Molten Salt Reactors and the Oil Sands: Odd Couple or Key to North American Energy Independence?

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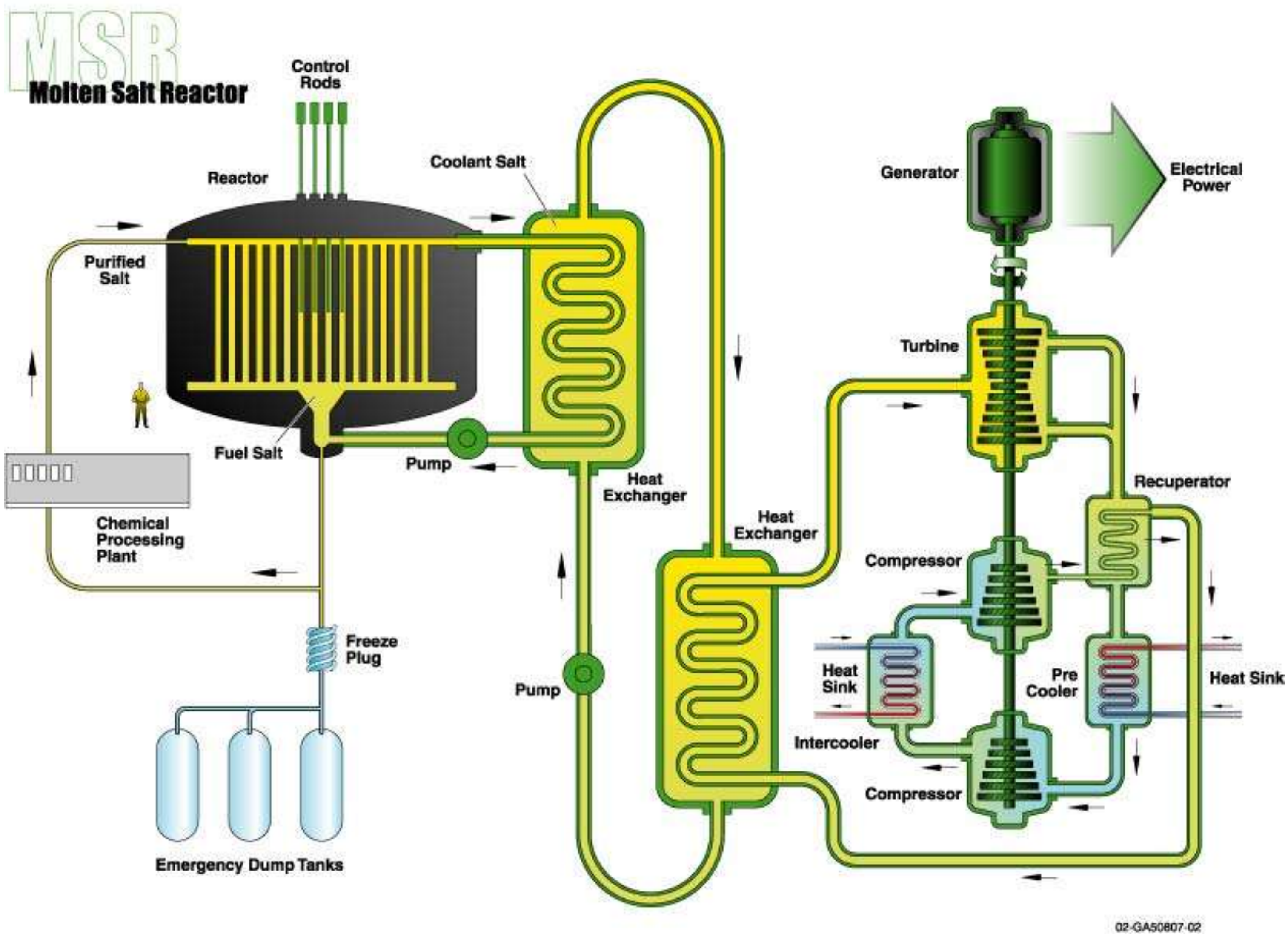
The Basics: Molten Salt Reactors

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



Breeder vs Burner?

- **Breeder**
- Makes its own fuel after startup
- If “just enough” called Break Even
- Requires processing to continuously remove fission products
- **Burner (i.e. converter or DMSR)**
- Needs annual fissile makeup
- Skips fuel processing
- Much less R&D needed
- Core design greatly simplified

A Brief History of Molten Salt Reactors

- Earliest efforts in support Aircraft Reactor Program
  - Large knowledge base developed
  - Test reactor operates at 860 ^{o}C
- Major reactor development program at Oak Ridge National Labs late 1950s until early 1970s
  - Major focus of ORNL
  - Mandated to be a Breeder reactor in competition with Sodium Fast Breeder

A Brief History of Molten Salt Reactors

- Very successful 8MWth test reactor from 1965 to 1969, MSRE
- Design goes through several phases up to the Single Fluid MSBR (1968)
- In 1973, very controversial decision made to cancel program
- Limited work continued at ORNL until early 1980s, highlighted by the Denatured Molten Salt Reactor

A Brief History of Molten Salt Reactors

- Like all reactor programs, very little done in 1980s and 90s
- Major boost in 2002 with MSRs chosen as one of only six Gen IV designs worldwide
- Pre-2011: Strong programs in France, Russia and Czech republic, but still near zero funding elsewhere
- U.S. funded efforts on using molten salts as coolants of TRISO solid fuel
  - Viewed as intermediate step to salt “fueled”

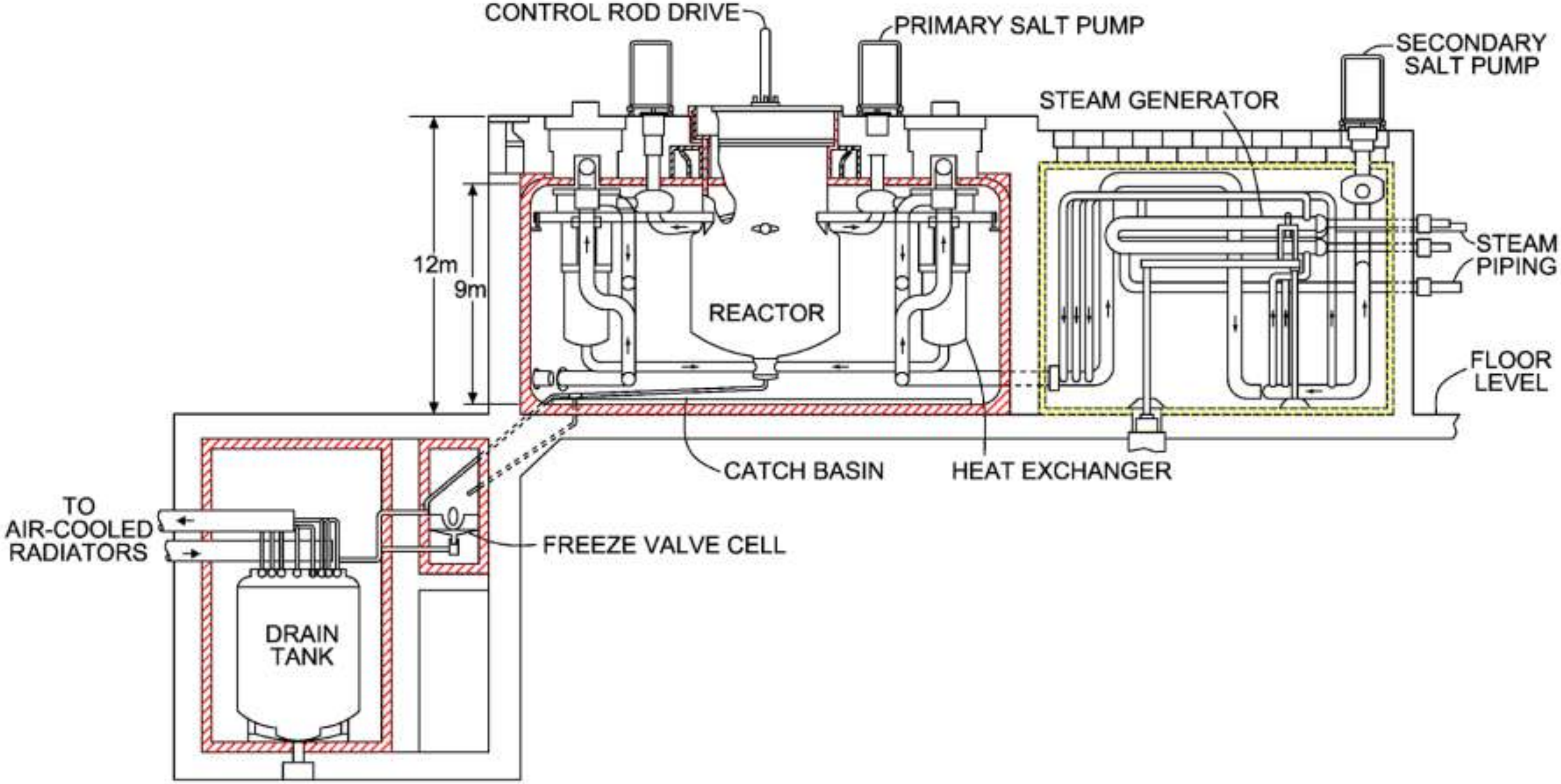
Molten Salt Reactor Advantages

- Many potential variations but sharing unique advantages
- Increased Safety
- Reduced Costs
- Resource Sustainability
- Greatly Reduced Long Lived Wastes

Advantages of all Molten Salt Reactors
Safety

- No chemical driving forces (steam build up or explosions, hydrogen production etc)
- No pressure vessel
- Almost no volatile fission products in salt
  - Continuously removed to an Off Gas system
  - Cesium and Iodine stable within the salt
  - A spill solidifies and traps fission products
- No excess reactivity needed
  - Even control rods are optional
- Very stable with instantly acting negative temperature reactivity coefficients
- Passive Decay Heat removal

All radiation within a sealed "Hot Cell"



Advantages of all Molten Salt Reactors
Low Capital Costs

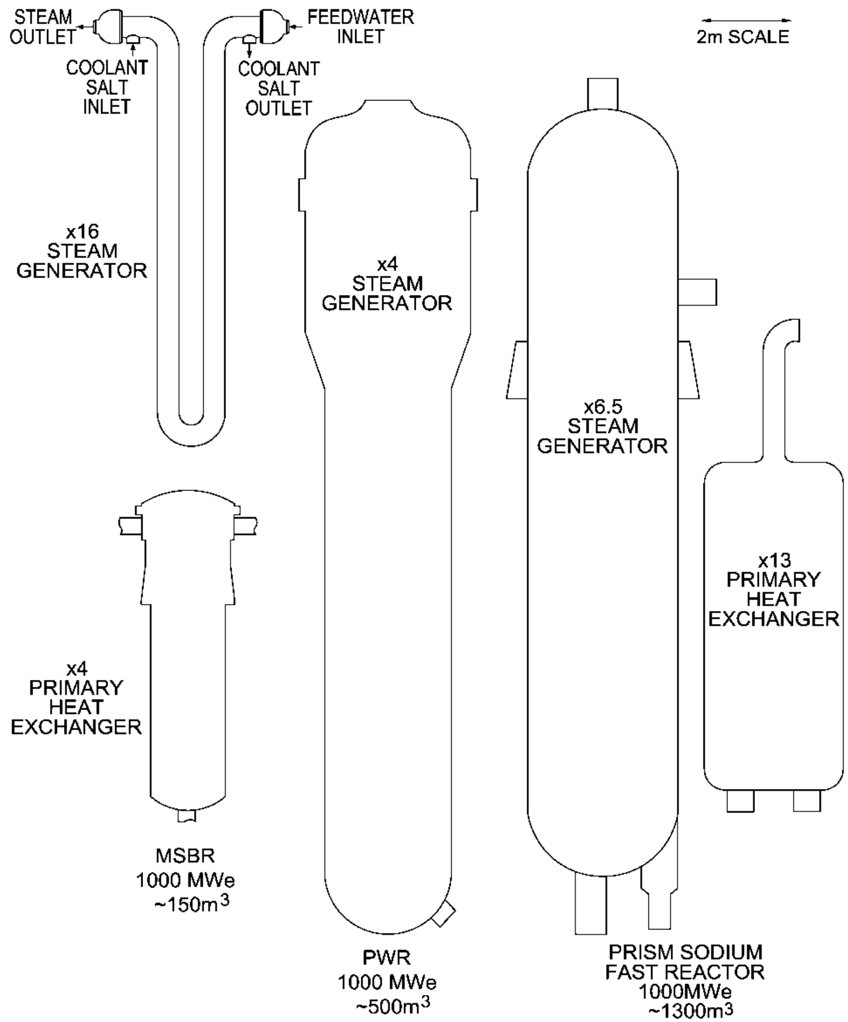
- Molten salts are superior coolants so heat exchangers and pumps are smaller and easy to fabricate
- This has a trickle down effect on building design, construction schedules and ease of factory fabrication
- Much higher thermal efficiency (up to 50%) than LWR or FBR using Steam or Gas (He, CO_2, N_2)
- Fuel cycle costs extremely low
- Inherent safety reduces need for elaborate engineered defenses. No massive internal structure for steam containment and vast water reserves

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

Greatly Reduced 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 Mountains"
- All designs produce less TRUs and can be kept in or recycled back into the reactor to fission off
- Over a thousand fold improvement over conventional "Once Through"

Reexamining MSRs

- MSRs often thought of as the "thorium" reactor
- By mandate they were developed as breeders to compete with the Sodium Fast Breeder
- The belief at the time was Uranium resources were extremely limited, we now know better
- MSRs can be both "burners" or "breeders" but choices must come down to pragmatic facts, not ideology or imposed funding mandates
- However, no one can dispute the success of advancing "thorium" to the public
- *Come for the Thorium*
  Stay for the REACTOR!

Back to *Breeder vs Burner*

- Researchers tend to focus on pure breeders
- However, the required R&D and operational costs of continuous salt process higher than most assume
- Removing the requirement to breed opens up all manner of design simplification
- A "burner" has almost negligible fuel costs, assured resources, enhanced anti-proliferation features and overall is much simpler with less R&D
- Appears the obvious choice and breeder options can be pursued later

DMSR Converter Reactors

- Starting Premise is Oak Ridge`s *30 Year Once Through Design* (1980)
- 1000 MWe output
- Start-up with LEU (20% ^{235}U) + Th
- No salt processing, just add small amounts of LEU annually
- Low power density core gives 30 year lifetime for graphite (8m x 8m)
- Lower fissile start-up load than LWR (3.5 t/GWe)
- Better reactivity coefficients than MSBR

Denatured Molten Salt Reactors

- Only 1/6th the annual uranium needs of conventional reactors
  - 35 tonnes per GWe-year
  - 200 tonnes for LWRs
  - 150 tonnes for CANDU
- No fuel fabrication cost or salt processing = extremely low fuel costs
  - Under 0.1 cents/kwh

Denatured Molten Salt Reactors

- After 30 year batch, Uranium can be removed and reused
- Done by bubbling fluorine gas through salt to turn UF_4 to gaseous UF_6
- Transuranics should also be recycled
- Under 1 tonne TRUs in salt at shutdown
- Assuming typical 0.1% processing loss, less than 1 kg in 30 years! As low or lower radiotoxicity than the pure Th-^{233}U cycle
- Reducing the Earth`s Radioactivity?
  - After 300 years, a net reduction of radiotoxicity (mainly from natural U234 being transmuted)
  - No other reactor can make this claim

How does a DMSR do so good?

- Isn't Heavy water better than graphite?
- Key is far less parasitic losses of neutrons
  - No internal structure
  - No burnable poisons
  - Less neutron leakage
- LWR 22% parasitic losses (without FPs)
- CANDU 12%
- DMSR 5%
- Plus almost half of fission products and all important Xe135 leave to Off Gas system
- Plus fissile produced in situ is almost all burned in situ. LWRs and CANDU throw most out

Suggested Improvements on ORNL Design

- *Shorter batch cycles of the salt*
- If U is recycled (TRUs can wait) large improvement in U needs
- 10 to 15 year batches likely
- **20 t U per GWe year and 24,000 SWU**
- Just 10% of LWR requirement
- All world's electricity (2500 GWe) without needing new mining or enrichment

A LEU Only DMSR

- Running without thorium has many interesting advantages
- Neutron economy not as quite as good but still excellent uranium utilization
- No Protactinium
  - Can run any power density
- Lower melting point
- Simpler to re-enrich uranium (no U232) to recycle Uranium indefinitely

- Many new options not ready yet for public disclosure but next is a hint…

Thanks ORNL
Turning "cooled" to "fueled"

Basic idea is take ORNL's new 50 MWe Salt "Cooled" SmAHTR and replace TRISCO core with simple graphite and put fuel into the salt

Integration of IHX within core and keeping vessel top away from salt and neutron flux a great idea

Short shutdowns to open vessel and replace graphite and/or IHXs every 4 years

Easily go to higher power density but likely keep it to 100 MWe (200 MWth) to fit new CNSC small reactor regulations

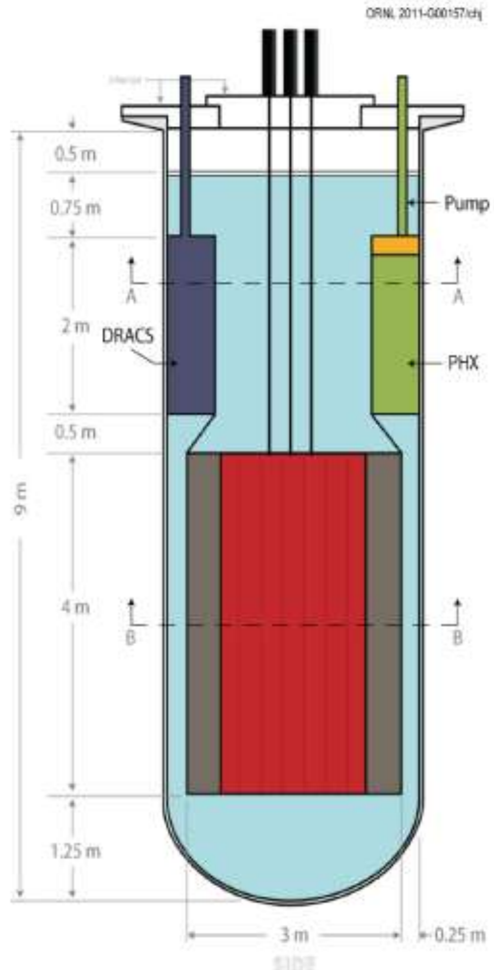


Fig. ES.2. SmAHTR dimensions.

A MSR Renaissance?

- For past several years, academic, public and media attention growing
  - Thorium *angle* at the forefront but it is the reactor itself that is the real draw
- 2011 saw two game changers
  - China announces major MSR program
  - Fukushima has everyone looking into safer designs
- Widespread investor interest but as usual, regulation situation the great unknown

Made in China?

- Program announced early 2011
- Run by Chinese Academy of Science in Shanghai
- 500 M$, 5 year budget, staff of 400
- Plan first reactor by 2015
  - First a Zero Power reactor, then 2MWth, 10 MWe and100 MWe
- Focus on Thorium Breeder
- Plan to license technology and sell to the West

Elsewhere…

- U.S. efforts hindered by ineffectual DOE, NRC and Congress
- Europe focus on Fast spectrum MSFR with many benefits but much larger R&D challenge and little funding
- Japan has had long term MSR activity, now watching China take over
- India just declared MSR interest and will host a major conference Jan 2013

Molten Salt Reactors
Oh Canada!

For Better or Worse

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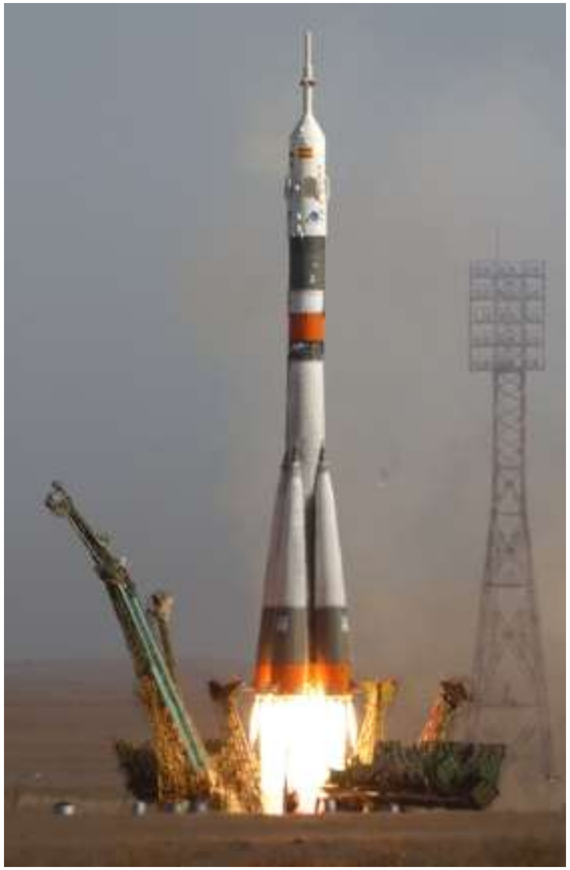


Corporate and Academic Pursuit of New CANDU Designs Halted

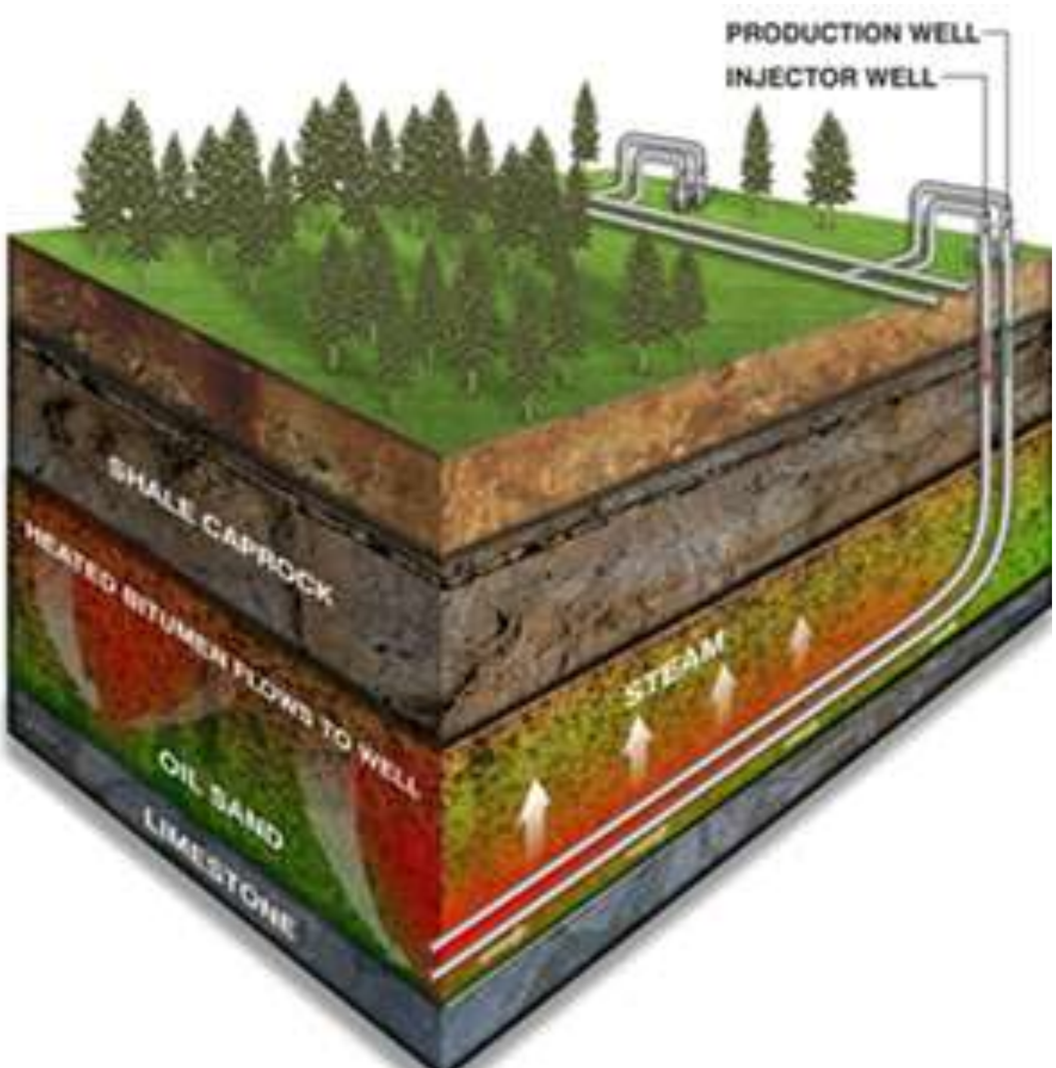
Molten Salt Reactors
Oh Canada!

- CANDU EC6 a great design the world will hopefully rediscover
  - But no new R&D for foreseeable future
- Canada has enormous nuclear brain trust going to waste
- We went our own way before, we can do it again
- Canada also has unique opportunities in our Oil Sands

The MSR, Oil Sands Connection

- Using nuclear produced steam for Oil Sands production long studied
- Vast majority of oil only accessible by In-Situ methods
- Steam Assisted Gravity Drainage SAGD main method and surpassing mined oil sands
- Availability and price stability of Natural Gas long known to be a bottleneck
- As well, global acceptance of Oil Sands oil hindered by large CO2 releases

Steam Assisted Gravity Drainage SAGD



SAGD Needs

- Typically 7 to 12 MPa (over 1000 psi) and 275 to 330 C
  - Cyclic Steam Simulation need higher T and P
- Pressure and temp drop in piping limits distance of wells to facility (~3 MPa and 40 ^{o}C drop for 10 km)
- 300 MW(th) steam output for a standard sized 30,000 bbls/day facility
- Above all, nuclear must be modest cost to compete with Natural Gas

The Oil Sands Allure

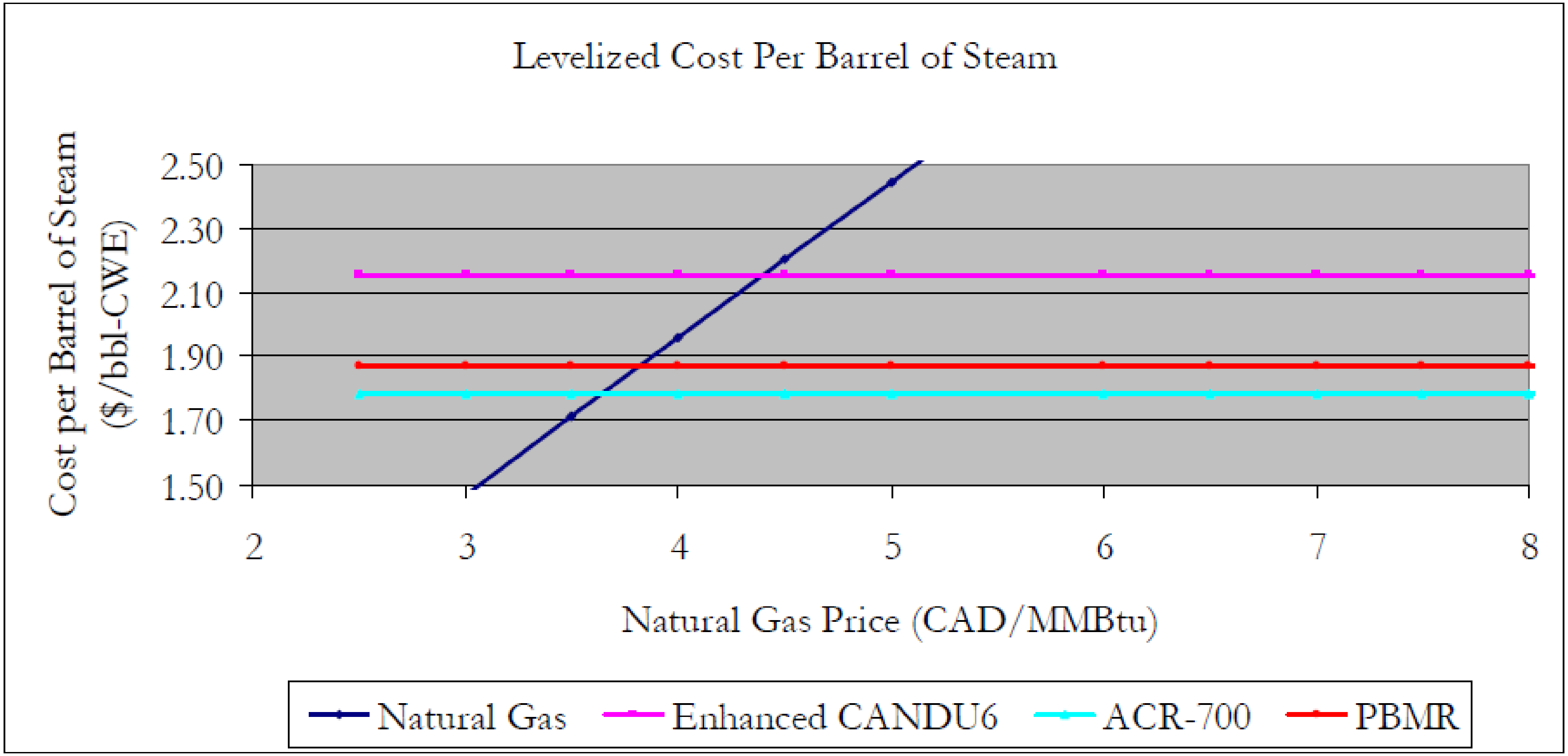
- Long viewed an ideal proving ground for nuclear technology
- No turbine island needed
  - 30% to 40% the capital cost saved
  - R&D for any new turbine can sink a nuclear development (ask the South Africans)
- Oil sands producers expected to pay 200 Billion$ on carbon taxes over the next 35 years, funds mandated to be spent on cleantech initiatives

MIT Thesis 2006

Integration of Nuclear Power with Oil Sands Extraction Projects in Canada

By Ashley Finan

- For overnight capital costs of 2.6 to 3.4$/watt(e) and 1/3 reduction on $/watt(th) for no turbine

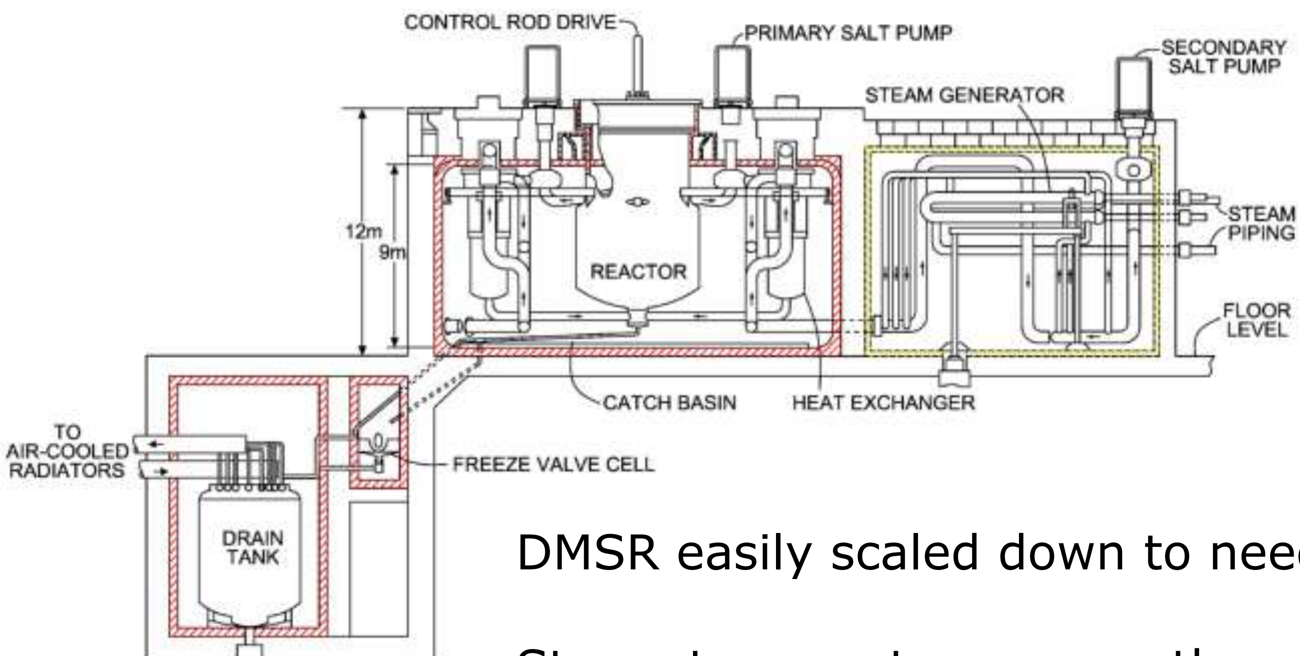


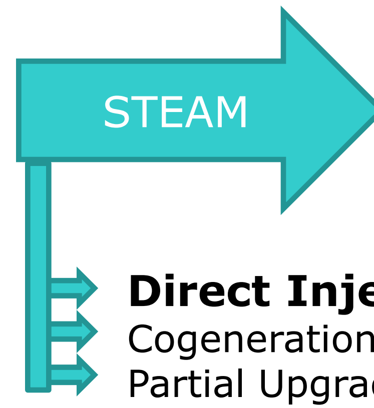
Then why not conventional nuclear?

- Why Not CANDU or LWRs to supply steam?
- As another 2003 CERI study put it
  - 1) The facilities are too large
  - 2) The pressures too low and not flexible
  - 3) Steam cannot be transported far enough
- Some work on Lower Pressure SAGD but desire is still high pressure
- Even CANDU6 far too large for any SAGD facility
- Current Small Modular Reactors either too low in steam temperatures or other problems such as cost or physical size issues

DMSR + SAGD: Basic Concept

BRING THE HEAT – Replace Traditional Natural Gas fired boilers with a Molten Salt Reactor





Direct Injection
Cogeneration
Partial Upgrading

DMSR easily scaled down to needed output

Steam temperatures more than enough for SAGD

Top end heat can be used for Cogeneration or various upgrading methods

Key to North American Energy Independence?

- Current Oil Sands production about 1.5 million barrels/day
- Current U.S. supply by OPEC and Gulf States 6.4 million bbls/day
- Oil Sands in ground reserves of 2 trillion barrels, current estimate 10% recoverable (likely much higher with cheaper steam)
- 64 GWth nuclear to add 6.4 million bbls/day (200B$/year revenue)
  - Output of 30 CANDU6 (not suitable size though)
  - Needed as about 200 small 300MWth MSRs
- Oil Sands a bridge to MSRs then with time, MSRs a bridge to not needing oil
  - *Don't tell them I said that!*

Canada Pieces Fitting in Place

- Ottawa Valley Research Associates (OVRA) patenting numerous design innovations with goal of minimizing R&D and regulatory hurdles
  - KISS philosophy, Keep It Simple Stupid
  - Working towards 25 MWe prototype and 100 to 200MWe base units for next stage
- Extensive network of connections with many other world experts in the U.S., Japan and Europe
- Penumbra Energy of Calgary working with OVRA and having success seeking Oil Sand corporate involvement
- Biggest news is great interest of a large Canadian based engineering firm

Team Canada

- ***Insert Company Name*** not quite ready to publicise involvement (but soon)
- Efforts lead by ex AECL expert who headed advanced reactor studies (Supercritical Water Reactor, Thorium in CANDU, GNEP)
- Hiring and expanding their team while working out collaboration agreements with OVRA
- Working towards a consortium to include McMasters and University of Ontario (Canada's largest nuclear schools) along with Chalk River Labs with likely involvement of University of Saskatchewan (and of course ORNL)
- Future is looking very bright…

MSR and the CNSC

- No allusions that licensing a new reactor design will not be a huge challenge both for the vendor and CNSC
- Fluid fuel is indeed a foreign concept but the inherent safety and lack of explosive or driving forces can not be forgotten
- Initial discussions with CNSC very encouraging
- CNSC has introduced has streamlined “small” reactor licensing, six year period possible

Conclusions

- By just about any standard, Molten Salt Reactors can be superior to all other offerings
  - And not just marginal improvements
- Originally mandated to be breeders, the much simplified converter option appears an obvious route forward
- Will take large and far sighted investment but potential return enormous
- All factors point to Canada being an ideal location for realizing this great potential for the world

EXTRA SLIDES…

Estimating C.R. for shorter batch cycles (15 years or less)

Eta 1.99
To start

Eta 2.10 (more U233)
At 15 years
C.R. back to 0.8

Ave Eta values from next slide

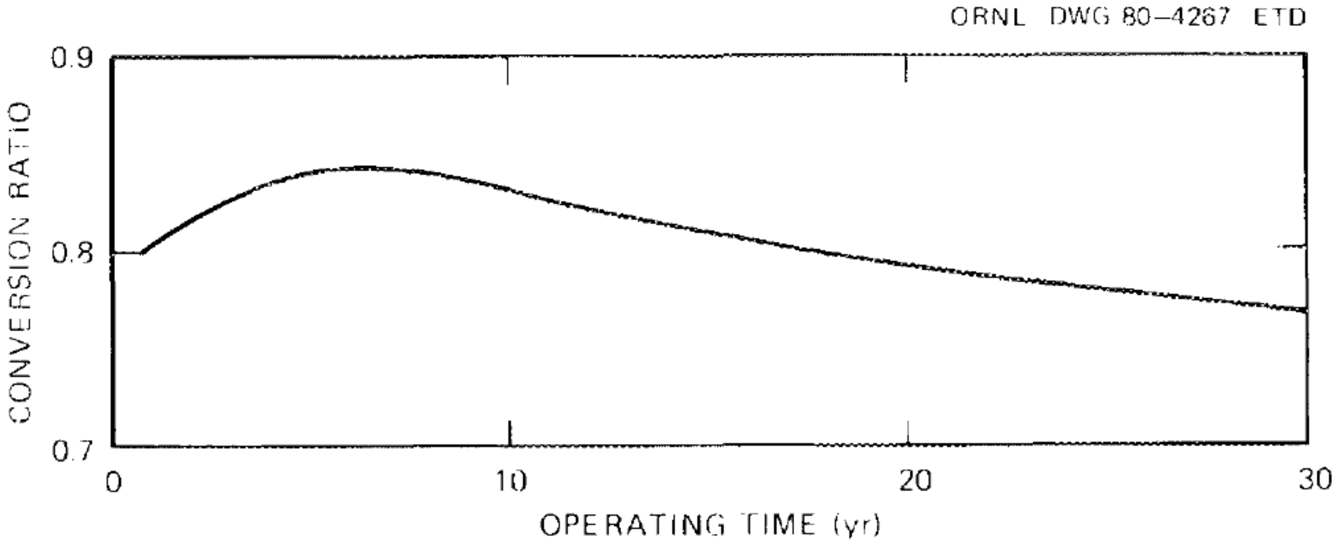


Fig. 6. Conversion ratio vs time.

New average C.R. can attain 0.85 to 0.9 for 10 to 15 year batches. About 1000kg fission per Gwe year so as low as 100kg shortfall = 22.8 t at 0.2% tails or **17.7 t at 0.05% tails**

Eta- C.R. – 1.0 =0.19
(early parasitic losses)

If restarted with eta 2.1 at 15 years expect early C.R.=2.1-1-0.19=0.91

Table 10. Nuclide concentrations and neutron utilization after 15 years of DMSR operation

Nuclide	Concentration[a] ($\times 10^{24}$)	Neutron absorption[b]	Fission fraction	$\nu\sigma_f/\sigma_a$
^{232}Th	2,561	0.2561	0.0017	0.0070
^{233}Pa	1.13	0.0018	0.0000	0.0033
^{233}U	49.0	0.2483	0.5480	2.2427
^{234}U	9.21	0.0120	0.0002	0.0143
^{235}U	25.1	0.1161	0.2272	1.9894
^{236}U	16.2	0.0075	0.0001	0.0168
^{237}Np	1.83	0.0047	0.0000	0.0102
^{238}U	476	0.0901	0.0017	0.0194
^{239}Pu	4.34	0.0896	0.1578	1.7905
^{240}Pu	2.46	0.0324	0.0001	0.0032
^{241}Pu	1.84	0.0293	0.0628	2.1754
^{242}Pu	2.38	0.0039	0.0001	0.0136
Transplutonium[c]		0.0014		
^{238}Pu	0.882	0.0024	0.0003	0.1245
Total actinides		0.8956	1.0000	
Fluorine	48,000	0.0079		
Lithium	24,500	0.0062		
Beryllium	5,470	0.0012		
		0.9109		
Graphite	92,270	0.0172		
Fission products		0.0563		
Total		0.9844		

[a]Nuclei per cubic meter of salt or moderator.

[b]Absorption per neutron born; leakage is 0.0156.

[c]Includes ^{240}Pu, ^{241}Pu, and ^{242}Pu produced from a decay of ^{244}Cm.

74%LiF-16.5% BeF2-9.5%(U,Th)F4 ***versus*** 53%NaF-20%RbF-27%(U,Th)UF4 *mp 500 C*

- New salt has 77% more heavy atom density
- Can thus run at lower relative salt fraction in core (same Carbon to Fissile Ratio)
- Na for thermal neutrons is only 6 times the absorption cross section of 99.995% ^{7}LiF
- In DMSR, more losses to fluorine than Li
  - Will have 56% less fluorine, 65% less Na+Rb compared to Li (and no Be)
  - Works out to roughly same neutron loss (estimate only, ignores higher resonances bands for Na and Rb)