Practical Aspects of Liquid-Salt-Cooled Fast-Neutron Reactors

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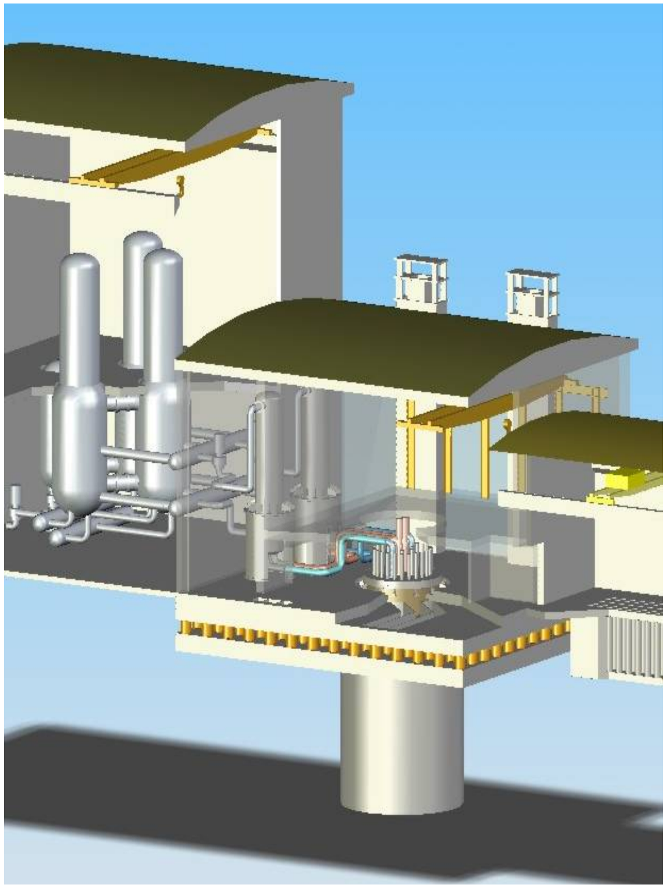

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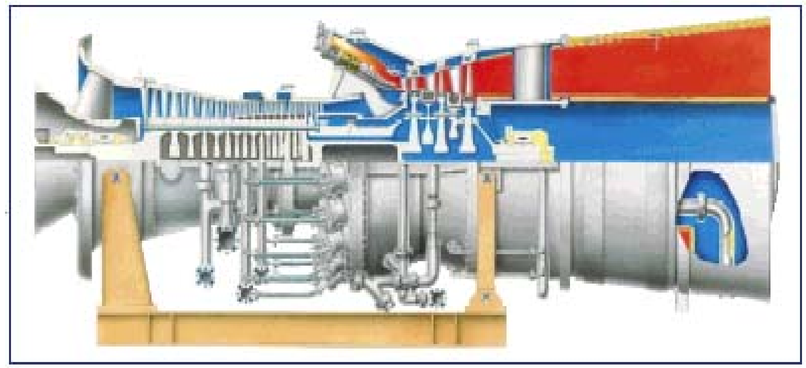
OAK RIDGE NATIONAL LABORATORY

Outline

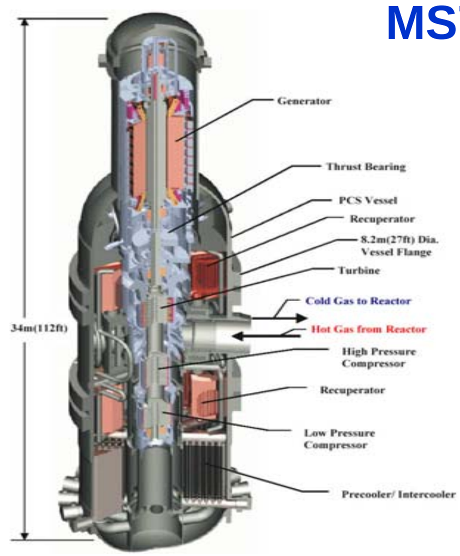
- What has changed?
- The liquid-salt-cooled fast reactor (LSFR)
- Economics
- Technical Challenges
- Conclusions

There is New Interest in High-Temperature Reactors Because of Brayton Technologies

- **High-temperature heat for a utility is only useful if it can be converted to electricity.**
- **Steam turbines (with a 550ºC peak temperature) have been the only efficient, industrial method to convert heat to electricity**
- **Development of large efficient high-temperature Brayton cycles *in the last decade* makes high-temperature heat useful for electricity production**
- **New basis to consider high-temperature reactors**



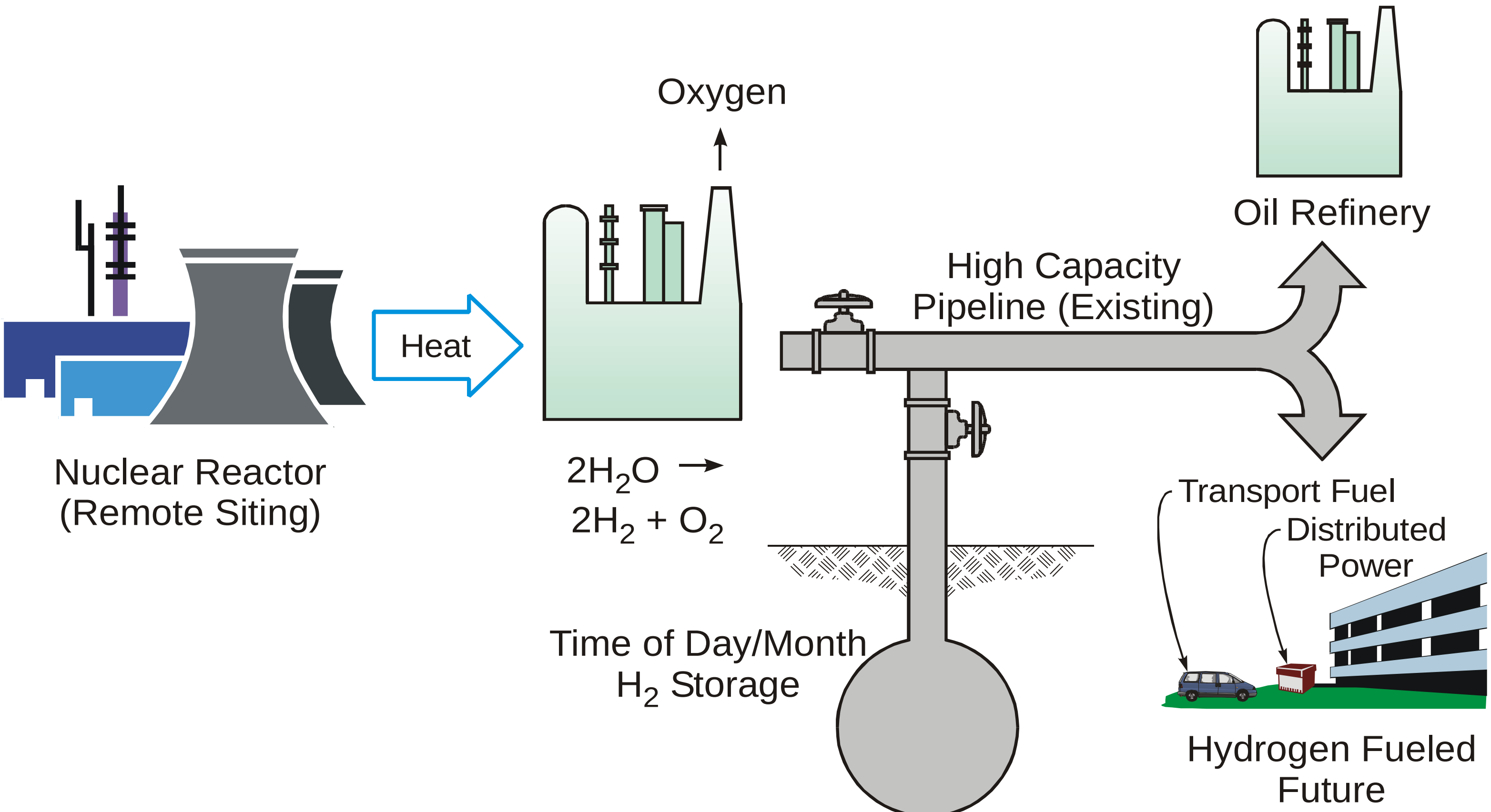
GE Power Systems MS7001FB



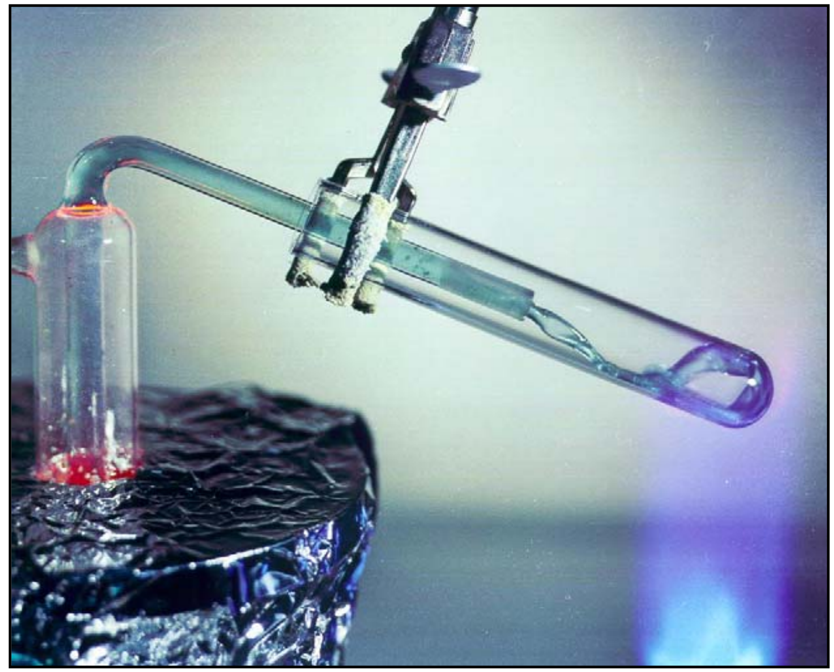
General Atomics GT-MHR Power Conversion Unit (Russian Design)

There is a New Interest in High-Temperature Reactors Because of Hydrogen Demand

(Heat Required at Temperatures Between 700–850ºC)



There are Two Demonstrated High-Temperature Nuclear Reactor Coolants



Helium

(High Pressure/Transparent)

Liquid Fluoride Salts

(Low Pressure/Transparent)

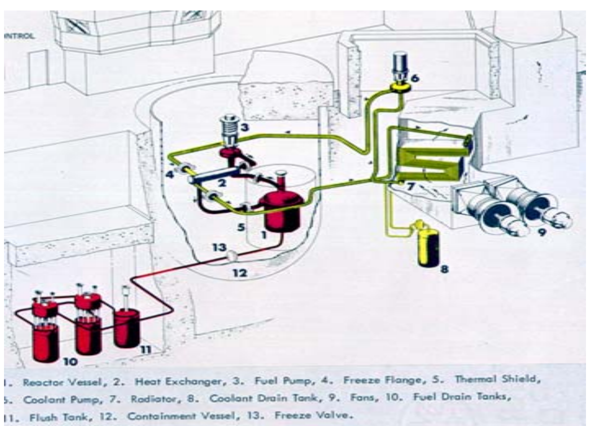
Liquid Salt Coolants Were Developed to Support Several Programs (1950–1970)

Molten Salt Reactors: Fuel Dissolved in Coolant

Aircraft Nuclear Propulsion Program

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

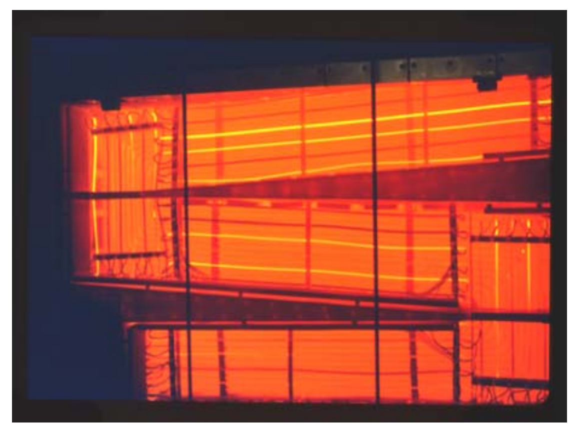
INEEL Shielded Aircraft Hanger→



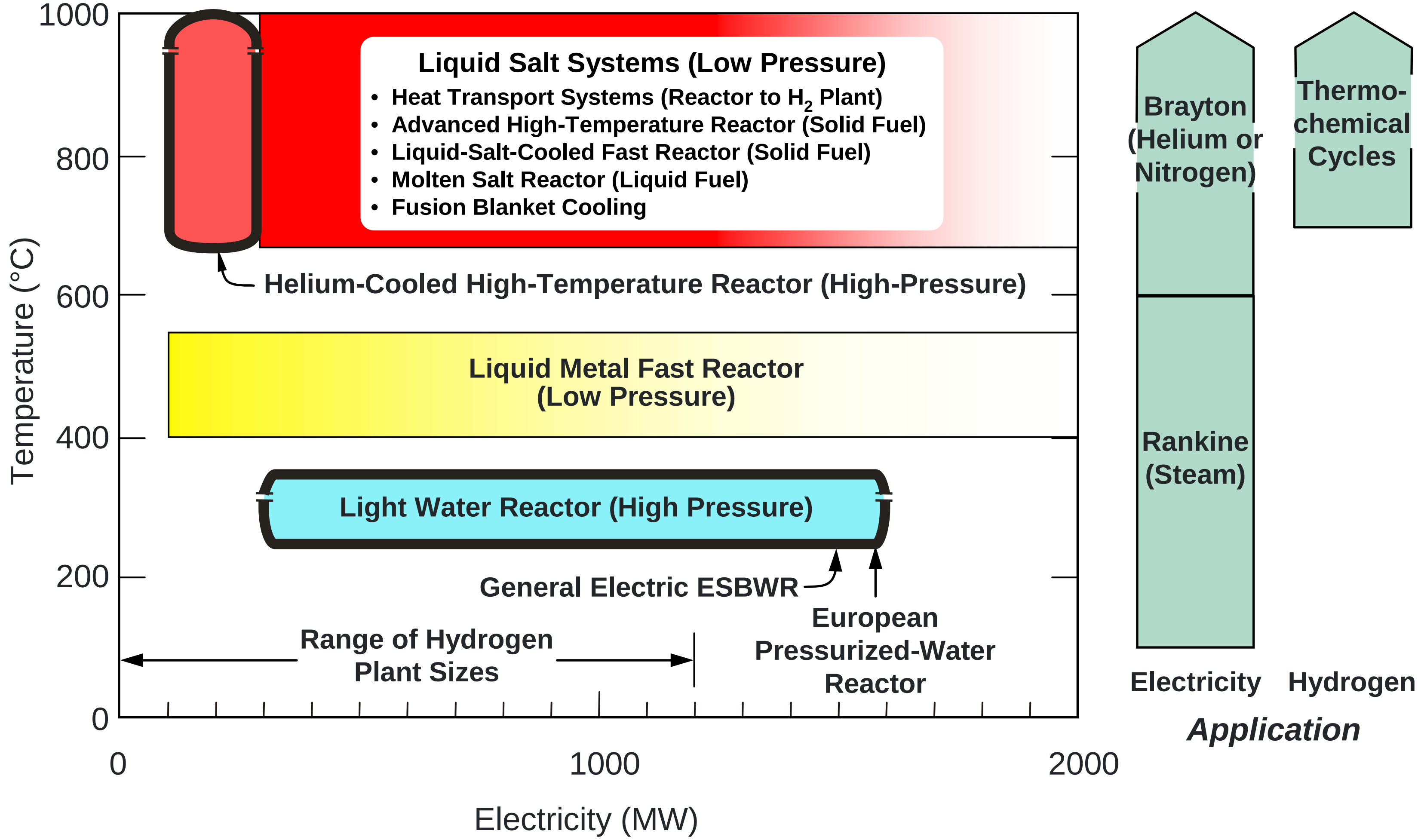
Molten Salt Breeder Reactor Program

← 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 →



Liquid Salt Coolants can be Used for Many Types of High-Temperature Reactors

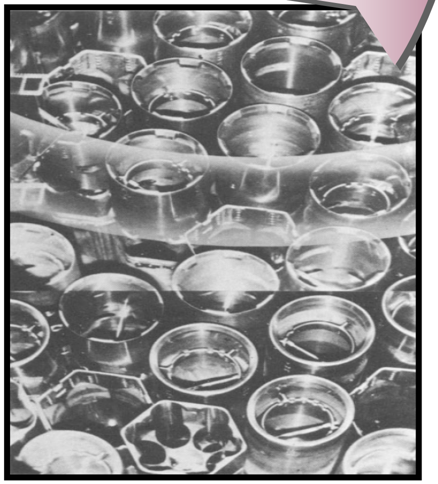


The Liquid-Salt-Cooled Fast Reactor

Higher-Temperature Liquid-Salt Coolant Replacing Sodium

Fast Reactor Facility Design

Brayton Power Cycles

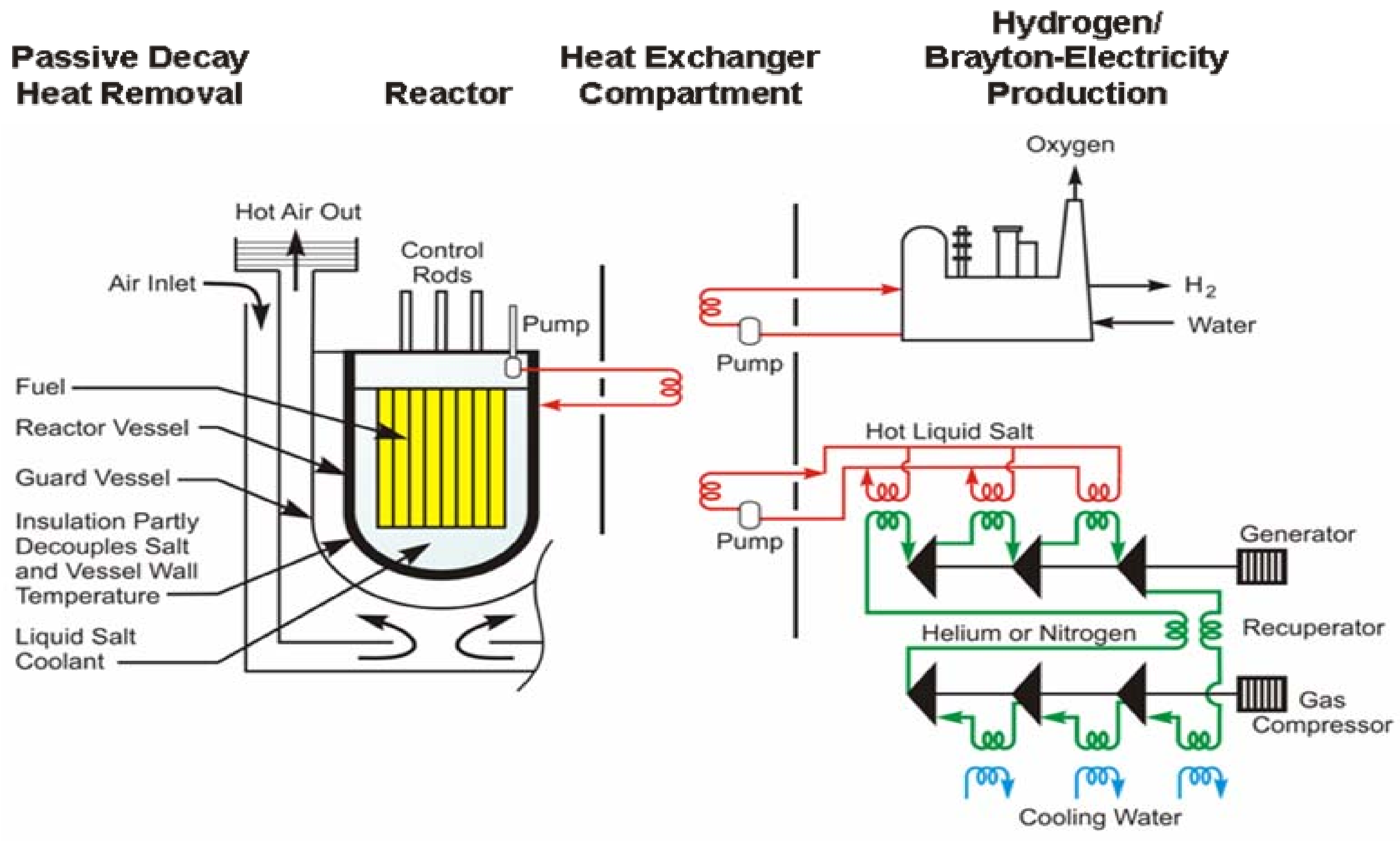


Fast Reactor Core

(Picture of PFR Core)

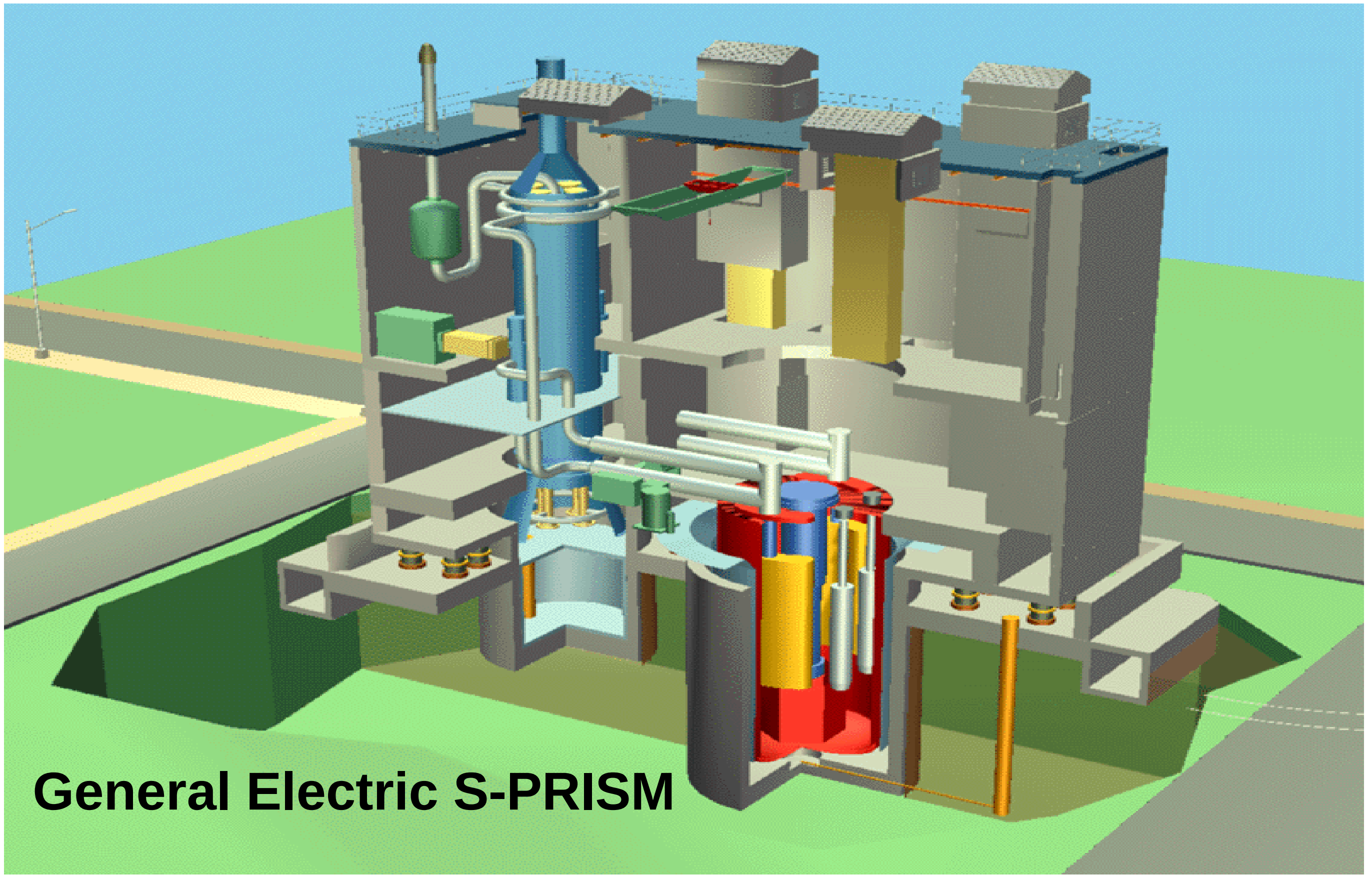
High-Temperature, Low-Pressure Transparent Liquid-Salt Coolant

Liquid-Salt-Cooled Fast Reactor (LSFR)



LSFR Facility Layouts are Based on Sodium-Cooled Fast Reactors

Low Pressure, High Temperature, Liquid Cooled

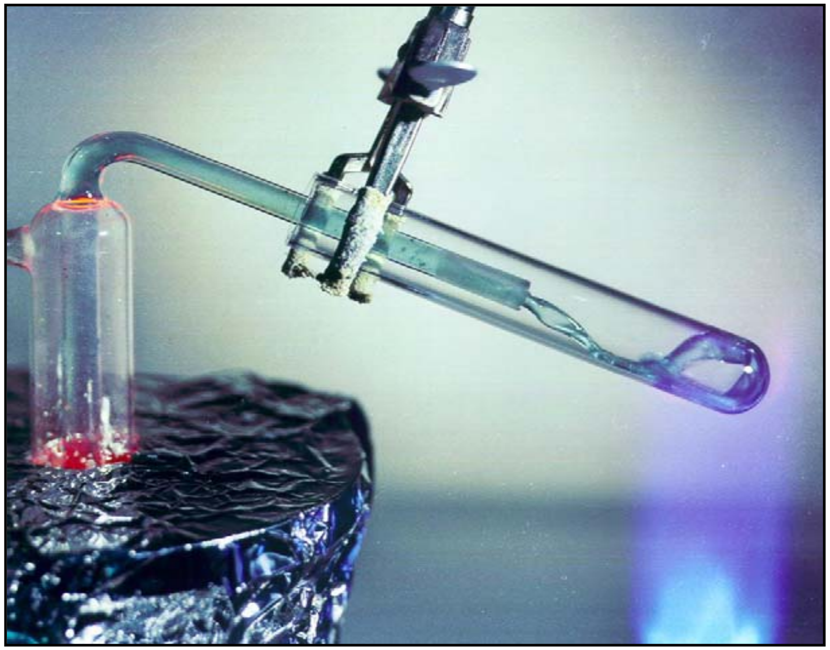


The LSFR is Not a Molten Salt Reactor

Cooled with a Clean Liquid Salt, No Fuel in Salt

- **MSR programs operated test loops for hundreds of thousands of hours**
- **MSR programs developed code-qualified alloys of construction to 750°C**
- **Experience showed major efforts required to develop materials for molten *fuel* salt (high concentrations of fission products and actinides in salt)**
- **Experience showed low corrosion rates with clean salts (similar to experience with other coolants)**

There are Significant Differences Between Liquid Salts and Sodium



Liquid Metal

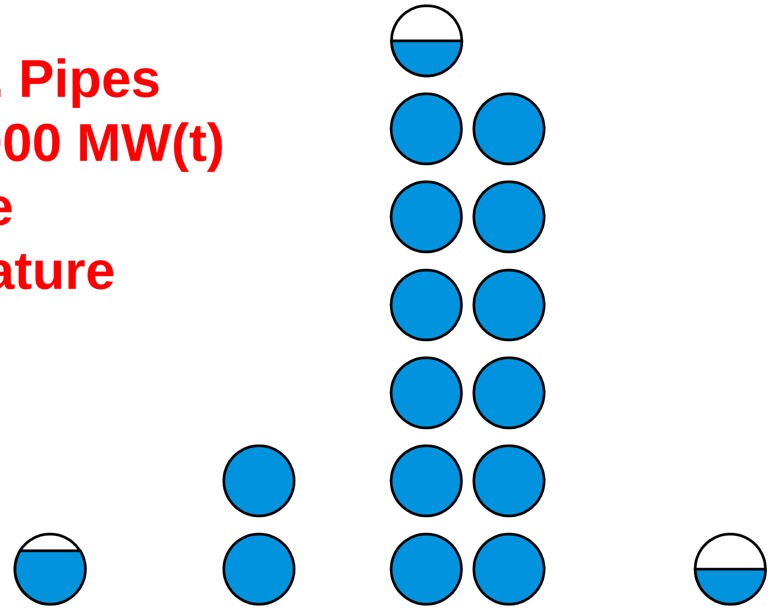
(Opaque; Na Boiling Point: 883ºC)

Liquid Fluoride Salts

(Transparent; Boiling Point >1200ºC)

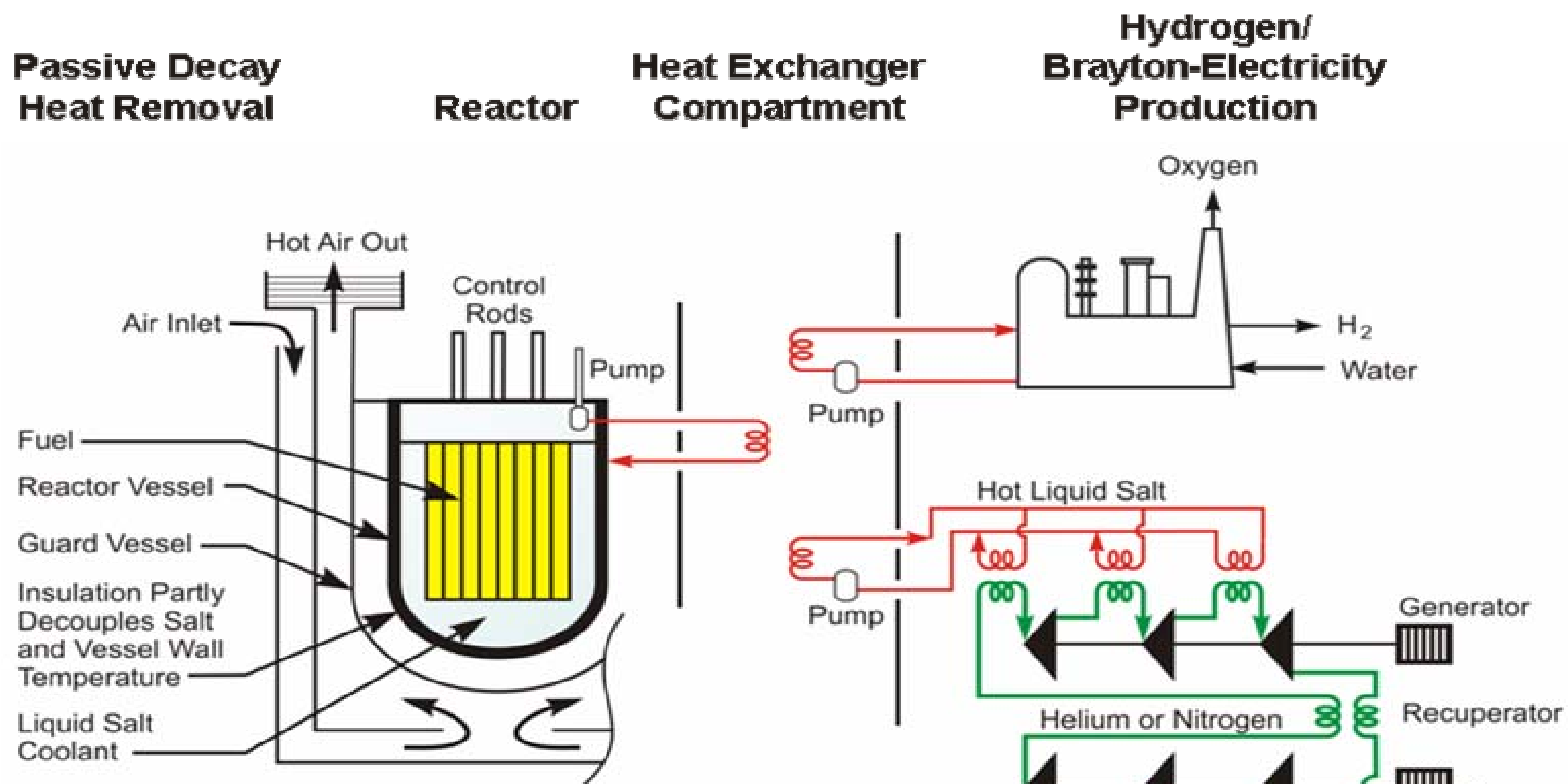
Liquid Salts Have Excellent Heat Transport Properties that Enable the Design of Large Reactors

Number of 1-m-diam. Pipes Needed to Transport 1000 MW(t) with 100ºC Rise in Coolant Temperature



	Water (PWR)	Sodium (LMR)	Helium	Liquid Salt
Pressure (MPa)	15.5	0.69	7.07	0.69
Outlet Temp (ºC)	320	540	1000	1000
Coolant Velocity (m/s)	6	6	75	6

Multi-Reheat Brayton Cycles Enable the Efficient Use of High-Temperature Heat

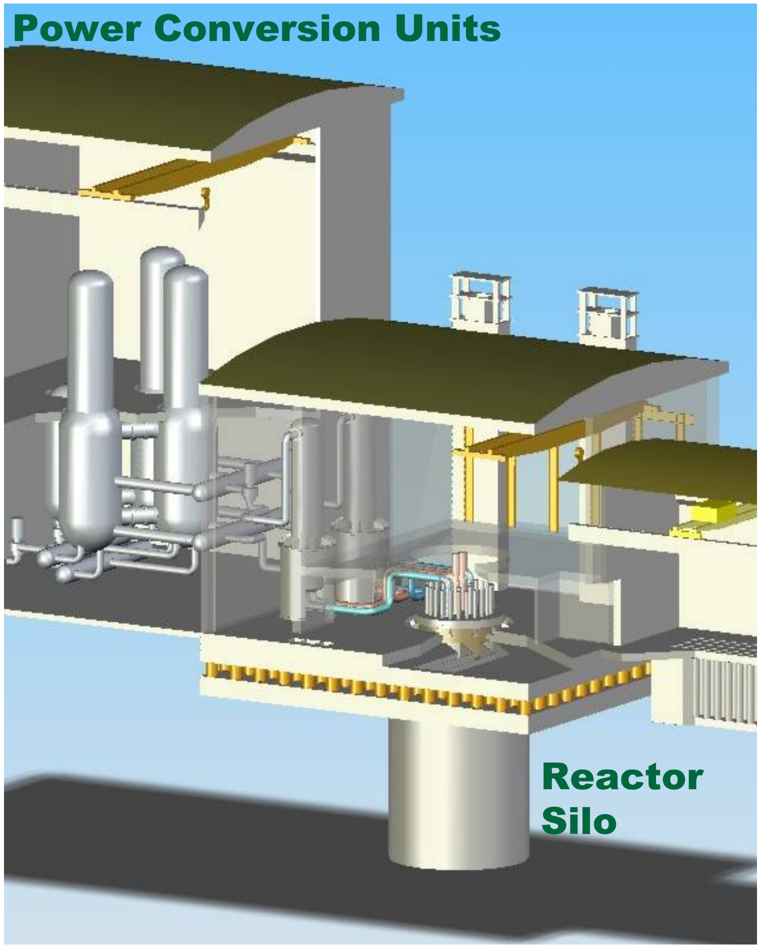


Efficiency Depends upon Temperature

- **705ºC: 48.0%**
- **800ºC: 51.5%**

Economics

LSFR Capital Costs Projected to be Less Than Sodium-Cooled Reactors



- **25% greater efficiency with high-temperature multi-reheat Brayton power cycle**
- **No sodium-water interactions (no steam cycle)**
  - **Salt non-reactive with air**
  - **Slow reaction with water**
- **Smaller equipment size with high volumetric-heat-capacity fluid**
- **Transparent coolant to aid refueling and inspection**
- **Smaller heat rejection system with higher temperatures**

Technical Challenges

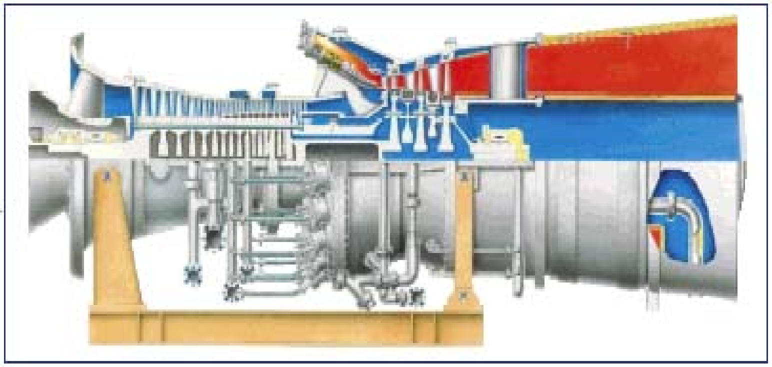
There are Major Technical Challenges Associated with the LSFR

New Reactor with Associated Uncertainties

- **Salt selection**
  - **Nuclear properties**
  - **Melting points (350 to 500ºC)**
- **Core design**
- **Clad materials of construction**
  - **Challenges**
    - **Higher temperatures**
    - **Liquid salt**
  - **Candidate alloy clad systems**
    - **ODS alloys**
    - **Nickel alloys**
    - **Molybdenum alloys**

Conclusions: The LSFR May Address the Challenge of Fast Reactors–Economics

- **Fast reactors have advantages in fuel production and waste management**
- **The challenge is economics**
- **LSFRs have potentially superior economics**
  - **Higher efficiency**
  - **Transparent fluid**
  - **Smaller equipment**
- **Technology built on sodium-cooled fast reactors**
- **New reactor concept with significant uncertainties**



Backup Slides

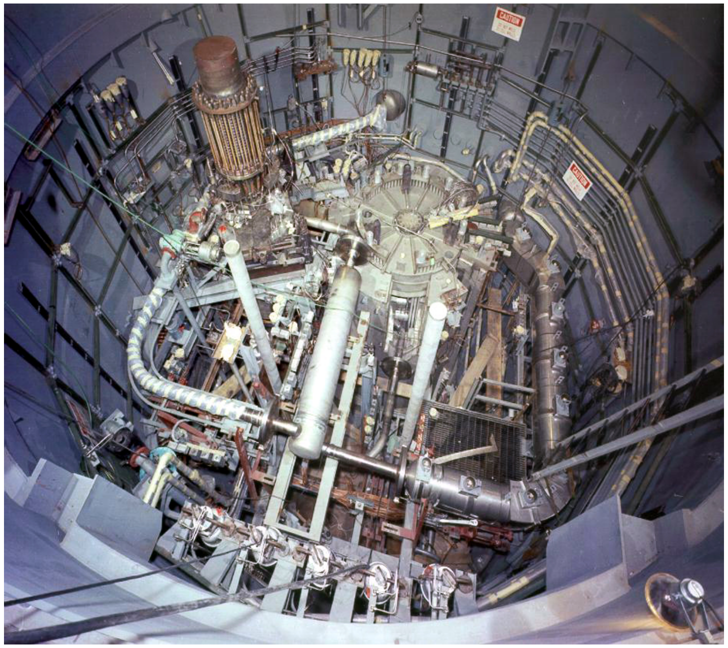
Backup Slides

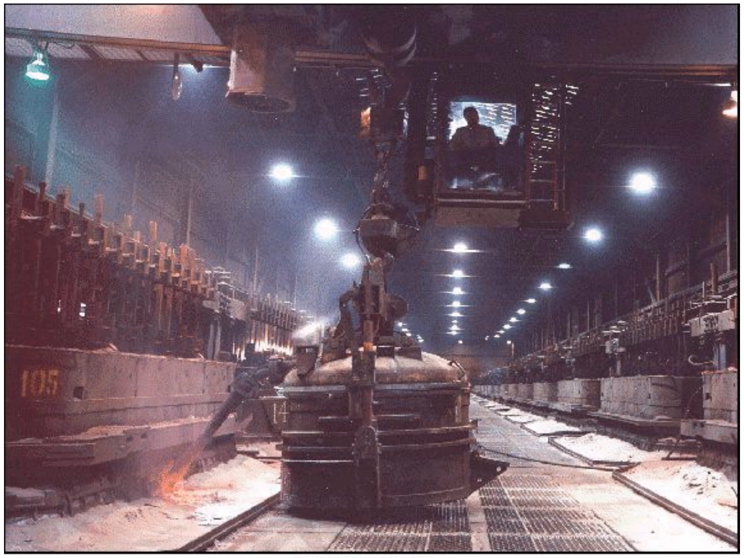
Backup Slides

The LSFR Uses a *Liquid Salt Coolant*

Good Heat Transfer, Low-Pressure Operation, and Transparent (In-Service Inspection)

Liquid Fluoride Salts Were Used in Molten Salt Reactors with Fuel in Coolant (LSFR Uses Clean Salt and Solid Fuel)





Tapping aluminum

Aluminum is tapped from a Kitimat Works electrolytic-reduction cell into a steel vessel called a crucible. The crucible holds approximately 4,000 kg of aluminum and is used to transfer the molten aluminum to the furnaces in the casting department.

Molten Fluoride Salts Are Used to Make Aluminum in Graphite Baths at 1000°C

Liquid-Salt-Cooled Reactors are Intrinsically High-Temperature Reactors

- **Freezing points are between 350 and 500ºC**
  - **Fluoride salts**
  - **Freezing point dependent on salt composition**
- **Not suitable for a low-temperature reactor**
- **Salt-cooling matches new power cycles and needs**
  - **Brayton power cycles**
  - **Hydrogen production**

R&D Challenge: Salt Selection

- Requirements
  - Low nuclear cross sections
  - High thermodynamic stability relative to materials of construction (corrosion control)
  - Appropriate physical properties (viscosity, low melting point)
- Potential candidate salts (partial list; mol %)
  - NaF (10%)-KF(48%)-ZrF_4(42%): mp: 385ºC
  - NaF(6.2%)-RbF(45.8%)-ZrF_4(48%): mp: 380ºC
  - NaF(50%)-ZrF_4(50%): mp: 510ºC

R&D Challenge: Core Design

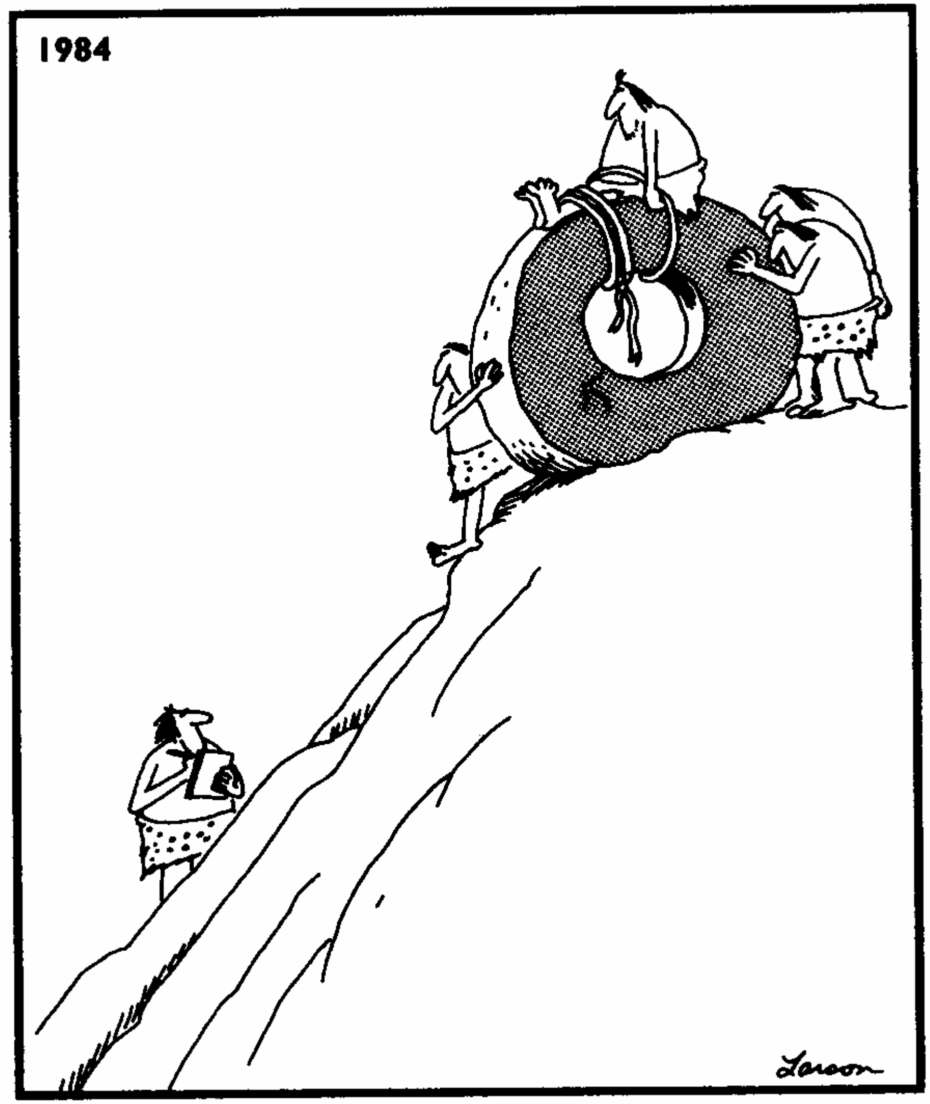
- Incentives to minimize coolant volume in the reactor core to maintain hard neutron spectrum
  - Very high volumetric heat capacity relative to sodium
  - Need only a fraction as much coolant in the core
  - Spectrum softening of fluorine is similar to sodium
  - Potential incentives for alternative fuel designs
- Liquid salt fundamental heat transfer differences
  - High volumetric heat capacity relative to sodium
  - Significantly lower thermal conductivity
  - Potential for significant infrared radiation heat transport in transparent coolant at higher temperatures
- Choice of fluoride salt to control physical properties
  - Neutron cross sections
  - Physical properties (viscosity, conductivity, etc.)

R&D Challenge: Fuel Clad

- **Requirements**
  - Higher temperature operation
  - Corrosion control (fluorides of metals must be less thermodynamically stable than salt components)
  - Radiation resistance
- **Candidate clad systems (not a full list)**
  - **ODS alloys**
    - Currently being developed for sodium-cooled reactors
    - Need for corrosion testing
  - **Nickel alloys**
    - Good compatibility with high-temperature salts
    - Mixed experience in high neutron fluxes
  - **Molybdenum alloys**
    - Excellent compatibility with high-temperature salts
    - Good neutronics
    - Concerns about ductility

The LSFR:

A good idea that still needs some work



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