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GenIV Roadmap R&D – Molten Salt Reactors

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TWG 4: Non-Classical Reactors

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Molten Salt Reactors

History and Background

- The Idea of using Molten Salt and Liquid Metal Fuels was conceived in early 1940's and led to:
  - BNL U-Bi Eutectic Fuel Reactor R&D program ~ 1947
  - ORNL UF_4-ThF_4 Based MSR R&D Program ~ 1948
- Aircraft Reactor Experiment (ARE) 1954
- Conceptual design of MSR for Power 1956
  - Net output power: 260MWe (~ 44% efficiency)
  - Est. capital cost: $270/KWe (~$1700/KWe in 2002)
  - Generated power cost: $8.85/MWe (~$55/MWe in 2002)
- ORNL MSRE & MSBR (1966-1969)

Principal Advantages of MSRs

- **Over Solid Fuel Reactors**
  - High negative temperature coefficient of reactivity
  - Lack of radiation damage that can limit fuel burnup
  - Potential for continuous fission-product removal
  - No cost of new fuel elements fabrication
  - Online addition of makeup fuel, precluding installment of excess reactivity

Principal Advantages of MSRs

- **Over other Liquid Fuel Reactors**

  - Stability of molten salt fuel under radiation
  - High solubility of uranium and thorium fluorides in molten-salt mixtures
  - Availability of corrosion resistance structural materials with no need for protective coating formation

A Concluding Commentary

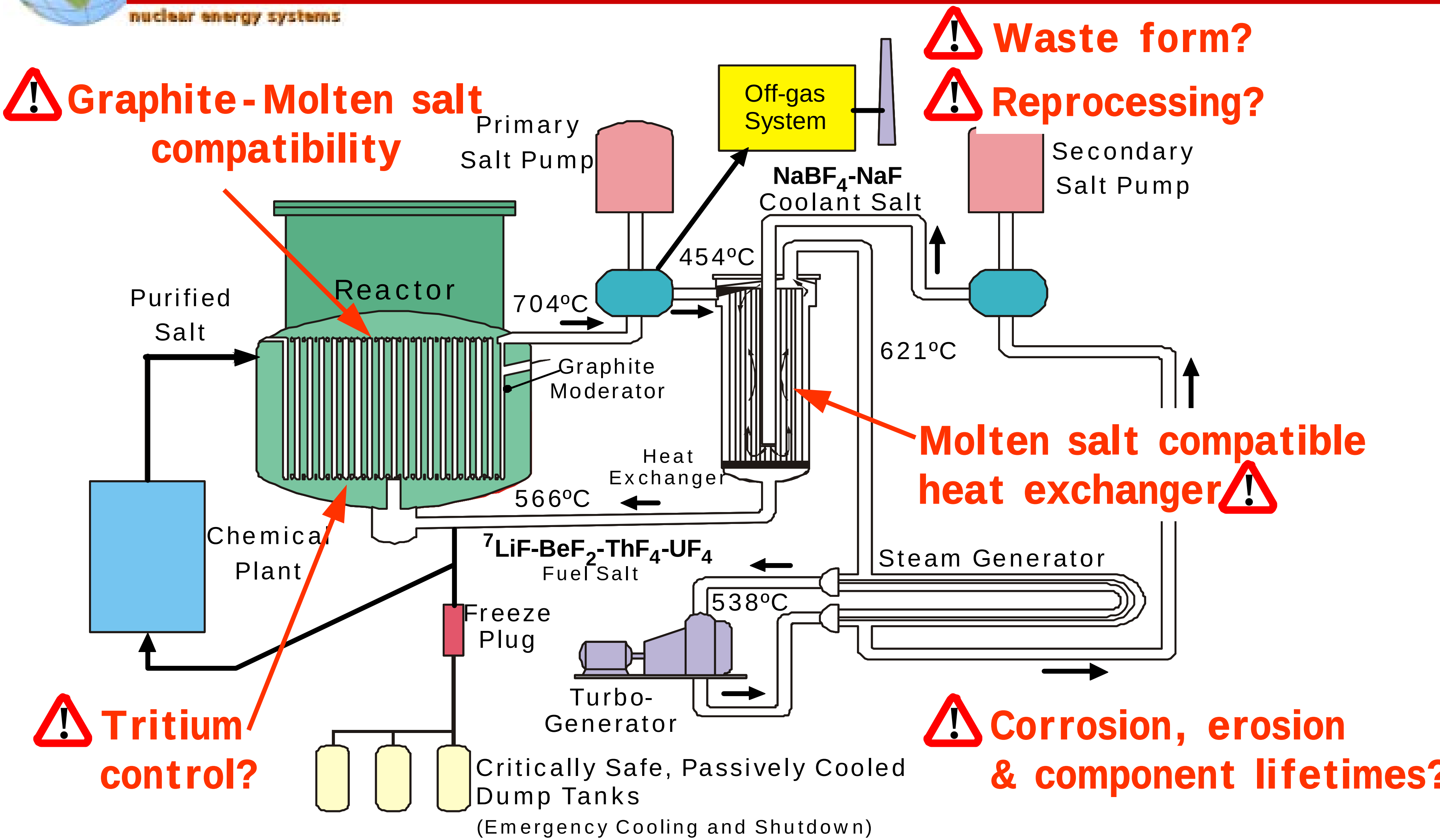
(at the end of the first decade of MSR R&D – 1948-58)

Those who have actually built and operated high-temperature, high-powered liquid (Molten Salt Fuel) reactors have become impressed with their difficulty – the difficulty primarily of handling vast amounts of radioactivity in labile form. It seems now that liquid reactor systems, when reduced to practice, are in many ways more complicated than their solid competitors.

Yet in spite of their difficulties, the two underlying motivations for liquid and other fluid systems remain: their fuel cycle is simpler and their neutron economy is better than for solid fueled reactors.

Alvin M. Weinberg
June 1958

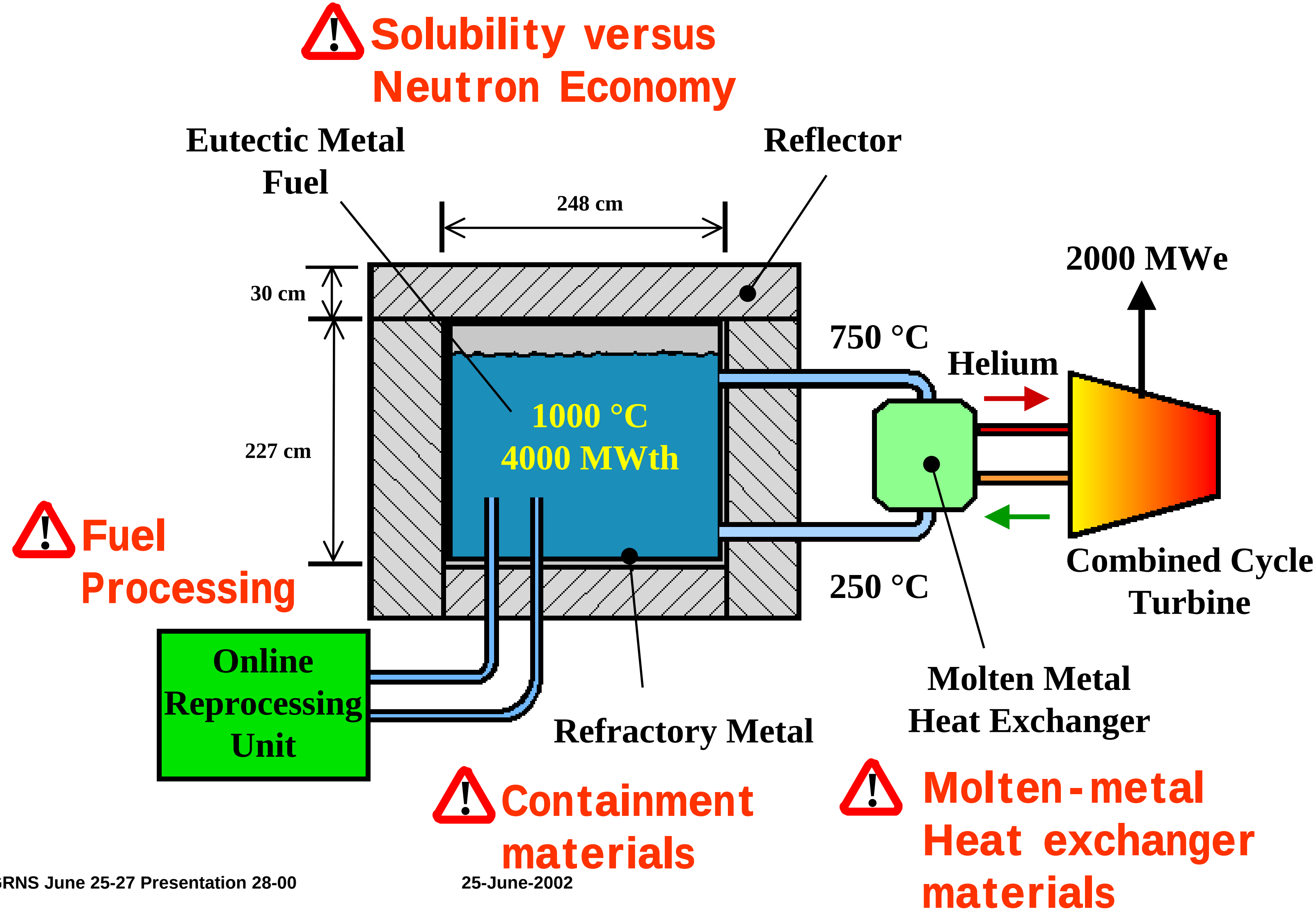
Molten Salt Reactor (MSR)



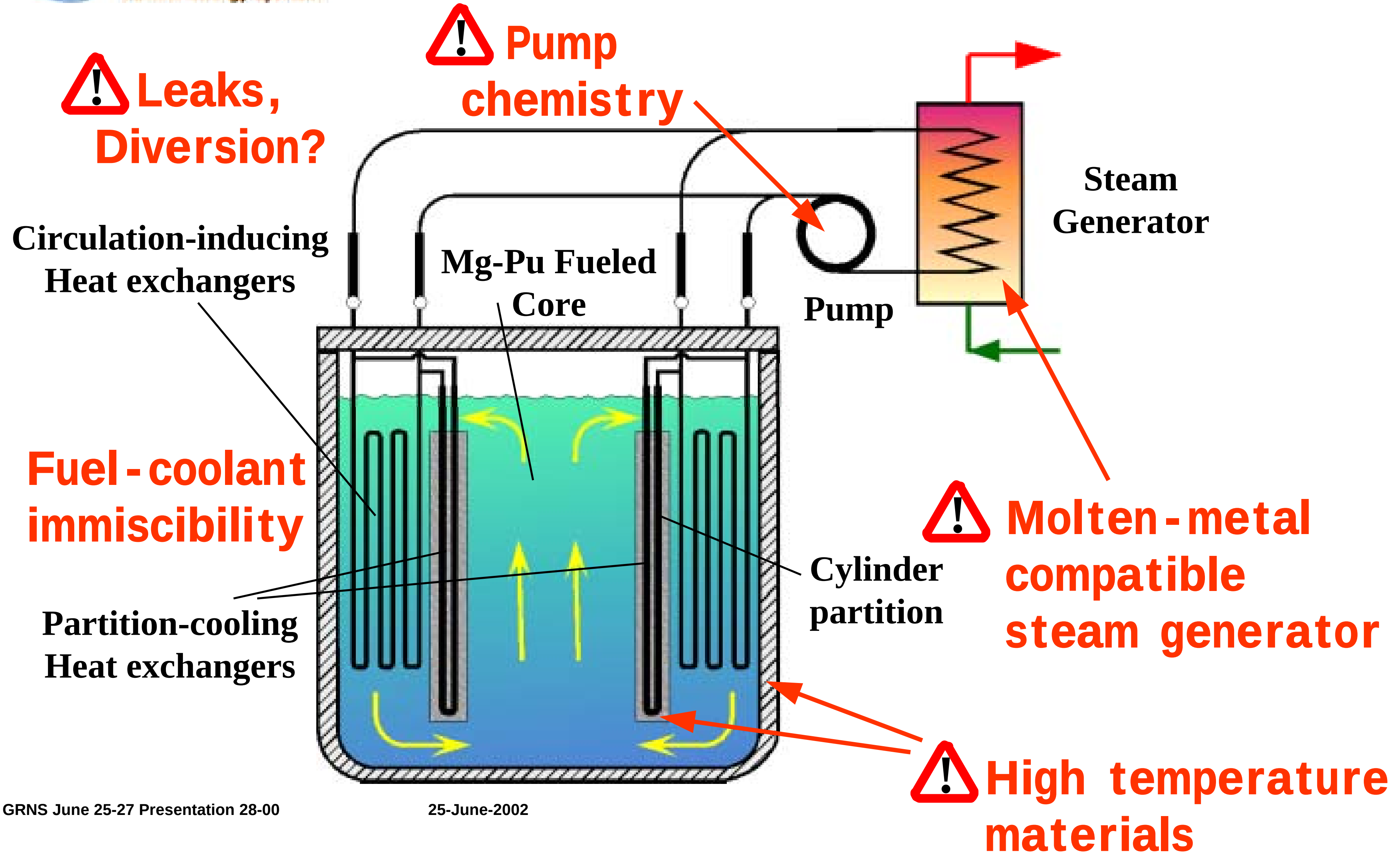
MSR—Key Features

- Alkali metal fluoride solute–Thorium-Uranium Fluoride Fuel.
- Circulating molten fuel.
- Fuel and Coolant one and the same (MSR).
- Thermal breeder, actinide burner, or once-through cycle.
- Large negative reactivity coefficient, passive cooling safety features.
- Fission products and actinides soluble in molten salt.
- Online feeding, processing and fission product removal.
- Passive cooling, failsafe drainage.
- High temperatures—high efficiency and potential for thermochemical hydrogen production.

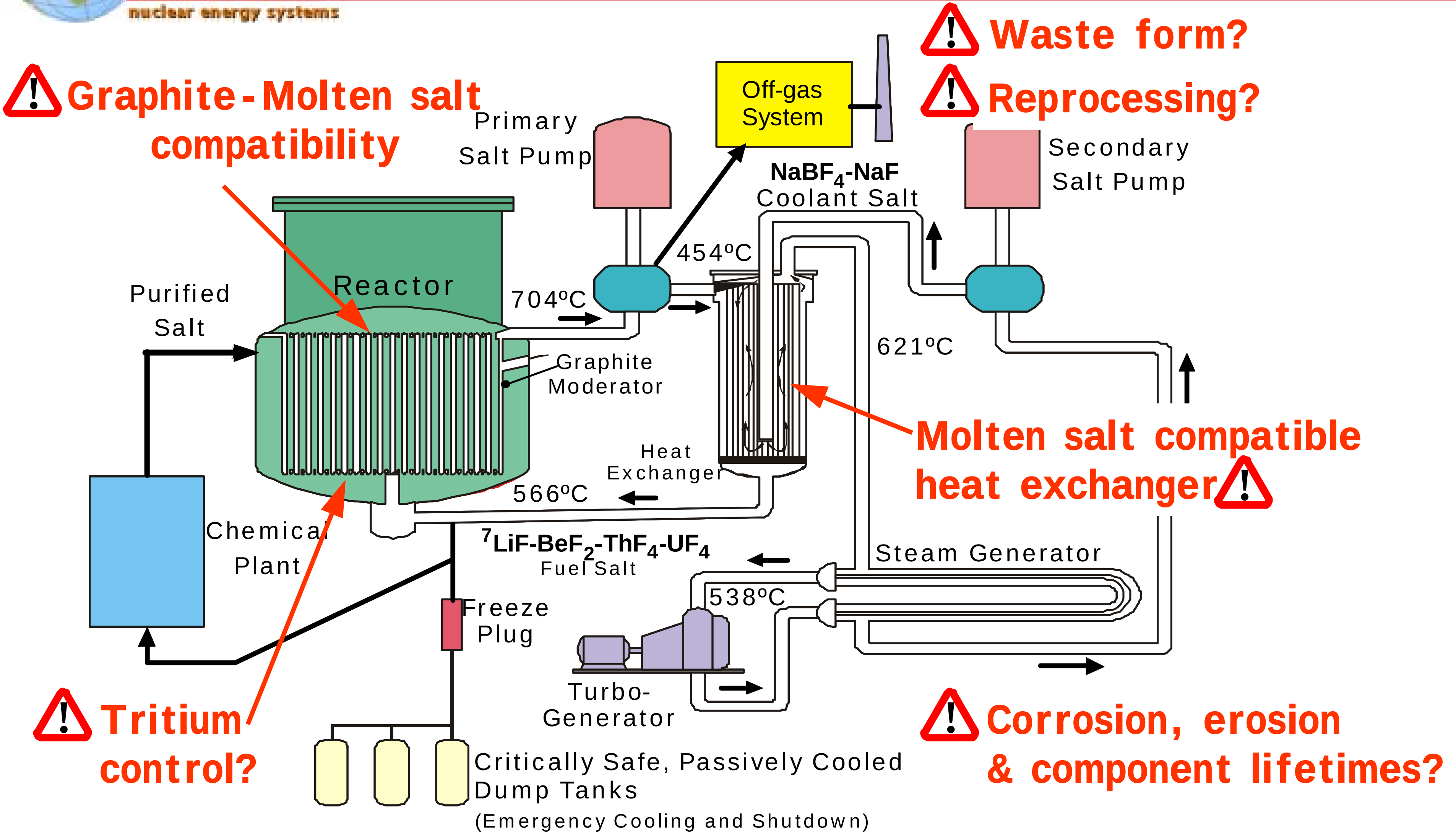
Molten Metal Core Reactor (MMR)



Liquid Metal Fast Reactor (LMR)



Molten Salt Reactor (MSR)



MSR—Important R&D Issues

- **Research needs on salt processing include,**
  - **Higher quality waste form/waste immobilization,**
  - **Breeding ratios ~1,**
  - **Actinide transmutation.**
- **Long term molten salt-material compatibility.**
- **Liquid-liquid extraction.**
- **Assessment of Non-proliferation characteristics.**
- **Circulation of high volume and mass of irradiated fuel/working fluid.**

MSR—Fuel and Material R&D Issues

- Fuel Salt Selection.
  - Fuel Salt Solubility (currently limits fissile concentration can't have fast spectrum MSR).
- Cross Sections and New Fuel Data.
- Investigation of New Salt Compositions.
- Secondary coolant salt selection.
- Heat exchanger leak & mix testing.
- Tritium control (chemical trap or counter diffusion?).
- Alloy corrosion resistance testing.
- Graphite testing
  - Sealing techniques,
  - Improved dimensional stability,
  - Spent graphite reprocessing and recycling.

Molten Salt Fuels – Knowledge & Gaps

- UF_4 Based Fuels
  - UF_4-NaF-ZrF_4 (ARE) — T_{melt} ~ 765ºC
  - UF_4-LiF-BeF_2 — T_{melt} ~ 500ºC
  - UF_4-LiF-BeF_2-ZrF_4
- ThF_4 Based Fuels
  - ThF_4-LiF-BeF_2 — T_{melt} ~ 550ºC
- UF_4/ThF_4 Based Fuels
  - UF_4/ThF_4-LiF-BeF_2 — T_{melt} ~ 550ºC
- PuF_3 Based Fuels
  - PuF_3-LiF-BeF_2 — T_{melt} ~ 550ºC

….Continued

Molten Salt Fuels – Knowledge & Gaps
(Continued)

- **All fuels are well characterized with complete phase diagrams**
- **Physical, thermal, and some transport properties are known**
- **Purification process available**
  - Removal of oxides, oxyfluorides, and sulfurs
- **Radiation stability**
  - Up to ϕ_{th} ~ 10^{14} n/cm^2.s, PD ~ 8 MW/lit, 800 hours of irradiation at 815ºC

Molten Salt Fuels – Knowledge & Gaps
(Continued)

- **Fission Products Behavior**
  - Lack of adequate chemical thermodynamic data
  - Limited irradiation data
- **Uncertainty in valance state of some fission products**

Valance state of Fission Products

- **Well defined valance**
  - **Noble gases (He, Ne, Ar, Xe)**
    - **Low concentration of Xe in ARE fuel**
  - **Rb, Cs, Sr, Ba, Zr, Y, and lanthanides form very stable fluorides**
- **Uncertain Valance**
  - **Nonmetallic elements (Se, Te, Br, I)**
  - **Ge, As, Nb, Mo, Ru, Rh, Pd, Ag, Cd, Sn, Sb could be reduced by wall material alloying elements (such as Cr)**
    - **Large fraction of Nb and Ru was deposited on ARE Inconel walls)**

Roadmap GENERATION IV nuclear energy systems

Breakdown of MSR R&D Plan

1. Fuels

Goal	Priority	(time)*	~Cost†
1.1 Fabrication and design,	1	(Short)	$ 20 M
1.2 Salt composition,	2	(Mid)	$ 3 M
1.3 Fuel recycling,	2	(Mid)	$ 150 M
1.4 Fuel refabrication/refueling,	2	(Mid-long)	$27 M
1.5 Separation product management,	2	(Long)	$ 10 M
1.6 Waste form development,	2	(Long)	$ 10 M
1.7 Spent fuel management,	2	(Long)	$ 80 M
			$ 300 M

* May reflect many research activities with disparate time frames.

† Note some overlap and R&D dependencies may lower costs (US dollars).

continued...

… breakdown of MSR R&D Plan

2. Coolant & Tritium Control

Goal	Priority (time)	~Cost
2.1 Tritium trapping in secondary,	1 (Mid-long)	$ 8 M
2.2 2ndary coolant selection,	2 (Short-mid)	$ 2 M
2.3 2ndary coolant compatibilities.	2 (Mid)	$ 5 M
3.1 Testing of technology.	1 (Mid)	$ 15 M
		$ 30 M

3. Salt processing

Goal	Priority	~Cost
3.1 Waste form & safety req. design.	1 (Mid-long)	$ 100 M

MSR – Structural Materials

- **Nickel Based Alloys**
  - Inconel (Ni-15Cr-10Fe-…)
  - INOR-8 (Ni-7Cr-5Fe-18Mo-…)
  - Hastelloys B (Ni-6Fe-30Mo,…)

- **INOR-8**
  - Strong, stable, corrosion-resistant alloy with good welding and forming characteristics.
  - Fully compatible with graphite and:
    - Non- sodium molten salts up to 815ºC
    - Sodium containing molten salt up to 700ºC

… breakdown of MSR R&D Plan

4. Structural materials

Goal	Priority (time)	~Cost
4.1 Fuel-coolant reaction,	2 (Mid-long)	$ 20 M
4.2 Alloy testing,	2 (Short-long)	$ 40 M
4.3 Ni alloy welding tech.,	2 (Mid)	$ 1 M
4.4 Alternative materials,	3 (Long)	$ 5 M
4.5 Graphite moderator tests,	2 (Mid)	$ 10 M
4.6 Graphite recycling/reprocess,	3 (Very long)	$ 25 M
4.7 Graphite lifetime extending.	2 (Mid-long)	$ 24 M
		$ 125 M

MSR – Heat Transport and Energy Conversion

- **Molten Salt Pumps**
  - ARE Pump Experience
    - 2000 hours, 150gpm, 820ºC, 75m pressure head
  - ORNL MSR development Program
    - 8000 without maintenance, 1500gpm, 800ºC
- **Heat Exchangers**
  - Design specific
- **Valves, Joints, and other Fittings**
  - Transition from room temperature to MSR operating temperature is a challenge

… breakdown of MSR R&D Plan

5. Heat exchangers & Energy Conversion

Goal	Priority	~Cost
5.1 Rigorous testing of HX's.	1 (Mid)	$ 10 M
5.2 thermal hydraulics modeling & code validation.	2 (Short-long)	$ 10 M
10.1 Turbine technology develop.	3 (Mid)	$ 100 M
10.2 Balance of plant design.	2 (Mid-long)	$ 5 M
		$ 125 M

Reactor Design and Fuel Utilization R&D Issues

- **Heterogeneous Graphite Moderated Reactor**
  - 45vol% graphite – 55vol% molten salt fuel
  - 600 MW_{th} Reactor diameter 3.7m
  - U-233 (213Kg), ThF_4 (2.5%), LiF (61%), BeF_2 (36.5%)
  - Thermal spectrum breeder (CR ~ 1.07)
- **Many conceptual design studies including:**
  - U-235 base burner (CR ~ .3 to .6)
  - Graphite moderated U-233/ThF4 based converter/breeder (CR ~ .8 to 1.07)
- **Burnup for 20 years of continuous operation**
- **Fuel and graphite reactivity coefficients measured/calculated**

… breakdown of MSR R&D Plan

6. Reactor system

Goal	Priority (time)	~Cost
6.1 Validate cross sections,	1 (Mid-long)	$ 10 M
6.2 Simulation tools,	2 (Mid-long)	$ 5 M
6.3 Scaled critical experiments,	2 (Very long)	$ 35 M
6.4 Activity & decay heat expmnts,	2 (Mid-long)	$ 5 M
6.5 Heat transport,	2 (Mid-long)	$ 3 M
6.6 Monitoring & safety protections,	1 (Long)	$ 12 M
6.7 Refueling mechanics,	2 (Long)	$ 20 M
6.8 Structure/containment design.	3 (Mid)	$ 10 M
		$ 100 M

… breakdown of MSR R&D Plan

7. Dynamic monitoring & control

Goal	Priority (time)	~Cost
7.1 In-line fuel composition/chem.,	2 (Mid-long)	$ 30 M
7.2 REDOX control & monitoring.	2 (Mid)	$ 10 M
		$ 40 M

8. Hydrogen production

Goal	Priority	~Cost
8.1 Feasibility study,	3 (Long)	$ 2 M
8.2 Safety/economics performance.	3 (Very long)	$ 10 M
		$ 12 M

… breakdown of MSR R&D Plan

9. Off-gas system

Goal	Priority (time)	~Cost
9.1 Immobilize fission products,	2 (Short-long)	$ 25 M
9.2 Optimize non-solubles extractn.	3 (Mid)	$ 10 M
		$ 35 M

10. Maintenance & repair

Goal	Priority	~Cost
10.1 Asses remote/robotics needs,	3 (Mid)	$ 10 M
10.2 Adapt or develop technology.	3 (Very long)	$ 50 M
		$ 60 M

11. Non-Proliferation enhancement

Goal	Priority	~Cost
11.1 Thorough analysis of characteristics.	2 (Mid-long)	$ 10 M

Roadmap GENERATION IV nuclear energy systems

MSR—Safety & Control R&D Issues

- Online measurement techniques for irradiated fuel composition.
- Off-gas system immobilization techniques.
- Robotic maintenance.
- Regulatory and design certification issues.
- Comprehensive safety analysis.
- Updated economic evaluation.
- Dynamics and control techniques.
- Experimental test loops.

Roadmap GENERATION IV nuclear energy systems

… breakdown of MSR R&D Plan

12. Safety & Regulatory design

Goal	Priority (time)	~Cost
12.1 Perform thorough tests & analysis,	2 (Mid-long)	$ 50 M
12.2 New principles/criteria,	1 (Mid-long)	$ 5 M
12.3 Safety & performance analysis	1 (Mid-long)	$ 20 M
		$ 75 M

13. Economics evaluation

Goal	Priority	~Cost
13.1 Comprehensive update,	2 (Short-mid)	$ 3 M
13.2 Factor in H_2 production?,	3 (Very long)	$ 20 M
13.3 Comparative assessment tools,	2 (Mid)	$ 2 M
		$ 25 M

Molten Salt Reactor R&D Phases

1. Preliminary Design Phase.

- Define critical issues
- Address key technology needs
- Establish basic design specifications

2. Extended R&D Phase.

- Establish nuclear (static & dynamic) design
- Develop & benchmark nuclear design analysis models
- Address irradiation effects on fuel and materials
- Fuel cycle design
- Fuel handling and processing
- Heat transport and energy conversion

continued …

Molten Salt Reactor R&D Phases

3. **Prototype Design Phase.**
   - Scale nuclear power system design
   - Establish heat transport/energy conversion design
   - Establish operation and maintenance cost
   - Establish safety & reliability performance
4. **Design Certification Phase.**
   - Full scale design specifications
   - Top-level peer review of design
   - Full assessment of economics
5. **Deployment.**

Summary R&D Phases–MSR