The Tube in Tube Two Fluid Approach

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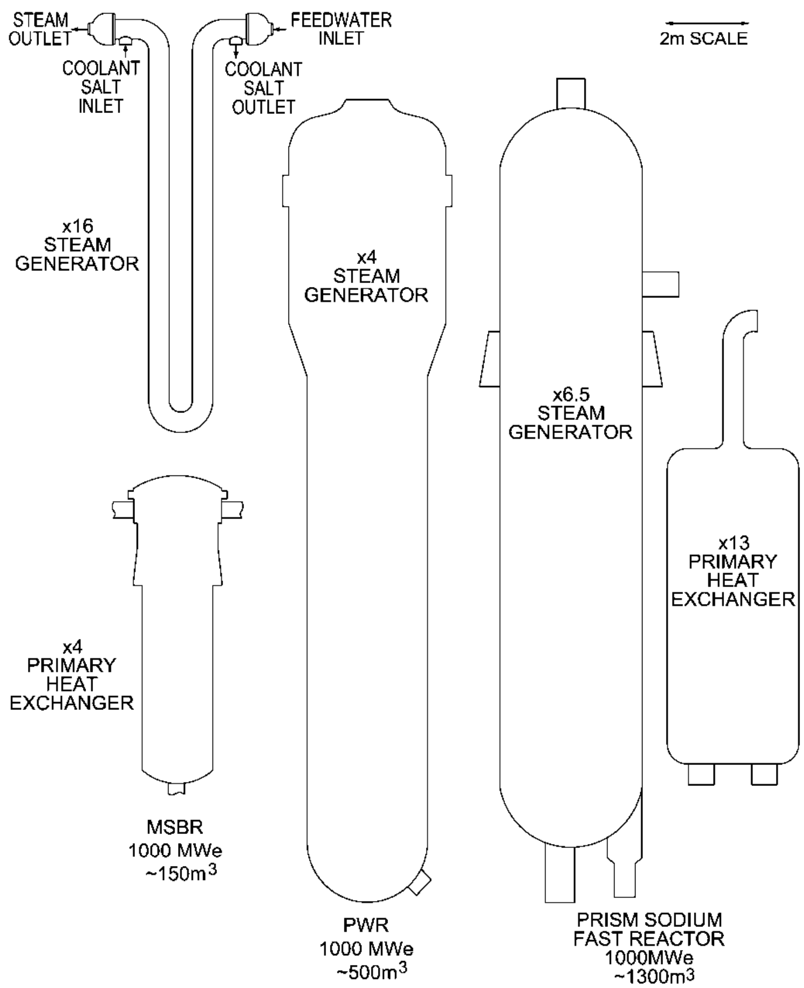
Advantages of all Liquid Fluoride Reactors

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

Advantages of all Liquid Fluoride Reactors

- Potential for low capital cost
  - Molten salts are excellent coolants so heat exchangers and pumps smaller and easy to fabricate
  - This has a trickle down effect on building design, construction schedules and ease of factory fabrication
  - High thermal efficiency on either Steam or Gas Brayton (He, CO_2, N_2)
  - 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 Liquid Fluoride Reactors

- Resource Sustainability
  - Once started many designs only require minor amounts of thorium (about 1 tonne per GWe year)
  - At the most, some designs may require modest amounts of uranium (20 to 35 tonnes per GWe year versus 200 tonnes for LWRs)

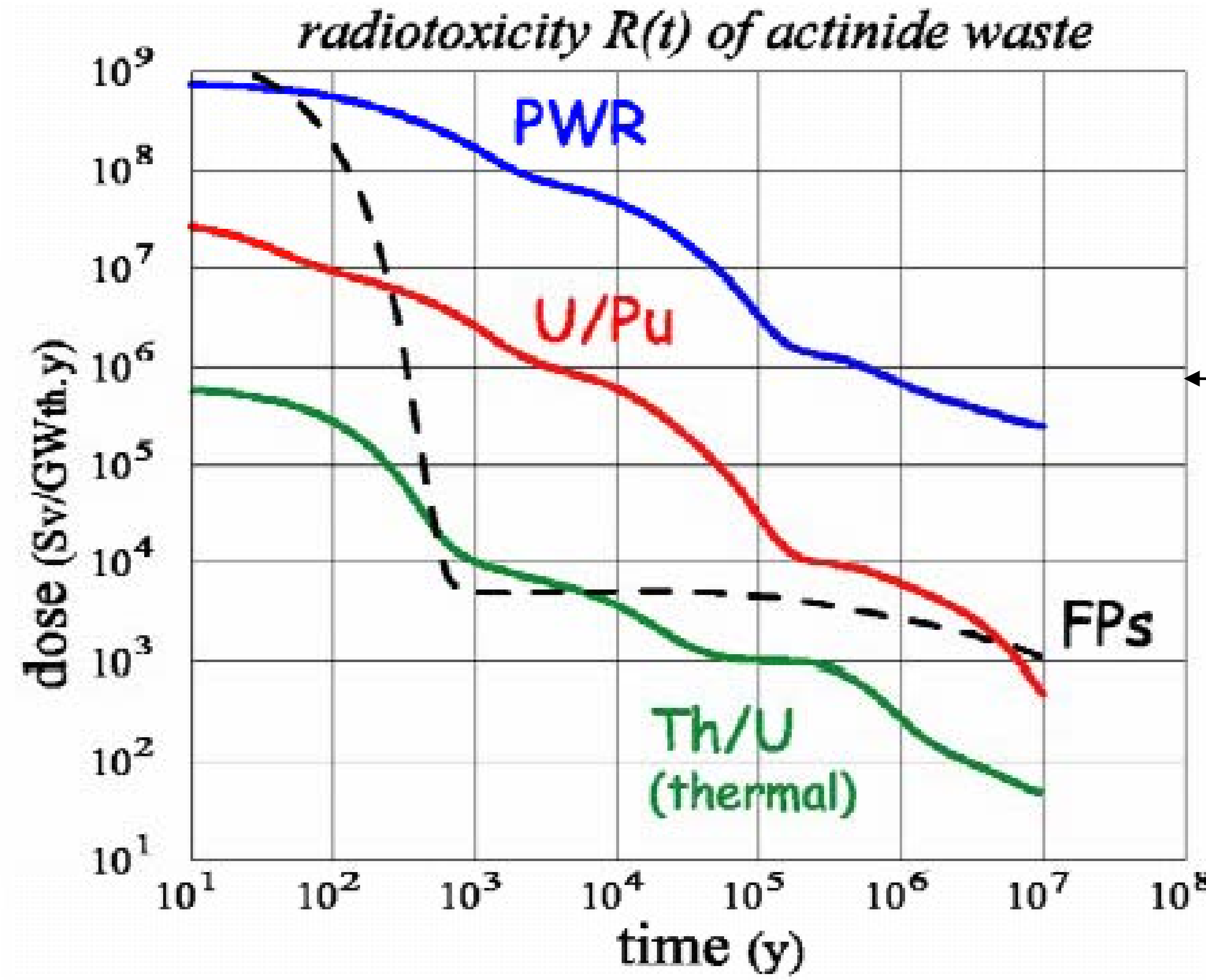
Advantages of all Liquid Fluoride Reactors

- Very Low Long Lived Radiotoxicity
  - Fission products almost all benign after a few hundred years
  - It is the transuranics (Np,Pu,Am,Cm) that are the real issue and reason for “Yucca Moutains”
  - All designs produce much less TRUs and these can be recycled back into the reactor to fission off

Radiotoxicity PWR vs FBR* vs LFR*

*Assuming 0.1% Loss During Processing

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



PWR Ore Levels

FPs
Fission Products

Turns waste management into 500 year job, not million year

What factors differentiate between various Liquid Fluoride designs?

- R&D required and level of technological uncertainty
- Start up requirements of fissile material and thus deployability
- Whether fission product removal is required and if so, its degree of difficulty
- Reactivity coefficients
- Degree of Proliferation Resistance
  - All very good but still major differences

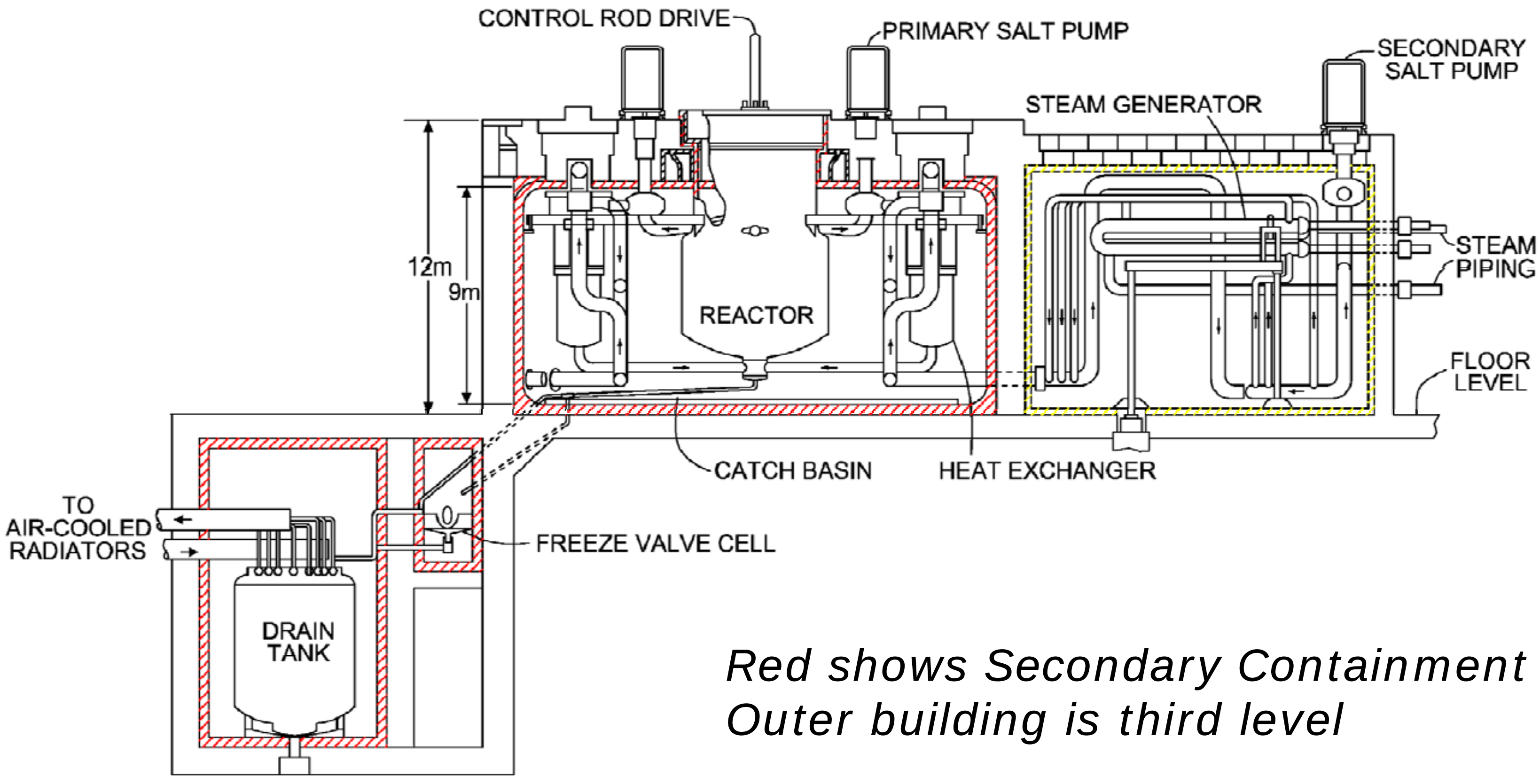
First Question: Breeder or Converter?

- Breeders offer the ultimate in minimising resource usage but at the capital and R&D cost of fuel processing
- Converters require an outside fissile source but greatly simplify development and operation

Comparing Proposed Breeder Designs

- Single Fluid Graphite (70s MSBR)
- DMSR Breeder
- 1 ½ Fluid (TMSR, now called MSFR)
- Interlaced Two Fluid (mid 60s MSBR)
- Non Interlaced Two Fluid?
- New Tube within Tube design

Single Fluid Graphite MSBR (70s)



Red shows Secondary Containment
Outer building is third level

Single Fluid Graphite MSBR (70s)

- ADVANTAGES
- Relatively simple core
- No structural material or barriers needed within strong neutron flux
- Modest starting Inventory (1.5 t/GWe)
- High thermal inertia (slow to change temp as lots of salt and graphite)
- As with any practical design, negative temperature coefficient (at least initially)

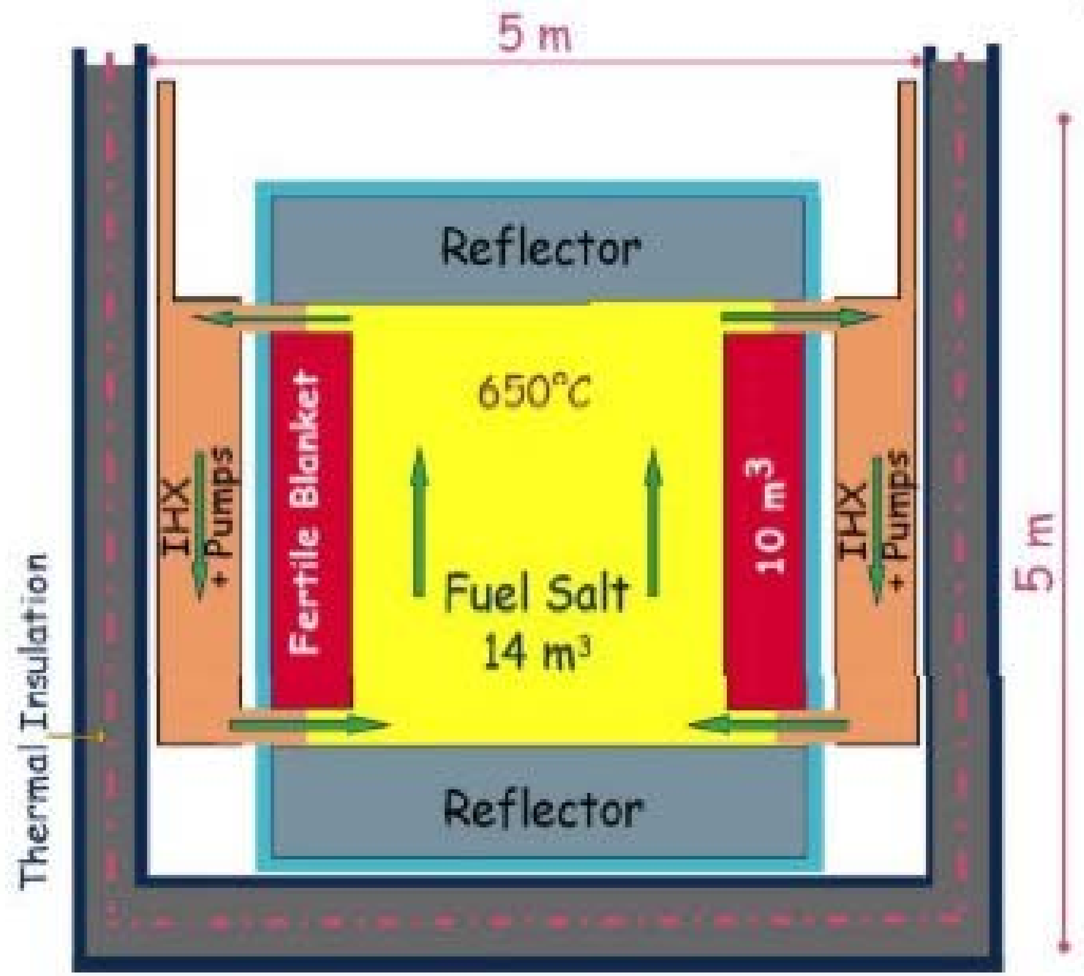
Single Fluid Graphite MSBR (70s)

- DISADVANTAGES
- Complex and rapid fission product removal with much R&D needed
- The longer term reactivity coefficient (10s of seconds after any power surge) may be slightly positive
- To start, needs hard to obtain U233 or LWR transuranics which are of limited availability for large fleet deployment

Late 1970s DMSR Breeder

- ORNL late 70s version of the standard MSBR but denatured with U238
- Proposed to increase proliferation resistance
- Added benefit of much better reactivity coefficients than MSBR
- Easy startup on Low Enriched Uranium
- However, even more complex fission product removal to just barely break even

1 ½ Fluid MSFR (was TMSR)



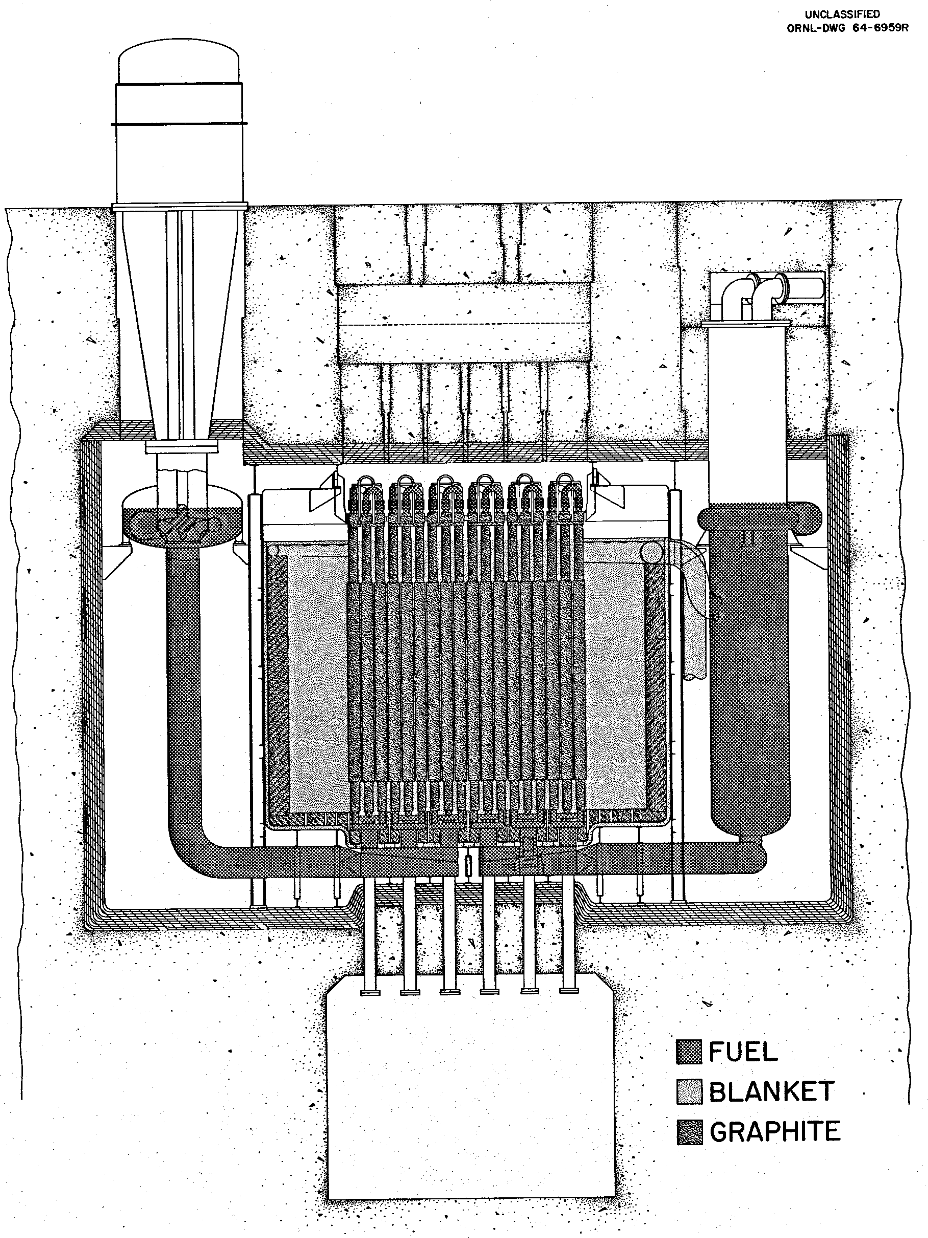
Design has a thorium blanket but only radial, not axially (which would be very difficult)

1 ½ Fluid MSFR (was TMSR)

- Advantages
- Much lower daily processing rate than the MSBR (but just as complex)
- No graphite to replace or dispose of
- Very good reactivity coefficients
- Compact, fairly simple core
- Very high breeding ratio possible (upwards of 1.12 vs 1.06 of MSBR)

1 ½ Fluid MSFR (was TMSR)

- Disadvantages
- Large fissile inventory (5-8 t U233, Pu)
- Calls for much higher temp of 800 ^{o}C (mainly to assure solubility of PuF_3)
- Much materials R&D needed for barrier to blanket and axial reflectors (higher temp and strong neutron flux)
- Blanket salt likely has weakly positive temp reactivity coefficient?
- Very small thermal inertia (15 m^3 salt)



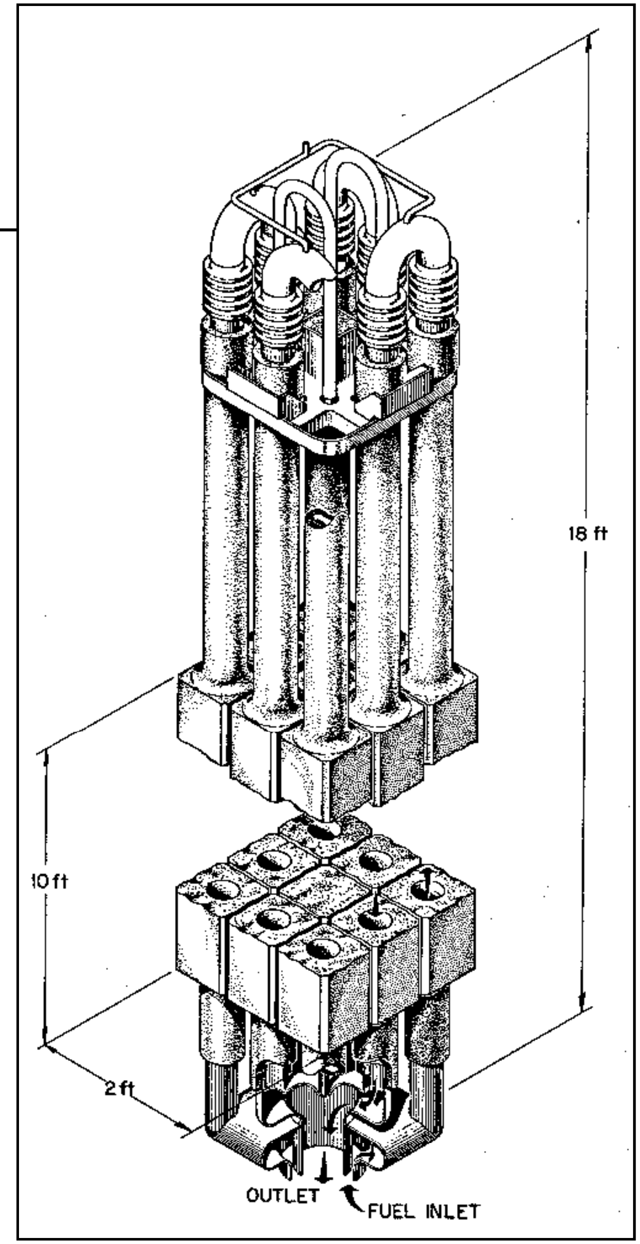


Fig. 2. Two-Region Molten-Salt Breeder.

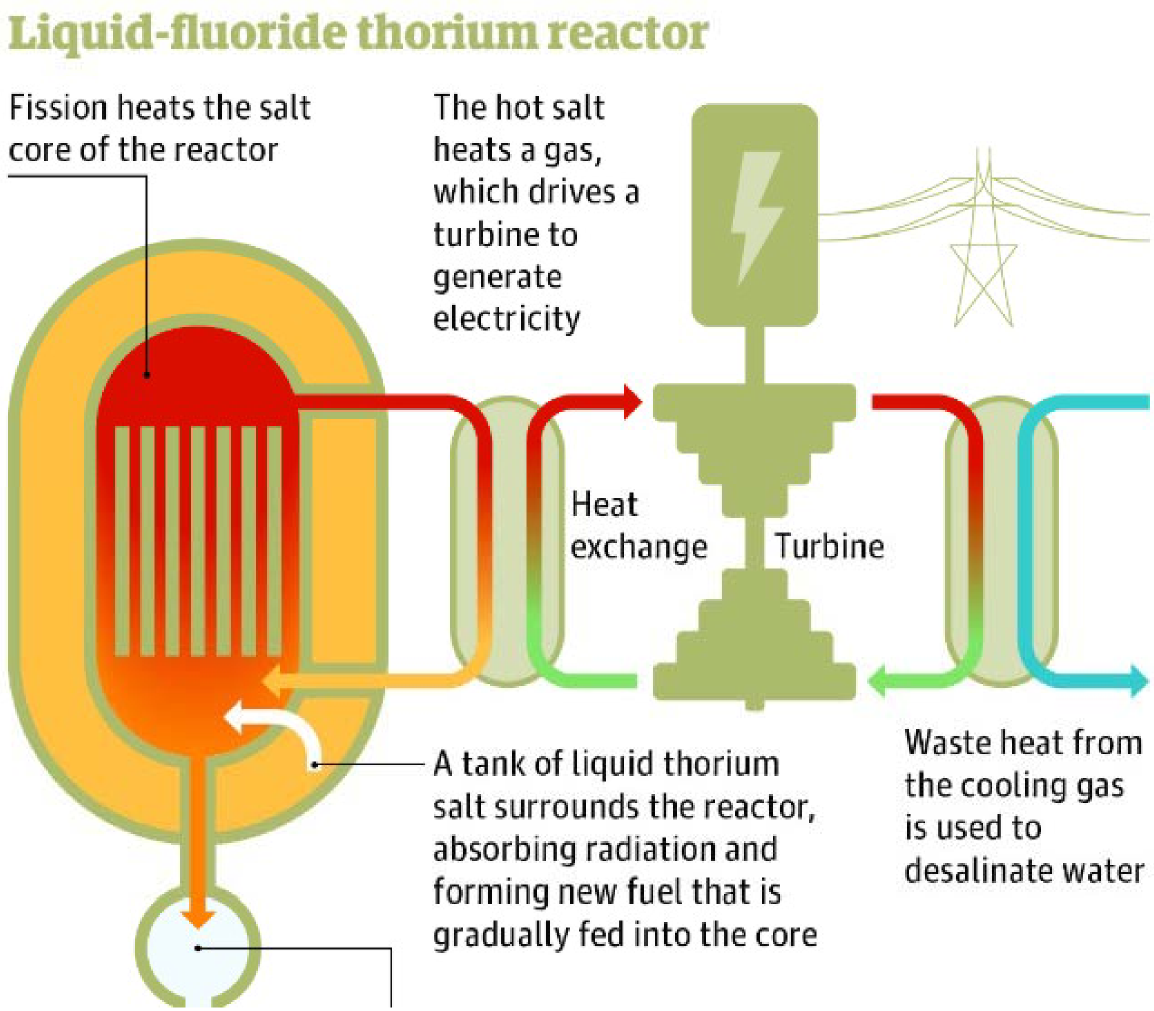
Mid 60s ORNL Two Fluid MSBR

- Advantages
- Much simpler removal of fission products as no thorium in fissile salt
- Only graphite in strong neutron flux
- Strong negative temp coefficient for fissile salt
- Very low fissile (0.7 t/GWe)

Mid 60s ORNL Two Fluid MSBR

- Disadvantages
- Core plumbing a huge challenge as graphite shrinks then swells
- A single tube failure means entire core replaced
- Strongly Positive temp coefficient for blanket salt

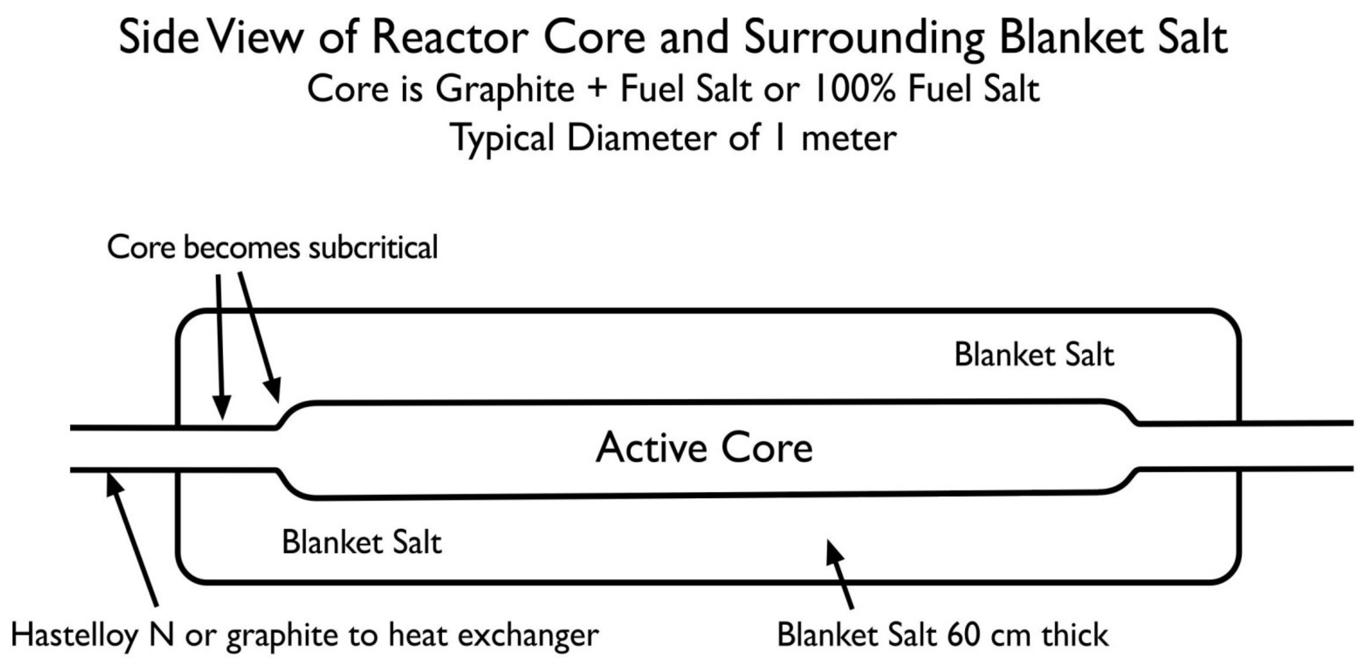
Why Interlace the Two Fluids?



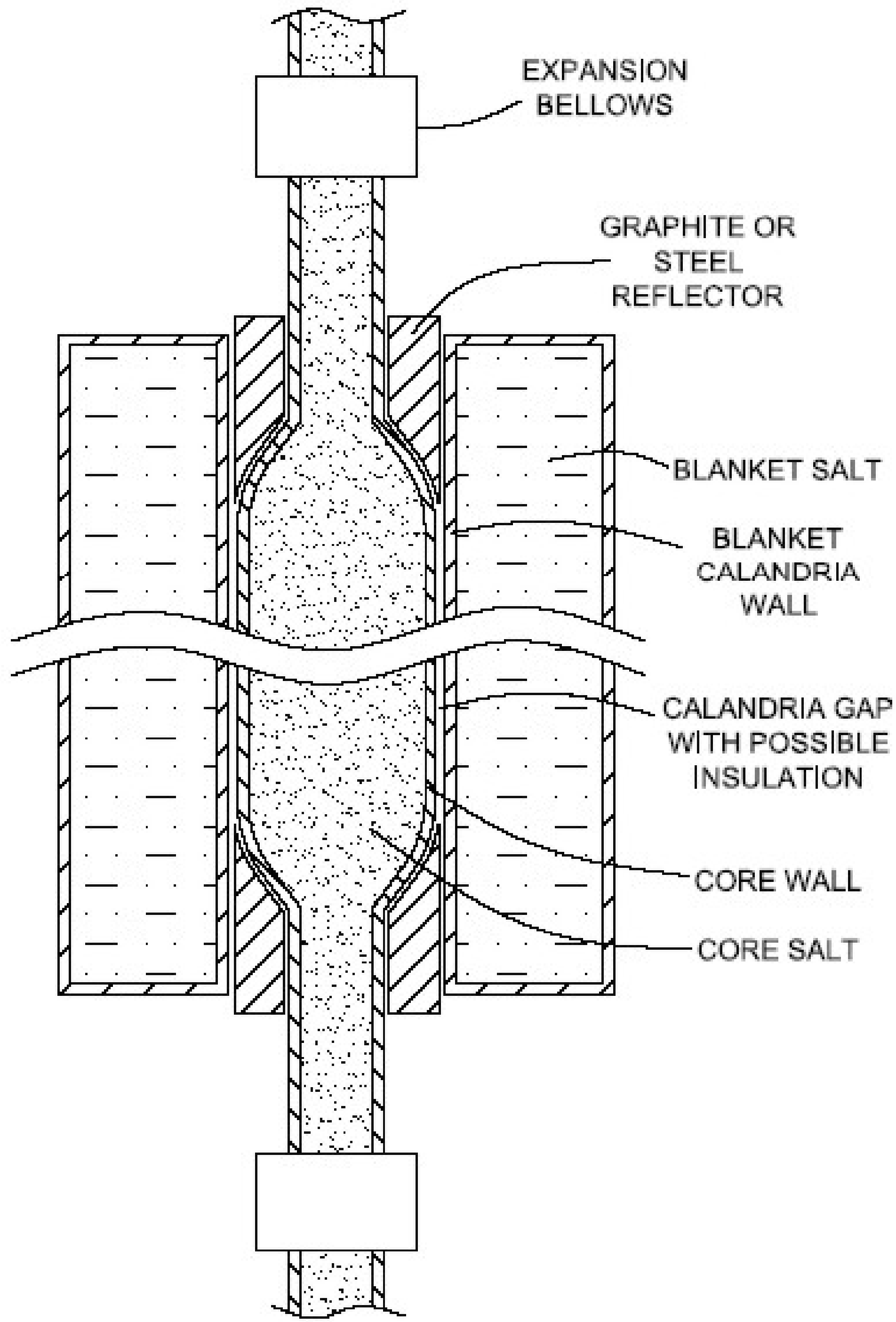
Why Interlace the Two Fluids? As ORNL often explained…

- If you do not interlace, the core is only about 1 m in diameter (with or without graphite is about the same)
- Since power density is limited for many reasons, If you stick to short cylinder geometry, total power is quite small (especially with graphite)

Tube within Tube Geometry



Expands power producing volume while maintaining the small inner core needed for a simple Two Fluid design


EXPANSION BELLOWS
GRAPHITE OR STEEL REFLECTOR
BLANKET SALT
BLANKET CALANDRIA WALL
CALANDRIA GAP WITH POSSIBLE INSULATION
CORE WALL
CORE SALT

New Concepts Advantages

- Can use simple Two fluid fuel processing without the "plumbing problem"
- Very strongly negative fuel salt coefficients
- Blanket will **also** have negative temp/void coefficient as it acts as a weak reflector
- Simple, transportable cores
- Ease of modeling and prototyping
- Fissile inventory of **400 kg per GWe** or even lower is possible.

Tube within Tube Geometry

- Disadvantages
- Like any Two Fluid design, a barrier within neutron flux must be maintained and not allow fissile salt to enter blanket
  - All Two Fluid designs run fissile salt at higher pressure (any leak will be blanket inwards)
- Core is not in minimally reactive configuration (but no Two Fluid design ever is)
  - If graphite is used, run horizontally
  - Even worst case scenario would only appear to make an expensive mess within secondary containment zone (with the containment building itself as backup)

Critical Issue: Core-Blanket Barrier

- Viability of barrier materials in high neutron flux
  - Much recent work in the fusion field using same $2^7LiF\text{-}BeF_2$ salt as coolant
  - Molybdenum, SiC/SiC or simple carbon composites leading candidates
  - Hastelloy N also possible as new French work suggests
  - Ease of “retubing” means even a limited lifetime still may be attractive

Conclusions

- The tube in tube Two Fluid approach may offer the best overall breeder (break even) package
- Of course though there is need to further evaluate all options and good to pursue several routes