Molten Salt Reactors: A 2 Fluid Approach to a Practical Closed Cycle Thorium Reactor

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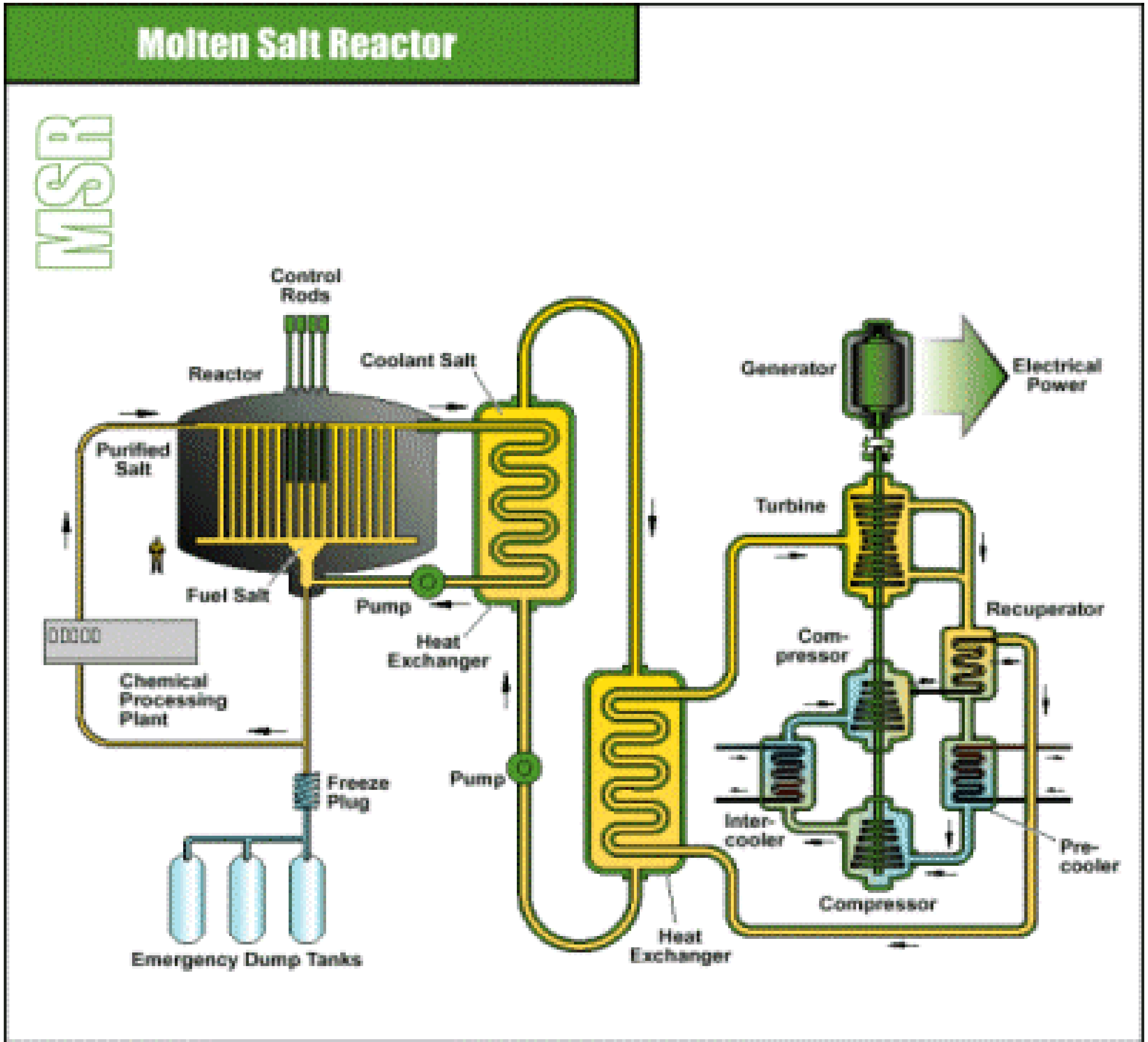
Outline

- **1968 to Today**
  - The Single Fluid Molten Salt Reactor
- **Molten Salt Design Fundamentals**
  - Fast, Epithermal or Thermal
  - Fuel Processing
  - Single Fluid vs 1 and ½ Fluid vs 2 Fluid
- **1950 to 1968**
  - The Rise and Fall of the 2 Fluid Reactor
- **2007 Solving the "Plumbing Problem"**

The Single Fluid Molten Salt Reactor



General Attributes

- $Li^7F\text{-}BeF_2$ + 12% ThF_4 + 0.3% $U^{233}F_4$
- Hastelloy N used for vessel, exchangers
- 44% on steam cycle, 48% on gas cycle
- Liquid Bismuth Reduction Reaction
  - 20 day cycle for Fission Product Removal
  - 3 to 10 day cycle for Protactinium
- Specific Inventory of 1500 kg
- Breeding Ratio of 1.06
- 20 year doubling time

Major Benefits

- Low pressure operation, high boiling point
- Volatile fission products continuously removed and stored, including Xenon.
- Passive decay heat removal
- Low Fissile Inventory
- Ability to utilize thorium cycle
  - Simply burn about 1 tonne per year per Gw
  - Transuranic production extremely low to zero
  - Much lower long term radioactivity
  - Accidental criticality of wastes not an issue

Major Issues

- Limited graphite lifetime
- Fuel processing costly, complex and relatively unproven
- Some delayed neutrons emitted outside core which activates circuit
- High melting point of fuel means entire vessel and primary circuit in “hot cell”
- Tritium is produced and must be controlled
- Some unique proliferation concerns

Proliferation Issues

- Uranium in fuel salt will be mix of isotopes
  - 70% U^{233} + U^{235}, remainder U^{232}, U^{234} and U^{236}
  - U^{234} and U^{236} are better denaturants than U^{238}
  - U^{232} has extremely hard gamma ray emission
  - Is bomb making even possible due to heating?

- Pa removal system more of a concern
  - Ability to remove clean U^{233}
  - Can still break even without Pa removal but only with a much larger fissile inventory

From the 70s to Today

- 70s and 80s
  - Major U.S. funding terminated in early 70s
  - Modest studies continue at ORNL and worldwide
  - Highlights include
    - 30 year Once Through Design
    - Denatured cycle with no Pa removal and still break even, Breeding Ratio = 1.0
- 90s
  - Use of compact heat exchangers to limit out of core salt volumes
  - Switch to closed gas cycles such as Brayton

From the 70s to Today

- Most Recently
  - Major re-examination by large group in France
    - Find reactivity problem with 70s MSBR
    - Look to decrease processing needs by allowing breeding ratio to drop
    - Calculations show significant advantages of a harder spectrum without graphite
  - U.S. based effort to examine the use of clean salts as coolant for TRISCO type fuels. Many advantages if positive void can be avoided

Molten Salt Design Fundamentals

- Fast, epithermal or thermal
- Homogeneous or graphite moderation
- Fuel Processing, a historical review
- Single Fluid vs 1 and ½ Fluid vs "standard" 2 Fluid

Neutron Spectrum

- Fast Spectrum
  - A fluoride carrier salt will never have a very hard spectrum
  - Graphite must be avoided
  - Number of neutrons per absorption in U^{233} goes up substantially at higher energies
  - Losses to fission products or carrier salt drops
  - Fissile inventory typically high
  - Prompt neutron lifetime is shorter which complicates reactor control

Neutron Spectrum

- Epithermal
  - Very wide range of average energy possible
  - Number of neutrons per fission drops but remains well above 2
  - Losses to fission products and carrier salt increase
  - Resonant absorptions more an issue
  - Fissile inventory lowered
  - Prompt neutron lifetime improved

Neutron Spectrum

- Thermal
  - Graphite or other good moderator needed
  - Number of neutrons per absorption rises
  - Fissile inventory lowest
  - Losses to fission products and carrier salt highest
  - Any extra structural material must be very limited or breeding not possible

Homogeneous or Graphite Moderation

- Graphite is excellent moderator but...
  - Needs special sealing against Xenon
  - Dimensional changes and limited lifetime
  - Radioactive graphite is disposal problem

- Homogeneous
  - Pure salt contained by Hastelloy N or graphite core walls
  - No way to get to thermal energies and still breed
  - Great simplicity of core design possible

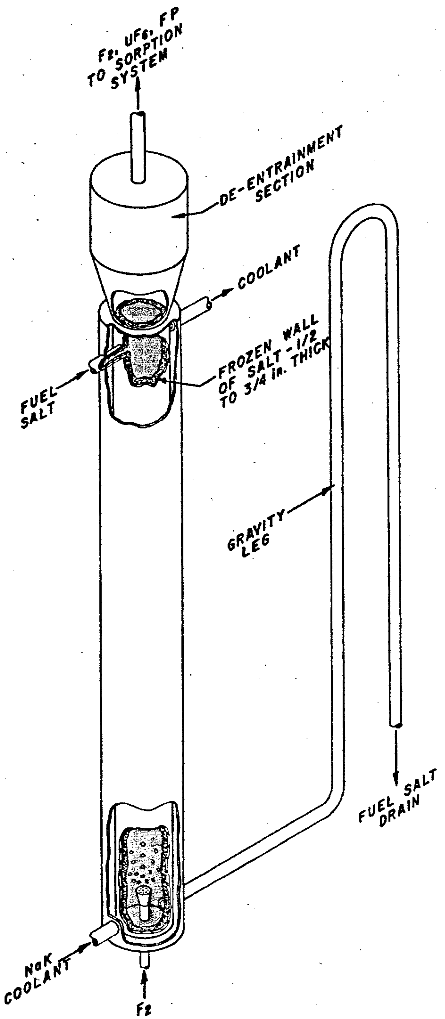
Fuel Processing

- Fluoride Volatility Process
  - Removes uranium from carrier salt
- Fission Product Removal
  - Essential if breeding desired
  - Several year cycle possible in some reactor designs
- Protactinium Removal and Hold Up
  - Non essential but improves breeding

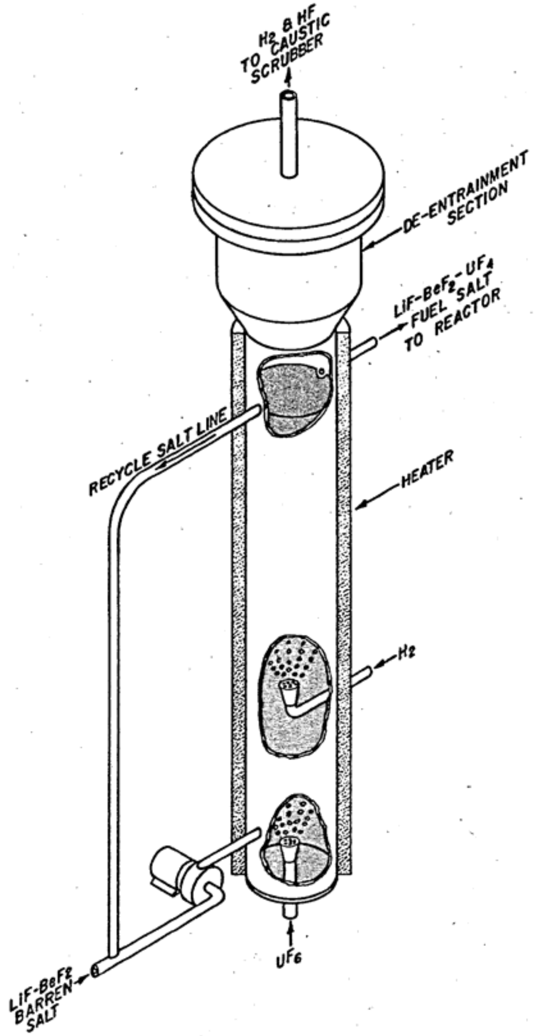
Fluoride Volatility

- Simple bubbling of fluorine gas through carrier salt
- Converts UF_4 to gaseous UF_6
- Conversion back to UF_4 done by adding H_2 which produces HF
- Well established process, known since 1950s

Conversion of UF_4 to UF_6

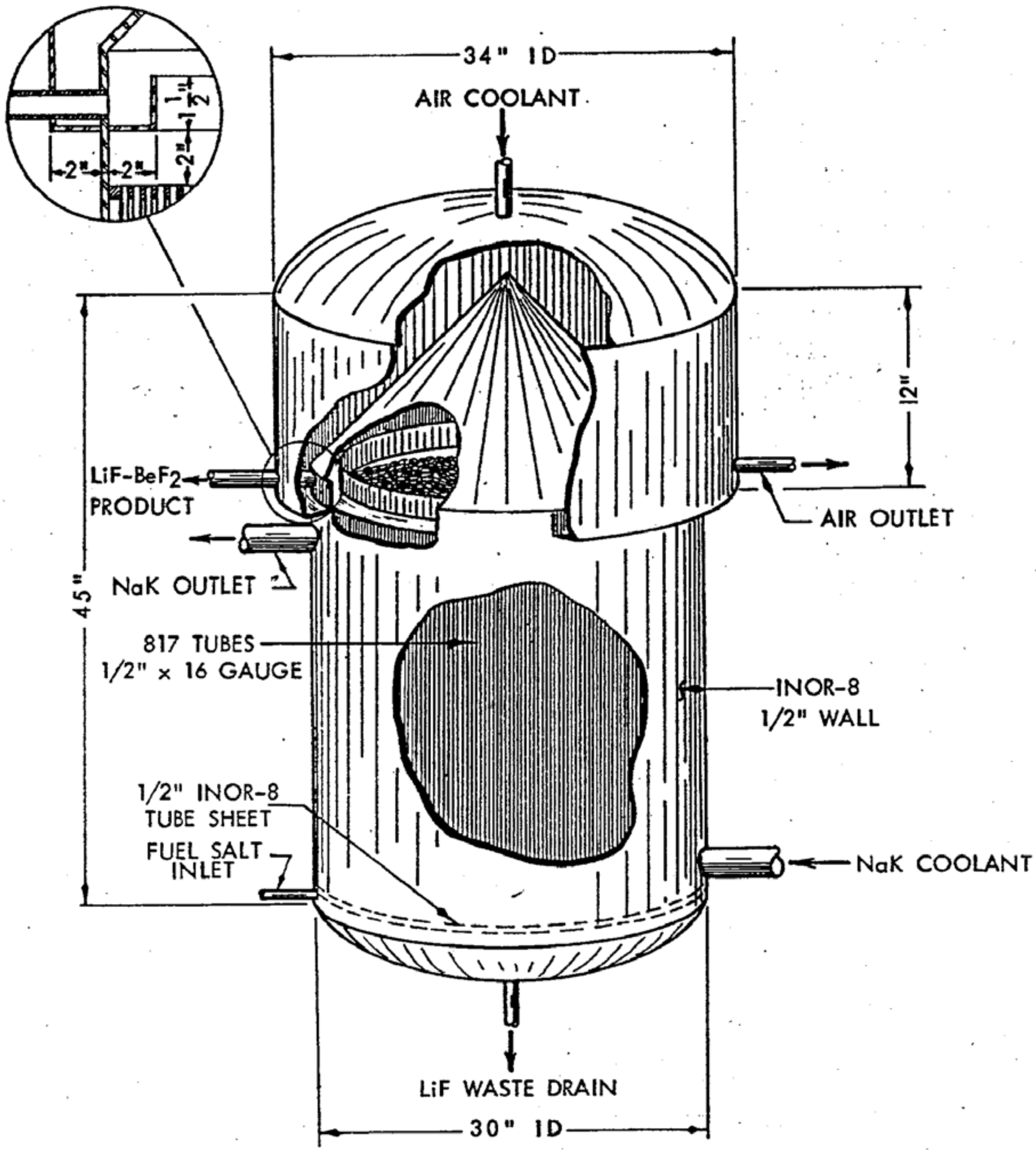


Conversion Back to UF_4 in Fuel Salt



Fission Product Removal

- 1950 to 1964
  - No process proven to be practical
    - Salt Discard
    - CeF_3 substitution for rare earths
    - Aqueous processing
- 1964 Vacuum Distillation
  - Simple system to boil off carrier salt and leave behind fission products
  - Thorium would remain with fission products, so only for a 2 fluid design



34" ID
AIR COOLANT
12"
AIR OUTLET
LiF-BeF2
PRODUCT
NaK OUTLET
45"
817 TUBES
1/2" x 16 GAUGE
INOR-8
1/2" WALL
1/2" INOR-8
TUBE SHEET
FUEL SALT
INLET
NaK COOLANT
LiF WASTE DRAIN
30" ID

Fuel Processing

- 1968 Liquid Bismuth Reduction
  - Ability to process for fission products with thorium present
  - Thorium behaves much like rare earth fission products which makes the process “delicate”
  - Complex and costly

Fuel Processing

- Protactinium Removal and Hold Up
  - Same liquid bismuth reductive reaction method used
  - Must be rapid to have effect on 27 day half life Pa, 3 to 10 days typical
  - Pa sent to holding tanks to await decay into U^{233}
  - Adds unique proliferation concerns

Single Fluid vs 1 and ½ Fluid vs 2 Fluid

- Single Fluid Designs
  - Mix fertile thorium and fissile U^{233} , U^{235} or Pu in same carrier salt
  - Simple core design
  - Complex fuel reprocessing
  - Breeding not possible without graphite
  - Non ideal reactivity coefficients
  - Significant neutron leakage
    - Minimized by an under moderated outer annulus

Single Fluid vs 1 and ½ Fluid vs 2 Fluid

- 1 and ½ Fluid Design
  - A central core of a mixed single fluid that is surrounded by a blanket salt
  - More complex as a barrier needed between regions
  - Low leakage but barrier a parasite
  - Even more complex fuel reprocessing
  - Breeding possible without graphite moderator

Single Fluid vs 1 and ½ Fluid vs 2 Fluid

- "Standard" 2 Fluid
  - Separate salt streams
    - Thorium blanket salt
    - Fissile U^{233} fuel salt with no thorium
  - Blanket salt surrounds core and in "standard" design is also interlaced within the core region
  - This need for internal plumbing of the two salts greatly complicates design

Mid 60s 2 Fluid Molten Salt Reactor

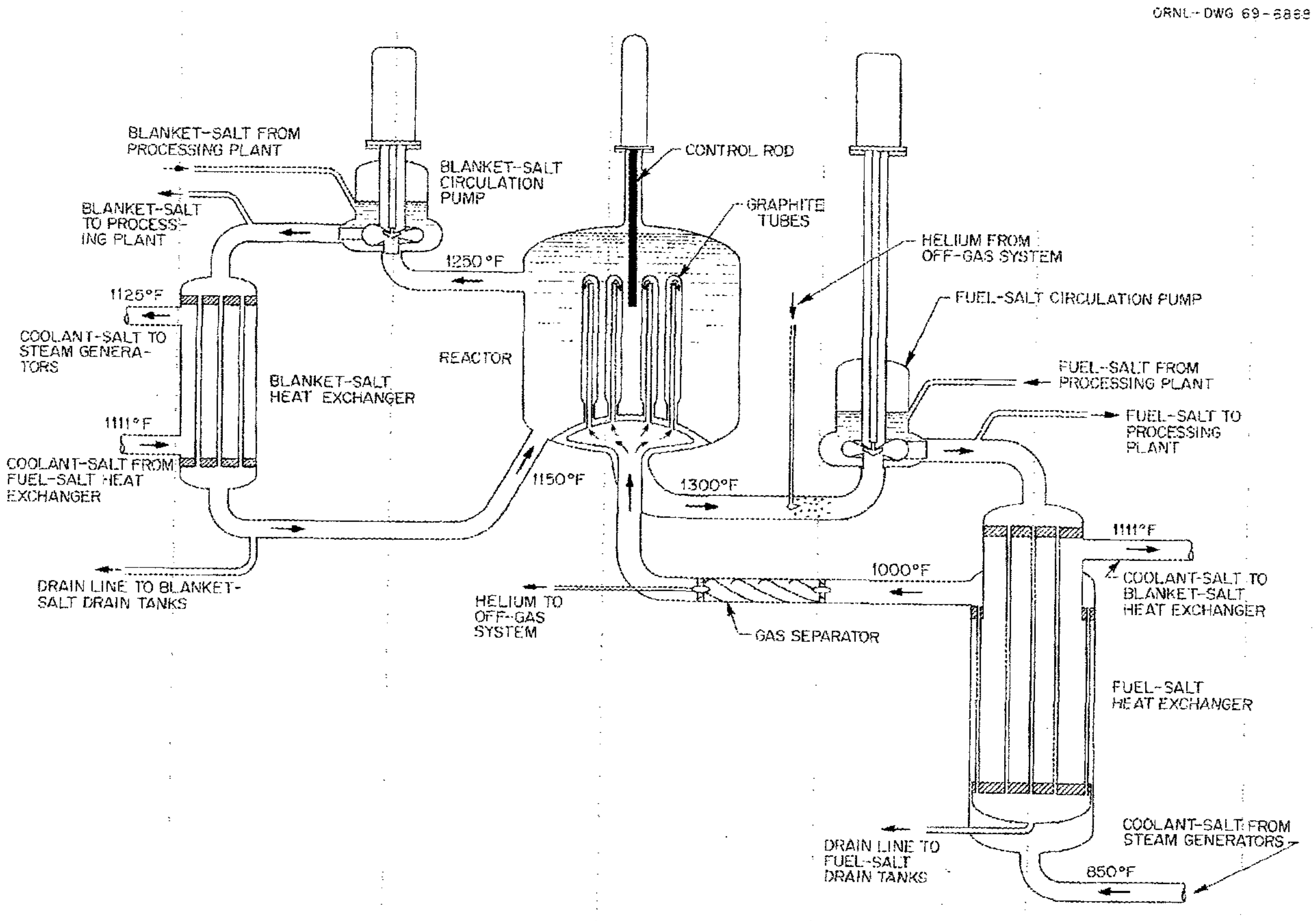
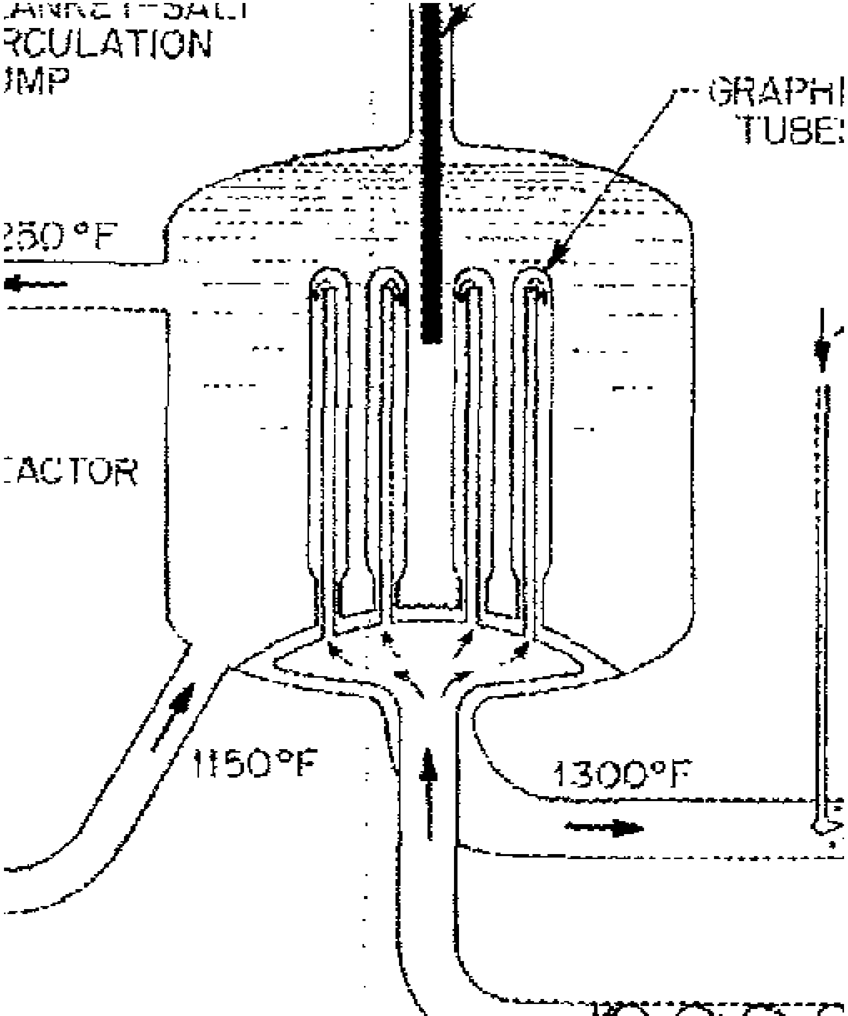


Fig. 2.1. Simplified Flow Diagram of Two-Fluid MSBR.

Mid 60s 2 Fluid Molten Salt Reactor



Complex Plumbing to Keep Fuel and Blanket Salts Separated Within Core

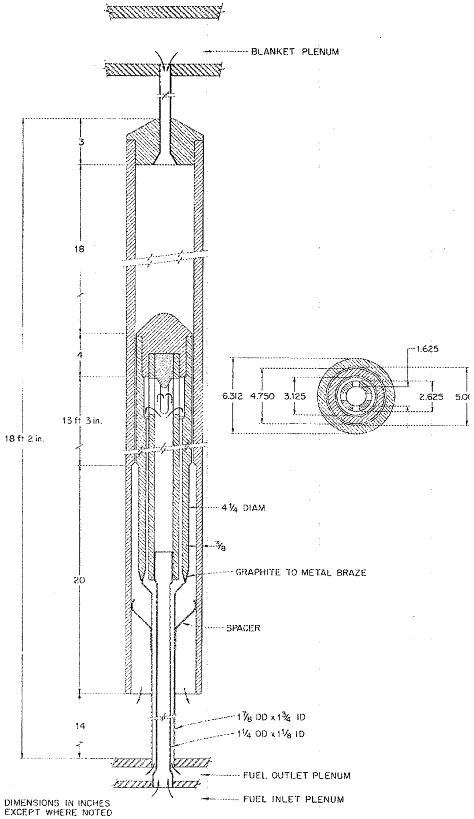
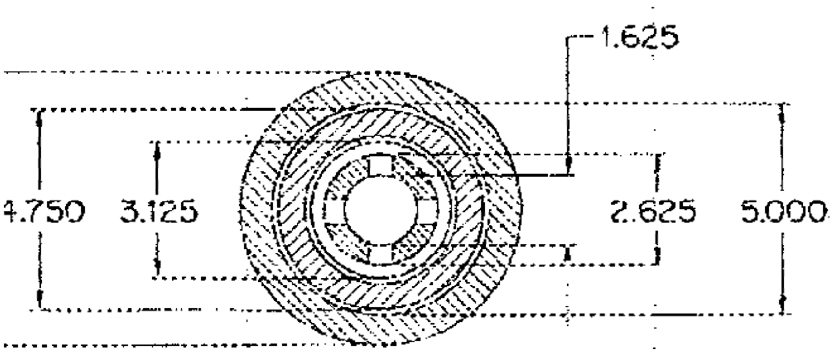


Fig. 5.5. Graphite Fuel Tube Assembly for Core Region.



ΔM

“Standard” 2 Fluid Design

- Simple Fuel Processing
  - Fluoride Volatility + Vacuum Distillation for fuel salt
  - Fluoride Volatility for blanket salt
- Simply increasing the blanket volume reduces losses to protactinium
- Strong negative void and temperature coefficients for fuel salt
- Positive coefficients for blanket salt

The Rise and Fall of the 2 Fluid Reactor

- 1950 to 1968 MSR Development
  - Early 50s
    - Design and operation of the Aircraft Reactor Experiment
    - Very high temperature 857 ^{o}C
    - Canned BeO moderator
    - $NaF\text{-}ZrF_4$ carrier salt
    - Points the way to possible power reactor

The Rise and Fall of the 2 Fluid Reactor

- Late 50s
  - Main focus on homogeneous reactors
  - Looked at both U^{235} converter reactors and thorium breeders
  - True thermal spectrum not attainable and still breed
  - No proven fission product processing
  - All studies spherical geometry with 1/3 inch Hastelloy N core walls

Homogenous Molten Salt Reactor Late 50s ORNL

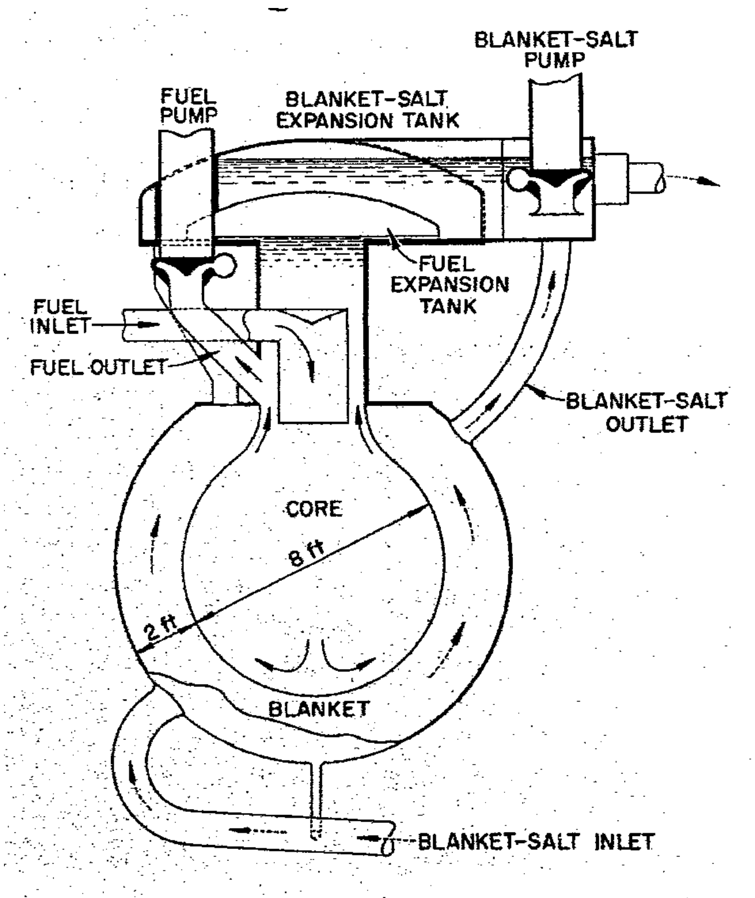


Fig. 1.1.1. MSR Layout with Outrigged Blanket-Salt Pumps and No Blanket Salt Around Neck of Core.

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Two Region Homogeneous Reactor Projected breeding ratio with thicker blanket and 1/6 inch vessel wall ORNL 2551, 1958

Core Diameter	3 feet	4 feet	4 feet	8 feet
ThF4 in fuel salt mole %	0	0	0.25	7
U233 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
Median fission energy	174 ev	14.2 ev	19.1 ev	243 ev
Breeding ratio (Clean Core)	0.972	0.856	0.929	1.078
Projected B.R.	1.055	0.977	1.004	1.091

The Rise and Fall of the 2 Fluid Reactor

- Early 60s Breeder Designs
  - Graphite now proven long term compatibility with salt
  - Lower fissile inventory leads to change focus to a graphite 2 fluid reactor
  - 2 fluid homogeneous designs without graphite also considered
  - Still no truly practical method of fission product removal.

Molten Salt Reactor Experiment MSRE

- Early 60s MSRE 8 Mw(th) Reactor
  - Chosen to be single fluid for simplicity
  - Graphite moderated, 650 ^{o}C operation
  - Designed from 1960 to 1964
  - Start up in 1965
  - Ran very successfully for 5 years
  - Operated separately on all 3 fissile fuels, U^{233} , U^{235} and Pu
  - Several issues solved

The Rise and Fall of the 2 Fluid Reactor

- 1964 to 1968
  - Discovery of Vacuum Distillation in 1964. Practical processing possible for the 2 Fluid design
  - Methods of separating fuel salt and blanket salt within core proving very complex
  - Little mention of homogeneous designs

The Rise and Fall of the 2 Fluid Reactor

- 1968
  - Establishment of liquid bismuth technique
  - 2 Fluid system abandoned
  - “Plumbing Problem” left unsolved and virtually all work since has focused single fluid or 1 and ½ fluid designs

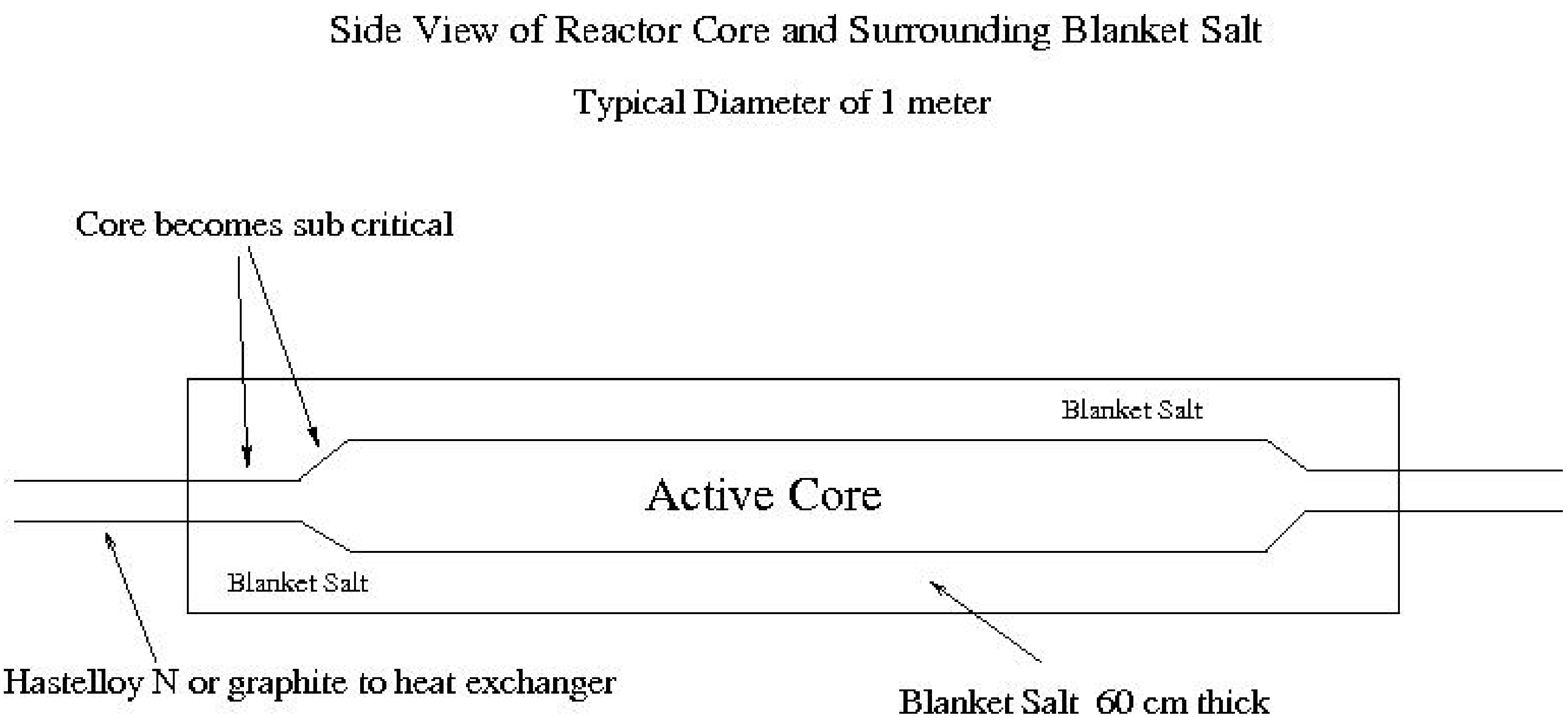
Restating the 2 fluid problem

- Core power density hard to exceed 100 kw/l in graphite designs
- Minimum core volume thus 22 m^3 for 2200 Mw(th)
- If only fuel salt in core region, critical diameter is about 1.5 m for a fissile density that can still breed
- “Standard” conclusion is fuel and blanket salts must be interlaced

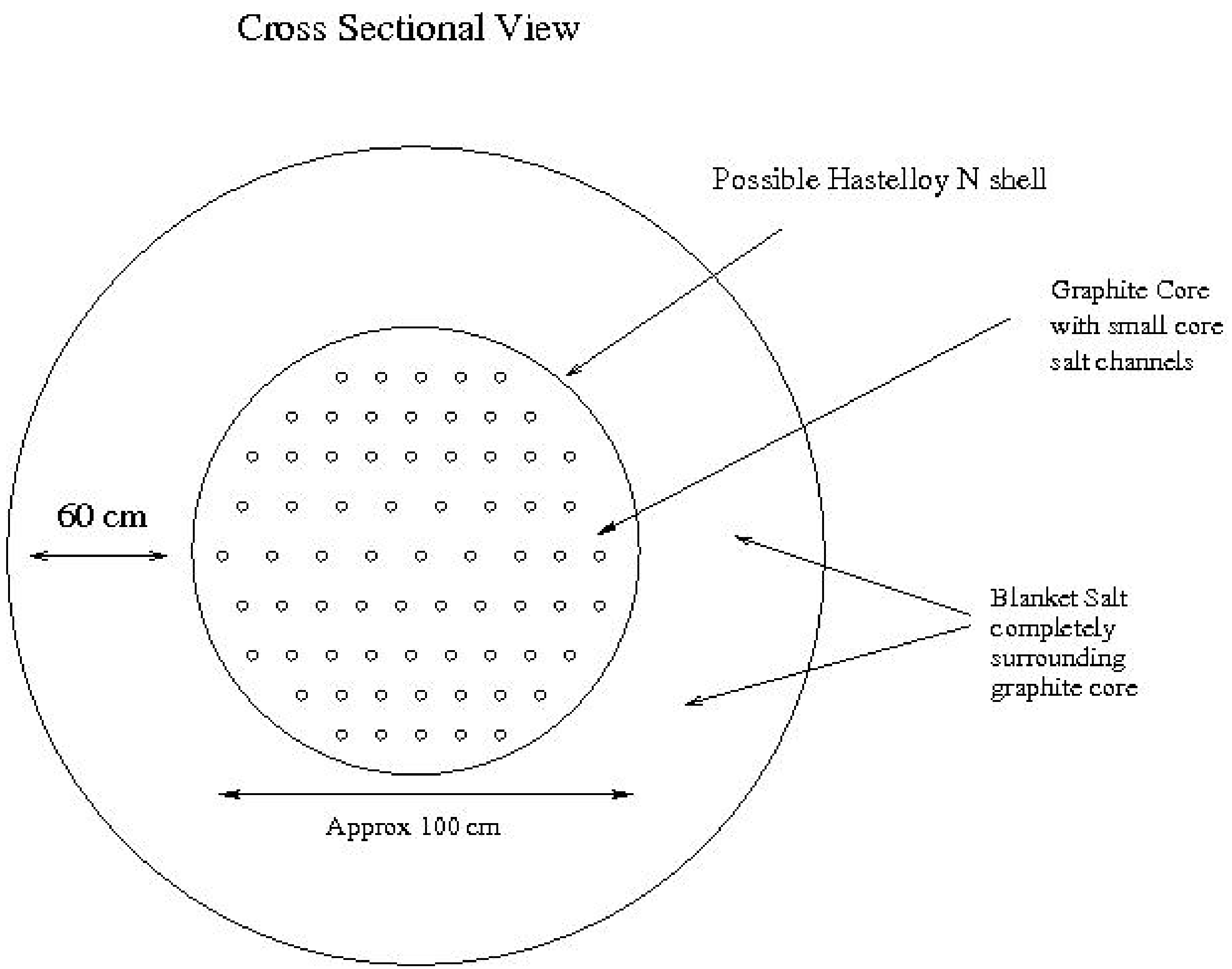
What is the solution?
How about a hint?

Geometry	Buckling^2	Ratio to B_{sphere}
Sphere	$\left(\frac{\pi}{R}\right)^2$	1
Infinite Cylinder	$\left(\frac{2.405}{R}\right)^2$	0.766
Finite Cylinder	$\left(\frac{2.405}{R}\right)^2 + \left(\frac{\pi}{H}\right)^2$	If *H = 10 R* 0.772
Infinite Slab	$\left(\frac{\pi}{a}\right)^2$	0.5

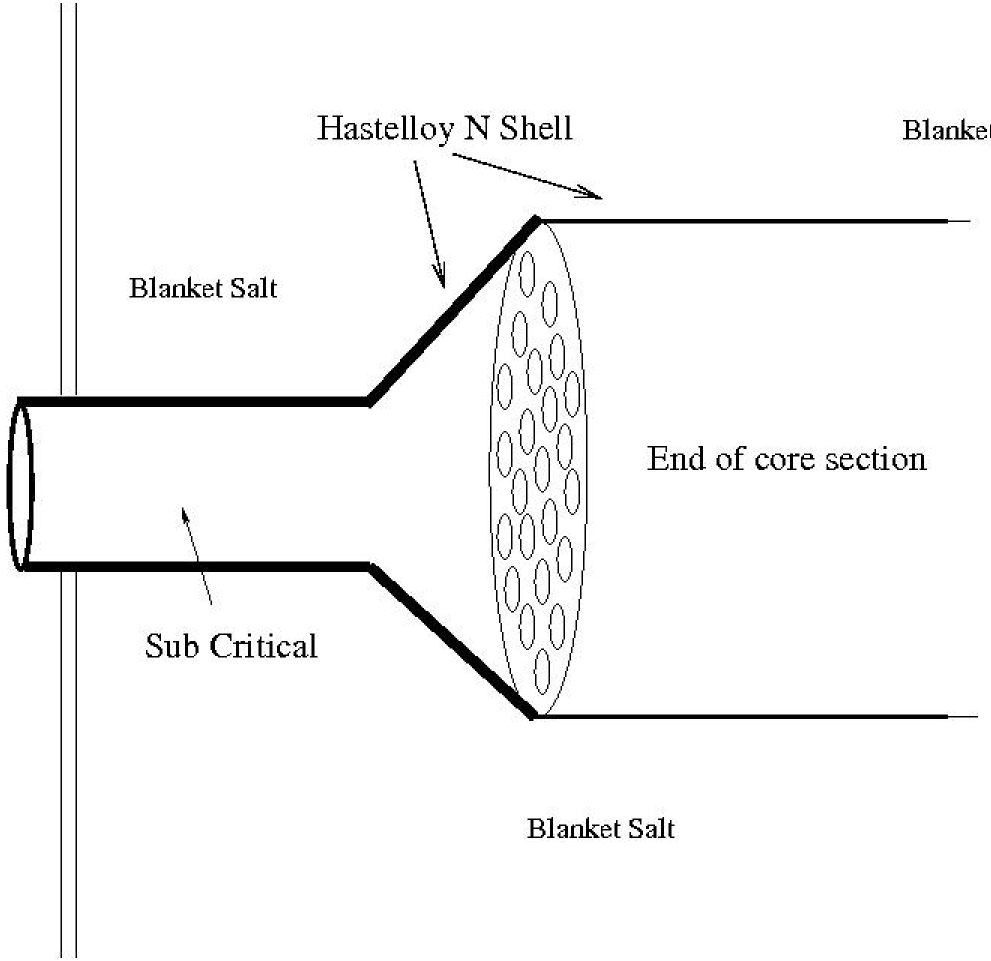
Modified Geometry 2 Fluid Reactor



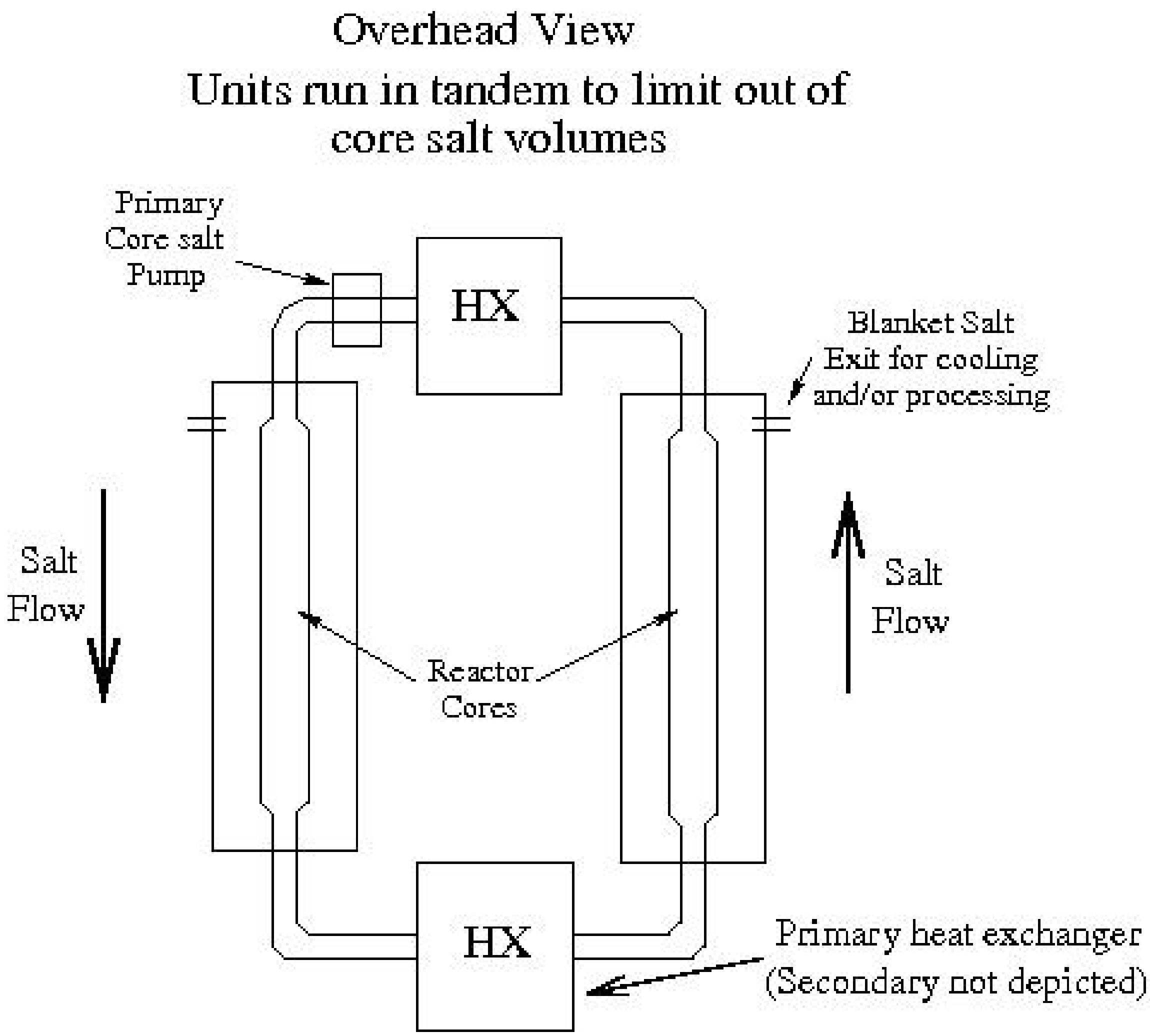
Modified Geometry 2 Fluid Reactor



Modified Geometry 2 Fluid Reactor



Modified Geometry 2 Fluid Reactor



Graphite Moderated

- Assumptions
  - 80% Graphite 20% Fuel Salt
  - 60 cm blanket salt surrounding core
  - Critical diameter for long cylinder with 0.3% $U^{233}F_4$ will be about 1 meter
  - Fuel salt velocity of 4.5 m/s
  - $\Delta T = 140\ ^{o}C$
  - Volumetric heat capacity of Flibe carrier salt is $\rho C_p = 4.69\ MJ/m^3\ ^{o}C$

Graphite Moderated

Volumetric Flow = Salt velocity x π x r^2 x 20%

= 4.5 m/s x π x $(0.5m)^2$ x 0.20

= 0.707 m^3/s

Heat Production = Vol Flow x ρC_p x ΔT

= 0.707 m^3/s x 4.69 $MJ/m^3\ {}^oC$ x 140 ^oC

= 464 MJ/sec

= 464 Mw(th)

= 200 Mw(e) at 43%

Core Length is 7.4 meters if 80 kw/l power density

System Advantages

- Can use simple 2 fluid fuel processing without the “plumbing problem”
- Very strongly negative fuel salt coefficient
- Blanket will **also** have negative temp/void coefficient as it acts as a partial reflector
- Ease of graphite core fabrication and replacement
- Ease of modeling and prototyping
- Specific inventory less than 800 kg per Gw at 0.3% and much lower is possible.

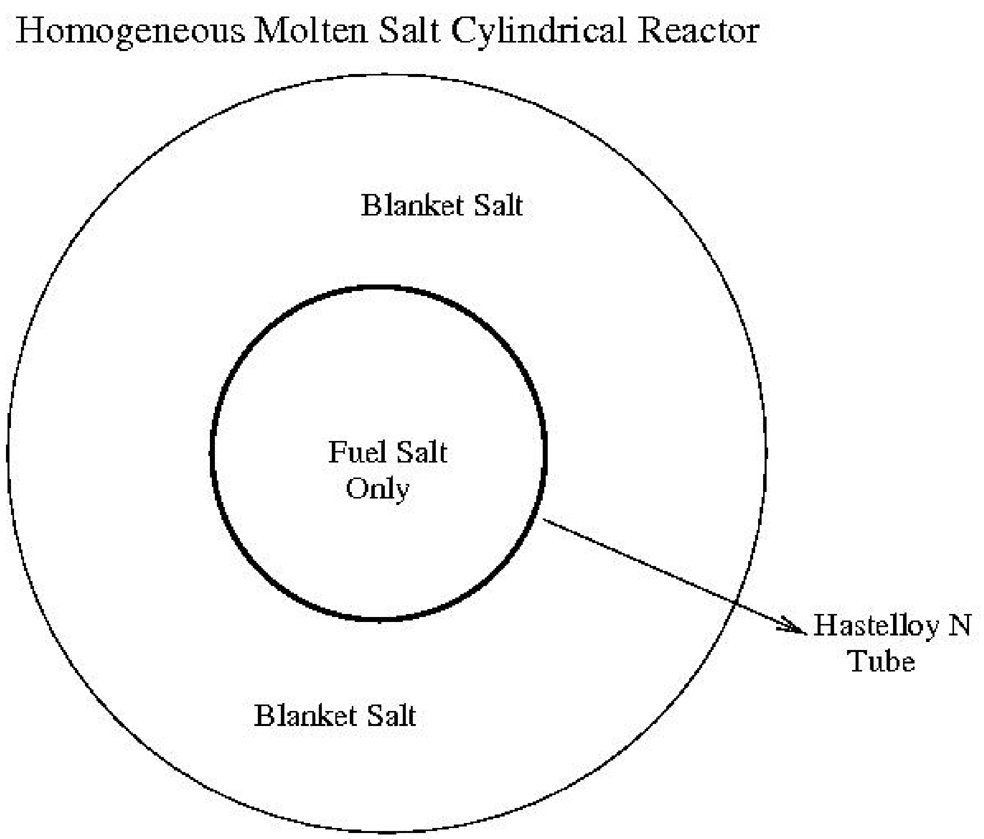
Operational Specifications

- Hastelloy N shell does not act structural so it can be thin. Having only graphite also a strong possibility
- As with ORNL 2 Fluid designs, should run blanket salt at higher pressure
- Hotter end of cylinder should be slightly wider as fuel salt is less dense
- Recommended to run horizontal such that gravity can not act to compress core. Also lowers head pressures

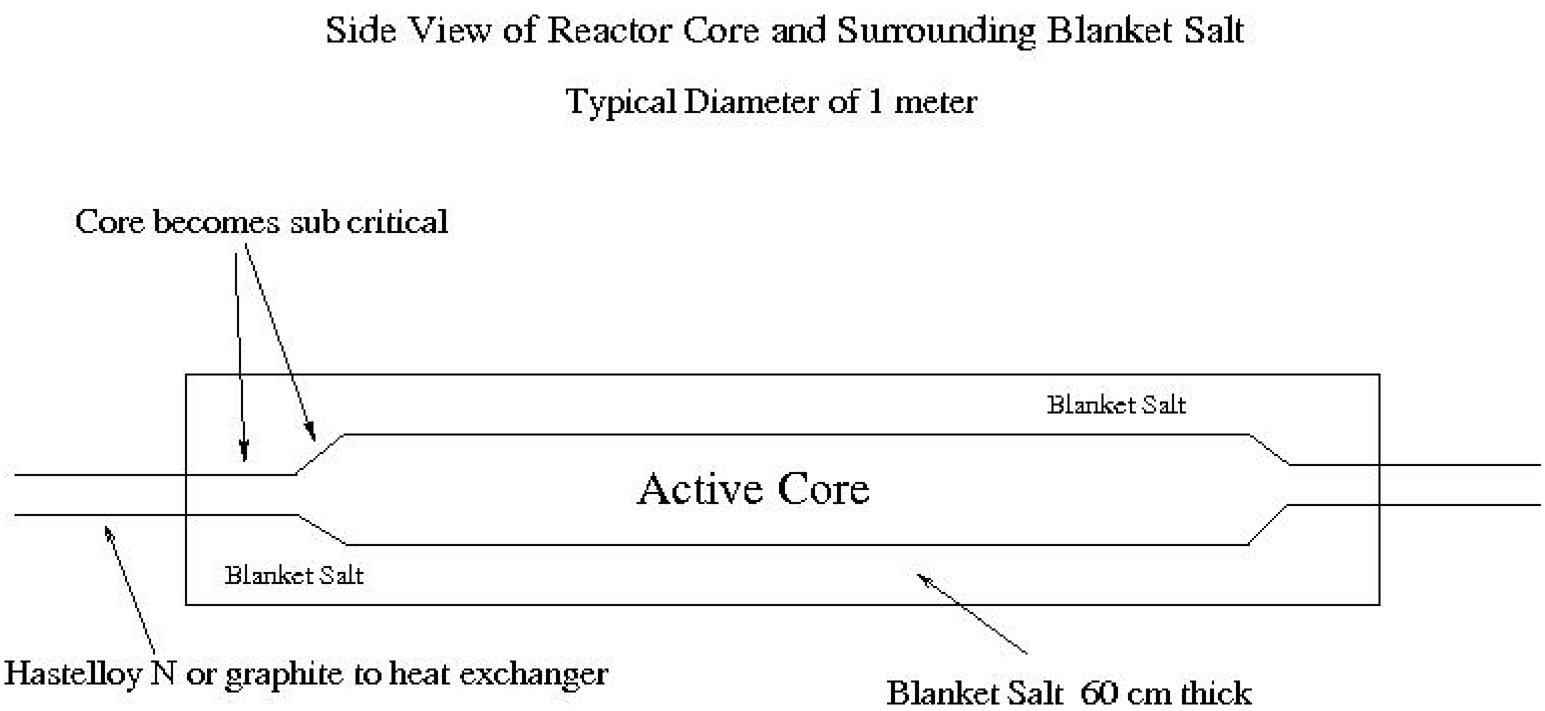
Homogeneous (graphite-less)

- Many advantages to not using graphite
- High power density as 100% salt
- 3 foot sphere needed 0.6% U^{233}
- This will be a 70 cm wide cylinder
- Specific Inventory under 1600 kg
- Hastelloy N needed as barrier but not as thick as the large ORNL 50s designs

Hastelloy N Tube Reactor



Hastelloy N Tube Reactor



Hastelloy N Tube Reactor

Volumetric Flow = Salt velocity x π x r^2

= 4.5 m/s x π x $(0.35m)^2$

= 1.73 m^3/s

Heat Production = Vol Flow x ρC_p x ΔT

= 1.73 m^3/s x 4.69 $MJ/m^3\ {}^oC$ x 140 ^oC

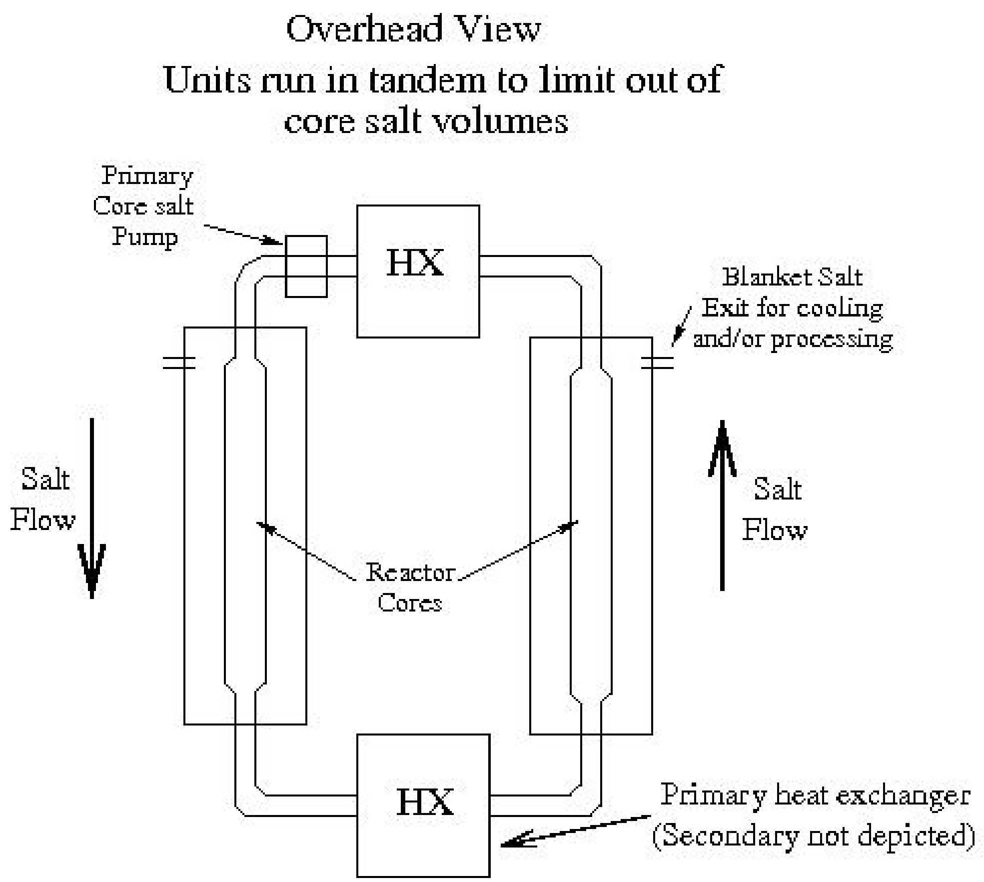
= 1136 MJ/sec

= 1136 Mw(th)

= 454 Mw(e) at 43%

Core Length 6.9 meters if 400 kw/l salt power density

Hastelloy N Tube Reactor
900 Mw(e) Tandem Unit

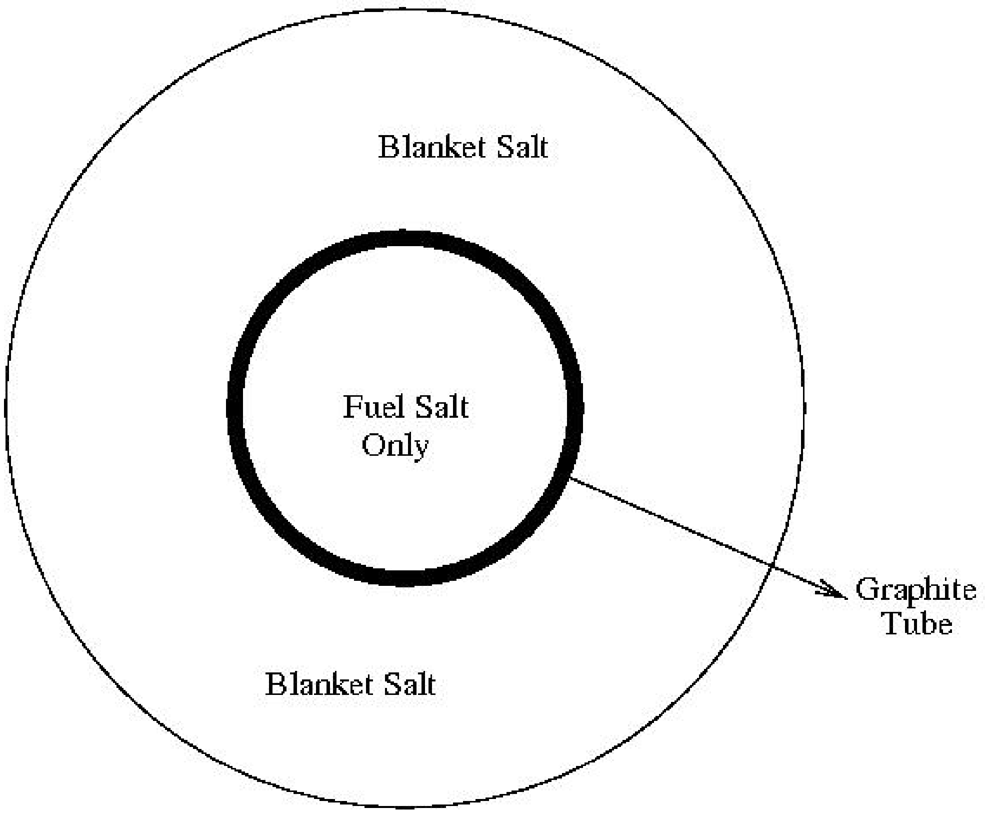


Hastelloy N Tube Reactor

- If 0.6% $U^{233}F_4$ used, specific inventory approx 1600 kg per Gw
- Lowering to 0.3% with wider tube likely possible for B.R. =1.0
- Hastelloy N tube easy to replace if lifetime limited
- Utmost in simplicity

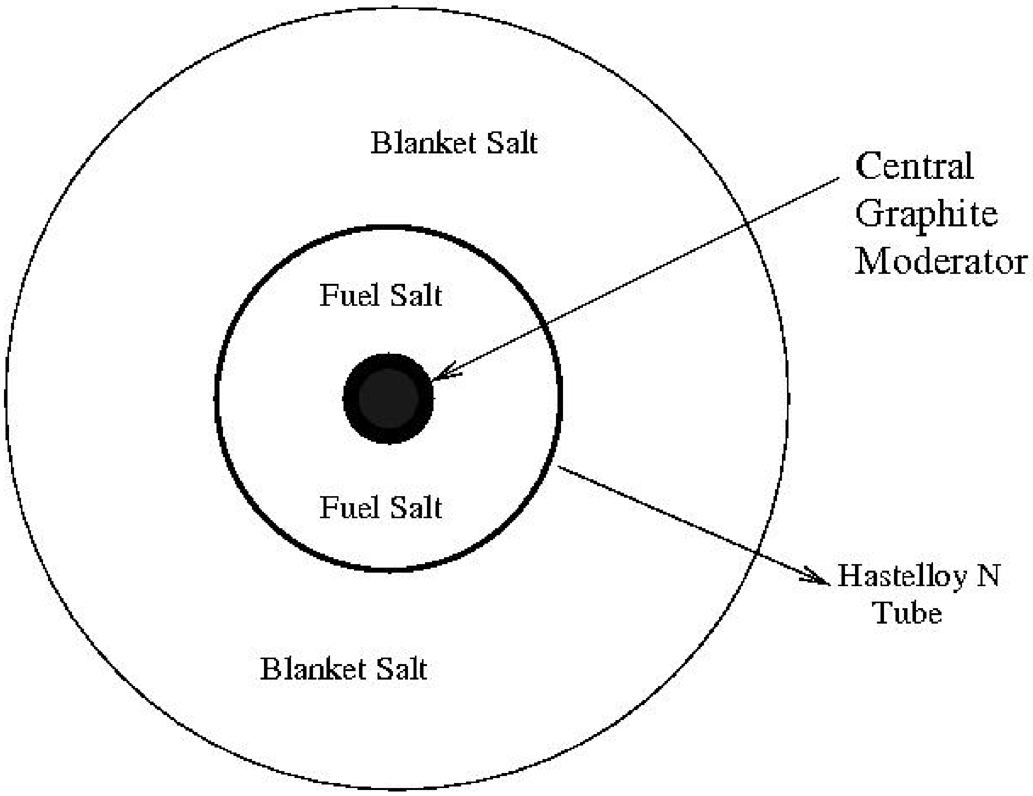
Graphite Tube Design

Graphite Tube Molten Salt Cylindrical Reactor



Hybrid Spectrum Design

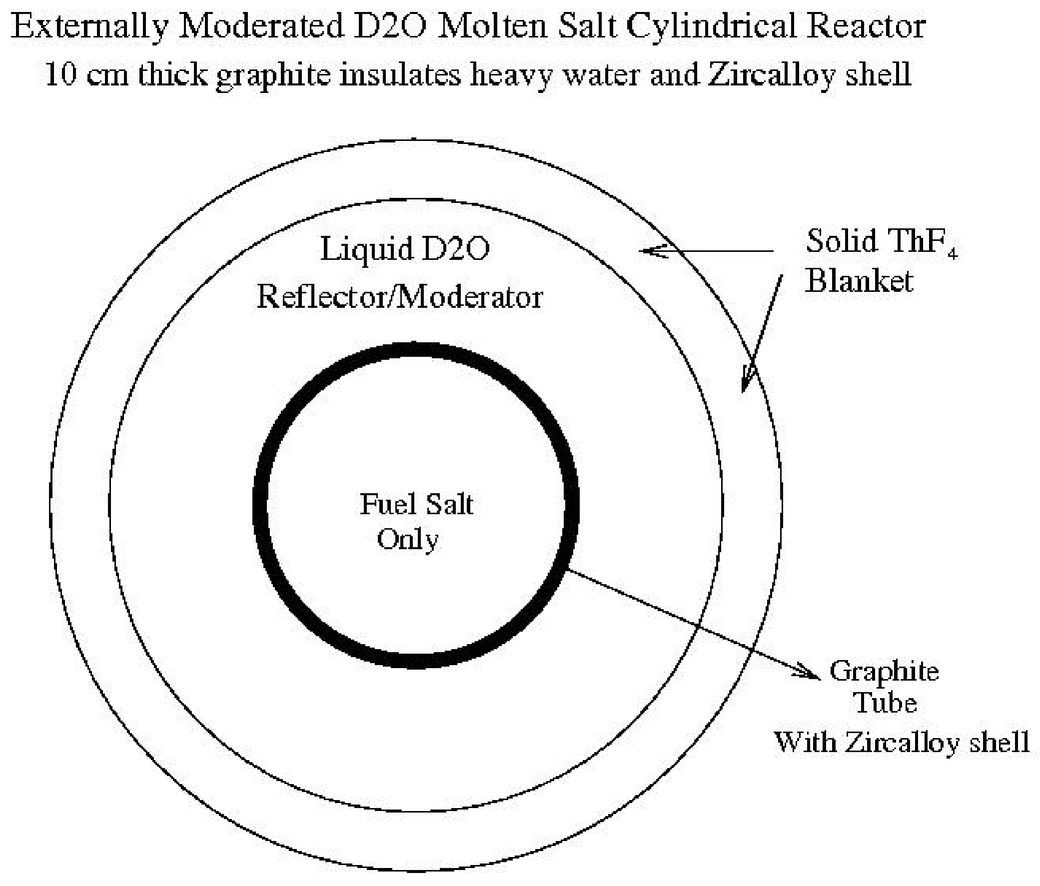
Hybrid Spectrum Molten Salt Cylindrical Reactor



Hybrid Spectrum Design

- Shown in 1950s that if fraction of fissions occur from thermal neutrons, the longer prompt neutron lifetime will dominate
- Will be large power spike at graphite interface but quickly intermixed by the salt flow
- Best of both worlds as Hastelloy barrier stays in harder spectrum while specific inventory drops

External D_2O Reflector/Moderator



Summary

- Elongated cylindrical or slab geometry allows the fuel processing benefits of 2 fluid designs without the "plumbing problem"
- With graphite moderation, extremely low specific inventories are possible. With 80 kw/l, reduced plenum volumes and new compact heat exchangers, 300 kg ^{233}U per Gw is an attainable goal. Start up on reactor grade Pu would require even less.
- Graphite free designs offer even greater simplicity but less operational experience

Conclusions

This Page Under Construction…