Molten Salt Reactors: Designs Options and Outlook

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Presentation to
TEA4

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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

Molten Salt Reactor Advantages

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

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)
  - 30,000$ of thorium = 0.5$ Billion electricity
  - BUT must add in processing costs
  - AND cost of startup fissile material
- Converter designs are 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**

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*
- *U mining is only a tiny fraction of other mining (less than 0.1%) and good employment*
- *If uranium is used in DMSR designs, 100% of world’s electricity (2500 GWe) without increasing current mining*

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 MSR designs produce less TRUs and can be kept in or recycled back into the reactor to fission off
- Up to a ten thousand fold improvement over conventional "Once Through" Reactors

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
- Salt Processing should be much cheaper than for solid fuels *BUT*
- PUREX ~2000$/kg
- How much cheaper would salt processing need to be?
- For the standard MSBR (1970) for it to match the fuel cost of a DSMR converter processing costs would need to be:
  - **Under a dollar a kg!**

Back to *Breeder vs Burner*

- Removing the requirement to breed also 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
- 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
- Transuranics (TRUs) 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

Extremely High Proliferation Resistance

- No fuel processing ever required
- 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
- If the enrichment needed for LEU a concern, spent fuel of a single CANDU could feed several DMSRs on the same site
  - Natural Uranium in, Electricity and Fission Products out

Non “denatured” Designs (LFTR)

- Some interesting non proliferation features BUT
- Likely no expert would ever claim an improvement over existing reactors
- Widespread claims of Thorium being a solution to proliferation will only hurt us in the long run
- Claims of U232 effects greatly exaggerated
  - Read Dr. Ralph Moir’s or other credible reports
- Yes, a country developing graphite pile reactors easier, but not if one can buy a reactor with its tonnes of U233
- Proliferation dangers will always be exaggerated by those opposed to nuclear power but the answer is not in making similar exaggerations

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
- Start on common <5% enrichment
- Neutron economy not as quite as good but still excellent uranium utilization
- No Protactinium
  - Can run any power density
- Lower melting point

- 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 head 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

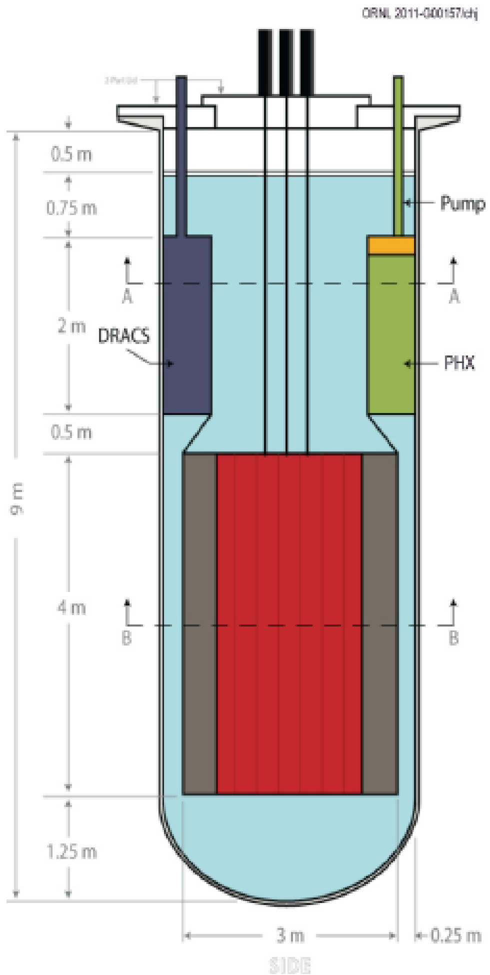


Fig. ES.2. SmAHTR dimensions.

Molten Salt Reactors
Oh Canada!

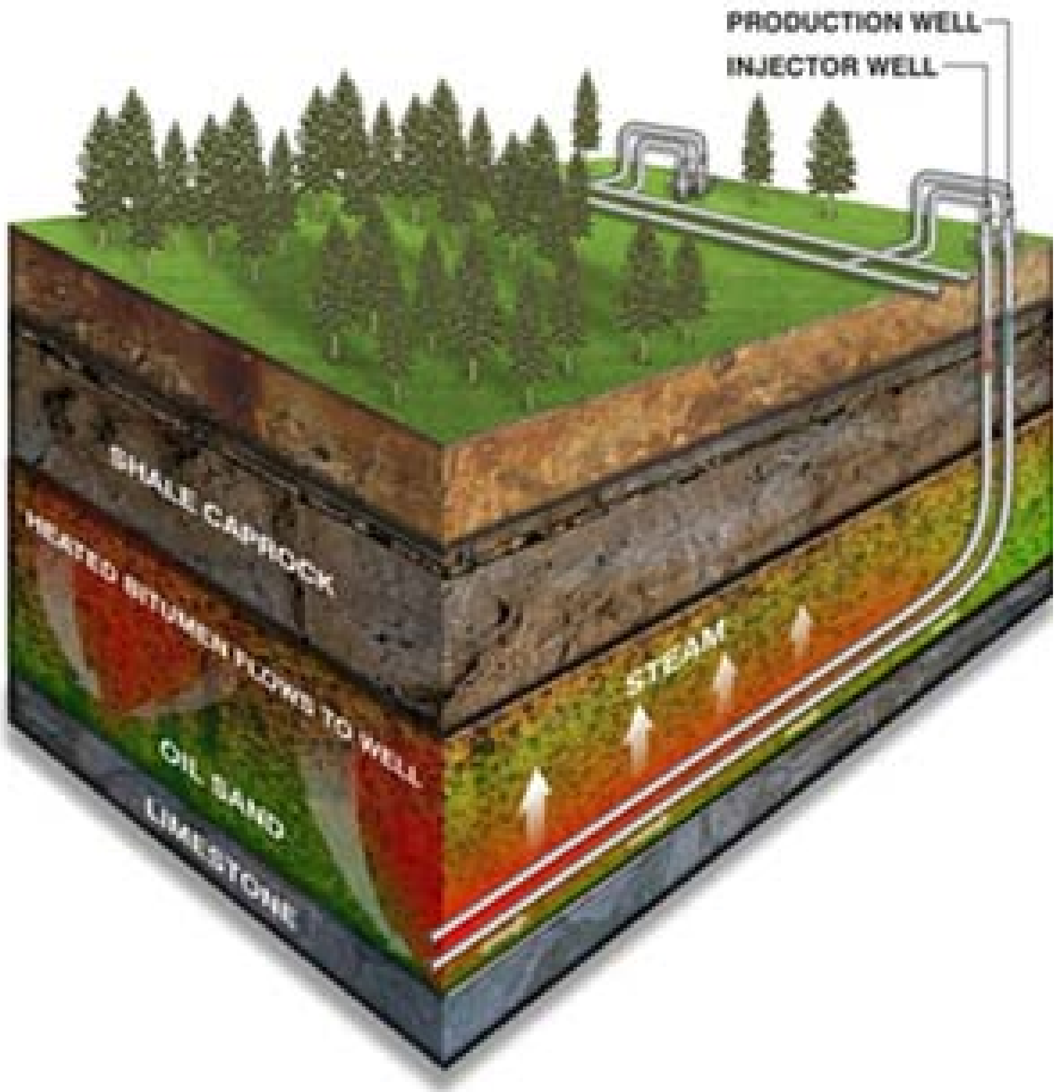
- CANDU6 a good design available now
  - But no new R&D for foreseeable future since sale of AECL to SNC-Lavalin
- Canada has enormous nuclear brain trust going to waste
- We went our own way before, we can do it again
- Canada also has unique opportunities in our Oil Sands

Canadian Oil Sands

DMSR's ideal proving ground

- 175 Billion Barrels of *recoverable* reserves estimated in place, 2 Trillion resource
- 2nd largest in the world and cheap steam could push reserves far higher
- 80% only recoverable from *in-situ* methods
- Leading in-situ technology is Steam Assited Gravity Drainage (SAGD)
- 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



- ~3 barrels of steam per barrel of bitumen
  - 7 to 12 MPa (over 1000 psi) and 275 to 330 C
- Production diluted 30 – 50% with gas condensates for pipe transport, on site upgrading of huge potential
- Pressure and temp drop in piping limits distance of wells to facility (~ 10 km)
- 300 MW(th) steam output for a standard sized 30,000 bbls/day facility
- ‘Conventional nuclear’ not a fit

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)
- Remote use away from population relieves the NIMBY factor

The Oil Sands Allure

- Many past studies have shown nuclear produced steam to be cost effective
- Price of conventional nuclear options have risen but construction of natural gas steam systems in the oil sands have risen even faster
- Oil sands producers expected to pay 200 Billion$ on carbon taxes over the next 35 years, funds mandated to be spent on cleantech initiatives

Then why not conventional nuclear?

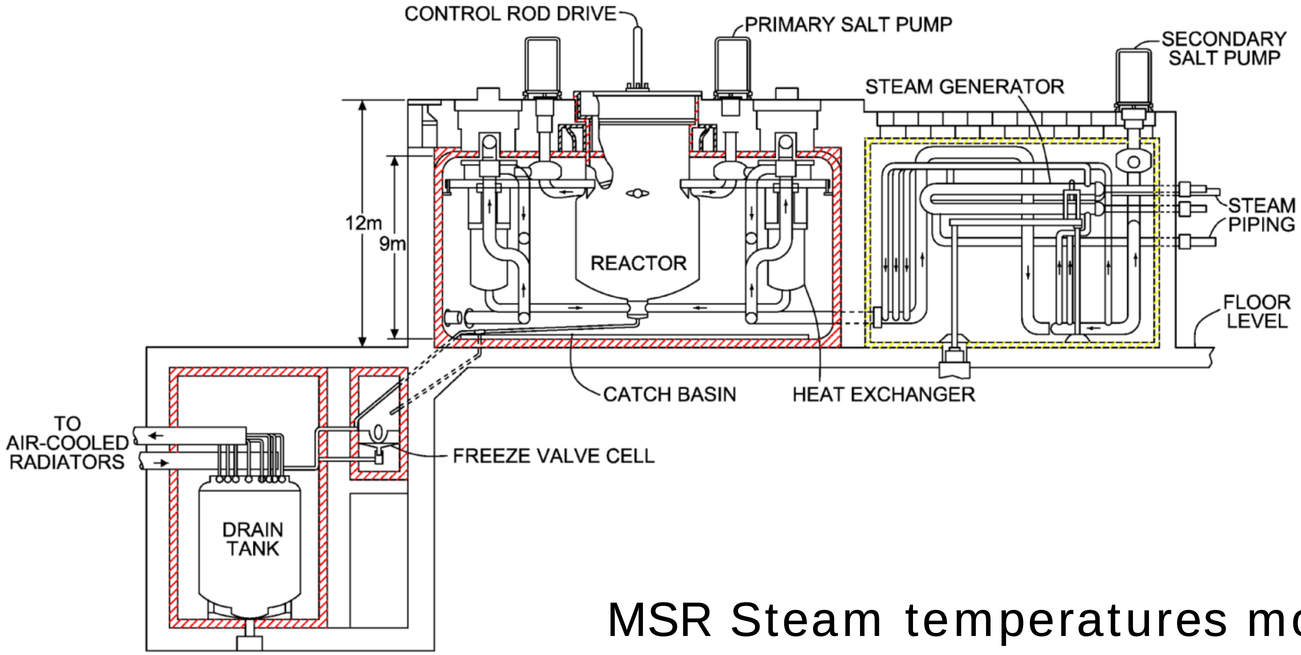
- Why Not CANDU or LWRs to supply steam?
- As a 2003 CERI study put it
- 1) The facilities are too large
- 2) The pressures too low and not flexible
- 3) Steam cannot be transported far enough

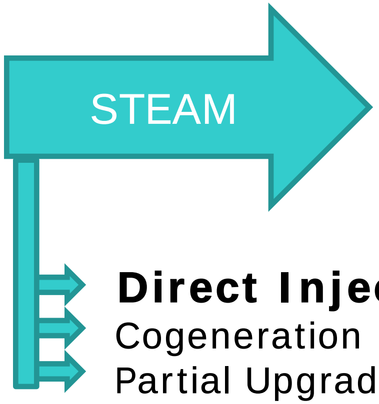
- Ideal size is 300 to 400 MWth for a 30,000 barrel/day facility

- Other potential SMRs very poor fit
  - Ask me later

DMSR + SAGD: Basic Concept

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





Direct Injection
Cogeneration
Partial Upgrading

MSR 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

Canadian 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/demonstration and 100-250MWe 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 raising interest of Oil Sands firms
- 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...

MSRs and the CNSC
(Canadian Nuclear Safety Commission)

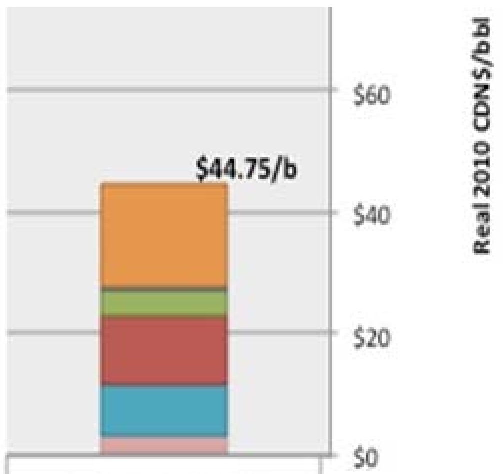
- No allusions that licensing a new reactor design will not be a huge challenge both for the vendor and CNSC
- Fluid fuel is indeed a foreign concept but the inherent safety and lack of explosive or driving forces can not be forgotten
- Initial discussions with CNSC very encouraging
- CNSC has introduced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

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 focal point of broader North American efforts to realize this great potential for the world

EXTRA SLIDES…

SAGD Economics



	SAGD 10% ROR (a)
Fixed Capital (Initial & Sustaining)	$16.91
Operating Working Capital	$0.40
Fuel (Natural Gas)	$4.38
Other Op. Costs (Fixed, Variable, Elec)	$11.15
Royalties	$8.47
Income Taxes	$2.81
Emissions Compliance Costs	$0.60
Abandonment Costs	$0.02

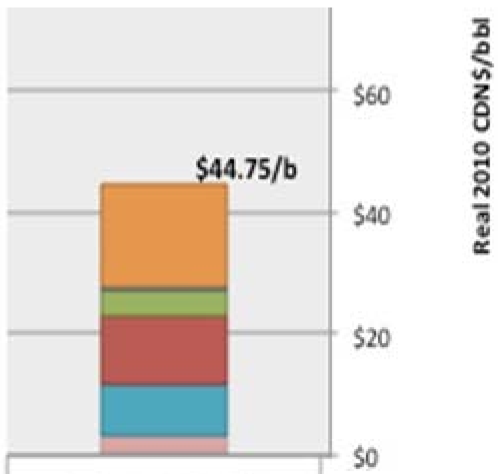
Note: (a) Return on Investment Included

b) Does not include diluent and transportation costs- $10 - 15/bbl

c) Does not include loss from heavy oil differential - $8-30/bbl

- Most Sensitive to:
  - Initial Capex
  - Fuel Opex
  - Diluent volumes
  - Heavy Oil Differential
- Immediate DMSR Impact:
  - Fuel costs drop dramatically (10 – 20% increased profit margin overnight)
  - Zero carbon taxes, scrubs ‘dirty oil’ label away
- Future Impacts:
  - Cogeneration reduces variable opex, increases operational flexibility and enables more remote project locations
  - Partial Upgrading reduces diluent needs and closes heavy oil differential gap

SAGD Economics



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What about Small Modular Reactors

- mPower (500 MWth)
  - Reasonable size, steam conditions marginal
  - 4 times the uranium needs of PWR (23 times standard DMSR)
  - Trading natural gas price instability for Uranium instability?
- NuScale (165 MWth)
  - Too low of steam temp and pressure
  - Lowered to allow natural circulation

Small Modular Reactors

- Toshiba 4S (10 MWe)
  - Many units each SAGD (~25 MWth)
  - Claim low cost but Fast Reactor track record indicates otherwise
  - Proving a 30 year fuel cycle?
  - Starting fissile load estimated at 1700 kg U235 (85M$ or 8.5$/watt just for fuel!)
- Pebble Beds
  - Safety case not as clear cut as advertised
  - Requires TRISO fuel fabrication plant
  - Costs increase if not multi unit site
  - A reasonable fit on paper. But...

Other SMRs on same scale

Molten Salt "fueled" version easily 300 MWth this size

Molten Salt "cooled"