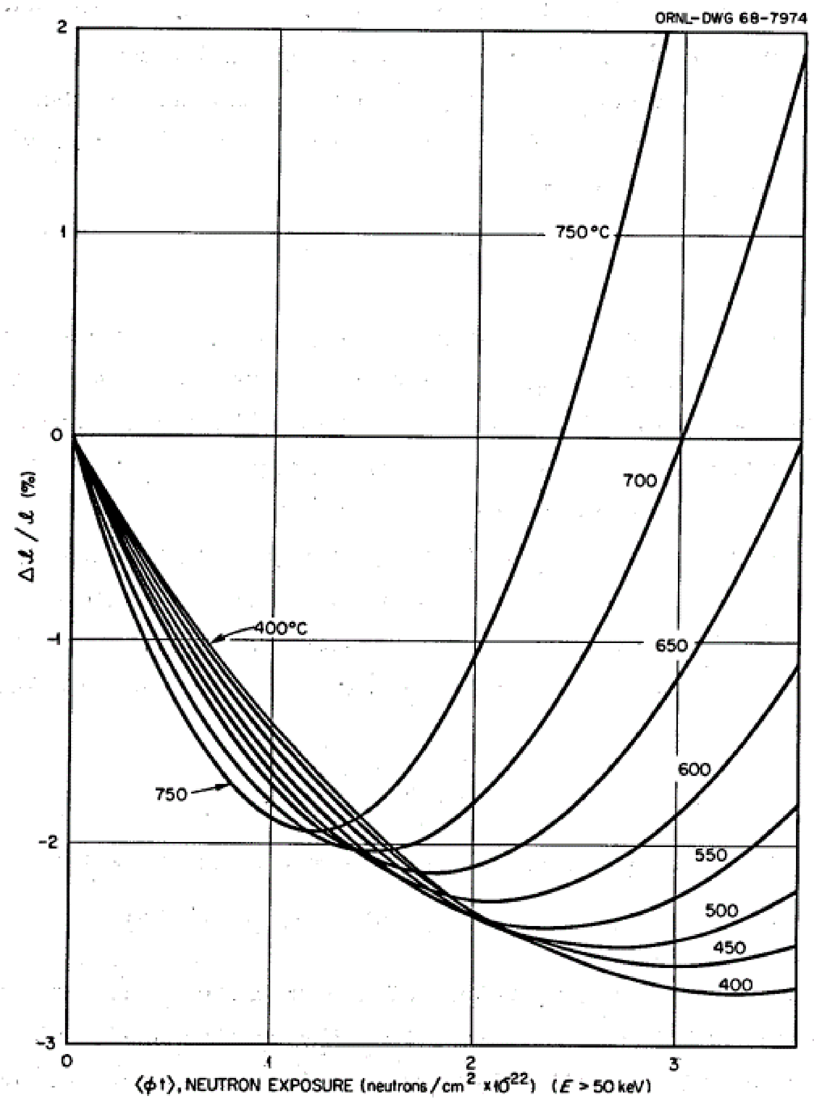
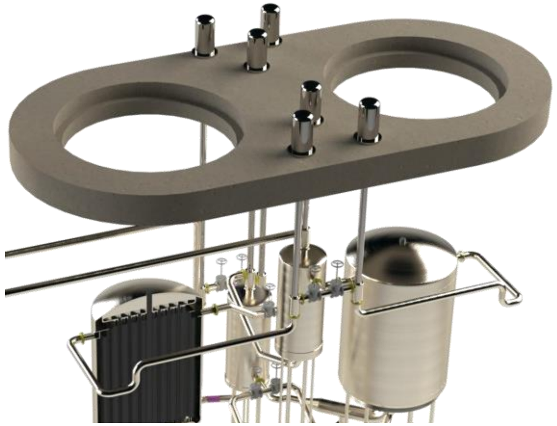


Fig. 3.6. Radiation Induced Dimensional Changes in Gilso Graphite at Various Temperatures

1969-Kasten-Graphite Behavior and Its Effects on MSBR Performance
2017-Heijna-Comparison of irradiation behavior of HTR graphite grades

- **Application**. Both short-term (1-20 years) and long-term deployments targeted. Microreactors initially.
- **Lifetime**. Replace shortly after turnaround, and before crossover. Modify design parameters to target appropriate replacement schedules (ASME BPVC Sec XI Div 2 (RIM)). Example parameters include:
  - Temperature: 700°C (volume-averaged in vicinity of peak fast neutron flux)
  - Power density: 20 kW/L avg (40 kW/L max)
  - Neutron flux: 0.94e14 neutrons/cm^2-s avg (E>50
    max)
  - Turnaround fluence: 1.7e22 neutrons/cm^2 (12 dp
- **Replacement**. Replacing large and intensel
  will be difficult. A two-vessel configuration
  maintenance times.
- **Waste Management**. Graphite oxidation sy
  Minimize HLW volume.



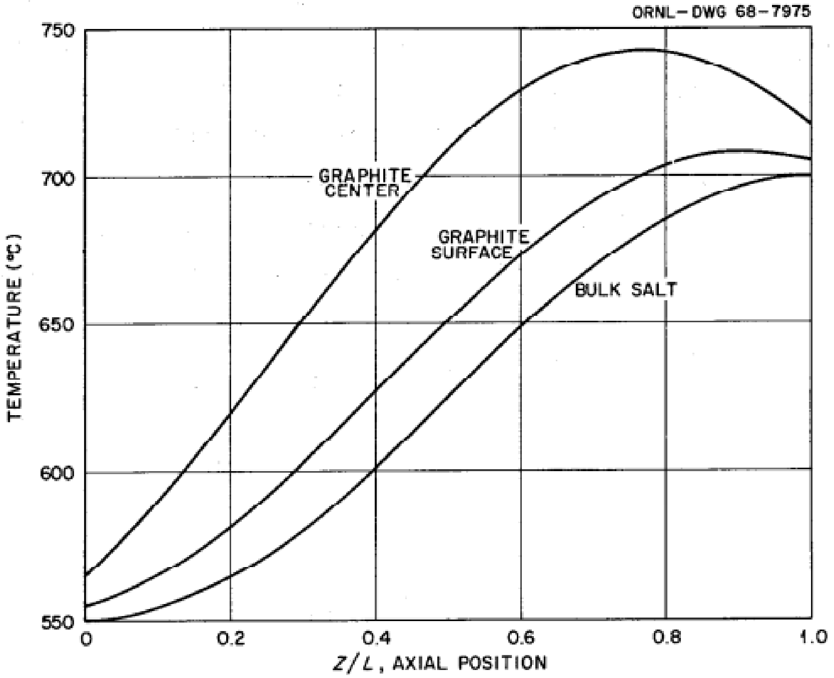
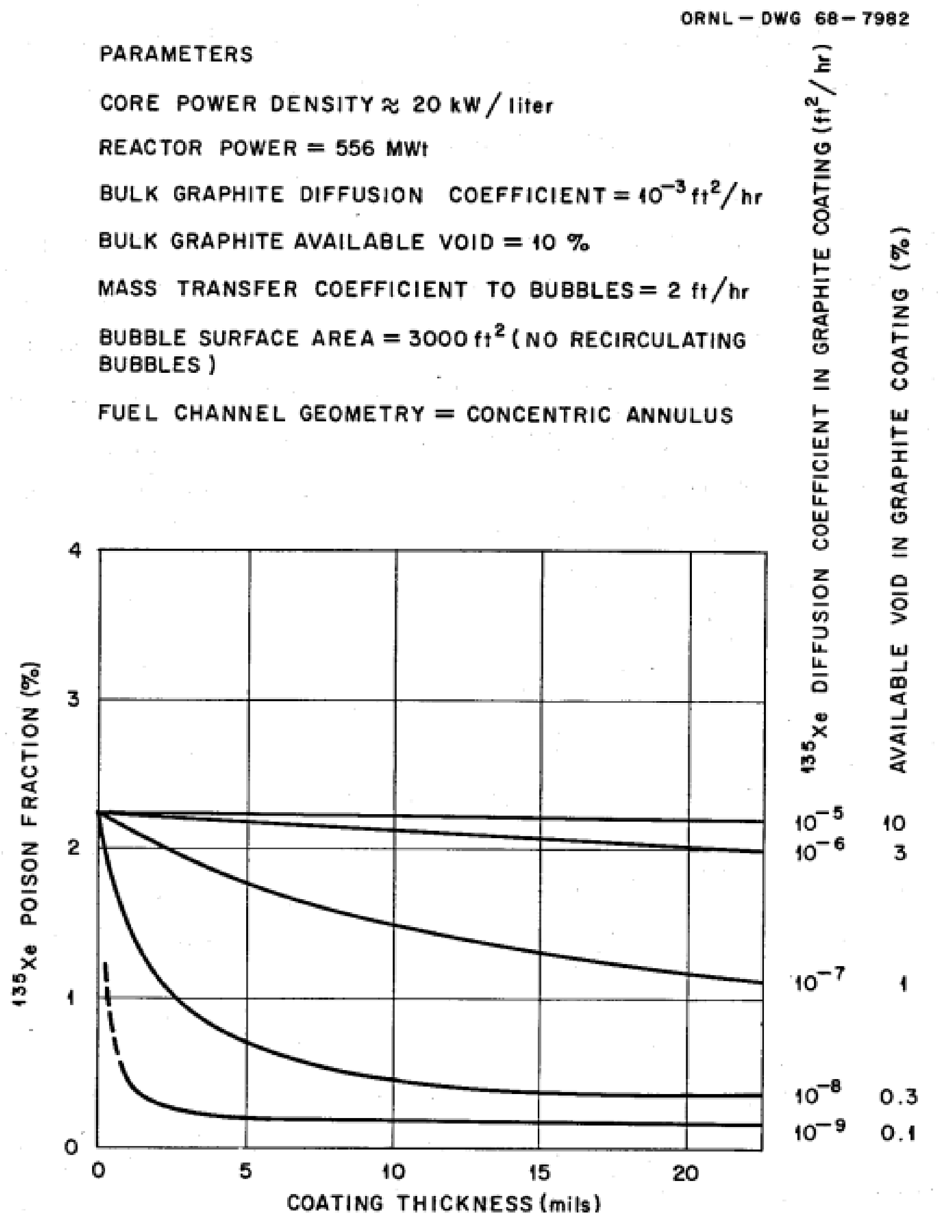


Fig. 3.7. Axial Temperature Profiles in Center Channel of a Single-Fluid MSBR

Graphite Sealing

- Reducing salt and gas permeability would 1) help ensure a breeding ratio of at least 1.0, and 2) reduce the waste management burden.
- Achieved not only through pitch impregnation and graphitization, but also with pyrolytic carbon on surface pores.
- To avoid spalling due to dimensional changes, deposits can be made near the surface, but not on the surface.
- Seals may accelerate degradation and turnaround dose.



PARAMETERS

CORE POWER DENSITY ≈ 20 kW/liter

REACTOR POWER = 556 MWt

BULK GRAPHITE DIFFUSION COEFFICIENT = 10^{-3} ft^2/hr

BULK GRAPHITE AVAILABLE VOID = 10 %

MASS TRANSFER COEFFICIENT TO BUBBLES = 2 ft/hr

BUBBLE SURFACE AREA = 3000 ft^2 (NO RECIRCULATING BUBBLES)

FUEL CHANNEL GEOMETRY = CONCENTRIC ANNULUS

Fig. 5.3. Effect of Graphite Surface Seal on ^{135}Xe Poison Fraction.

Additional thoughts

- **Fabricability**. 9-12 months fabrication timeline. Too big (length or diameter) for existing equipment. Machining curved geometries or pores. Costs. Stability of ownership of equipment.
- **Binder pitch**. Graphite grades with little or no binder pitch may be preferred, as irradiation-induced cracking generally initiates there.
- **Isotropy**. Isotropic graphite preferred for improved geometric stability (linear change preferred, reduce overall volume change). Note that cracks may only be significant after ~10% volume change (confirmation?).
- **Maintenance**. Replacing some of the graphite at each shutdown – but not all of the graphite – may improve economics, but will require more detailed analysis.
- **MDS-1**. Work with supplier to fill out ASME forms and characterize other needed information.
- **Prototype**. Testing would include a Graphite Characterization Program.

A special grade of coated isotropic graphite will have to be developed or identified for use.

<u>But FEI's #1 concern from an R&D perspective is graphite waste management. HLW or LLW off-site storage? On-site oxidation, fission product retention, and volume reduction? Another approach?</u>

Thank you!

U-238
Fast Breeder
(LMFBR)

U-235
Burner
(PWR)

Th-232
Thermal Breeder
(MSBR)

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