Recommendations for a restart of molten salt reactor development

Incentives for molten salt reactors are so great that one asks why the reactor has not already been developed

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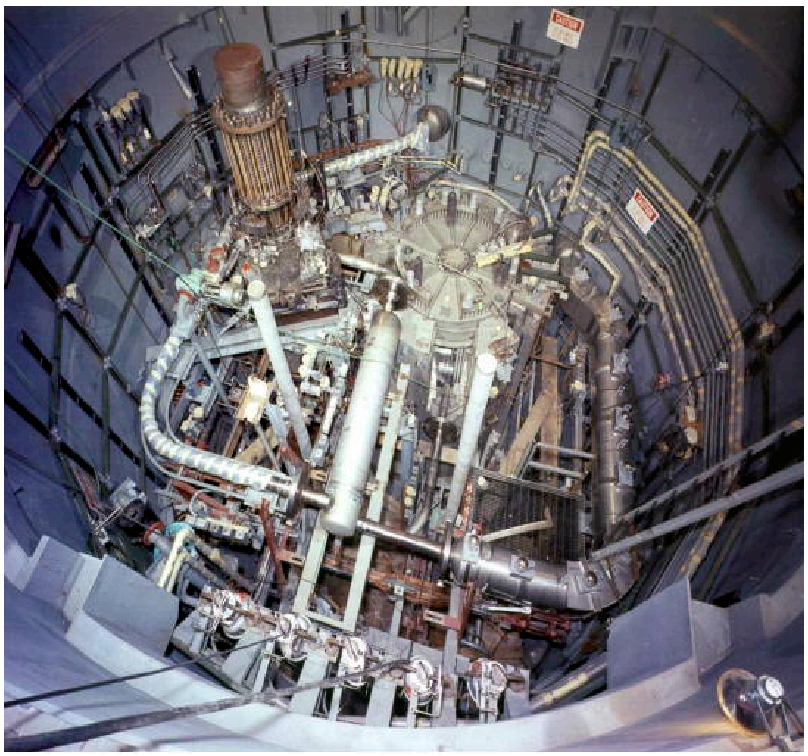
Talk plan: Why I am giving this talk

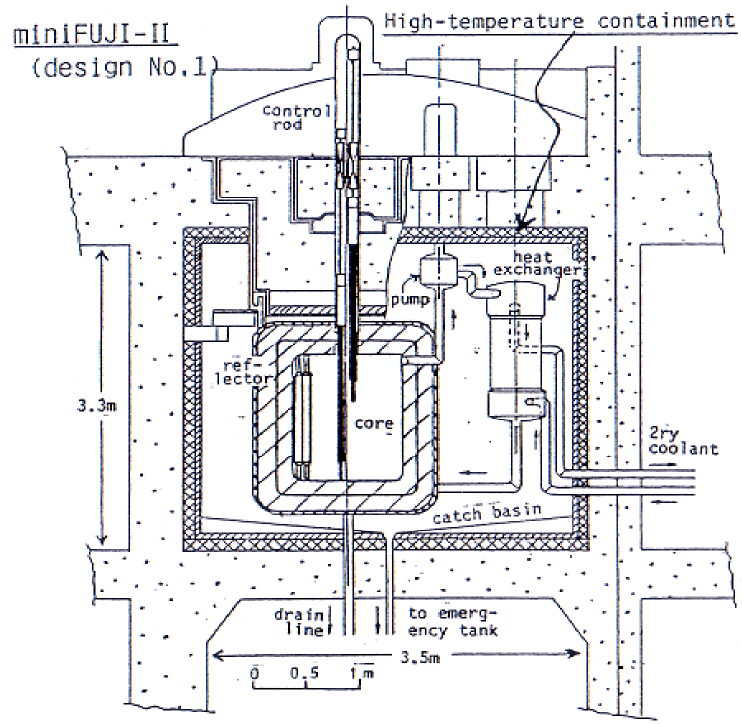
- Incentives
- Economics
- Development steps → Deployment scenario
- Non-proliferation arguments → Thorium
- Sources of startup fuel
- Carbon composite material development
- Summary of recommendations

Proposal: A molten salt reactor development restart makes it a candidate for deployment of 10 TWe by 2100

Recommendation: Build a 10 MWe prototype

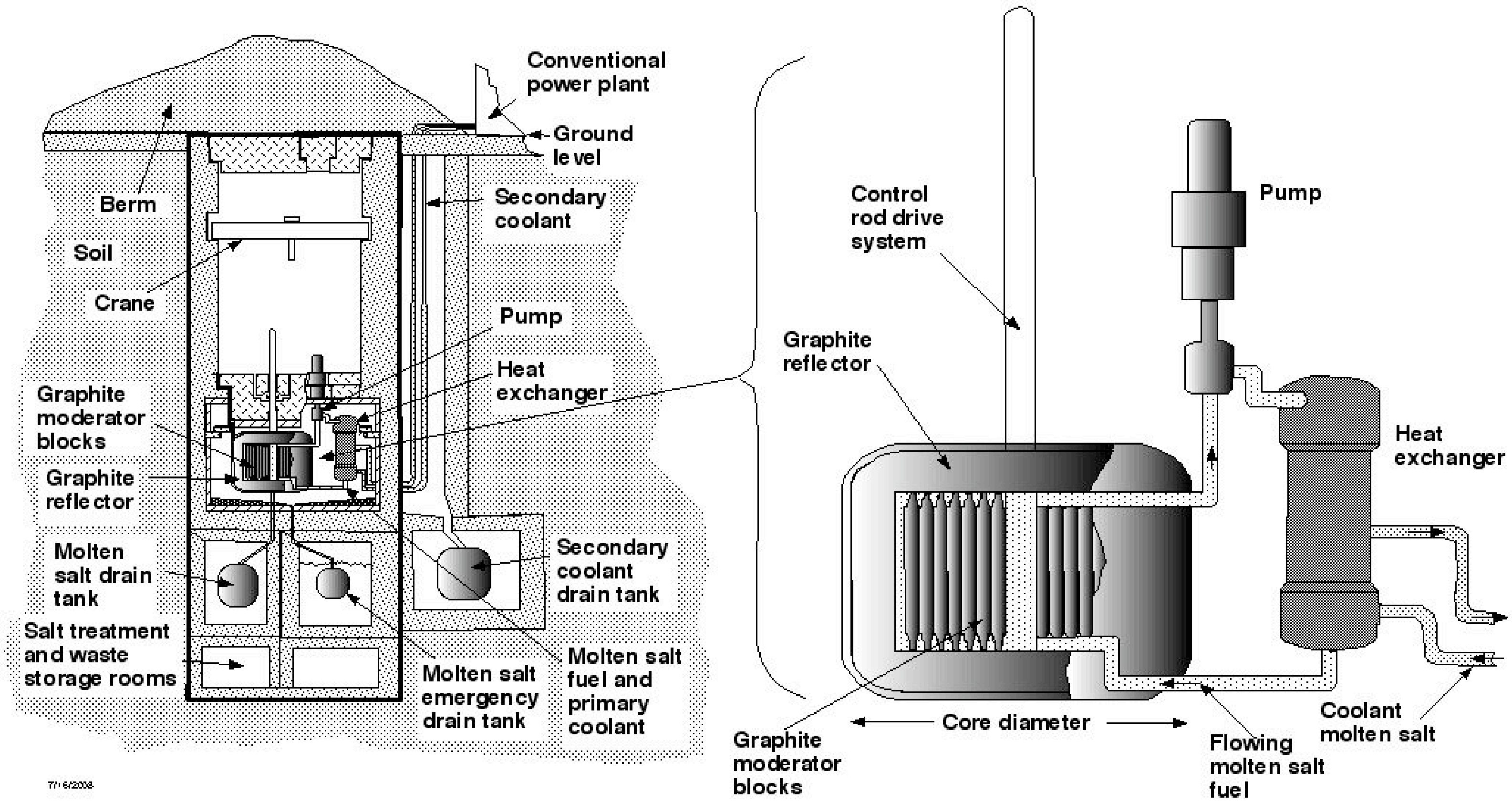


Molten Salt Reactor Experiment, ORNL, 1965-68



Furukawa et al., ICENES 2007

Underground construction and operation is advised



R. W. Moir and E. Teller, "Thorium-fueled underground power plant based on molten salt technology," *Nuclear Technology* **151** (2005) 334-340.

Strong incentives for the molten salt reactor design are its good fuel utilization and flexibility and its good economics. It can:

- Use thorium or uranium
- Fission uranium isotopes and plutonium isotopes
- Be designed with lots of graphite to have a fairly thermal neutron spectrum or without graphite moderator to have an an epithermal neutron spectrum
- Produce less long-lived wastes than today's reactors by a factor of 10 to 100
- Operate with non-weapon grade fissile fuel or, in suitable sites, it can operate with enrichment between reactor-grade and weapon-grade fissile fuel
- Be a near breeder
- Operate at temperature >1000 °C if carbon composites are successfully developed

Economic motivation and predictions

Based on 1978 designs, the MSR was estimated to produce electrical energy at lower cost than PWR and coal.

$/MWh, 2000$

	MSR, 20% enriched	MSR, 100% enriched	PWR	Coal
Capital	20.1	20.1	20.7	15.8
O&M	5.8	5.8	11.3	8.0
Fuel	11.1	4.0	7.4	17.2
Waste disposal	1.0	1.0	1.0	0.9
Decom	0.4	0.4	0.7	--
Total	**38.4**	**31.3**	**41.1**	**41.9**

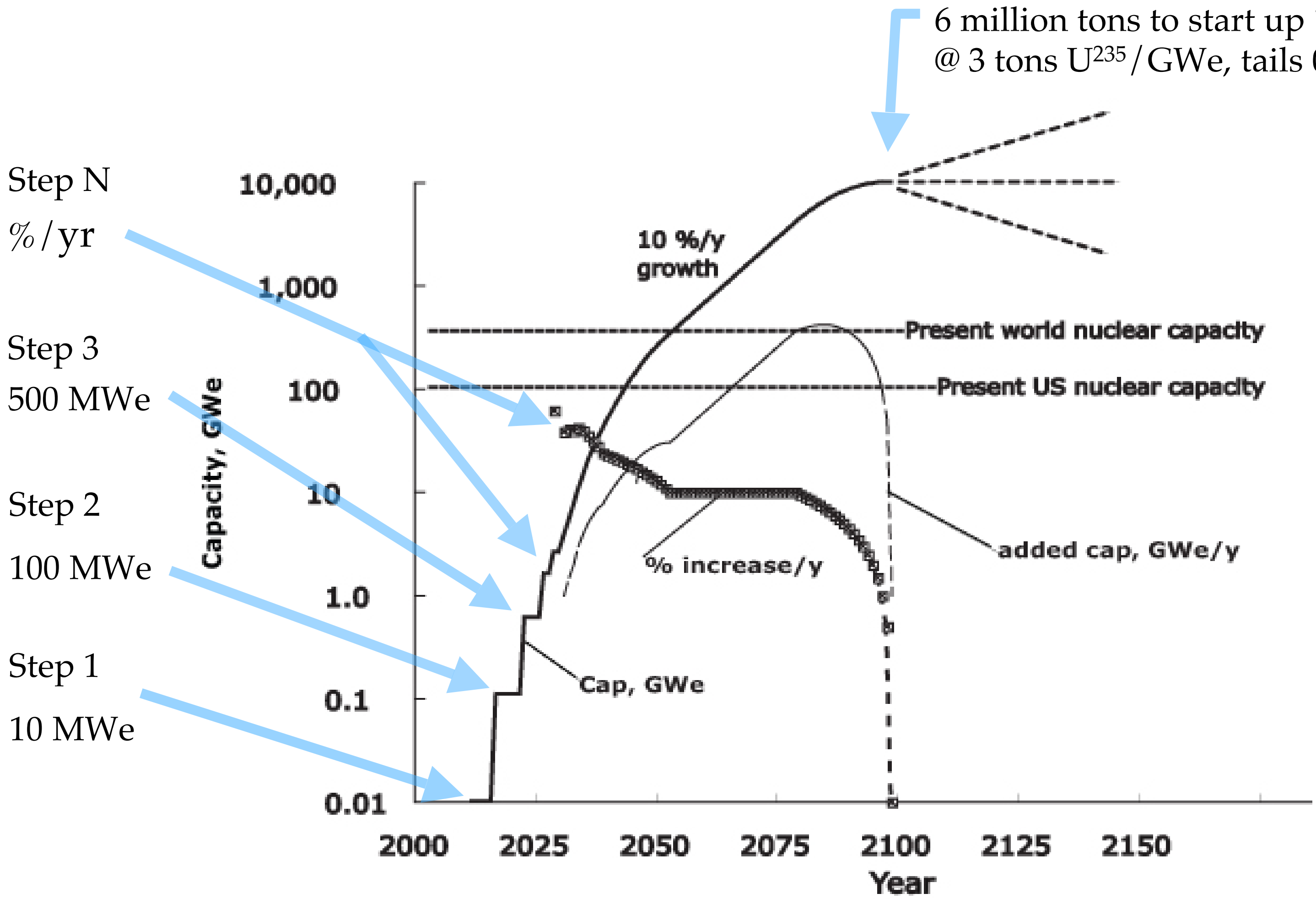
PWR uses too much uranium

Coal with carbon sequestration will be even more expensive

R. Moir, Nucl. Tech. **139** (2002) 93-5.

Recommendation: Verify economic predictions

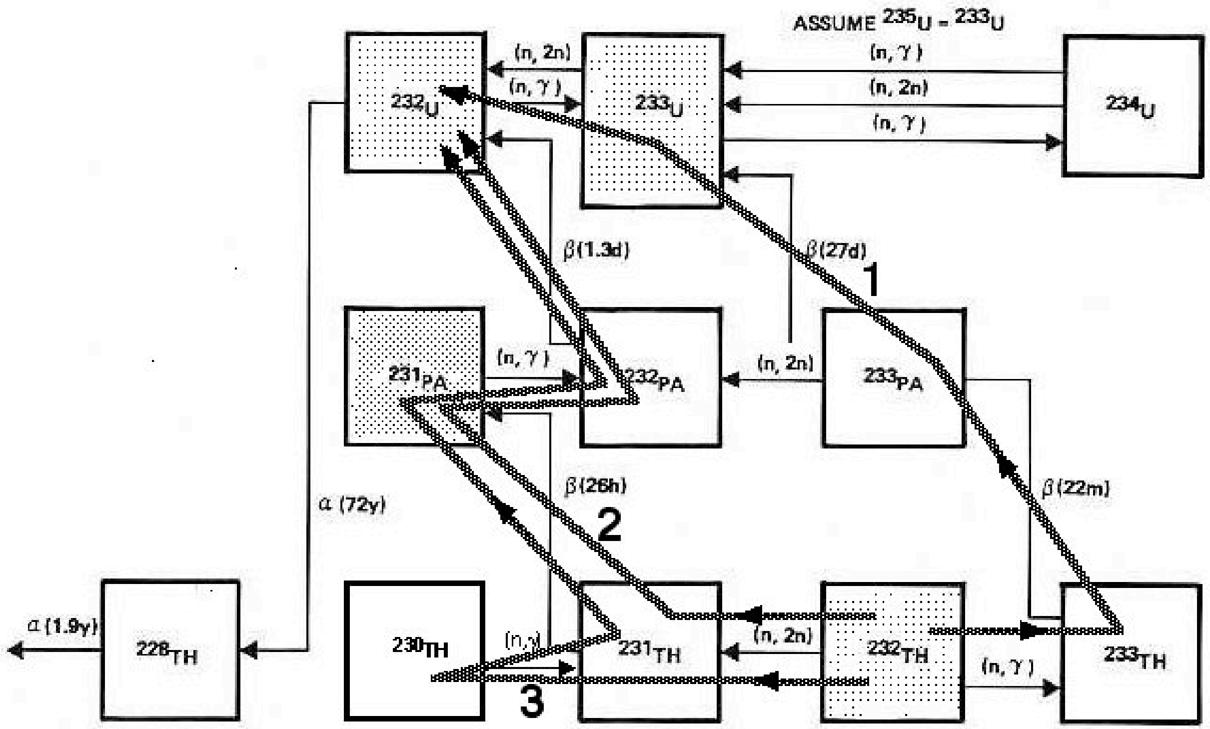
Deployment scenario



Any new fission system must be able to meet the goal of 10 TWe in one hundred years

Hypothetical worldwide deployment scenario of new MSRs illustrates only a doubling of nuclear power by 2050 but twenty-five fold increase by 2100.

Nonproliferation in thorium cycle



^{232}U produced while making ^{233}U has a 2.6 MeV gamma making it undesirable for nuclear weapons

Recommendation: Determine how much ^{232}U will make a significant contribution to non-proliferation.

Nonproliferation arguments and the role of ^{232}U in thorium cycle

$$n + {}^{232}Th \rightarrow {}^{233}Th \underset{22\,\min}{\rightarrow} {}^{233}Pa + e^- \underset{27\,d}{\rightarrow} {}^{233}U + e^-$$

The following important reactions lead to ^{232}U:

1

$$n + {}^{232}Th \rightarrow {}^{233}Th \underset{22\,\min}{\rightarrow} {}^{233}Pa + e^- \underset{27\,d}{\rightarrow} {}^{233}U + e^-$$

$$n + {}^{233}U \rightarrow 2n + {}^{232}U$$ (fast) two-step reactions

2

$$n + {}^{232}Th \rightarrow 2n + {}^{231}Th \underset{1.1\,d}{\rightarrow} {}^{231}Pa + e^-$$ (fast)

$$n + {}^{231}Pa \rightarrow {}^{232}Pa \underset{1.3\,d}{\rightarrow} {}^{232}U + e^-$$ two-step reactions

There are more remote low probability reactions that also lead to ^{232}U:

3

$$n + {}^{232}Th \rightarrow 3n + {}^{230}Th$$ (fast)

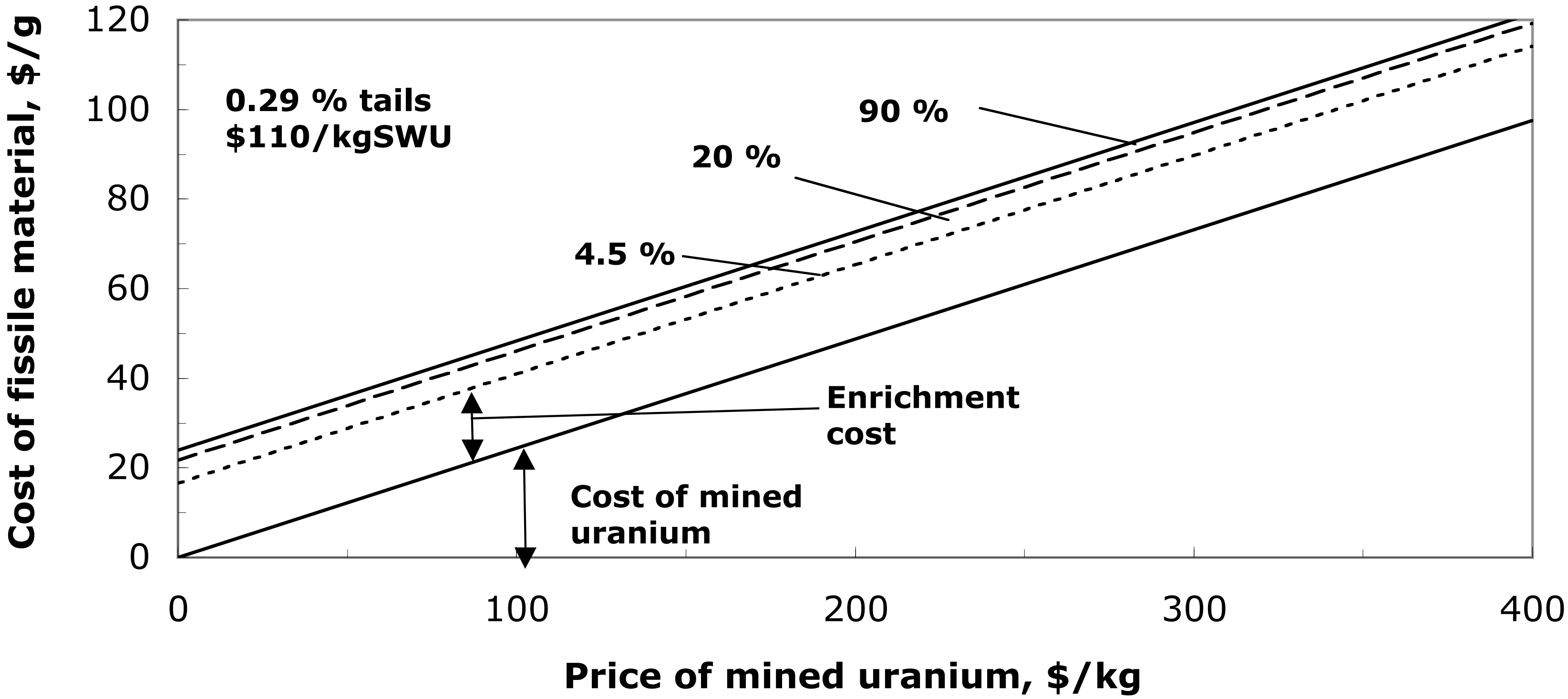
$$n + {}^{230}Th \rightarrow {}^{231}Th \underset{1.1\,d}{\rightarrow} {}^{231}Pa + e^-$$

$$n + {}^{231}Pa \rightarrow {}^{232}Pa \underset{1.3\,d}{\rightarrow} {}^{232}U + e^-$$ three-step reactions

Options for MSR startup fuel

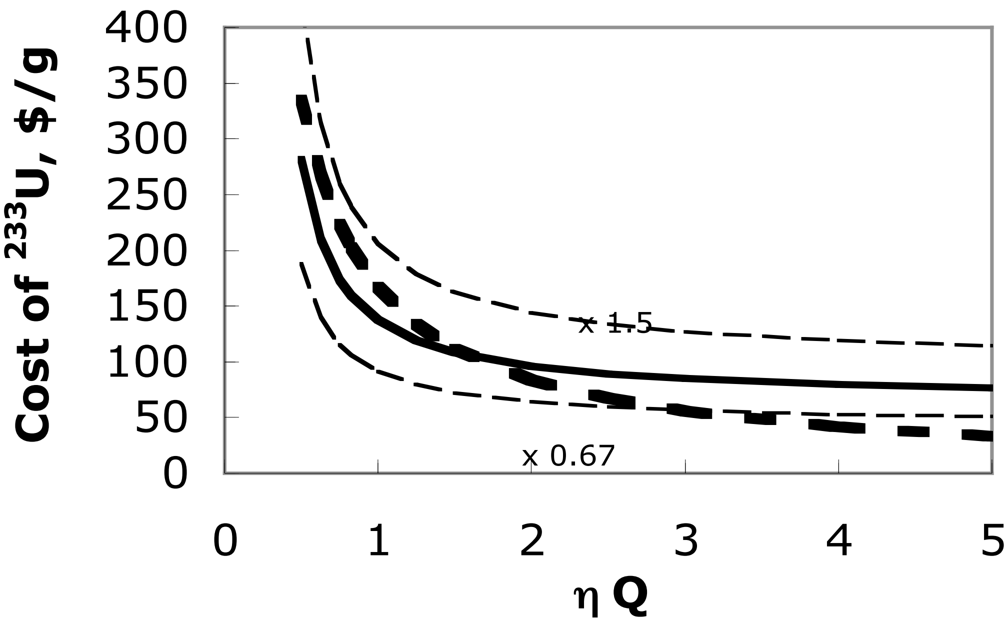
Mined and enriched ^{235}U

Current practice low cost ~60$/g



Options for MSR startup fuel

Fusion produced $^{233}U + ^{232}U$ Low cost but not proven



R. W. Moir, et al., "Design of a Helium-Cooled Molten Salt Fusion Breeder", *Fusion Technology* **8** (1985) 465-473.

Options for MSR startup fuel

Accelerator produced $^{233}U + ^{232}U$

Expensive but feasible; electric bill alone is estimated at 240$/g

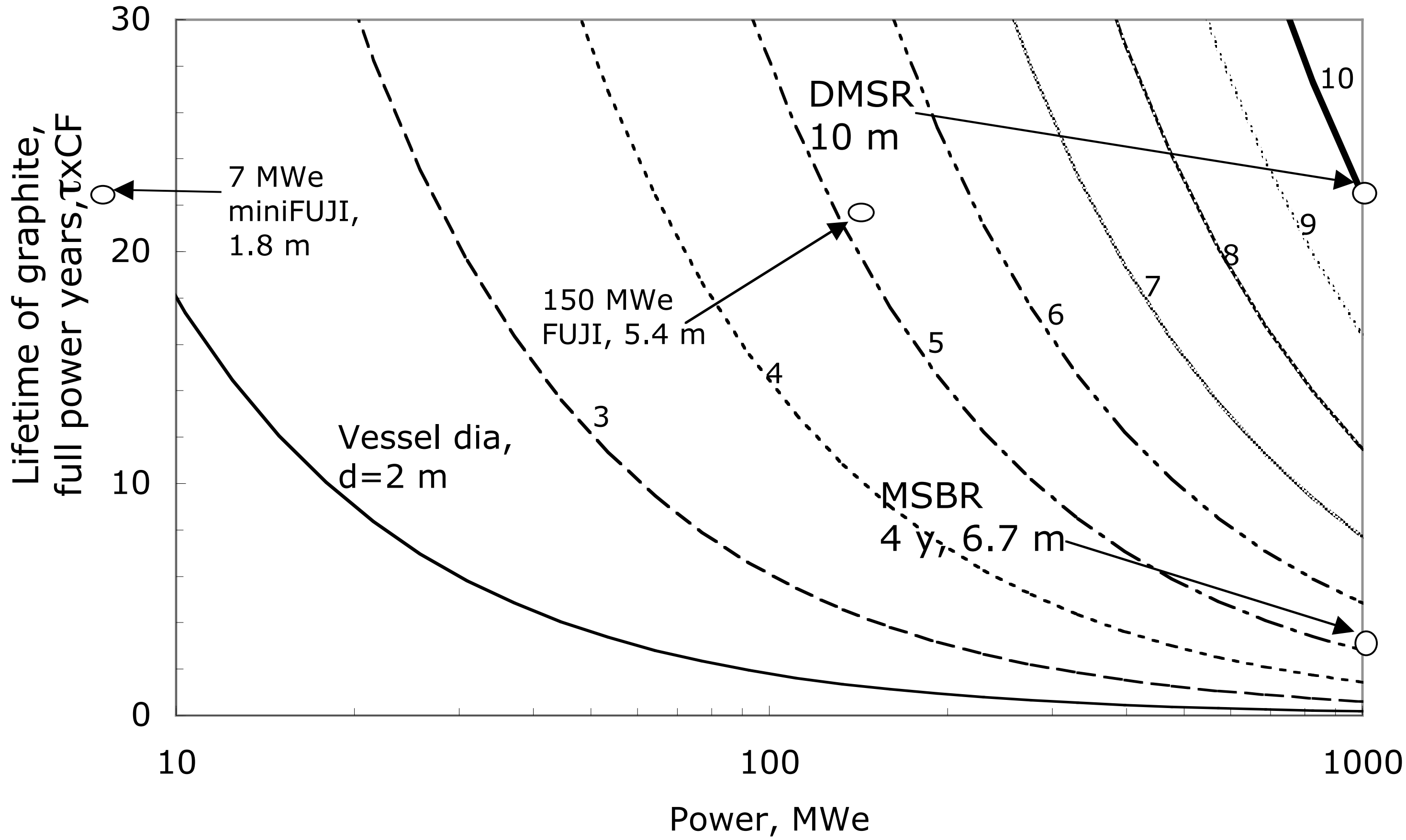
LWR or CANDU produced $^{233}U + ^{232}U$

Process thorium spent fuel to recover $^{233}U + ^{232}U$

Recommendation: Study sources of low cost startup fuel for MSRs

Graphite damage lifetime in thermal neutron (graphite moderated) MSR is an important design variable

Vessel diameter varies from 2 to 10 m.



Radiation damage lifetime of graphite can be varied by vessel size and power level

Parameters for various MSR designs

	Vessel diam, m	Power	CF	**Graphite lifetime**
MSRE	1.4	8 MWth	0.4	**3.3 y***
miniFUJI	1.8	7 MWe	0.75	**30 y**
FUJI	5.4	150 MWe	0.75	**30 y**
MSBR	6.7	1000 MWe	0.75	**4 y**
DMSR	10	1000 MWe	0.75	**30 y**

*Operating time June 1965 to October 1968, 11,500 full power hours.

Carbon-composite (C/C) material development

- C/C material to replace nickel vessels, piping and heat exchangers.
- Carbon compatible with molten salt and allows temperature to 1000° and over
- Development requirements:
  1. Develop leak-tight composites or design to accommodate a porous/leaky material
  2. Develop means to join C/C vessels and pipes
  3. Develop means to repair C/C components

Carbon composite development for flat plate heat exchangers, pipes and vessels

Typical C/C-SiC parts (disc brakes, rocket nozzles, telescope mirrors, etc.) fabricated by the LSI process using random oriented chopped C/C felt (BPM/IABG).

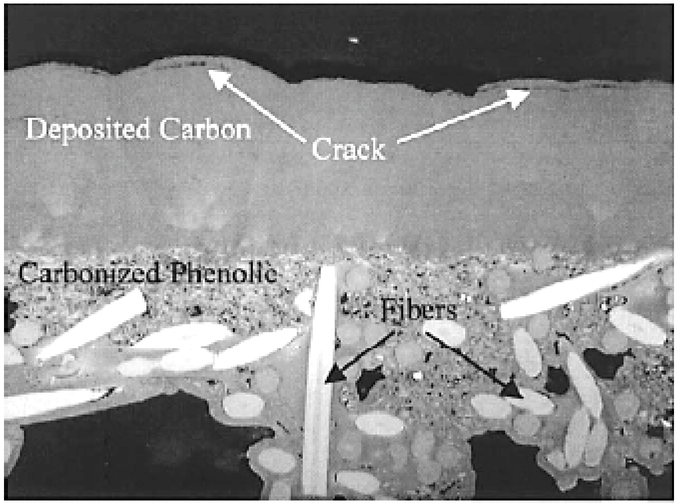
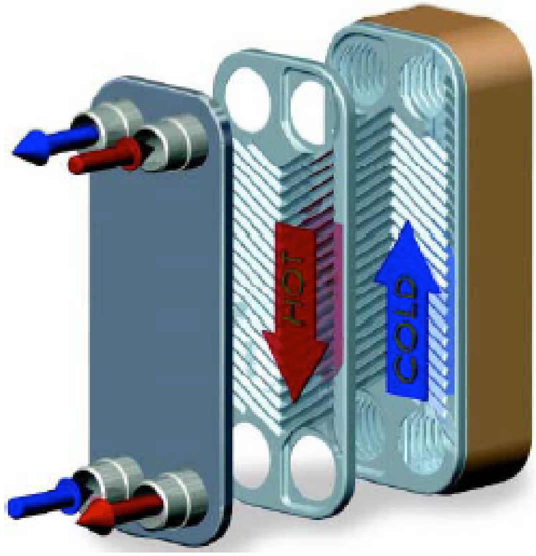
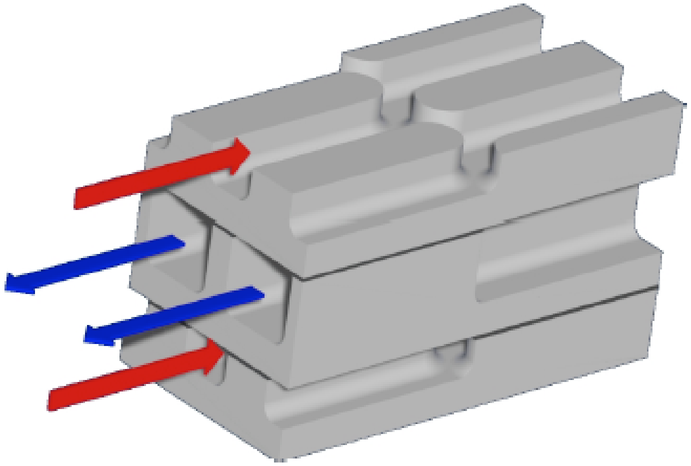


Photo of CVI-deposited carbon layer on a carbon-carbon composite plate [6].



Flat plate heat exchanger



C/C table top development

- An experimental development program could begin by building a small carbon composite vessel with a diameter of about 0.1 m to mock up full size units. Full size units might be 2 m dia for ~10 MWe and 5 to 10 m dia for a few hundred MWe to a GWe.
- Tests could use the surrogate molten salt NaCl $+MgCl_2$ that is nearly identical thermo-chemically to LiF $+BeF_2$.
- A vacuum oven would be needed to bake out gases, especially oxygen and hydrogen.

Recommendation: Initiate carbon composite research for molten salt reactor application.

Summary of recommendations for MSR

1. Restart program with early construction of ~10 MWe unit similar to MSRE
2. Verify prediction of costs lower than PWR and coal
3. Determine how much ^{232}U will make a significant contribution to non-proliferation
4. Study sources of low cost startup fuel for MSRs: Mined and enriched uranium, fusion, accelerators and LWR or CANDUs
5. Initiate carbon composite research for molten salt reactor application

Conclusions

- Stopping the MSR program in ~1970 was a mistake
- The incentives for MSR are so strong that development should be restarted so that MSR will be an option for the goal of 10 TWe in 100 years