Molten Salt Nuclear Reactors

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Outline

• Motivation for Molten Salt Reactors
• Molten Salt Reactor Designs
• Molten Salt Research
The (almost) Nuclear Plane XB-70 Valkyrie
The Nuclear Jet Engine

FUEL PUMP DRIVE TURBINE
NO PUMP DRIVE TURBINE
AIR TURBINE
Nk EXPANSION TANK
WEB OF CANTILEVER BEAM FROM REAR WING SPAR
BLEED-OFF AIR
Nk TO INTERMEDIATE HEAT EXCHANGER (1000°F)
EXTERNAL SHIELD (RUBBER CONTAINER FILLED WITH BORATED WATER)
LEAD SHIELD
INSULATION
REACTOR
Nk PUMP
Nk TO ENGINES (1500°F)

ENGINE DATA
MODIFIED WRIGHT TURBOJET
COMPRESSOR RATIO 4:1 (CORRECTED FOR SEA LEVEL)
AIR FLOW 220 lb/sec (CORRECTED FOR SEA LEVEL)
DIAMETER = 44½ in.
LENGTH = 140 in.
ENGINE WEIGHT = 3400 lb (WITHOUT RADIATOR)
RADIATOR WEIGHT = 1500 lb (WITH Nk)

Fig. 4.33. Aircraft Power Plant (200 Megawatt).
The Nuclear Jet Engine

HTRE-3 Reactor:
MX-1589 Project
The Nuclear Plane
MSBR70 Reactor (ORNL) 1965-1969

Operated with the main 3 fissile fuels: U-233, U235 and Pu-239
High-Temperature Reactors

Applications

**Hydrogen Production**
Future fuel

**Electricity generation**
Better Efficiency

**Desalination**
Lower temperature use

Desirables

- Thorium
  - Proliferation Resistance
- Safety
  - ve reactivity coefficients
- Higher Burnup

<table>
<thead>
<tr>
<th>Moderator</th>
<th>Graphite or BeO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inert Coolant</td>
<td>He, Pb-Bi eutectic, Molten Salt (2FLi-BeF2)</td>
</tr>
<tr>
<td>Fuel</td>
<td>TRISO coated particle Form</td>
</tr>
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</table>
# High-Temperature Reactors

**Requirement:** Process heat applications

<table>
<thead>
<tr>
<th>Process temperature</th>
<th>Up to 700°C</th>
<th>Up to 900°C</th>
<th>Up to 950°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity production</td>
<td>Rankine (steam) cycle</td>
<td>Brayton (direct) cycle</td>
<td></td>
</tr>
<tr>
<td>Utility applications</td>
<td>Desalination</td>
<td>H₂ via steam reforming of methane</td>
<td>Thermochemical H₂ production</td>
</tr>
<tr>
<td>Oil and chemical industry</td>
<td>Tar/oil sands and heavy oil recovery, Syncrude, Refinery and petrochemical</td>
<td>Syngas for ammonia and methanol</td>
<td>Thermochemical H₂ production</td>
</tr>
</tbody>
</table>

[http://www.world-nuclear.org/info/inf116_processheat.html](http://www.world-nuclear.org/info/inf116_processheat.html)
Historic Overview of MSR

1950s • Aircraft Reactor Experiment (ARE)*

1960s • Molten Salt Reactor Experiment (MSRE)*

1970s • Molten Salt Breeder Reactor (MSBR)*

1990s • Accelerator-driven transmutation of Nuclear Waste (ATW)**

2000s • Generation IV, Amster, Sphinx, Tier, Fuji…

2010s • MSFR, Mosart…

Future • U-Th breeding, transmutation of Actinides, H₂ production …  ?

* ORNL, ** LANL
MSR: One of the GEN-IV Designs

1) VHTR  Very-High Temperature Reactor
2) SCWR  Supercritical-Water-Cooled Reactor
3) GFR  Gas-Cooled Fast Reactor
4) LFR  Lead-Cooled Fast Reactor
5) MSR  Molten Salt Reactor
6) SFR  Sodium-Cooled Fast Reactor
Gen-IV MSR

1) VHTR  Very-High Temperature Reactor
2) SCWR  Supercritical-Water-Cooled Reactor
3) GFR   Gas-Cooled Fast Reactor
4) LFR   Lead-Cooled Fast Reactor
5) MSR   Molten Salt Reactor
6) SFR   Sodium-Cooled Fast Reactor

- **Inherent safety**
  (fail-safe drainage, passive cooling, low inventory of volatile fission products, and negative temperature feedbacks)

- **Excellent neutron economy**
  (high availability, low inventory, breeding, burning)

- **Liquid fuel**
  (online refueling, reprocessing, volatile fission products removal, no fabrication)
Uses of Molten Salts in Nuclear Technology

- Molten Salt as Liquid Coolant
  - High Temperature Reactors

- Molten Salt as Liquid Fuel

- Molten Salt as Process Medium
  - Advanced Partitioning Processes based on Pyro-processing of Spent Nuclear Fuel

MSRE at ORNL from 1965-69

CMSNT2013, Jan 9-11, 2013, Mumbai
Specific features of MSR comes out from the use of liquid (molten-salt) fuel circulating in the primary circuit.

MSR can be operated either as thorium breeder (in thermal or fast/resonance spectrum) within the $^{232}\text{Th} - ^{233}\text{U}$ fuel cycle or as actinide transmuter (in resonance/epithermal spectrum) incinerating transuranium fuel.

Typical fuel: fluorides of actinides dissolved in fluoride carrier salt.
MSR – Thorium Breeder

MSR is the only reactor system from the GEN IV reactor family for which the thorium fuel is considered. 

$^{233}\text{U}$ is the only fissile material in the thorium – uranium fuel cycle

MSR – Th breeder with higher breeding cannot be operated without the on-line reprocessing

Typical fuel: ThF$_4$ and UF$_4$ dissolved in $^7\text{LiF} – \text{BeF}_2$ carrier molten salt.
Fuel Cycle Technology on MSR System

Conversion into fluoride form → Anh. HF → ThF₄ → Liquid fuel processing → Molten-fluoride-salt carrier → Th, (²³³U) → Molten-Salt Reactor → Th, (Pa), U, Pu, MA → Spent fuel on-line reprocessing (fuel salt clean up) → Waste disposal → FP
Advantages of MSR

Safety
Inherent safety, understandable to the public
Hard to even imagine accidents hazardous to the public

Reduced Capital Cost
Low pressure, high thermal efficiency and far superior coolants (smaller pumps, heat exchangers)

Long Lived Waste Profile
Even converter designs can have closed cycles that see almost no transuranics going to waste
Ideal system for consuming existing transuranic wastes

Resource Sustainability and Low Fuel Cycle Cost
Thorium breeders obvious but MSR converters also extremely efficient on uranium use
Neutronics Characteristics of MSR

Categories:
- Safety
- Economics
- Sustainability

Online criticality maintenance (high availability)

Flexible fuel composition (without blending and fabrication, enables actinides recycling)

Online refueling and reprocessing

Excellent neutron economy

Utilization of low absorption materials

Available “free” neutrons (thorium breeding and/or actinide burning, fixed fuel cost)

Low fuel load (low excess reactivity)

Low source term (low radiotoxic risk)

Low absorbers and fuel presence in salt (negative thermal feedback coefficient)
Molten Salt Features and Characteristics

**Categories:**
- Safety
- Economics
- Sustainability

Chemically inert substance

(no rapid reaction with water
no fire or explosion hazard )

Radiation resistant substance

(unlimited use only with purification)

Freezing is inherent and passive

(dispersion and freezing after leakage)

| freezing < 500°C | 1400°C < boiling |

High-temperature operation

(potential for hydrogen production)

Low vapor pressure of fluoride salts

(reduced stresses on vessel and piping)

Fuel is molten and in liquid state

(it can be drained, no melting accidents)

molten fluoride salts for MSR are transparent
Advanced High Temperature Reactor (AHTR) is ORNL’s design concept for a central station type (1500 MW<sub>e</sub>) FHR. Objective is to demonstrate the technical feasibility of FHRs as low-cost, large-size power producers while maintaining full passive safety. Focus on developing a functional, self-consistent system.
**SmAHTTR**

Small, modular Advanced High Temperature reactor (SmAHTTR) has been designed for modular, factory fabrication, and truck transport

- 125 MW\textsubscript{th}
- Plate assembly fuel
- Cartridge core
- Integral primary heat exchangers

Technology development requirements for small and large FHRs is virtually identical
What defines an HFR?

The general characteristics of a Fluoride Salt Cooled High Temperature Reactor (FHR) are:

- Use of coated particle ceramic fuel
- Use of fluoride salt as primary coolant
- Use of a low-pressure, pool type primary system configuration
- Delivery of heat at temperatures greater than 600°C
- Strong passive safety features

No requirement for active response to avoid core damage or large off-site release following even severe accidents
Relevance of HFRs

Large FHRs have transformational potential to provide lower cost, high efficiency, large scale electrical power

- May be cheaper than LWRs due to higher thermal efficiency and low-pressure, and passive safety

Small, modular FHRs can be cost effective, local process heat sources

- High temperature, liquid cooling enables efficient hydrogen production
- Domestic oil shale based gasoline production requires large-scale, distributed process heat

FHRs have a high degree of inherent passive safety

- No requirement for offsite power or cooling water
- Low-pressure primary and intermediate loops

Plant concept and technologies must be matured significantly before the potential for FHRs can be realized

- Lithium isotope separation technology must be reindustrialized
- Tritium capture technology must be developed and demonstrated
- Structural ceramics must become safety grade engineering material
- Safety and licensing approach must be developed and demonstrated
- Layered TRISO fuel manufacturing technology must be demonstrated
US FHR Project

- MIT
- University of California Berkley
- University of Wisconsin
- Oak Ridge National Laboratory
- Idaho National Laboratory
FHR Combines Existing Technologies

Fluoride Salt-Cooled High-Temperature Reactor (FHR)

Passively-Safe Pool-Type Reactor

GE Power Systems MS7001FB
Brayton Power Cycles

High-Temperature Coated-Particle Fuel

High-Temp., Low-Pressure Liquid-Salt Coolant (Transparent)
Many Fuel Options
Mostly Graphite-Matrix Coated-Particle Fuels

- Pebble bed: Current technology
- Flat fuel: Existing materials, new design
- Pin assembly: New clad materials required
FHR-Pebble Bed Uses Coated-Particle Fuel
Same Fuel: High-Temperature Gas-Cooled Reactors

Pebbles 3-cm Diameter
Higher Power Density than HTGR
FHR uses Fluoride Salts Coolants

- Low-pressure high-temperature coolant
- Base-line salt Flibe (Li$_2$BeF$_4$)
  - Melting point: 460°C
  - Boiling point: >1400°C
- Heat delivered to power cycle between 600 and 700°C
  - Avoid freezing salt
  - Limits of current materials
**Base Case Salt is FLIBE ($^7\text{Li}_2\text{BeF}_4$)**

There Are Alternative Coolant Salts

<table>
<thead>
<tr>
<th>Coolant</th>
<th>$T_{\text{melt}}$ (°C)</th>
<th>$T_{\text{boil}}$ (°C)</th>
<th>$\rho$ (kg/m$^3$)</th>
<th>$\rho C_p$ (kJ/m$^3$°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^7\text{Li}_2\text{BeF}_4$ (Flibe)</td>
<td>459</td>
<td>1430</td>
<td>1940</td>
<td>4670</td>
</tr>
<tr>
<td>59.5 NaF-40.5 ZrF$_4$</td>
<td>500</td>
<td>1290</td>
<td>3140</td>
<td>3670</td>
</tr>
<tr>
<td>26 $^7\text{LiF}$-37 NaF-37 ZrF$_4$</td>
<td>436</td>
<td>2790</td>
<td>3500</td>
<td></td>
</tr>
<tr>
<td>51$^7\text{LiF}$-49 ZrF$_4$</td>
<td>509</td>
<td>3090</td>
<td>3750</td>
<td></td>
</tr>
<tr>
<td>Water (7.5 MPa)</td>
<td>0</td>
<td>290</td>
<td>732</td>
<td>4040</td>
</tr>
</tbody>
</table>

Salt compositions are shown in mole percent. Salt properties at 700°C and 1 atm. Sodium-zirconium fluoride salt conductivity is estimated—not measured. Pressurized water data are shown at 290°C for comparison.
No FHR has been built: new concept

United States activities
- MIT, University of California at Berkeley (UCB), University of Wisconsin (UW), Westinghouse Consortium
- Oak Ridge National Laboratory
- Idaho National Laboratory

Chinese Academy of Science
- Small 2-MWt test reactor by 2017
- Use pebble bed fuel from Chinese high-temperature gas-cooled reactor program
## FHR is in Different Reactor Design Space

<table>
<thead>
<tr>
<th>Coolant Temperature</th>
<th>System Pressure</th>
<th>Reactor Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Low</td>
<td>Light-Water Reactor</td>
</tr>
<tr>
<td>Medium</td>
<td>Sodium Fast Reactor</td>
<td>Sodium Fast Reactor</td>
</tr>
<tr>
<td>High</td>
<td>High Inlet Temperature</td>
<td>High-Temperature Gas-Cooled Reactor</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low Inlet Temperature</td>
</tr>
</tbody>
</table>

FHR: Fast Breeder Reactor
Severe Accident Strategy

If Major Failures, Conduct Heat to Ground
Keep $T_{\text{fuel}}$ below $T_{\text{failure}}$
Summary

• Active research on MSR being pursued in the world: USA, EU, China, India….

• Great potential for combined & flexible power generation grids

• Molten Salts also being considered for solar applications