Potential of Thorium Fueled Molten Salt Reactors

May 12th 2011

Thorium Energy Alliance Conference

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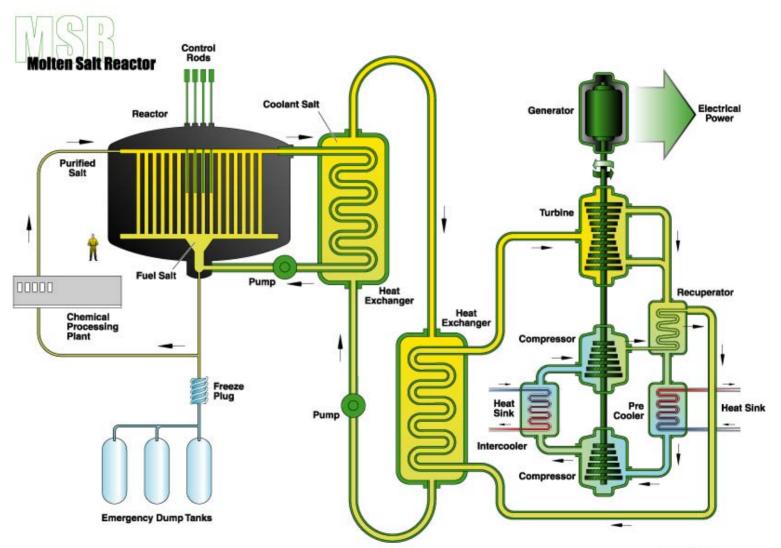
The Basics: Thorium

- Thorium can not fission on its own so use in a reactor requires a starting fissile load
- Once started, cheap and abundant thorium can keep a reactor going indefinitely if fission products are slowly processed out
- Can do this in all types of neutron spectrums, from thermal to fast
- Processing is extremely difficult for solid fueled reactors but much easier for fluid fuels i.e. Molten Salts
- Without any processing, thorium with the aid of uranium, can yield far superior converter reactors than current LWRs

The Basics: Molten Salt Reactors

- Fuel (Th, U and/or Pu) dissolved in fluoride carrier salts like 2Li⁷F-BeF₂
- This fluid fuel is also the coolant and carries heat out of the core to heat exchangers
- High temperature operation (700 °C) couples well to many systems with high efficiency (44% and higher)
- Supercritical CO2, Ultra Supercritical Steam, Helium or even open air cycles

The Single Fluid, Graphite Moderated Molten Salt Breeder Reactor (MSBR)



The Basics: Design Choices Breeder vs Converter?

Breeder

- Makes its own fuel after startup
- If "just enough" called Break Even
- Requires processing to continuously remove fission products
- No enrichment plants once established

Converter

- Needs annual fissile makeup
- Skips fuel processing
- Much less R&D needed
- Core design simplified

The Basics: Design Choices Single Fluid vs Two Fluid?

Single Fluid

- Everything in a one carrier salt
- Core design often simpler
- Processing to remove fission products the most complex (i.e. for breeders)

Two Fluid

- Blanket salt for thorium, Fuel salt for the U233 it produces
- Fission product removal much simpler
- Core design "was thought" to be complex
- Need to verify barrier materials

The Basics: Design Choices *Harder or Softer Spectrum?*

- Harder Spectrum (fast)
- Can skip graphite use
- Easier to breed
- Takes far more fissile material to startup
- Avoiding neutron "leakage" can be difficult
- Softer Spectrum
- Control is easier
- Much smaller fissile startup
- Must remove fission products faster to breed

My Main Design Efforts...

- Two Fluid, Tube within Tube
 - Solves decades old "plumbing problem"
 - High performance but R&D needed
- DMSR Single Fluid Converter
 - Basically a larger version of 1960s test reactor so little R&D needed
 - Uses Low Enriched Uranium and Thorium
- Since Oct 2010
 - I've gone "dark", sorry no hints...
 - Two major new design directions

How to Judge a Reactor Concept

- Safety
- Costs
- Resource Sustainability
- Long Lived Waste Issues

- Proliferation Resistance
- Rapid Deployment Capability
- Technological Uncertainty

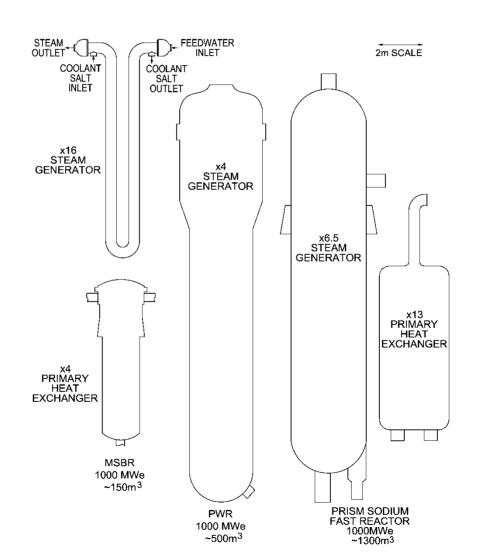
Advantages of all Molten Salt Reactors Safety

- No pressure vessels
- No chemical driving forces (steam build up or explosions, hydrogen production etc)
- Almost no volatile fission products in salt
 - They are passively and continuously removed
- No excess reactivity needed
 - Even control rods are optional
- Very stable with instantly acting negative temperature reactivity coefficients
- Freeze valve drains salt to tanks designed to remove decay heat

Advantages of all Molten Salt Reactors Low Capital Costs

- Molten salts are superior coolants so heat exchangers and pumps are smaller and easy to fabricate
- This has a trickle down effect on building design, construction schedules and ease of factory fabrication
- 44% and higher thermal efficiency on either Steam or Gas Brayton (He, CO2, N2)
- Fuel costs extremely low
- No need for elaborate "defence in depth" or massive internal structures for steam containment and vast water reserves

Comparing Heat Exchange Equipment MSBR vs PWR vs Sodium FBR



Advantages of all Molten Salt Reactors Resource Sustainability

- Once started breeder designs only require minor amounts of thorium (about 1 tonne per GWe year)
 - 30 k\$ of thorium = 500 M\$ electricity
- Converter designs are simpler and only require modest amounts of uranium
 - Typically 35 tonnes U per GWe-year versus 200 tonnes for LWRs
 - Fuel cycle cost under 0.1 cents/kwh

Uranium is not the enemy...

- Only "cheap" uranium is in limited supply
 - 500\$/kg assures virtually unlimited supply
 - Still only 0.2 cents/kwh for DMSR
- ~1.7 Mt of uranium ore in 2009 (51 kt U at world ave 3% ore grade)
- 2500 Mt of copper ore (0.6% ore ave)
- 1700 Mt of iron ore and 7000 Mt of coal!
- If uranium is used with thorium in DMSR designs, 100% of world's electricity (2500 GWe) without increasing current mining
- Even if we needed to go to very low grade ore (0.03%) still only 200 Mt ore

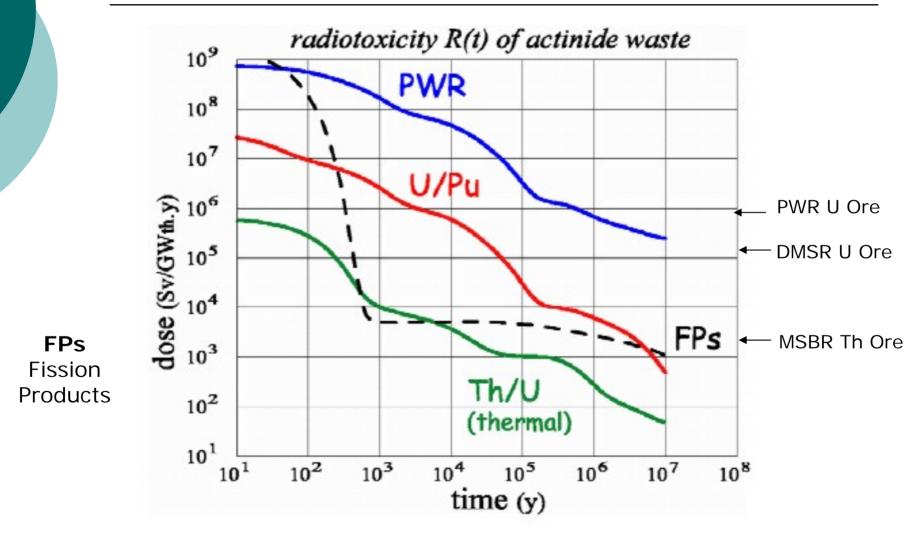
Advantages of all Molten Salt Reactors Long Lived Waste

- Fission products almost all benign after a few hundred years
- The transuranics (Np,Pu,Am,Cm) are the real issue and reason for "Yucca Moutains"
- All designs produce less TRUs and these can be recycled back into the reactor to fission off
- Converters can do just as well as Breeders

Radiotoxicity PWR vs FBR* vs MSR*

*Assuming 0.1% Loss During Processing

Data and graph from Sylvain David, Institut de Physique Nucléaire d'Orsay



Turns waste management into 500 year job, not million year

Areas with significant difference between MSR/LFTR designs

Proliferation Resistance

Rapid Deployment Capability

Technological Uncertainty

Proliferation Resistance

- Proliferation is far more a "political" issue than technological one
- That said, still important to maximize proliferation resistance of designs
- Media often portrays thorium as somehow eliminating proliferation concerns. This is NOT true

Proliferation Resistance The *Pure* Thorium – ²³³U Cycle

- o ²³²U present in significant quantities
 - 69 year half-life with strong 2.6 MeV gamma ray from daughter product ²⁰⁸Tl
 - Makes illicit use difficult and highly detectable
 - No national program ever based on ²³³U
- o ²³³U can be *instantly denatured* by dumping ²³⁸UF₄ into the molten fuel salt
- 233Pa removal can lead to "clean" 233U and thus should be avoided
- Only small amounts Plutonium are present,
 it is of poor quality and very hard to extract

Proliferation Resistance Denatured Cycles

- The pure Th-²³³U cycle does though represent the use of Highly Enriched Uranium (a "non starter" for some)
- Running denatured by including enough
 238U makes uranium useless for weapons
- It does mean more plutonium present but still of poor quality and is much harder to remove from the salt
 - About 3 times the spontaneous fission rate of LWR Pu and 5 times the heat rate (72.5 W/kg)
- DMSR Converter likely the highest proliferation resistance of any nuclear reactor

Rapid Deployment Capability

- What fissile to start and how much?
- No U233 available, Spent Fuel Pu limited
- Fast Spectrum Single or 1 ½ Fluid require much more (up to 8 tonnes/GWe)
- Two Fluid Breeder, any Denatured design can start with Low Enriched Uranium
- Is small power feasible? 100 MWe?
- Two Fluid designs with full blankets, YES
- Single Fluid graphite Converter, YES
- Single Fluid graphite Breeder, VERY HARD
- Single Fluid Fast Breeder, VERY HARD

Technological Uncertainty

- Biggest differentiator between designs
- Fission product removal needs much R&D to commercialize
 - Two Fluid simpler but still a challenge
- Only Single Fluid graphite designs do not require new materials to be verified in a strong neutron fluance
- Going beyond 700 C adds uncertainty
- If graphite used, either large cores or must prove replacement techniques

Summary

- All MSR designs excel in Safety, Costs, Resource Usage and Long lived wastes
- Tube in Tube Two Fluid may offer best overall capital costs and rapid deployment
- DMSR offers very low technological uncertainty and the ultimate in proliferation resistance

Conclusions

- Molten Salt designs have inherent features that favour overall safety, waste reduction, low cost and rapid deployment
- They also have great flexibility to match varying priorities
 - Can attain the absolute highest levels of proliferation resistance
 - Can run on minute amounts of thorium, or modest amounts of uranium for the utmost in simplicity

The Future?

 Many exciting recent developments on many fronts

But, sorry...

Not quite ready for public disclosure

Backup Slides

| Reactor | Lifetime Uranium Ore (t) | Annual Uranium Ore (t) | Annual Ore Costs 50\$/kg U | Annual Fuel Costs 50\$/kg U | Annual Fuel Costs 5000\$/kg U |
|---------------------------|--|------------------------------|---|--|--|
| LWR | 6400 | 200 | 8.5 million | ~40 | ~880 |
| LWR with U- Pu Recycle | 4080 | 125 | 5.3 | | |
| Sodium Fast Breeder | 2400 If start up on ²³⁵ U | 1 | | | |
| DMSR Converter | 1800 | 35 | 1.5 | ~6 0.001\$/kwh | ~155 <0.02\$/kwh |
| DMSR single U recycle | 1000 | 35 | 1.5 | ~6 | ~155 |

Based on 0.2% tails, 75% capacity factor, 30 year lifetime

LWR data from "A Guidebook to Nuclear Reactors" A. Nero 1979

3.9 million\$ annual enrichment costs for DMSR at 110\$/SWU

At \$5000/kg, uranium from sea water likely feasible and unlimited resource

1950s and 1960s Design Priorities

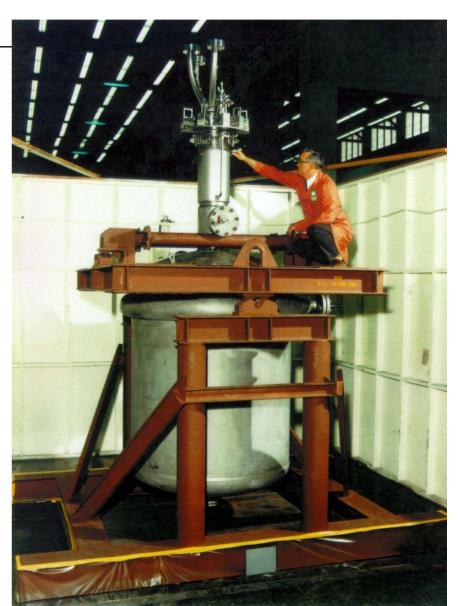
- Safety No problem...
 - If we engineer it right, do proper maintenance and extensively train our staff "There is NO safety issue"
- Power Costs Important
- Resources Extremely Important
 - We will run out of uranium by the 1980s
 - LWRs OK for now but we will need breeder reactors
- Rapid Deployment Important
 - Power needs expected to continue to rise exponentially so breeder reactors must have very short doubling times

1950s and 1960s Design Priorities

- Proliferation Resistance
 - What?
- Long Term Radiotoxicity
 - What?
- R&D Requirements
 - Every concept needs plenty but funding is plentiful

Molten Salt Reactor Experiment 8 MWth





A Strange Beginning An Aircraft Reactor?

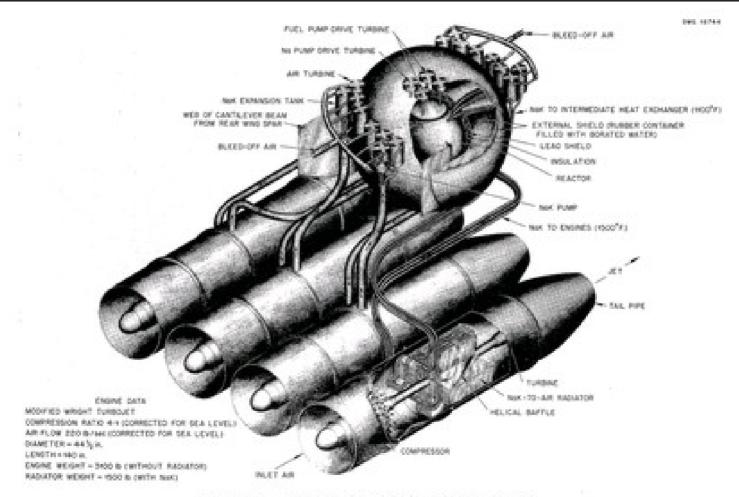
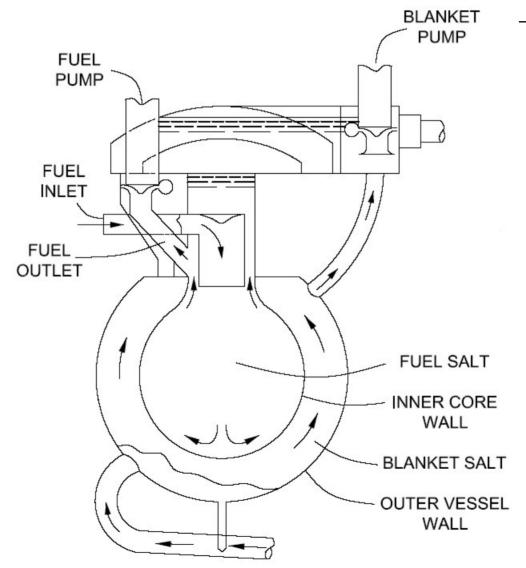


Fig. 4.33. Aircraft Power Plant (200 Megawatt).

The Aircraft Reactor Experiment

- Test reactor of early to mid 1950s
- Very high temperature 860 °C
- Canned BeO moderator
- NaF-ZrF₄ carrier salt
- Points the way to possible power reactors (even if the idea of an airborne reactor far fetched)

Homogenous Molten Salt Reactor Late 50s ORNL



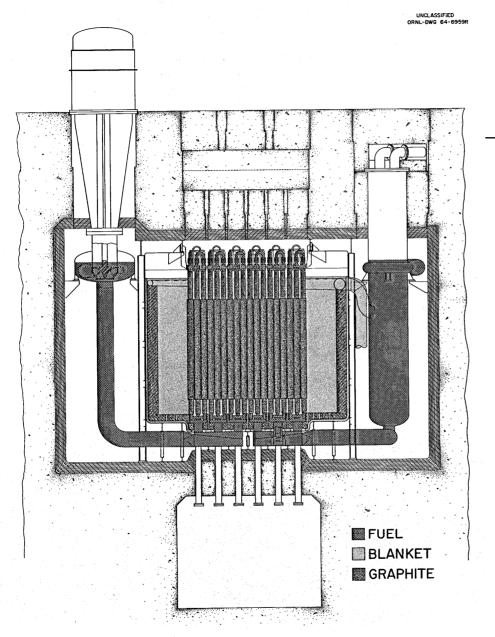
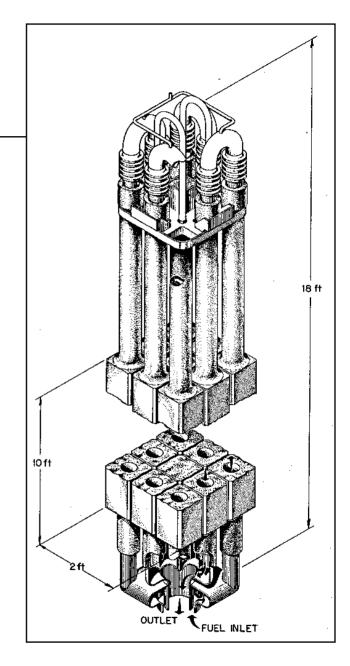


Fig. 2. Two-Region Molten-Salt Breeder.



Quality of Produced Plutonium

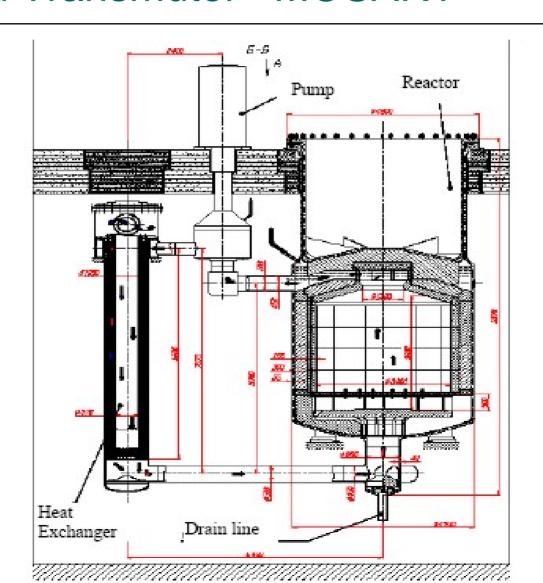
| Isotope | Proliferation | PWR | DMSR | MSBR Pure Th – ²³³ U cycle |
|-------------------|------------------------------------|---------|-------------------------|---|
| | properties | Reactor | 30 Year Once Through | |
| | | Grade | | |
| ²³⁸ Pu | Generates heat from alpha emission | 1.3% | 12.6% | 73% |
| ²³⁹ Pu | Main fissile | 60.3% | 31.1% | 9.5% |
| | Component | | | |
| ²⁴⁰ Pu | Spontaneous fissions high | 24.3% | 18.1% | 4.4% |
| ²⁴¹ Pu | Fissile and adds hard gamma rays | 5.6% | 13.6% | 4.8% |
| ²⁴² Pu | fertile | 5.2% | 24.3% | 7.4% |

Meanwhile, also in the mid 60s... Molten Salt Reactor Experiment MSRE

MSRE 8 MW(th) Reactor

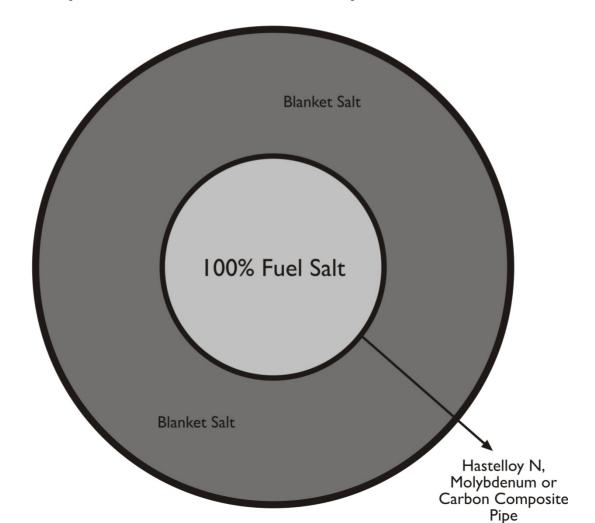
- Chosen to be Single Fluid for simplicity
- Graphite moderated, 650 °C operation
- Designed from 1960 to 1964
- Start up in 1965
- Ran very successfully for 5 years
- Operated separately on all 3 fissile fuels, ²³³U, ²³⁵U and Pu
- Some issues with Hastelloy N found and mostly resolved in later years

Russian MOlten Salt Actinide Recycler and Transmuter MOSART



Cross Section Graphite Free

Graphite Free Molten Salt Cylindrical Reactor

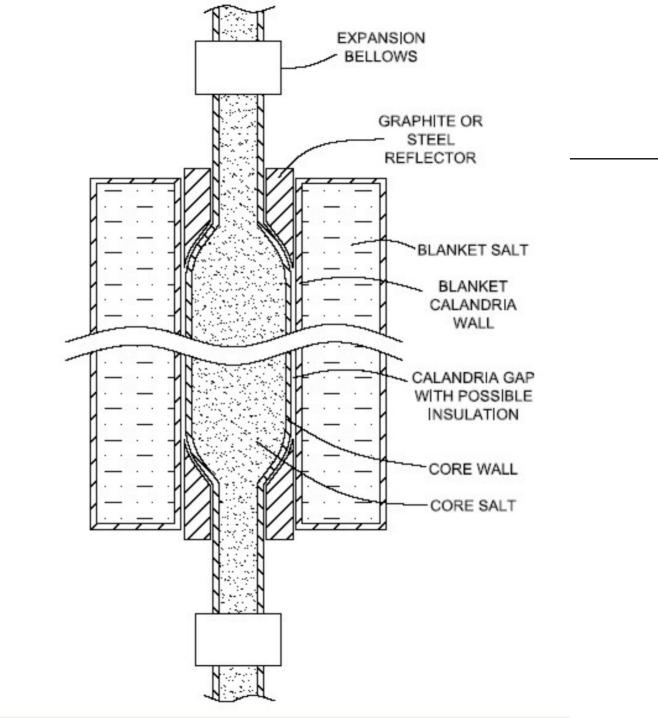


Example: Graphite Free, Carbon or SiC composite for barrier

- Using ORNL modeling for a 122 cm "spherical" core, 0.16% ²³³UF₄ should be able to reach Break Even Breeding
- A 122 cm sphere equates to 94 cm diameter in elongated cylindrical geometry
- Assuming;
 - Core power density of 200 kW/L
 - 2 m/s salt velocity in core
 - Standard 565 C/705 C for Inlet/Outlet Temp
- o Gives 404 MWe (911 MWth), 6.6 m core

Other Variations

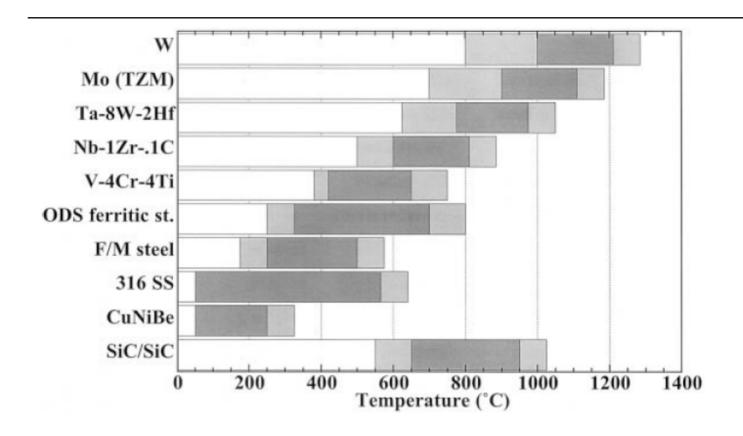
- Modestly higher concentration of ²³³UF₄ (0.2% to 1%) gives excess neutrons to allow:
 - Metal barriers such as Hastelloy N, Stainless Steels, Molybdenum
 - Alternate carrier salts to reduce costs and tritium production
 - Even greater simplification of fission product processing. 20 year or longer removal time for fission products



Critical Issue: Core-Blanket Barrier

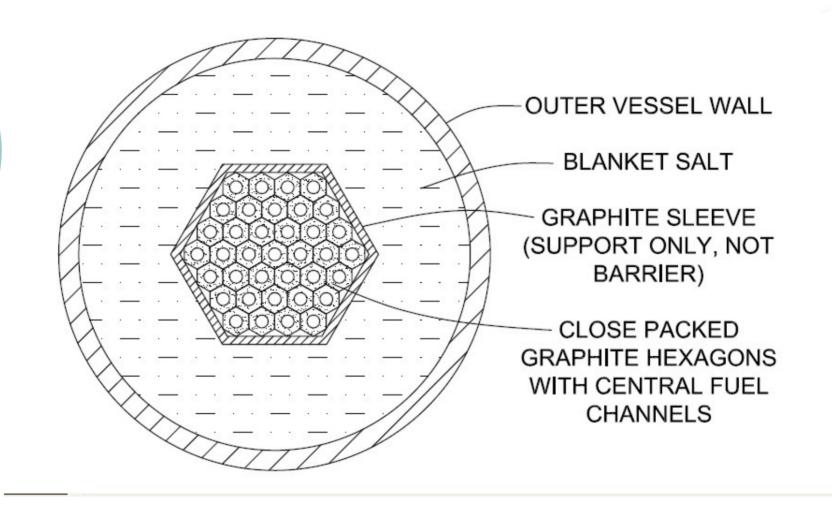
- Viability of barrier materials in high neutron flux
 - Much recent work in the fusion field using same 2⁷LiF-BeF₂ salt as coolant
 - Molybdenum, SiC/SiC or simple carbon composites leading candidates
 - Hastelloy N and Stainless Steels possible with a modest temp reduction
 - Ease of "retubing" means even a limited lifetime still may be attractive

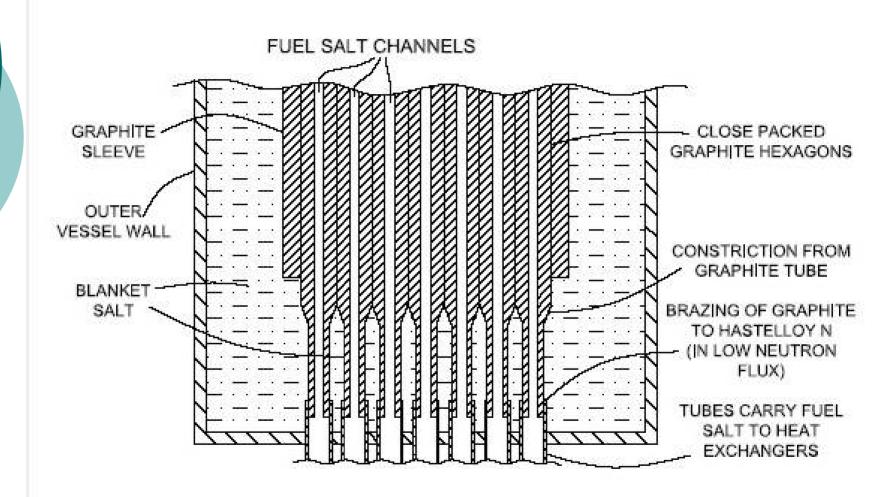
Fusion Structural Materials Studied



Operating temperature windows (based on radiation damage and thermal creep considerations)

"Operating Temperature Windows for Fusion Reactor structural Materials" Zinkle and Ghoniem, 2000





What Way Forward?

- Corporate interest will always be difficult to attract
 - No lucrative fuel fabrication contracts
 - Min 15 year return on investment a tough sell to shareholders (no matter how big the return may be)
 - Existing nuclear players have their choices in place

What Way Forward?

- Other Corporate Players?
 - Big Oil
 - For a small fraction of current profits, can retain their position in the energy market after "Peak Oil"
 - Chemical Giants
 - A majority of the needed R&D and engineering work would fit their skill set
- o Individuals with Deep Pockets?
 - What better way for those such as Gates,
 Branson, Allen, Buffet to invest in the future

What Way Forward?

- International Cooperation is key way to spread the costs and rewards
- ITER model as rough guide but with greater corporate involvement
- Likely no one design will be best for all nations or utilities so best to move forward on several versions
 - 95% of R&D needed would serve entire community
 - Nothing like competition to yield the best results

What is Needed Short Term

- Neutronic modeling
- Fuel Salt chemistry and corrosion studies of various carrier salts and materials for heat exchangers or potential 2 Fluid barriers
- Non-nuclear component testing of pumps, valves, heat exchangers etc.
- Minor levels of funding to support these efforts (the hardest part of all!)

Two Region Homogeneous Reactor

Projected breeding ratios assume thicker blanket and alternate barrier. From ORNL 2751, 1958

| Core Diameter | 3 feet | 4 feet | 4 feet | 8 feet |
|--------------------------------------|--------|--------|--------|--------|
| ThF ₄ in fuel salt mole % | 0 | 0 | 0.25 | 7 |
| ²³³ U in fuel salt mole % | 0.592% | 0.158% | 0.233% | 0.603% |
| Salt Losses | 0.087 | 0.129 | 0.106 | 0.087 |
| Core Vessel | 0.090 | 0.140 | 0.109 | 0.025 |
| Leakage | 0.048 | 0.031 | 0.031 | 0.009 |
| Neutron Yield | 2.193 | 2.185 | 2.175 | 2.20 |
| Breeding ratio (Clean Core) | 0.972 | 0.856 | 0.929 | 1.078 |
| Projected B.R. (thinner wall) | 1.055 | 0.977 | 1.004 | 1.091 |
| Projected B.R. (carbon wall) | 1.105 | 1.054 | 1.066 | 1.112 |