Relevant MSRE and MSR Experience

A short review for the US DEMO FW/Blanket and ITER MS TBM Assessment

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What is MSRE?

- MSRE is an 8 MW(th) fission reactor in which molten fluoride salt at 649°C circulates through a small core (54” in diameter and 64” tall) filled with graphite bars.
- Its purpose was to demonstrate the practicality of the key features of molten-salt power reactors.
- The MSRE was designed with essentially the same materials as the proposed MS breeders.
- It operated from January 9, 1965 to the conclusion of nuclear operation in December 12, 1969.
- It accumulated operation experience of the MS reactor and demonstrated the prospect of low-cost continuous fuel reprocessing.
- It demonstrated that the single-region reactor is not capable of breeding and pointed to the direction of a larger two-region breeder reactor.
MSRE Program History

(During run periods achieved reactor criticality 80% of the time and availability for planned experimental work was 87% of the period.)

- MSRE design initiation: 1960
- Salt first loaded into tanks: October 24, 1964
- Salt first circulated through core: January 12, 1965
- First criticality: June 1, 1965
- First operation in MW range: January 24, 1966
- Reach full power of 8 MW(th): May 23, 1966
- Complete 30-day run: January 14, 1967
- Complete 3-month run: April 28, 1967
- Complete 6-month run: March 20, 1968
- End nuclear operation with $^{235}$U: March 26, 1968
- Strip U from fuel carrier salt: August 23-29, 1968
- First critical with $^{233}$U: October 2, 1968
- First operation at significant power with $^{233}$U: October 8, 1968
- Reach full power of 8 MW(th) with $^{233}$U: January 28, 1969

(Impression: With properly designed equipment, handling the high-melting point salt proved to be workable.)
Materials of MSRE

Fuel Salt: $^7\text{LiF-BeF}_2-\text{ZrF}_4-\text{UF}_4$ (65.0-29.1-5.0-0.9 mole %)
  Melting point: 434°C
  Density: 141 lb/cu ft @ 649°C,
  Heat capacity: 0.455 Btu/lb °F
  Tin: 632°C, Tout: 654°C, at 1200 GPM

Coolant salt: $^7\text{LiF-BeF}_2$ (66-34 mole %)
  Melting point: 455°C
  Density: 120 lb/cu ft @ 574°C
  Heat capacity: 0.526 Btu/lb °F
  Tin: 546°C, Tout: 579°C, at 850 GPM

Moderator: Grade CGB graphite

Salt containers: Hastelloy-N (68 Ni-17 Mo-7 Cr-5 Fe)
  (With control of $\text{U}^{3+}/\text{U}^{4+}$ ratio to above 0.005, the wall corrosion rate was about 0.1 mil/year)

Cover gas: Helium @ 5 psig

Experience from the coolant salt will be directly applicable to us
Layout of the MSRE

Fuel pump
Reactor vessel
Coolant pump
Radiator
Fans
Drain tank

Drain tanks
Flow Sheet

Primary loop

Stack
Absolute filter
Charcoal bed

Coolant loop

Reactor vessel

Drain and Flush tank
Reactor Vessel and Heating Tubes

Reactor vessel

Heating tubes around Reactor vessel
Heat Exchanger and Impeller and Motor

Primary heat exchanger ~8 ft long

Impeller and motor for the vertically mounted centrifugal fuel pump
Alternate Coolant Salt Considered for the Secondary H/T Loop

For lower cost and lower melting point:
They considered a eutectic mixture of sodium fluoride and sodium fluoroborate (8% NaF-92%NaBF₄), it melts at 385°C.
It has relative high vapor pressure, ~1/3 atm pressure of BF₃ gas at the expected max. operating temperature. It is considerably more corrosive than the fuel salt @several mils/year. At high purity an average corrosion rate of 0.7 mil/year has been measured. A high-purity salt loop has a corrosion rate of 0.2 mil/year.

Different coolant salt had been considered and corrosion can be impacted by purity control.
For tritium control a secondary loop would be needed for the self-cooled MS concept.
MSRE Operation Experience: Heating and Cover gas, and the Avoidance with direct contact with water

- All parts of the salt-containing system are heated electrically above the liquidus temperature of 449°C to 454°C. The total capacity of the heaters is ~1930 kw, actual consumption is about ½ of this.
- All salt-containing lines are thermally insulated and provided with electrical heaters capable of maintaining the salt above 544°C. (Thermal insulation can be divided into 1. the metallic, multiple-layer reflective type, 2. the low thermal conductivity ceramic fiber or expanded silica types.)
- Most of the heaters are of removable type. Some are non-removable insulations.
- A high purity helium (below 1 ppm) cover-gas system protects the oxygen-sensitive fuel from contact with air or moisture.
- A steam leak directly into the fuel salt would cause rapid precipitation of oxides and make the fuel salt corrosive by the formation of HF.

For fusion: MSRE Heating and insulation experience can be applicable to ITER MS TBM module design.

Self-cooled Flibe may need a secondary loop to avoid steam leak directly into the fuel salt. This may also be necessary for tritium containment.

DC design with helium coolant could be used as cover and heating gas, the avoidance of water interface, but the tritium contamination problem will have to be resolved. We should review the approach of APEX task IV, with the use of He like a cover gas for Flibe.
MSRE Operation experience (continued)

- Details on the experience with MSRE are available in many papers in the literature and ORNL documents.

- These will be very useful for the planning on the development of our DEMO FW/blanket design, and the MSRE experience during the testing phase will be especially useful for the development of the MS ITER TBM design.

- Some of the specific experience documented includes:
  - several times plugs developed at several points in the fuel off-gas system,
  - air inleakage,
  - electrical shorts in the different power leads,
  - break up of the hub and blades in one of the blower,
  - fuel-pump bowl was accidentally over-filled,
  - cooling pumps went down with a lubricating-oil leak,
  - minor change in surface tension occurred when Be was exposed in the salt containing some unreduced corrosion products
  ...etc.

- Documentation of different equipment performance:
  - salt pumps,
  - heat exchangers (lower heat transfer coefficient was observed possibly due to inapplicability of the basic heat transfer correlation),
  - salt samplers,
  - containment,
  - maintenance of radioactive systems
  ...etc

A thorough study of available MSRE documents relevant to our design becomes mandatory.
**MSRE Chemistry**

- This is an area of vital importance for MSRE due to concerns on U-separation, production of fission products, compatibility with Pu and other materials and the goal for chemical processing.

- Oxide formation is controlled by the use of high purity (<10 ppm) He cover gas.

- The control of excess fluorine is to have the presence of UF₃ to guarantee a reducing non-corrosive environment by maintaining a small fraction of the U in the form of UF₃. This is accomplished by occasionally exposing a rod of Be metal to the salt in the fuel-pump bowl. (~10 g of Be forms BeF₂ in 10 h, reducing UF₄ to UF₃ and counteracting the effect of the transmutation over more than 10000MWh of operation.)

For fusion, the specific experience from MSRE fuel will not be applicable, but the general approach of REDOX control is very useful. The addition of Be or Li* into the MS could do the job. With a burn up rate of Li about 5 times of Be, therefore Li may be a preferred material to maintain composition balance. Based on MSRE experience with the use of Be rod, the REDOX process could be done outside of the FW/blanket module. Details will have to be studied.

* Also identified by Cheng and Sze, 2003.
Molten Salt Reactor Tritium

- A 1000 MW(e) MS reactor will produce tritium at 2420 Ci/day, 98% from (n,α) with Li.
- Briggs devised a model to describe the transport of tritium in the form of T₂ and HT. At the metal surface, some of the T₂ would dissociate into atoms, dissolve in the metal and diffuse to the outer surface. TF will release some T atoms but this is a relatively minor contribution.
- His model gave a good fit to observed distribution of T in the MSRE (~46-56% in the fuel off-gas system, 15% on the graphite, 5-9% in the reactor cell, and a similar amount in the cooling air coming from the radiator heat dump. As much as 20% of the calculated production is unaccounted for, and the T is most likely retained in a hydrocarbon residue in the pump bowl or off-gas system.)
- Applied to the 1000 MW(e) reactor, Briggs’ model indicated as much as 60% or 1500 Ci/day could end up in the steam system of the turbogenerator plant. Still far from the 10 Ci/day plant effluent level.

For fusion with burn-rate at 56kg/year per 1000 MW fusion, which implies a tritium generation rate of:

\( \frac{56\text{kg/year}}{365\text{days/year}} \times 1.1\text{TBR} \times 2.5\text{GW}_f \times 103\text{gm/kg} \times 104 \text{ Ci/gm} = 4.2 \times 10^6 \text{ Ci/day} \).

Therefore, the tritium containment requirement is much more difficult as also pointed out by Dai-Kai Sze.
Molten Salt Reactor Costing

• Based on 1970 construction costs
• A 1000 MW(e) three-region single fluid breeder was $203M.
• Light water reactor, on the same basis, was estimated at $210M.
• Direct cost of the MS system is about $12 M lower for the turbine plant equipment because of higher temperature steam, but this advantage is used up in such items as auxiliary boiler ($3M), maintenance equipment ($4.5M) and extra allowance for contingencies ($6M).

MS FW/blanket may have a simpler internal design than more conventional FW/blankets and with high thermal efficiency, but could be off-set by the costs of similar additional equipment. This will have to be assessed.
Summary

• MSRE can be considered as a very successful MS development experience. It prepared the ground work for a two region MS breeder fission reactor.

• MSRE literature and documents should be mandatory reading for the development of fusion MS DEMO FW/blanket design and the MSRE initial operation experience will also be relevant to ITER MS test module program

• Li$_2$BeF$_4$ was used in the coolant loop of MSRE

• In the fuel MS loop corrosion control was done by maintaining the ratio of UF$_3$ and UF$_4$ and with the addition of Be rod.

• For our case, REDOX with Be or Li should be considered depending on the chemistry details. Our situation would be further complicated with the tokamak geometry and operating environment of high energy neutrons and magnetic and electric fields.

• Tritium control was a concern for MS fission reactor and we will have a much higher production rate of tritium.

• We should look into the availability of existing facilities, equipment (pumps, monitors, freeze valves...etc.) and materials, including personnel from the MS fission reactor program for adaptation into our DEMO and ITER test-module program.
Selected References

4. F. A. Smith, “The Molten Salt Reactor-An Ingredient of Nuclear Progress,” Power Reactor Technology and