

ADVANCED REACTOR, FUEL CYCLE, AND ENERGY PRODUCTS WORKSHOP FOR UNIVERSITIES

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Gas-Cooled Fast Reactor (GFR)

Idaho National Engineering and Environmental Laboratory

*Workshop for Universities
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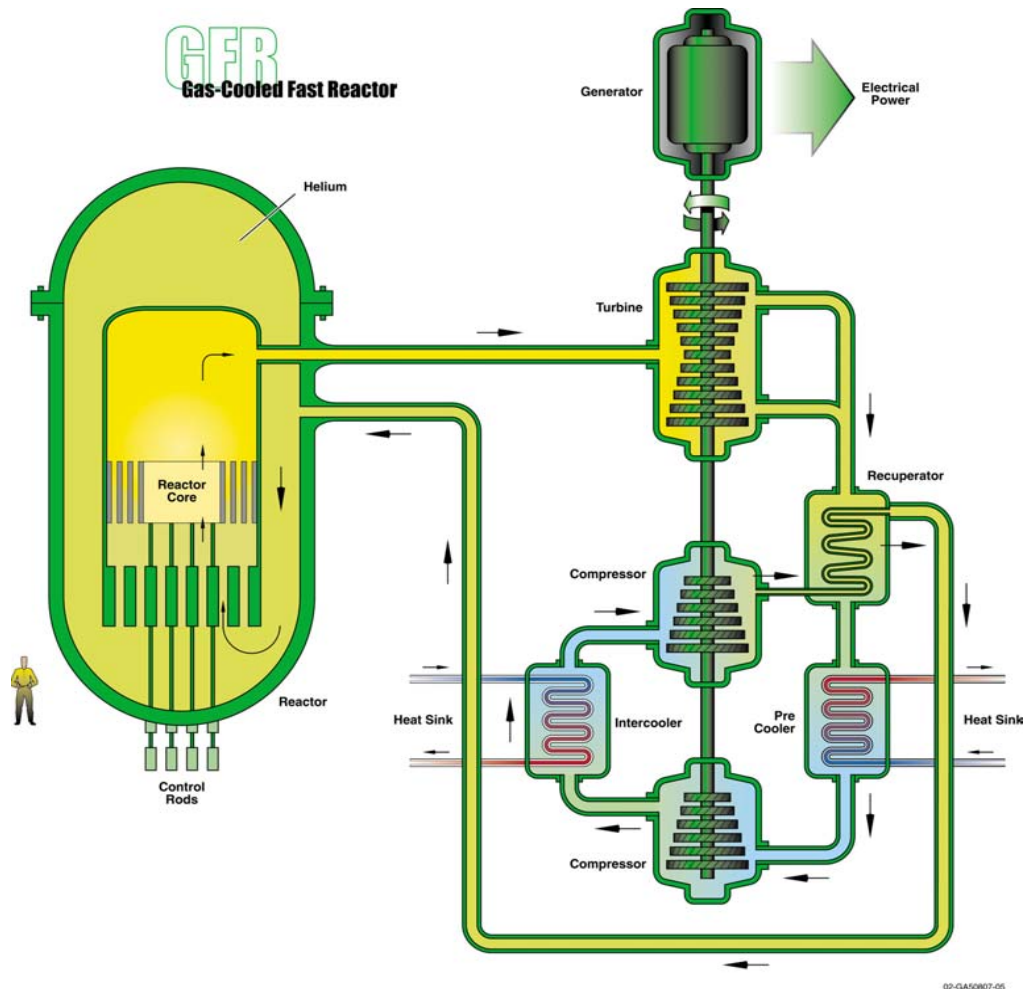
THIS RESEARCH AREA INCLUDES

- ◆ **Demonstrating technical feasibility of a GFR**
- ◆ **The GFR project is part of the Generation-IV program**
- ◆ **The Generation-IV program calls for the development of:**
 - the next generation of nuclear systems for production of high-value energy products such as electricity and hydrogen, and
 - development of fast reactor systems for the actinide management mission (GFR, LFR, SFR)



GFR Objectives

- ◆ High level of safety
- ◆ High sustainability with a closed fuel cycle and full TRU recycle
- ◆ Fast- spectrum core
- ◆ Direct Brayton cycle, high-efficiency energy conversion
- ◆ Production of H_2
- ◆ Estimated deployment time: 2025





Near Term GFR Projects

◆ GFR Design and Safety

- Define GFR reference design features (fuel technology, coolant, unit power) and operating parameters (power density, temperatures)
- Identify safety systems capable of decay heat removal

◆ GFR Fuels, Core Materials, and Fuel Cycle Processes

- Identify fuels and core materials capable of high temperature operations, high fission product confinement, and reasonable burnup/fluence
- Identify and test fuel treatment and refabrication processes



GFR FY03 Budget and Tasks

Level 3 Activity	Level 4 Activity	INEEL	ANL	BNL	ORNL	AU	MIT	UNLV	UofW	TOTAL
Safety systems design & evaluation	DHR studies	135	100	50						485
	PRA guided design						50			
	Project Management	150								
High temperature materials	High temperature materials screening		110						20	605
	Design methodology				150					
Materials for CO ₂ compatibility	ODS joining*	75				100				
	CO ₂ radiolysis						100			
	CO ₂ corrosion	50								
Turbomachinery design**	(n/a)						150			150
Fuel feasibility for medium and high temperature	Fuels physics studies	20								220
	Fuel dissolution studies							50		
	Fuel feasibility for high temperature		75							
Fuel actinide management feasibility	(n/a)		75							
TOTAL		430	360	50	150	100	300	50	20	1460



GFR FY04 Budget and Tasks

◆ Funding for FY04 was \$400k, and supported 4 tasks:

- safety system optimization (\$80k, ANL)
- high temperature fuel modeling (\$120k, ANL)
- ATR support calculations for fuel/fuel matrix irradiations (\$50k, INEEL)
- project management (\$150k, INEEL)



Relationship to NE Program Priorities

- ◆ **The gas-cooled fast reactor (GFR) was chosen as one of the Generation IV nuclear reactor systems to be developed based on its excellent potential for sustainability through reduction of the volume and radiotoxicity of both its own fuel and other spent nuclear fuel, and for extending/utilizing uranium resources orders of magnitude beyond what the current open fuel cycle can realize**
- ◆ **Viability research is being performed to determine whether the GFR can meet the Gen IV goals**



GFR System Design and Safety

GFR Design Options

◆ Reference design features:

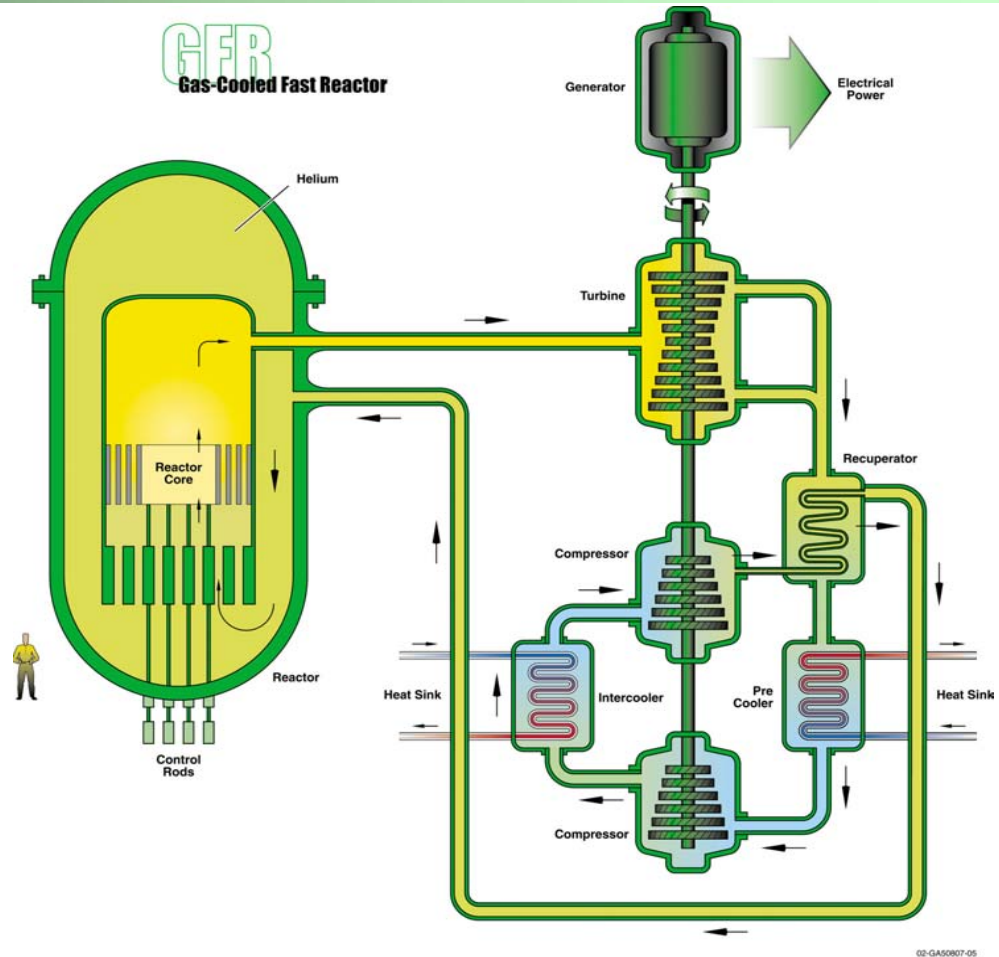
- Coolant: He (at 850°C and 7MPa)
- Direct Brayton cycle
- Unit power: 600-2000 MW_{th}
- Power density: 50-100 MW/m³

◆ Alternate design features:

- Coolant: He (at 600-650°C and 7MPa)
- Indirect Brayton cycle (with S-CO₂ on the secondary side)
- Unit power: 600-2000 MW_{th}
- Power density: 50-100 MW/m³

◆ Optional design features:

- Coolant: S-CO₂ (at 550°C and 20MPa)
- Direct Brayton cycle
- Unit power: 600-2000 MW_{th}
- Power density: 50-100 MW/m³

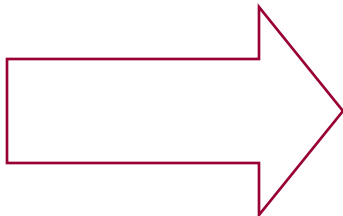


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System Design and Safety

- ◆ Perform thermal-hydraulic and physics studies for candidate designs
- ◆ Scoping studies for DHR in case of depressurization with loss of offsite power in a GFR with 50 –100 MW/m³
 - Heat storage
 - In core conduction and vessel radiation
 - In core exchangers – heat pipes, cold fingers
 - Forced circulation
 - Natural circulation
 - Heavy gas injection
 - Other?



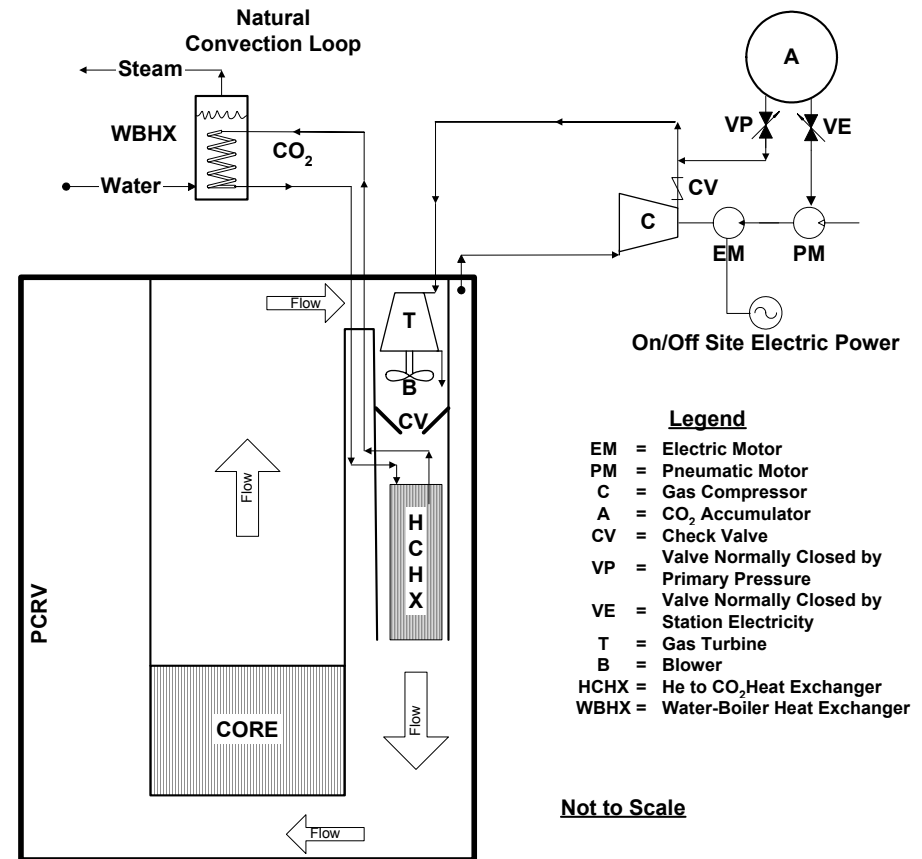
Adiabatic temperature increase of typical cores (7% Nominal Power)

GT-MHR	0.2°C/s	
GCFR (50 MW/m ³)	2.5°C/s	
GCFR (100 MW/m ³)	5.2°C/s	(+400°C less than 100s)



GFR Design and Safety Work

- ◆ **Safety systems capable of decay heat removal using natural circulation have been identified**
- ◆ **Heat storage, in core conduction, and vessel radiation**
 - Combination of these three alone could not realize an effective DHR approach
- ◆ **In core heat exchangers (heat pipes, cold fingers)**
 - Potentially very effective systems but have neutronic impact, technological difficulties, question of the ultimate heat sink, reliability, and safety impact
- ◆ **Forced circulation**
 - Very efficient : 3% nominal flow enables the core cooling while fulfilling fuel temperature criteria
 - Circulators of a very limited power (100 KW) meet the requirements





GFR Design and Safety Work

♦ Helium natural convection

- Sufficient with a top mounted HX at nominal pressure
- Requires a significant back pressure in case of depressurization (function of MW/m³, HX elevation, core ΔP ,...)

♦ Heavy gas injection

- Increase of temperature of the injected gas
- Enhancement of natural circulation when compared with helium

♦ Conclusions

- Helium natural circulation is not suitable alone for high power density (high back pressure needed)
- Heavy gas injection presents perspectives for effective cooling at the beginning of the transient, and would provide for easier natural circulation

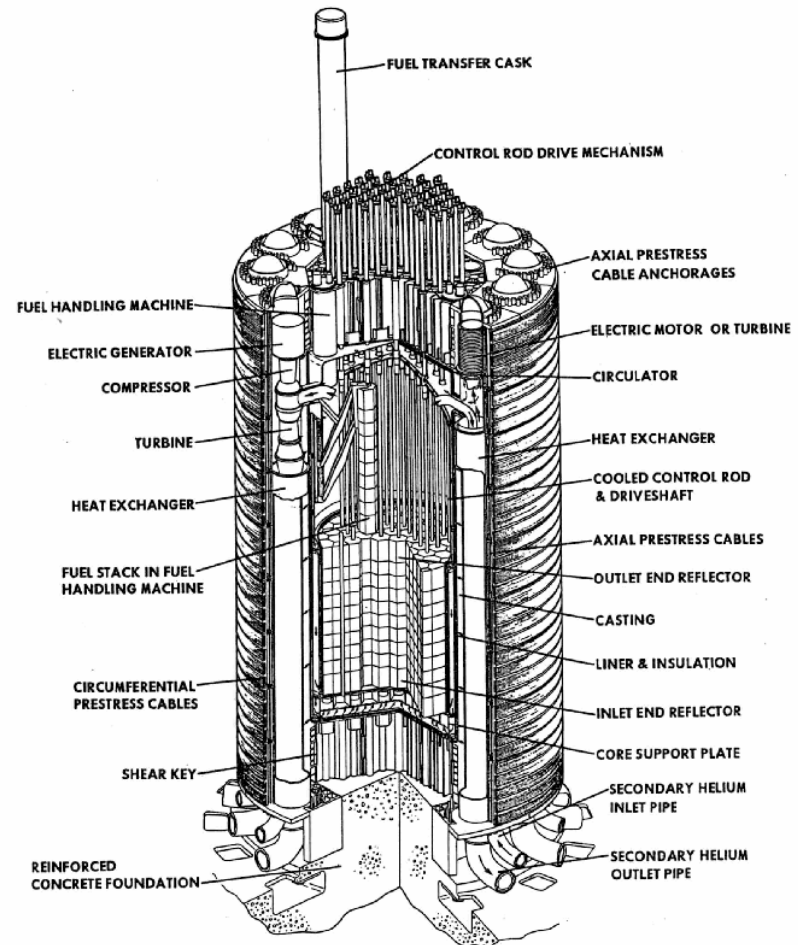


Fig. 1. VHTR for process heat.



GFR Design and Safety Work

◆ DHR strategy

- DHR could be realized by a **complete active system** (circulators, heat exchanger, valve); this system should be classified “safety”, redundant and diversified
- A second system, for increased prevention of core degradation, could be designed/based on **natural circulation**, enhanced by a preliminary heavy gas injection phase (determined by pressure limitation in the containment building)
- Design of the primary circuit and containment building should be adapted for sufficient back pressure (<15 bar) for a specified time
- In addition, design provisions favoring conduction paths, energy storage, etc., should be investigated

◆ Future work will optimize the current designs



Proposed University Contributions to GFR System Design and Safety

◆ FY05-FY07 (~\$100K/yr per project)

- Thermal-hydraulic analysis of current safety system design, i.e., model development and transient analysis using semi-passive DHR systems (does not exclude development of new designs, given they meet the goals of the system)
- Initial PRA studies to determine the best safety systems (or combination of systems) that satisfy Gen IV goals in safety and reliability
- Neutronic/physics core design, including analysis of reactivity coefficients during accident conditions, and reactivity limited burnup



GFR Materials

Main components

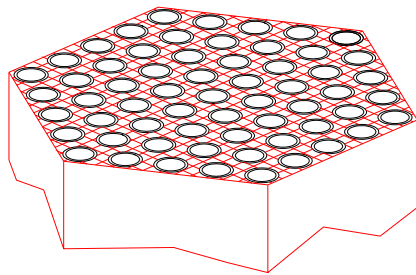
Core structural materials

- Particle concept: **Basket & supporting structures**
- Composite concepts: **Hex.canning (block) & casing (plate)**
- Solid solution fuel concept: **clad & wrapper**
- Other structures: **reflectors & control rods**

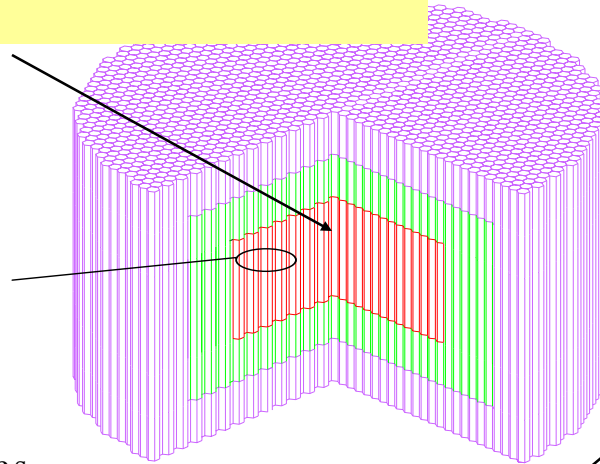
Gas circuits & turbine (not shown)

- Other hot gas circuits of the power conversion system
- Discs & blades of the turbine

Block concept



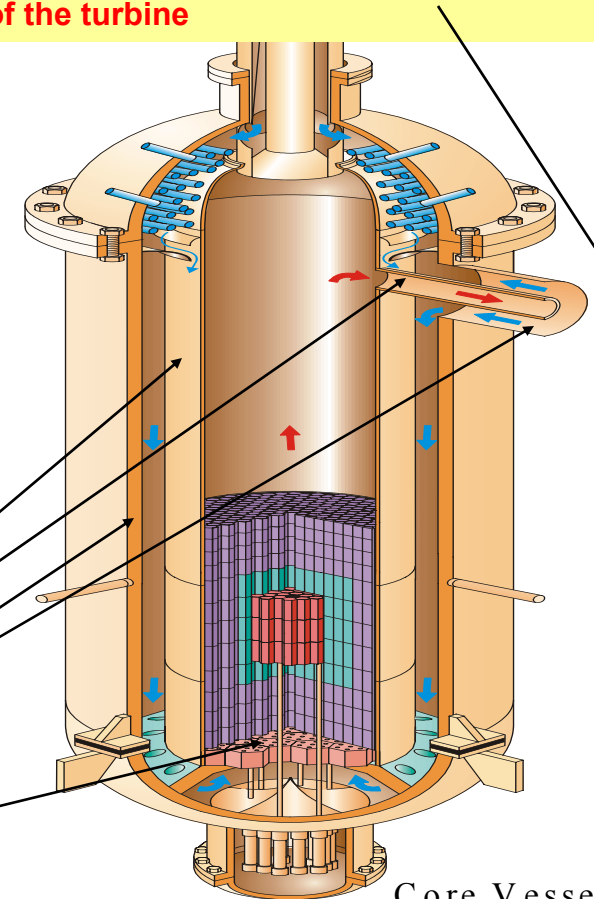
Composite Ceramics
Fuel Element



Core Lay-out

Internal & vessel structures

- Gas duct barrel & hot gas duct
- Reactor vessel & cross vessel
- Core support components



Core Vessel



Material Requirements

◆ In-core structures

Key point : in-service mechanical integrity under prolonged irradiation at high temperature imply development of new innovative material solutions that are, today, not yet proven

Adequate initial & in-pile following characteristics :

- Physical properties (e.g., heat capacity, heat transfer coefficient, thermal expansion), neutronic transparency, chemical compatibility with He (and impurities) & actinide compounds and resistance to gas permeability,
- Tensile, creep, fatigue, and toughness properties.
- Microstructure and phase stability
- Irradiation creep, in-pile creep and swelling resistances,
- Mechanical & chemical stabilities in LOCA transients and air ingress conditions

Ability to weld/join and fabricate components at a reasonable cost

◆ Out-of-core structures

- Fabricability & welding capabilities on thick products
- Adequate tensile, creep, fatigue, and toughness properties



GFR fuel matrix and structural material reference requirements

Requirement	Reference Value
Melting/decomposition temperature	>2000°C
Radiation induced swelling	< 2% over service life
Fracture toughness	> 12 MPa m ^{1/2}
Thermal conductivity	> 10 W/mK
Neutronic properties	Materials allow low core heavy metal inventory and maintain good safety parameters

Candidate ceramic matrix materials: SiC, ZrC, TiC, ZrN, TiN, and AlN



GFR In-Core Materials

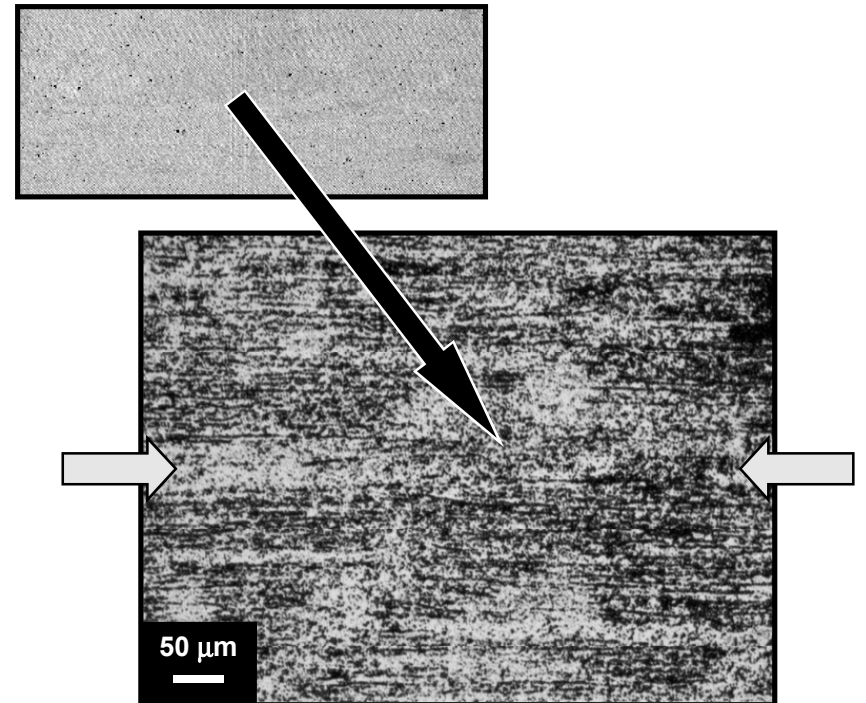
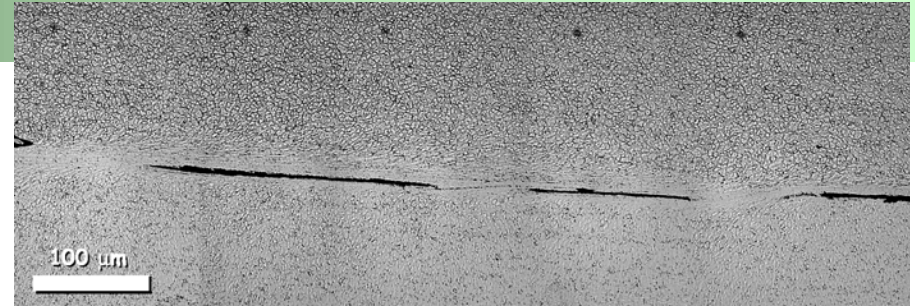
- ◆ **The following materials are being considered:**
 - Alloy 800H, ferritic steel T-122, and oxide dispersion strengthened (ODS) alloys MA957, MA754, and PM2000

- ◆ **The initial design of an ion-beam irradiation stage for materials testing of the potential GFR core structure materials has been completed**



GFR In-Core Materials

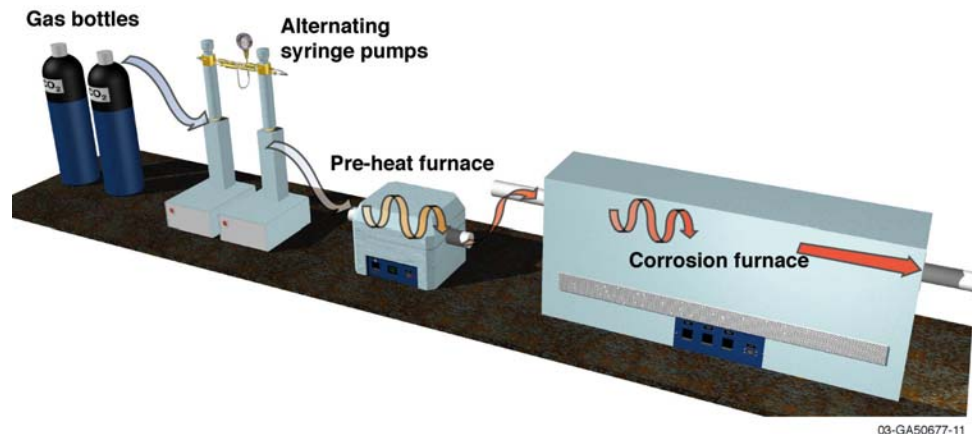
- ◆ **Welding/joining studies of ODS materials has begun**
 - Both resistance pressure welding (RPW), and transient liquid phase (TLP) bonding studies were performed
- ◆ **Initial RPW studies have shown unbonded areas, but may be due to the effects of the unconstrained thin wall**
- ◆ **Initial TLP bonding shows promise, as there were no major microstructural discontinuities**





GFR CO₂ Corrosion Studies

- ◆ Designed, built, and tested a supercritical CO₂ once through corrosion apparatus
- ◆ Purchased testing materials for experimental campaign
- ◆ Obtained internal safety approval to conduct high temperature and pressure experiments in FY04

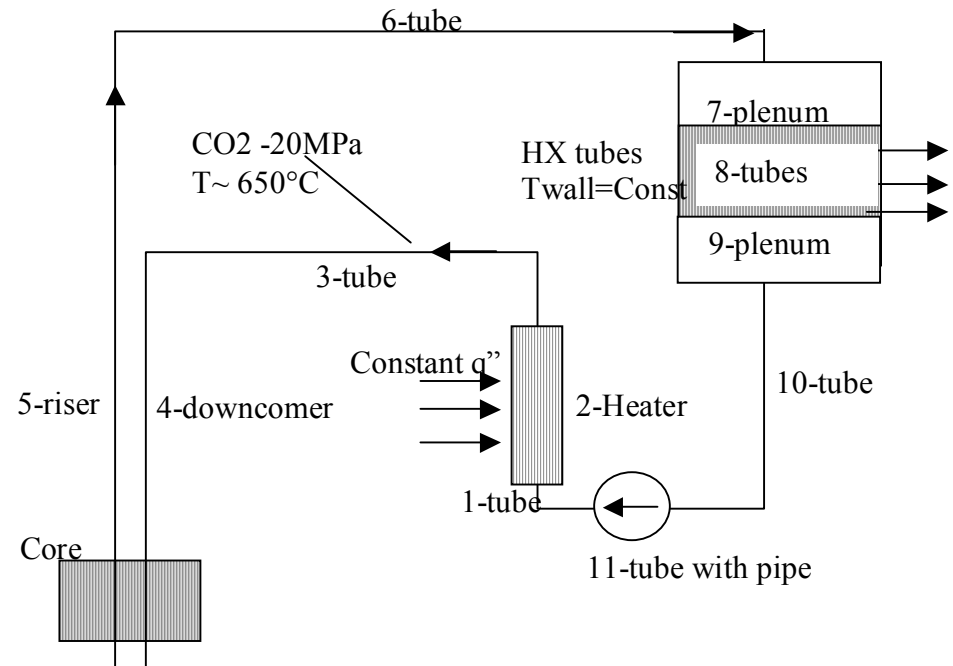




GFR CO₂ Radiolysis Studies

◆ An in-pile radiolysis loop has been designed with the following components:

- Main heater
- Autoclave,
- Regenerative heat exchanger
- Non-regenerative heat exchanger
- Circulating pump, and
- Back pressure regulator





Proposed University Contributions to GFR Materials Development

◆ FY05-FY07 (~\$100K/yr per project)

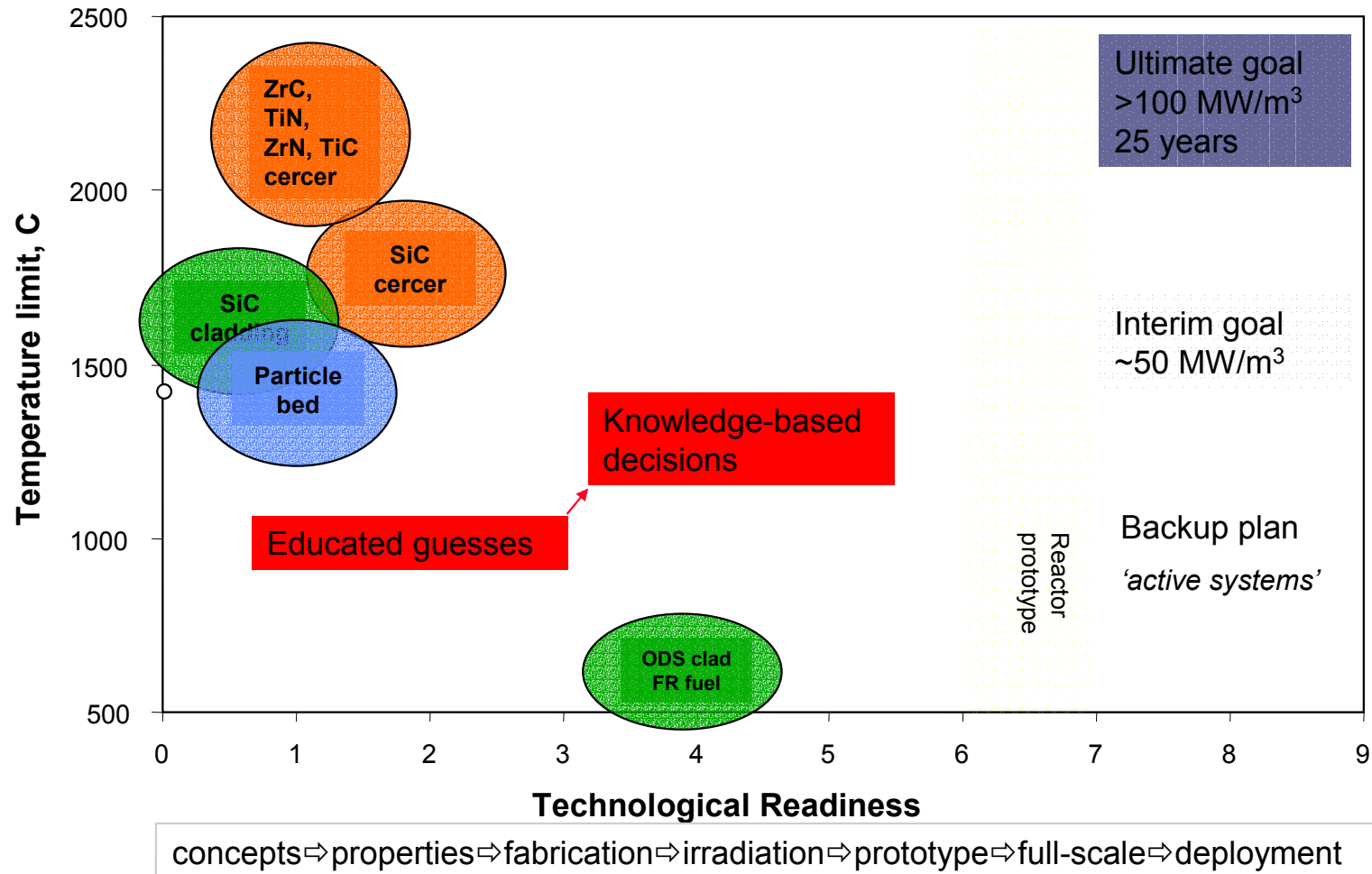
- Measure missing thermo-mechanical/physical properties for those ceramics of interest (e.g., carbides and nitrides)
- Joining/welding studies of candidate materials (both ceramic and metallic)
- Supercritical CO₂ corrosion studies on materials of interest (both ceramic and metallic)
- Supercritical CO₂ radiolysis studies (decomposition and recombination rates)
- Other related proposals involving materials applicable to the GFR (including possible in-pile or accelerator irradiations)



GFR Fuels






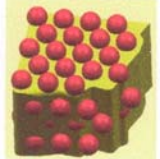

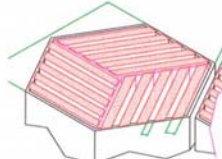
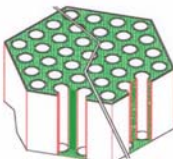



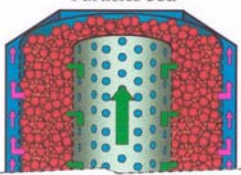

Current GFR Fuel Status



GFR Fuel

Dispersion fuel

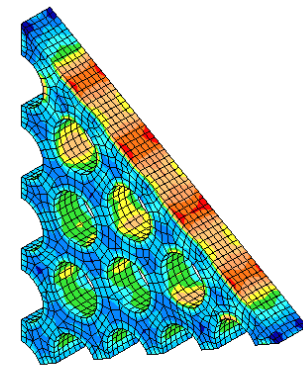
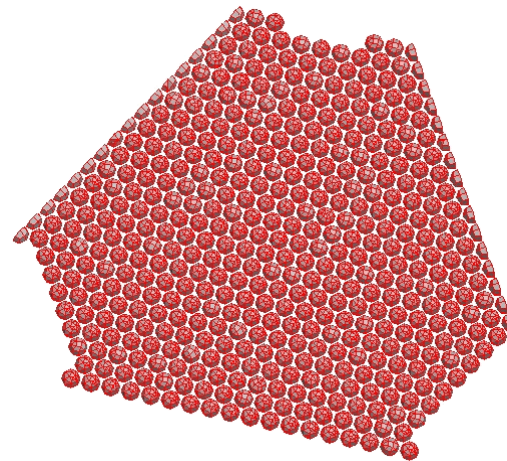
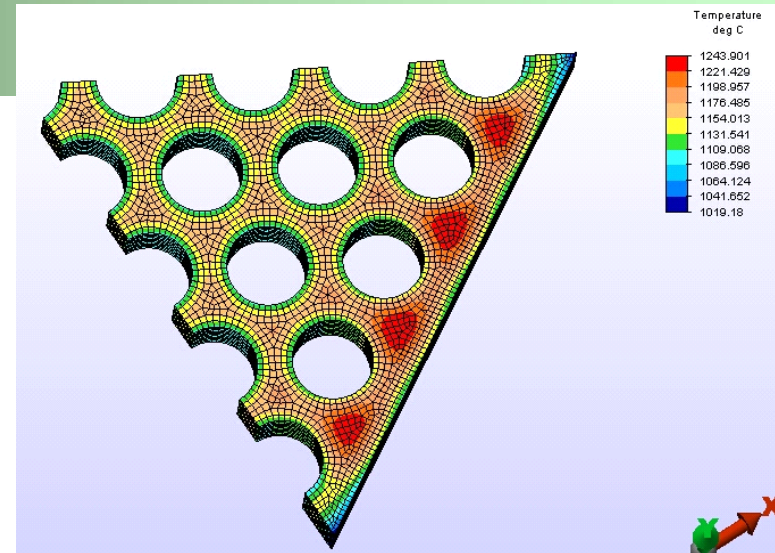
- Fuel form: fibers or spheres
- Initial matrix material selection: SiC
- Fuel composition: UC or UN (will also include Pu+MA)
- Initial fuel loading goal: 50% fuel & 50% matrix
- Fuel loading objective 70% fuel & 30% matrix
- Rationale: Best from neutronics standpoint and will withstand high temperatures during accidents
- Optional fuel is coated particles

	Fuel	Fuel element	Sub-assembly
1- DISPERSION FUEL	Cylindrical or Hexagonal sticks 	Coated compact 	Pseudo-hexagonal sub-assembly with compact stack 
	Spheres / particles 	Coated plates 	Sub-assembly with plates  Prismatic block type with coated channels 
	Fuel	Fuel element	Sub-assembly
2- PARTICLES	2 sized particles 	Particles coated with x layers  T/D~0,12 Compact with coated particles 	Particles bed  Sub-assembly with compact stack 



GFR Fuel Modeling

- ◆ Current concept is for plate type dispersion fuel with
- ◆ Finite element fuel models have been constructed for local and global temperature and stress profiles
 - Peak fuel temperature of $\sim 1250^{\circ}\text{C}$
 - Peak stress of $\sim 150\text{MPa}$

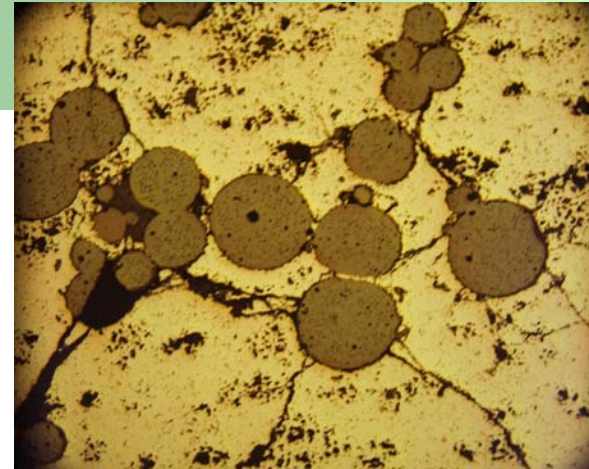


Load Case: 1 of 1
Maximum Value: 1.51698e+008 N/(m²)
Minimum Value: 1.00091e+007 N/(m²)

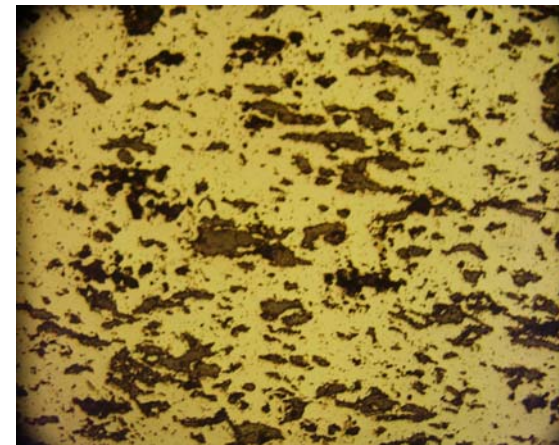


GFR Fuel Fabrication

- ◆ 10 exploratory hot press runs, 4 sintering trials, and 12 reaction bonding trials were completed as scoping tests of potential fuel fabrication processes
- ◆ After hot pressing of ZrC at 1900°C for 2 hours at 70 MPa, a density of only 66% of theoretical was attained
 - Probably inadequate for use as a GFR matrix due to the inability of a porous matrix to retain fission gas
- ◆ Specimens fabricated with excess graphite by hot pressing at 2000°C for 4 hours appear to have high density and no surface connected porosity



ZrC containing carbon spheres hot pressed at 2000°C for 4 hours.



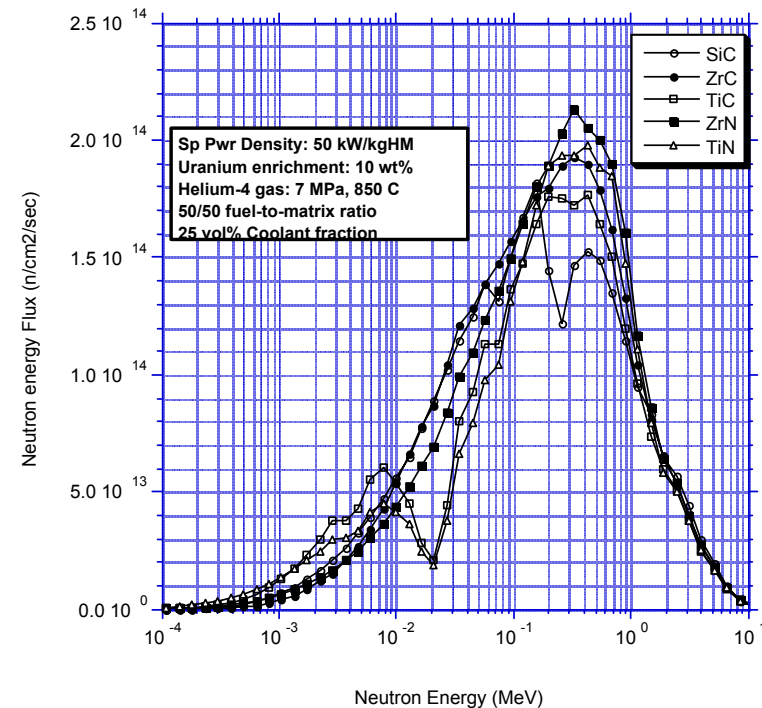
Optical micrograph of ZrC containing excess graphite hot pressed at 2000°C for 4 hours (approximately 150X magnification)



GFR Preliminary Fuel Neutronics

Matrix Material	k-inf	Δk	Δk (Dollars)
SiC (ref)	1.104277	0.000000	0.00
ZrC	1.063023	0.041254	6.35
TiC	1.094072	0.010205	1.57
ZrN	1.024439	0.079838	12.28
TiN	1.043491	0.060786	9.35

Using SiC as the reference fuel matrix, and UN as the fuel, all other matrices show a lower infinite multiplication factor





GFR Fuel Dissolution Studies

- ◆ **Injection of heavy gas (e.g., CO₂), or use of heavy gas as the primary coolant, may create fuel dissolution challenges**
- ◆ **Studies of the oxidation kinetics for UC and UCUS under CO₂ were carried out**
- ◆ **UC curves typically all contain two sharp CO peaks at approximately 450 and 600°C**
- ◆ **UCUS samples followed similar patterns, except the higher US content samples only produced a single prominent CO peak at approximately 500°C**
- ◆ **Currently, kinetic analysis of the data is being performed**



Proposed University Contributions to GFR Fuels Development

◆ FY05-FY07 (~\$100K/yr per project)

- Innovative matrix material fabrication techniques for ceramics of interest
- Fuel performance modeling using UC and UN in ceramic matrices (specifically thermo-chemical)
- Ion irradiation/implantation of ceramics (particularly heavy ion irradiation)
- UC and UN oxidation studies (air ingress, CO₂ ingress, etc.)
- Preliminary assessment of the GFR fuel cycle (includes flow sheet development, physics/neutronics analysis of equilibrium cycle, and possible surrogate material experiments)