An Advanced Molten Salt Reactor Using High-Temperature Reactor Technology

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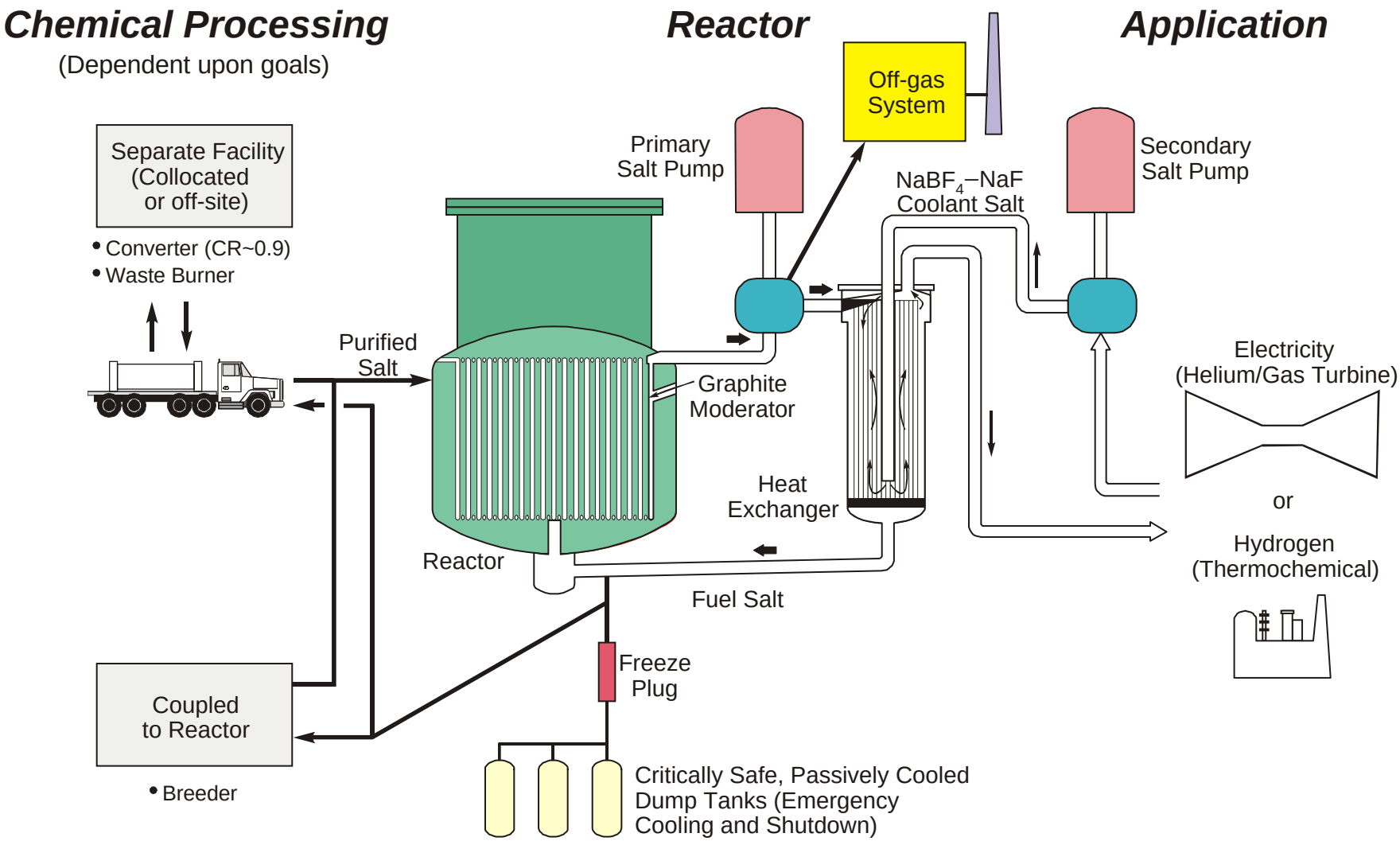
There is Renewed Interest in MSRs Because of Changing Goals and New Technologies (Since 1970)

- **MSR is one of six Generation IV concepts**
  - **Only liquid-fueled reactor selected**
- **Original basis for development**
  - **Thorium-cycle breeder reactor ($^{232}Th + n \rightarrow {}^{233}U$)**
  - **Backup for the liquid-metal breeder reactor program**
  - **Program cancelled**
    - **Decision to develop only one type of breeder reactor**
    - **As a breeder reactor, MSR has a low breeding ratio, slightly above one**
- **Basis for renewed interest**
  - **Thorium-based MSR produces wastes with a very low actinide content (reduced waste management burden)**
  - **Breeder with low breeding ratio is acceptable**
  - **Unique capability to burn actinides**
  - **New technology (Subject of this talk)**
    - **Reduces cost**
    - **Reduces technical challenges**

Molten Salt Reactor

Molten Salt Reactors



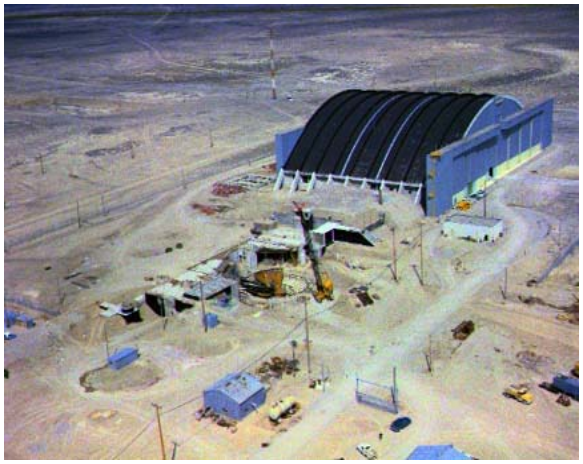
Molten Salt Reactors Were Developed in the 1950s and 1960s

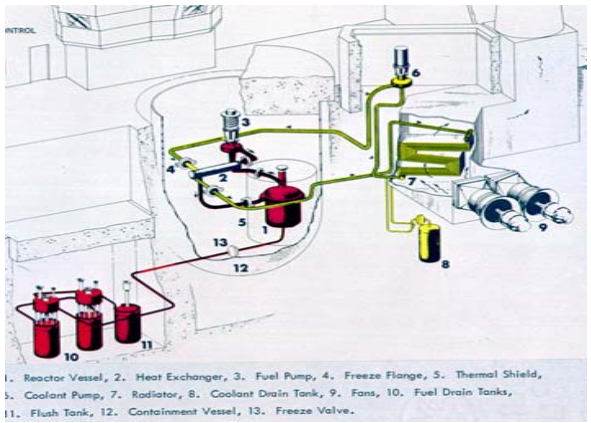
Molten Salt Reactors: Fuel Dissolved in Coolant

Aircraft Nuclear Propulsion Program

← ORNL Aircraft Reactor Experiment: 2.5 MW; 882ºC Fuel Salt: Na/Zr/F

INEEL Shielded Aircraft Hanger→

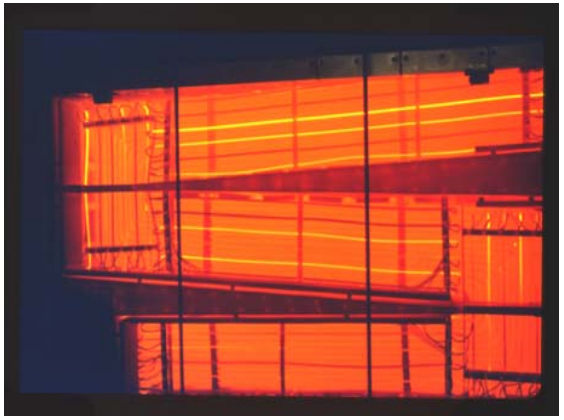




Molten Salt Breeder Reactor Program

←ORNL Molten Salt Reactor Experiment Power level: 8 MW(t) Fuel Salt: ^{7}Li/Be/F Clean Salt: Na/Be/F

Air-Cooled Heat Exchangers→



The Molten Salt Reactor Experiment Demonstrated the Concept

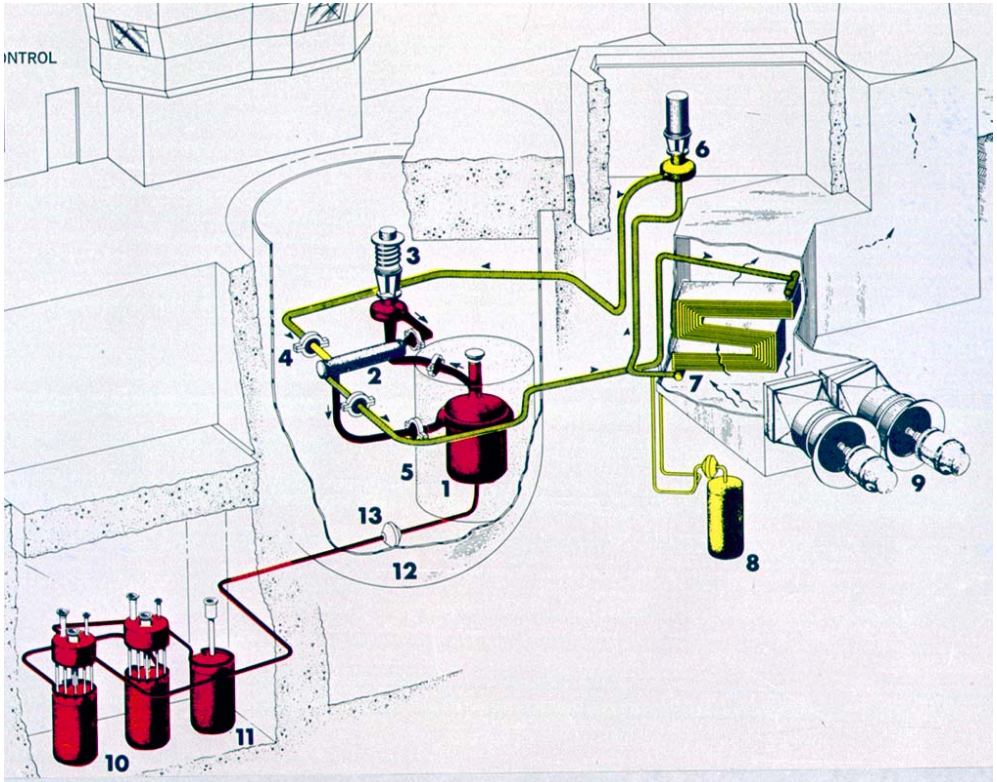
Hours critical	**17,655**
Circulating fuel loop time (hours)	**21,788**
Equiv. full power hrs w/ ^{235}U fuel	**9,005**
Equiv. full power hrs w/ ^{233}U fuel	**4,167**

1960s Goal: Breeder

- **Base technology established**

Today's Option

- **Actinide burning**
- **New requirements**
- **Changes in the base technology**



1. Reactor Vessel, 2. Heat Exchanger, 3. Fuel Pump, 4. Freeze Flange, 5. Thermal Shield, 6. Coolant Pump, 7. Radiator, 8. Coolant Drain Tank, 9. Fans, 10. Fuel Drain Tanks, 11. Flush Tank, 12. Containment Vessel, 13. Freeze Valve.

MSRE power = 8 MW(t)
Core volume <2 cubic meters

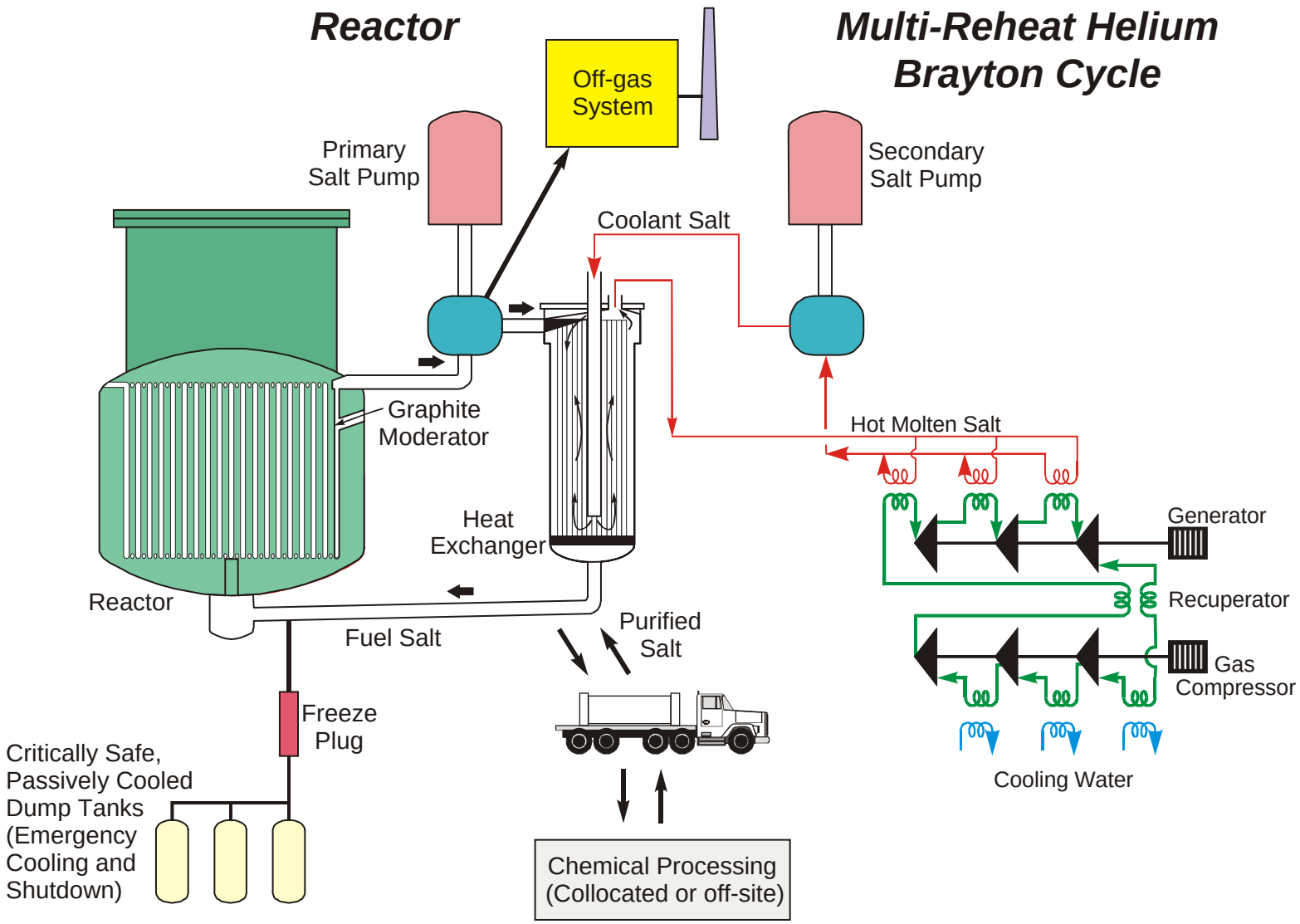
Three Technical Developments May Dramatically Improve MSR Viability

(Technologies Being Developed for High-Temperature Reactors)

- **Brayton power cycles (aircraft derived)**
- **Compact heat exchangers (chemical industry)**
- **Carbon-carbon composite components and heat exchangers**

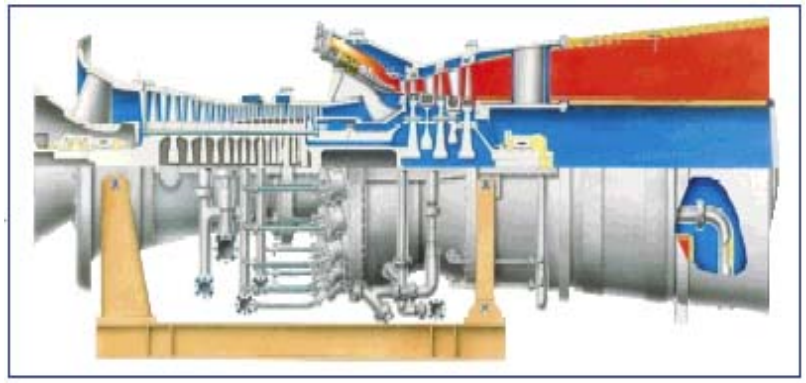
Brayton Power Cycle

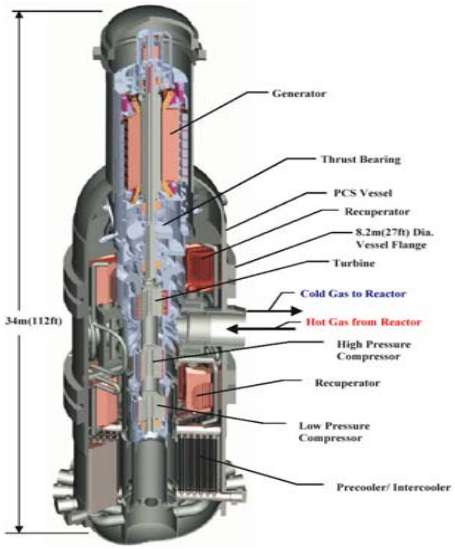
Molten Salt Reactor



Brayton Cycles Eliminate Multiple Technical Challenges of the MSR

- **Simplified tritium control**
  - **Tritium in fuel salt may diffuse into power cycle via hot heat exchangers**
  - **Tritium in steam cycle is difficult to manage**
  - **Tritium in a dry Brayton cycle is easy to remove in the cold sections of the cycle**
- **No salt interactions if a heat- exchanger failure occurs**
  - **Steam and salt slowly react**
  - **Helium or nitrogen does not react with salt**
- **Higher efficiency**
  - **High temperatures match salt properties (avoid freezing)**
  - **Brayton cycles match preferred salt temperatures**



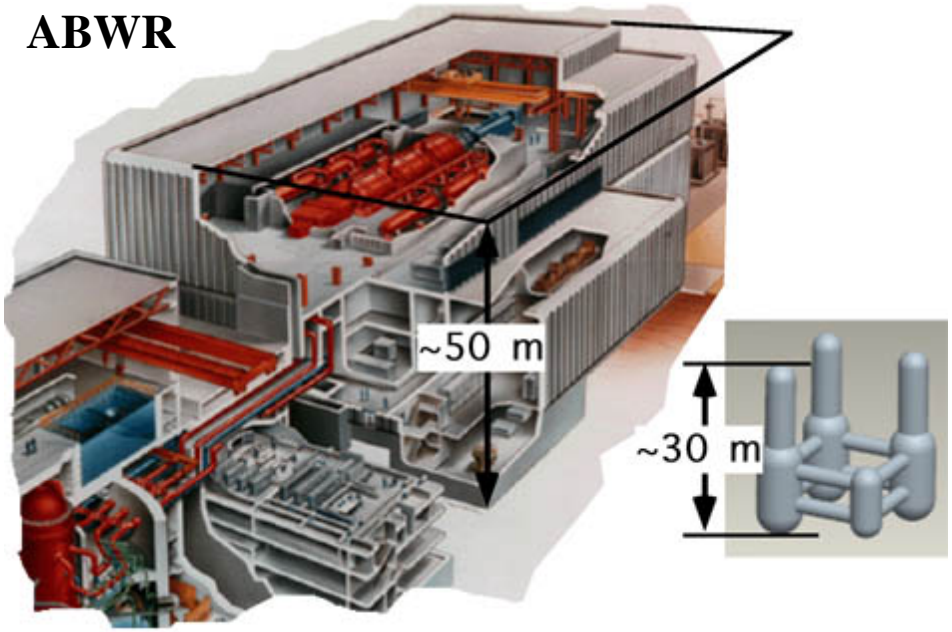


Above: GE Power Systems MS7001FB

Left: GT-MHR Power Conversion Unit (Russian Design)

Scaled Comparison of the 1380-MW(e) ABWR Turbine Building and ~1300-MW(e) MSR

ABWR



Advanced helium Brayton cycles can likely achieve a substantial reduction of the turbine building volume

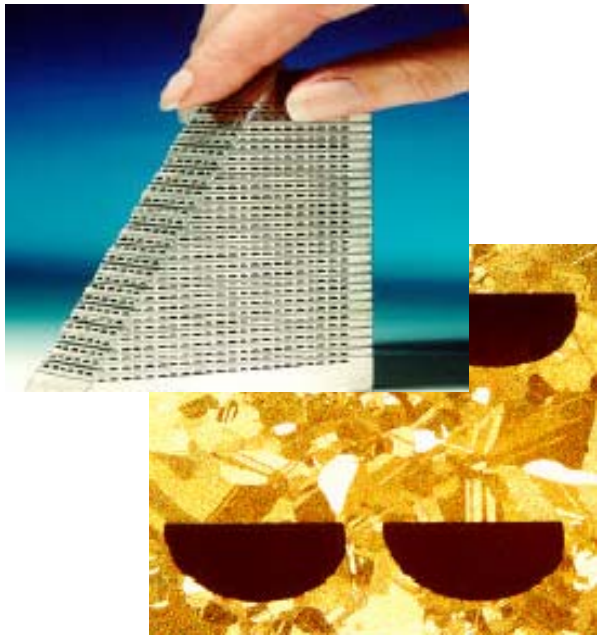
Helium-Brayton Cycle with Three Power Conversion Units (Similar to GT-MHR)

- **MSR turbine building must also contain crane, turbine lay-down space, compressed gas storage, and cooling water circulation equipment**
- **MSR requires ~1100 MW(t) of cooling water capacity, compared with 2800 MW(t) for ABWR; no low-pressure turbines (steam)**

Compact Heat Exchangers

Compact Heat Exchangers May Reduce Fuel Salt Inventory by Up to Half

- **MSRs of the 1970s used "tube-and-shell" heat exchangers**
- **New compact heat exchangers have been demonstrated**
  - **Temperatures to 900°C**
  - **Large units**
  - **>1000 psi**
- **Reduce size of heat exchanger by a factor of four**
  - **Heat exchanger in hot cell**
- **Reduced salt inventory**
  - **Half the fuel inventory**
  - **Half the fuel salt to process**



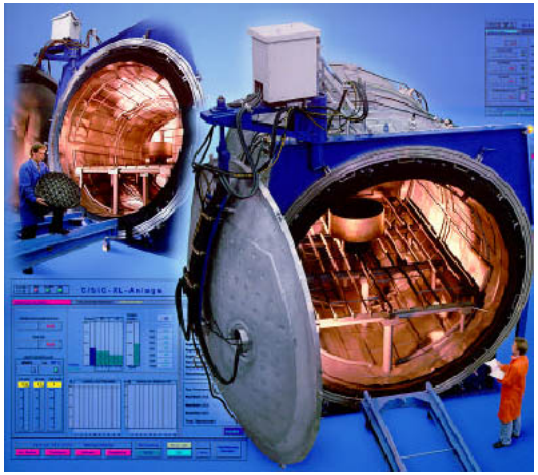
Structure of "Printed Circuit" Heatric® Heat Exchanger

Carbon-Carbon Composites

Liquid Silicon Infiltration (LSI) Carbon-Silicon Composites (CSiC) Are Candidate Materials for Use with Molten Salts

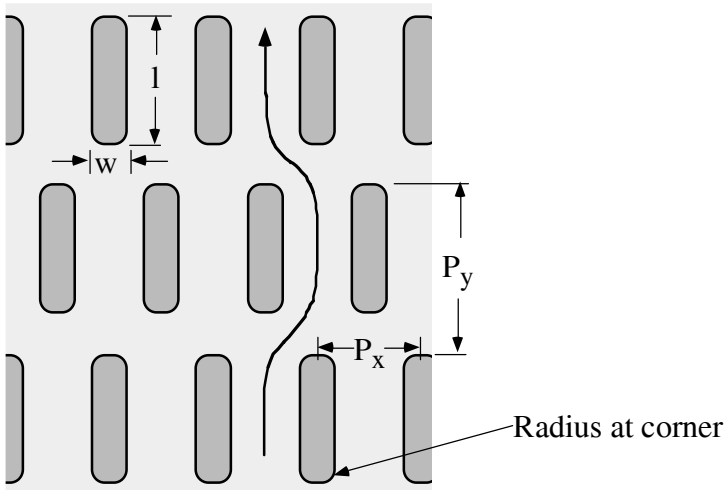
- **Allow higher-temperature operations**
  - **Molten salt properties improve with higher temperatures**
  - **Higher efficiency**
  - **Option for thermochemical hydrogen production**
- **Reduce noble metal plate-out in the primary MSR system**
  - **Some noble metal fission products plate out on metal heat exchangers**
  - **Plate-out on carbon materials is much less pronounced**
  - **Potential for efficient control of where noble metals plate out**

Highly complex part geometries

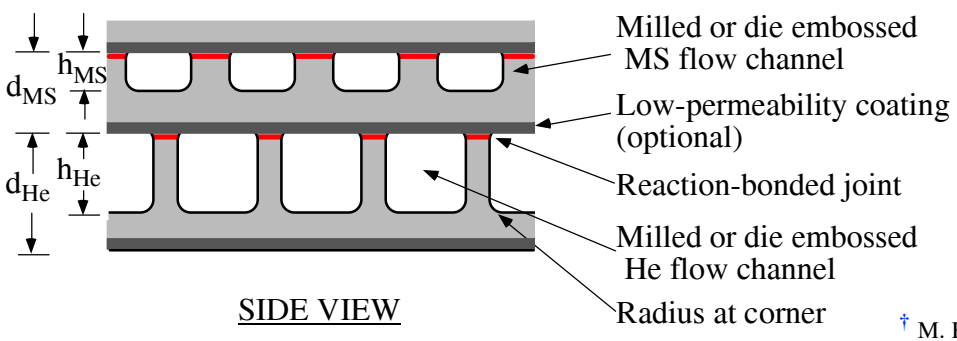


IABG large furnace for CSiC fabrication

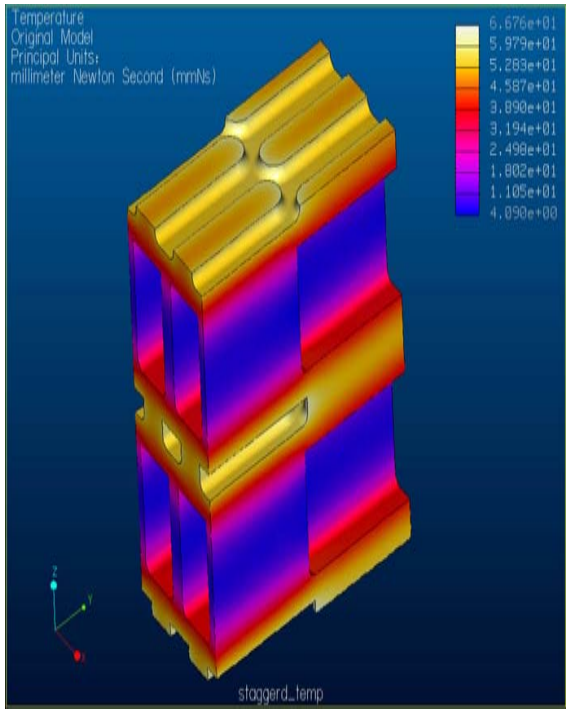
Heat-Exchanger Monolith Can Be Formed by a Reaction Bonding Multiple Green Plates, a Standard LSI Technique



PLAN VIEW

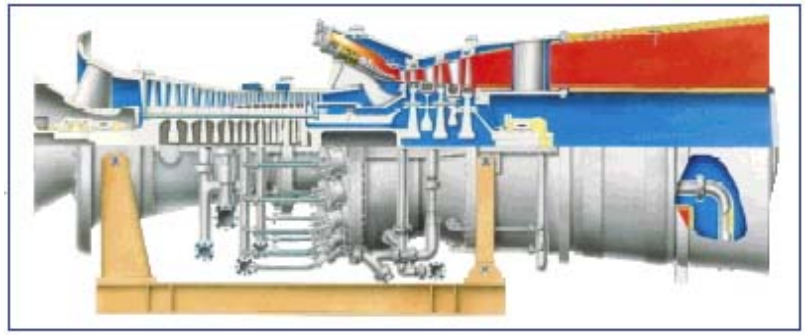


SIDE VIEW



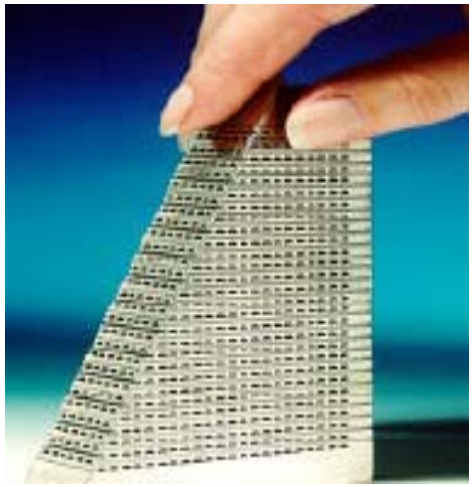
† M. Krödel, G.S. Kutter, M. Deyerler, and N. Pailer, "Short carbon-fiber reinforced ceramic -- Cesic -- for optomechanical applications," SPIE Optomechanical Design and Engineering, Seattle, Washington, July 7-9, 2002.

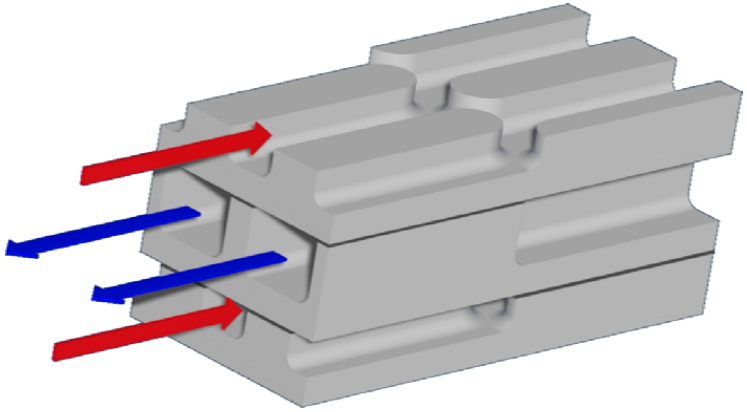
Conclusions: New Technologies Being Developed for High-Temperature Reactors May Dramatically Improve the Viability of MSRs



←Brayton Power Cycles

Compact Heat Exchangers→





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