Carbon-Carbon-Composite Salt-Cooled Electric Space Reactors

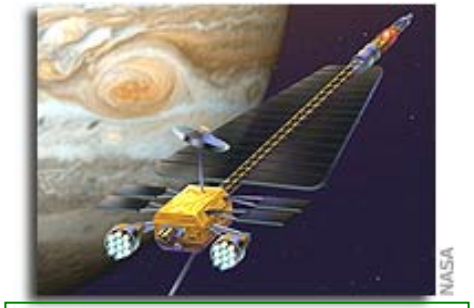
C. W. Forsberg
T. D. Burchell, D. F. Williams,
D. E. Holcomb, R. F. Holdaway, A. L. Qualls

Oak Ridge National Laboratory
P.O. Box 2008; Oak Ridge, TN 37831
E-mail: forsbergcw@ornl.gov
Tel: (865) 574-6783

Space Nuclear Conference 2005 (SNC'05)
Session: Space Power Concepts—II
Tuesday June 7, 2005; 2:30–4:30 p.m.
Embedded Topical in
2005 American Nuclear Society Annual Meeting
San Diego, California
June 5–9, 2005

The submitted manuscript has been authored by a contractor of the U.S. Government under contract DE-AC05-00OR22725. Accordingly, the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes. File: SNC05.CarbonSpaceReactor

Electric Space Reactor Requirements



NEP spacecraft concept

Surface power concept

BNTP spacecraft concept

1. Generate heat in the reactor core
2. Move heat from reactor core to the heat-to-electricity conversion unit
3. Convert thermal power to electrical power
4. Reject waste heat
5. Shield astronauts and/or payload

Practical systems: Maximize power-to-weight ratio

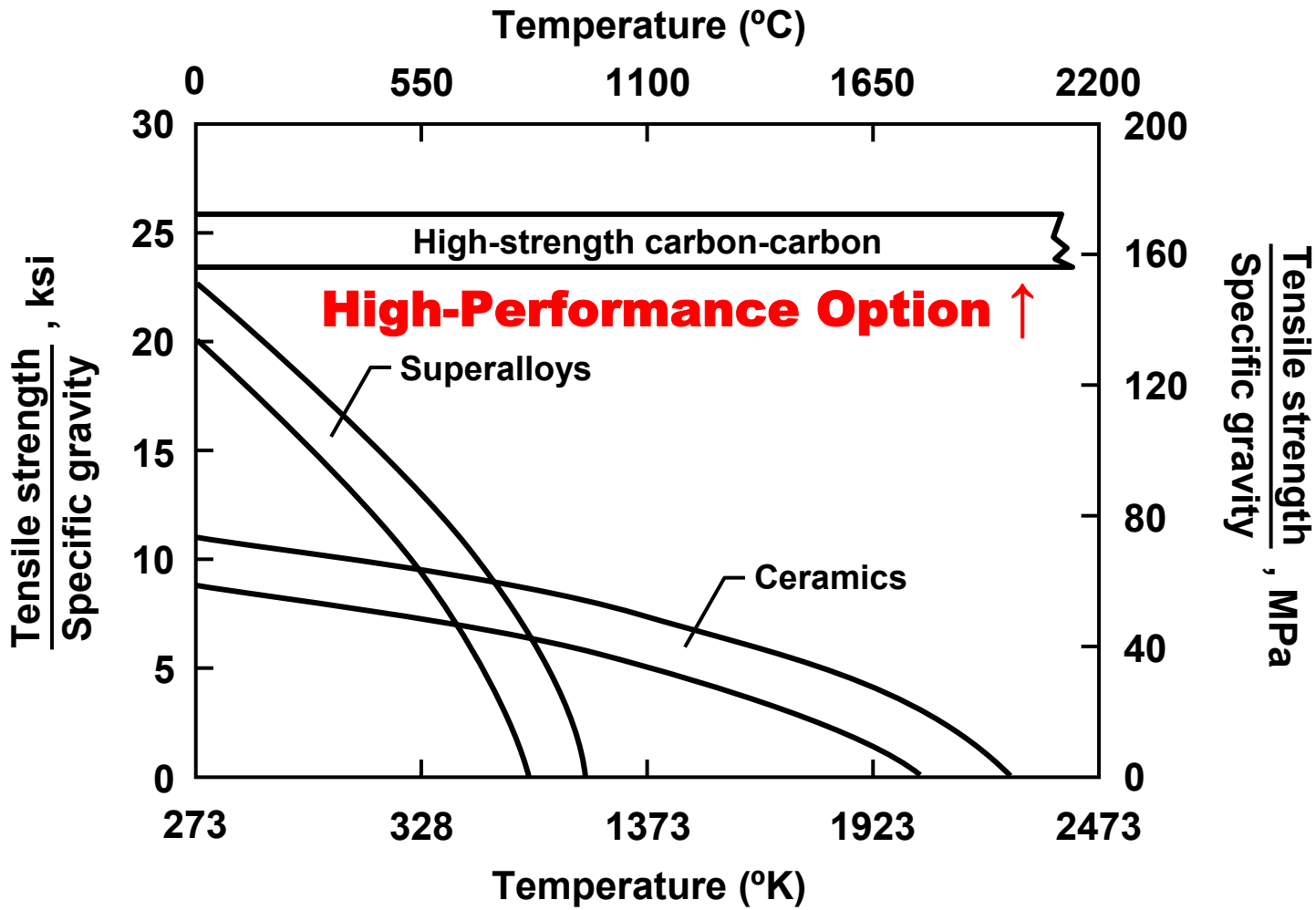
→ Maximize efficiency (high temperatures)

→ Minimize weight

Study Ground Rules and Objectives

- Design goals
  - Operating reactor temperature: 1800 to 2300ºK
  - Long life
- Design driven by materials considerations
- Our study goals
  - Is such a reactor potentially feasible?
  - Not design of a specific reactor
- Long-term reactor option (20 years)

One Material Option Exists to Maximize Space Reactor Performance



Carbon-Carbon Composites Have Two Fundamental Limitations
Neither Applies to Space Reactors

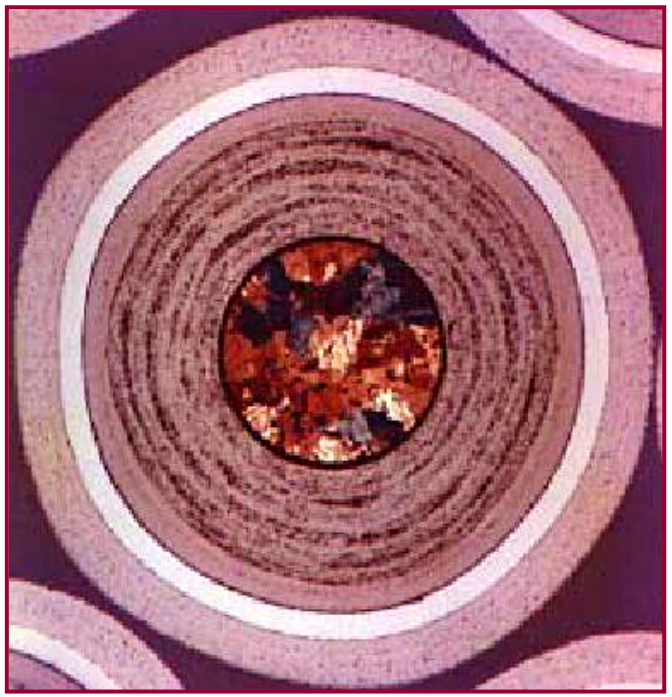
- Carbon burns
  - Not an issue for space or moon operations
  - Protective coatings a possibility for oxidative environments such as Mars—<u>but very large challenges</u>
- Composites are difficult to repair
  - Most space missions do not allow repair of hardware (No Maytag repairman)
  - Major challenges to make repairs for high-performance composites

Carbon-Carbon Composites are Made in Complex Forms for Multiple Applications

- **Carbon composites have desirable properties**
  - Low specific density
  - Tunable stiffness and strength
  - Low coefficient of thermal expansion
  - High thermal conductivity and diffusion
  - High temperature resistance (>2100°C)
- **Only "new" industrial material since last major development effort on space reactors**

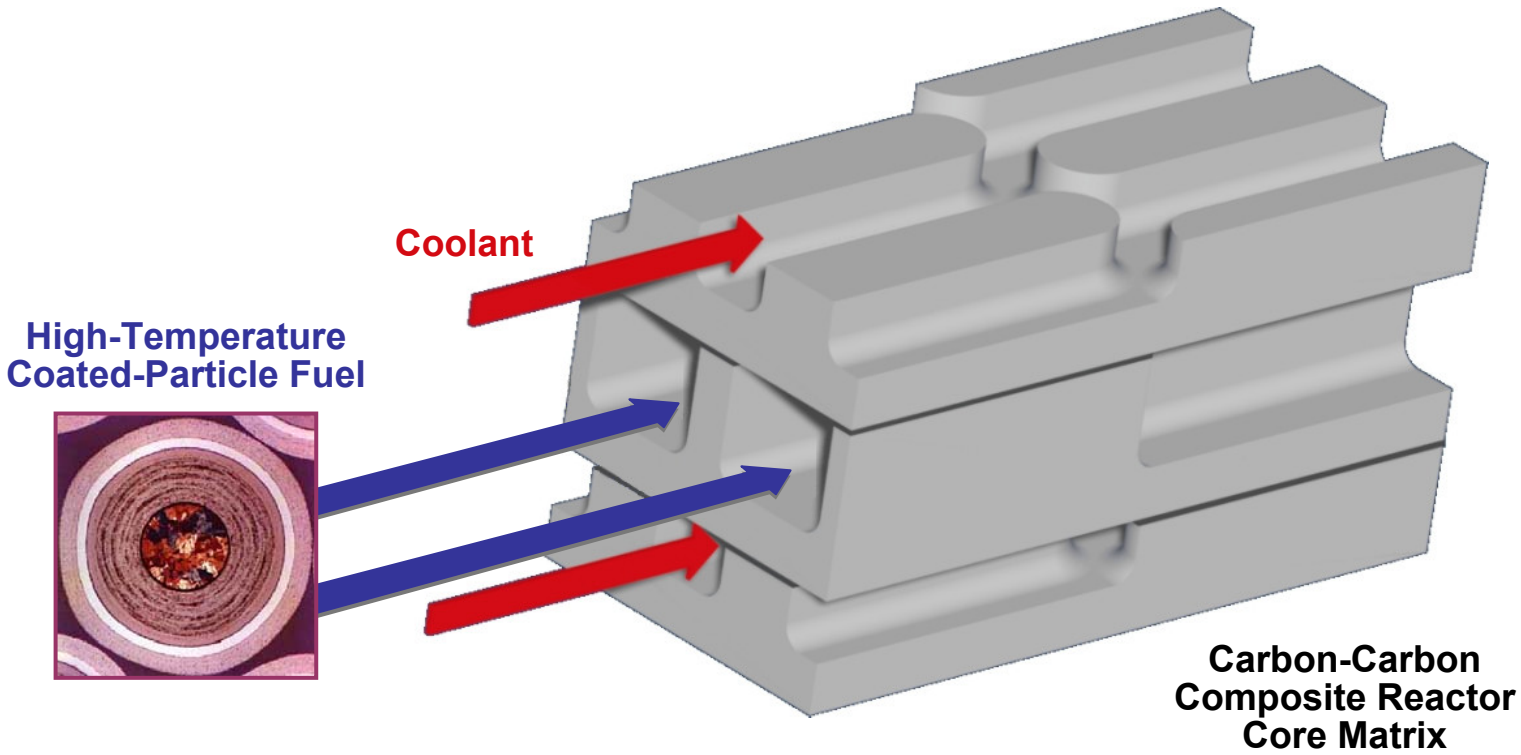
Coated Particle Fuels Have Very High-Temperature Capabilities

ZrC Coated-Particle Graphite-Matrix Fuel



- Limited testing to 2500ºC
- Compatible with carbon-carbon composites
- Potential for extreme temperature operation

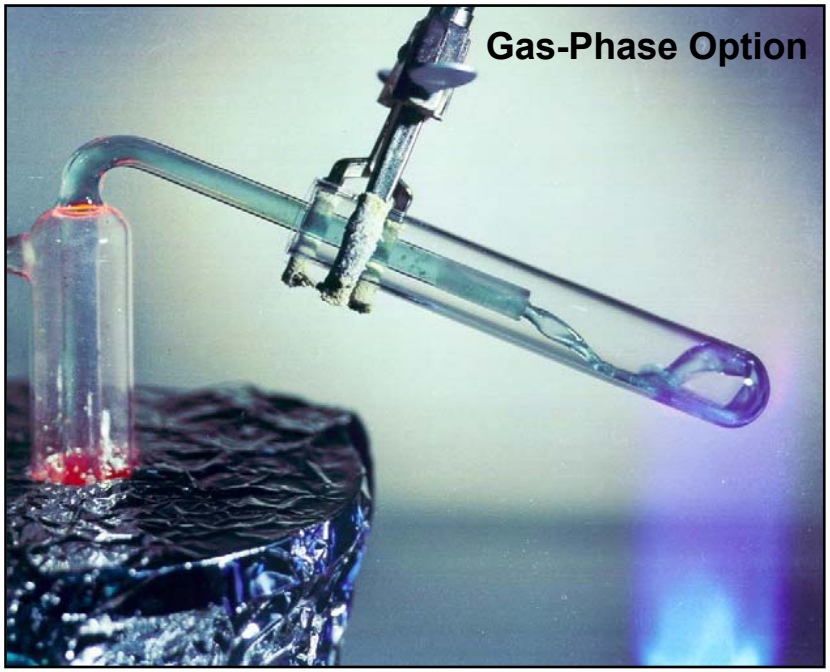
Schematic of an Option for an Advanced Space Reactor Core



Critical Carbon-Carbon Composite Technical Challenges

- Radiation Damage
  - Radiation damages carbon materials
  - Very-high-temperatures anneal carbon composites and other carbon materials
  - Theory indicates significant self healing
  - No experimental data at relevant temperatures
- Permeability
  - Composites can be permeable to fluids
  - Methods exist to eliminate permeability
  - Major technical challenge

Two Coolants are Compatible with Graphite Materials and High-Temperature Operations



Inert Gases (He, Xe, etc.)

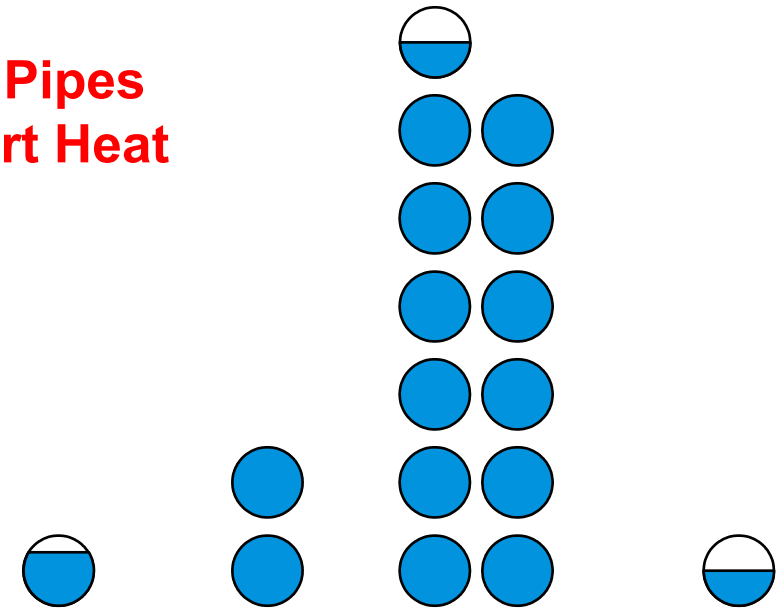
(High Pressure/Transparent)

Fluoride Salts

(Low Pressure/Transparent)

Liquid Salts Have Excellent Heat Transport Properties

Relative Number of Pipes Required to Transport Heat

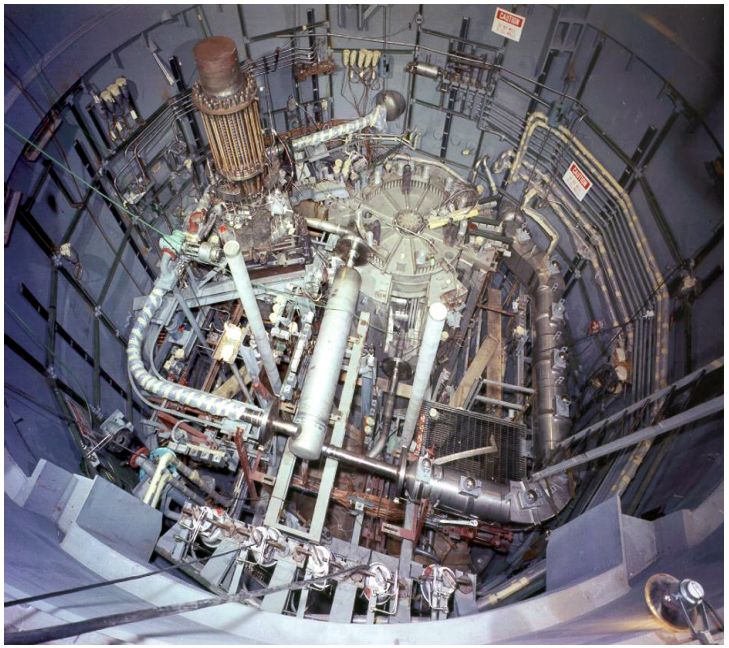


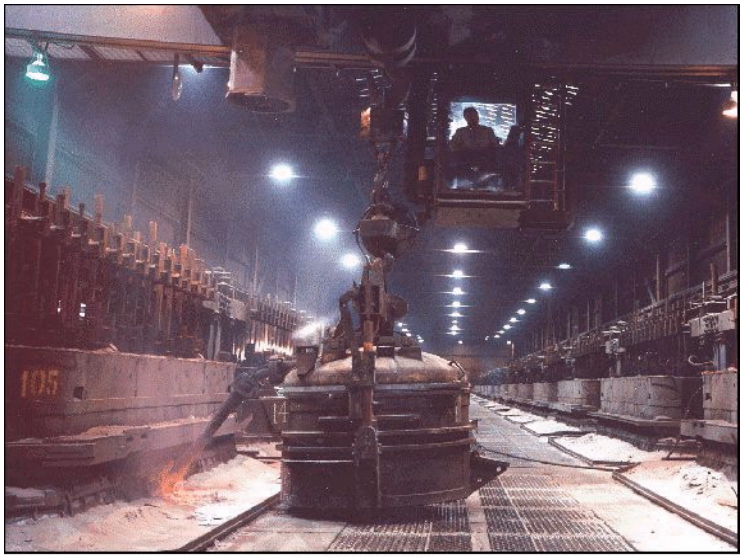
	Water (PWR)	Sodium (LMR)	Helium	Liquid Salt
Pressure (MPa)	15.5	0.69	7.07	0.69
Outlet Temp (ºC)	320	540	1000	1000
Coolant Velocity (m/s)	6	6	75	6

Large Experience Base with Fluoride Salts and Carbon Materials

Compatibility Demonstrated to 1400ºC

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



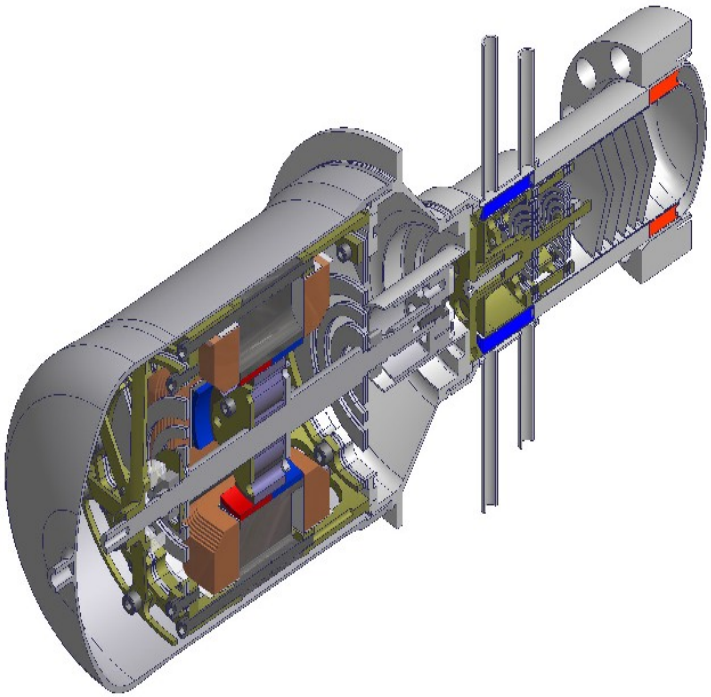


Tapping aluminum

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

There are Multiple Power Conversion Options—All Requiring Major Development

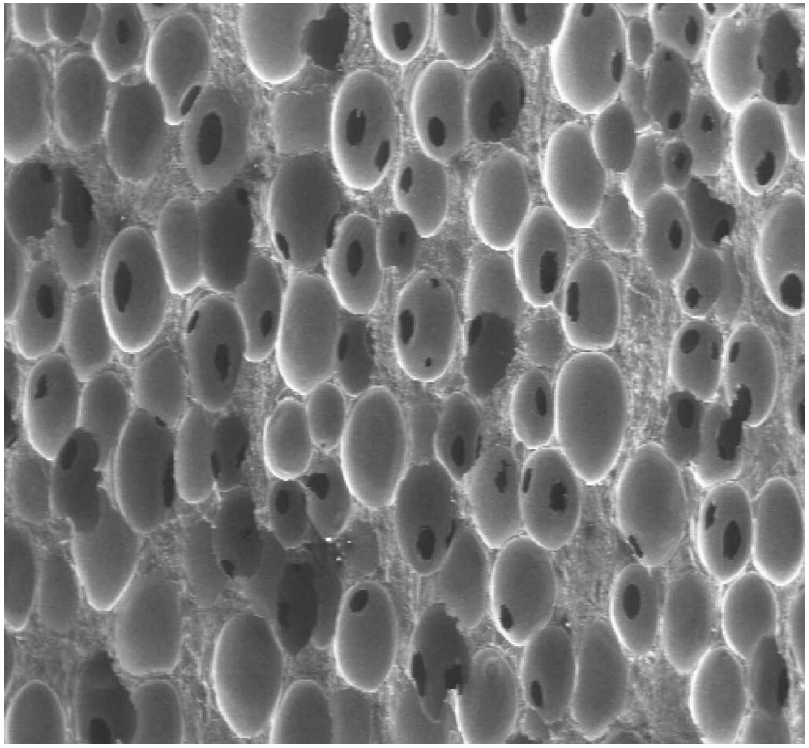


Courtesy of Stirling Technology Company

Stirling Engine Example

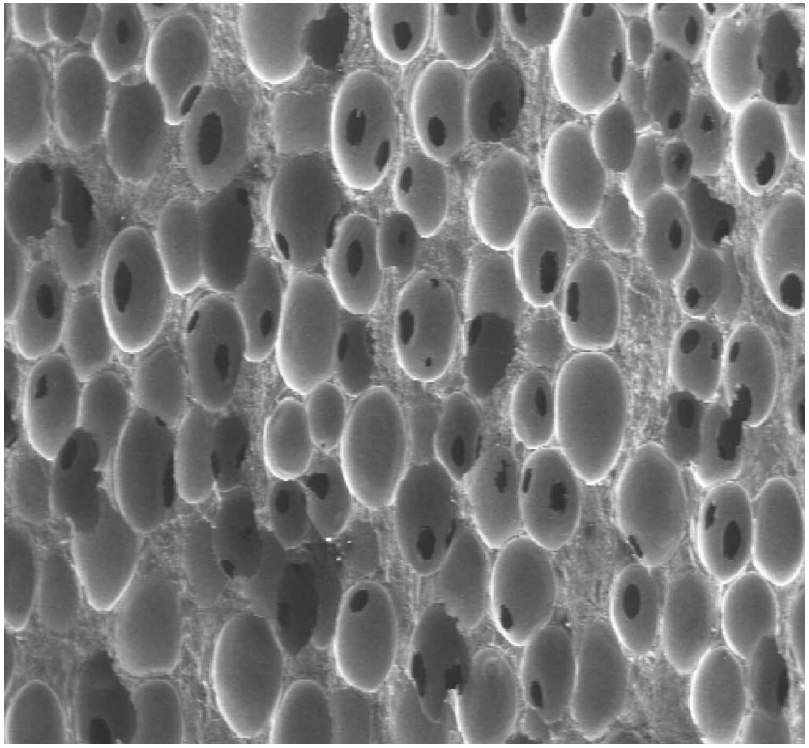
- Piston engine
- Development is underway for carbon-carbon composite internal combustion engines
- Same base technology needed for Stirling engine
- Requires separation and cooling of electrical components

Carbon Foams may Enable Very-High-Temperature Radiators



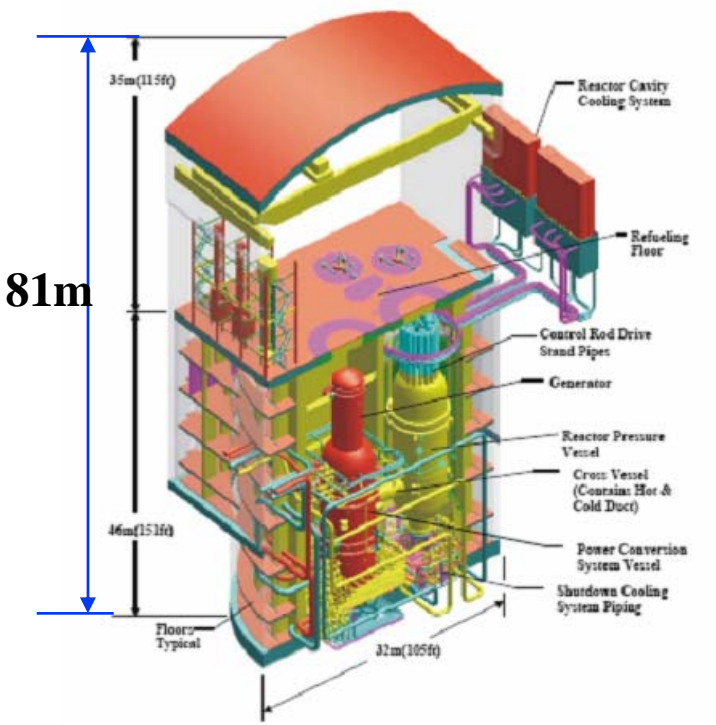
- NASA qualified as radiator for lower temperatures
- Thermal conductivity similar to aluminum and copper
- Densities 15–25% of aluminum
- Can be used to improve heat transfer

Carbon Foams and Carbon-Carbon Composites can Form the Backbone for Shielding

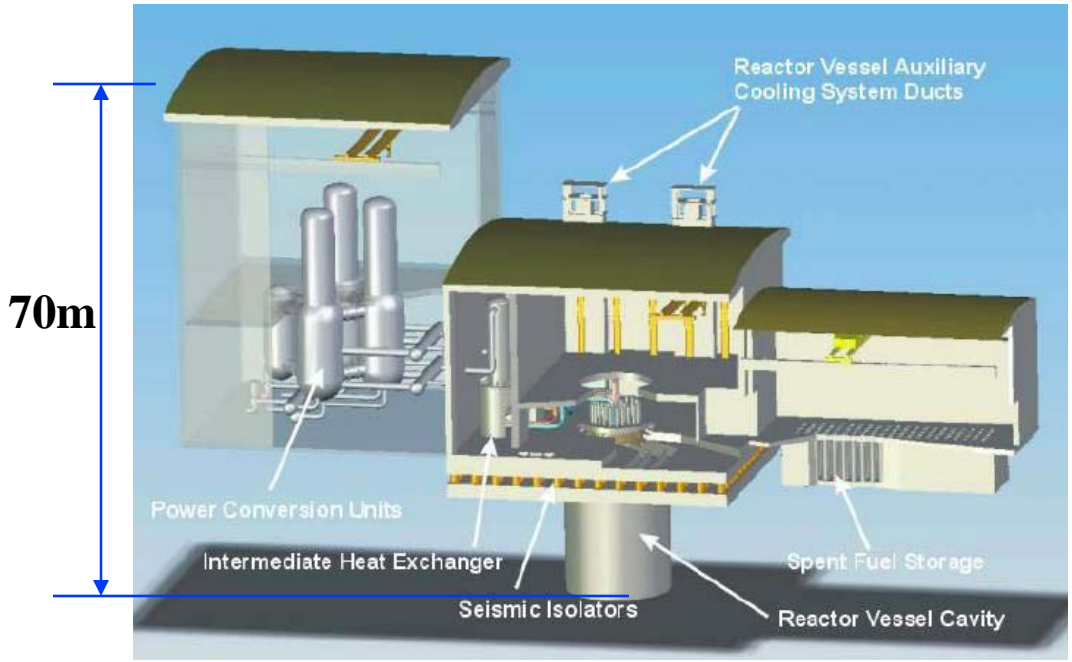


- High thermal conductivity
- Can incorporate high-neutron-cross section lithium into the carbon structure
  - Between graphite plains
  - Basis for commercial lithium batteries
- Structure for high-density materials

Some Key Technologies Being Developed for High-Temperature Power Reactors

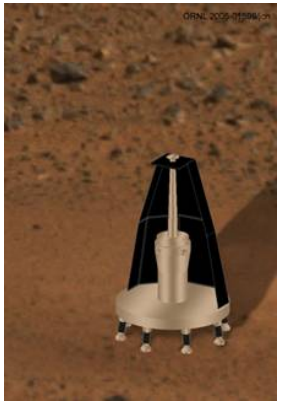


High-Temperature Gas-Cooled Reactor
GT-MHR (600 MW(t))



Advanced High-Temperature Reactor
AHTR (2400 MW(t))

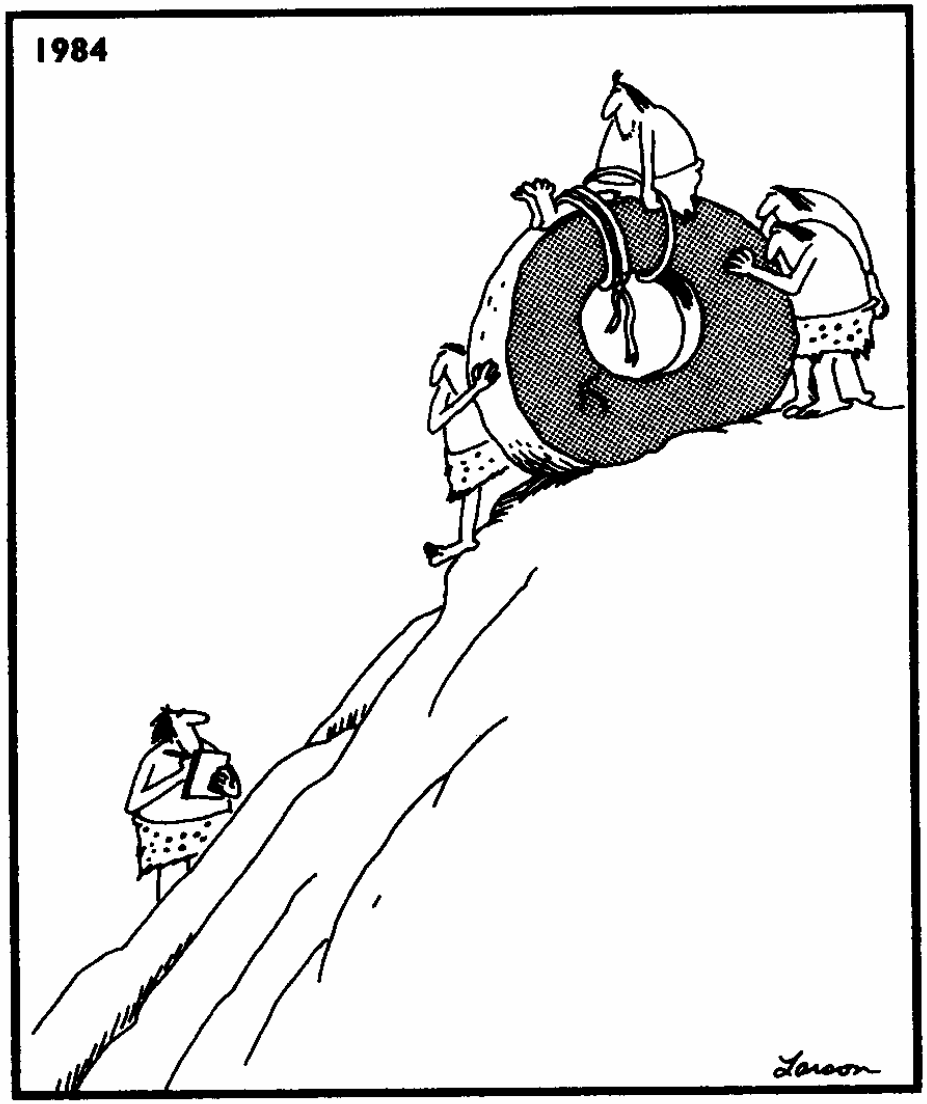
Conclusions and Path Forward



- Potential carbon-based reactor performance far exceeds other options
- Temperatures require the entire reactor system to be based on carbon materials
- Recent developments show a path forward to such a reactor
- A multi-year program required to show scientific feasibility
- A major long-term development program would be required for deployment

Carbon-Carbon Composite Reactors:

A good idea that still needs some work

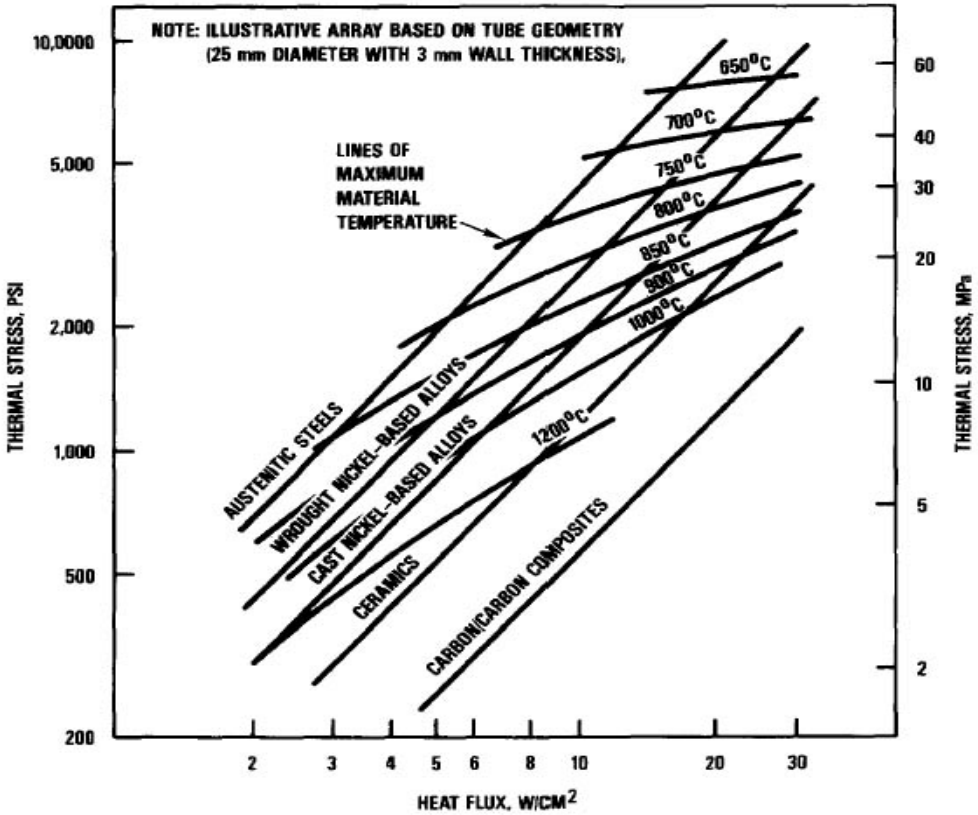


Backup Slides

Backup Slides

Backup Slides

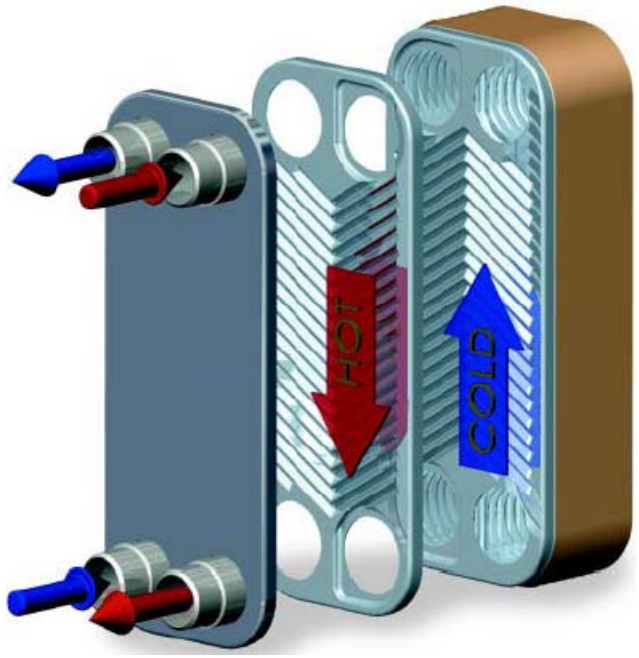
C-C Composites have Highly Desirable Properties for High Heat Flux, High-Temperature Compact Heat Exchangers



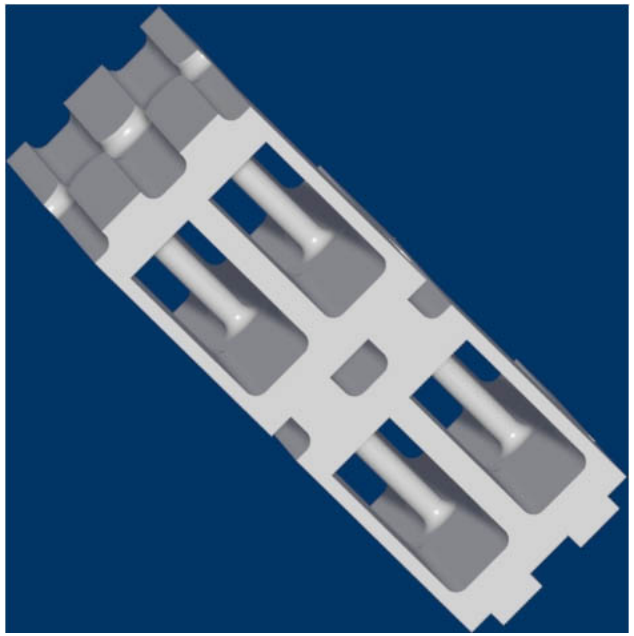
Thermal stress limits on HX heat fluxes at various operating temperatures

Fig. 18, C.F. McDonald, "Review paper: Compact buffer zone plate fin IHX," *Applied Thermal Engineering*, Vol. 16, pp. 3-32, 1996.

LSI Carbon-Carbon Offset Fin Plate Heat Exchangers Could have Attractive Specific Surface Area

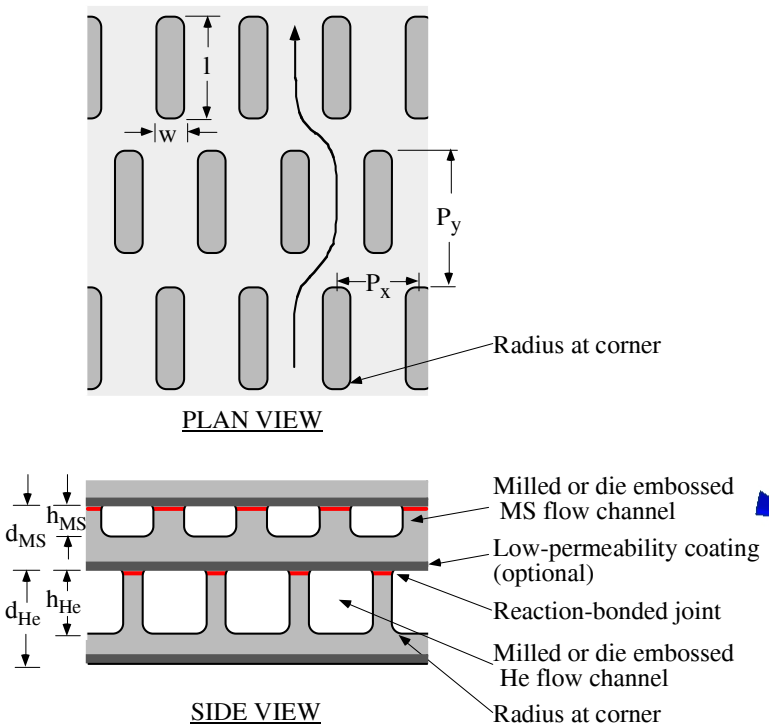


Countercurrent plate heat exchanger

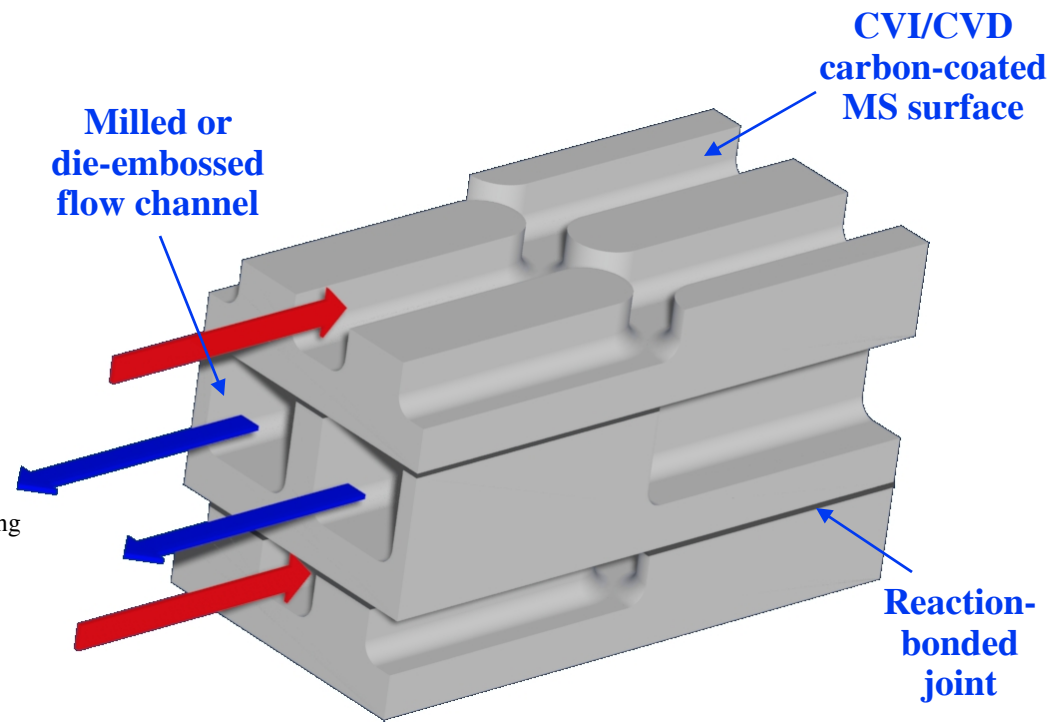


Unit cell of offset-fin LSI plate heat exchanger

LSI CSiC Composite Offset Fin Plate Heat Exchangers (HXs)

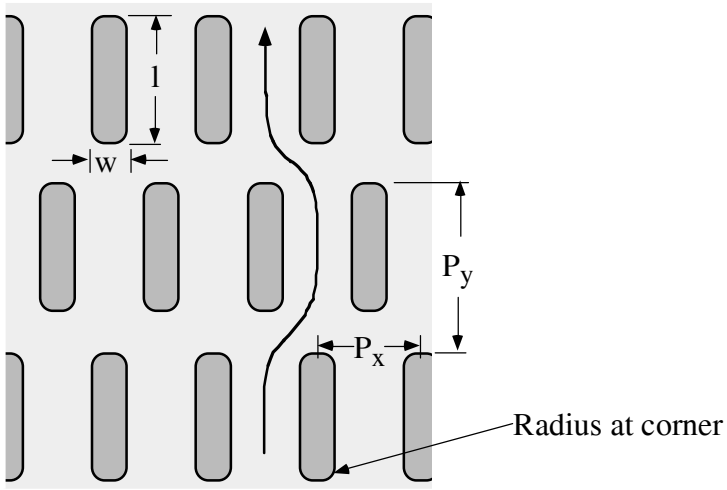


Schematic of potential compact C/C-SiC heat exchanger channels and fins.

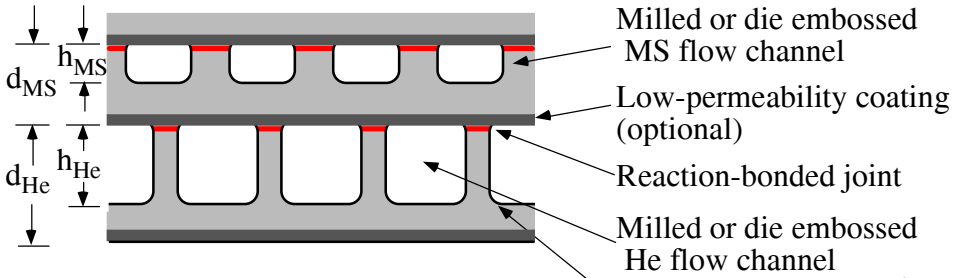


Unit cell of offset-fin LSI plate heat exchanger

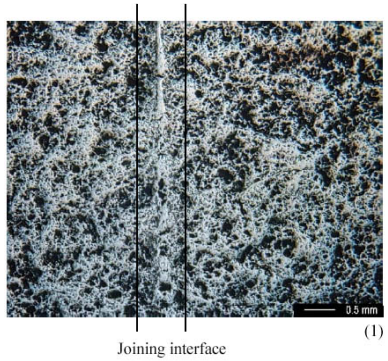
Monlithic HX can be Formed by Joining Multiple Green Plates with Phenolic Resin

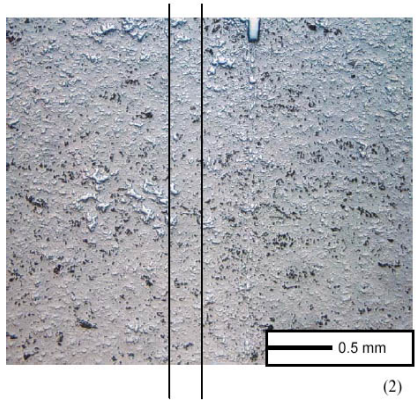


PLAN VIEW



SIDE VIEW

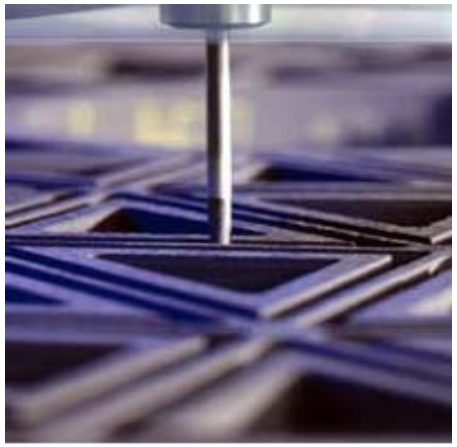




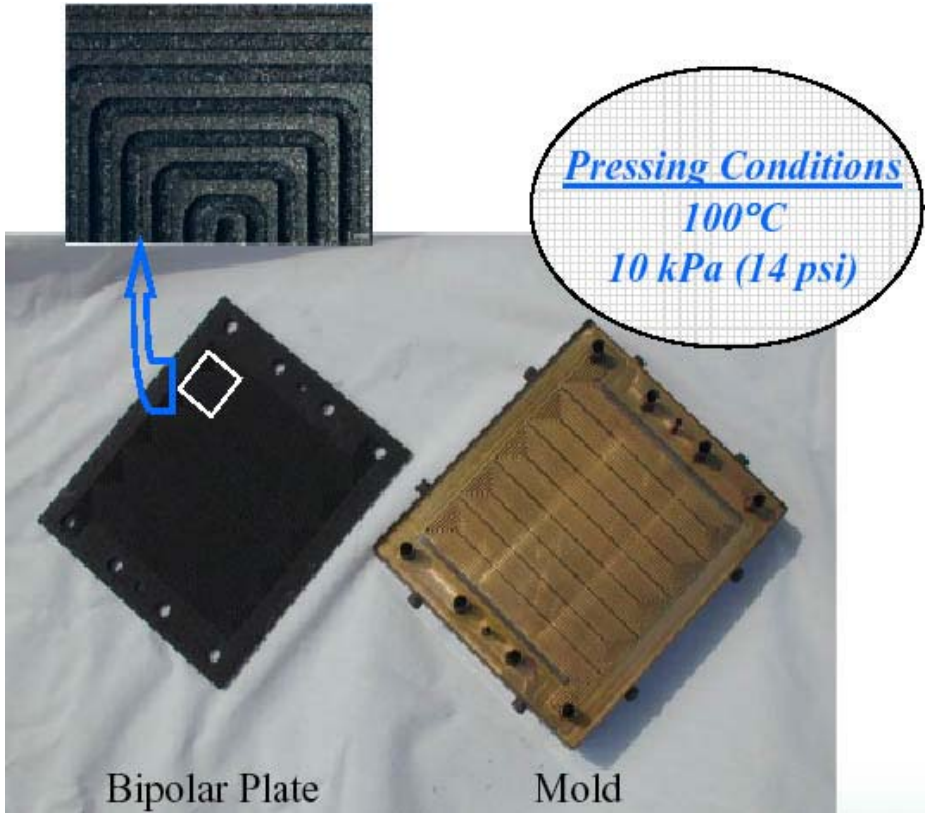
Typical reaction-bonded C/C joint before and after LSI †

† 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.

Milling or Die-Embossing can be Used to Form Flow Channels in Plates



Milling has been demonstrated for fabrication of LSI parts



ORNL has demonstrated die-pressing to form 1-mm wide flow channels in short-fiber carbon/carbon plates for fuel cells

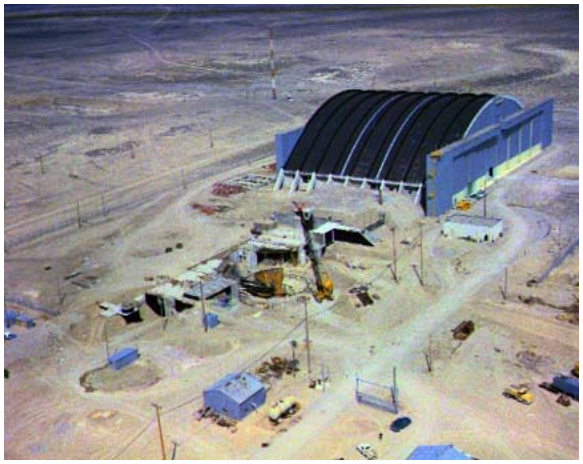
Liquid Salt Technology was Developed to Support Several Large Programs (1950–1970)

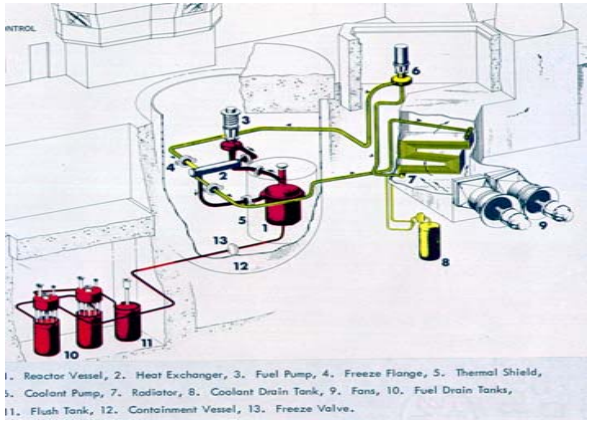
Molten Salt Reactors: Fuel Dissolved in Coolant

Aircraft Nuclear Propulsion Program

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

INEEL Shielded Aircraft Hanger→

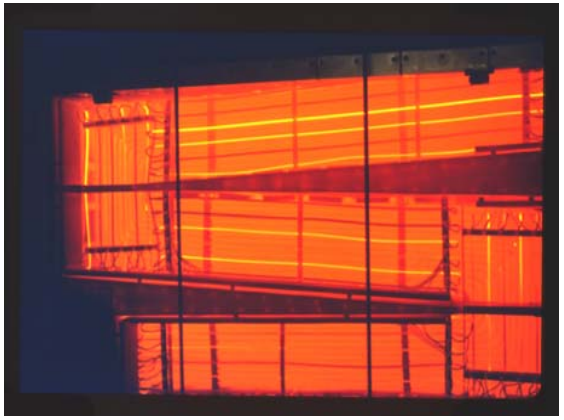




Molten Salt Breeder Reactor Program

← 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 →



Graphite Foam Experimental Properties

Property	Foam I	Foam II	Foam III	Aluminum 6061
Density (g/cm_3)	0.57	0.59	0.70	2.88
Porosity	0.75	0.74	0.69	0
Fraction Open Porosity	0.98	0.98	n.m.	0
Average Cell Size (microns)	350	60	360-400	---
Coefficient of Thermal Expansion (ppm/ºC)	0-1 (z) 1-3 (x-y)	n.m.	n.m.	17
Max Operating Temperature in Air (ºC)	500	500	500	600
Tensile Strength (MPa)	0.7	n.m.	n.m.	180
Compressive Strength (MPa)	2.1	5.0	5.1	---
Compressive Modulus (GPa)	0.144	0.180	0.413	70
Bulk Thermal Diffusivity (cm^2/s)	4.53	3.1	3.52	0.81
Bulk Thermal Conductivity (W/m k)	175	134	170	180
Specific Heat Capacity (J/Kg K)	691	691	691	890

END
END
END