The Bon-Bon Road to

Core Wall Neutron Flux Suppression to enable

A Homogenous Fast-MSR fueled by Spent Fuel & Depleted Uranium Wastes

http://www.youtube.com/watch?v=mMPT09lJjcE

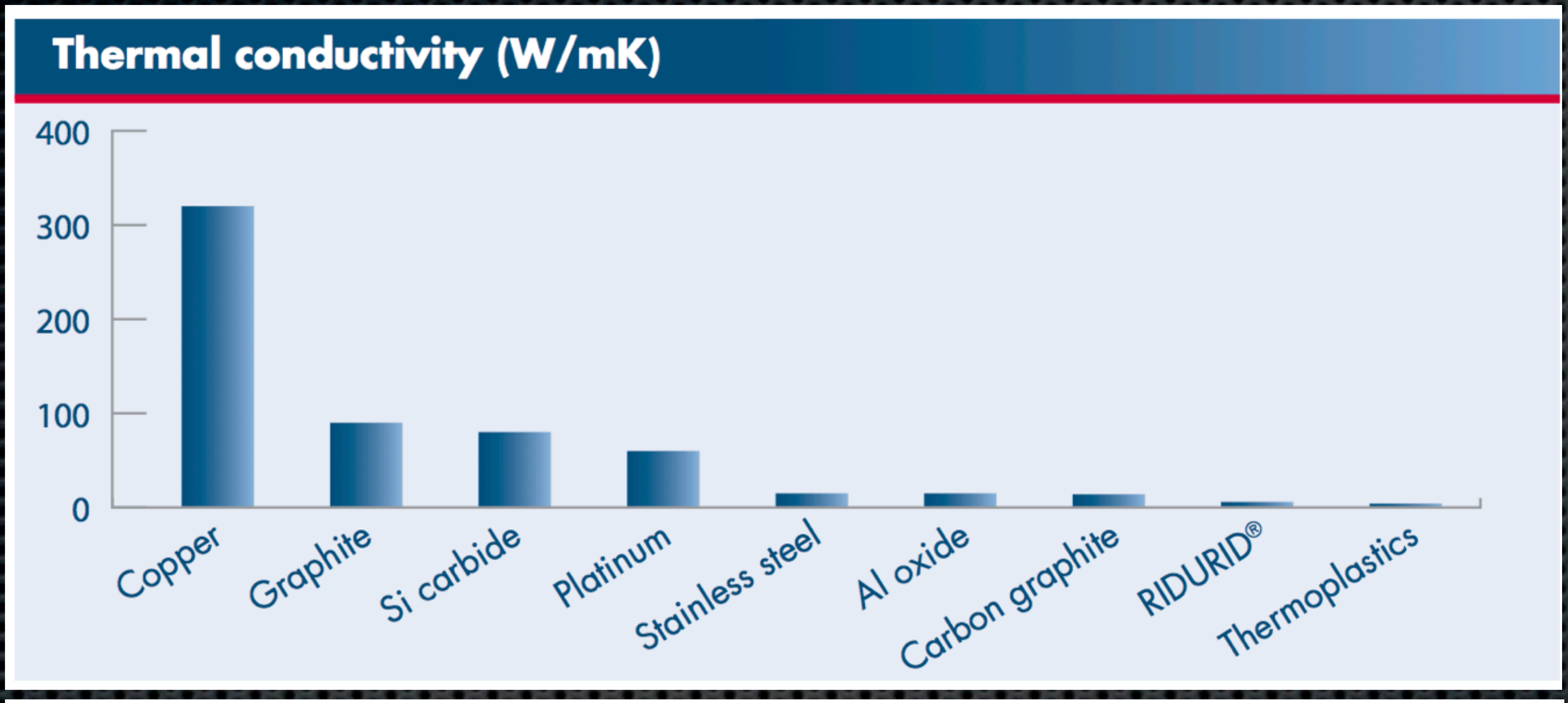
First, Some Predictions

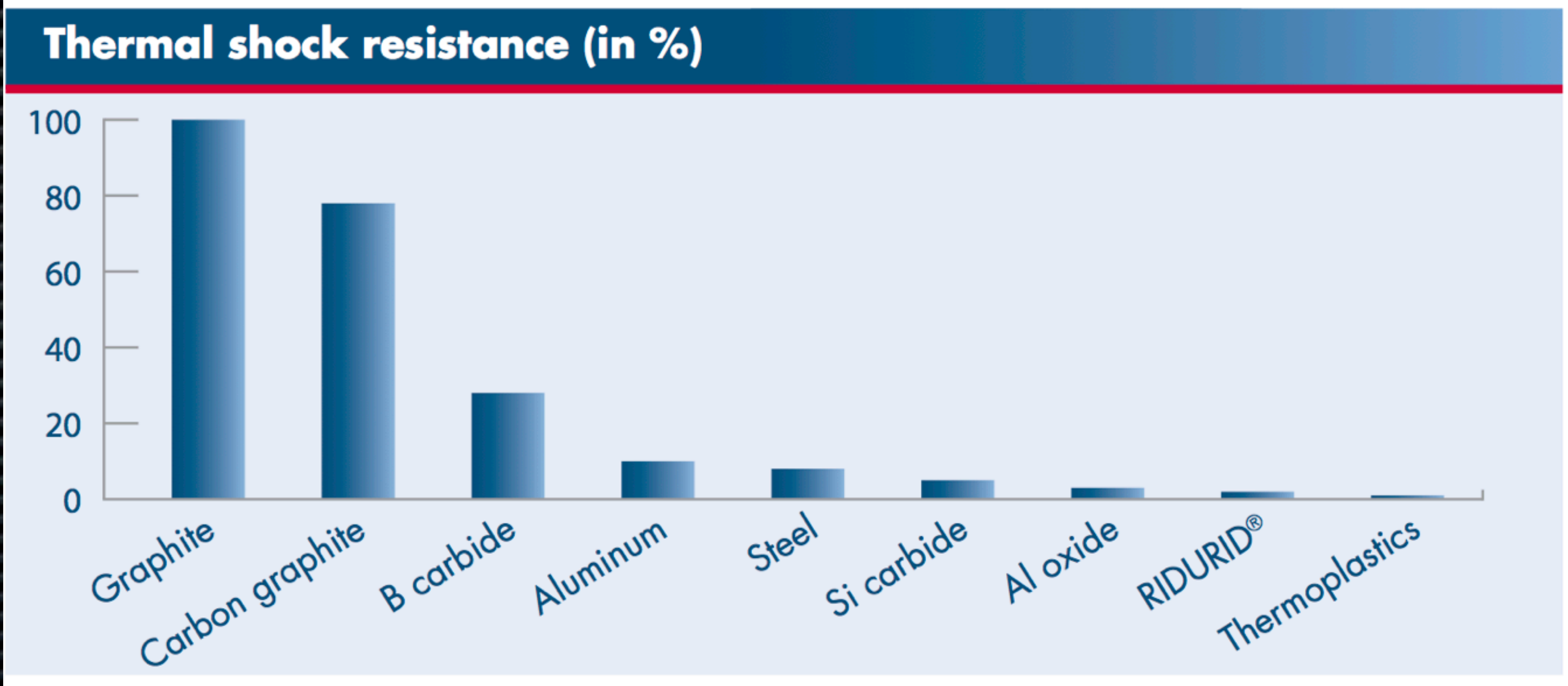
- Last Century was Iron & Steel Age, the 21st Century will be Graphite & Graphene Age
- MSRs (LFTRs, ...) are all about the Plumbing
  - MSR cores are boring ...
    - What Salt? Graphite Moderator; yes or no?
  - MSR "Action" is in the HX, Pumps, and Processing
- Radioactive wastes will become resources (e.g., SF)

Graphite

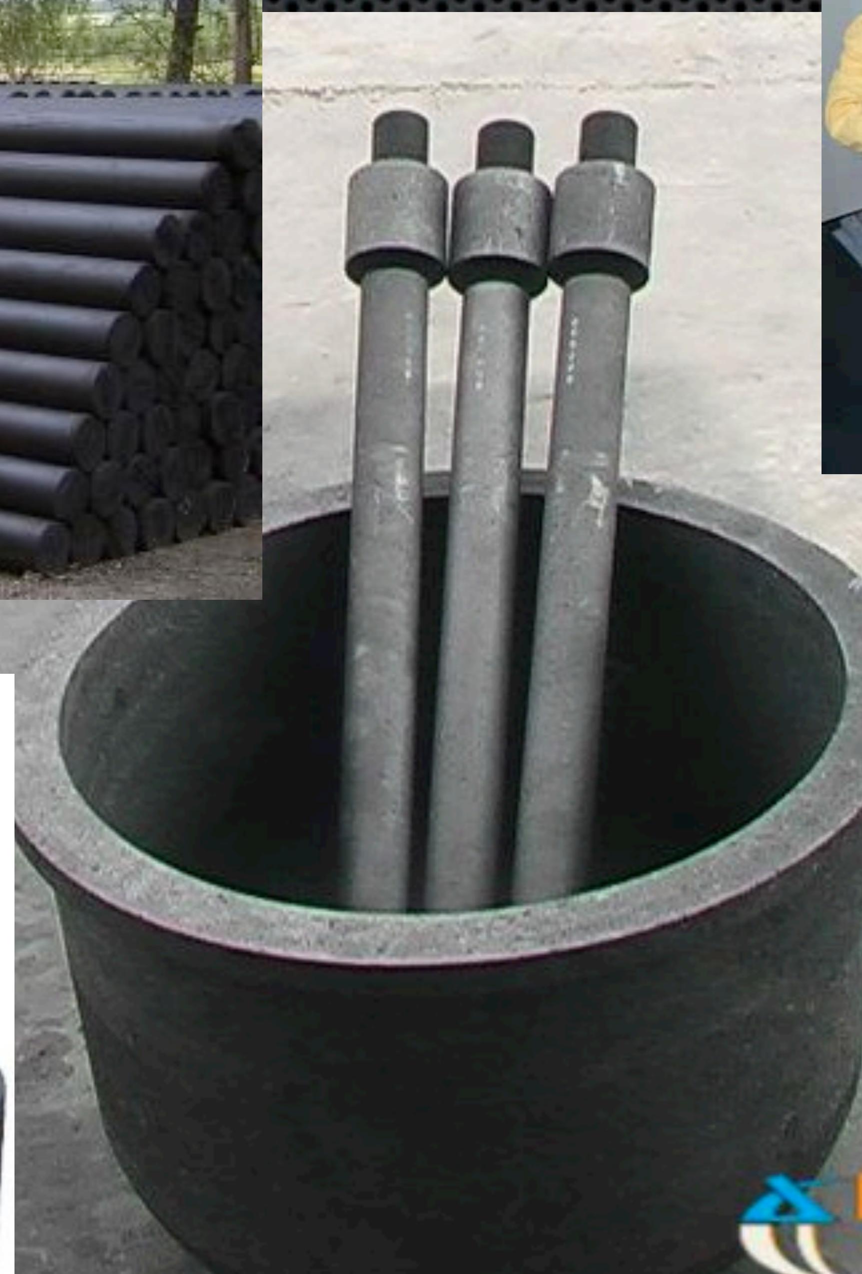
- is key to what we want to do (MSRs)
- is an Unknown that is becoming Known (Graphene)
- is compatible with all molten Fluorides Salts (1889)
- Highest? Melting Point (sublimes @ 3,825° C)
- Gets stronger at higher temps (max @ 2,500° C)
- Mixture of Strongest & Best Conductor with weak

Graphite Compared





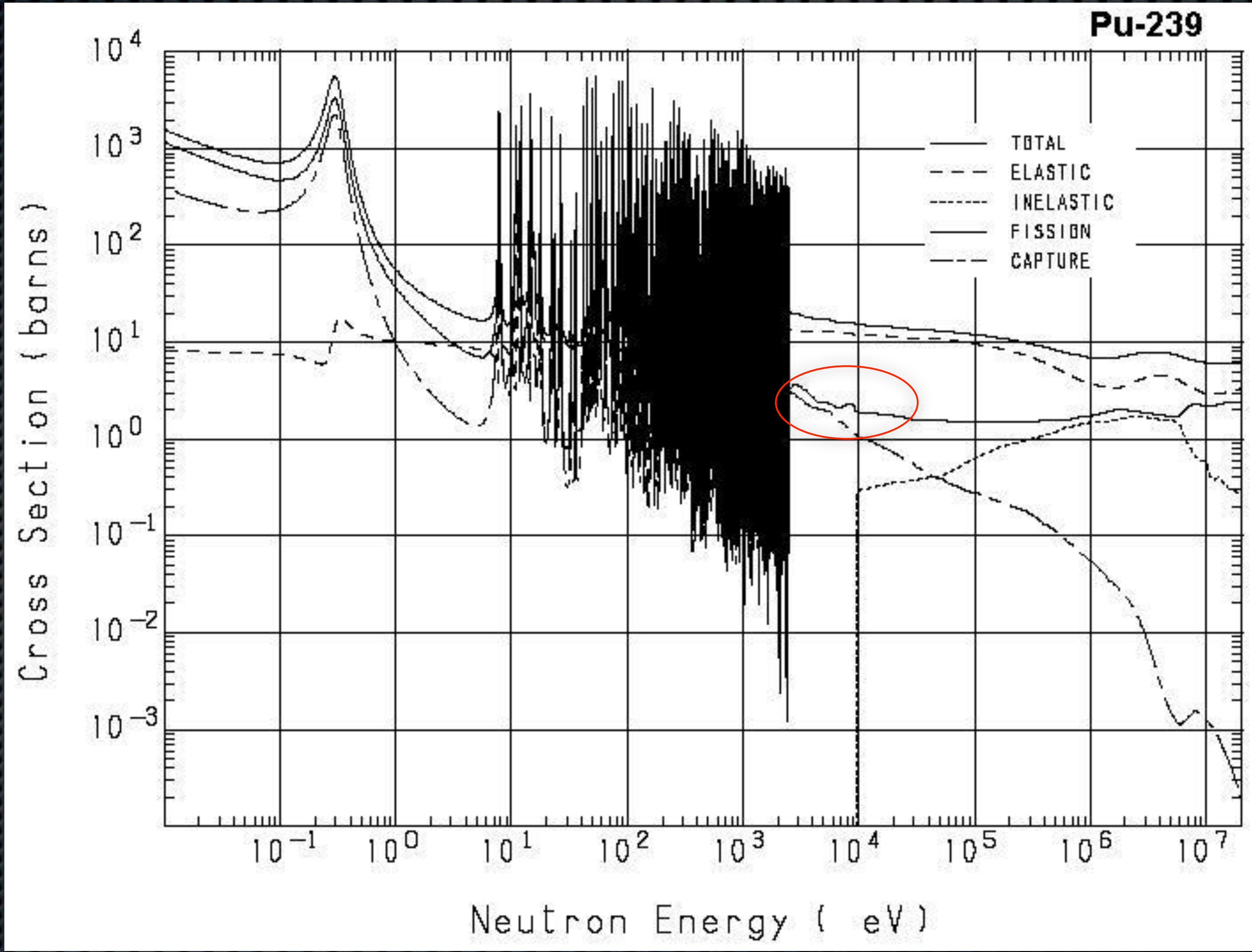
Graphite Things



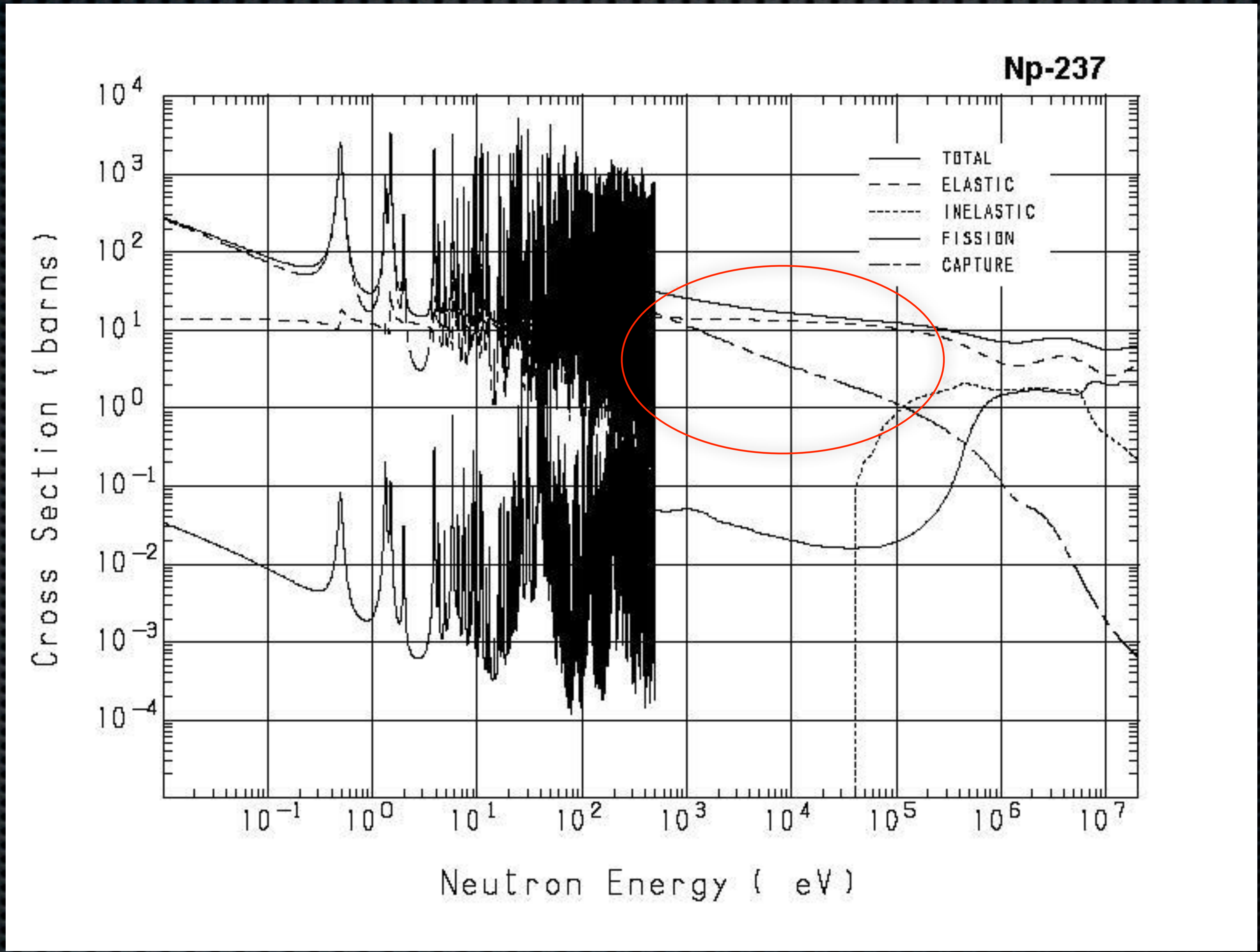
Some basic Nuclear knowledge

- Fission process
- Criticality
- **Resonance Escape Probability**
- Inelastic collisions, especially Fluorine

Pu-239 (Resonance Escape)

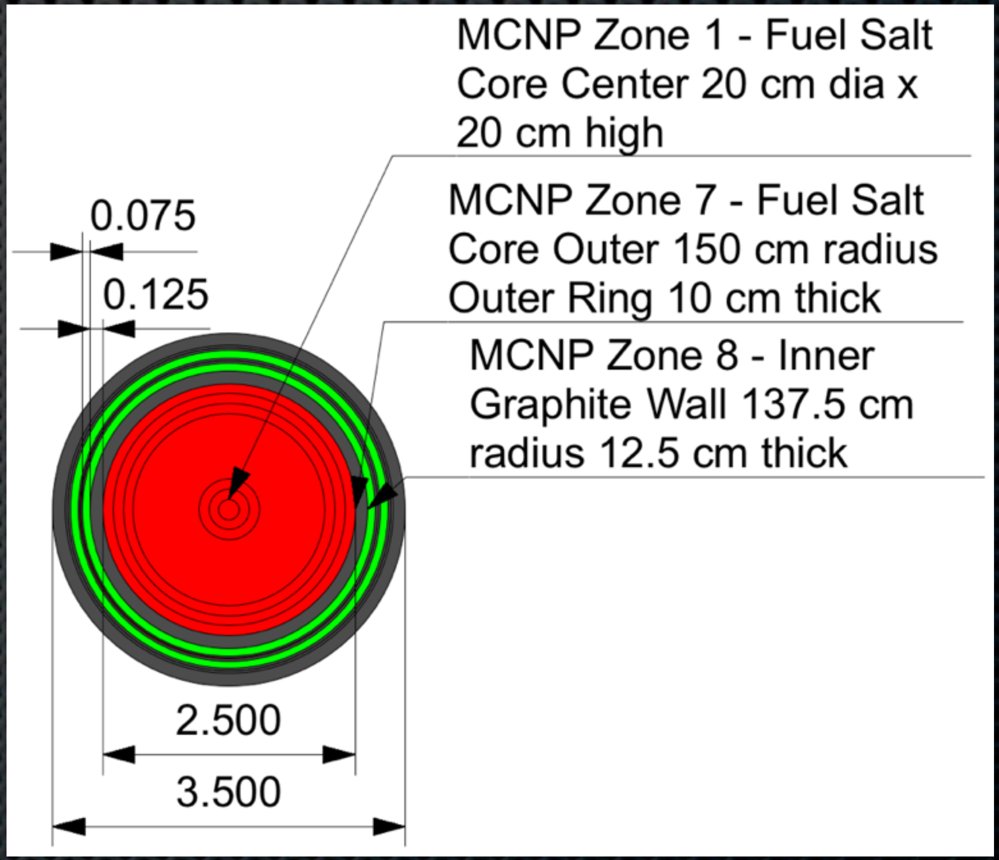


Np-237 (Capture Escape)



2 MCNP5 Blanket Modeling

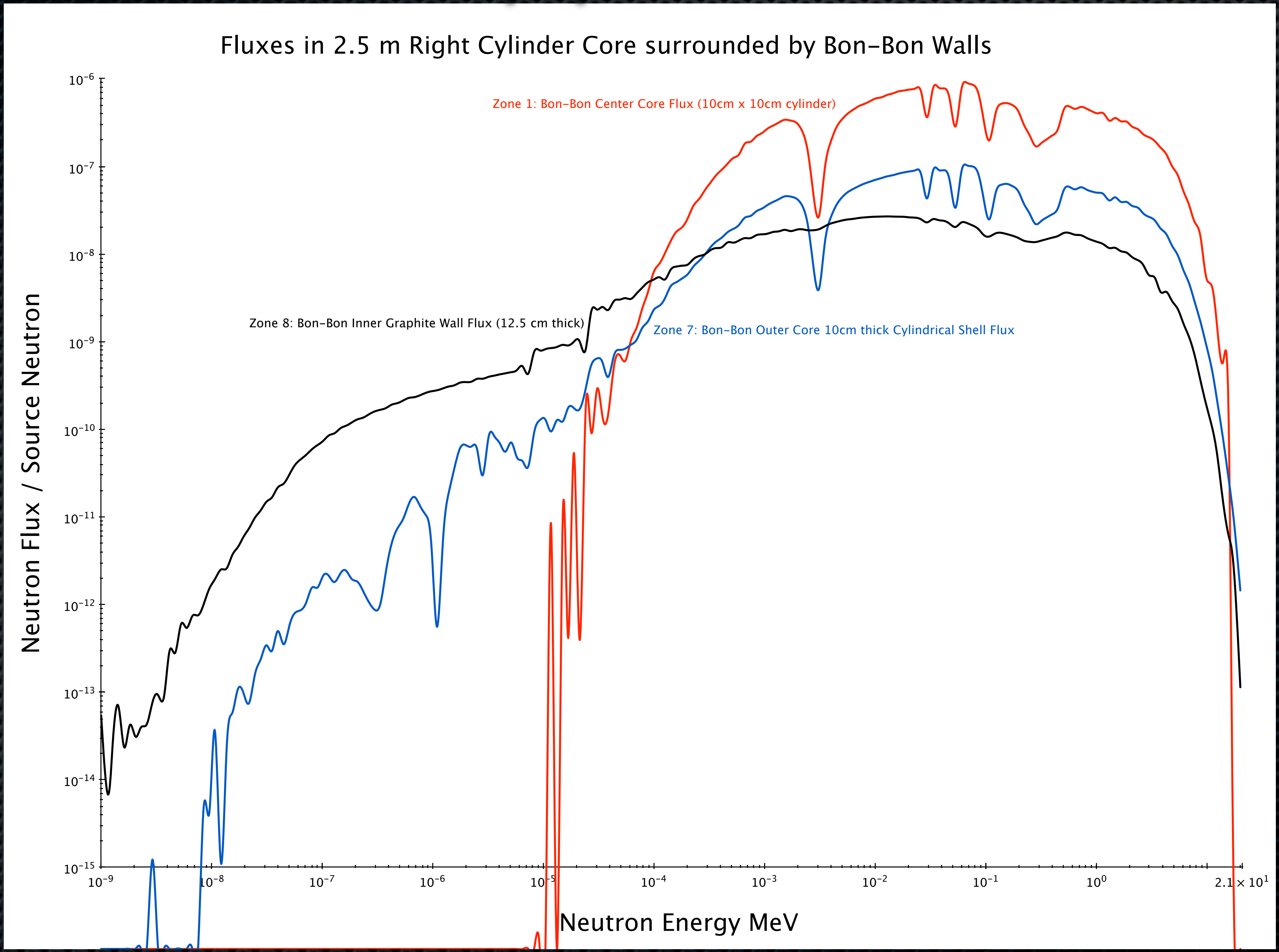
- Both simulations used 72% NaF - 28% AcFx Fuel Salt
- Both were 2.5m Dia x 2.5m High, homogenous cores
- Both had 0.5m thick Blankets & 2 Fuel Salt Returns
  - One had Bon-Bon type Blanket
  - Other had Graphite Blanket



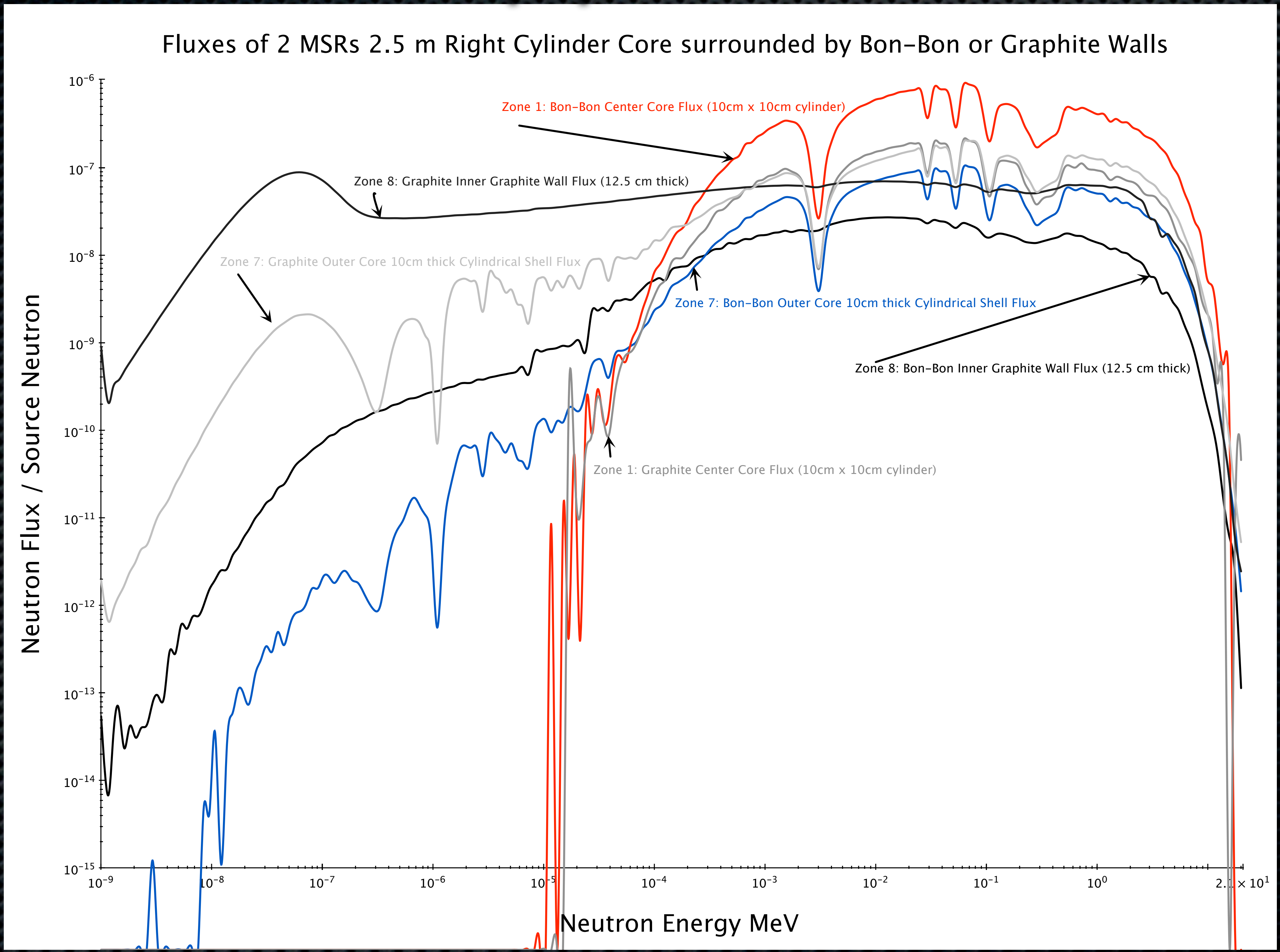
Core Wall Flux Suppression

- Absorbs neutrons that are not Fast (> 100 keV)
  - Absorb slower neutrons in the Wall (e.g., ThF_4) & in the Fuel Salt (e.g., Np-237) by **partial** C moderation
- 2 Graphs of 72% NaF-28% AcF_x (UTRUNaF) Fast Salt 2.5 m Right Cylinder Core with 0.5 m thick Bon-Bons & Graphite Walls
  - Radial & Axial Flux graph in each MCNP Zone
  - Power Density graph in each MCNP Zone

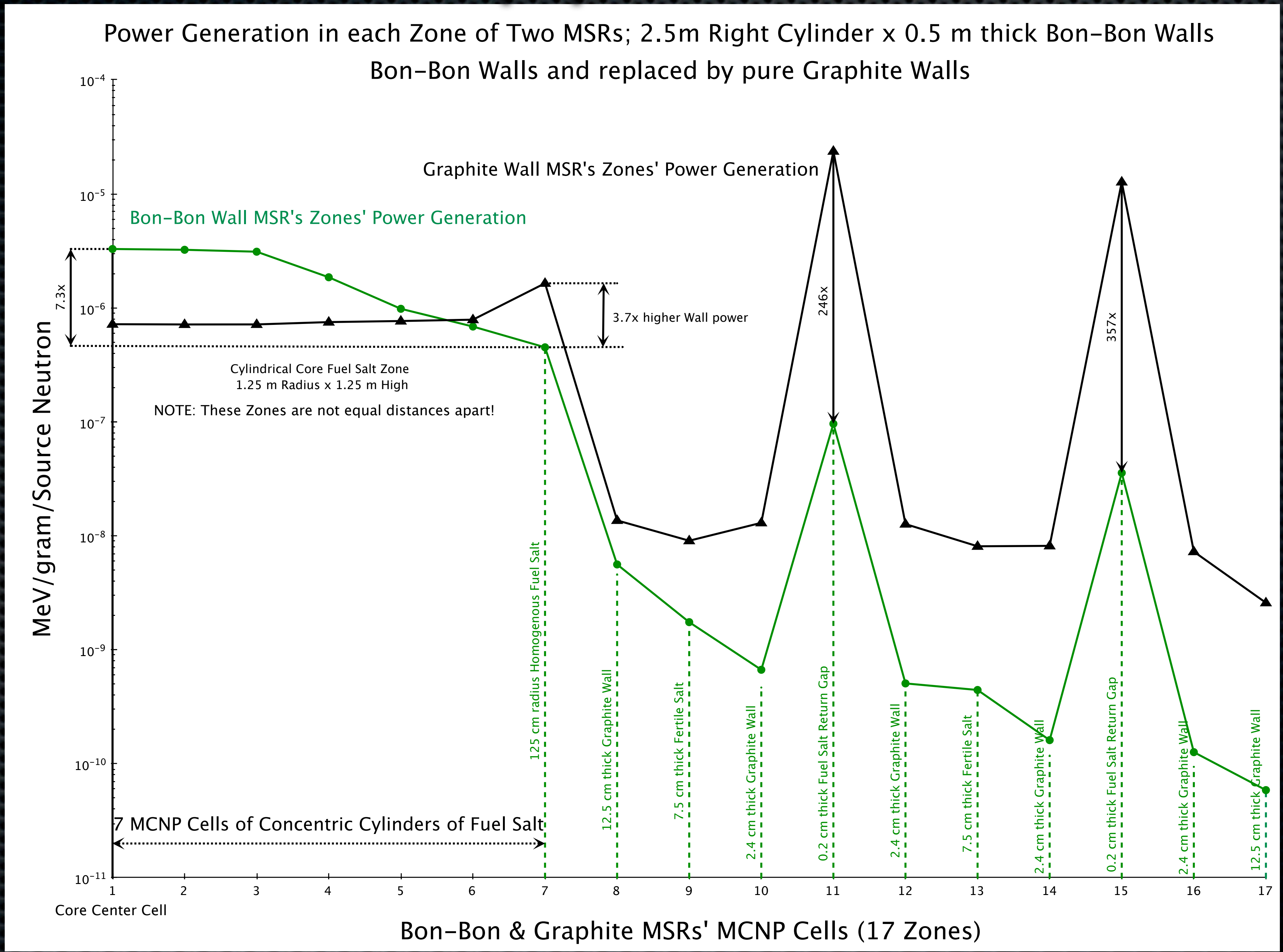
Wall Flux Suppression #1



Wall Flux Suppression #1



Wall Flux Suppression #2



Let's become Paper Reactor Designers...

MSRs give a designer too many choices ...

- What salt?
- What geometry?
- What purpose? What market to sell to?
  - No Business model, no Reactor.
  - “Do Gooding” is not a business model

What molten salt?

- To answer this, the last question must be answered!
- Business I chose is:
  '*Safely store abundant Spent Fuel and release it's energy*'. Why? Paying customers' demand!
- The USA has ~70,000 tonnes of Spent Fuel
  - USA also has ~700,000 tonnes of Depleted Uranium
- The World has >250,000 tonnes of Spent Fuel growing at 4% per year.

http://www.fissilematerials.org/ipfm/site_down/ipfm-spent-fuel-overview-june-2011.pdf

Spent Fuel and Casks

Narrow down Choices

- Salt should have significant amounts of uranium and plutonium to “store” Spent Fuel
- The “Market” says:
  Actinides and even “Fissile” (U-233, U-235, & Pu-239) are no longer resources, they are wastes!
- Safe storage is what paying customers want
- Energy (electricity) may help to pay for “storage”
- Capital Costs must be kept low

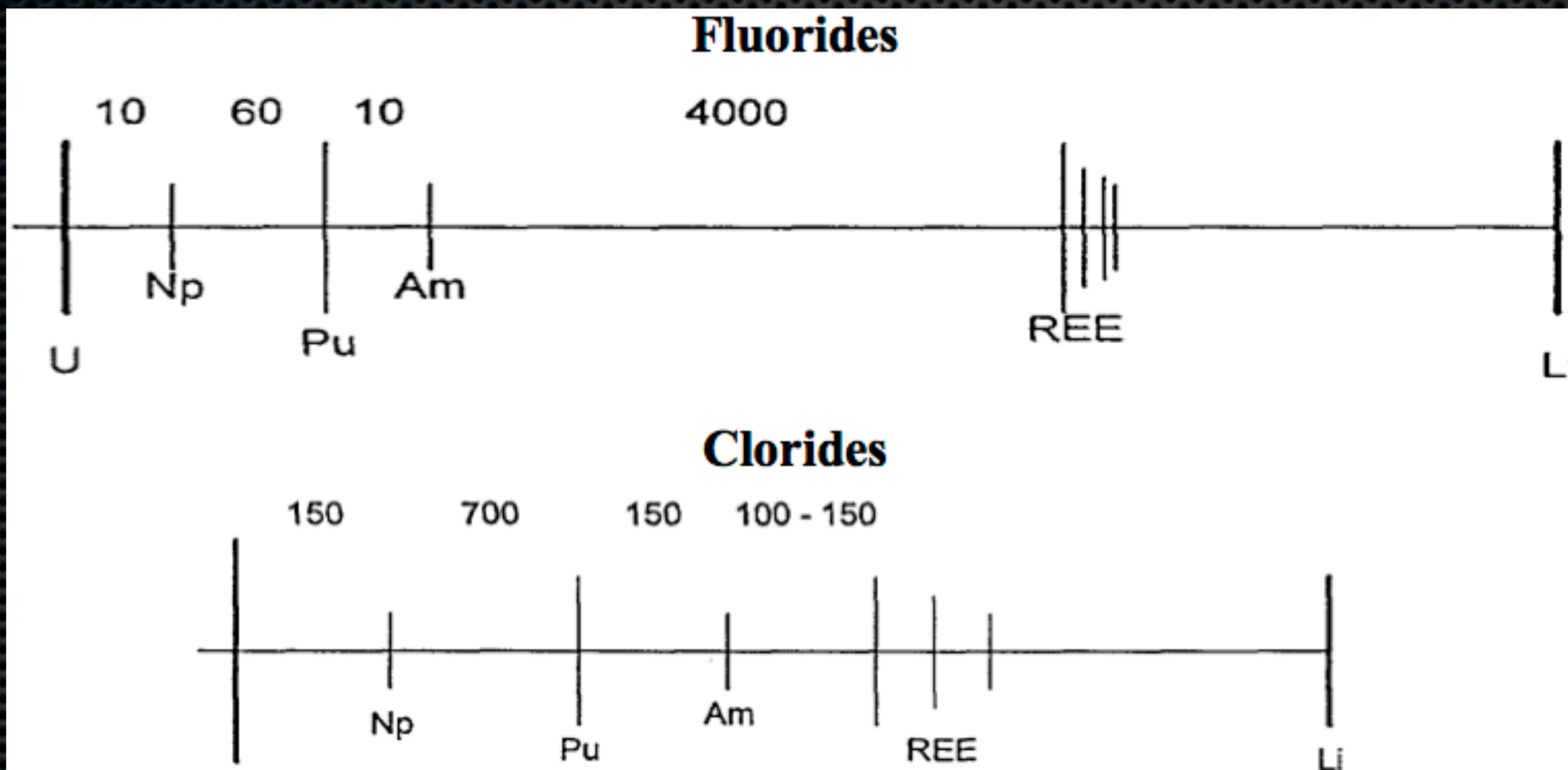
Further narrowing the choices

- Fuel Salt must have high U & TRU solubilities
- Thermal Spectrum reactors have low fissile inventories & thus low Uranium and TRU storage ability
- Fast Spectrum requires ~5x more fissile
- Fast Spectrum “burns” SF’s actinides the best
- Fast Spectrum is easier to “breed” (make new fissile)

Chloride vs. Fluoride Salts?

- Chlorides allow a faster neutron spectrum --> Breeding may be better than Fast Fluorides. Proliferation?
- Chlorides 1 advantage is not needed today, as the world is awash in fissile (excess military & commercial)
- More Cl Negatives than Positives:
  Cl Corrosion less known, Can't be Thermal Spectrum, Cl-36 long lived waste, Lower Max Temperature, Higher vapor pressure, no Fluoride Volatility processing, & Electrochemical Separation may be worse

Chlorides vs. Fluorides Electrochemistry



{"MOLTEN SALT FUELS FOR NUCLEAR WASTE TRANSMUTATION IN ACCELERATOR DRIVEN SYSTEMS"
V.V. IGNATIEV
URL: http://www.iaea.org/inisnkm/nkm/aws/fnss/fulltext/te_1365_11.pdf}

Why no Th in the Fast Fuel Salts?

- U-238 Fast Fissions 4-5x more than Th-232
- Pu-U gives more neutrons in Fast than U-Th in Thermal
- Thorium complicates salt processing, e.g., F_2 Volatility
- ThF_4 has high melting point, & increases Fuel Salt MP.
- 2-5x more thorium in Blanket than uranium in core = (Geometry says, “More blanket than core volume”) + (Pure Fertile Salt)

NaF - LiF - UF_4 Phase Diagram

Excellent
Fast Fluoride
Fuel Salt

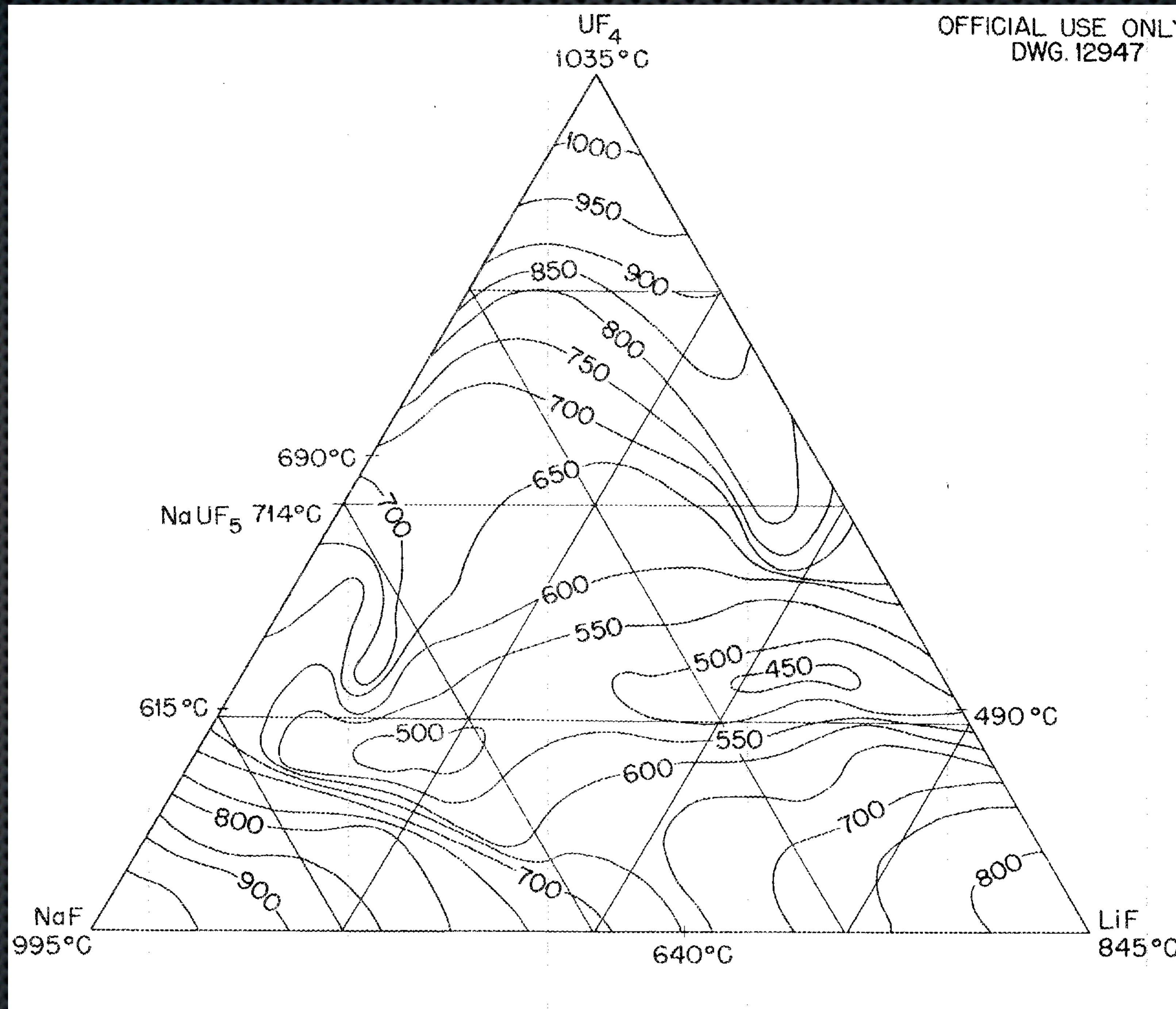
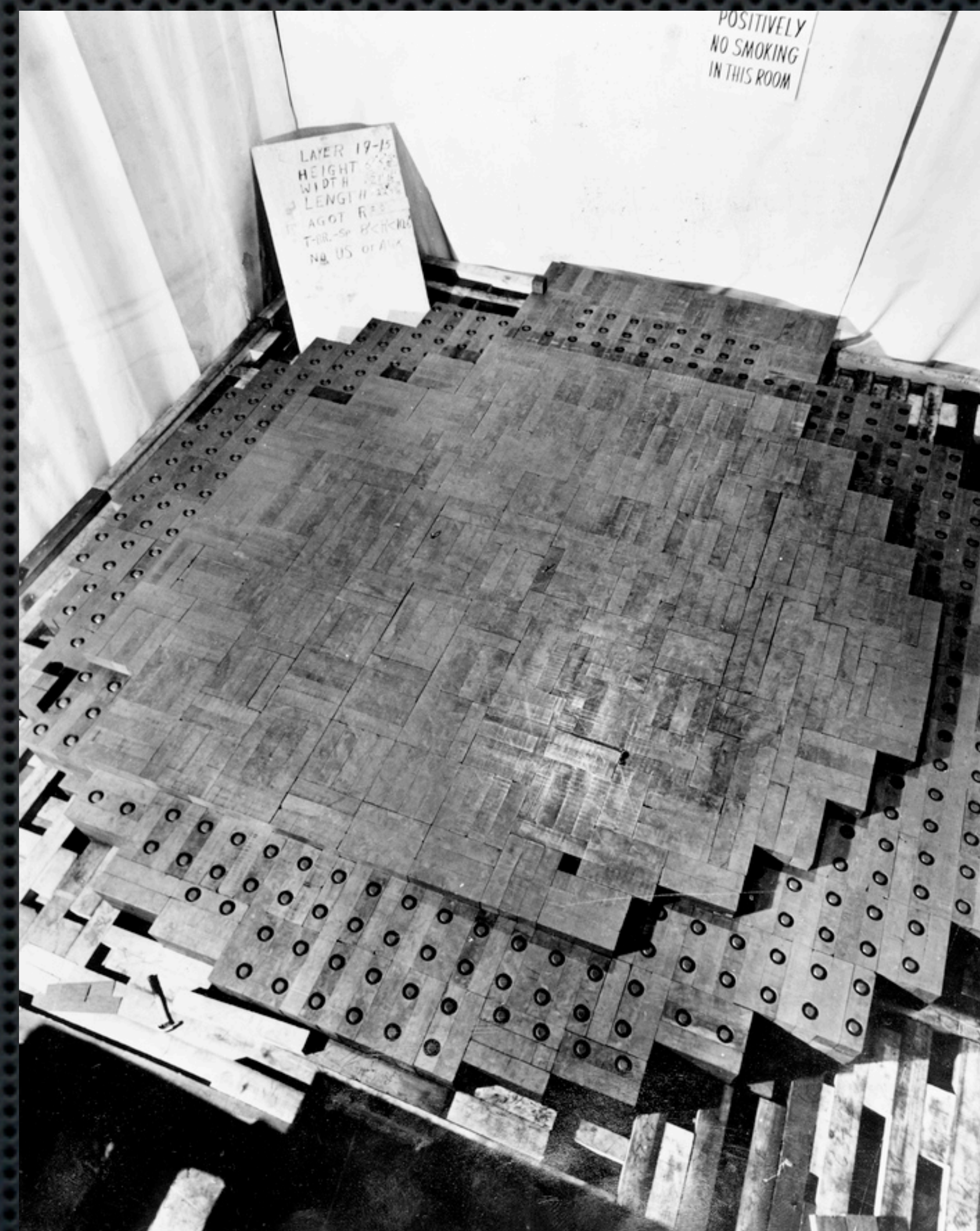
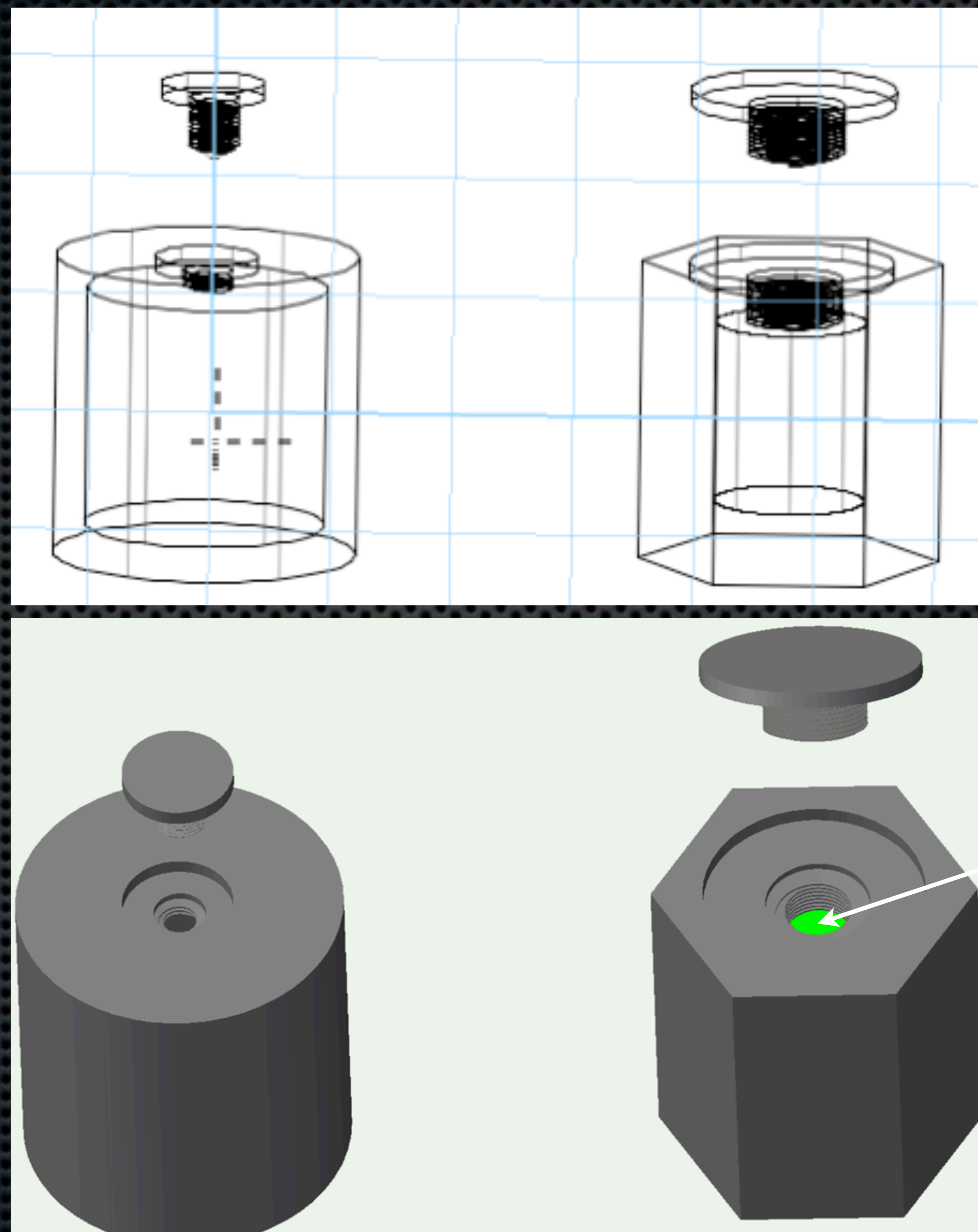


Fig. 13.1 - The System NaF-LiF-UF_4.

Back to the Future CP-1!



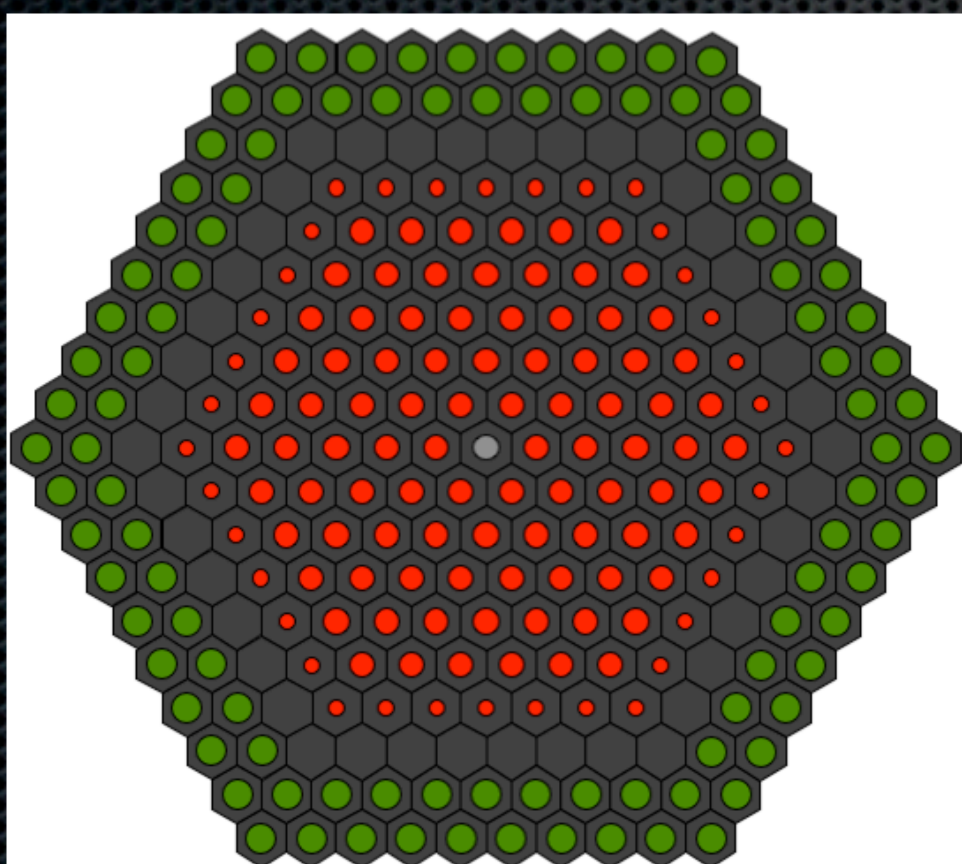
“Bon-Bon” Bricks

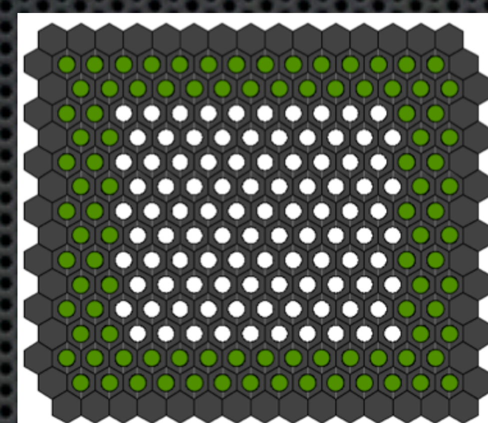


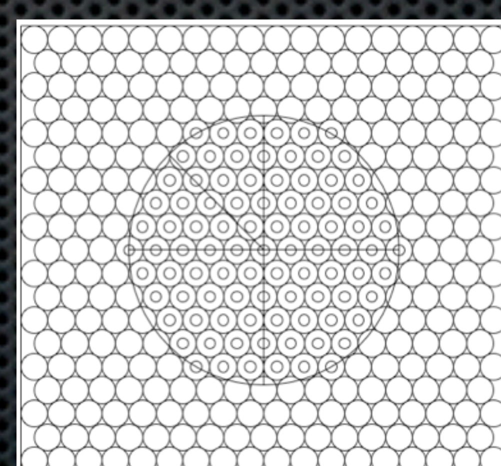
Graphite containers of ~90% ThF_4

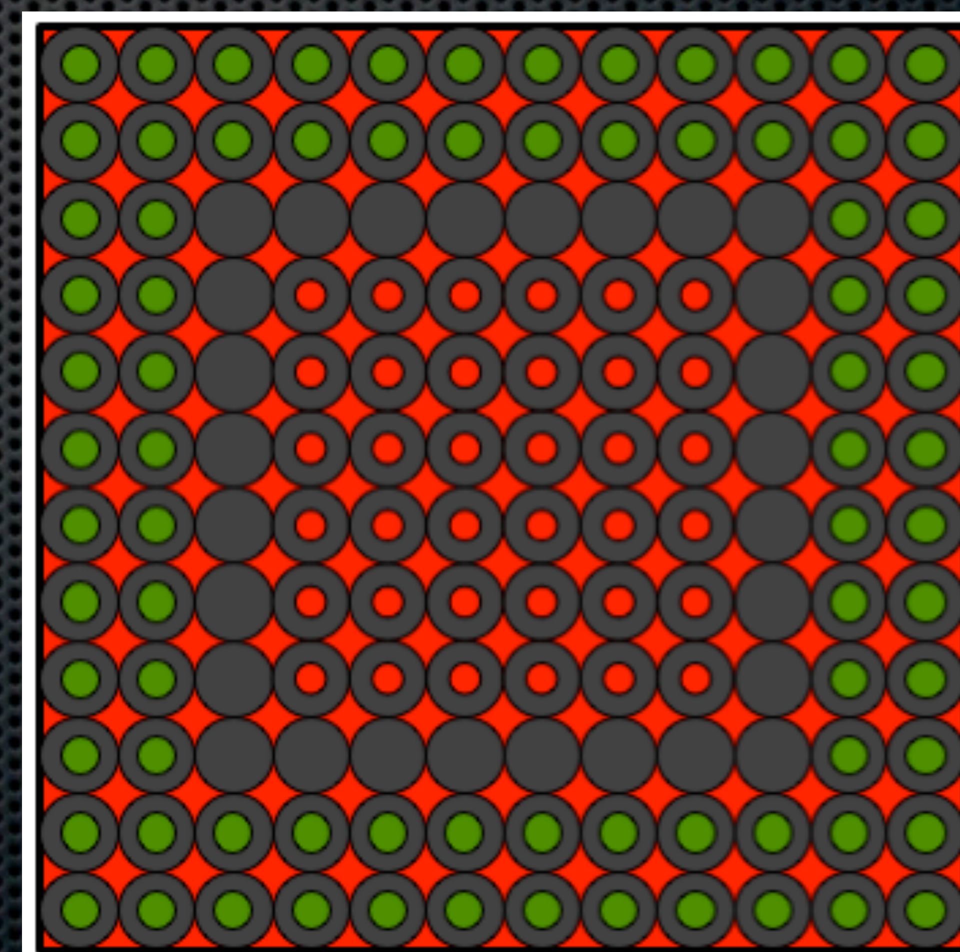
Potential Bon-Bon Layouts

- Graphite Decanters can be arranged like stacked bricks of original “Chicago Pile” (CP-1) Reactor









Bon-Bons Fertile Salts' Material Properties -

- ThF_4 MP 1,110° C, BP 1,680° C, Density 6.1 g/cc
- UF_4 MP 1,036° C, BP 1,417° C, Density 6.7 g/cc
- ThF_4 & UF_4 form continuous solution
  - 90% ThF_4 + 10% UF_4 ≈ 1,100° C MP

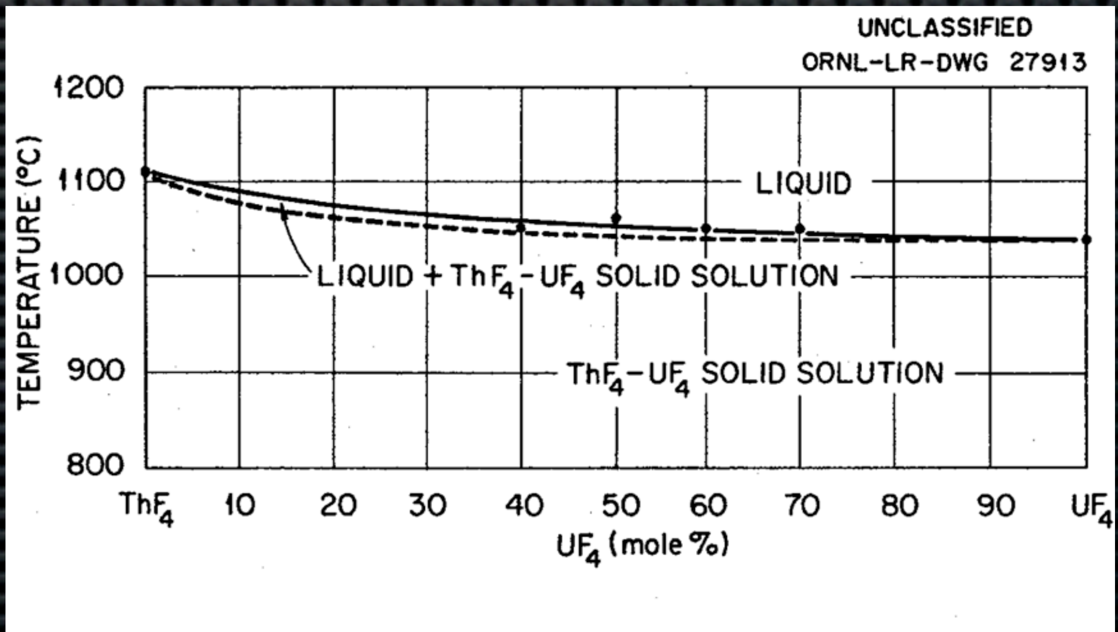


Fig. 3.63. The System ThF_4–UF_4.

Back to the Future with ORNL too:

<u>2 Zone, not 2 Fluid</u>
Liquid Fuel Salt
surrounded by
Solid Fertile Salt
Blanket
&
No Pipes:
HX is the "pipe"

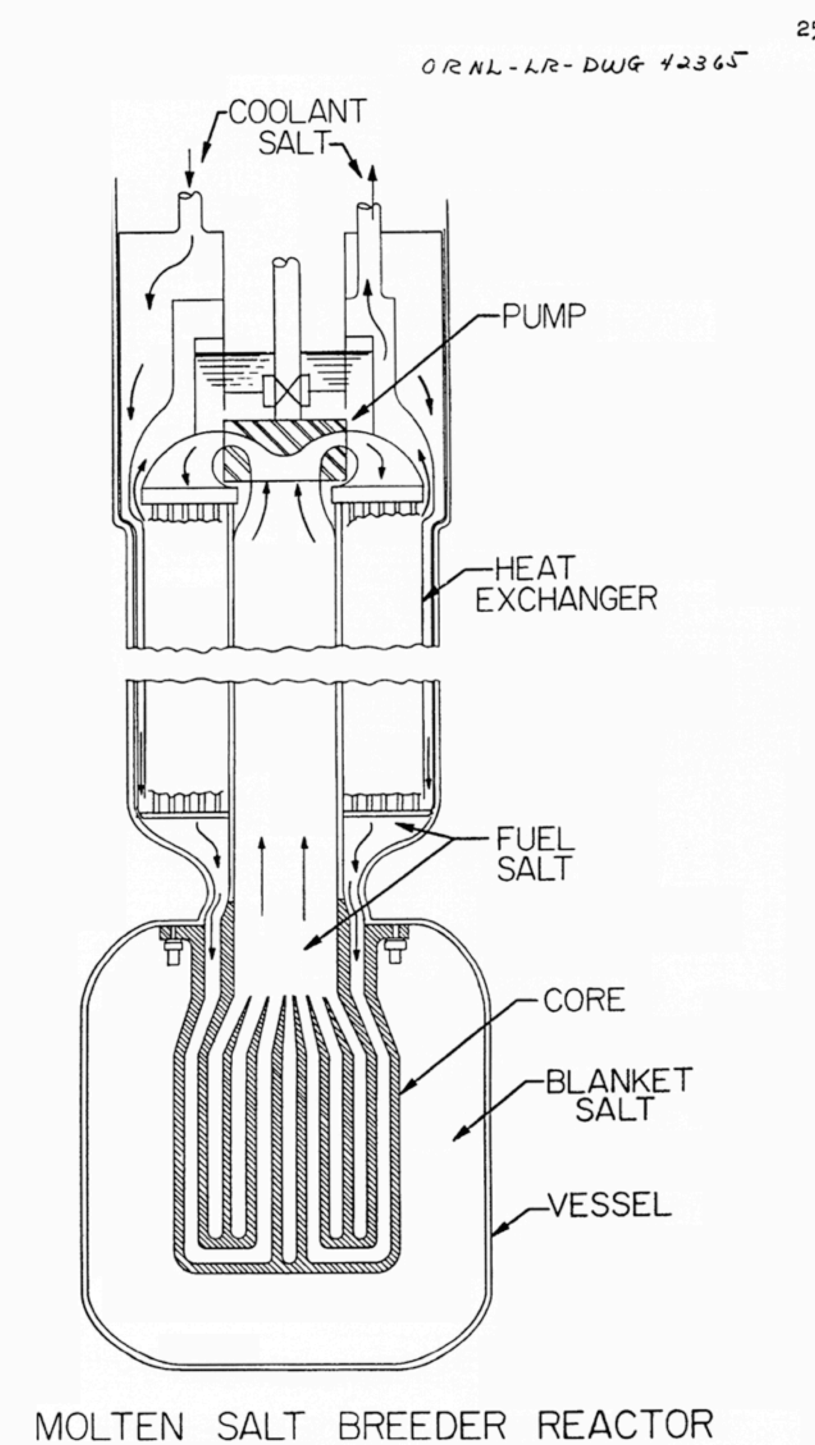


Figure 6

Modify core to Homogenous

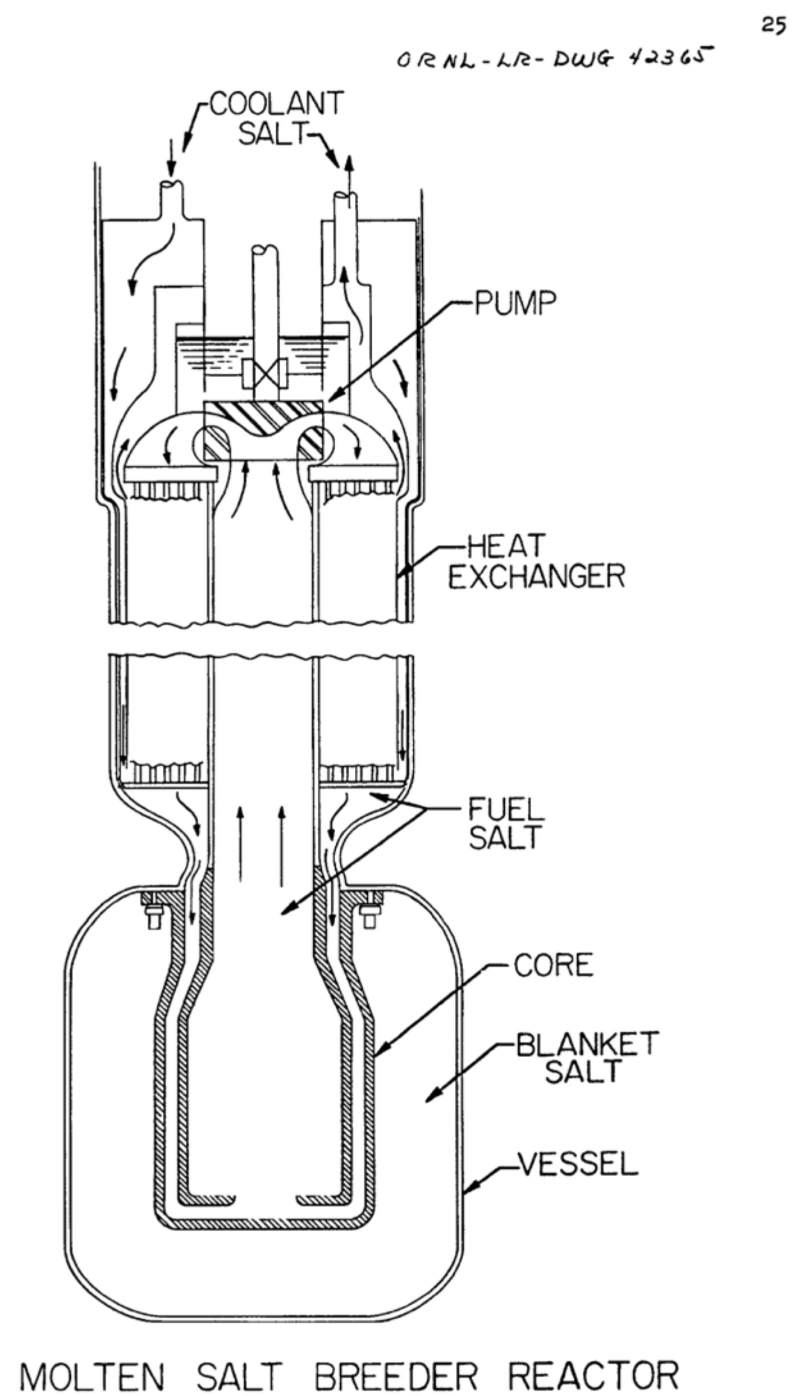


Figure 6

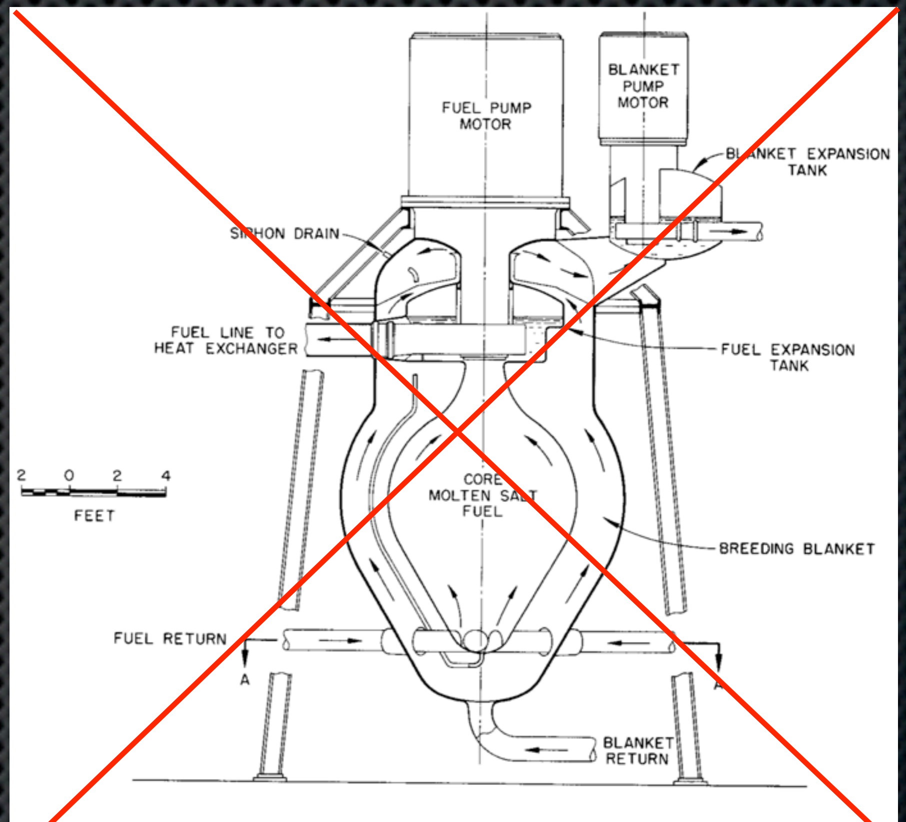


Fig. 7. General Arrangement of Core and Blanket.

No:

Fuel Salt Pipes

High-Nickel Alloy (Hastelloy) core walls

Pumped blankets filled with diluted fertile

Designing with factors to support my Business Issues!

- Recapping my Business Model's preferences:
  - High Actinide Storage capacity
  - Low Capital Costs
  - Fissile conservation unimportant today
  - Low waste production, Cheap Wastes and Low Toxicities, e.g., Tritium & K-40 are to be avoided, with easy processing (e.g., Fluoride Volatility, etc.)

Boring Core design work is done, now plumbing...

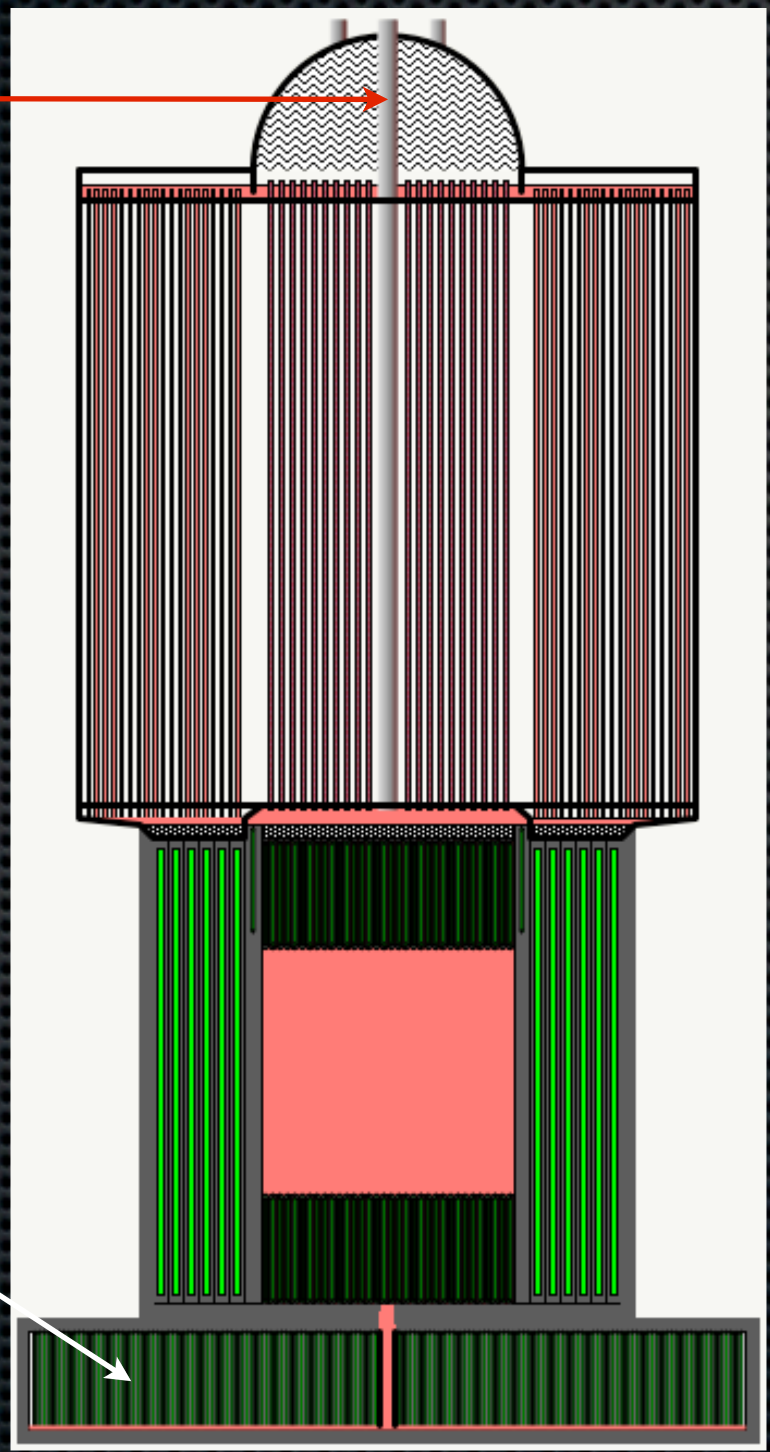
- Reduce Piping & make it all out of Graphite!
  - Make Piping the HX
  - Make Piping the Pump too (via Gas Lift)
- Keep Mechanicals out of Radiation Flux zones
  - Use Gas Lift for pumping
    - Aggressive Sparging removes Fission Products

Bon-Bons MSR Designs

Fast

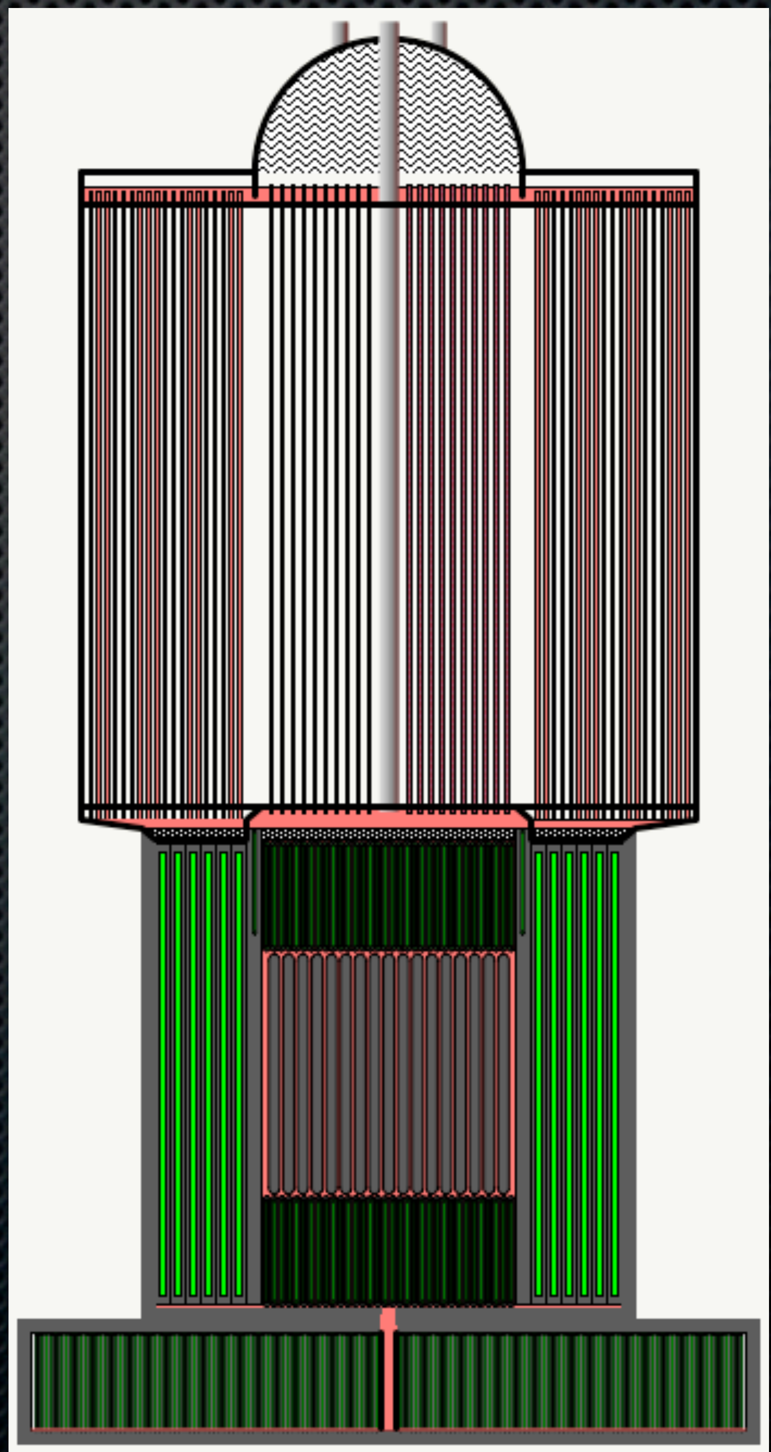
Thermal

Gas-Lift
Salt
Demister



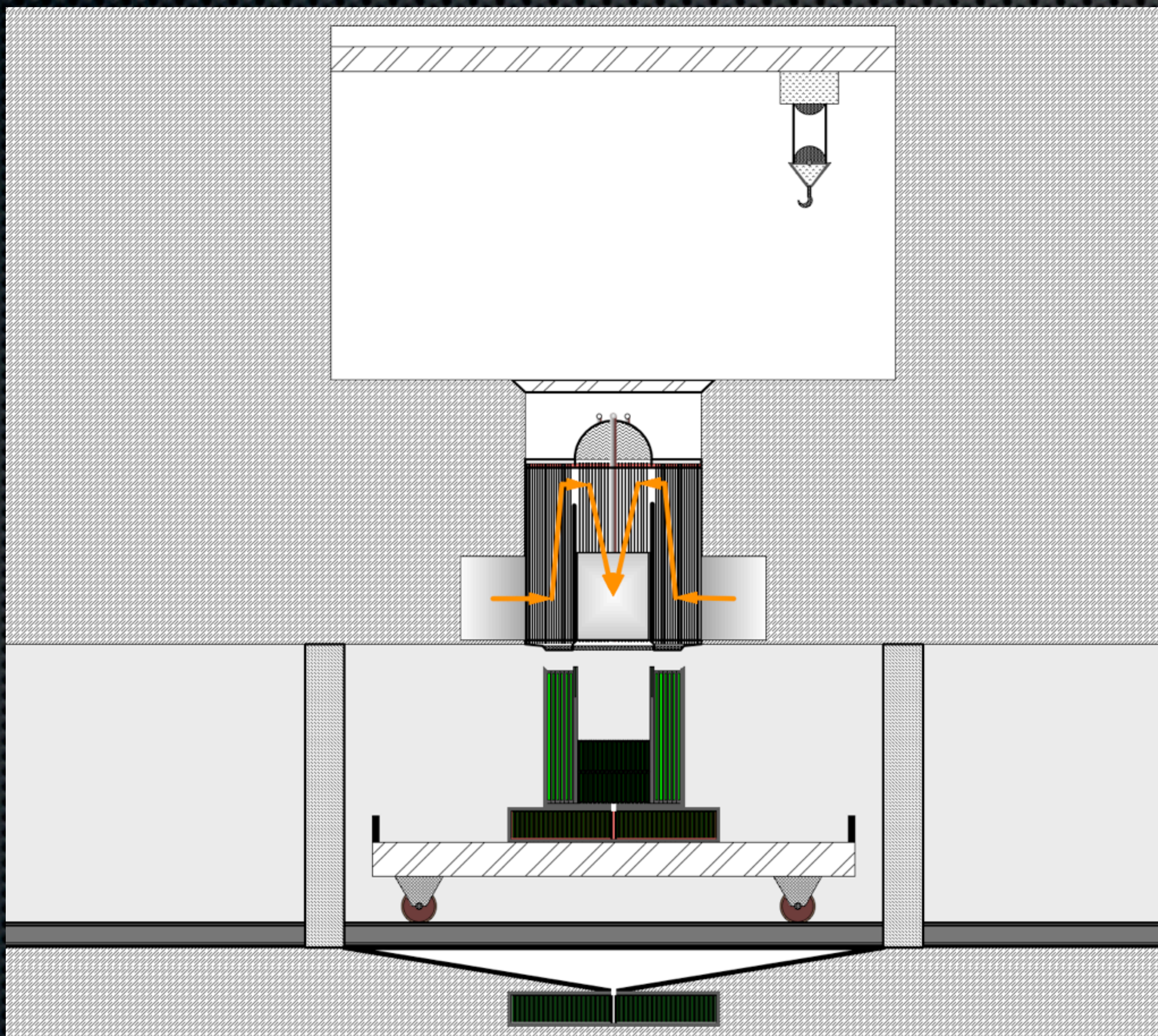
Pipes
&
Pump
is the
HX

Core
&
Blanket



Pneumatic
Drain
Tank

Bon-Bons Replacement



Bon-Bons Reactor Layout

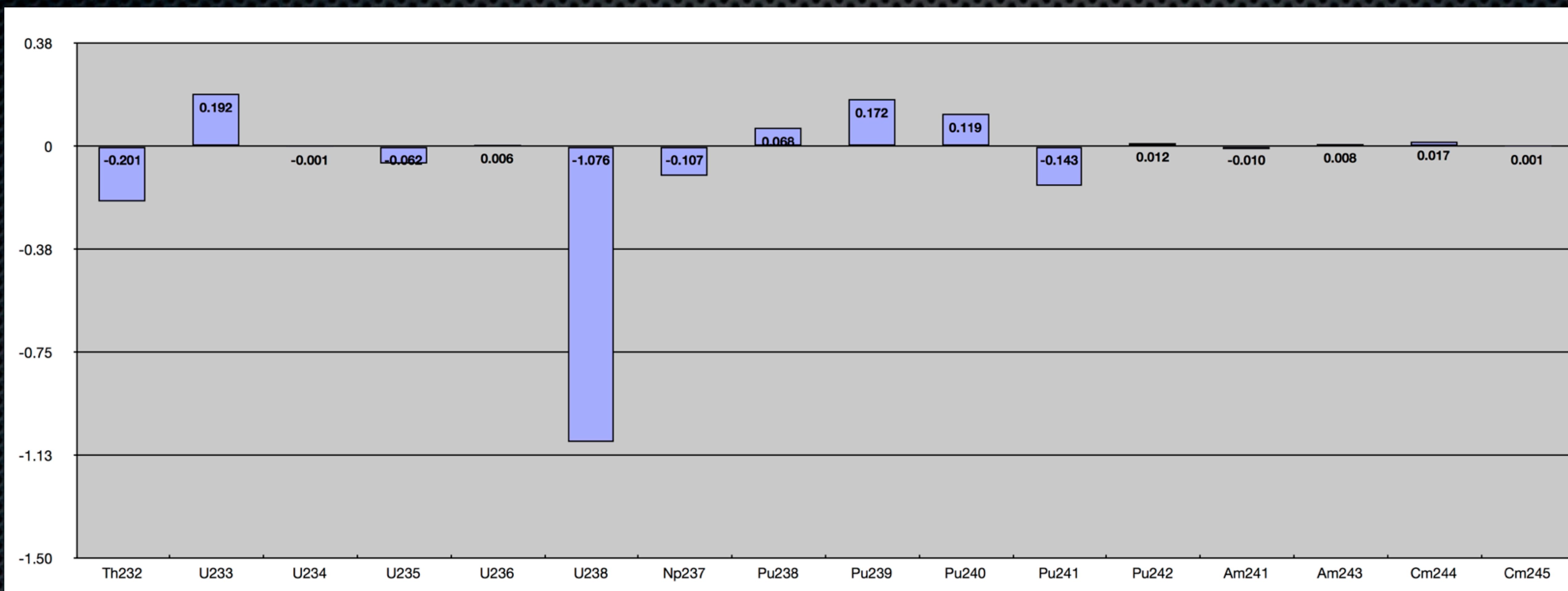
- Modular & Small, and made out of small components
- Salt Pumping aided by cold-hot density differences
- Use “Off the Shelf” Gas Turbines & Steam Turbines
- Pneumatic Fueling and Safety
- Pump Choices - Gas Lift or Pump in Cooled salt
- Reactor Core & Drain Tank Lifted Onto HX
  - Eases Reactor Core components replacement

Cylindrical core 2.5m dia x 2.5m high Fast-MSR results

- 12.5 m^3 Core Vol w 0.5 m Bon-Bon Blanket (3.5m Dia)
- 72% NaF-28% AcF_x Core BR = 0.92, Total BR = 1.14
- 3.75 Tonnes fissile, ~155 T Mass, 31 T U, & 62 T Th
- Fission: 5% U235, 9% U238, 55% Pu239, 21% Pu241

MSR Type	Core Salt Power Density MWth/m^3	Total Power (MWth)	Total Power (MWe)	Specific Power kWth / kg fissile	Fissile Ratio over DMSR	Total Electric Installed Power (GWe)	Doubling Time (yrs)	Graphite Lifetime (yrs)
DMSR	27	2,250	1,001	1,467	---	411	∞, not breeder	30
2.5 m Bon-Bon	50	826	413	220	6.66	69	84	41
2.5 m Bon-Bon	100	1,651	826	440	3.33	139	42	21
2.5 m Bon-Bon	150	2,477	1,238	661	2.22	208	28	14
2.5 m Bon-Bon	200	3,302	1,651	881	1.67	277	21	10
2.5 m Bon-Bon	250	4,128	2,064	1,101	1.33	347	17	8
2.5 m Bon-Bon	300	4,954	2,477	1,321	1.11	416	14	7
2.5 m Bon-Bon	207	3,418	1,709	912	1.61	287	20	10
2.5 m Bon-Bon	414	6,836	3,418	1,823	0.80	574	10	5

2.5m Right Cylinder Core 0.5 m Bon-Bon - Fast MSR



Actinide Isotope atom Destruction or Creation per Fission (D-Values)

Bon-Bons' Problems

- Gas Lift pumping is less efficient
- Gas Lift may not pump enough
- Gas Lift large volume of hot, radioactive gas handling
  - Gas Lift off-gas has much entrained fission products
- Need to design & test Very High Temperature Graphite components
- Core & Tank - Jacket & Cooling engineering

The Bon-Bon Road is the Fast-MSR Road to success

- Bon-Bons solve the “Wall Problem” (lifetime issue)
  - Via Wall Neutron-Flux Suppression
- Buoyant Bon-Bons create wall & floor, & terminate Flux
- Gas Lift super-sparges & eliminates core mechanicals
- Graphite HX offers high temperature and long life
- Small, modular size & low mass of lower cost materials help keep Capital Costs low

The Bon-Bon Road is the Fast-MSR Road to success

- Store and destroy wastes (U, Pu, Np, Am, Th, & F)
- SF wastes can support a Large Electrical Infrastructure
- No Fuel Fabrication (e.g., MOX) necessary
- No proliferation sensitive materials produced or needed
- Low, cheap-graphite consumption (no expensive C)
- Very High Temperature (700° - 1000° C) output

Questions?

- Bruce Hoglund
- bhoglund@me.com

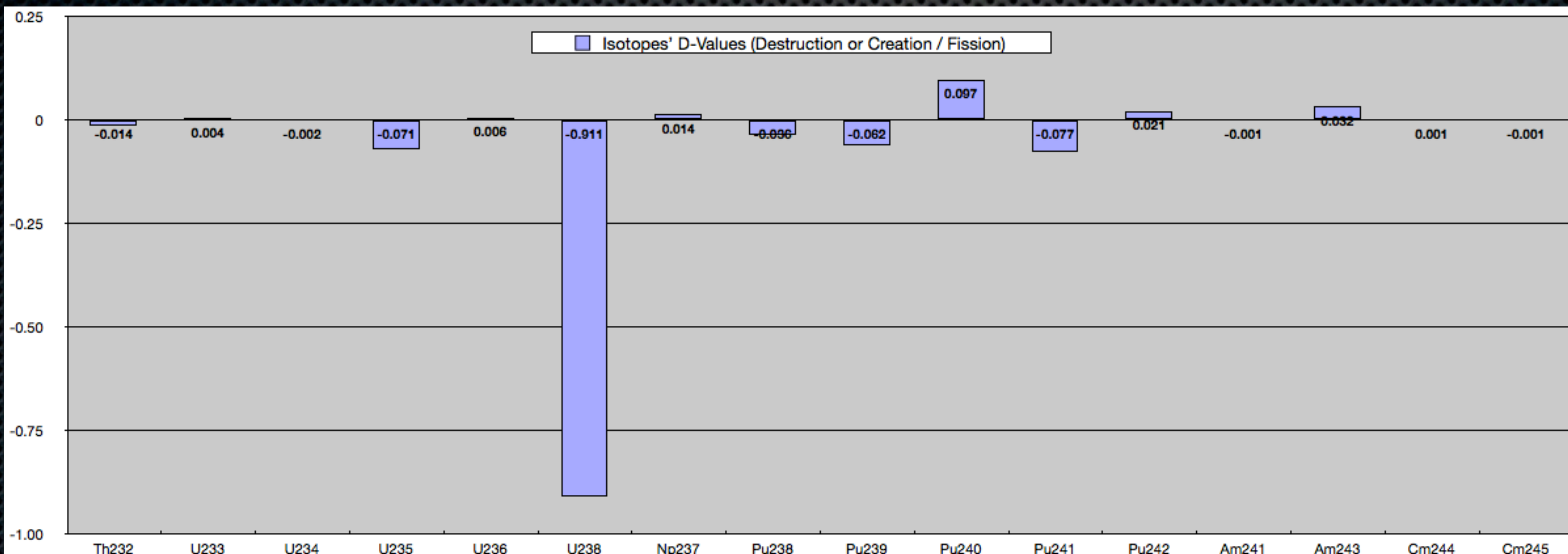
Addendum

Cylindrical core 2.5m dia x 2.5m high Fast-MSR results

- 12.5 m^3 Core Vol w 0.5 m **Graphite** Blanket (3.5m Dia)
- 72% NaF-28% AcF_x Core BR = 0.84, Total BR = 0.84
- 3.00 Tonnes fissile, ~91 T Mass, 25 T U, & 0.2 T Th
- Fission: 5% U235, 7% U238, 62% Pu239, 21% Pu241

MSR Type	Core Salt Power Density MWth/m^3	Total Power (MWth)	Total Power (MWe)	Specific Power kWth / kg fissile	Fissile Ratio over DMSR	Total Electric Installed Power (GWe)	Doubling Time (yrs)	Graphite Lifetime (yrs)
DMSR	27	2,250	1,001	1,467	---	411	∞, not breeder	30
2.5 m Bon-Bon	50	826	413	275	5.33	87	-57	11
2.5 m Bon-Bon	100	1,651	826	551	2.66	174	-29	6
2.5 m Bon-Bon	150	2,477	1,238	826	1.78	260	-19	4
2.5 m Bon-Bon	200	3,302	1,651	1,102	1.33	347	-14	3
2.5 m Bon-Bon	250	4,128	2,064	1,377	1.07	434	-11	2
2.5 m Bon-Bon	300	4,954	2,477	1,652	0.89	521	-10	2
2.5 m Bon-Bon	56	925	462	308	4.76	97	-51	10
2.5 m Bon-Bon	112	1,849	925	617	2.38	194	-25	5

2.5m Right Cylinder Core 0.5 m **Graphite** - Fast MSR



Actinide Isotope atom Destruction or Creation per Fission (D-Values)

Graphite

- Low strength (bonding energy 7kJ/mol)
- Low stiffness (36,5 GPa)
- High softness (mohs 0,5); good lubricant prop.
- High termal expansion ($28{,}6 \cdot 10^{-6}$/K)
- Low thermal conductivity (< 8W/(mK))
- High electrical resistivity (10^4 µΩm)

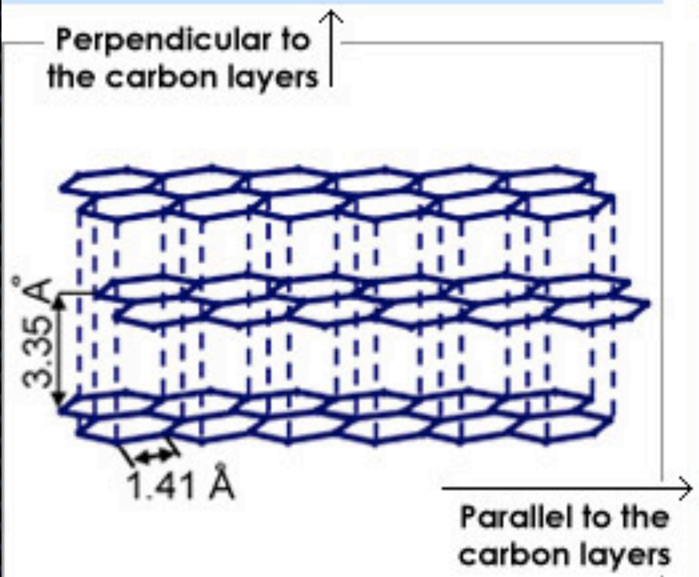
General properties:

Low weight (2.266 g/cm³)

High corrosion resistance

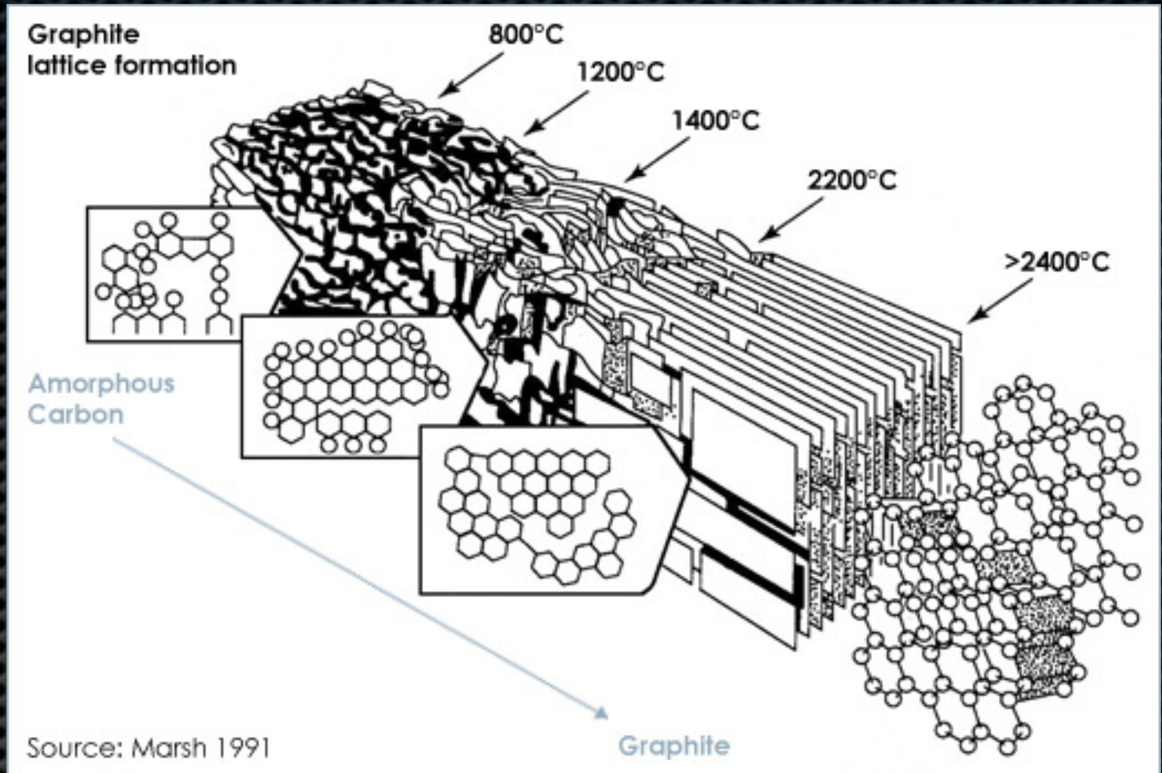
High-temperature resistance

Sensitivity to oxidation



- High strength (bonding energy 524kJ/mol)
- High stiffness (~1060 GPa)
- High hardness (mohs hardness 9)
- Low thermal expansion ($-1{,}5 \cdot 10^{-6}$/K)
- High termal conductivity (> 1000W/(mK))
- Low electrical resistivity (0.5 µΩm)

http://www.sglgroup.com/cms/international/products/lexicon-of-materials/index.html?letter=G&__locale=en



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Graphite's Biggest Problem

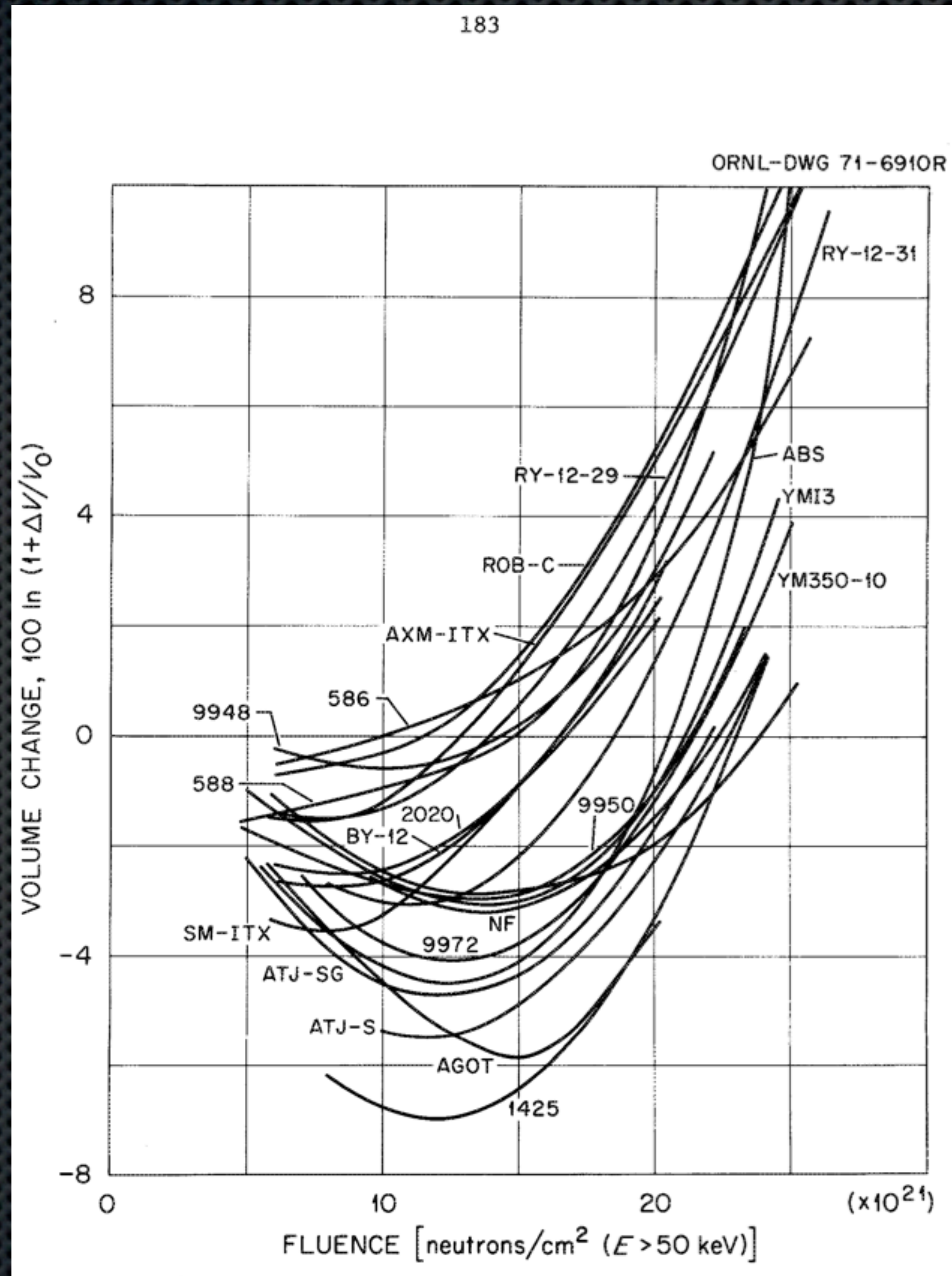
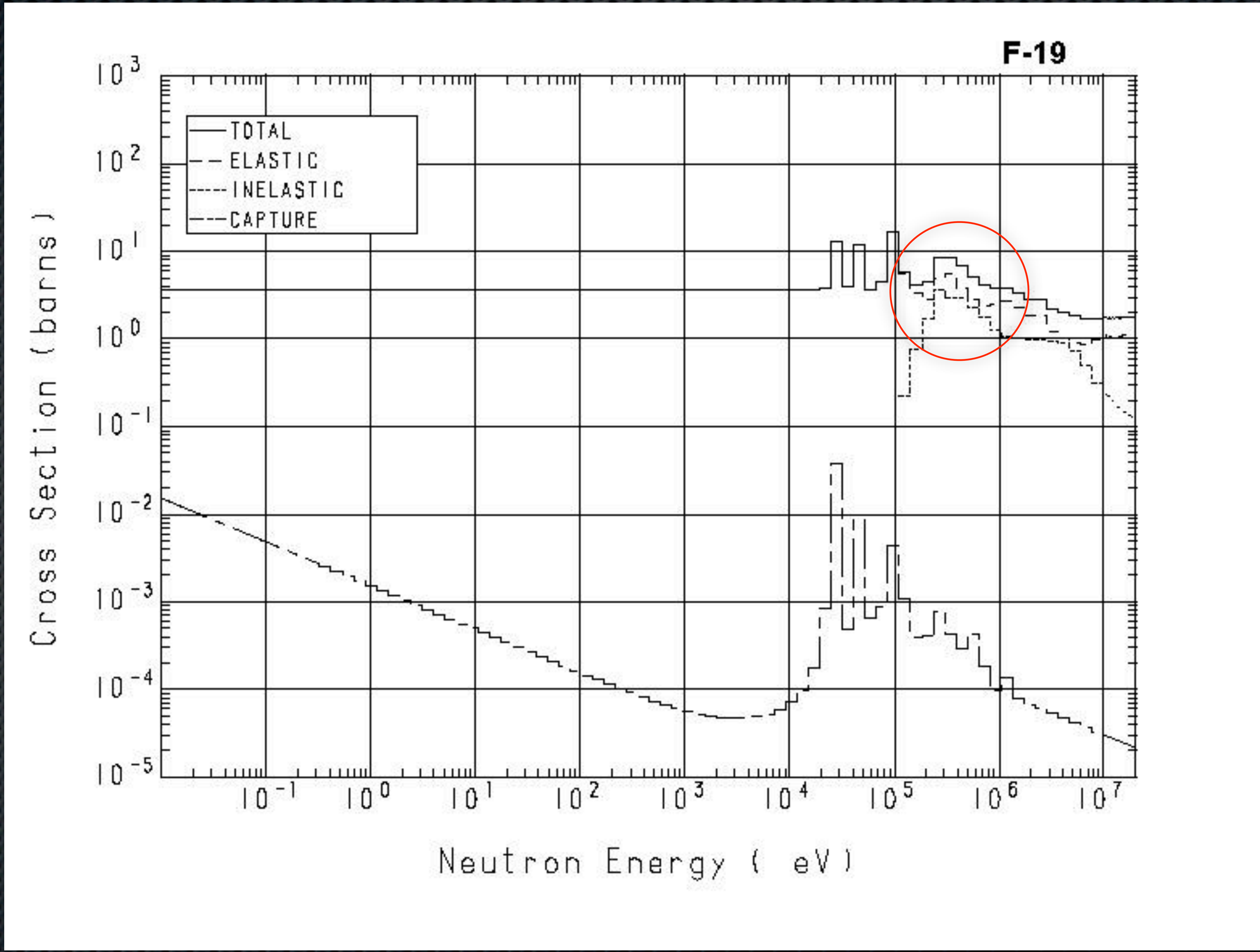


Fig. 6.5. Volume changes for conventional graphites irradiated at 715°C.

Fluorine (Inelastic Collision)



Subtle C-Moderator Issues

- Nuclear Graphite is expensive due to purity requirement
- Graphite moderated MSRs have ~80% of it's core as C
  - Thus Graphite MSRs have <1/5 the Power / Volume
    - Graphite MSRs are thus at least 1.7x larger
- Fuel Salt's fissioning is physically close to Graphite
  - Fuel Salt Power Density is lower to reduce graphite damage
  - DMSR has Fuel Salt power density of ~27 kW/liter

My Graphite Conclusions:

- Try to keep Graphite out of Neutron flux field
- Use graphite as a container for fertile Th materials
  - Fuel Salt surrounds the Fertile “Bon-Bons”
    - Graphite Containers containing ThF_4 salt
    - Recreate an “Atomic Pile” of Bon-Bons

What is Spent Fuel?

- What’s Spent Fuel?
  - Ignore the ~5-15% Fission Products & Structural
  - ~99% Uranium (0.9% U235, 0.39% U236, 97.7%U238)
  - ~1% TransURanics (TRUs)
    - 0.95% is Plutonium (4% Pu238, 53% Pu239, 24%Pu240, 12%Pu241, 7%Pu242)
    - 0.05% are “Minor Actinides” (MAs)
      - 0.04% is Np237
      - 0.01% are Am241, Am243, Cm242, Cm244, Cm245, Cm246, ...

Moderator issues & my Business Model suggests...

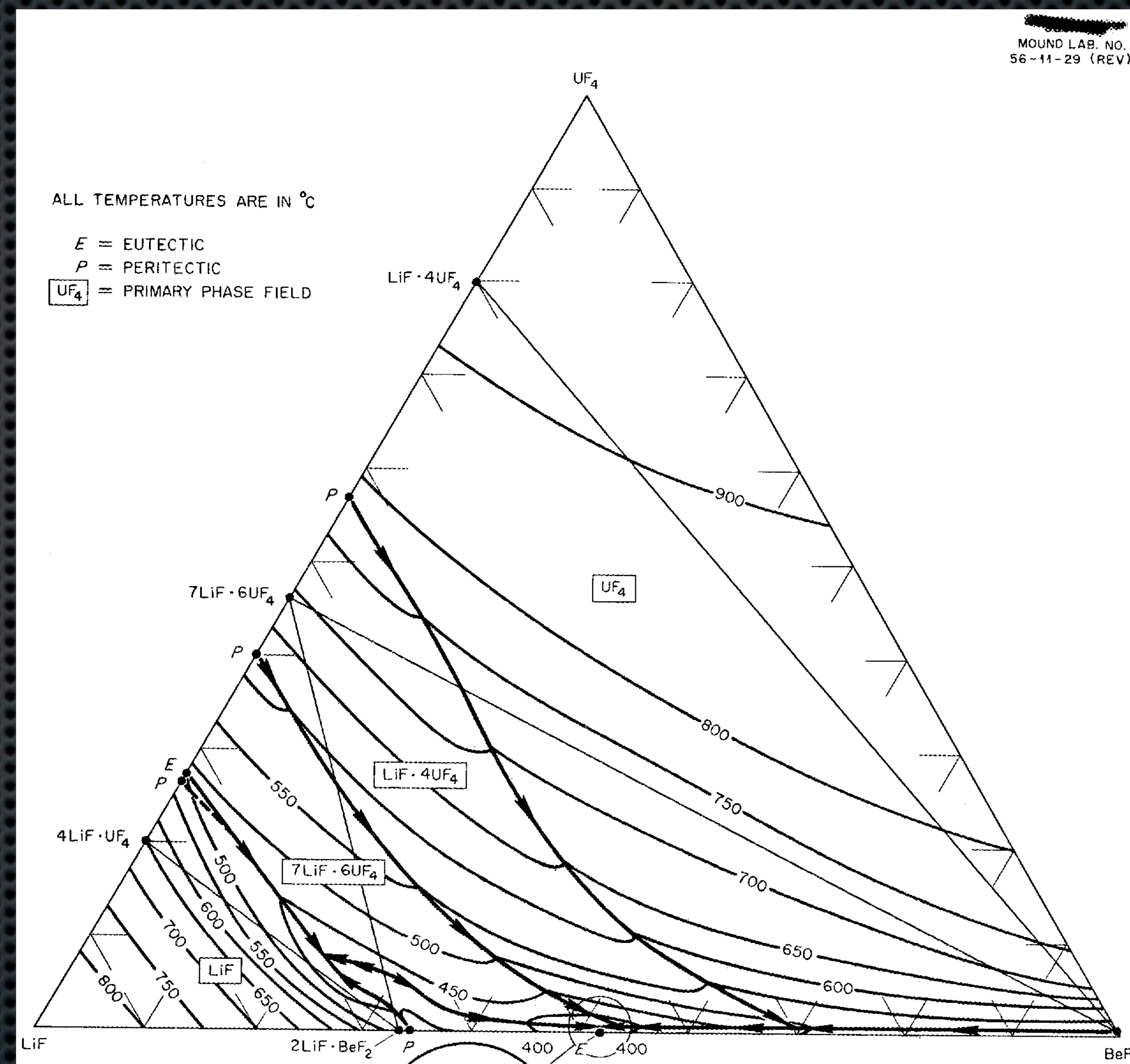
- Homogeneous MSRs, but Salt choice is still an issue
- Reexamined some of the salts Oak Ridge National Laboratory (ORNL) examined in the 1950s - 1960s:
  - 67% LiF - 33% BeF_2 (FLiBe) {MP - 458° C}
  - 53% NaF - 47% BeF (NaBe) {MP - 340° C}
  - 73% LiF - 27% UF_4 (UTRULiF) {MP - 490° C}
  - 72% NaF - 28% UF_4 (UTRUNaF) {MP - 620° C}
  - 46.5% NaF - 26% KF - 27.5% UF_4 (NaKUF) {MP - 530° C}
  - ?% NaF - ?% LiF - ?% UF_4 (UTRULiNaF) {MP - 445° - 650° C}

What Salt & Geometry?

- Since we're just starting... and don't yet know salt
- I did a Parametric Study like ORNL-2751
  "Nuclear Characteristics of Spherical, Homogenous, Two-Region, Molten-Fluoride-Salt Reactors", Sep1959.
- Change to a constant geometry of 2 meters diameter fuel salt sphere with a 0.5 m thick blanket
  - Vary both Fuel Salt & Blanket compositions
  - Measure neutron fluxes, graphite damage, isotopic parameters (capture, fission, etc.), leakage, etc...

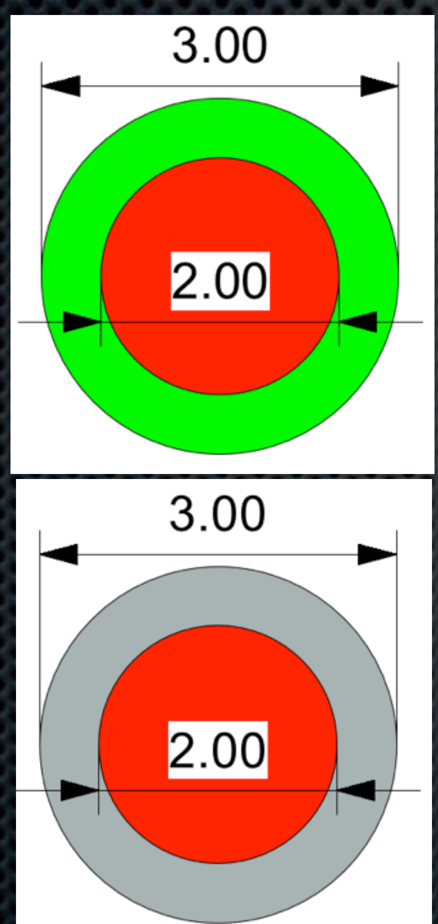
FLiBe (LiF-BeF_2) Phase Diagram

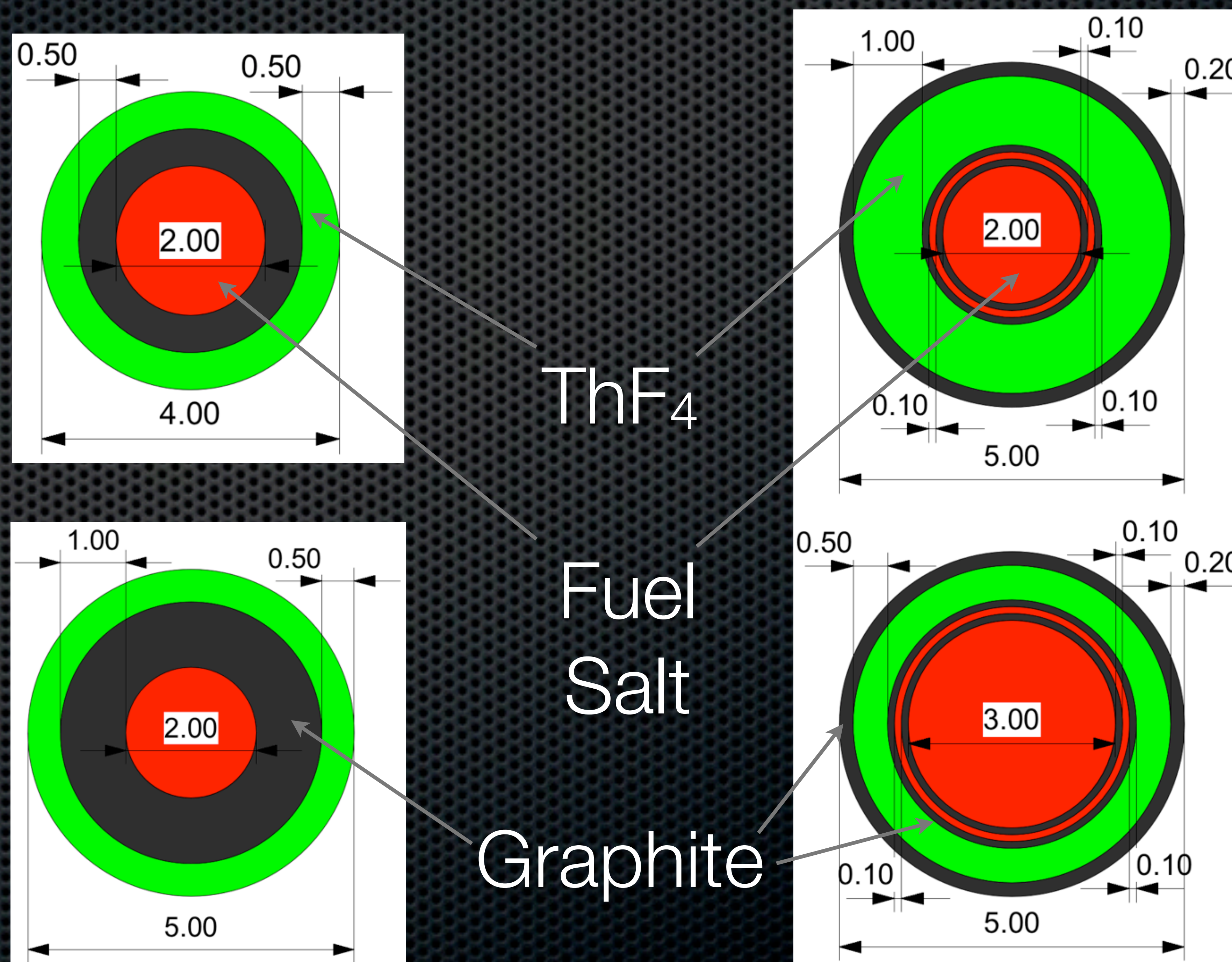
- >MP x% ThF_4 & UF_4
- ~2% PuF_3 @700° C



MCNP Tested 35 salts - basic (spherical) Geometries

Initial Geometry Tests:





Learned Some Basic Facts

- ThF_4 is a better blanket (less mass) than Thorium Metal
- Th metal is the best Fast Reflector
- Graphite Blankets / Reflectors leak a lot of neutrons
- Graphite Blankets cause power spike along core wall
  - Increases fission neutron Wall flux, and thus damage
  - Reduces graphite Wall lifetime - “The Wall Problem”!

Fuel Salt Matrix, No. 1

Salt:	FLiBe 67LiF - 33BeF_2	UTRUNaF 72NaF - 28AcF_x	UTRULiF 73LiF - 27AcF_x
Best MSR Service	Thermal Graphite & Homogenous (no C)	Fast-MSR	Fast & Thermal
Pros	Well Studied Good Moderator Salt Best "Slow" (thermal) Salt Best Heat Transfer	Cheap Highest PuF_3 solubility Best Fast Salt Good Heat Transfer?	490° C MP Broad Applicability Good Heat Transfer?
Cons	Cost - Isotopic Li7 Tritium production Low PuF_3 & AcF_x solubility BeF_2 "Toxicity"	625° C MP Na activation Thermal spectrum? No Bi ThF_4 processing?	Cost - Isotopic Li7 Tritium production

Fuel Salt Matrix, No. 2

Salt:	UTRULiNaF 36NaF-36LiF-28AcF_x 24NaF-44LiF-32AcF_x	47NaF- 26KF-28AcF_x	NaBe 53NaF - 47BeF_2
Best MSR Service	Fast & Thermal?	Fast-MSR	Thermal & Fast?
Pros	Cheaper than “pure” LiF Flexible AcFx amounts Good Heat Transfer? 480° C & 445° C MPs	Cheap Flexible AcFx amount 530° C MP	Cheap 340° C MP Good moderation
Cons	Cost - Isotopic Li7 Tritium production Na activation No Bi ThF_4 processing?	Na activation K-40 production High K neutron capture No Bi ThF_4 processing?	Little known salt Na activation BeF_2 “toxicity” No Bi ThF_4 processing?

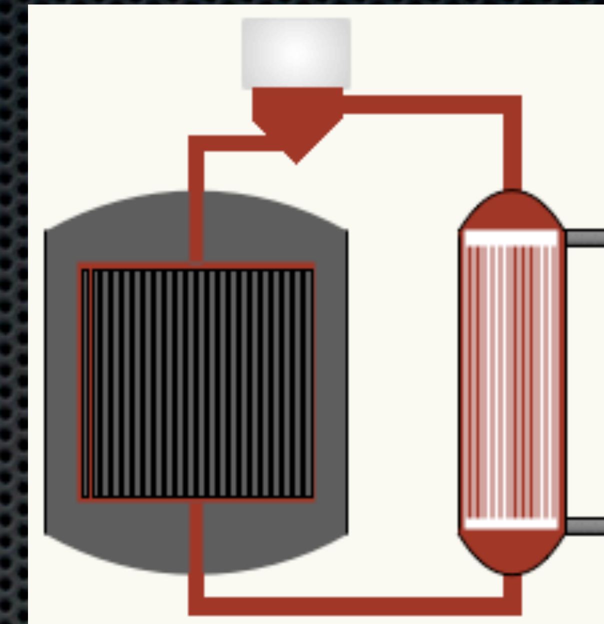
Fuel Salt Matrix, NO No. 2!

Salt:	UTRULiNaF 36NaF-36LiF-28AcF_x 24NaF-44LiF-32AcF_x	~~47NaF - 26KF-28AcF_x~~	NaBe 53NaF - 47BeF_2
Best MSR Service	Fast & Thermal?	Fast-MSR	Thermal & Fast?
Pros	Cheaper than "pure" LiF Flexible AcFx amounts Good Heat Transfer? 480° C & 445° C MPs	Cheap Flexible AcFx amount 530° C MP	Cheap 340° C MP Good moderation
Cons	Cost - Isotopic Li7 Tritium production Na activation No Bi ThF_4 processing?	Na activation **K-40 production** **High K neutron capture** No Bi ThF_4 processing?	Little known salt Na activation BeF_2 "toxicity" No Bi ThF_4 processing?

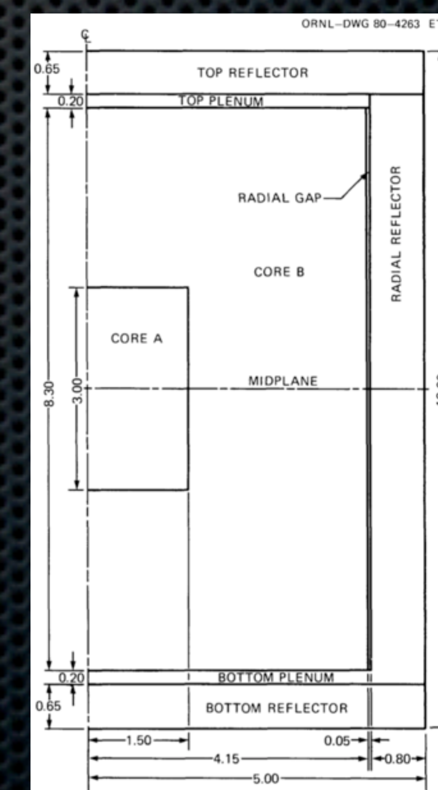
Fuel Salt Matrix, New No. 2

Salt:	UTRULiNaF 36NaF-36LiF-28AcF$_x$ 24NaF-44LiF-32AcF$_x$	32NaF- 29RbF-39AcF$_x$	NaBe 53NaF - 47BeF$_2$
Best MSR Service	Fast & Thermal?	Fast-MSR	Thermal & Fast?
Pros	Cheaper than “pure” LiF Flexible AcFx amounts Good Heat Transfer? 480° C & 445° C MPs	Cheap? Flexible AcFx amount 540° C MP	Cheap 340° C MP Good moderation
Cons	Cost - Isotopic Li7 Tritium production Na activation No Bi ThF$_4$ processing?	Na activation Poor Heat Transfer? High Rb neutron capture? No Bi ThF$_4$ processing?	Little known salt Na activation BeF$_2$ “toxicity” No Bi ThF$_4$ processing?

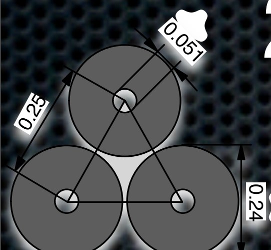
DMSR Reference Design



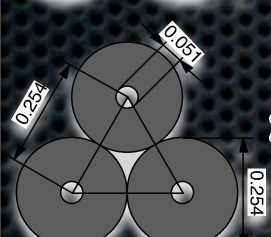
- Large (2,240 MWth) & ~10m x 10m
  - 450 m^3 core volume, 84.4 m^3 Fuel Salt



- ~300 tonnes Reactor Grade Graphite
- 2 Zones



  - Core A: 20% Salt 3m x 3m Undermoderated



  - Core B: 13% salt outer 8.3m dia x 8.3m high
  - Radial Reflector 0.8m thick - Axial 0.65m thick
  - Salt Power Density ~27 MWth / m^3

Fluorides' Potential on Various Cathodes

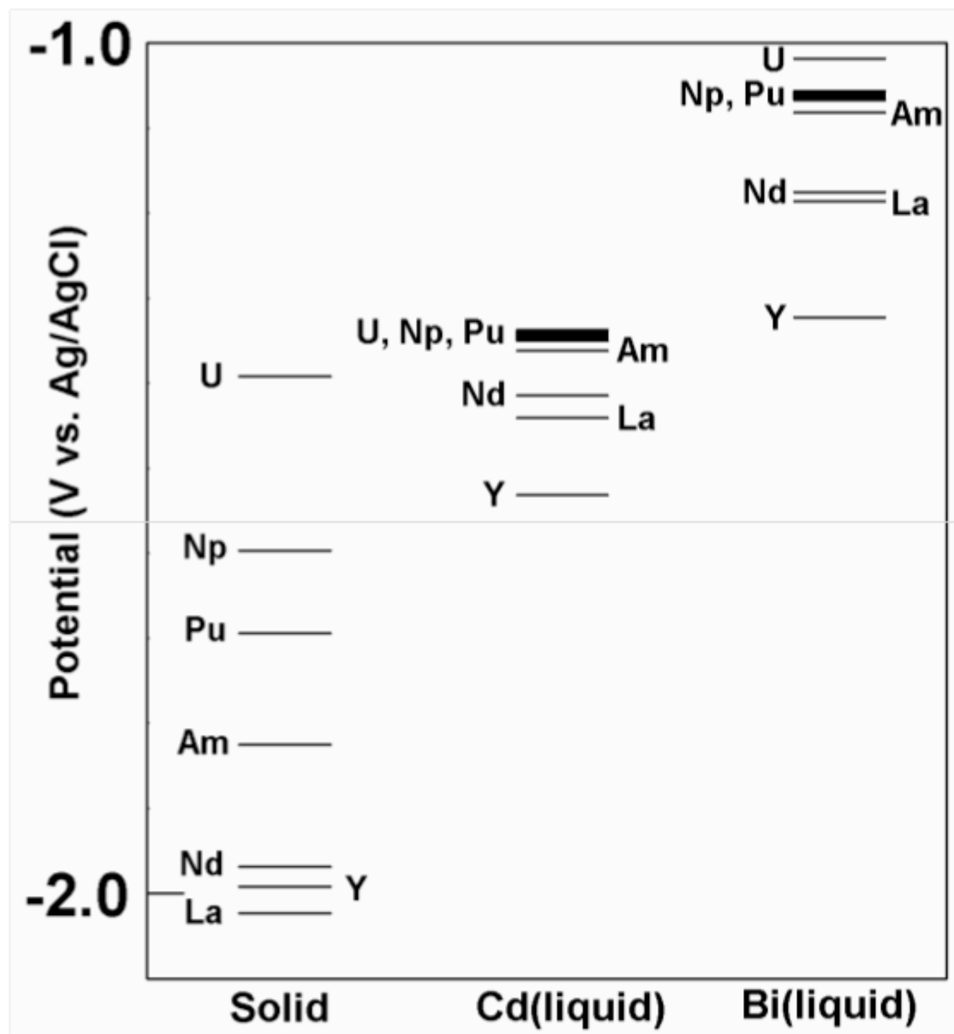
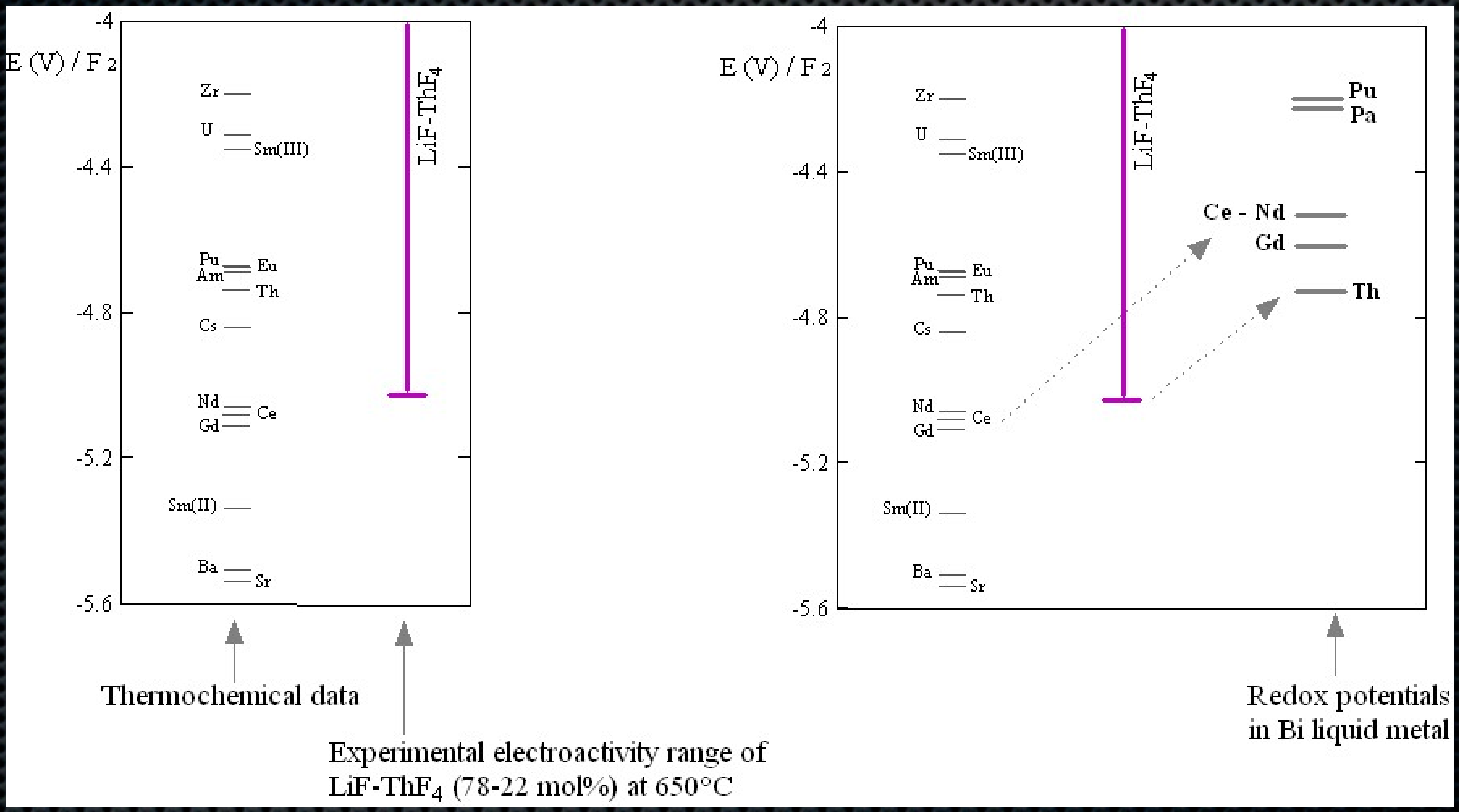


***Figure 3-9.** The effect of cathode material on deposition potentials /Ino-02/.*

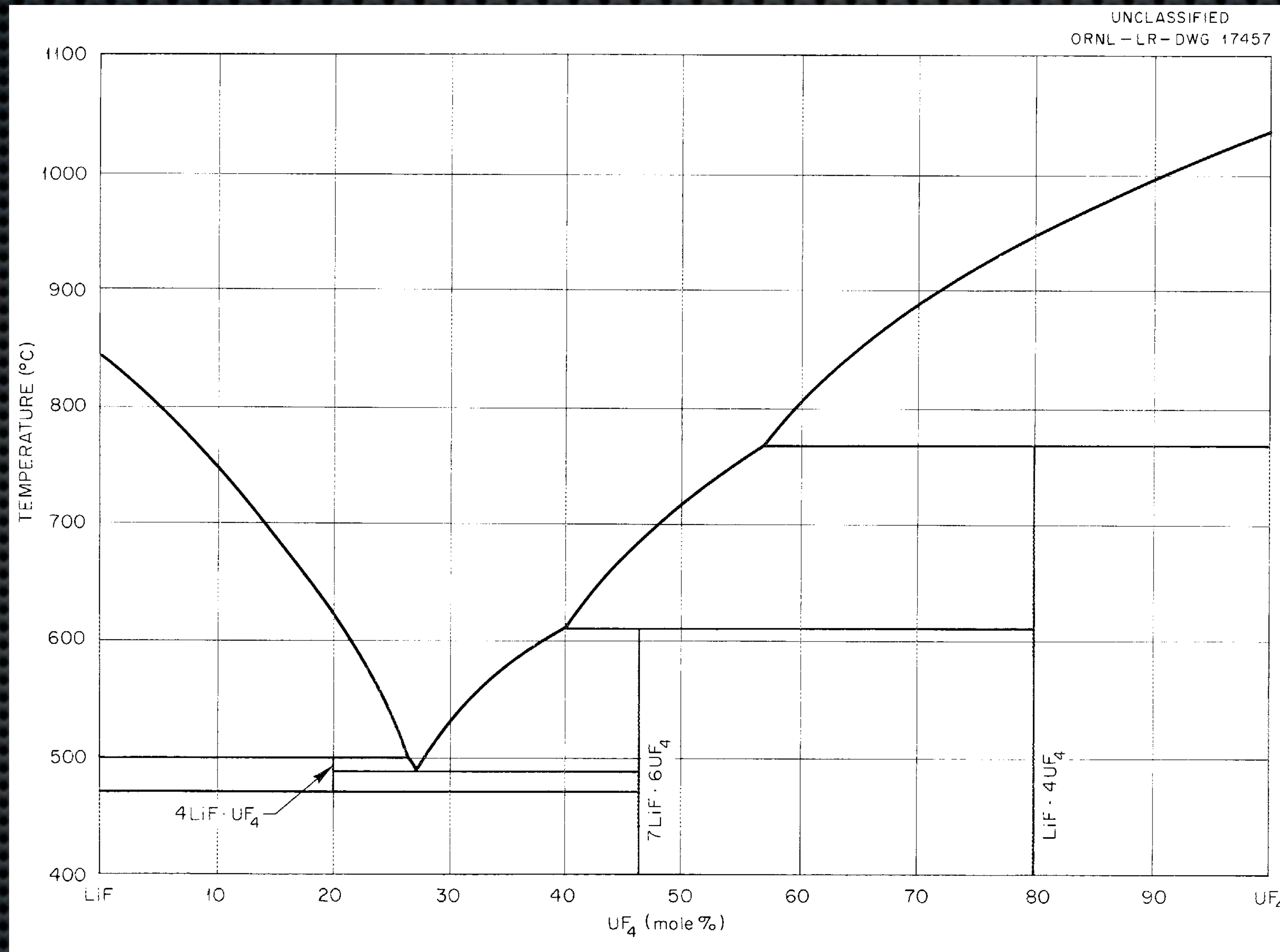
{PDF page 85, of http://www.skb.se/upload/publications/pdf/TR-04-15webb.pdf}

Fluorides' Potential on Various Cathodes



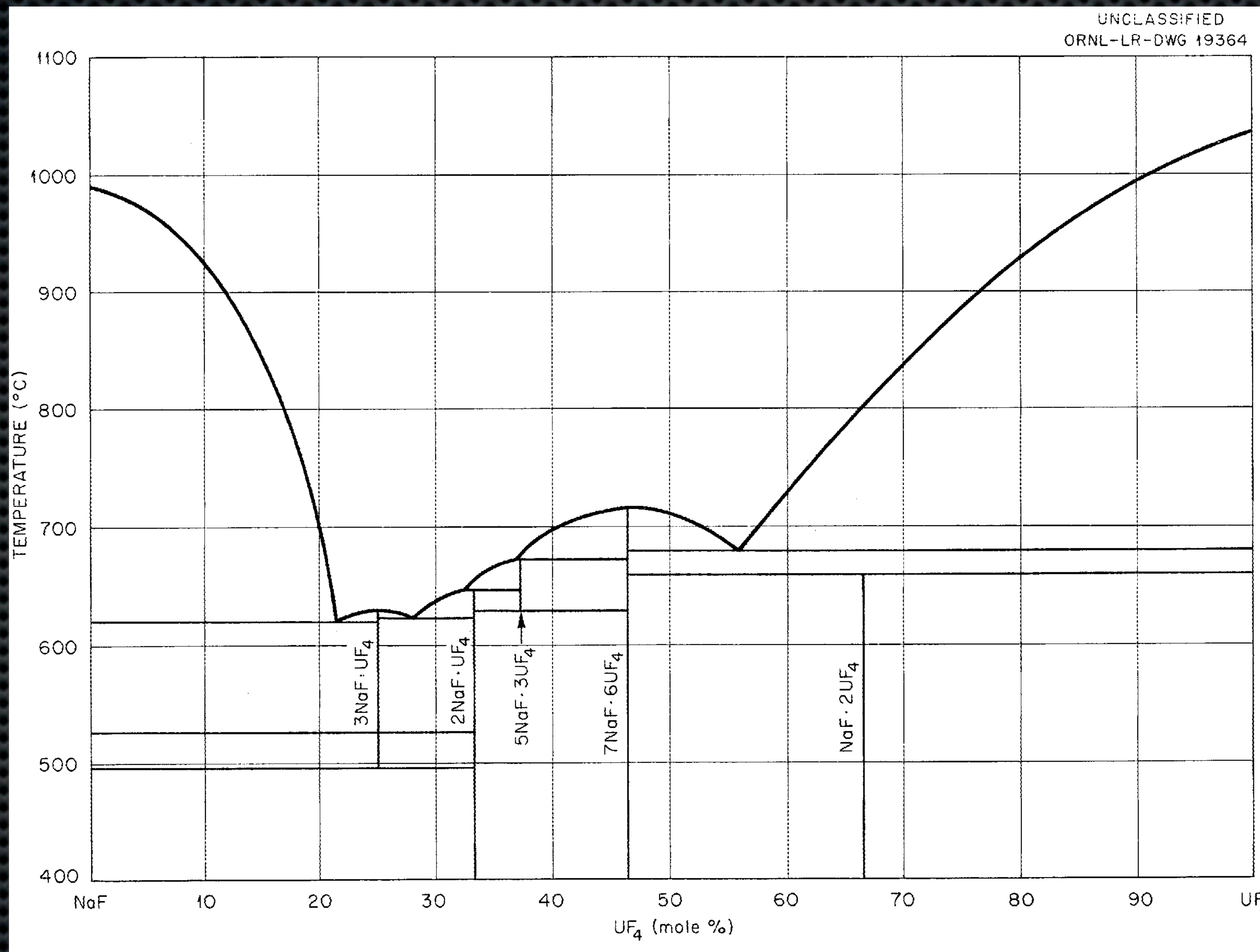
"Fig. 11 Comparison between several redox potentials on a inert electrode (left) and on a liquid bismuth electrode (right). The figures also give the electro-activity domain in LiF-ThF4 at 600°C. (the calculations are performed with the software HSC Chemistry version 4.1).", on PDF pg. 16 of 29, of "The CNRS Research Program on the Thorium cycle and the Molten Salt Reactors", Thorium Cycle – Molten Salt Reactors, June 2008.
URL: http://pacen.in2p3.fr/IMG/pdf/080607_CNRS_ThoriumMSR.pdf

LiF - UF_4 Phase Diagram



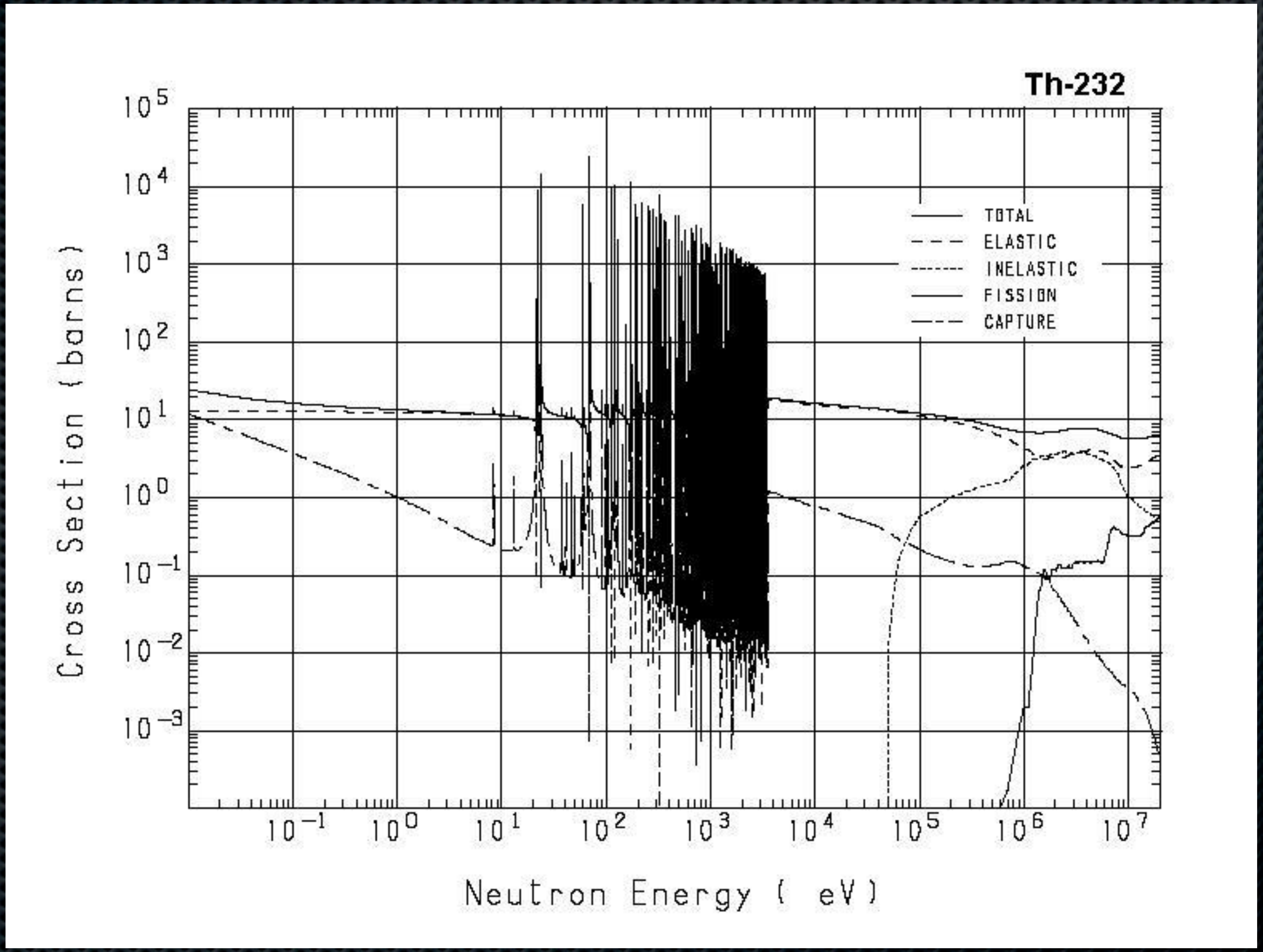
The System LiF—UF_4.

NaF - UF_4 Phase Diagram

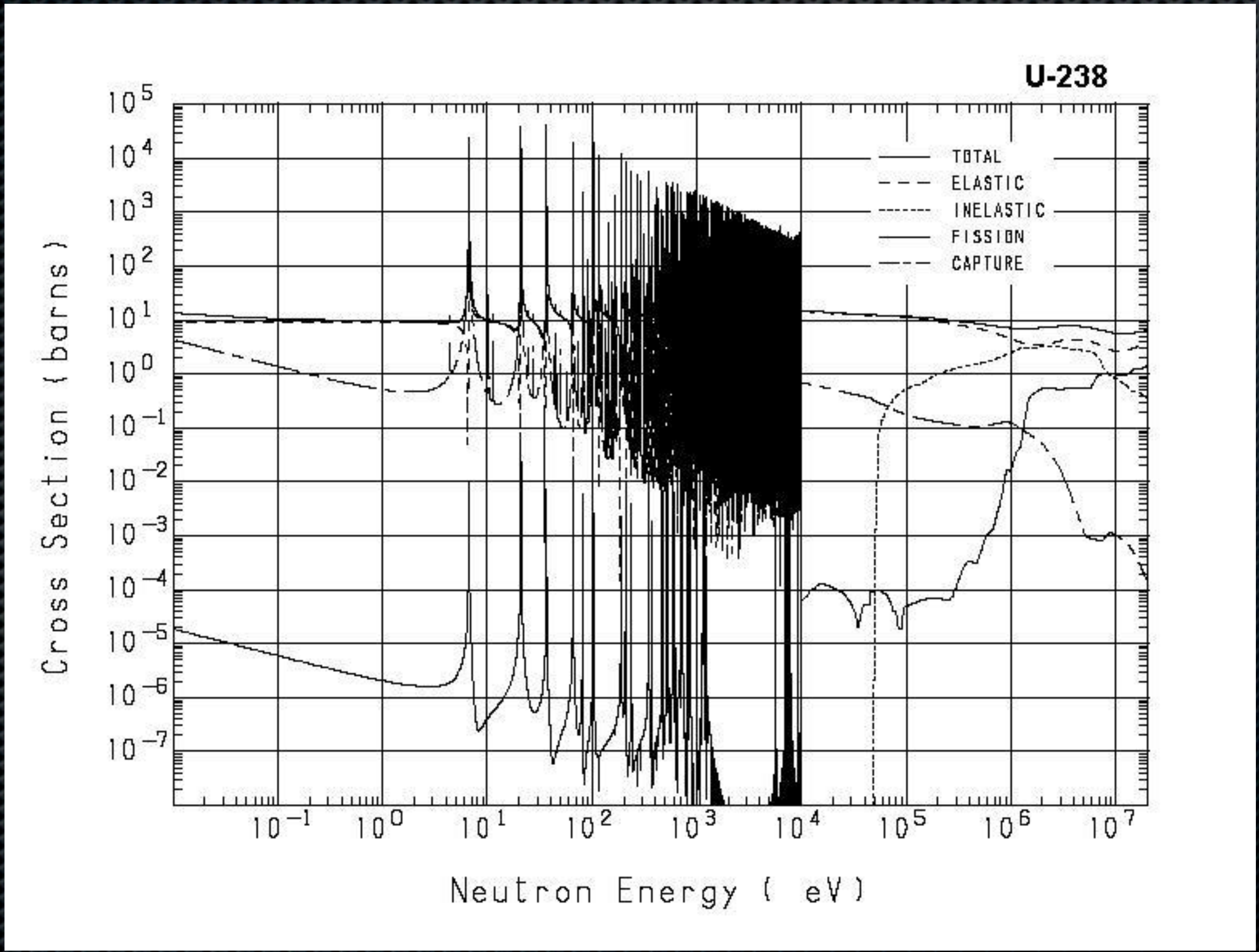


The System NaF–UF_4.

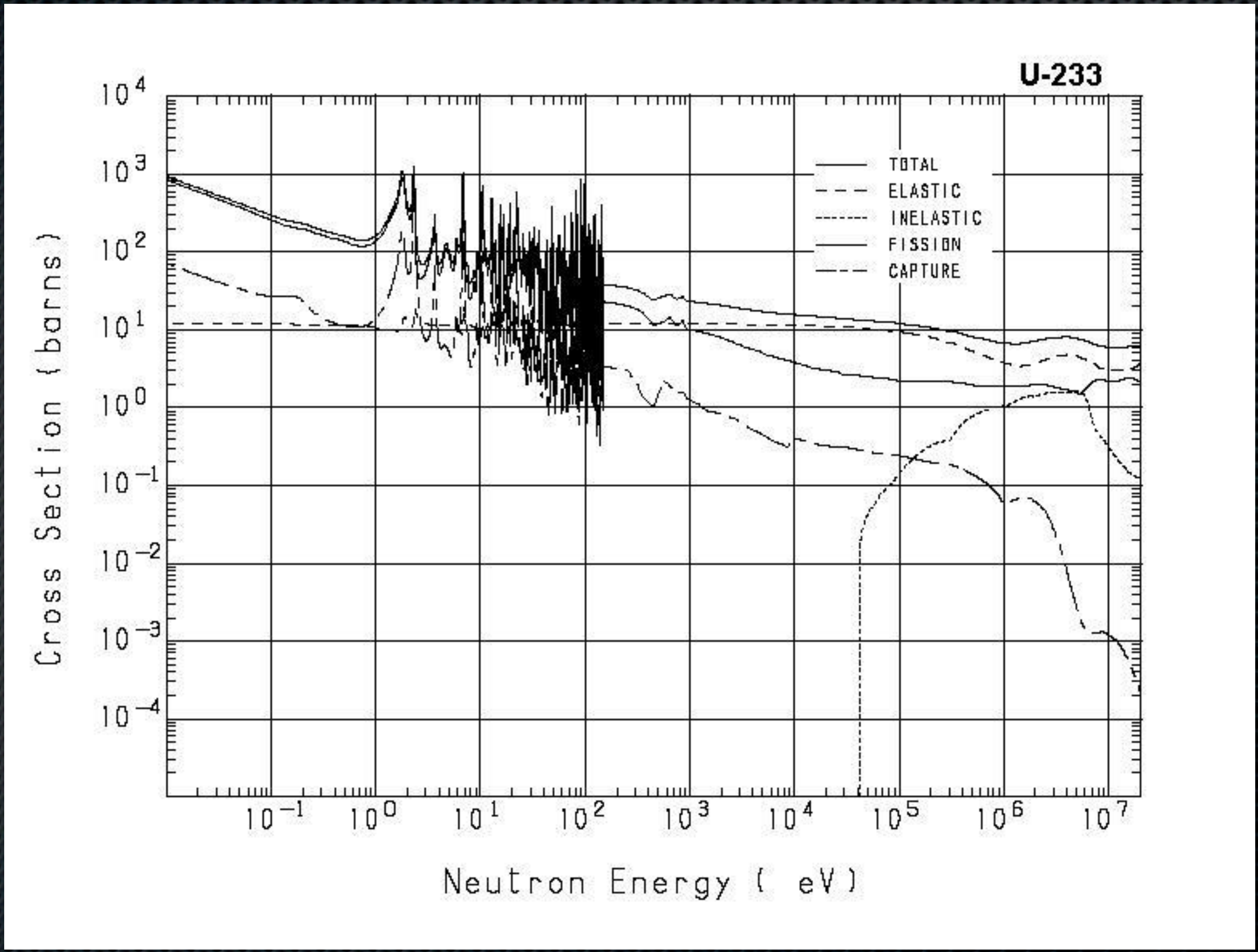
Th-232 neutronics



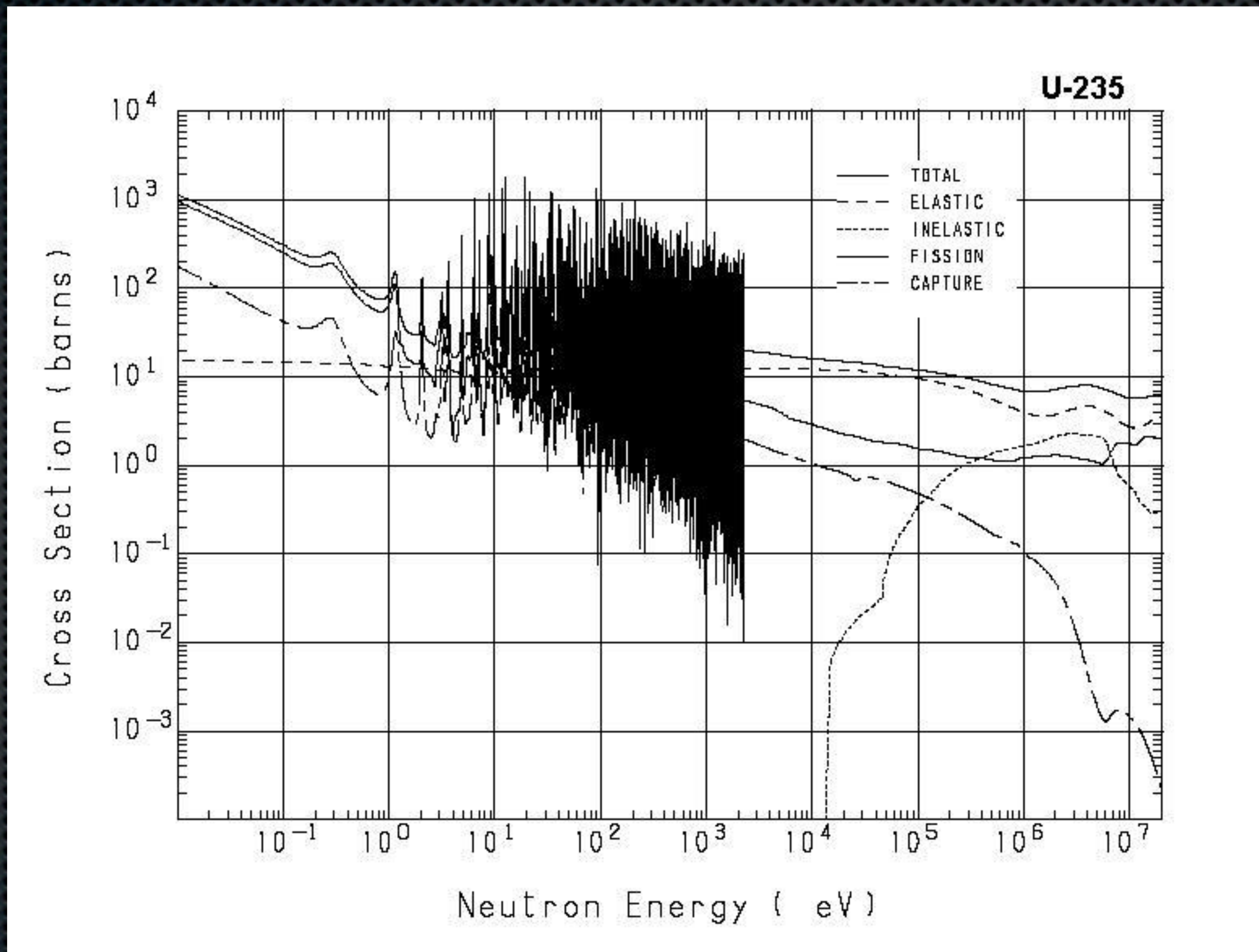
U-238 neutronics



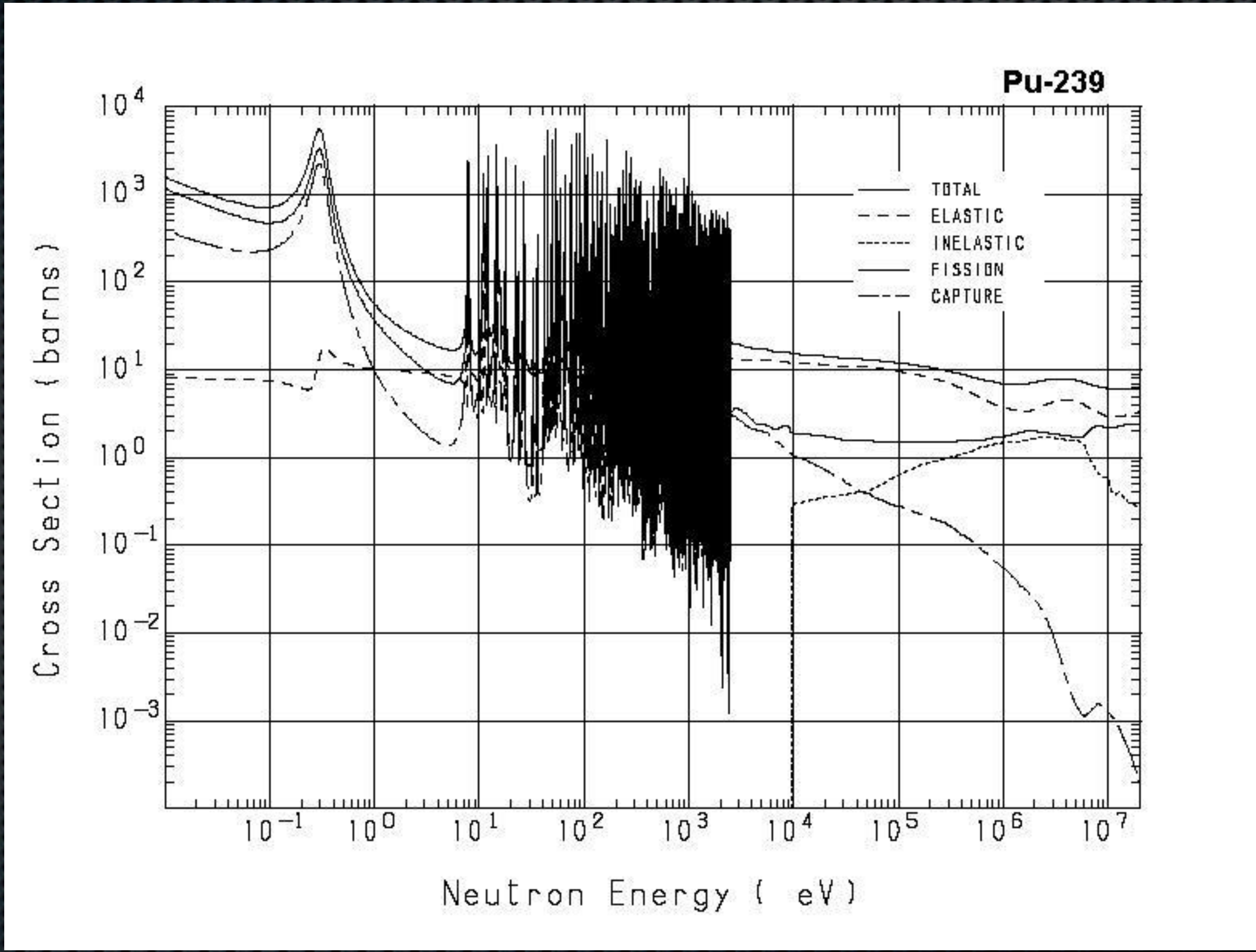
U-233 neutronics



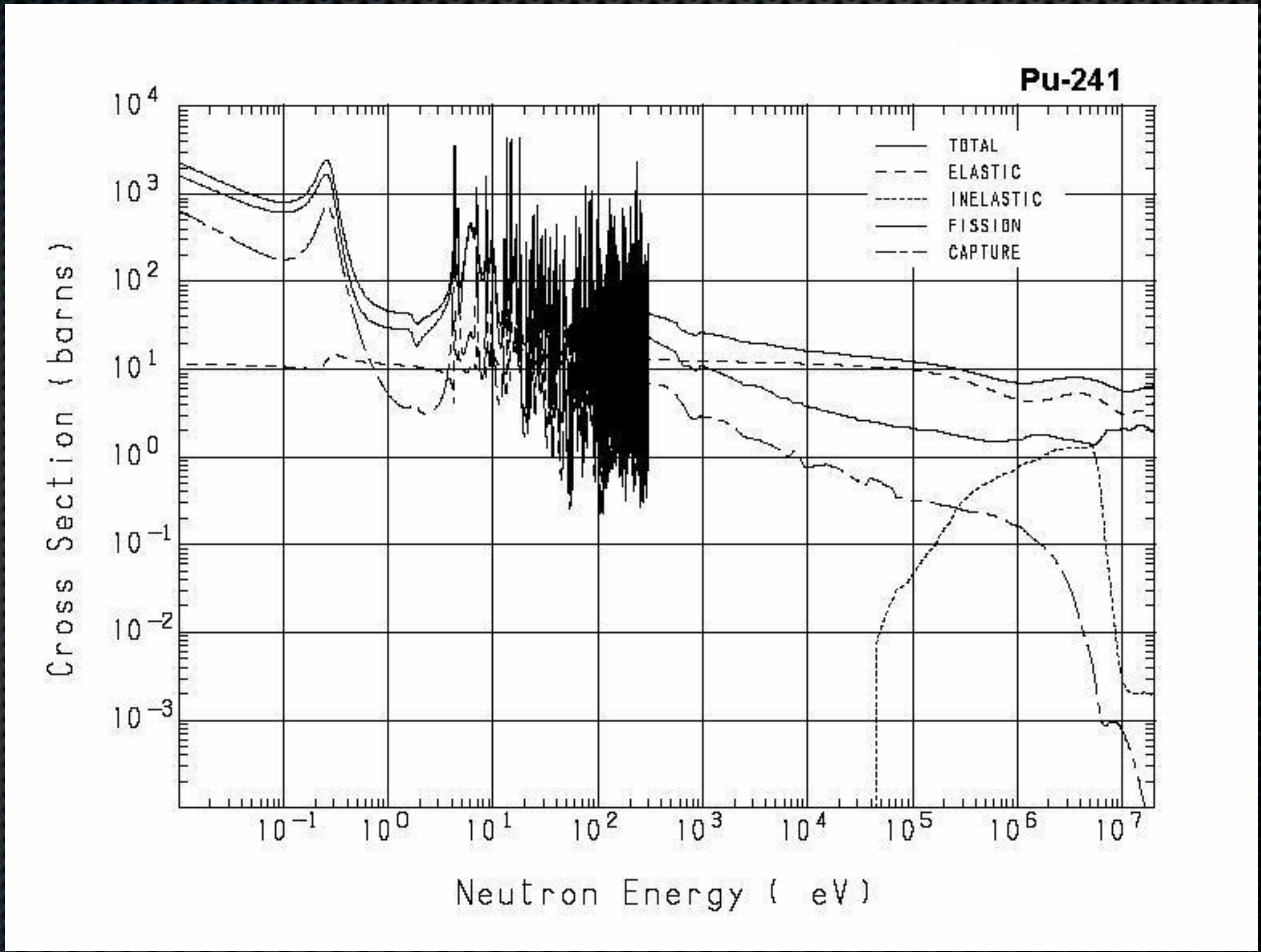
U-235 neutronics



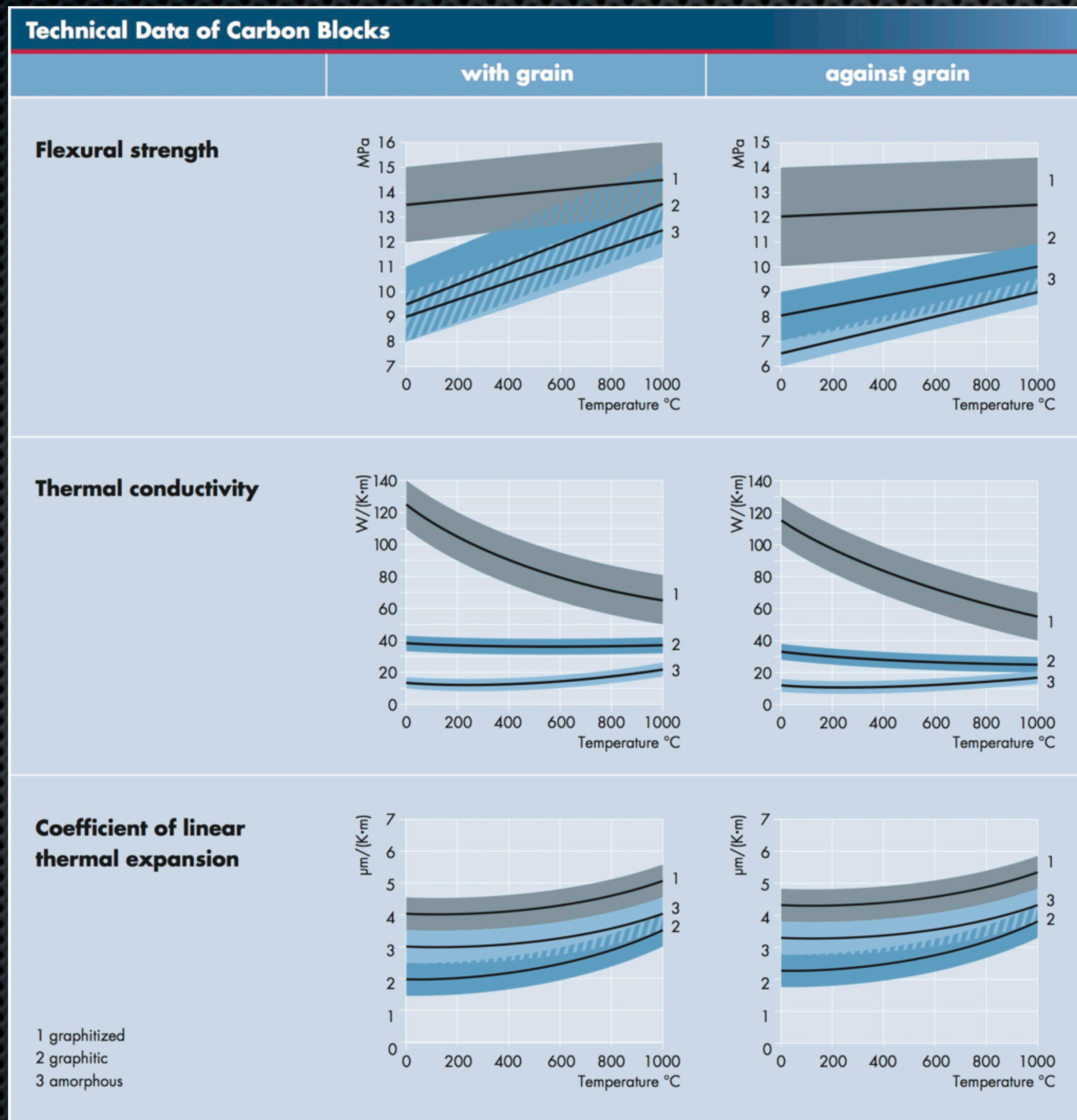
Pu-239 neutronics



Pu-241 neutronics



Graphite’s Properties



Dogfish Head Brewery: World's Largest Beer Vat made of Palo Santo Wood

Beer Vats' Volume:
10,000 gallons
37,854 liters
37.8 cubic meters

1 GWth @ 27 kW / liter