TERRESTRIAL ENERGY

Molten Salt Reactors

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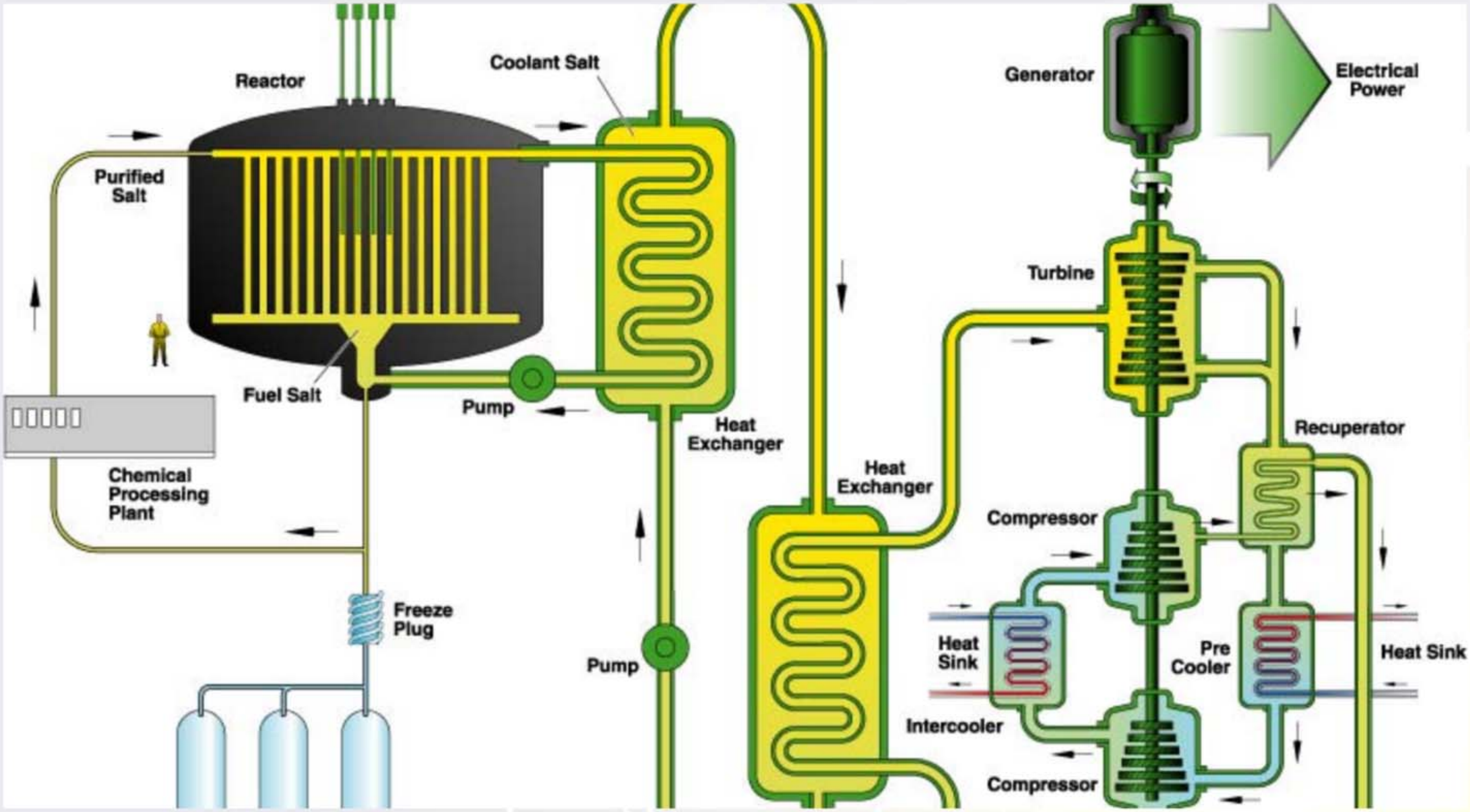
The Basics: Molten Salt Reactors

- Fuel (Th, U and/or Pu) dissolved in fluoride carrier salts like $2Li^7F\text{-}BeF_2$
- This fluid fuel is also the coolant and transfers heat to a secondary “clean” coolant salt
- High temperature operation (700 ^oC) couples well to many systems with high efficiency (upwards of 50%)
- Supercritical CO2, Steam, Helium or even open air cycles
- Typically graphite moderated

The 1970s Single Fluid, Graphite Moderated Molten Salt Breeder Reactor (MSBR)



Advantages of Molten Salt Reactors

- Safety
  - Inherent safety, passive decay heat removal, understandable to the public
  - Hard to even imagine accidents hazardous to the public
- Reduced Capital Cost
  - Low pressure, high thermal efficiency and far superior coolants (smaller pumps, heat exchangers)
- Long Lived Waste Profile
  - Even “burner” designs can have closed cycles that see almost no transuranics going to waste
  - Ideal system for consuming existing transuranic wastes
- Resource Sustainability and Low Fuel Cycle Cost
  - Thorium breeders obvious but MSR burners also extremely efficient on uranium use

KISS: Keep It Simple Stupid

- Many design choices possible
  - Single Fluid vs Two Fluid
  - Breeder vs Burner
  - Fast spectrum vs Thermal
  - Denatured or not
- Nuclear R&D and proving designs to regulators can be enormously expensive
- Every effort should be made to simplify and remove technological hurdles as well as proliferation and regulatory "what ifs"

Design Aspects to Avoid

- Continuous Reprocessing
  - High R&D, Capital cost and regulatory oversight
  - Some easier than others but none proven beyond lab scale
- Highly Enriched Uranium
  - Don't expect the world regulatory system to change for you
- Fertile Blankets
  - Why bring up proliferation "what ifs" if you can avoid it
- Fast Spectrum
  - Yes some advantages and likely can be made safe but will need to prove no chance of criticality accidents for any spills
- Implies Single Fluid, Softer Spectrum "burner" reactors

Design Choices
Breeder vs Burner?

- **Breeder**
  - Needs fissile to start (U233,U235, Pu) but afterwards makes own fuel
  - With MSRs this is traditionally the Thorium to U233 cycle
  - Requires processing of the salt to continuously remove fission products
  - Deemed a priority in the 1950s and 60s due to a mistaken belief in a severe shortage of uranium
- **Burner (i.e. converter)**
  - Needs annual fissile makeup
  - Can skip fuel processing
  - Less R&D needed
  - Core design greatly simplified

U.S. Historic Timeline

- First envisaged in 1940s
- 1950s becomes leading candidate in the well funded Aircraft Reactor Program
  - MSR to replace combustion heat for U.S. air force bombers
  - Even scientist skeptical of this, but attracted to the reactor
  - Huge knowledge base developed
  - Successful ARE test reactor operates in 1954 at over 800 C
  - Advent of ICMBs cancels program
- 1960s MSBR "Thorium Breeder"
  - Sodium Fast vs Thorium Thermal "Battle of the Breeders"
  - MSBR main goal of ORNL
  - Very successful 8MWth MSRE 1965-69, minor issues uncovered
  - He embrittlement (n,alpha reactions), Surface effects of Te fission product
  - Evolution from Two Fluid (1964-67) to Single Fluid "textbook" design 1968 onwards

U.S Historic Timeline

- Early 1970s
  - Program rolling along quite well
  - Modifying Hastelloy N and changing Ph of the salt address issues found in the MSRE
- 1973 Good old politics…
  - Many factors lead to first Alvin Weinberg, then the MSBR program falling out of favor
  - Program axed by the "infamous" Milton Shaw in favor of the fast breeder
  - Dixie Lee Ray named head of AEC, cleans house, including Milton Shaw
  - MSBR Program reinstated!
- 1976 Short lived reprieve
  - MSBR canceled again for "budgetary reasons"
- 1979-1980
  - Modest funding to examine highly proliferation resistant MSRs
  - Surprisingly attractive "Denatured MSR" the result
- Post 1980
  - Grant request for anything MSR related, a sure way to get denied from DOE
  - Hard to even speak the words MSR at ORNL as such a bitter memory of what could have been

World MSR Timeline

- Cancelation by the U.S. “inventors” of MSR not surprisingly curtailed world efforts
- However, over the decades, it has been revealed how wide and deep an interest there was in MSR development
- Long known France had a fairly extensive, independent MSR program
- In the 1990s we discovered Russia had a large program
  - Wide array of designs studied
  - Excellent work on improving nickel alloys
- Both China and India also had strong early programs

Summary of Current World Efforts

- Funded U.S. efforts now on "salt cooled, solid fueled" options or FHR (**F**luoride Salt, **H**igh **T**emperature Reactor). Many view as a compromise technology
- European efforts on Fast Spectrum, 1 and ½ Fluid design. Many challenges, only modest funding
- China has major 500M$ program with hundreds of staff and goal of first FHR Pebble Bed test reactor by 2017 and a true Molten Salt "fueled" reactor a few years later
- India actually was quite involved in the 1970s, large resurgent interest
  - Recent Molten Salt conference eye opening experience, moltensaltindia.org
- Several MSR Start Up firms in North America and worldwide

Conference on Molten Salts in Nuclear Technology, Mumbai, Jan 2013

Back to Breeder vs Burner

- Most researchers focus on pure breeders
- However, the R&D and operational costs of continuous salt process much higher than most assume
- A pure Th-U233 cycle also involves Highly Enriched Uranium. Many consider this a non-starter on proliferation grounds
- A “burner” has almost negligible fuel costs, assured resources, enhanced anti-proliferation features and overall is much simpler and less R&D and lower capital costs

DMSR Burner Reactor

- Oak Ridge`s 1000 MWe 30 Year Once Through Design (1980)
- Developed to maximize anti-proliferation
- Startup with LEU (20% ^{235}U) + Th or simply < 5% LEU
- No salt processing, just add small amounts of LEU annually
- Low power density core gives 30 year lifetime for graphite (8m x 8m)
- Only about **1/6th** the uranium needs of LWR
- Makeup Fuel cost only **0.1 cents/kWh**
- Better reactivity coefficients than MSBR
- Easily incorporates spent LWR fuel as a fuel source

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 "Burner" DMSR
- A few million tonnes U ore per year (51 kt U at world ave 3% ore grade)
- Compared to a few Gt (billion tonnes) iron and copper ore and 7 Gt of coal
- If uranium is used in DMSR designs, 100% of world's electricity (2500 GWe) without increasing current mining or enrichment
- Even if we needed to go to very low grade ore (0.03%) still only 200 Mt annual ore (most is now insitu recovery anyhow)

Denatured Molten Salt Reactors

- When salt finished, option to process and recycle
- Uranium simple and economical to remove, transuranics (Pu, Am, Np) should also be recycled
- Have up to 30 years to acquire equipment or do off site
- Under 1 tonne TRUs in salt at shutdown
- Assuming typical 0.1% processing loss, less than 1 kg in 30 years! As good or better radiotoxicity as pure Th-^{233}U cycle
- Reducing the Earth`s Radioactivity?
  - After 300 years, less radiotoxicity exists than before the reactor started (mainly from natural U234 being transmuted)
  - No other reactor can make this claim

Optimizing the DMSR Approach

- Majority of my work for several years
- Higher power density can lead to significant savings but means limited graphite lifetime
- Small Modular Reactor approach
- Shorter batches of salt can further improve uranium needs
- Alternate salts to avoid the need for enriched Lithium and/or contentious Beryllium of Flibe salt
- Many interesting options under investigation to simplify decay heat removal, off gas systems and pumping systems
- Borrow innovation in other fields where possible

New ORNL Innovation

- DOE funded work is on “salt cooled” or FHR (Fluoride salt cooled High temperature Reactor)
- Safety advantages and perhaps lower cost than LWRs but far short of true MSR potential
- MIT, UC Berkeley, Wisconsin effort on pebble bed design
- ORNL focus on solid fuel blocks, own set of pros and cons
- Focus on 1500 MWe AHTR design and small 50 MWe SmAHTR modular unit

ORNL's SmAHTR 50 MWe

Fig. ES.3. SmAHTR reactor vessel can be transported via tractor-trailer.

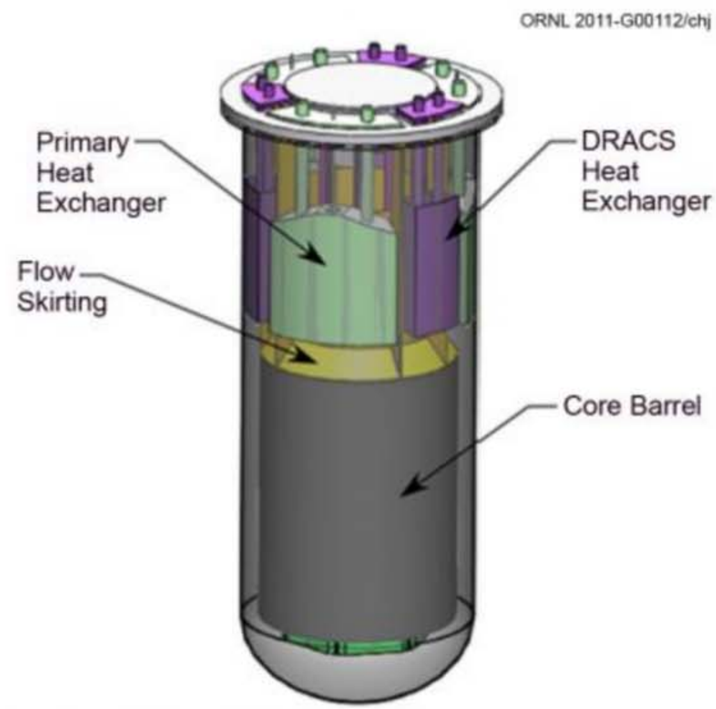


Fig. ES.1. SmAHTR integral primary system concept.

Many attractive innovations developed for SmAHTR, also attractive for DMSR

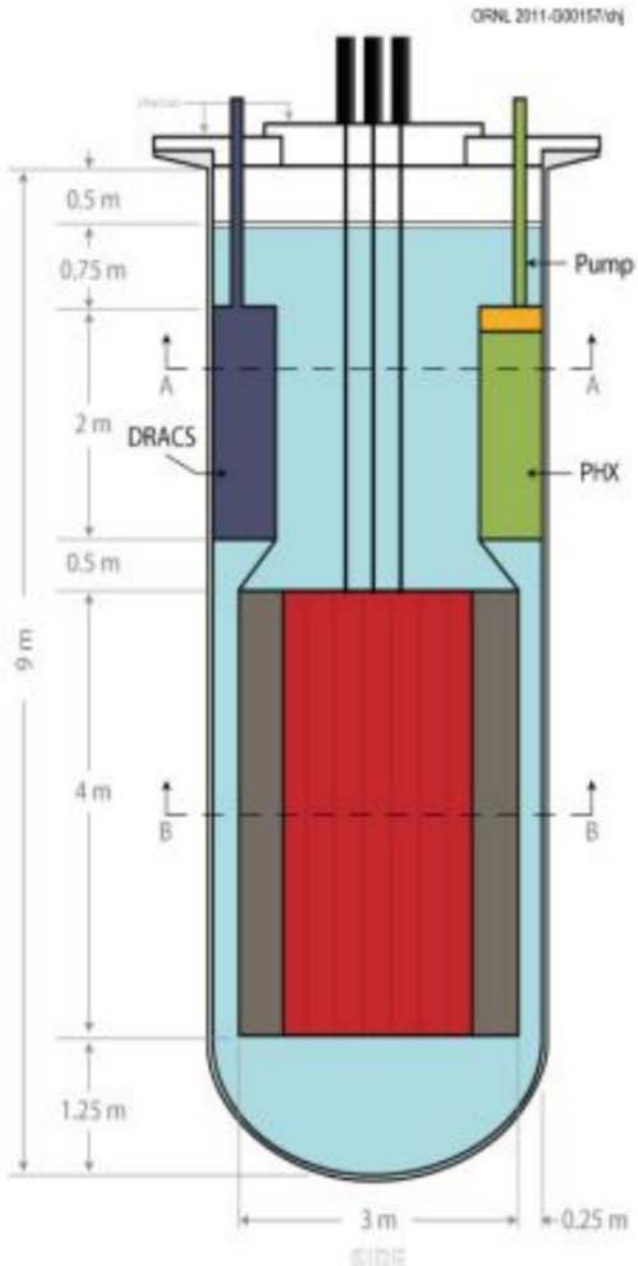
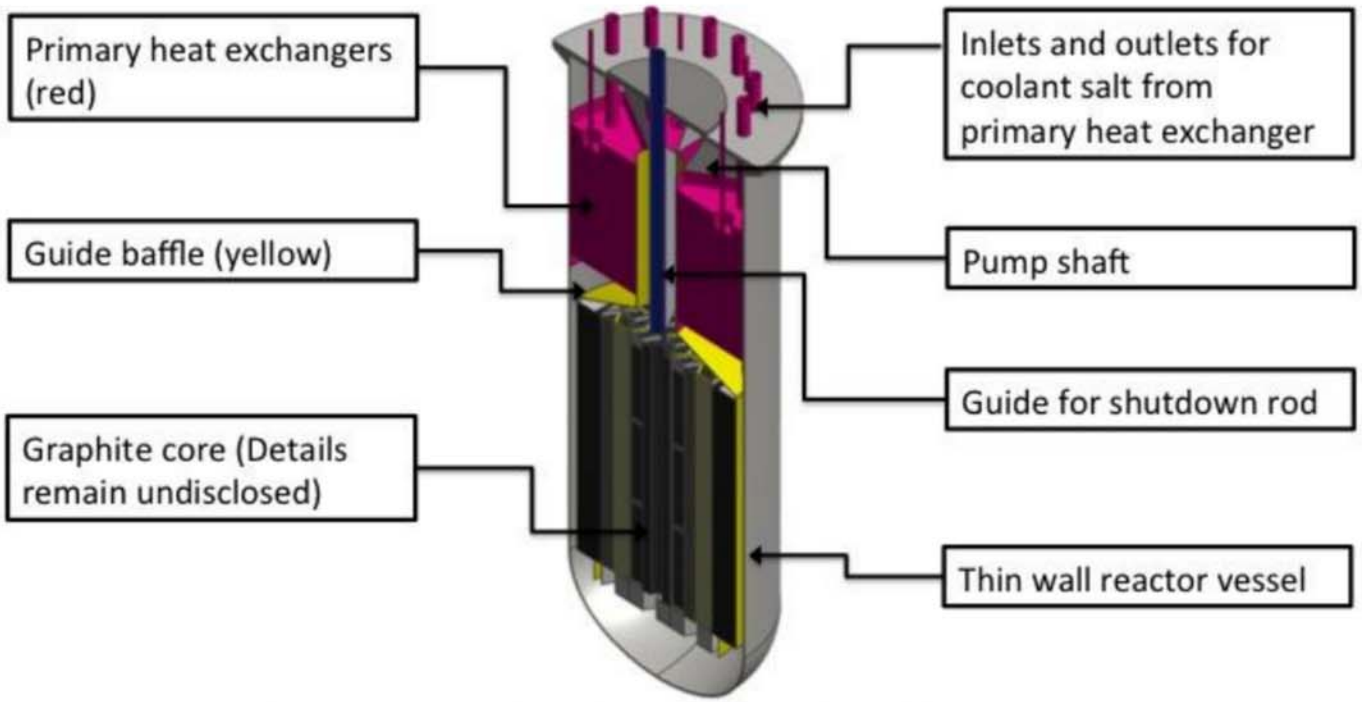


Fig. ES.2. SmAHTR dimensions.

Thanks ORNL
From “cooled” back to “fueled”?

- Integration of IHX within core and keeping vessel top away from salt and neutron flux a great idea
- Basic idea is take this and replace TRISCO core with simple graphite and put fuel back into the salt
- As heat generated directly in the fuel salt, easily go to higher power density, up to six times higher with similar graphite lifetime
- Units can be combined for even larger plants
- Obviously want to reduce out of core salt volume
- Larger internal heat exchangers for higher total power
- The following images only show “obvious” changes, much IP undisclosed.

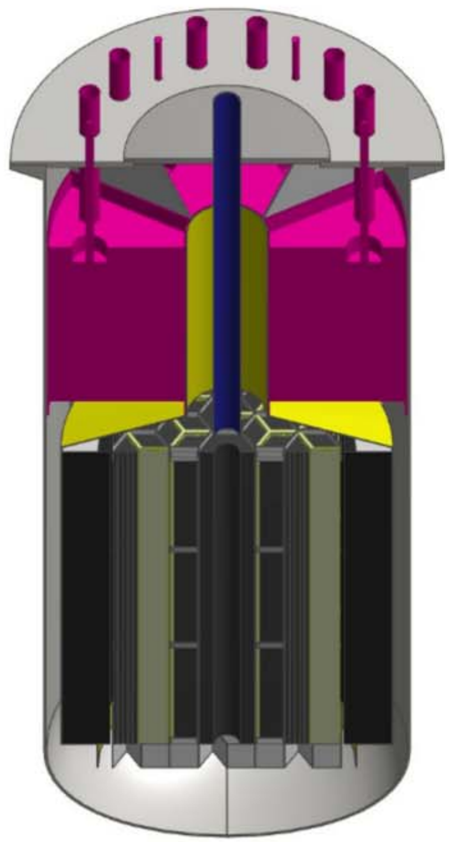
The Integral Molten Salt Reactor, IMSR (20MWe, 100MWe, 300MWe)



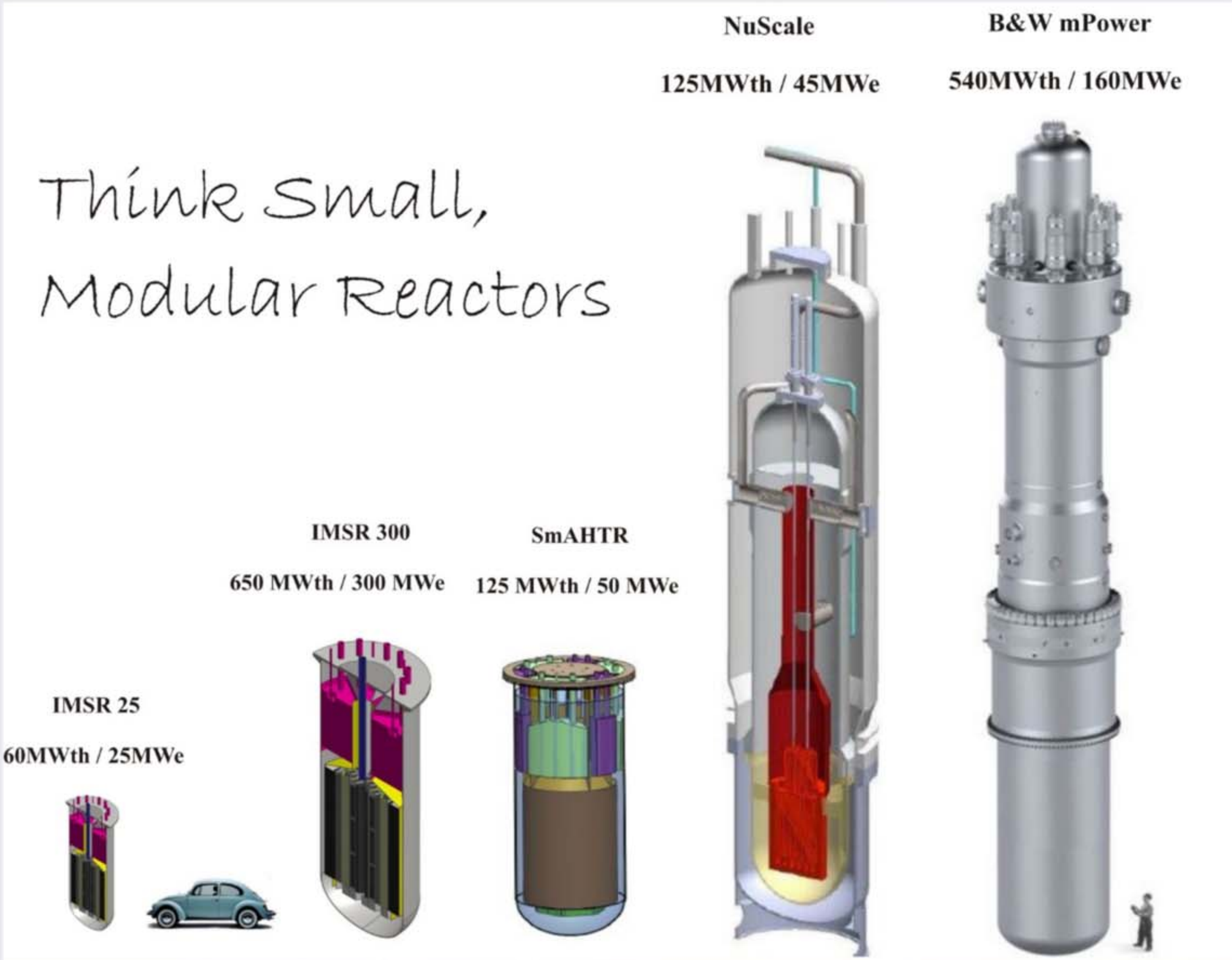
Fuel salt flows down the outside of the annulus, up through the core and then pumped through separate heat exchanges (red). Specifics of decay heat removal and Xenon and Krypton handling not depicted

Note: Many details undisclosed

Want Higher Power Density, More heat exchanger volume



IMSR version of SmAHTR can be upwards of 6 times the power output



Not So Fast…

- Many significant challenges
- Hastelloy N has limited lifetime when exposed to neutrons, must thus greatly limit flux reaching vessel
- Must design to ease replacement of components and graphite
- Opening the reactor to replace graphite and/or service heat exchangers NOT TRIVIAL
  - Even traces of volatile fission products will mean large regulatory challenges
  - Always a big debate at ORNL: Low power density and keep things shut for good favored by many but drives up cost
- Age old issue of interesting manufactures without the "razorblade" of long term fuel fabrication contracts

Where To From Here?

- Worldwide interest in Molten Salt Reactors continues to grow
- Safety case, improved waste profile and resource stability obvious selling points to the public
- Economic case has potential to win over governments and corporations
- For the private energy sector, long horizons a tough sell
- BUT, since industrial heat also our commodity, entire industries may realize they can't afford NOT to get involved
- Ex. Steam for Canadian Oil Sands Extraction
  - 15 to 25 year development horizons normal there

Canadian Focal Point?

- Strong Nuclear Community going idle as "advanced" CANDU work halted
- University sector and Chalk River Nuclear Laboratories very interested
- CNSC far less "inertia" than NRC and is very open to evaluating Small Reactor designs in Canada
- Oil Sands developers could fund entire IMSR development from pocket change
  - When affordable oil is gone, they'd still have a piece of the energy pie

Introducing…
Terrestrial Energy Inc.

- Recently founded by core group with diverse financial and entrepreneurial expertise including Oil Sands insiders all drawn to MSR's potential
- My job, with the help of gathered talent, to further refine and consolidate design for the most Capex and R&D efficient DMSR, the patent pending IMSR
- Their job, to attract the modest investment and industrial partners needed to get to the conceptual blueprint stage
- Followed by the more challenging stage of funding a demonstration reactor
- As IP and patents are disclosed, I hope to make their job a lot easier

Thank you for your attention!

EXTRA SLIDES…

LWR Fuel Cycle Costs

All assume 100$/kg U and 150$/kgSWU

- Light Water Reactor (per Gwe)
- 20M$ Uranium (200 Tonnes, 100$/kg)
- 20M$ Enrichment
- 10M$ Fuel Fabrication
- Annual Fuel Cost **0.6 cents/kwh**
- **But** must pay off initial fuel load
  - 3 to 5 Tonnes U235 + Fabrication
  - ~200M$ = 0.26 c/kwh (10% Discount Rate)

- Total Fuel Cycle ~ **0.86 cents/kwh**

Fast Breeder Fuel Cycle Costs

- Sodium Fast Breeder
- Capex of reprocessing equipment???
- Fabrication costs?
- Looking **only** at the initial load of fissile*
- Need ~ 18 Tonnes Reactor Grade Pu (12 T fissile)
  - 100$/gram = 1.8 B$ = **2.3 c/kwh**
- Or start on ~ 20 T U235 at 50$/g = 1.25 c/kwh
  - 20 years worth of U235 for a LWR
  - Over a hundred years worth for a DMSR
- This does ignore Pu production credit but processing costs must be factored in
- IFR or TWR are about half traditional FBR startup

- * Yes, there are current stockpiles of separated Pu but limited supply and paid by tax payers.

MSBR Fuel Cycle Costs

Estimate based on ORNL 4541 and 4812 (1972) and 7.5 times “nuclear” inflation
Old 75% capacity factor but new 10% discount rate (ORNL was 13.5%)

- Single Fluid Graphite Breeder (MSBR 1970s)
- 1500 kg/GWe starting fissile load
- 150 M$ fissile 100$/g U233 or Pu= 0.23 c/kwh
- Annual and startup Thorium = negligible
- Starting and makeup salt = 0.07 cents/kwh
  - Enriched Lithium costs an unknown factor but likely low impact
- 10 day processing cycle
- Processing Plant Cap + Op
  - ORNL 4541, 100M$ 0.16 cents/kwh
  - ORNL 4812, 260M$ 0.4 c/kwh
- Sounds high but still only 5$/kg of salt processed
  - PUREX is 1000$/kg
- Total Fuel Cycle = 0.46 to 0.7 cents/kwh
  - Large Processing cost uncertainty

MSFR Fuel Cycle Costs

Estimate based on ORNL 4541 and 4812 and 7.5 times "nuclear" inflation
Old 75% capacity factor but new 10% discount rate (ORNL was 13.5%)

- Fast Spectrum (MSFR 2005 to present)
- 5.5 T/GWe, 6 month processing time
- 550 M$ fissile 100$/g U233 or Pu= 0.85 c/kwh
- Less starting and makeup salt = 0.03 cents/kwh
- Processing Plant Cap + Op
  - Much lower rate (1/18th MSBR) but economy of scale lost?
  - Also need process blanket salt
  - ~0.1 cents/kwh? Perhaps much higher?
- Total Fuel Cycle ~ 1 cent/kwh
  - Again large cost uncertainty

DMSR Fuel Cycle Costs

Estimate based on ORNL 4541 and 4812 and 7.5 times “nuclear” inflation
Old 75% capacity factor but new 10% discount rate (ORNL was 13.5%)

- Single Fluid Graphite Converter (DMSR 1980)
- Runs off Thorium plus Low Enriched Uranium
- 3450 kg/GWe starting fissile, **No processing**
- 175 M$ fissile 50$/g U235= 0.26 c/kwh
- Annual and startup Thorium = negligible
- More carrier salt = 0.14 cents/kwh
  - Converter able to use inexpensive alternate salts
- Average Conversion Ratio 0.8 over 30 years
  - ~150 kg/year U235 (in LEU)
  - 50$/g = 7.8M$/year = **0.12 cents/kwh**
  -
- Total Fuel Cycle **= 0.52 cents/kwh**
  - Very little uncertainty
  - 9 T of Pu (IFR startup) would start and run for over 30 years
  - Great potential for improvement

MSR Fuel Cycle Costs

- If a thorium based MSR does not break even, needs makeup of Pu or U233
  - Uncertainty of supply and high cost
- If a Uranium or U+Th based MSR does not break even, simply makeup with LEU
- A DMSR can be modified to have even better Conversion Ratio still without processing
  - C.R. = 0.9, ~20 tonnes U/GWe-year, 0.06 c/kwh
- Or, a DMSR can be further simplified, low cost salts, lower cost graphite, less fissile startup etc.
  - C.R. = 0.7 ~60 tonnes U/GWe-year, 0.18 c/kwh

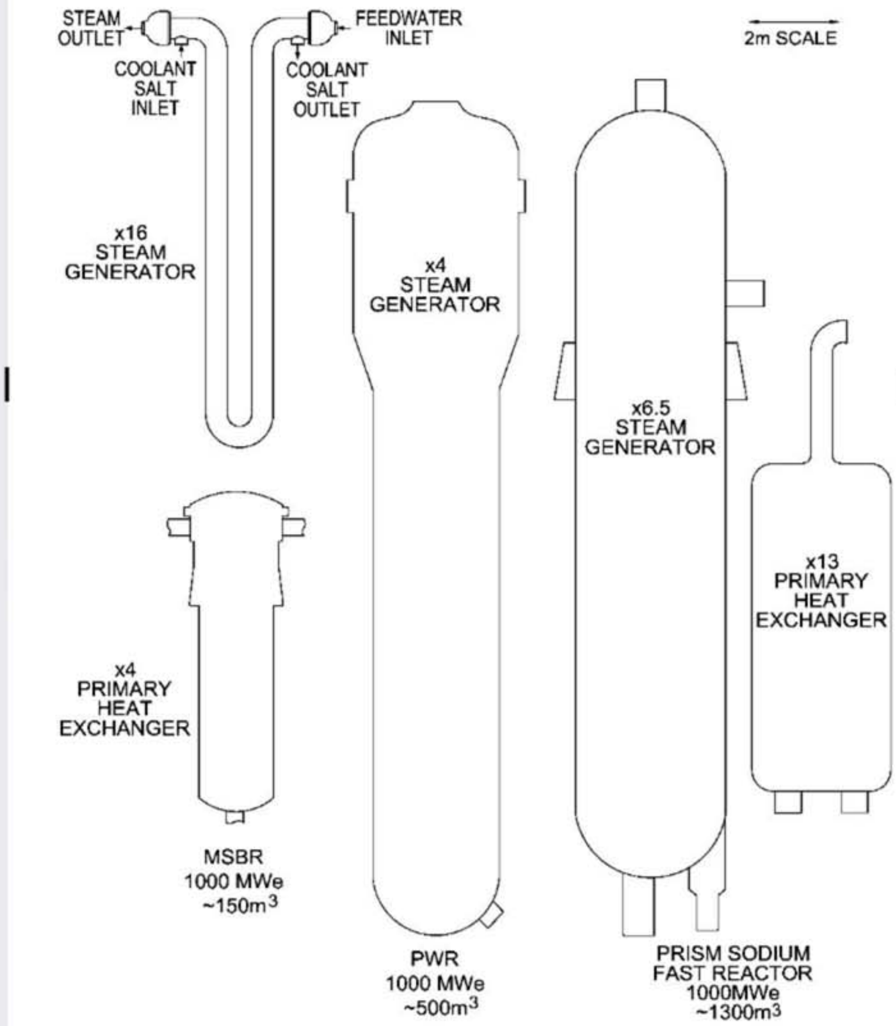
- More on the DMSR later….

What factors differentiate between various Molten Salt designs?

- R&D required and level of technological uncertainty
- Amount and type of startup fissile load and thus deployability
- Whether fission product removal is used and if so, its degree of difficulty
- Reactivity coefficients
- Degree of Proliferation Resistance

Comparing Heat Exchange Equipment
MSBR vs **PWR** vs **Sodium FBR**

MSR 1/ 3 the total volume of PWR



MSR 1/ 9 the total volume of FBR

Advantages of all Molten Salt Reactors
Safety

- No pressure vessel
- 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
  - Both Cesium and Iodine stable within the salt
- No excess reactivity needed
  - Even control rods are optional
- Very stable with instantly acting negative temperature reactivity coefficients
- Passive Decay Heat removal

Off Gas Both a Benefit and Challenge

- Dealing with fission products gasses and/or tritium a major challenge
- Many FPs have Xe or Kr precursors
  - Over 40% of FPs leave core
  - Large fraction of Cesium, Strontium and Iodine end up in Off Gas System
- ORNL work for 1000MWe plant
  - 2 hrs in drain tank (all Cs137) ~20MW
  - Then 47 hr delay charcoal beds ~2MW
  - 90 day long term beds ~0.25MW
  - 23 m3 of Kr+Xe a year in 8 gas bottles

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 can be kept in or recycled back into the reactor to fission off

Advantages of all Molten Salt Reactors

Resource Sustainability

- Once started breeder designs only require minor amounts of thorium (about 1-10 tonne per GWe year)
  - 30 k$ of thorium = 500 M$ electricity
  - Must include processing costs though
- Converter designs are far simpler and only require modest amounts of uranium
  - Typically 35 tonnes U per GWe-year versus 200 tonnes for LWRs
  - Annual Fuel cycle cost ~ 0.1 cents/kwh

A Strange Beginning
An Aircraft Reactor?

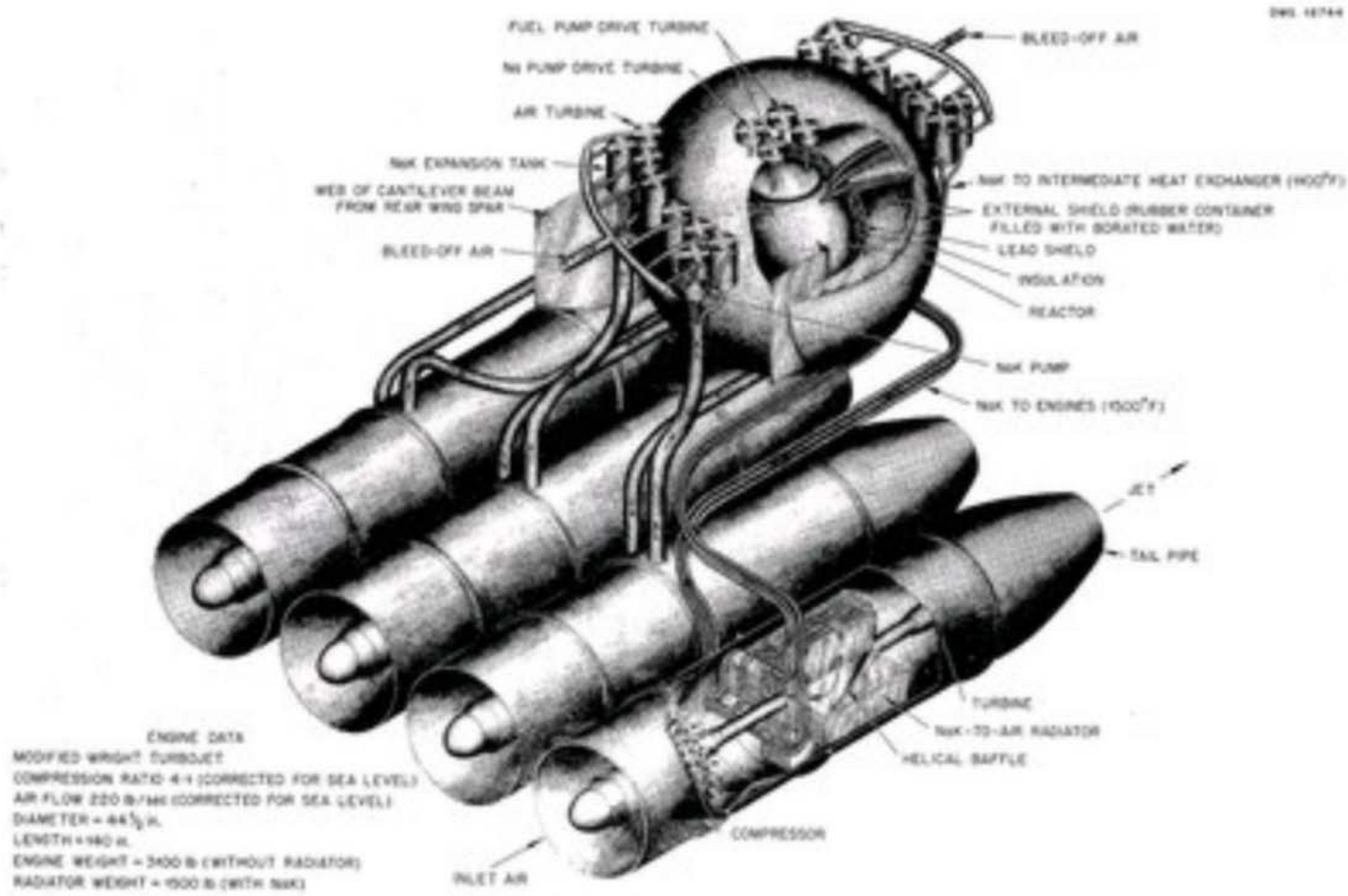


Fig. 4.33. Aircraft Power Plant (200 Megawatt).

I told you I'd bring this up Jess…

From Dr. Jess Gehin's excellent presentation

http://www.itheo.org/thorium-energy-conference-2011

There are several new technologies that must be introduced for deployment of Commercial MSRs

- >5 wt%U-235 LEU fuel (needed for startup)
- U-233 as the fissile material
- The use of thorium
- Salt processing system (possibly online during operation)
- Development and deployment of a new Li-7 enrichment capability
- High temperature operation (potentially with a Brayton power conversion system)
- Off-gas handling and storage system

No

No

No

No

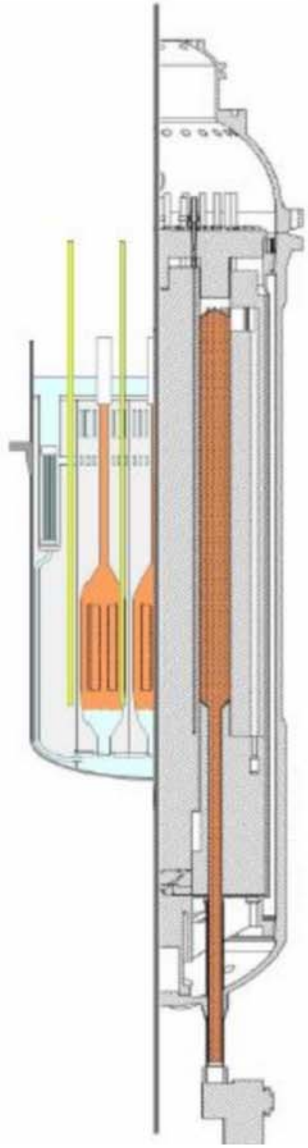
No

Not Really

Maybe

Pebble Bed FHR (MIT, UCB, Wisconsin)

900 MWth
FHR

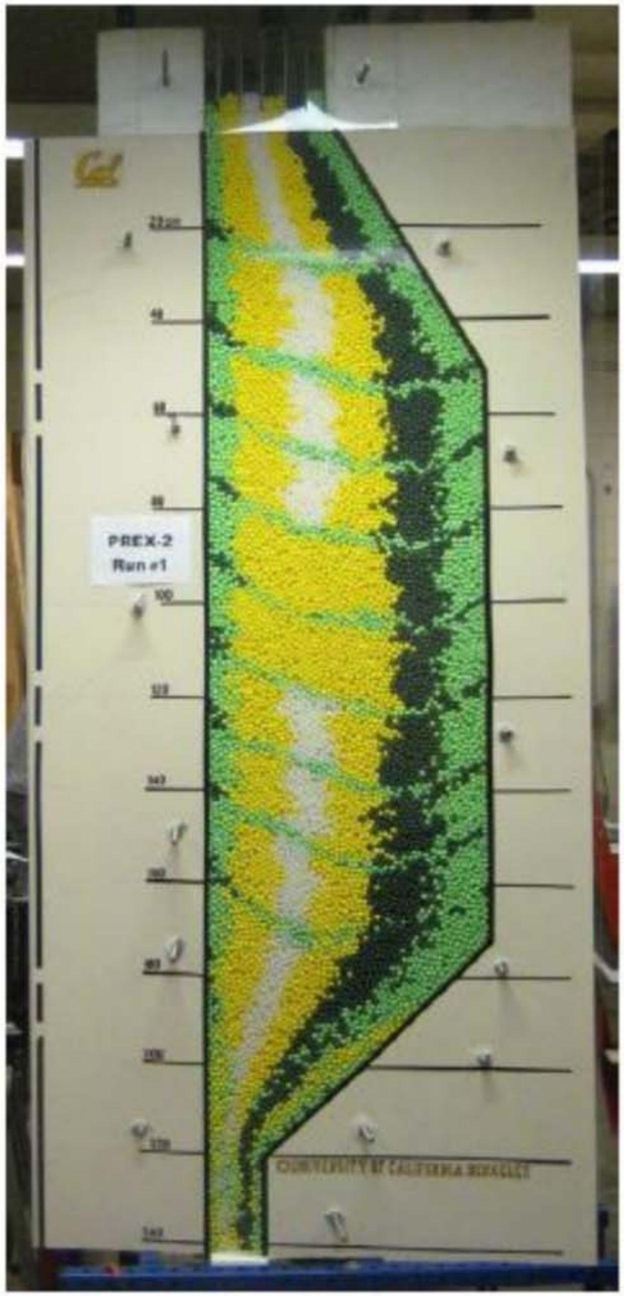


400 MWth
Gas Cooled

Pebble Bed FHR

- Pebbles can be cycled out so excess fissile and burnable poison not really needed
- Modest Uranium savings over LWRs (roughly CANDU levels)
- Newest version has Pebble stratified within core, varied by burn up

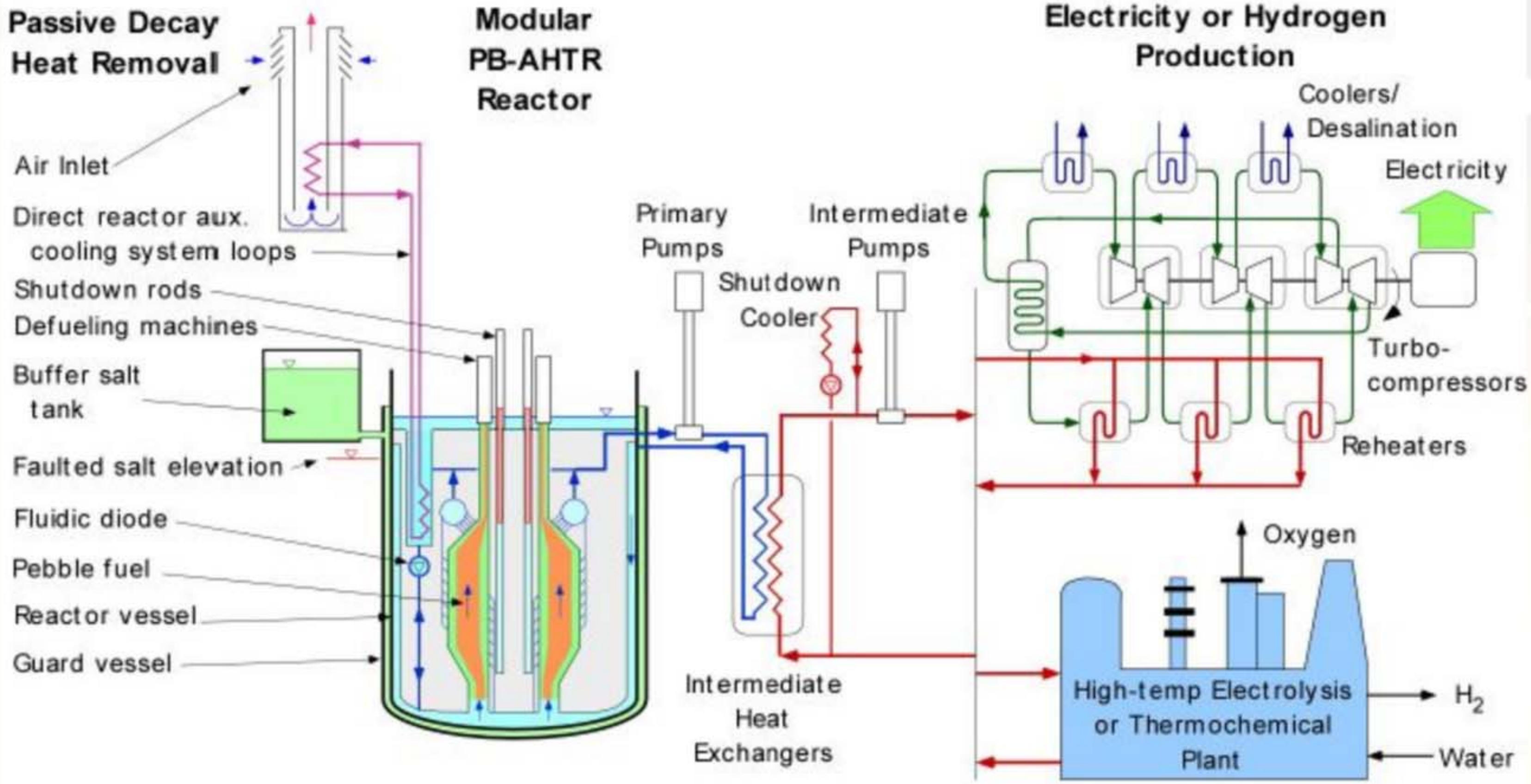
Testing
Pebble Flow
UC Berkeley



PREX-2

Also uses complex arrangement of Axial and Radial flow to lower pumping power

The modular PB-AHTR is a compact pool-type reactor with passive decay heat removal



DMSR Extremely High Proliferation Resistance

- Plant does not process the fuel salt
- Uranium always denatured, at no stage is it weapons usable
- Any Pu present is of very low quality, very dilute in highly radioactive salt and very hard to remove
  - About 3 times the spontaneous fission rate of LWR Pu and 5 times the heat rate (72.5 W/kg)
- No way to quickly cycle in and out fertile to produce fissile

What factors differentiate between various Molten Salt designs?

- R&D required and level of technological uncertainty
- Amount and type of startup fissile load and thus deployability
- Whether fission product removal is used and if so, its degree of difficulty
- Reactivity coefficients
- Degree of Proliferation Resistance

The World Needs Nuclear

- LWRs and HWRs mature technology but little area for improvements and widespread adoption unlikely
- Supercritical Water
  - Extremely challenging material science, still many years off
- Gas Cooled Prismatic or Pebble Beds
  - Good safety case, economics marginal
  - Must co-develop fuel fabrication and Brayton turbines
- Fast breeders
  - Decades and billions later, still unproven economics
- Small Modular LWR or FBRs
  - Fine for niche markets, unlikely a base load competitor
- **Molten Salt Reactors have the potential to be true game changers**

More on Molten Salt "Cooled" Reactors FHRs

- Basic concept is salt coolants are far superior to He or CO_2
  - TRISO fuel elements
  - Ambient Pressure
  - Can go to large total power and still have passive decay heat removal by natural convention of the salts
- Only "Flibe" $2Li^7F\text{-}BeF_2$ gives desired negative void coefficient
- Many involved would also favor true "fueled" MSRs but feel "cooled" is a more immediate or fundable step