A Brief History and Overview of High Temperature Reactor Technology Development and Deployment

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INL Advanced Reactor Technologies Development Office

July 14, 2016

Historical Info distilled (not locally sourced) from

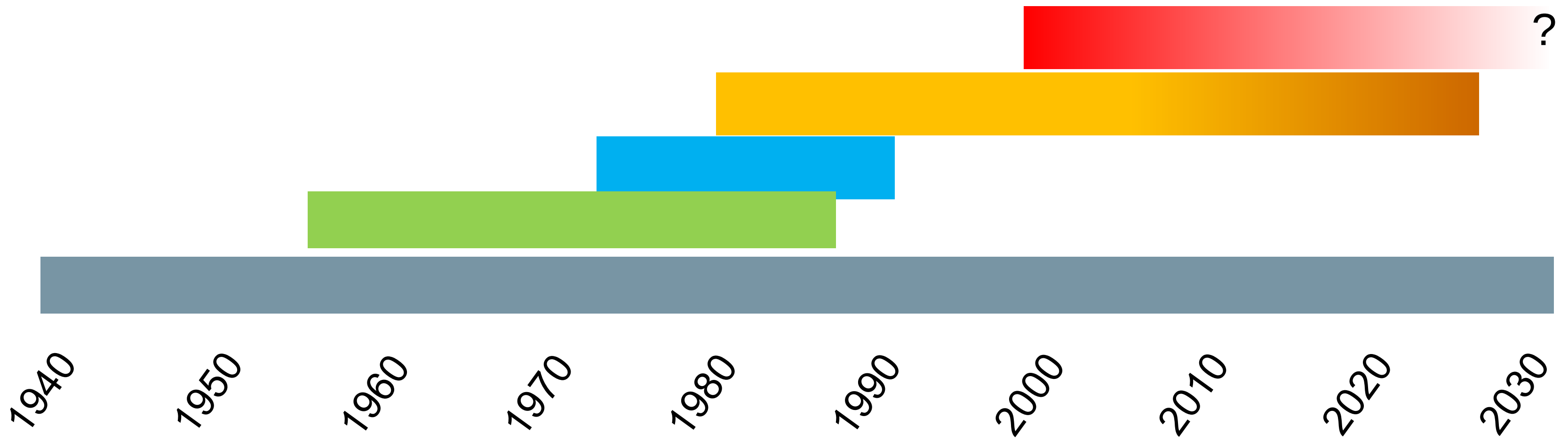
- W. von Lensa, 'Presentation of the former HTR Concepts and Large Experimental Facilities,' HTR/ECS High temperature Reactor School, Cadarache, FR, Nov. 2002
- P. Williams, 'Selected History and Background', ANS gas Reactor Technology Course, Washington DC, Sept. 2002
- A. Goodjohn, "Summary of Gas-Cooled Reactor Programs", Energy Vol. 16. No. 1,2, 1991

www.inl.gov

Idaho National Laboratory

Phases

- Prologue – CP-1 and the GCR
- Phase 1 – Proof of Concept
- Phase 2 – Commercial Demonstration
- Phase 3 – Small and Modular
- Phase 4 – Energy Security and Flexibility

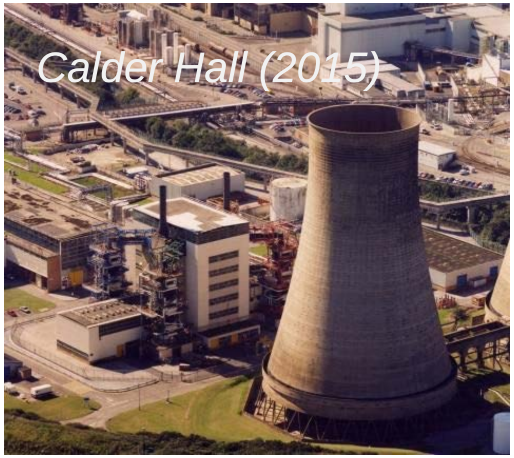


Prologue – Graphite-moderated, Gas-cooled Reactors

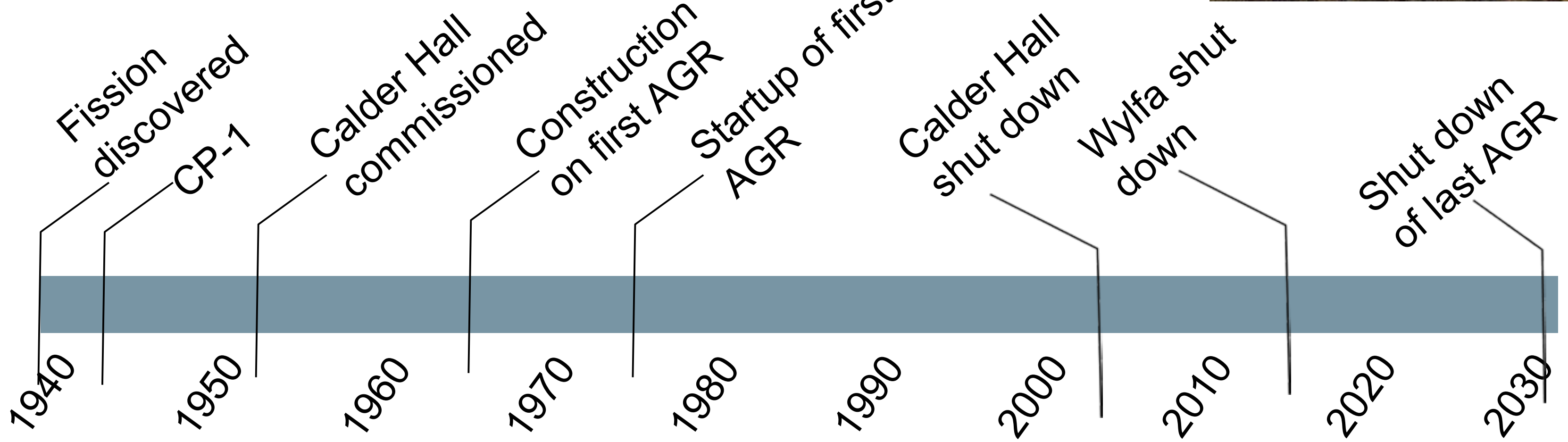
(US/UK/France)


Torness


Chicago Pile 1 (1942)


Calder Hall (2015)

- CP-1 (air-cooled)
- Production/Power Reactors
- CO_2 cooled
  - MAGNOX (UK), UNGG(Fr)
  - AGR (UO_2 pellets in SSTL, <650°C CO_2, concrete RPV, reasonable performance after a rocky start)


Fission discovered

CP-1

Calder Hall commissioned

Construction on first AGR

Startup of first AGR

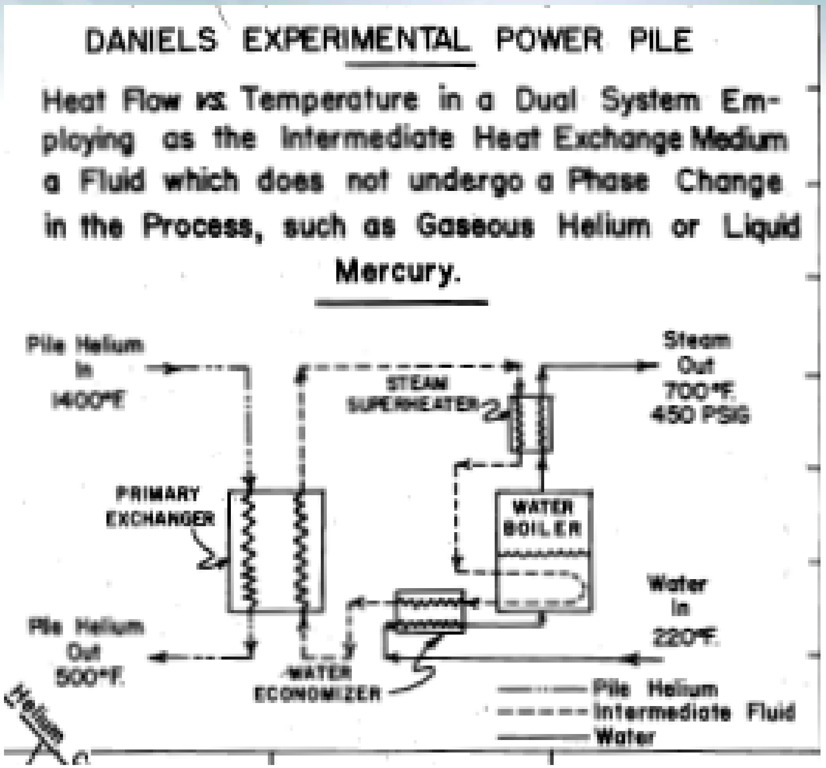
Calder Hall shut down

Wylfa shut down

Shut down of last AGR

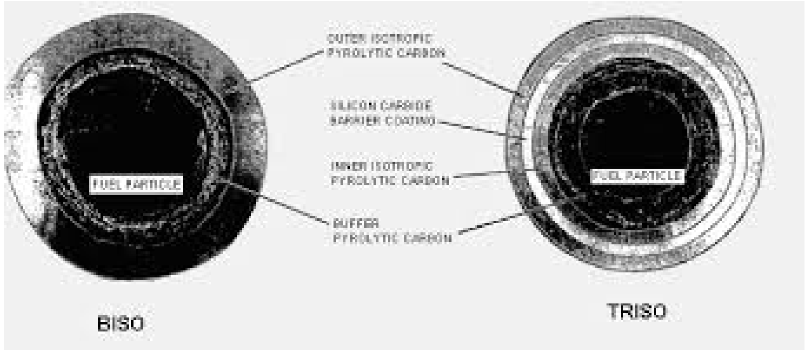
HTR Conceived

- Daniels Power Pile (1945)
  - F. Daniels (ORNL)
  - Graphite or BeO moderated
  - He cooled, 1350F/732C outlet
  - IHX and closed cycle Brayton
  - UC_2 or UO_2 in cladding
- Actual experimental reactors followed
  - GCRE, ML-1, EGCR
- Final puzzle piece, the coated fuel particle
  - UKAEA, Battelle idea (~1957)
  - Superior retention of fission products at elevated temperatures (esp. in the TRISO version)



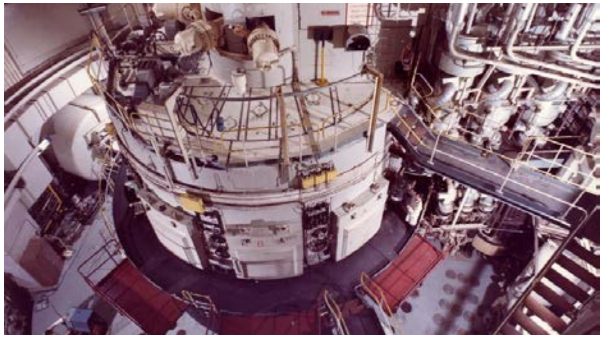
DANIELS EXPERIMENTAL POWER PILE

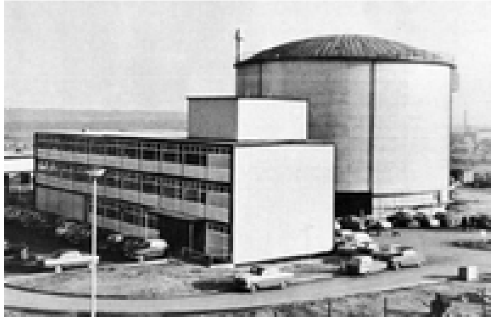
Heat Flow vs Temperature in a Dual System Employing as the Intermediate Heat Exchange Medium a Fluid which does not undergo a Phase Change in the Process, such as Gaseous Helium or Liquid Mercury.

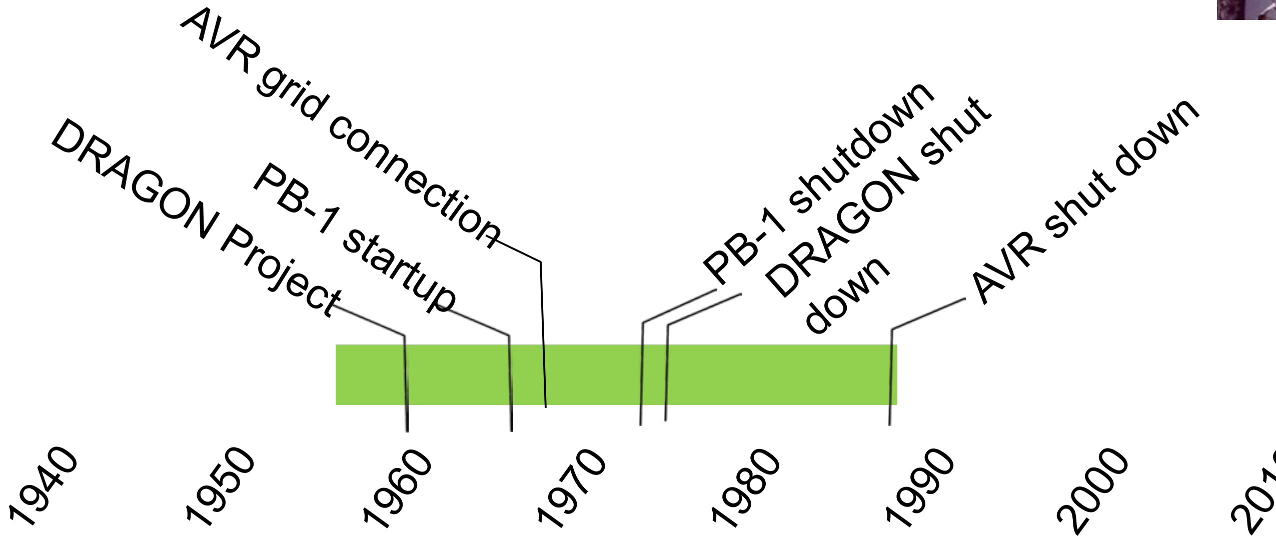


Phase 1 – Proof of Concept – DRAGON

- Built in the UK under a OECD/Euratom sponsorship
- HTR (TRISO) fuel and material testing
- Engineering challenges encountered and resolved
  - Control rod bowing
  - Replacement of inner reflector blocks
  - IHX and pipe corrosion

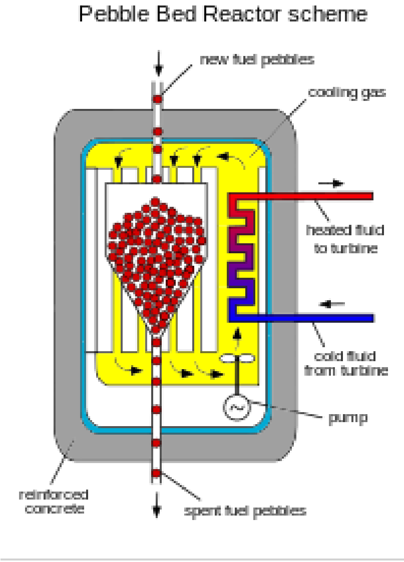


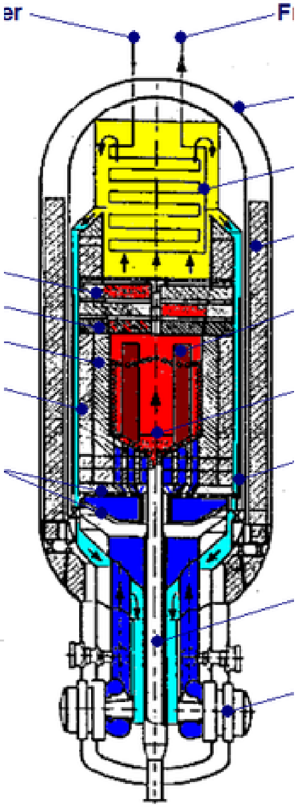




AVR (Germany)

- Pebble Bed reactor conceived by R. Schulten
- Arbeitsgemeinschaft VersuchsReaktor - 46 MWt/15 MWe prototype PBR for testing systems and fuels (BISO/TRISO)
- He-cooled up to 950°C at the outlet
- One (1!) operator needed for reactor/primary circuit operation
- Shutdown achieved by stopping forced circulation (rods inserted after cooldown)
- Growing pains
  - Leaky shield led to SG contamination
  - 1978 SG leak dumped 27 m^3 of water into the core (dried out and restarted)
  - Unpredicted high core temperatures



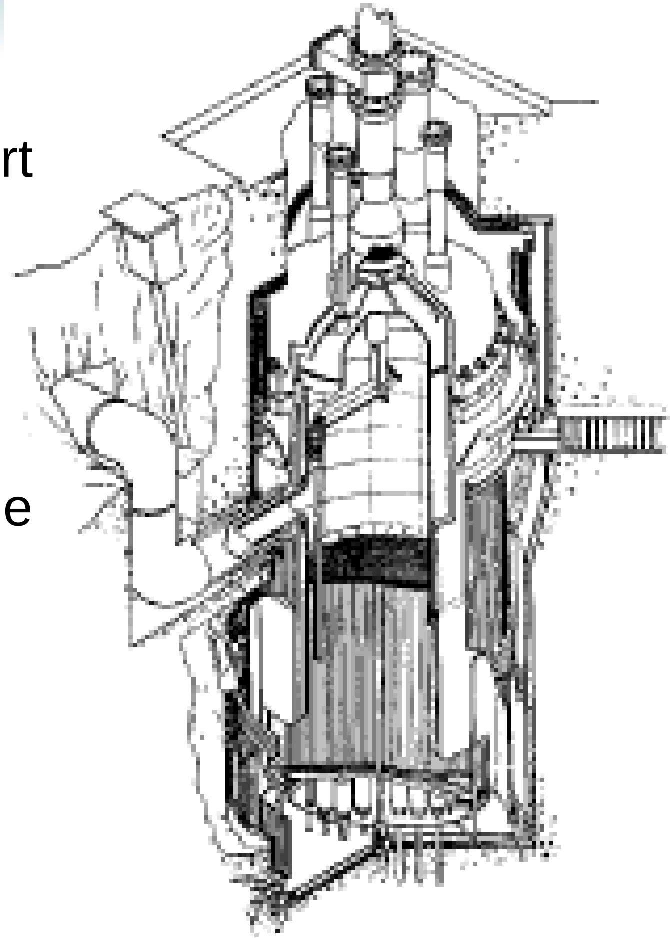


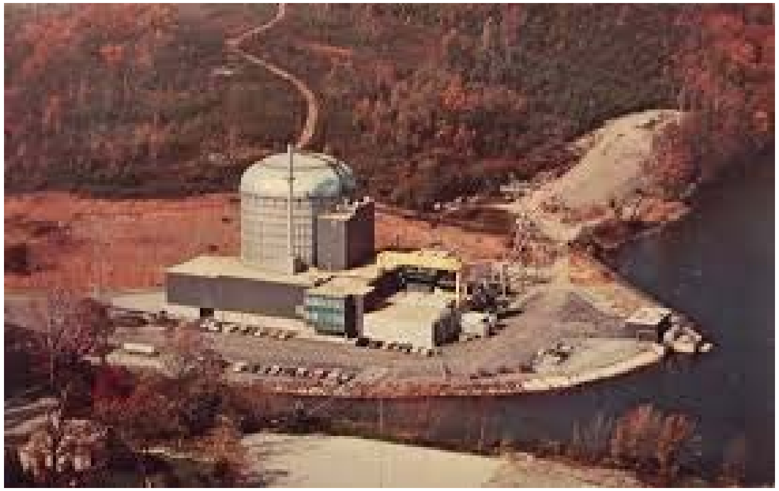
Despite some recent bad publicity, AVR is considered an HTR success story

By Cschirp at the German language Wikipedia, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=11451341

Peach Bottom 1

- 115 MWt/40 MWe designed by GA with support from the AEC and 57 utilities
- Prismatic – BISO cfp in compacts/blocks
- 85% availability, load following, low operator doses
- Growing pains – Some cracking of blocks in the first core





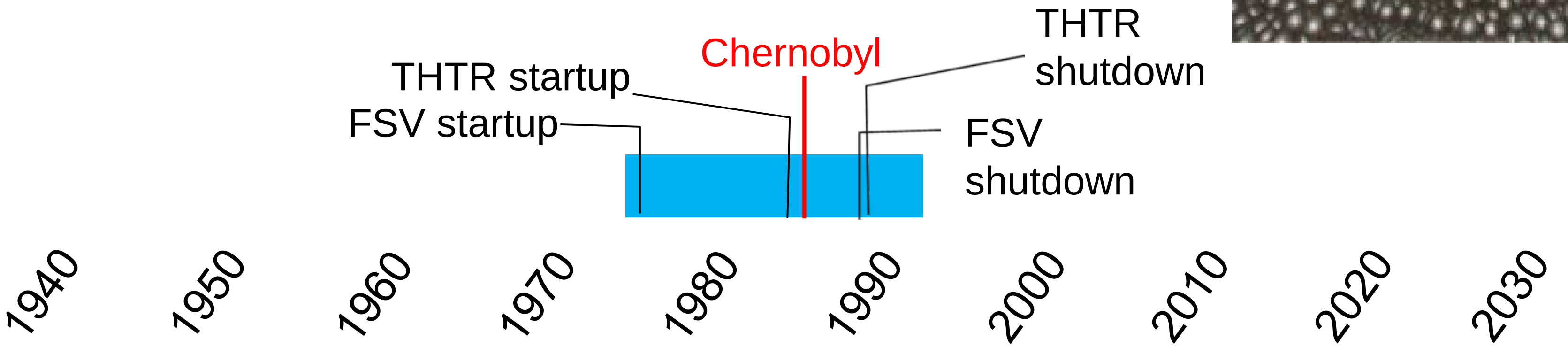
Phase 2 – Commercial Demo – Fort St. Vrain

- 842 MWt/330MWe General Atomics design built with support form 57 utilities
- HEU/TH cfp in compacts/blocks
- Prestressed concrete PV
- Squeaky clean – low worker doses
- Growing pains resulted in low availability
  - Core flexing→ coolant oscillations (restraints recommended)
  - Leaky water-lubed gas circulators led to large ingress event
  - Uncooperative control rods

Despite these engineering issues, modern HTGR technology was demonstrated.

THTR

- 750 MWt/300MWe German design
- HEU/TH cfp in pebbles
- Prestressed concrete PV
- Dry cooling
- Growing pains
  - Broken pebbles (shutdown rod insertion)
  - He upflow hindered pebble discharge
  - Bolt heads detached from hot duct assembly



THTR startup

FSV startup

Chernobyl

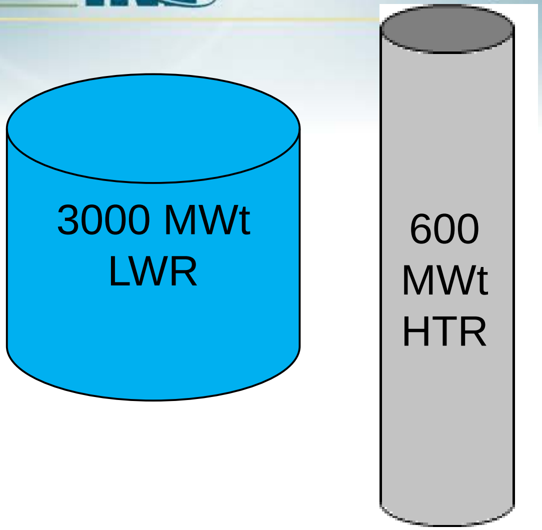
THTR shutdown

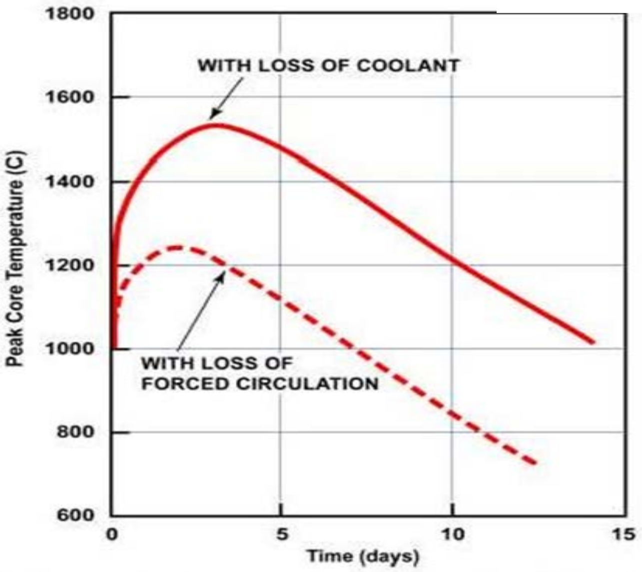
FSV shutdown

1940 1950 1960 1970 1980 1990 2000 2010 2020 2030

Phase 3 – Small and Modular

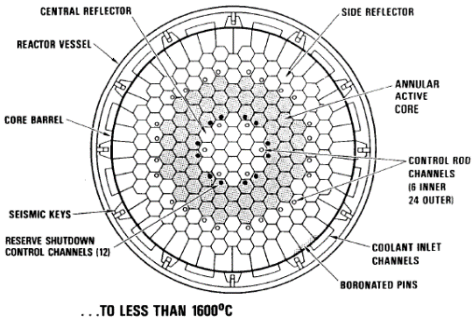
- Larger HTRs were envisioned after FSV and THTR
  - Low power density meant that the vessel would be huge
  - Active decay heat removal required
- Modularity was introduced
  - Mass-produced components assembled on site, simpler transport and construction, OR,
  - Multiple modules with staggered deployment
- Tall, skinny cores and low power density allowed for completely passive decay heat removal

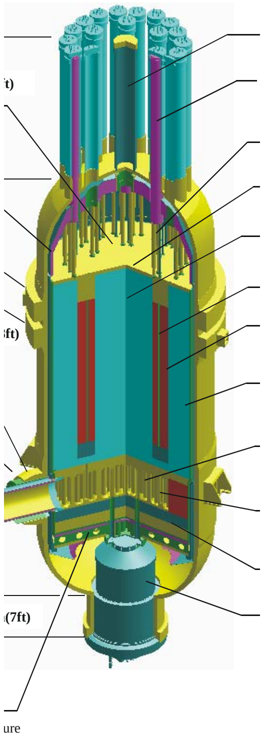


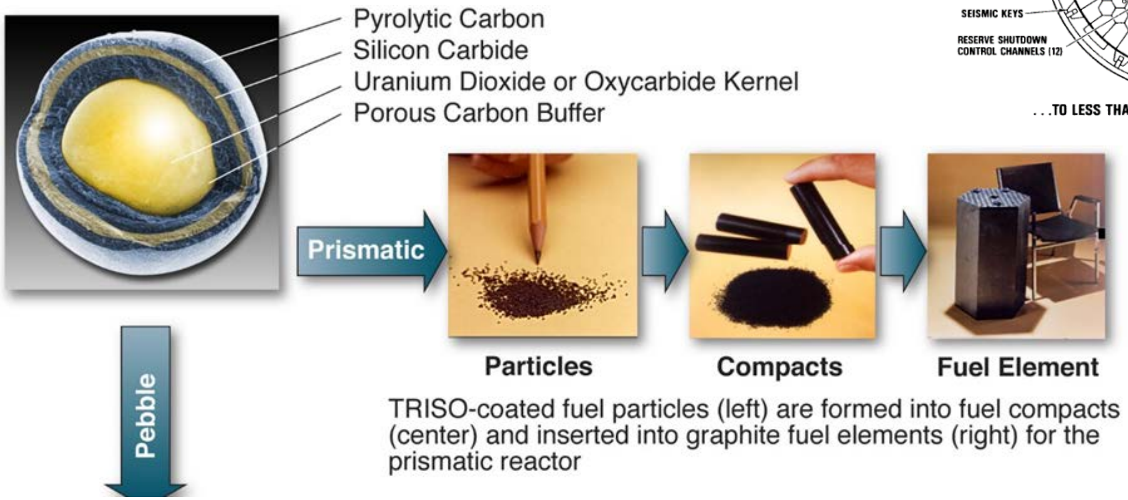


MHTGR

- GA design, coalition of industrial interests
- 350 MWt prismatic (annular core) in a steel RPV
- Pre-app SER issued by NRC – 1989
- The basis for subsequent modular prismatic reactor designs such as the New Production Reactor, GT-MHR, Deep Burn MHR, AREVA SC-HTGR



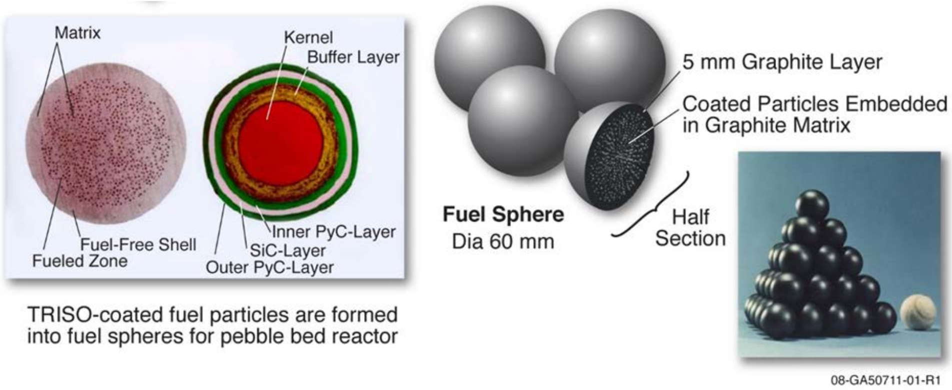




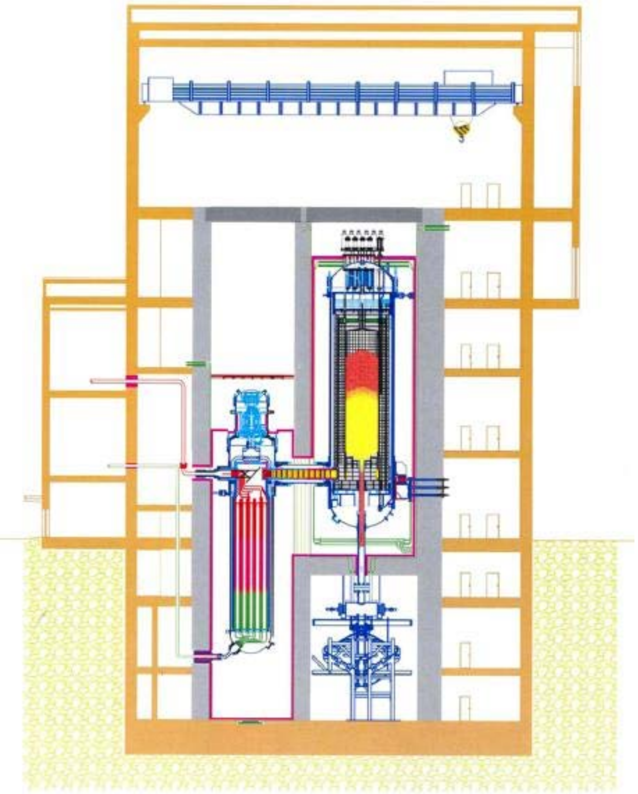
TRISO-coated fuel particles (left) are formed into fuel compacts (center) and inserted into graphite fuel elements (right) for the prismatic reactor

HTR Modul

- KWU/Siemens-Interatom
- 200 MWt pebble bed with online recirculating fuel (high burnup)
- Design submitted to German Licensing Authority in the late 1980’s
- The basis for subsequent modular PBR designs like the PBMR and HTR-PM



TRISO-coated fuel particles are formed into fuel spheres for pebble bed reactor

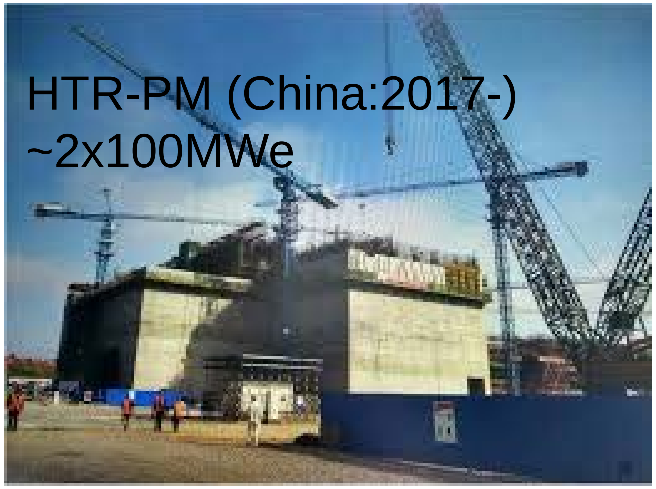


Other Efforts

- South Africa
  - In ~1998 the PBMR company tried to pick up where HTR Modul left off. Ran out of Government support in 2010
  - Some very nice test facilities constructed
- Japan
  - Steady prismatic HTR technology development since the 1980's
  - Nice 30 MWt engineering-scale reactor (to be connected to a gas turbine and H2 plant
  - 50, 300, and 600 MWt commercial designs
  - Working on gas turbine and H2 technology
- China
  - 10 MWt engineering scale reactor
  - 2 unit HTR-PM DPP to go critical in 2017
  - Impressive engineering test facilities

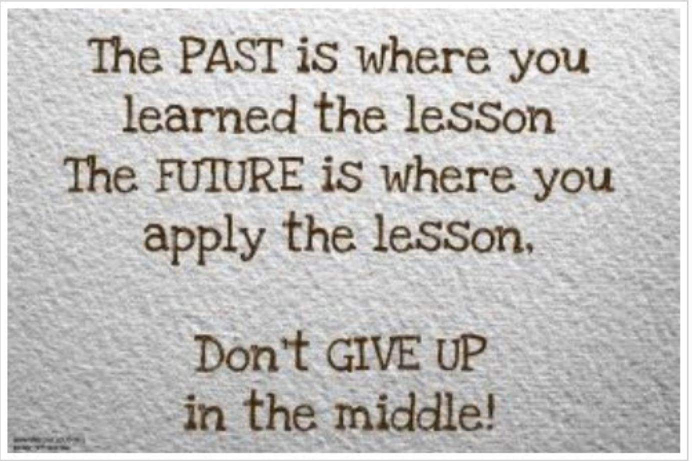

HTR-10 (China: 2000-)


HTTR (Japan: 1999-)


HTR-PM (China:2017-)
~2x100MWe

Lessons to be Learned?

- HTR Potential was recognized very early
  - accident tolerant fuel (TRISO)
  - process heat applications
  - Modularity
- Problems (engineering) were typical of FOAK efforts – not generally inherent to the technology
- Sensitive to the market, politics
- Various combinations of government/industry support attempted
  - Optimism and innovation
  - Government-sponsored research
  - Utility consortia
  - Technology pull vs. push

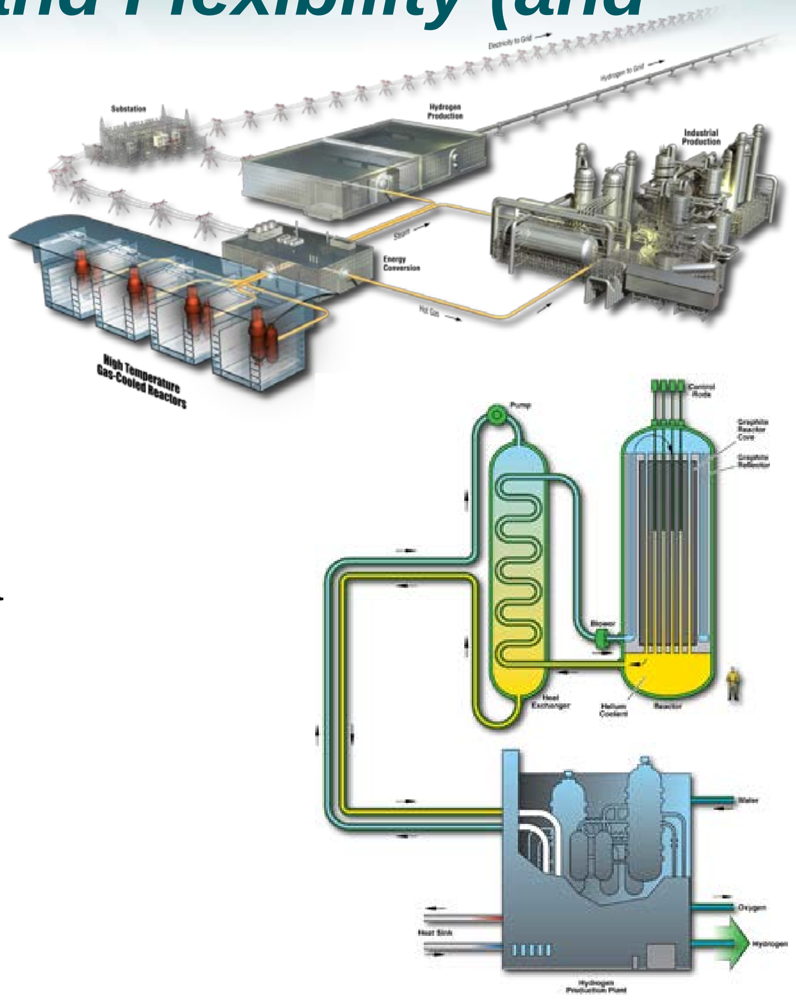


The PAST is where you
learned the lesson
The FUTURE is where you
apply the lesson.

Don't GIVE UP
in the middle!

What can we learn from these past efforts?

Phase 4 – Energy Security and Flexibility (and CO2-free)



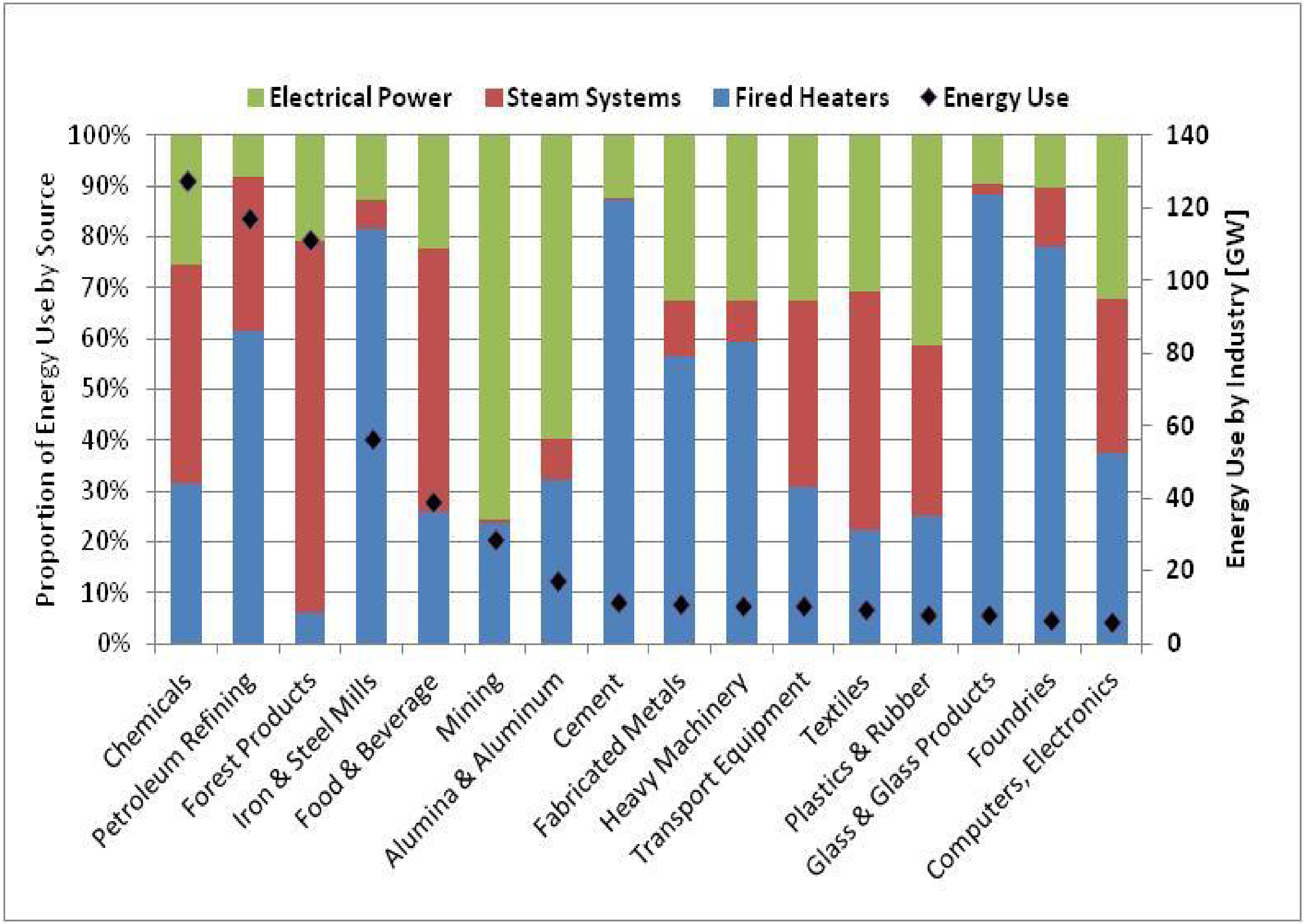
- Government-sponsored R&D
  - US (NGNP/ART) – EPACT 2005, fuel and material qualification, etc.
  - Japan (JAEA) – technology development since the 1980’s, HTTR, gas turbine and H2 technology
  - China (INET) – keeps it simple (200 MWt PBR), 2-unit demo under construction and a ‘6-pack’ looking for a site
  - Generation IV International Forum VHTR
- Industrial Interest
  - NGNP Alliance
  - AREVA, X-Energy, StarCore,
  - Hybrid Power Technologies, U-Battery, UltraSafe Nuclear

HTR-PM under construction in Weihai, China

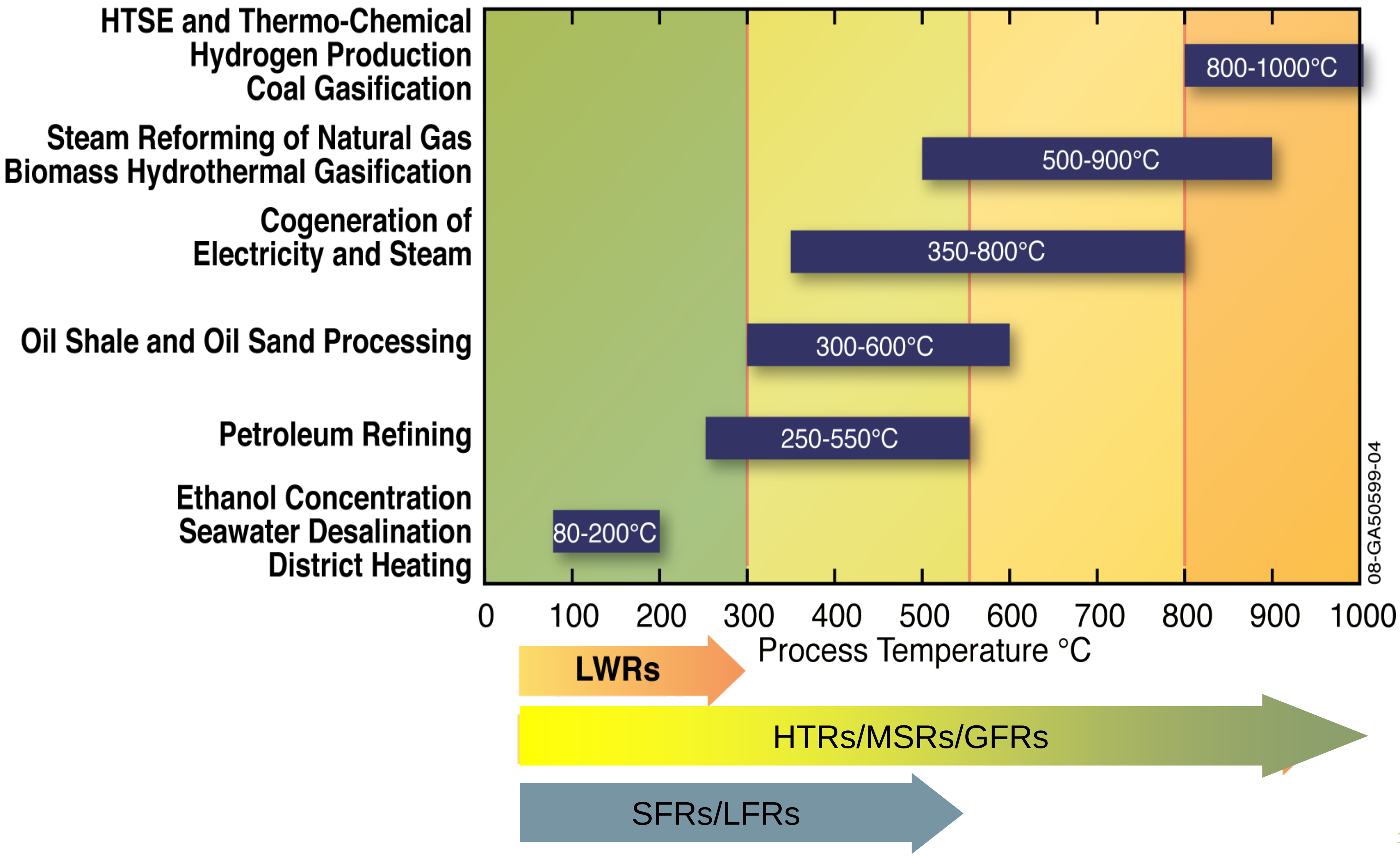
HTR-PM (China:2017-) ~2x100MWe

Civil construction is complete

Is there a Process Heat Market?



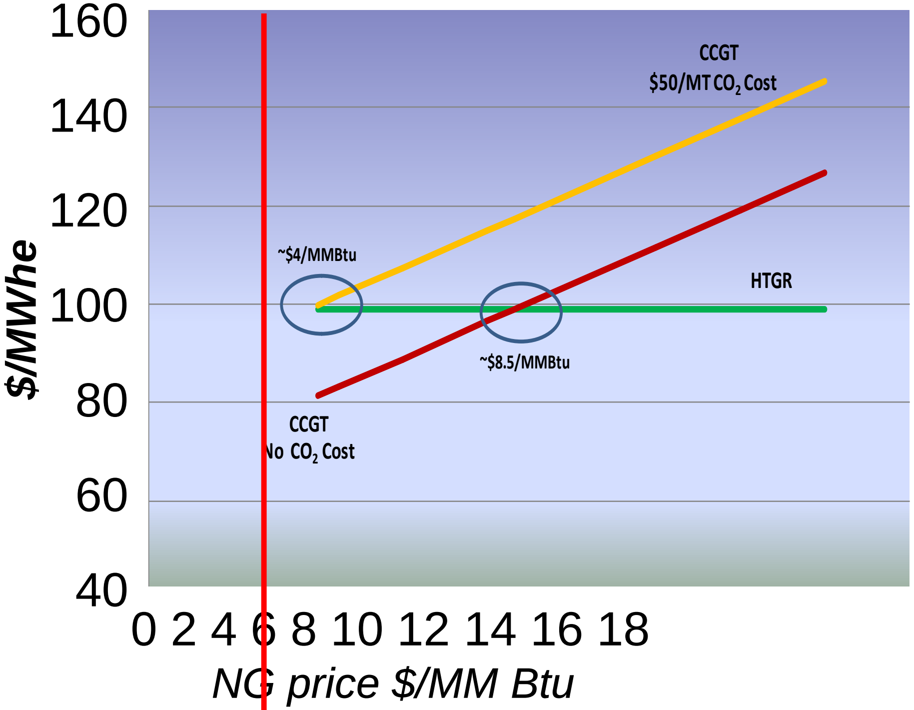
Technically, yes



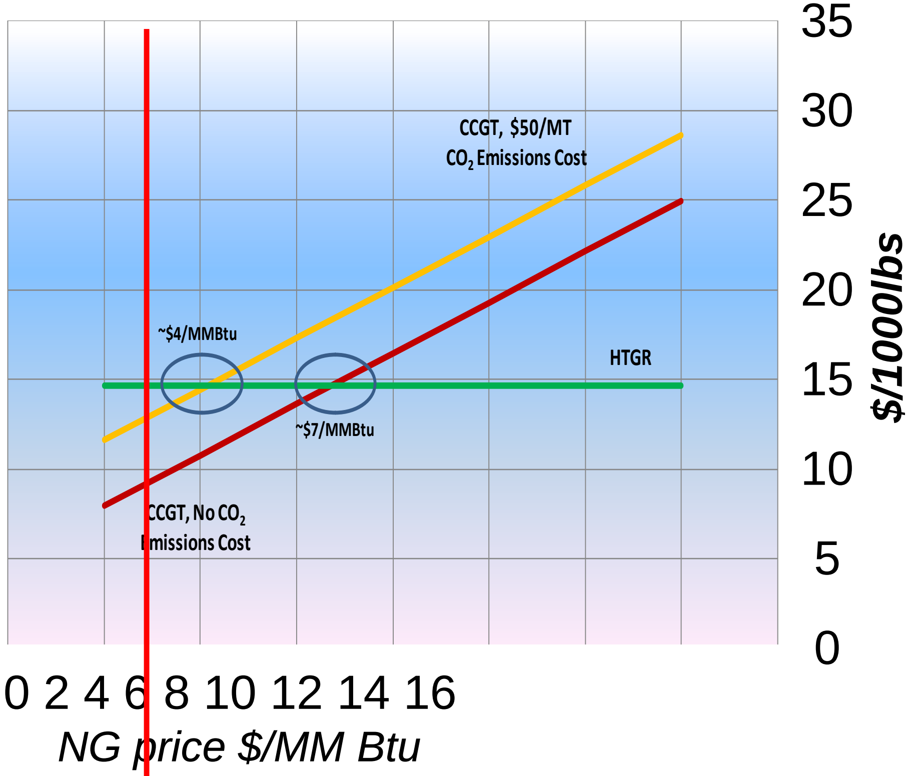
But it’s a tough sell (currently)

**High Temperature Gas-Cooled Reactor Projected Markets and Preliminary Economics, INL/EXT-10-19037 rev. 1, Aug. 2011.*

HTR and CCGT NG Electricity Production Price vs. Price of Natural Gas with and w/o carbon tax



HTR and CCNG Steam Production Price vs. Price of Natural Gas with and w/o carbon tax



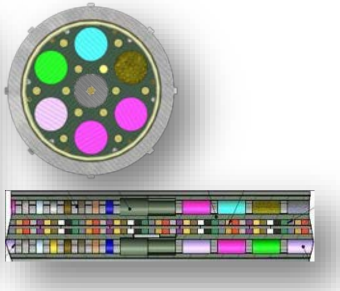
Reality Check: Henry Hub Spot Price of NG =$2.79 on June 27, 2016

DOE's Role in HTR Technology Development


High Temperature Materials Characterization, Testing and Codification

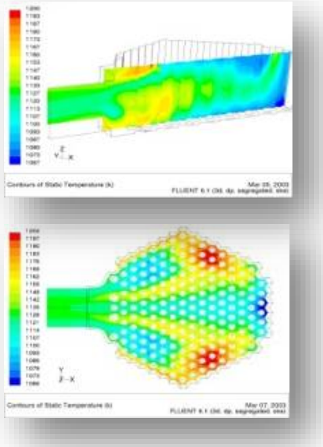

Fuel Fabrication, Irradiation, and Safety Testing

Graphite Characterization, Irradiation Testing, Modeling and Codification



Design and Safety Methods Development and Validation

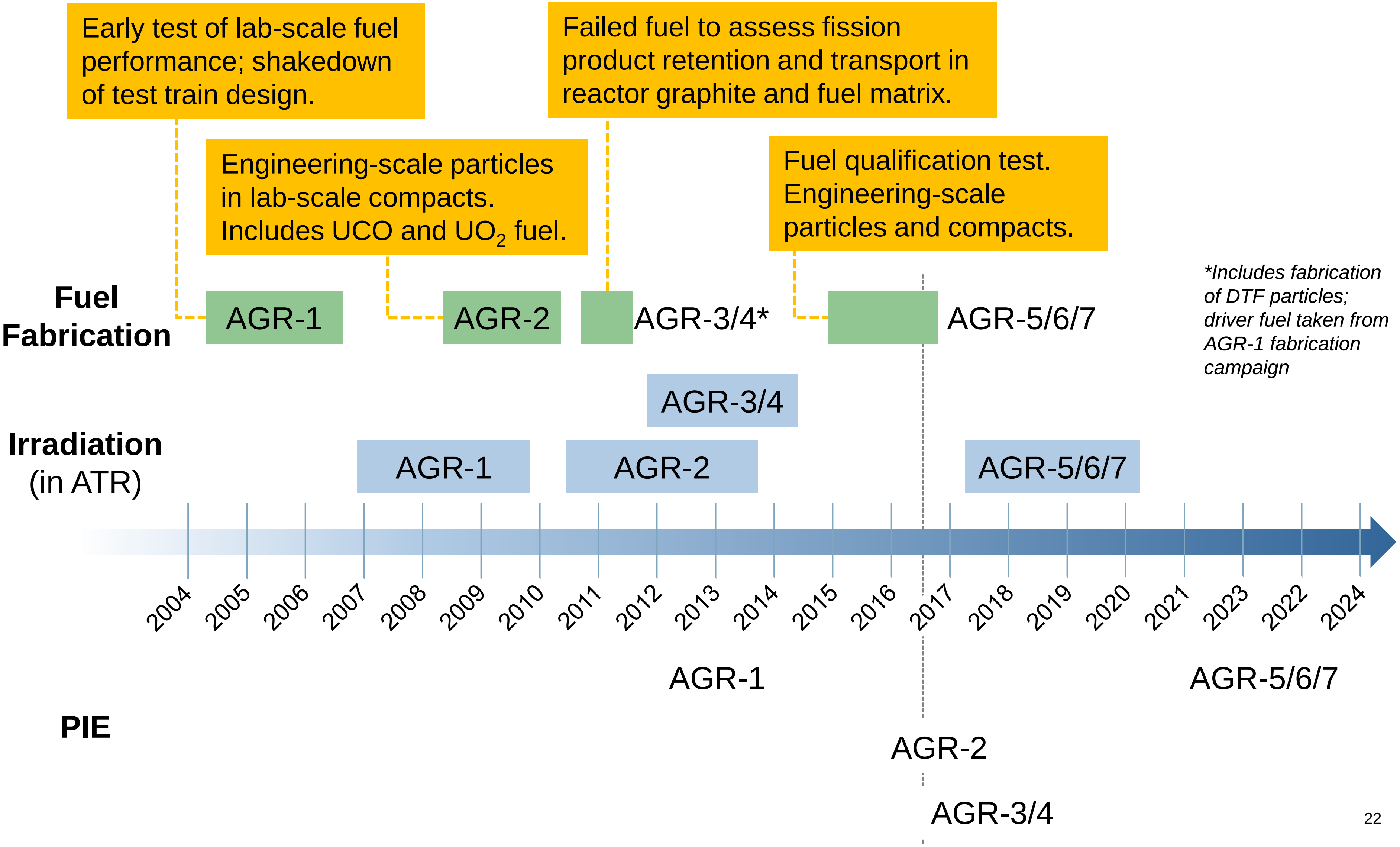


Objectives of the AGR Fuel Qualification Program

- Provide a fuel qualification data set in support of the licensing and operation of an HTGR
  - HTGR fuel performance demonstration and qualification comprise the longest duration research and development (R&D) task required for design and licensing
  - The fuel form is to be demonstrated and qualified for service conditions enveloping normal operation and potential accident scenarios
- Support deployment of the HTGR for hydrogen, process heat, and energy production in the United States by reducing market entry risks posed by technical uncertainties associated with fuel production and qualification *(i.e. design the fuel to be so robust that there is no significant source term release into the process heat plant)*
- Leverage DOE resources with partnerships with universities and other countries

AGR Program Timeline



Early test of lab-scale fuel performance; shakedown of test train design.

Failed fuel to assess fission product retention and transport in reactor graphite and fuel matrix.

Engineering-scale particles in lab-scale compacts. Includes UCO and UO_2 fuel.

Fuel qualification test. Engineering-scale particles and compacts.

Fuel Fabrication

AGR-1

AGR-2

AGR-3/4*

AGR-5/6/7

**Includes fabrication of DTF particles; driver fuel taken from AGR-1 fabrication campaign*

Irradiation (in ATR)

AGR-3/4

AGR-1

AGR-2

AGR-5/6/7

PIE

AGR-1

AGR-5/6/7

AGR-2

AGR-3/4

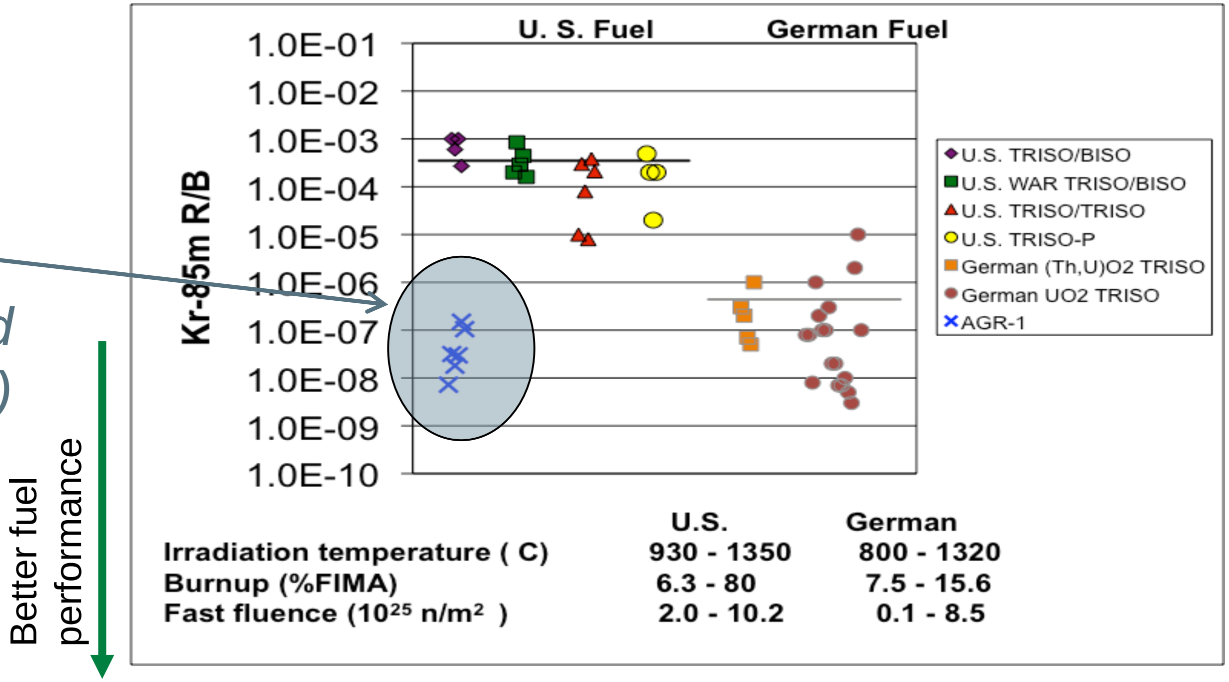
Recent AGR Accomplishments and Activities

- AGR 5/6/7 Fuel is being fabricated (by our industrial partner BWXT). It will be completed by February 2017
- AGR-2 and AGR-3/4 post irradiation examination (PIE) continues and will be completed in 2020
- Major PIE equipment development efforts:
  - A new furnace to investigate air/moisture ingress is being designed and built (completed by 2020)
  - AGR-5/6/7 disassembly and metrology equipment
  - Capsule fission product analysis equipment (capsule size precludes approaches used on AGR-1 and 2)
- AGR-5/6/7 PIE to commence in mid-2020 timeframe and is expected to occur over ~3 years. The work is performed at both INL and Oak Ridge National Laboratory (ORNL)

Coated Particle Fuel Development and Qualification (INL and Oak Ridge NL)

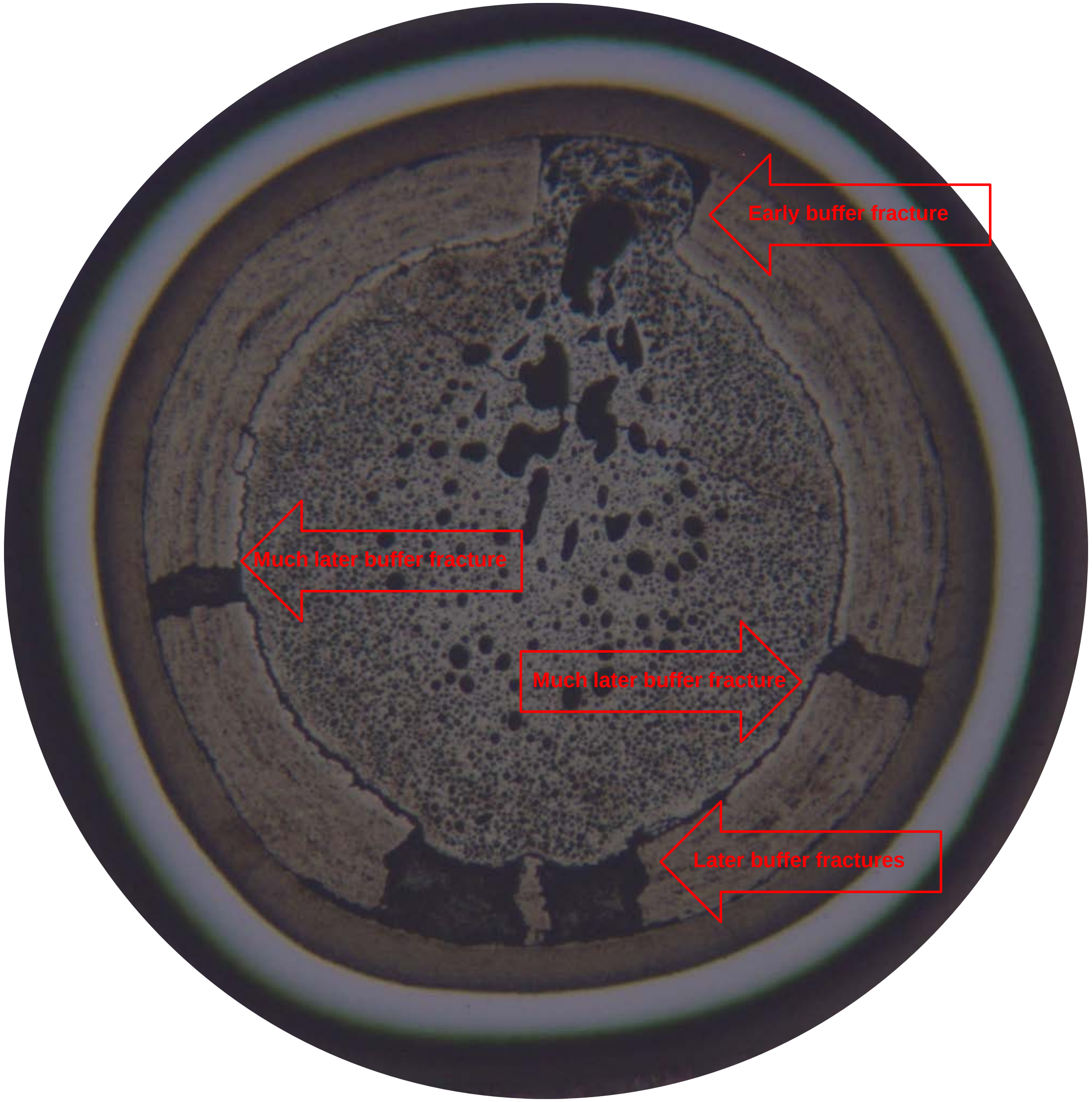
- German industrial experience demonstrated (UO2) TRISO coated particle fuel can be fabricated to achieve high-quality levels with very low defects.
- Early US fuel did not perform as well. Why not?
- Recent research led to improved understanding of CFP performance and fabrication techniques

AGR-1 irradiation of 300000 particles completed in 2009 (up to 19% FIMA and 1250^{o}C – no failures)



	U.S.	German
Irradiation temperature (C)	**930 - 1350**	**800 - 1320**
Burnup (%FIMA)	**6.3 - 80**	**7.5 - 15.6**
Fast fluence (10^{25} n/m^2)	**2.0 - 10.2**	**0.1 - 8.5**

Typical UCO Fuel Kernel Morphology with Buffer Fractures (‘f’ subtype) – AGR-2



Particle ID: 513654

Compact: 5-1-3

Particle Type: Af

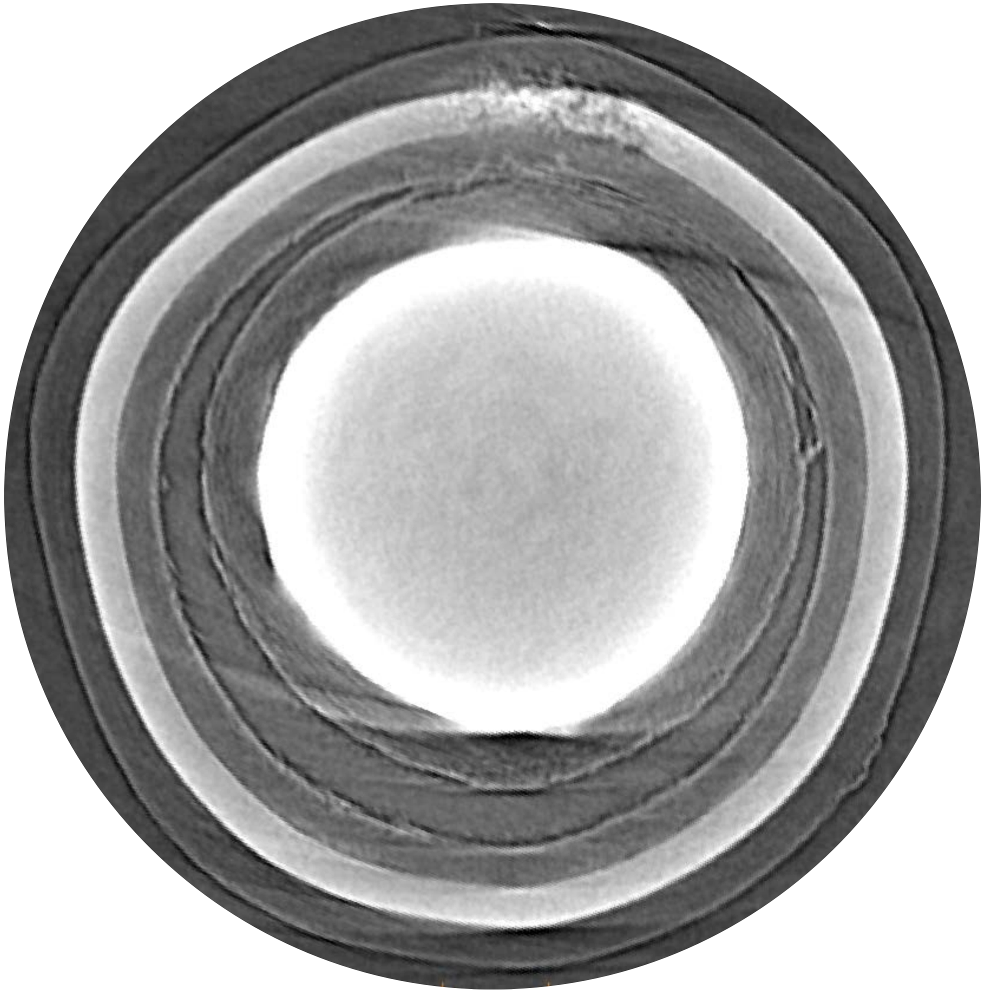
Fuel Type: UCO

TAVA: 1078° C

Average Fast Fluence: 3.03x 10^{21} n/cm^2

- General Observations:
- Larger pores noted in fuel kernels with buffer fractures.
- Hypothesis is that more fuel expansion into fracture region equates to occurrence of fracture earlier in irradiation cycle.

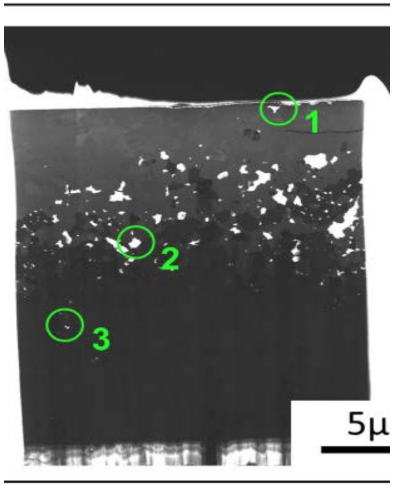
AGR-2 – Insights into Particle Failure

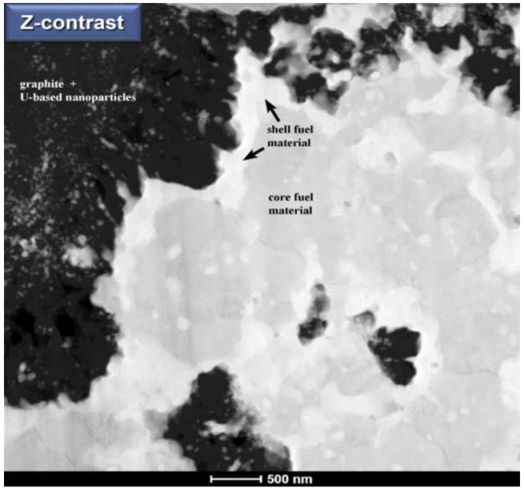


Partial buffer detachment from the iPyC stresses the iPyC, leading to cracking

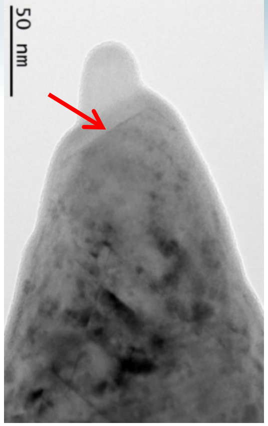
Advanced Microscopy

- Scanning Transmission Electron Microscopy (STEM)
- High Resolution Transmission Electron Microscopy (HRTEM)
- Atom Probe Tomography

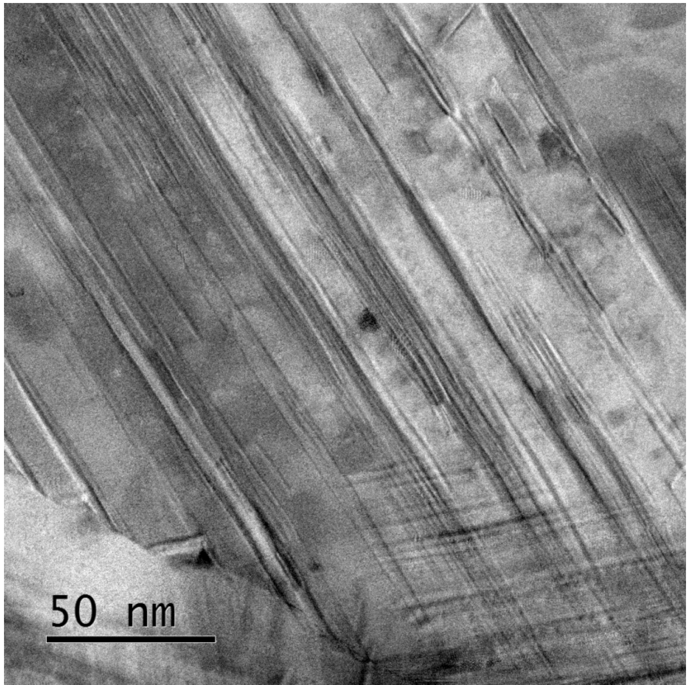




- Two phases are identified
  - Outer or shell material is U-rich, contains some Zr, Mo, and Ru, and is nearly metallic in nature
  - The core material is a U-(O,C) of approximate composition 1:2.
- Nano particles
  - No Pd or Ag
  - U based containing Zr, Mo, and Ru



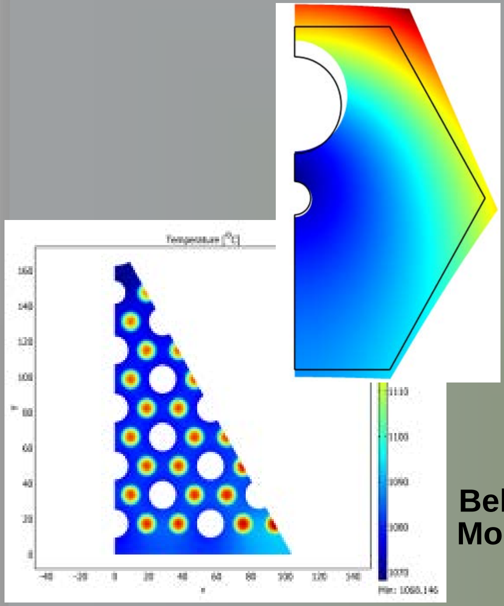
Pd movement and presence inside SiC grains



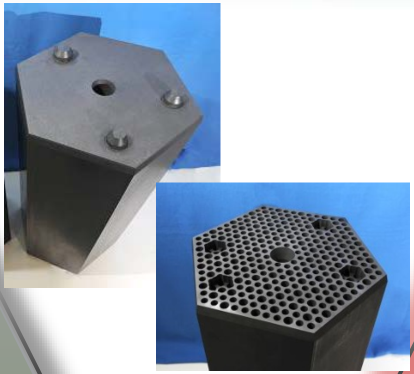
Fuel Future Activities (next 4 years)

- Complete PIE and safety testing of AGR-2 industrially produced TRISO particles
- Complete PIE and safety testing of AGR-3/4
  - This fuel contains designed to fail particles and provides crucial information about fission product release from failed/defective UCO TRISO fuel which is needed to support VHTR source term analysis
- Complete fabrication of final qualification fuel at B&W for AGR-5/6/7 campaign
- Complete design of AGR-5/6/7 irradiation test train and initiate irradiation of qualification fuel
- Beyond 2018, complete AGR-5/6/7 irradiation, complete PIE and safety testing including moisture and air ingress effects

Graphite Research Map

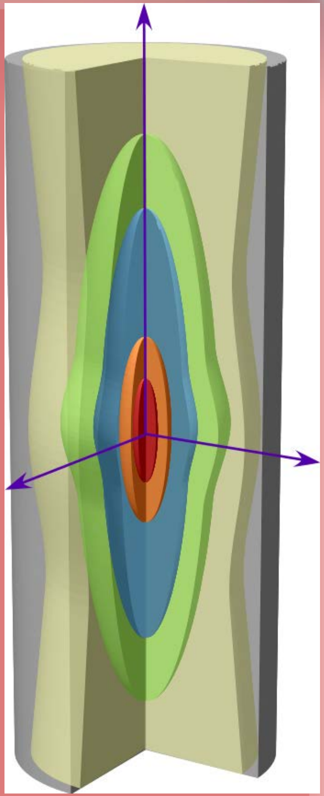


Behavior Modeling



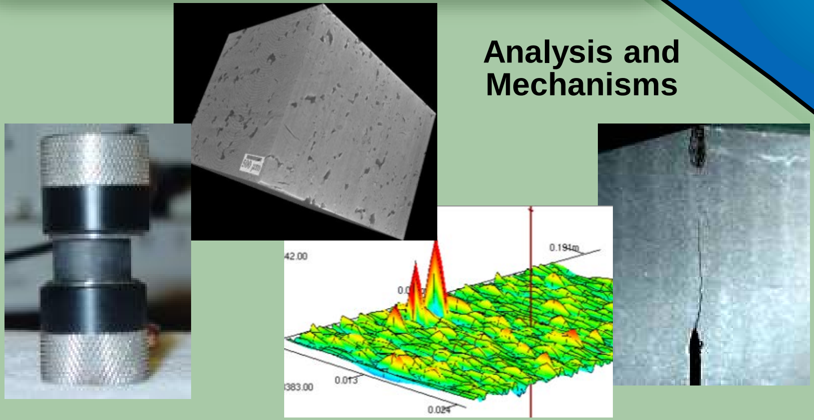
Licensing and Codes

- **Structural Graphite R&D**
- **Material Properties**
- **Irradiation Behavior**
- **Behavior Models**

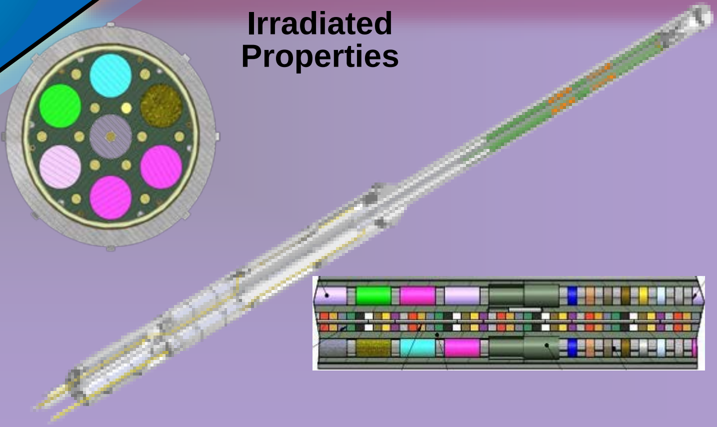


Baseline Properties

Analysis and Mechanisms



Irradiated Properties



Five different research areas *(W. Windes)*

Licensing and Code

- Establishes an ASME approved code (for 1st time)
- Develops property values for initial components and irradiation induced changes

Behavior models

- Predicts irradiated material properties and potential degradation issues
- Irradiation behavior for continued safe operation

Graphite R&D Program

Defines the safe working envelope for nuclear graphite and protection of fuel

Baseline

- (Statistically) Establishes as-received material properties
- Baseline data used to determine irradiation material properties

Mechanisms and Analysis

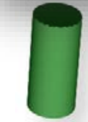
- Data analysis and interpretation
- Understanding the damage mechanisms is key to interpreting data

AGC

- Determines irradiation changes to material properties
- Irradiation behavior for continued safe operation

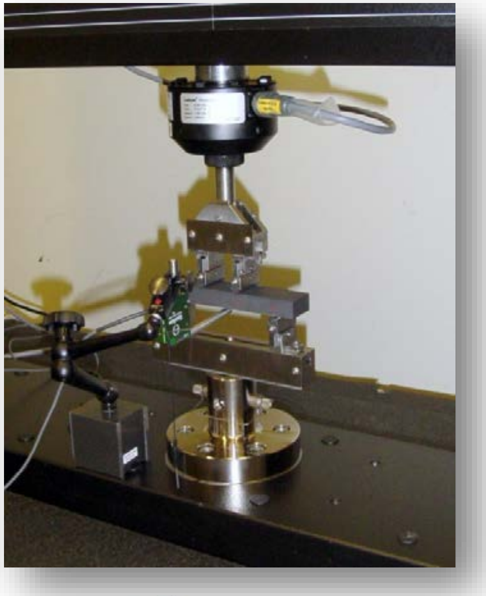
Baseline Characterization

Compression Testing



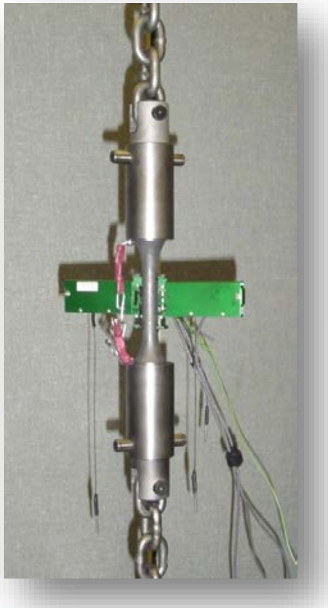
ASTM C695-91

Flexural Testing



ASTM C651-11

Tensile Testing



ASTM C749-08

Emerging Techniques

Brazilian Disc

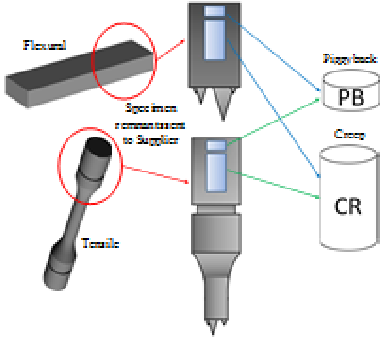
Sub-Sized 3-point Flexure

Physical Properties Testing

- Density
- Coefficient of Thermal Expansion
- Thermal Conductivity
- Resistivity

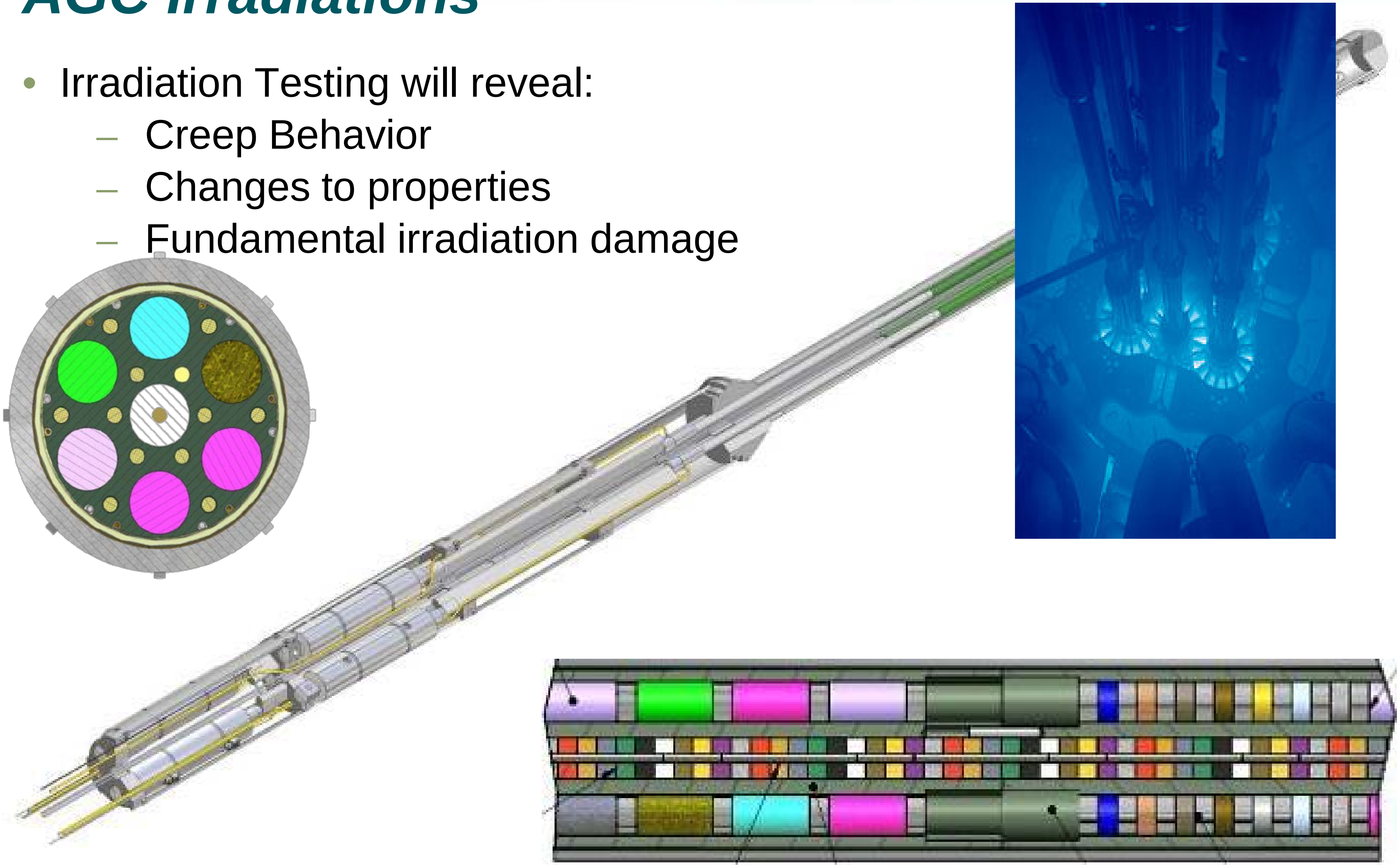
- Resonant Frequency (EDYN)
- Torsional Frequency (GDYN)
- Sonic Velocity
- Fracture Character*

Not a non-destructive evaluation

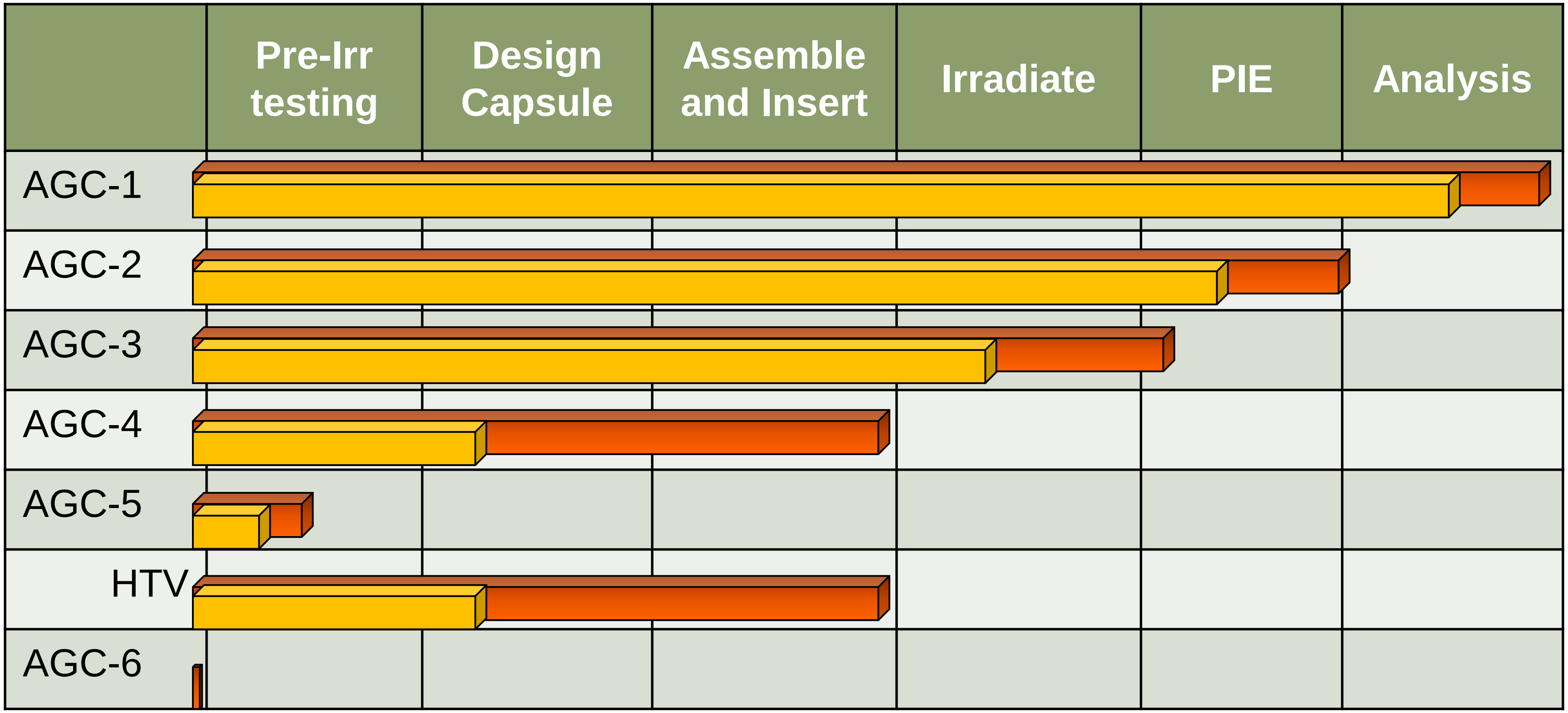


AGC Irradiations

- Irradiation Testing will reveal:
  - Creep Behavior
  - Changes to properties
  - Fundamental irradiation damage

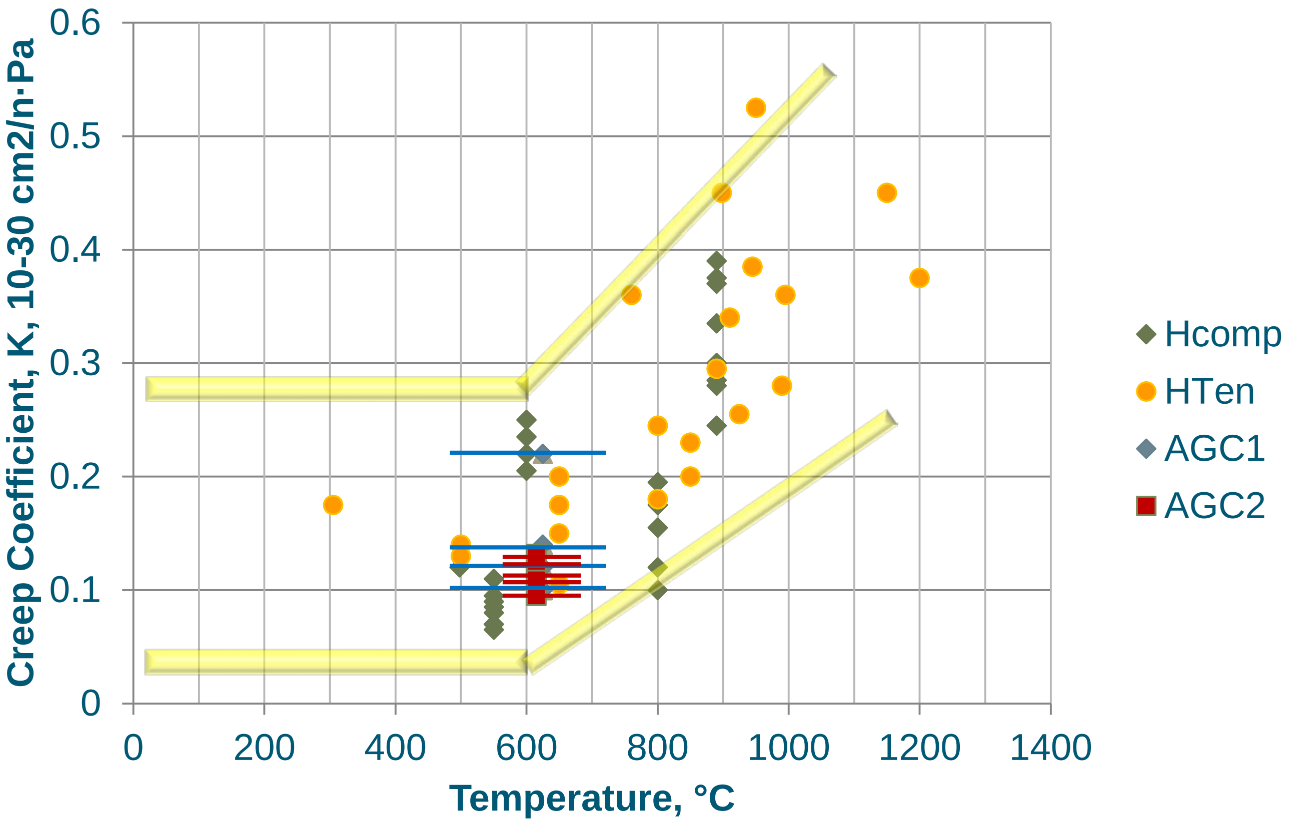


AGC Experiment – Status



- AGC-2 PIE initiated in March 2014
- AGC-3 irradiation endied in April. PIE began in Dec 2014
- AGC-4 irradiation began Feb 2015
- HTV irradiations began mid-June. Analysis completed in Jan. 2016
- Decision to proceed with AGC-6 in 2016 – may achieve turnaround

Creep coefficient – Comparing Historical and new data



- Compares reasonably well with historical data
- Appears that creep coefficient might just be temperature independent below 600-650°C

Model Development – Graphite Oxidation

$$Rate(P_{H2O}, P_{H2}, T) = \frac{k_1 (P_{H2O})^m}{1 + k_2 (P_{H2})^n + k_3 (P_{H2O})^m} \quad k_i = A_i exp\left(-{}^{E_i}/_{RT}\right)$$

$$m(T) = m_{max} \frac{exp\left(\frac{\Delta T}{\theta}\right)}{1 + exp\left(\frac{\Delta T}{\theta}\right)}$$

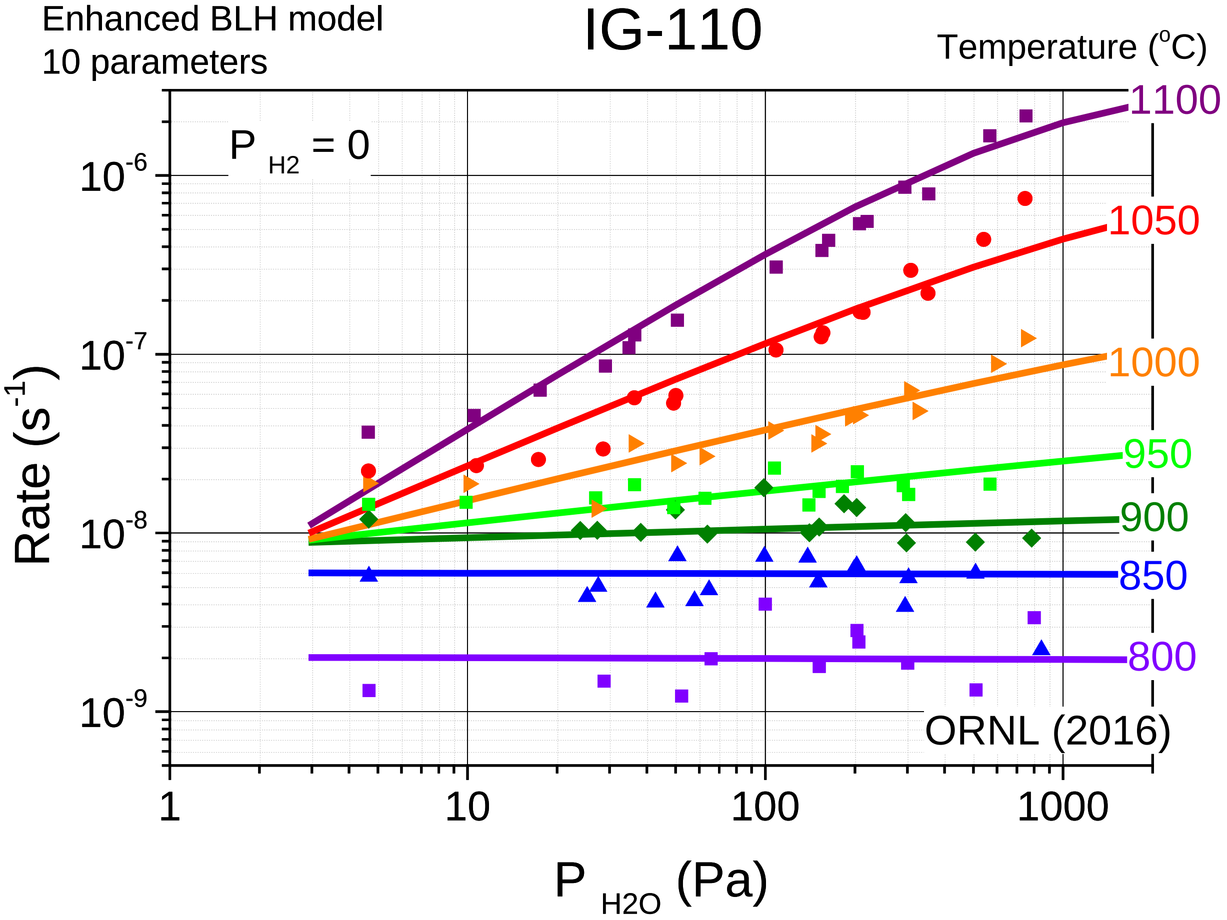
Model features

- Activation of surface sites
- Interactions between surface sites

Temperature-dependent reaction order modeled as a Boltzmann distribution function

Contescu, Mee. ORNL/TM-2016/195

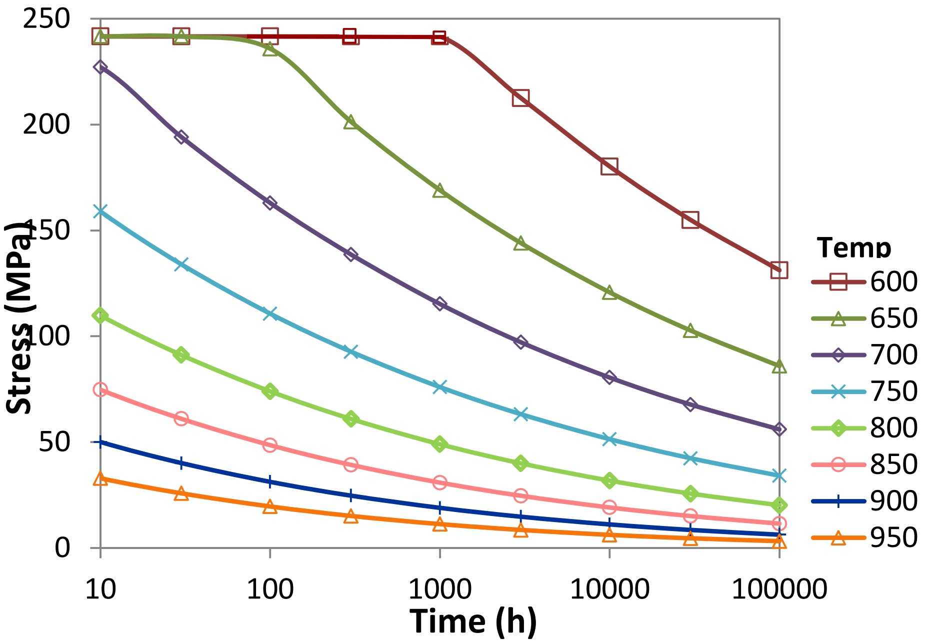
Enhanced BLH model
10 parameters



Objectives of the High Temperature Alloys Qualification Program

- Program Goals
  - To allow use of Alloy 617 (and 800H) in the ASME Code up to 950ºC (Code Case just submitted to ASME)
  - To develop experimentally validated elevated temperature design methods applicable to any high temperature nuclear system
  - Resolve Materials Issues Beyond Code Qualification that will allow design of components for life of plant

- Provide Technology Development to Support Future Design and Deployment of Very High Temperature Gas Cooled Reactors:
  - Pressure Vessel
  - Steam Generator and Intermediate Heat Exchanger (IHX)
  - Support Codes and Standards Activities for SiC/SiC composites and Materials Handbook

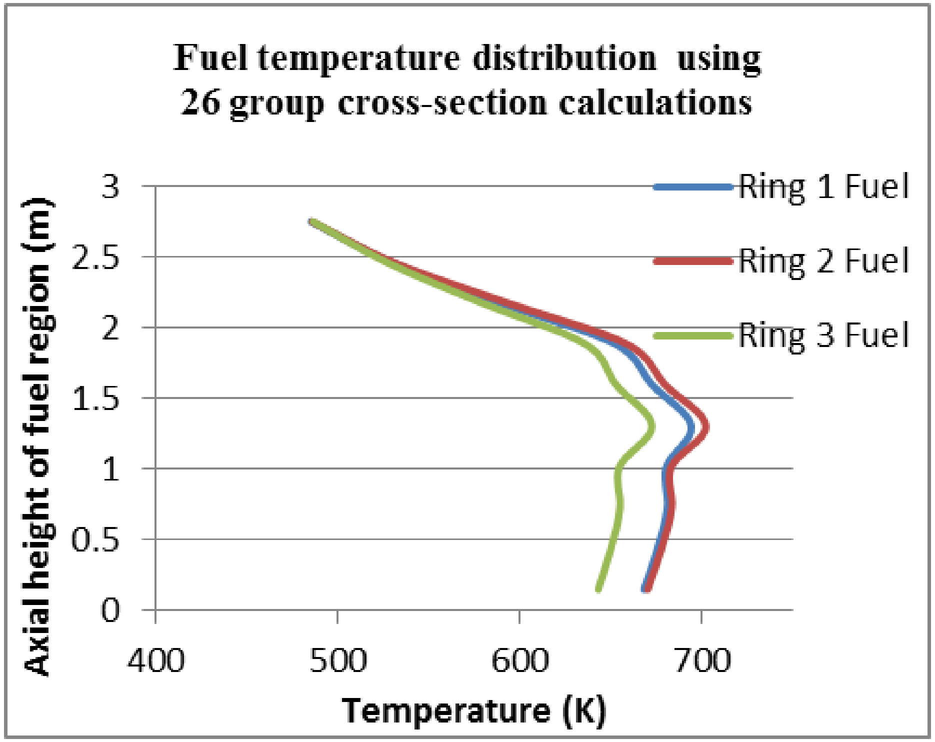


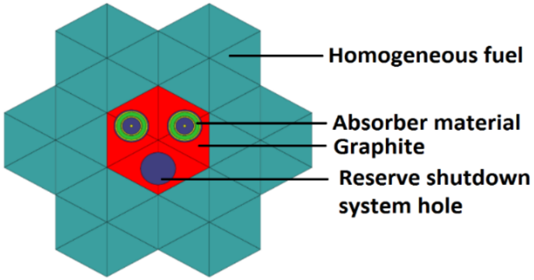
HTR Methods Activities

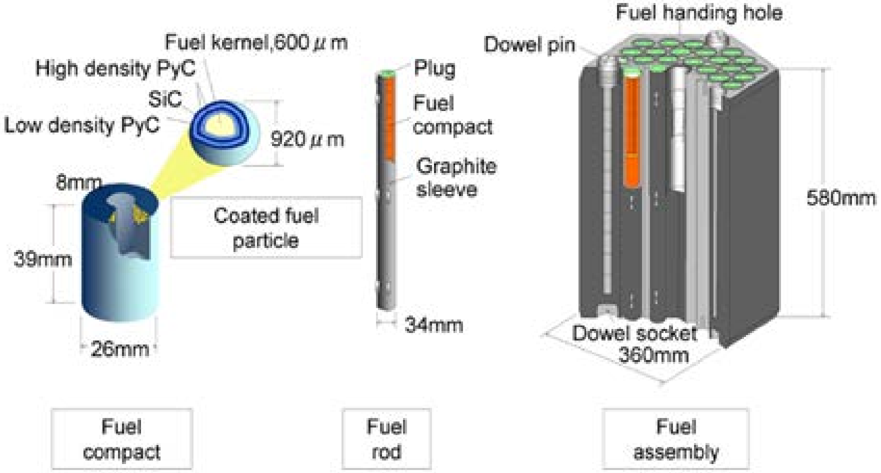
- Core Simulation
  - Development and validation of System and integral HTR simulation tools for general design and analysis of HTRs
  - Coupling with high performance multiphysics models for specific applications
- Experimental Validation
  - Reactor Cavity Cooling System studies in NSTF
  - Loss of Cooling and Air Ingress studies in HTTF (Oregon State)
  - Many DOE-funded university research projects
- International Collaboration
  - Multi-national benchmark evaluation projects (OECD, IAEA)
  - Bilateral R&D Project with JAEA
  - Multilateral validation project under Generation IV International Forum

Core/Plant Simulation

- Construct and assess tools of the type that would be used for licensing
- Apply high fidelity tools to explore complex behavior across length scales
- Current focus is in prismatic fuel but INL has developed pebble bed analysis capability as well



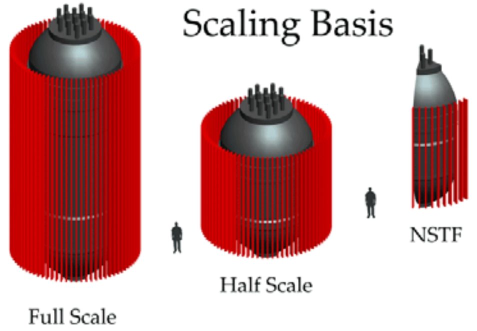


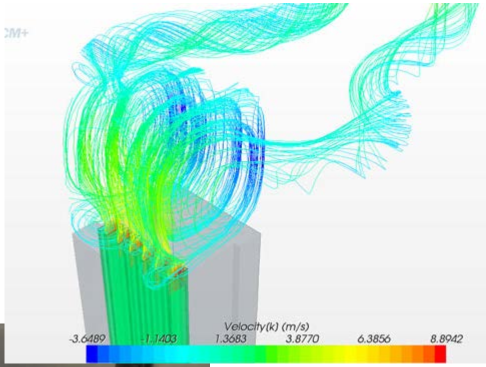


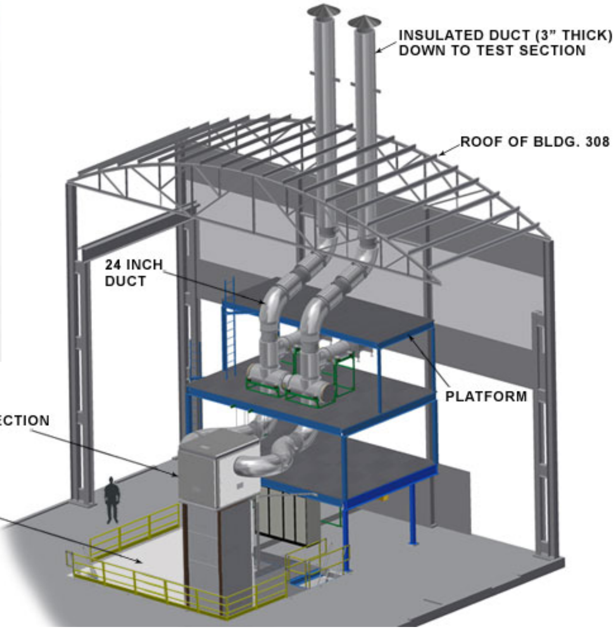
Experimental Validation – Natural circulation Shutdown heat removal Test Facility (NSTF) for vessel cooling studies

http://www.ne.anl.gov/capabilities/rsta/nstf/index.shtml

- Refurbished a sodium fast reactor (PRISM) experiment at Argonne NL to generate data revealing the performance of this passive safety system
- Air-cooled RCCS tests underway
- Conversion to a water-cooled configuration is planned (with input from AREVA)

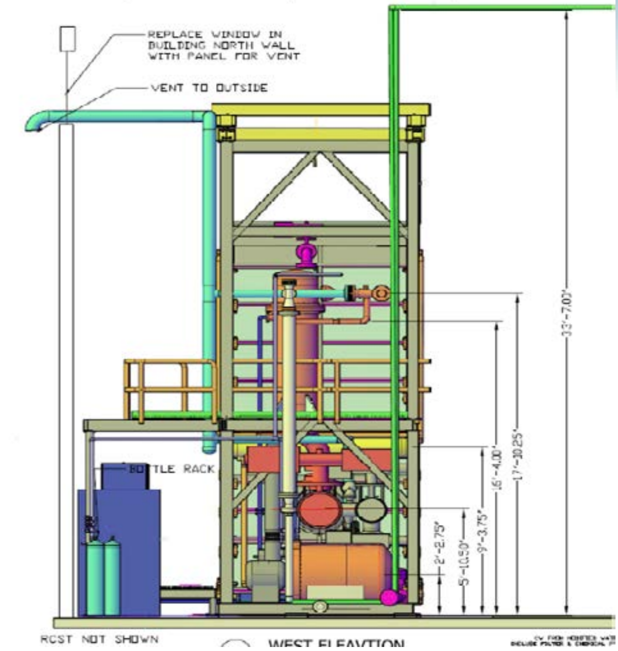


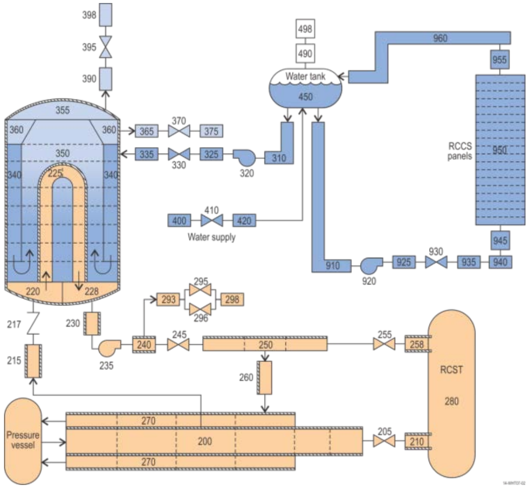




High Temperature Test Facility

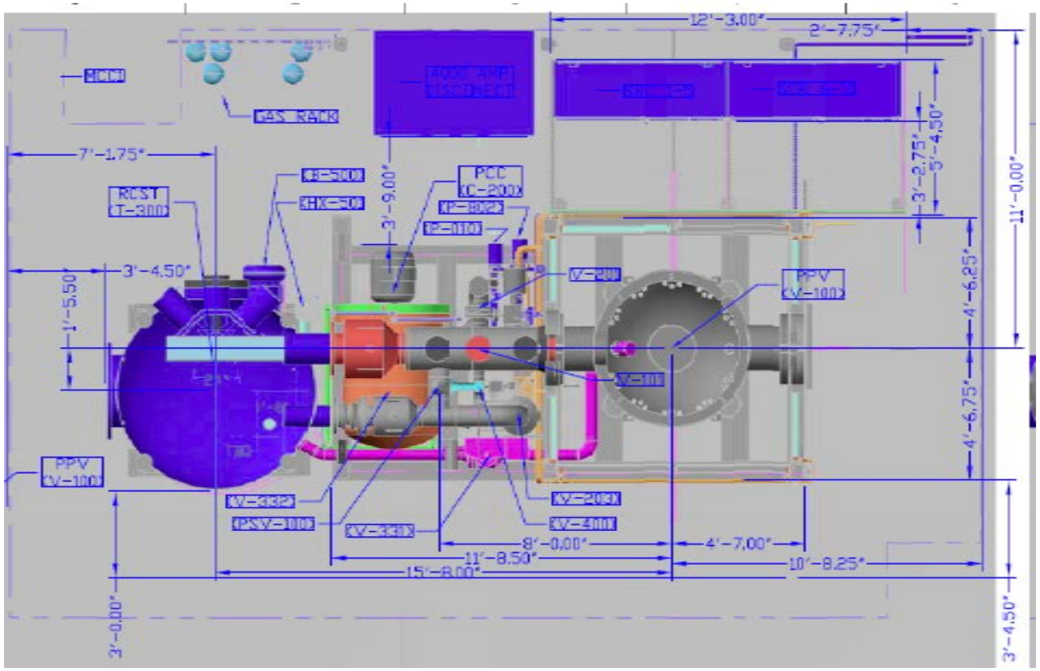
- Designed to simulate core behavior during and after a loss of forced circulation in a high temperature gas cooled reactor
- Design allows different pipe break configurations to characterize the exchange of helium and air between the primary loop and building
- 428 experiment measurements (362 thermocouples, 48 gas sensors, 18 others), 31 process instruments
- Primary focus is on depressurized conduction cooldown transient but other experiments are planned as well.
- Problems discovered in 2015 with the heater connections. We think they are now fixed. ‘Shakedown’ testing is underway
- Scaled the prismatic MHTGR but can be re-configured to look like a PBR



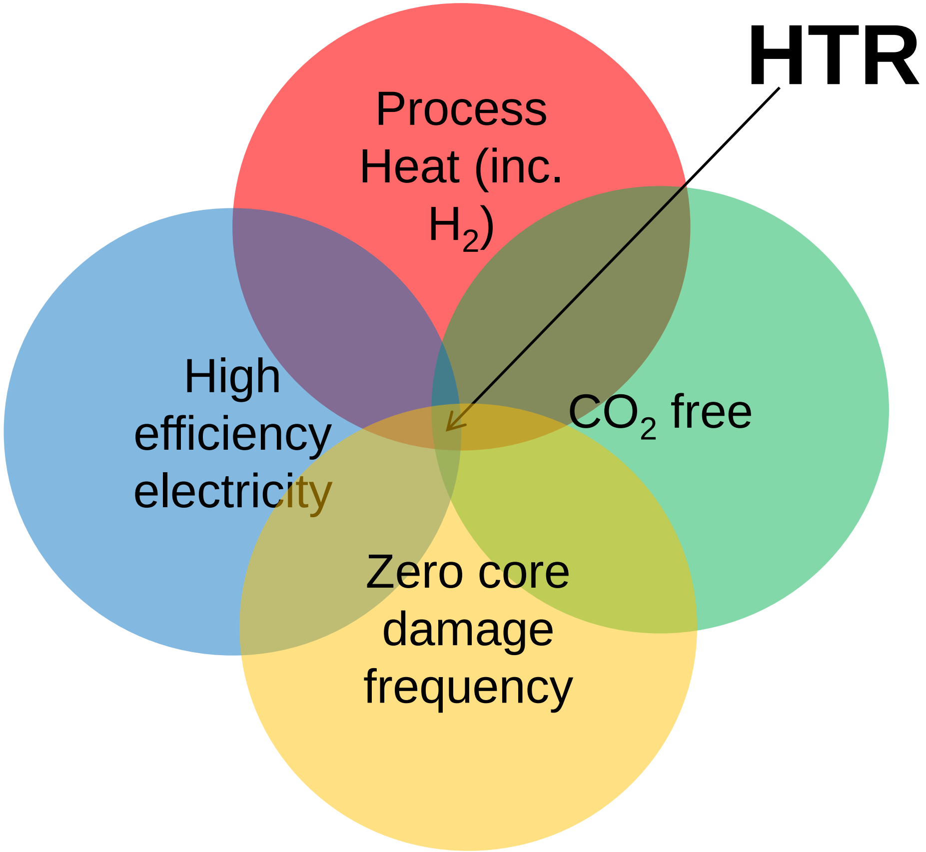


Tentative Schedule for HTTF

- Non-Power Shakedown Tests (April / May)
- Exchange Flow and Diffusion Test (May)
- Low power (<700kW) shakedown testing (June)
- Low power Matrix testing (700kW Power) (June and July)
- Full power (<2200kW) shakedown testing (August)



- Deploying HTRs in this market will take some new thinking … outside of the traditional NRC/DOE Box)
- DOE can help with technology development (ART) but we cannot tell you how to make these plants competitive. That’s your job. How can we help?



INL

Idaho National Laboratory