The ART GCR Program: Overview and ASI needs

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ART

ADVANCED REACTOR TECHNOLOGIES

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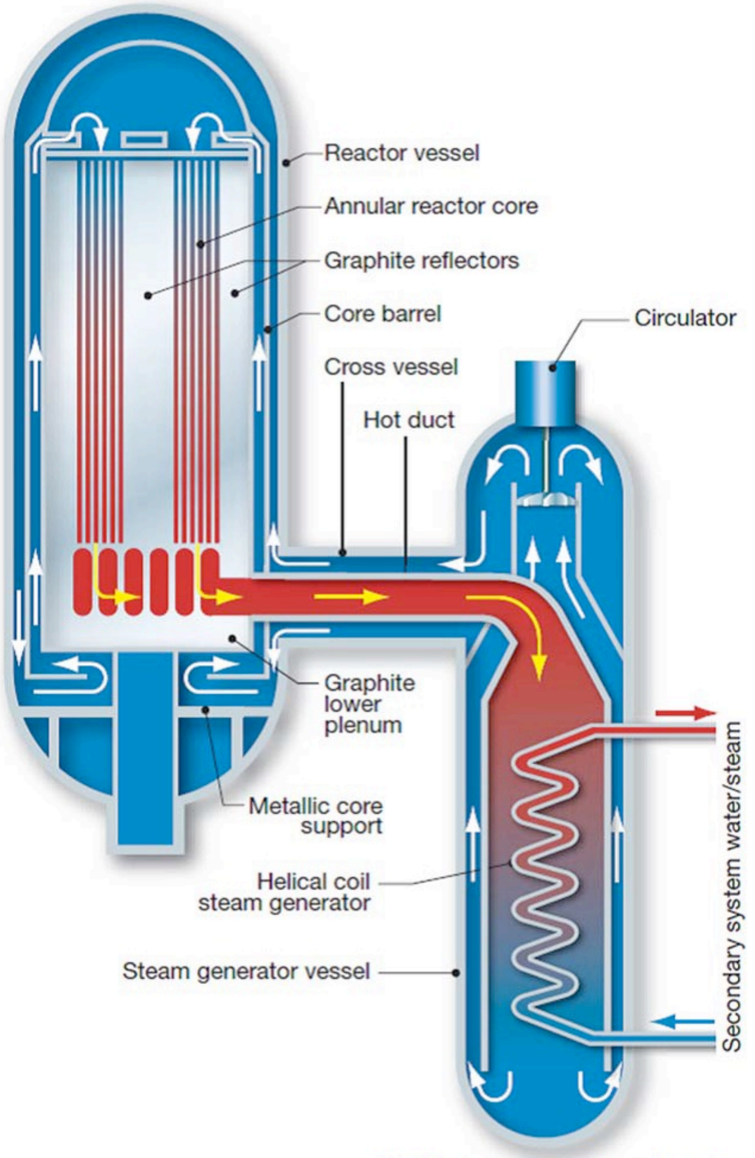
ART GCR Overview

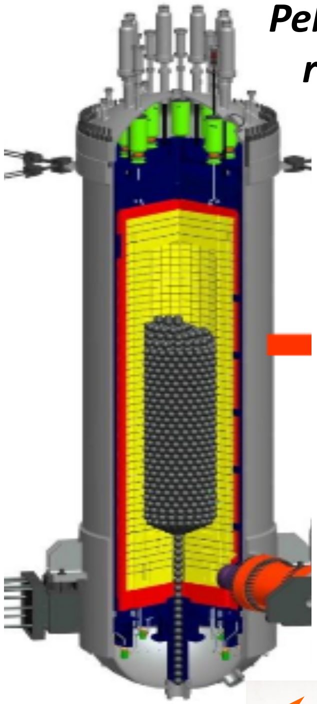
Relevant Attributes of Modular HTGRs

- Graphite-moderated and reflected
- Cooled (usually) by helium (~7 MPa)
- Large ΔT_c (>400°C) across the core (top to bottom)
- Fuel: TRISO fuel particles in a carbonaceous matrix
- Large aspect ratio: heat escapes radially via conduction and radiation if forced cooling is lost. This attribute also limits the power density (~400 MWt for PBRs; ~600MWt for prismatic reactors)
- Slow temperature response during accidents (high heat capacity and low power density)

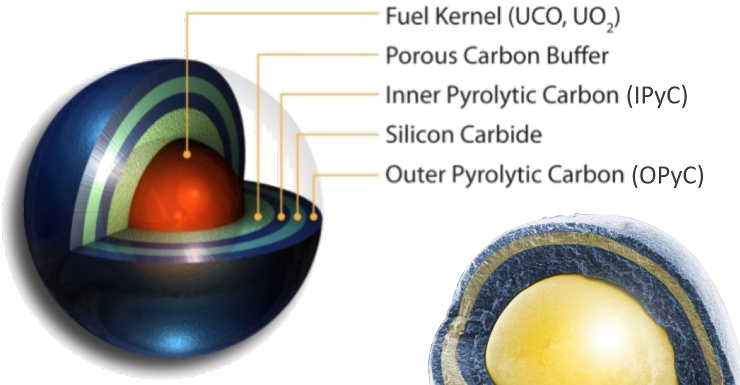


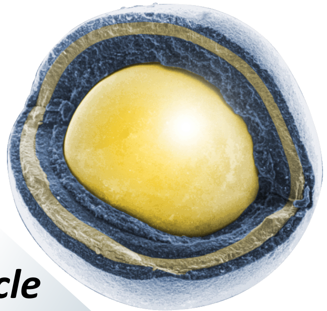
(1 of 2 steam generators shown)

Tristructural Isotropic (TRISO) Coated Particle Fuel

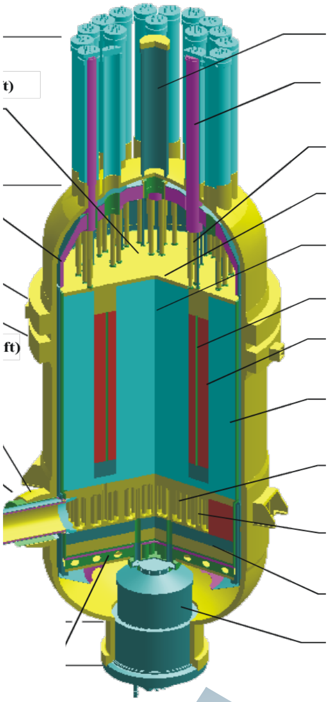


Pebble bed reactor

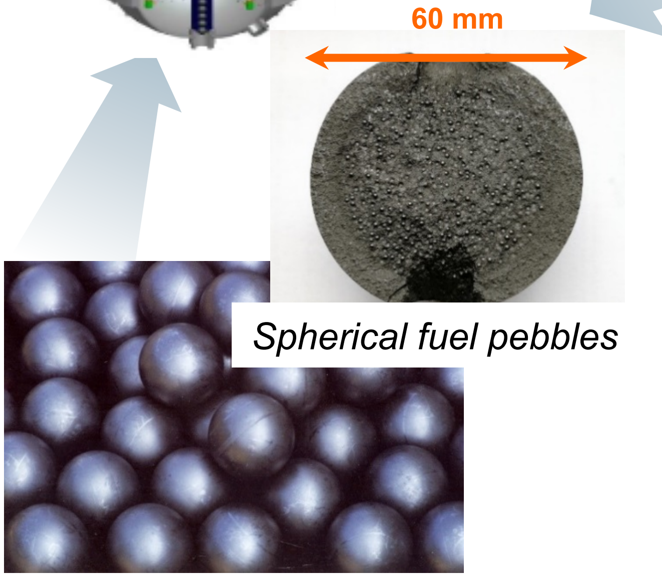




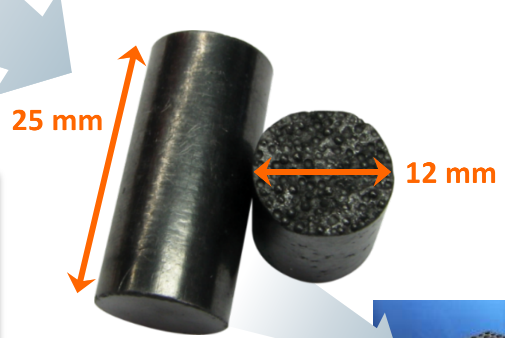
TRISO particle



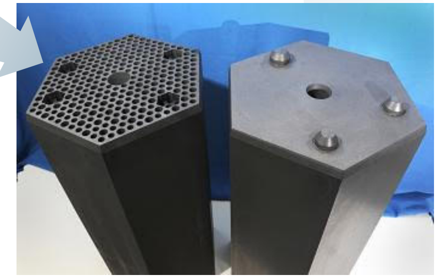
Prismatic reactor



Spherical fuel pebbles



Cylindrical fuel compacts



Prismatic graphite blocks

Particle design provides excellent fission product retention in the fuel and is at the heart of the safety basis for high temperature gas reactors

DOE-ART Gas-Cooled Reactor Campaign

ADVANCED REACTOR TECHNOLOGIES

Strategy:

Engage with industry, academia and the regulator to identify, prioritize, and conduct the tasks that require DOE resources to demonstrate HTGR technology with the goal of reducing technical risks

- **Fuel Qualification**
  - Fabricate and qualify fuel that performs better than vendor requirements so that an HTR can be sited next to a process heat user.
- **High Temperature Materials**
  - Qualify many commercial grades of graphite and establish design rules so that graphite vendors can compete.
  - Qualify alloys (800H, 617, even SA508/533) for high temperature service so that the outlet coolant temperature can be raised.
- **Methods Development and Validation**
  - Develop and validate core analysis methods and models so that margins can be reduced and performance enhanced.

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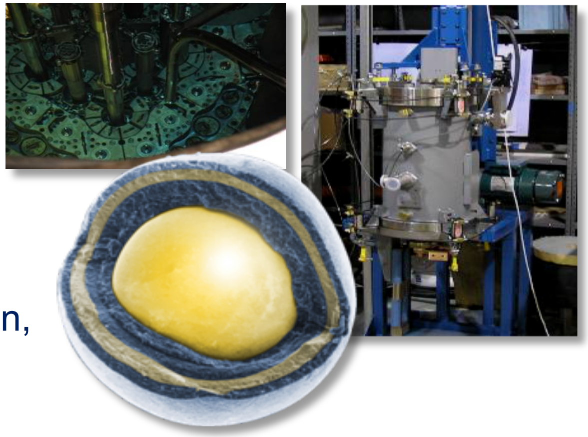
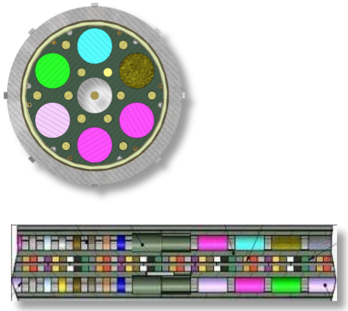
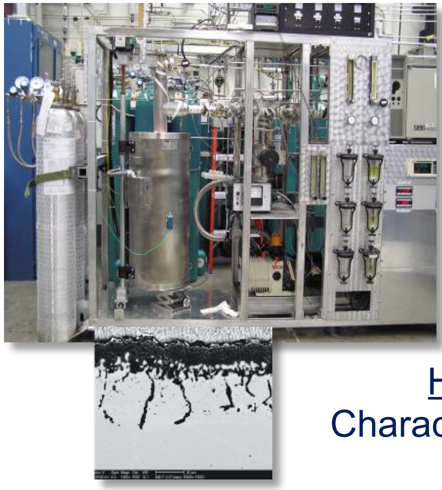
Major ART-GCR FY 2020 Activities



Fuel Fabrication,
Irradiation, and
Safety Testing

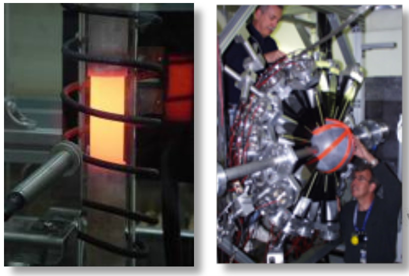
Graphite Characterization,
Irradiation Testing, Modeling and
Codification

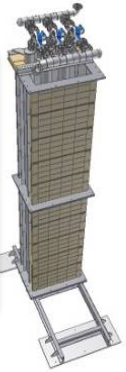


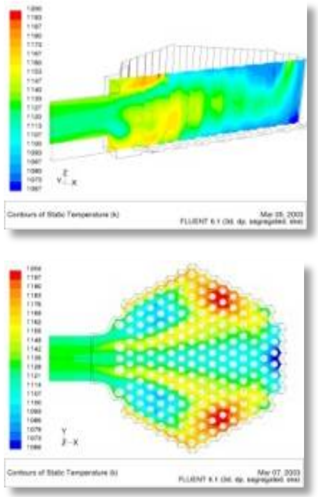


High Temperature Alloy
Characterization, Testing and
Codification

Design and Safety Methods
Development and Validation

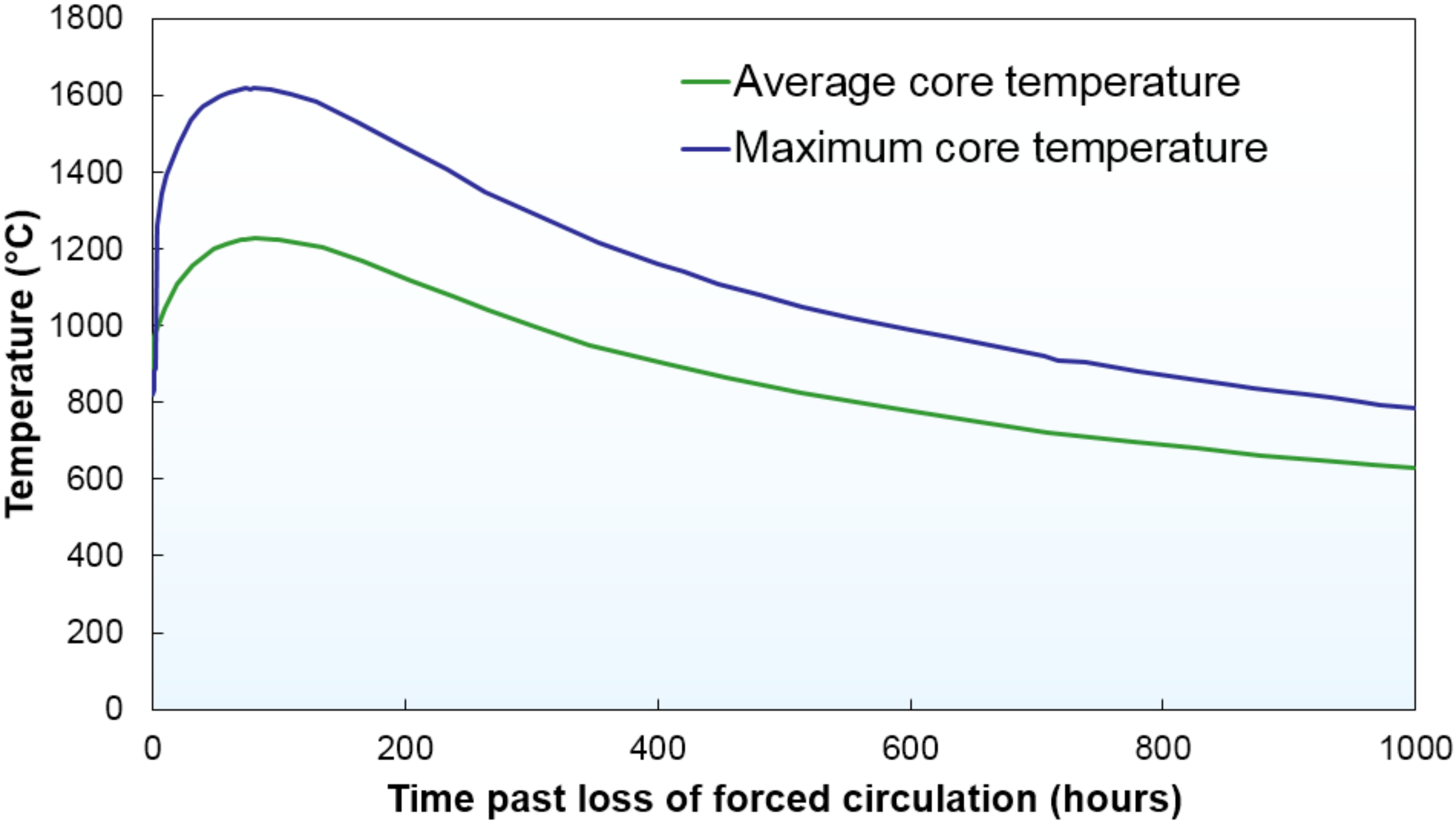






HTGR Environment

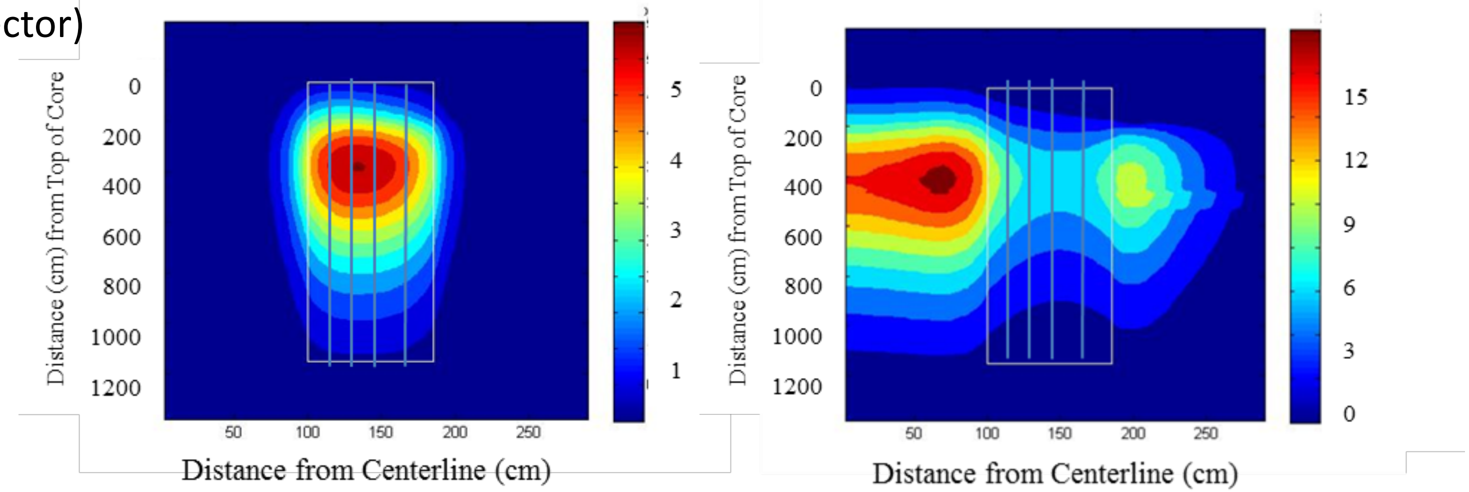
Typical Core Temperatures Following Depressurized Loss of Forced Cooling

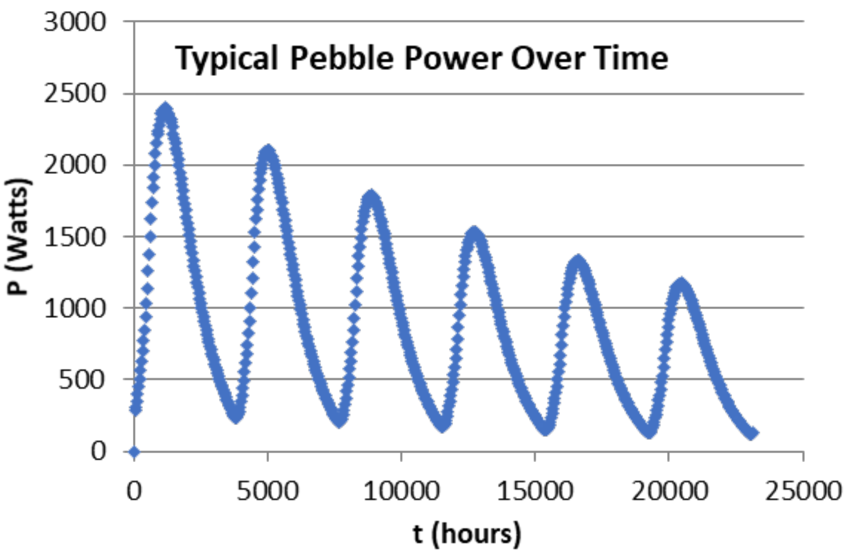


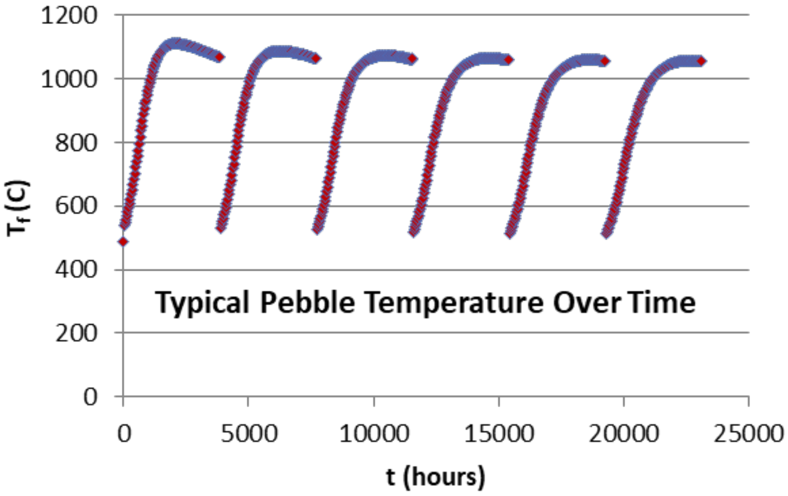
350 MWt Prismatic Core Design

Typical flux and temperature profiles

Fast (left) and thermal (right) flux profiles in the PBMR-400 equilibrium core (6-pass core with inner reflector)







Gougar, H.D., Ougouag, A. M., Terry, W. K., and Ivanov, K. I., "Automated Design and Optimization of Pebble Bed Reactor Cores, Nuclear Science and Engineering, Oct. 2008.

HTGR challenges

- Temperature measurements in upper and lower plena: during LOFC events, hot helium jest impinge on top plate (thermal stratification).

- Dimensional changes in graphite lead to alternate coolant pathways (bypass flow) – significantly altering the temperature profile in the core and reflector.

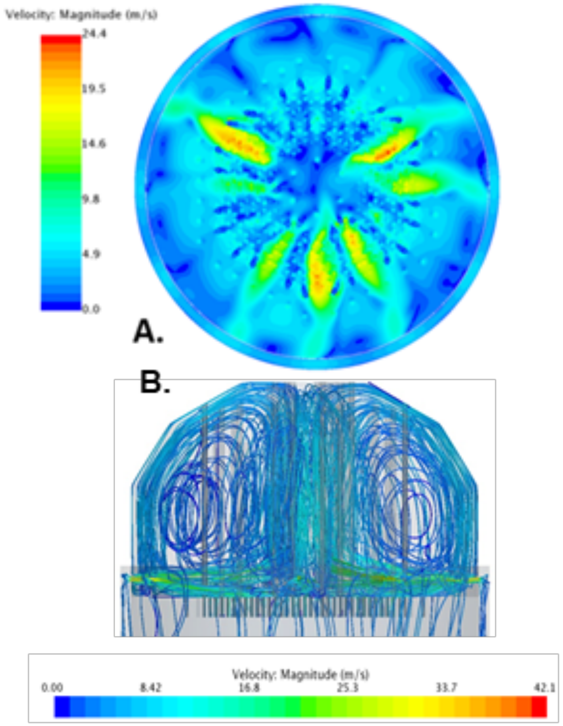
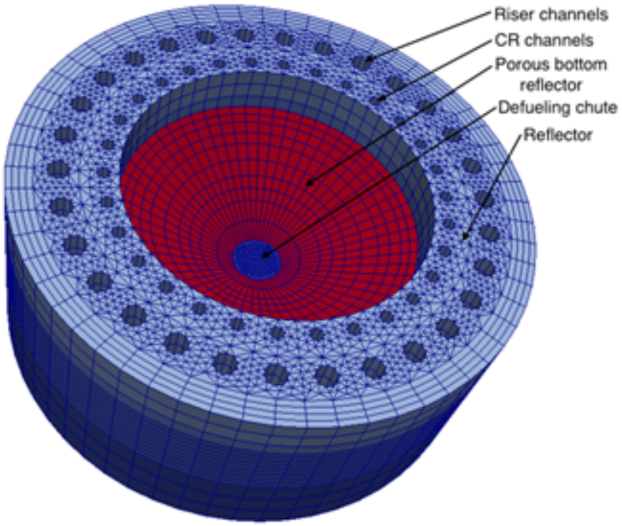
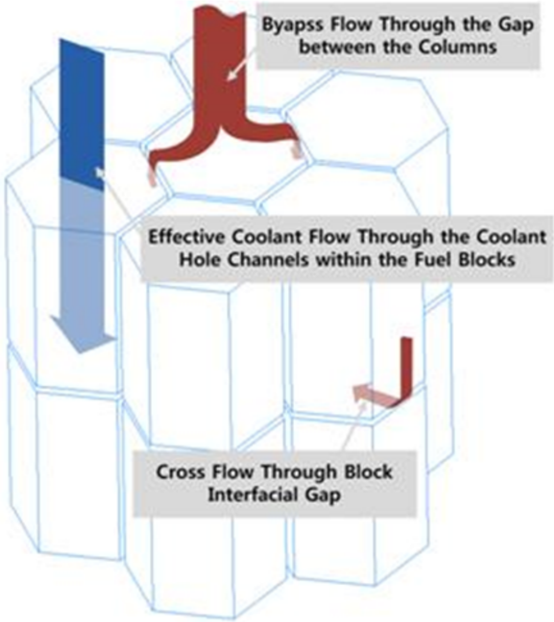


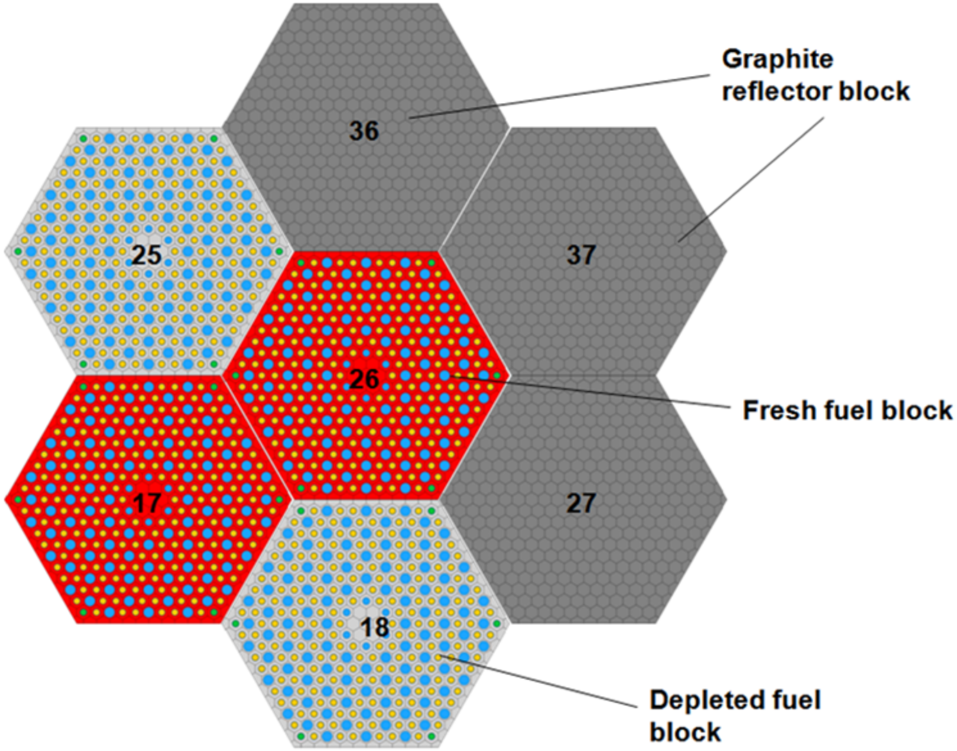
Figure 2. A. HTTF Upper Plenum velocity distribution, core entrance, normal operation B. Upper plenum streamlines.

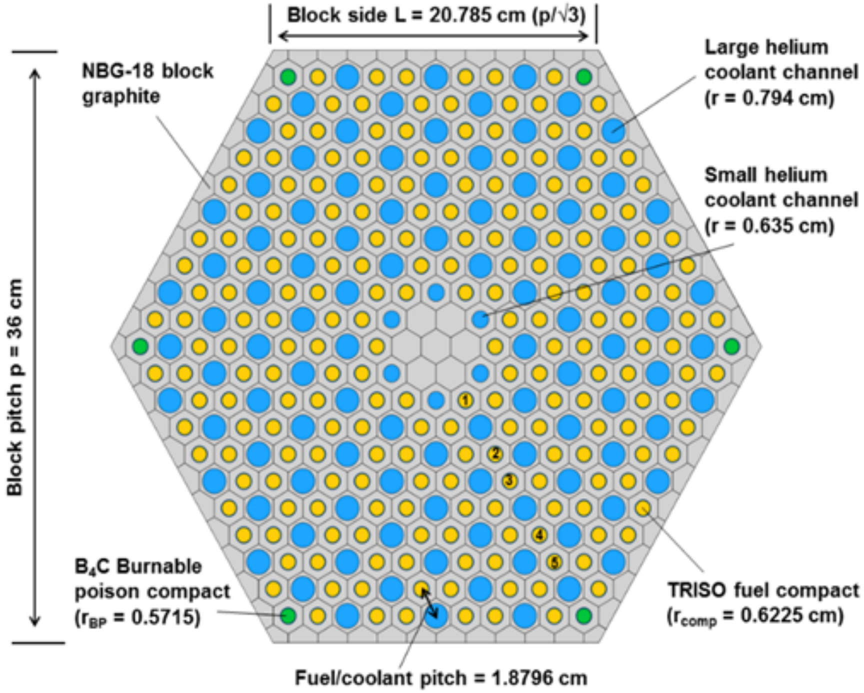


HTR-PM bottom reflector structure



Prismatic HTGR fuel and reflector blocks





HTGR ASI Needs

HTGR ASI needs

- NGNP study (INL/EXT-08-14825): “Instrumentation and Control and Human-Machine Interface Functional Requirements Description for the Next Generation Nuclear Plant”.
  - Temperature sensors for high temperatures must be developed with high accuracy, low drift, and insensitivity to radiation.
  - In-core neutron detectors probably very difficult for PBMR.
  - Might be necessary to locate neutron or gamma detectors outside reactor vessel to infer 3-D core power distribution (R&D required).
  - 3D core power shape is determined by neutron detectors in reflectors (600 - 800 ^{o}C)
  - Thermal fatigue will be of much greater concern in HTGRs, so instruments to monitor fatigue life must be located on the RCS and heat exchangers.
  - In-line helium gas-mixture purity measurement.
  - Mass flow measurement for by-pass flow predictions.

HTGR ASI gaps

- 2016 Report (ORNL/TM-2016/337): “Assessment of sensor technologies for advanced reactors”.
- Very detailed survey of HTGR/MSR/SFR status and needs
- Some identified gaps:
  - No suitable neutron flux measurement sensor is commercially available that functions at temperatures above 550 °C. HGTRs run at temperatures much above this, however previous programs have developed fission chambers that can function up to 800 °C. These detectors are not commercially available yet.
  - Gamma thermometers will require sheath materials to withstand the chemical environment and high temperatures.
  - To overcome the temperature vulnerability of fission chambers, low-outgassing structural materials and high-temperature-tolerant sealing materials and methods need to be devised.
  - The high pressure and high temperature primary flow environment has eliminated the use of any in-core flow meters. Until now the flow was inferred from the either the turbine-compressor or the helium circulator rotational speed.

HTGR components and interfaces

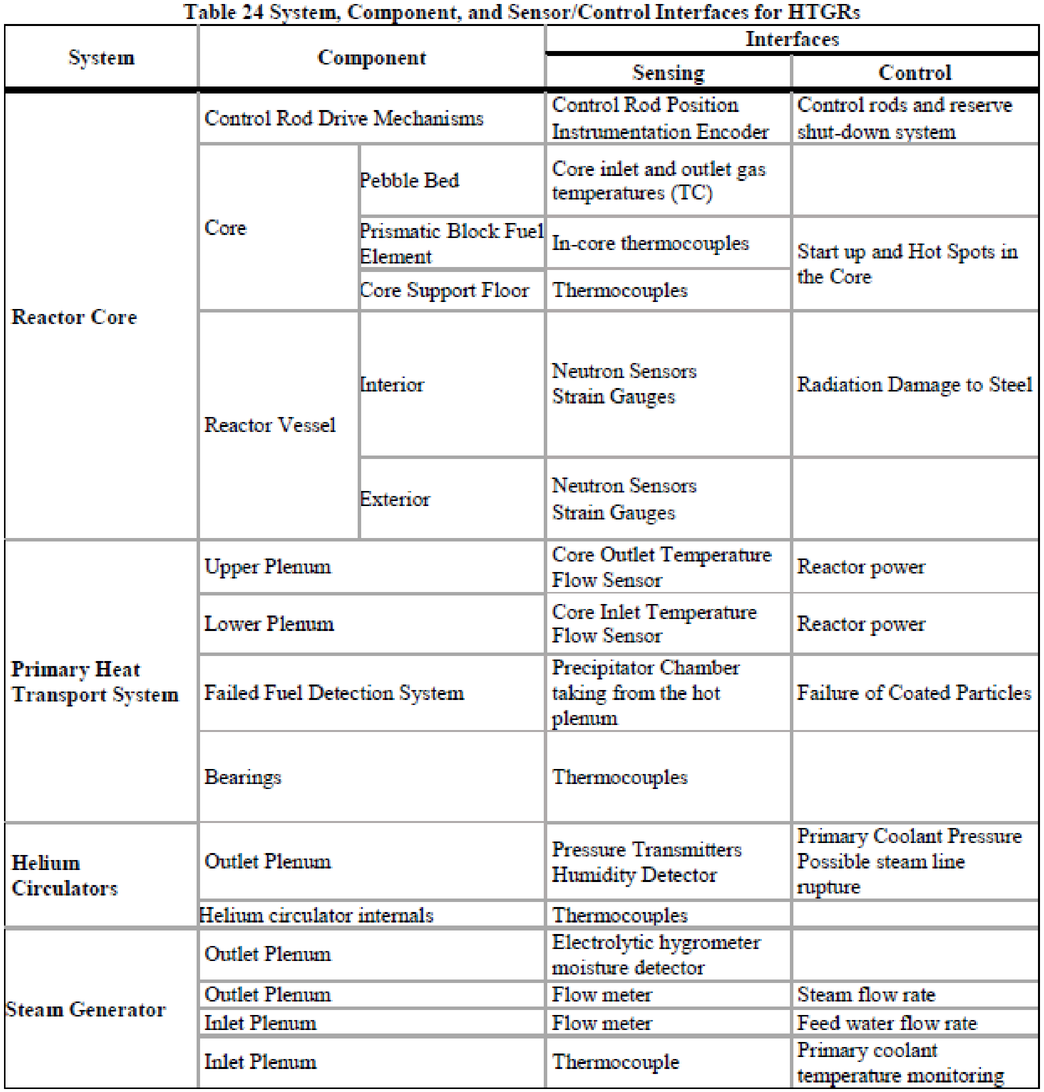


Table 24 System, Component, and Sensor/Control Interfaces for HTGRs

System	Component		Interfaces	
			Sensing	Control
Reactor Core	Control Rod Drive Mechanisms		Control Rod Position Instrumentation Encoder	Control rods and reserve shut-down system
	Core	Pebble Bed	Core inlet and outlet gas temperatures (TC)	
		Prismatic Block Fuel Element	In-core thermocouples	Start up and Hot Spots in the Core
		Core Support Floor	Thermocouples	
	Reactor Vessel	Interior	Neutron Sensors Strain Gauges	Radiation Damage to Steel
		Exterior	Neutron Sensors Strain Gauges	
Primary Heat Transport System	Upper Plenum		Core Outlet Temperature Flow Sensor	Reactor power
	Lower Plenum		Core Inlet Temperature Flow Sensor	Reactor power
	Failed Fuel Detection System		Precipitator Chamber taking from the hot plenum	Failure of Coated Particles
	Bearings		Thermocouples	
Helium Circulators	Outlet Plenum		Pressure Transmitters Humidity Detector	Primary Coolant Pressure Possible steam line rupture
	Helium circulator internals		Thermocouples	
Steam Generator	Outlet Plenum		Electrolytic hygrometer moisture detector	
	Outlet Plenum		Flow meter	Steam flow rate
	Inlet Plenum		Flow meter	Feed water flow rate
	Inlet Plenum		Thermocouple	Primary coolant temperature monitoring

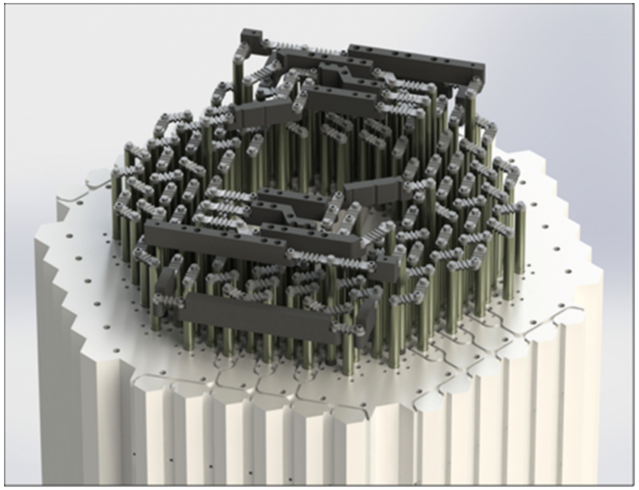
HTGR ASI: focus on primary system

- Temperature (20^{o}C-1800^{o}C)
  - Prismatic HTGRs: Desirable to obtain in-core data.
  - Pebble bed HTGRs: Inference of pebble temperatures from reflector TCs? Direct pebble temperature measurements (300,000 pebbles/core) impractical & slow (German AVR used metal melt wires).
- Helium flow rates (0-200 kg/s)
  - Core region (inlet/outlet plena) + various bypass flow channels (control rods, gaps).
- Flux/power
  - Prismatic & Pebble bed HTGRs: Ex-core flux measurements in reflectors capable of surviving >1000^{o}C for extended periods.
  - Prismatic HTGRs: in-core measurements possible next to fuel channels, but…
    - Limited space; non-interference with fuel loading/re-loading
    - High temperatures (up to ~1700^{o}C)

Complexity of temperature measurements: HTTF (Oregon State University)

Replaced all high temperature thermocouples.

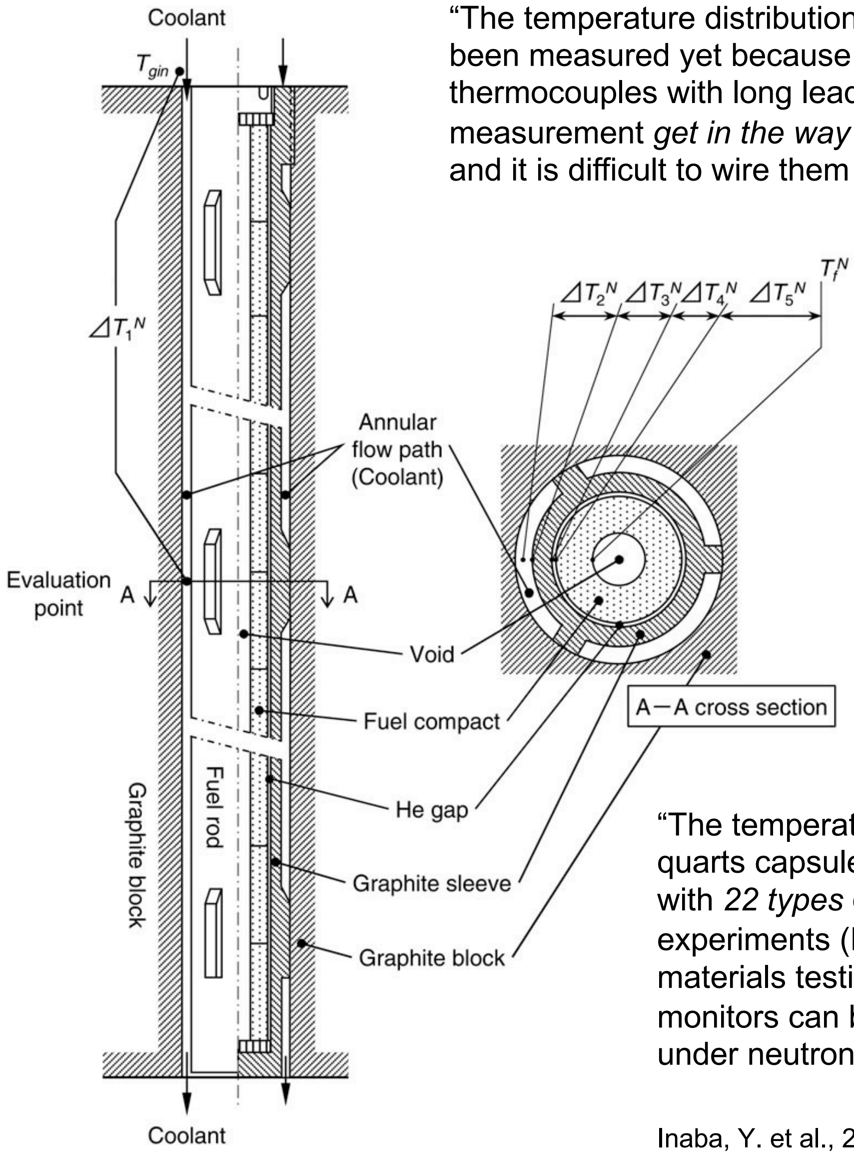
- Core thermocouples must be rated to 1600˚C—high temperature thermocouples.
- Replaced unsheathed C-type thermocouples with sheathed R-type thermocouples.



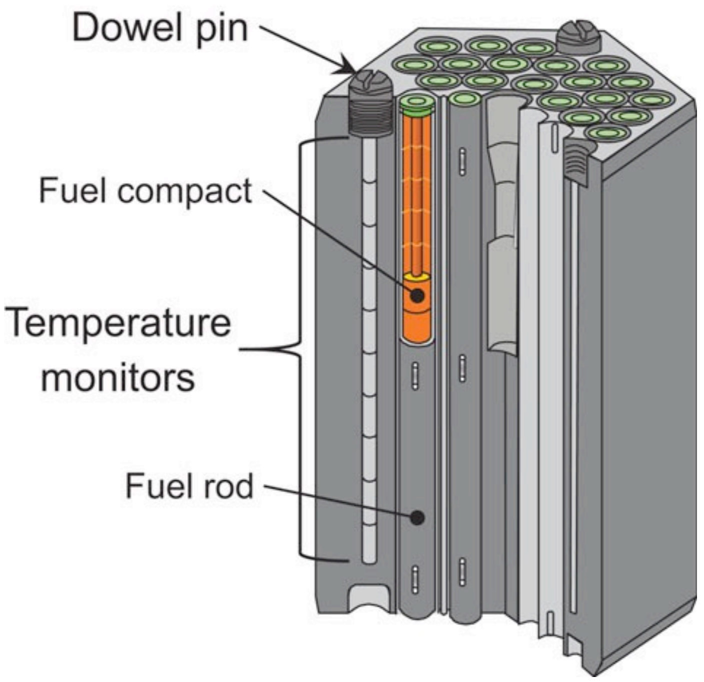
- **Redesigned heater distribution system.**
  - HTTF heater elements: connections must accommodate thermal expansion and contraction of core.
  - Switched to flexible molybdenum connections between graphite components.
  - Added tungsten weights to provide compressive force to increase graphite contact force.

Brian Woods: OSU HTTF Recovery Plan Report

Complexity of temperature measurements: HTTR (Japan)



"The temperature distribution of the HTTR has not been measured yet because using sheathed thermocouples with long lead wires for online measurement *get in the way of the fuel exchange* and it is difficult to wire them into the core".



"The temperature monitors consist of alloy wires with various melting points, sealed in quarts capsules. The temperature can be evaluated in the range from 600°C to 1400°C with *22 types* of the temperature monitors. The irradiation tests and post-irradiation experiments (PIEs) of the temperature monitors were carried out in the Japan materials testing reactor (JMTR). As a result, it was found that the temperature monitors can be used *up to 90 days* at 1100°C or up to 50 days at 1300°C – 1350°C under neutron irradiation".

Inaba, Y. et al., 2014. "Evaluation of maximum fuel temperature in HTTR".
Journal of Nuclear Science and Technology, Volume 51, Nos. 11–12.

INL AGR-5/6/7 Development and Testing Program

- Type C TCs failed in the OSU HTTF facility (no neutrons); unsheathed C-type thermocouples were replaced with sheathed R-type thermocouples that could handle 1600°C.

- It is difficult to measure very high temperatures in a reactor environment:
  - Standard base metal thermocouples (Type K and Type N) drift at high temperatures due to metallurgical changes (above 600°C for Type K and above 1050°C for Type N)
  - High temperature refractory thermocouples such as Types C, S, B, and R have high cross section alloying elements and are subject to rapid de-calibration (drift) because their alloying elements transmute into other elements with different electromotive properties

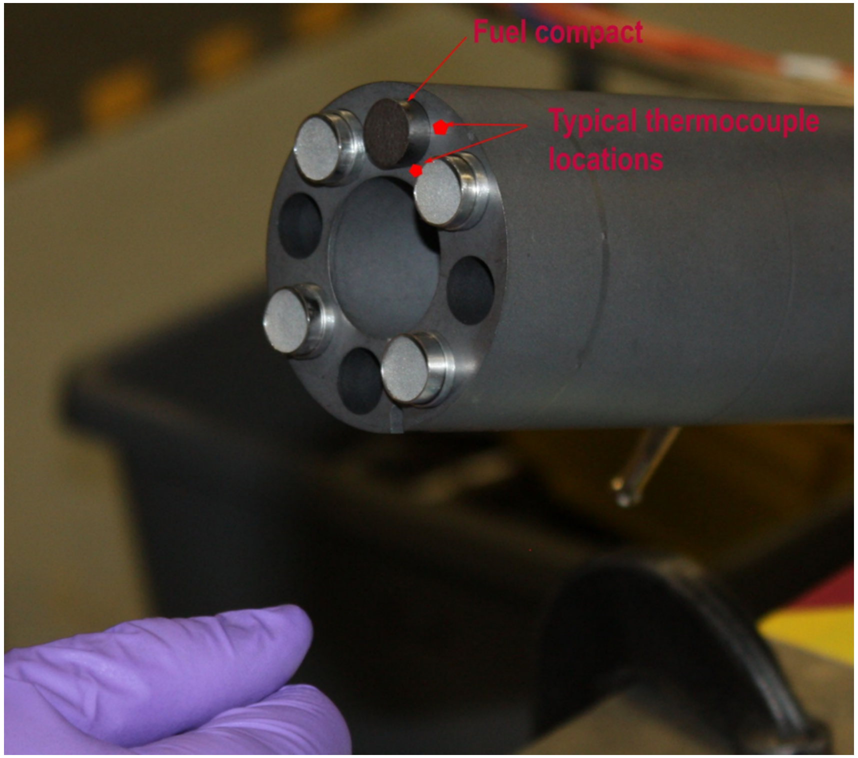
- A four-year instrumentation development and testing effort (2015–2018) was conducted in association with the AGR-5/6/7 experiment program. This was a two-pronged approach involving two very different thermocouple systems, capable of low-drift operation at temperatures above 1100°C for approximately 10,000 hrs.

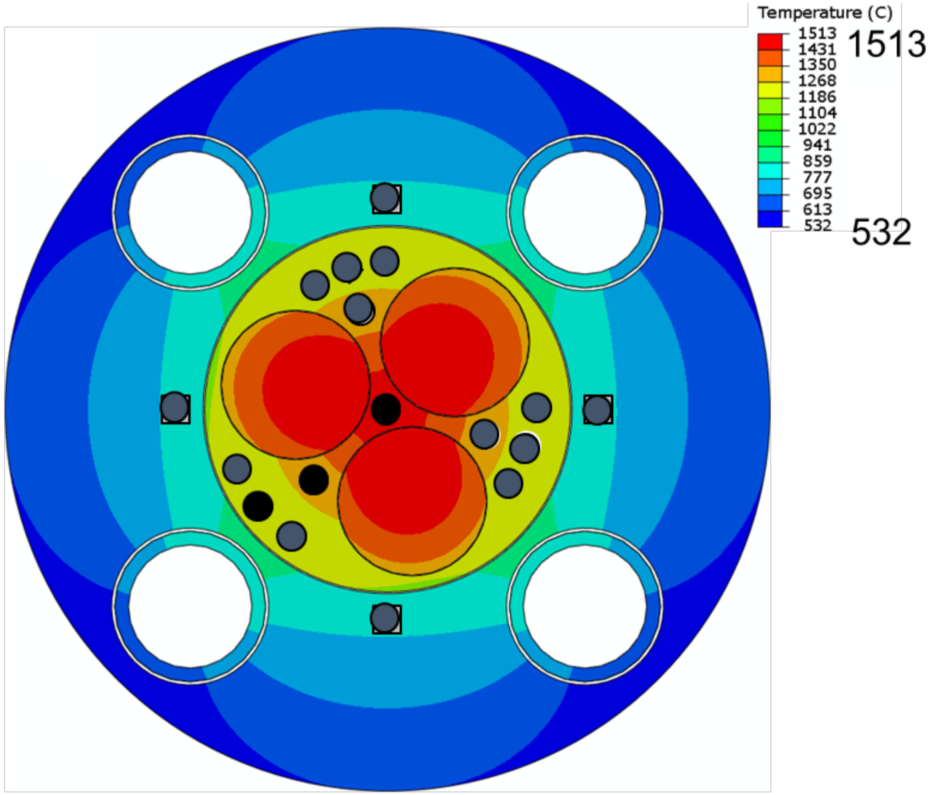
- Preliminary testing of a unique Type N thermocouple system developed at Cambridge University was very encouraging.

- In tests performed at 1200°C the Cambridge thermocouples exhibited a drift rate of about 5°C per 1000 hrs. (At this temperature a standard Type N thermocouple will drift at about 40°C per 1000 hrs.)

AGR-5/6/7 Center Capsule Predicted Temperature Distribution

Temperatures are driven solely by nuclear heating – no electric heaters





A. J. Palmer; et al., 2019. “Performance of Custom-Made Very High Temperature Thermocouples in the Advanced Gas Reactor Experiment AGR-5/6/7 during Irradiation in the Advanced Test Reactor”, ANIMMA2019-357654 - ANIMMA International Conference, 17-21 June 2019, Portoroz, Slovenia.

FY20 CNIR: HTGR TRISO Fuel Particle Materials (RC-4)

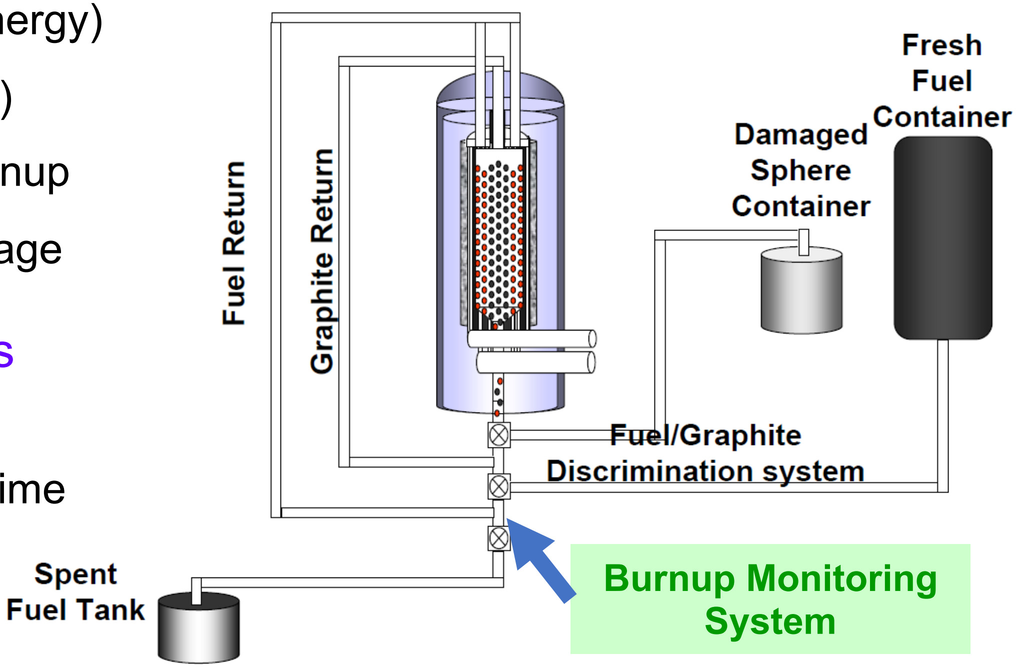
ROBUST INDIVIDUAL TRISO-FUELED PEBBLE IDENTIFICATION METHOD FOR EX-CORE EVALUATION (RC-4.2)

Motivation for this research:

- Pebble bed fuel moves stochastically through core
  - Gas-cooled: downward (e.g., X-energy)
  - Salt-cooled: upwards (e.g., Kairos)
  - Ex-core monitoring system for burnup
  - Core reinsertion or spent fuel storage

Tagging, tracking individual pebbles would be useful for:

- Determining individual residence time
- Avoiding excessive burnup
- Reducing uncertainty in pebble "flow line" computational models
- Addressing material control and accountability, and proliferation resistance issues



Eligible to Lead:	**Universities Only**
Maximum funding:	**$800,000**
Duration:	**Up to 3 years**

FY20 CNIR: HTGR TRISO Fuel Particle Materials (RC-4)

Proposals for RC-4.2 should:

- FOCUS on obtaining a robust, reliable tagging method that can handle:
  - Potential abrasion, corrosion, or degradation of pebble surface
  - High temperature, high neutron flux environment
  - Track and catalogue large number of pebbles (hundred of thousands)
  - Ex-core pebble burnup measurement systems (neutron, gamma)
  - Relatively rapid "reading" time ≤ burnup measurement system time to meet pebble throughput requirements.
  - Track each individual pebble's being reinserted into the core or sent to spent fuel storage
- MAY develop new computational algorithms or models that use this pebble tagging and tracking method and its data for reducing the uncertainty of pebble flow simulation models.
- NOT develop new burnup measurement/monitoring systems.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