U.S. DEPARTMENT OF ENERGY

Nuclear Energy

FHR

Fluoride Salt Cooled High Temperature Reactor

Current Status of Fluoride Salt Cooled High Temperature Reactor R&D Activities in the U.S.

GIF MSR Provisional Steering Committee Meeting at the Institute for Transuranium Elements (ITU)

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What Defines an FHR?

The general characteristics of a Fluoride Salt Cooled High Temperature Reactor (FHR) are:

- Use of coated particle ceramic fuel
- Use of fluoride salt as primary coolant
- Use of a low-pressure, pool type primary system configuration
- Delivery of heat at temperatures greater than 600°C
- Strong passive safety features

No requirement for active response to avoid core damage or large off-site release following even severe accidents

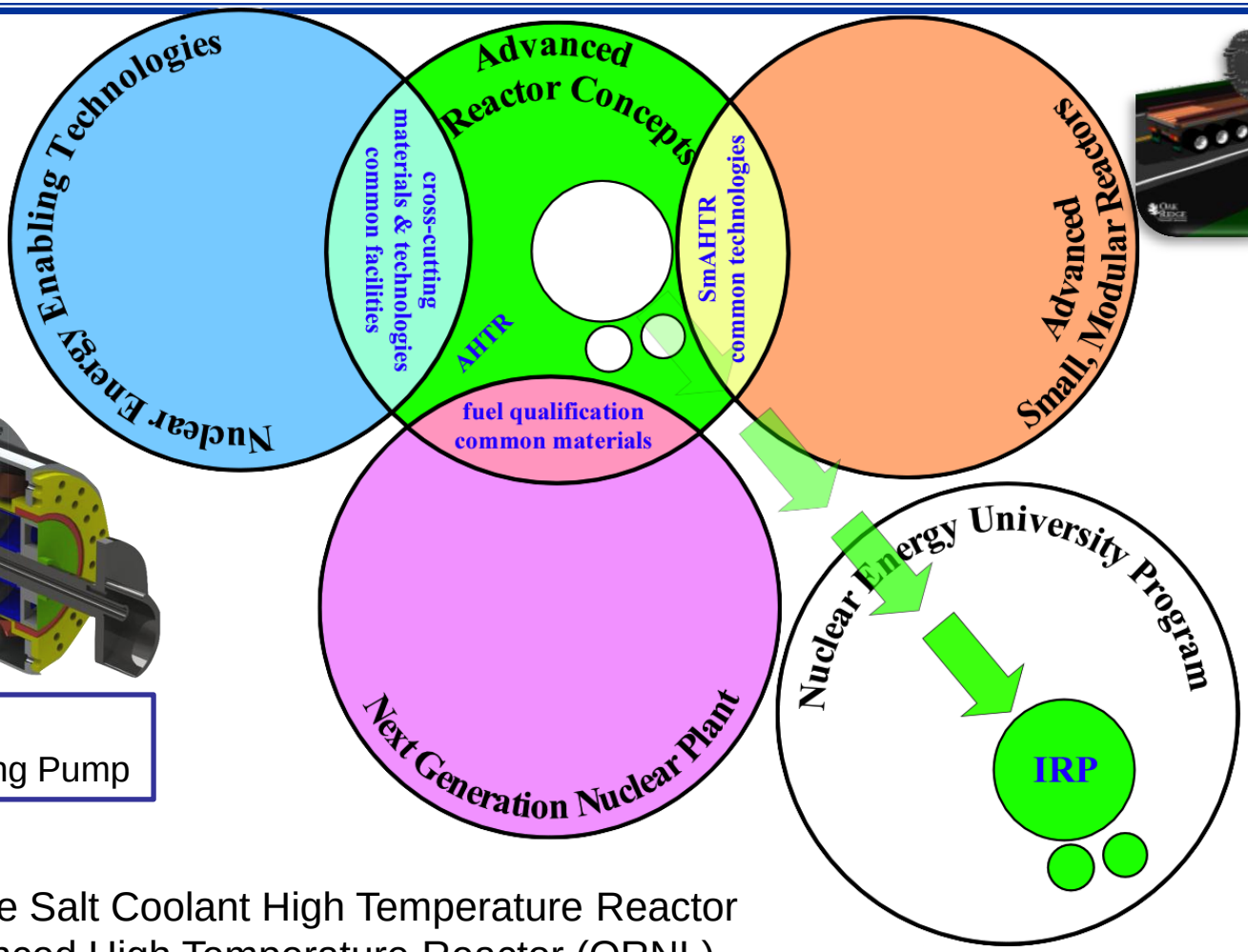
FHRs Support DOE-NE Missions for Electricity, Transportation Fuel, and Industrial Process Heat

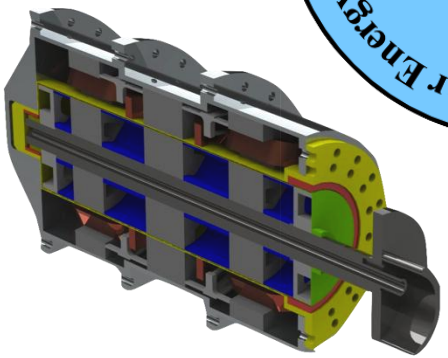
The advanced reactor concept's (ARC) mission is to develop and refine future reactor concepts that could dramatically improve nuclear energy performance (e.g., sustainability, economics, safety, proliferation resistance)

The strategic approach is to:

- **Tackle key R&D needs for promising concepts**
  - Fast reactors for fuel cycle missions
  - Fluoride salt cooled thermal reactor for high-temperature missions
  - Program includes both concept and technology development
- **FHR technology support is also embedded throughout DOE-NE program structure**
  - University research
  - Advanced gas reactor
  - Nuclear Energy Enabling Technologies (NEET)
  - Advanced Small Modular Reactors (aSMR)

Advanced Reactor Concepts Program is the US Integrating Organization for FHR Development





Canned Rotor,
Magnetic Bearing Pump

FHR = Fluoride Salt Coolant High Temperature Reactor
AHTR = Advanced High Temperature Reactor (ORNL)
SmAHTR = Small, Modular AHTR (ORNL)
Next Generation Nuclear Plant = High Temperature Gas Reactor (INL)
IRP = Integrated Research Project (MIT, UC Berkeley, and U Wisconsin)

Small Modular Reactors and Nuclear Energy Enabling Technologies Have Initiated FHR Relevant Projects

- **Johnson noise thermometry (ORNL)**
  - ORNL/TM-2012/346 - Johnson Noise Thermometry for Advanced Small Modular Reactors (aSMRs)
- **Optical access into primary coolant (PNNL)**
  - Vision and spectrometry based measurements, controls, and diagnostics
- **High temperature fission chambers (ORNL)**
- **Embedded instrumentation and controls for component performance and reliability improvement (ORNL)**
  - Demonstrating on canned rotor, magnetic bearing pump for FHRs
- **System modeling toolset development (ANL & ORNL)**
  - SFRs and FHRs are initial demonstration targets
- **SiC-SiC composites**
  - Fuel structure applications – focused on BWRs (INL)
  - ASME & ASTM code developments for core components (ORNL)
- **Develop candidate list of initiating events for aSMRs (ORNL)**

Advanced Gas Reactor Program Continues To Develop and Demonstrate TRISO Fuel

- **Program focus remains on HTGRs**
- **Identical fuel particles planned for use in FHRs**
  - Accelerated testing performed spans FHR power density
- **Performance requirements for FHR fuel different from HTGRs**
  - Molten salts retain leaking radionuclides except noble elements
  - Low primary circuit pressure minimizes leak driving force
  - Limited water/air ingress potential – intermediate loop & no water in reactor building
  - FHR fuel is more intimately coupled to primary coolant lowering operating temperature
    - *Lower fuel temperature decreases radionuclide (e.g. ^{110m}Ag) diffusion*
    - *Identified accidents do not raise fuel temperature to failure*
  - Multiple layers of containment

Test #	Description/Objective
1	Laboratory fuel performance demonstration
2	Commercial scale fuel performance demonstration
3/4	Designed to fail fuel to test radionuclide migration
5/6	Fuel qualification

DOE-NE Has Awarded a Large FHR Focused University Integrated Research Project

- **Massachusetts Institute of Technology**
  - Pre-conceptual test reactor design and material testing at the M research reactor
- **University of California at Berkeley**
  - Thermal hydraulics, safety, licensing, and neutronics
  - Pre-conceptual commercial reactor design
- **University of Wisconsin**
  - Materials and corrosion
- **Additional individual university FHR technology development projects are also underway**
  - The Ohio State University – Direct Reactor Auxiliary Cooling System design and testing
  - University of California at Berkeley – Pebble bed fuel motion modeling and demonstration using simulant materials

ORNL Has Issued Several Reports on FHRs

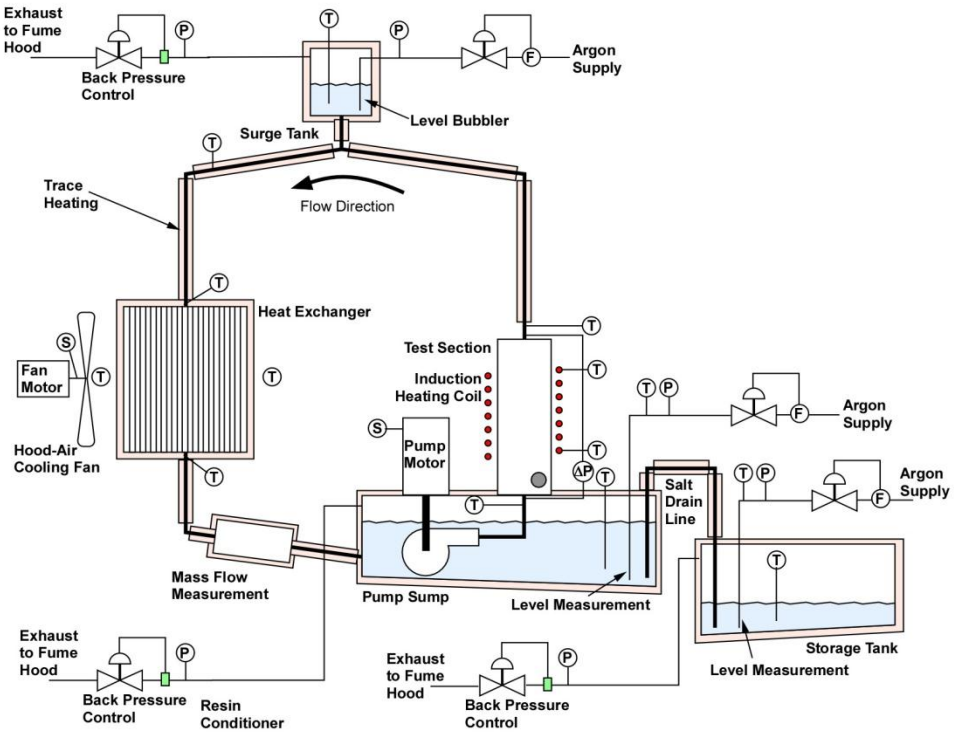
- **ORNL/TM-2012/174 - *Advanced High Temperature Reactor Dynamic System Model Development***
  - *Describes dynamic modeling tools being used for performance evaluation*
  - *Modelica® based models – similar to EdF (*Electricité de France)
- ***ORNL/TM-2012/292 - AHTR Refueling Systems and Process Description***
  - *Provides conceptual overview of the technology and process for refueling FHRs*
- ***ORNL/TM-2012/226 - FHR Generic Design Criteria***
  - *Based upon LWR licensing approach modified for SFRs*
  - *Intended as input to an American Nuclear Society Design/Safety Standard*
- ***ORNL/TM-2012/320 - AHTR Mechanical, Structural, And Neutronic Preconceptual Design***
- ***All are available for download through DOE's Office of Scientific and Technical Information (osti.gov)***

Versatile Liquid Salt Test Loop Has Been Constructed at ORNL

- **Primary construction complete**
  - Shakedown and acceptance testing of both loop and components remains to be performed
  - Salt not yet loaded
- **Installation of HF-H_2 based salt cleanup system in progress**
- **Funding not yet identified for loop commissioning or operation during 2013**
- **First experiments will examine liquid salt heat transfer to pebble bed**

Loop Represents Initial Portion of a Liquid Salt Component Test Facility

- **Loop includes several innovative features**
  - Silicon carbide test section
  - Inductively heated pebble bed (200 kW)
  - Ultrasonic salt flowmeter
  - Impulse line type pressure gauge
  - Radar based level measurement
- **Vertical shaft, gas seal, sump type, centrifugal pump**
- **Loop is intended to be reconfigurable to enable different tests**
  - Natural circulation heat rejection
  - Fluidic diode performance
  - Vision based instrumentation
  - Advanced pump performance validation
  - Salt redox measurement and control



Advanced Reactor Concepts FHR Specific Work is Very Limited in FY2013

- **Only major task is creation of an FHR development roadmap under the current budget**
  - Full year budget has not been passed by Congress
  - Roadmap will include materials issues that directly support MSRs
- **Continued funding for limited international cooperation remains available**
- **No technology or concept development tasks are being performed in FY2013**

U.S. is Providing Isotopically Selected Fluoride Salt to Czech Republic in Return for Criticality Measurements

- **Subdivide existing canister of 2^7LiF-BeF_2 of into 75 kg aliquots**
  - Shipment awaits MOU signatures and DOE permission
  - Mid November ship date?

U.S. and China Are Cooperating in FHR Development

- **Scope and depth of cooperation remain under discussion**
- **Initial focus for cooperation has been on liquid salt heat transport loops**
- **Chinese are participating at IRP workshops on FHRs**
  - 29 – 31 August at the University of Wisconsin at Madison
    - *Materials and components*
  - 1-2 November at MIT
    - *Test reactor requirements*
- **Shanghai Institute of Applied Physics hosted international review of their Thorium Molten Salt Reactor (TMSR) program in July**
  - Focused on FHR test reactor program

Strong FHR Safety Case Makes Licensing Through Evolutionary Change to NRC Process Possible

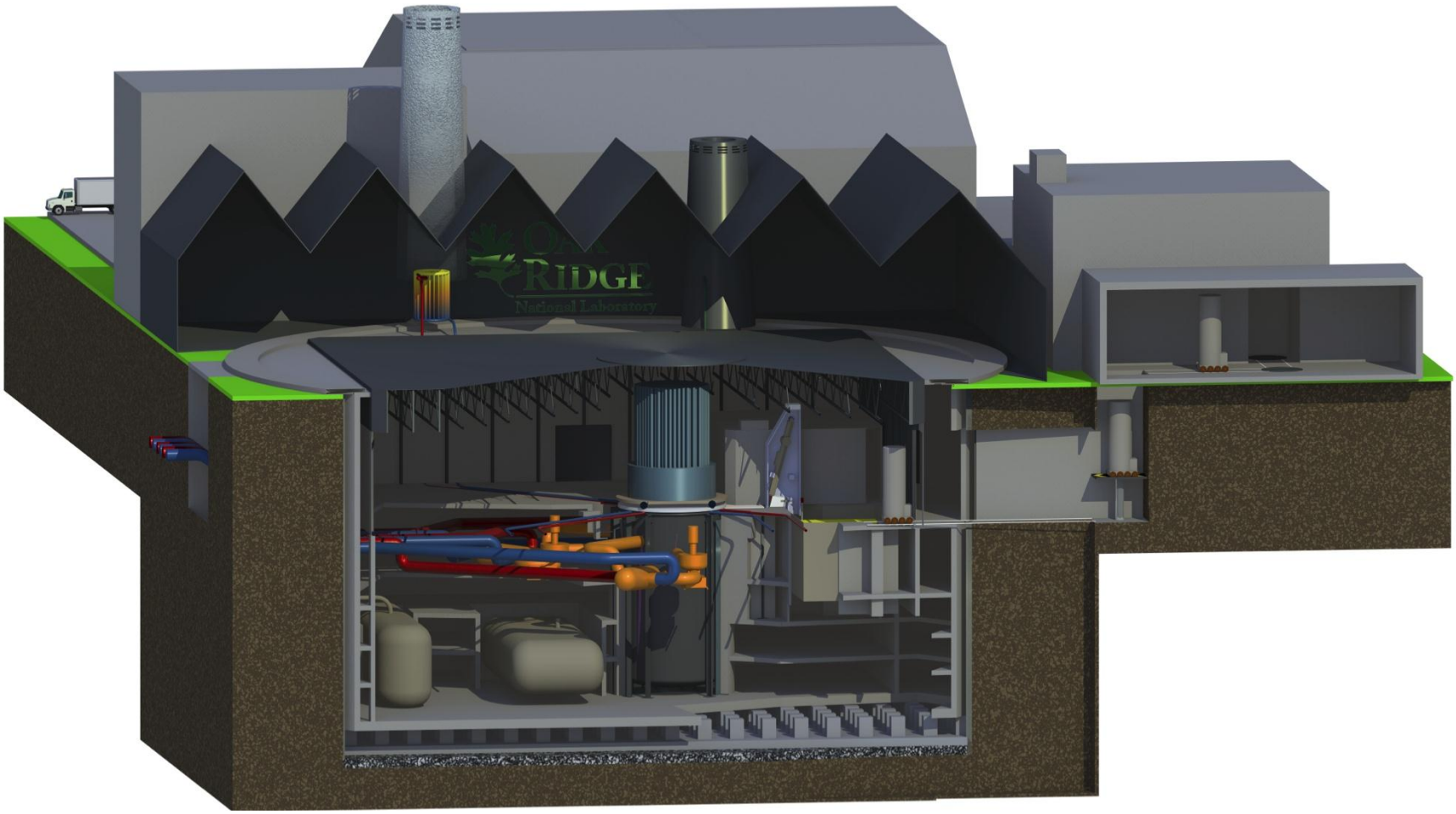
NRC Has Very High Inertia and Revolutionary Change is Unlikely to Succeed

- **10CFR Part 50 Appendix A provides set of general design criteria (GDC)**
  - Current Appendix A criteria are LWR focused
  - FHRs will require a custom set of GDCs
  - Gas cooled reactors and liquid metal cooled reactors are already developing modified GDCs in the form of ANS safety standards (ANS 53.1 & ANS 54.1)
- **FHR safety standard will provide FHR customized set of GDCs**
  - Will require NRC endorsement
  - Will provide guidance on experimental demonstrations required
- **Design specific safety analysis report will show how GDC are fulfilled**
  - SAR shows how plant systems, structures, and components are designed to perform safety functions and respond to accident initiators
- **FHR specific GDCs combined with safety standard will guide development of FHR specific standard review plan**
  - NUREG 0800 — Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition

American Nuclear Society Has Initiated a Design/Safety Standard on FHRs

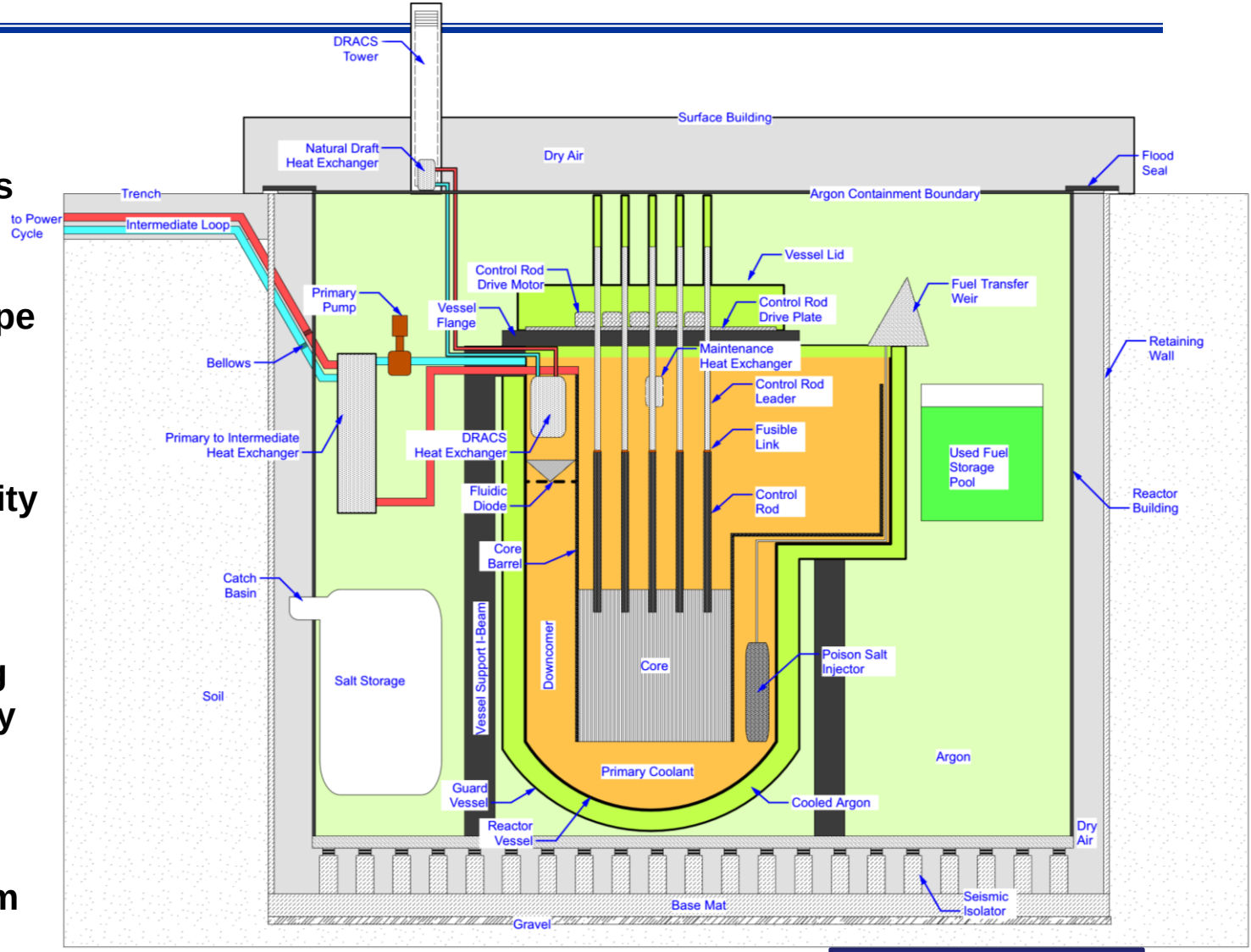
- **Organizing meeting held in June at ANS meeting in Chicago**
  - Co-chaired by US (Ed Blandford and Matt Denman) and China (Zhimin Dai)
  - Representatives from US and Chinese nuclear safety authorities participating
- **First writing meeting scheduled for San Diego in November preceding ANS meeting**
  - Scope yet to be established
- **Risk informed, performance-based licensing process envisioned**
  - NUREG-2150 provides guidance on risk informed regulatory approach
  - Candidate draft GDCs provided to standard committee
  - Recent ANS 54.1 SFR draft safety standard used for guidance on low pressure, passive decay heat removal aspects
  - Need to identify design basis events and accidents for FHRs

AHTR Mechanical and Structural Maturation Was FHR Concept Development Focus During 2012



Overall Mechanical and Structural Layout of the AHTR Has Been Created

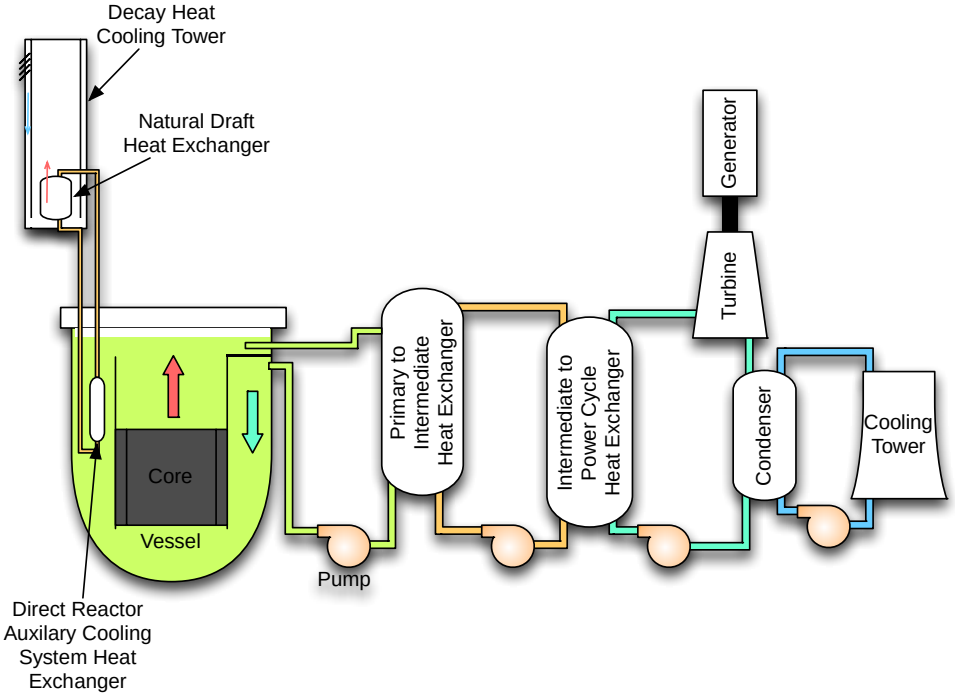
- **Advanced High Temperature Reactor (AHTR) is ORNL's design concept for a central station type (1500 MW_e) FHR**
- **Objective is to demonstrate the technical feasibility of FHRs as low-cost, large-size power producers while maintaining full passive safety**
- **Focus on developing a functional, self-consistent system**



AHTR Schematic

AHTR is Progressing Towards a Preconceptual Design Level of Maturity

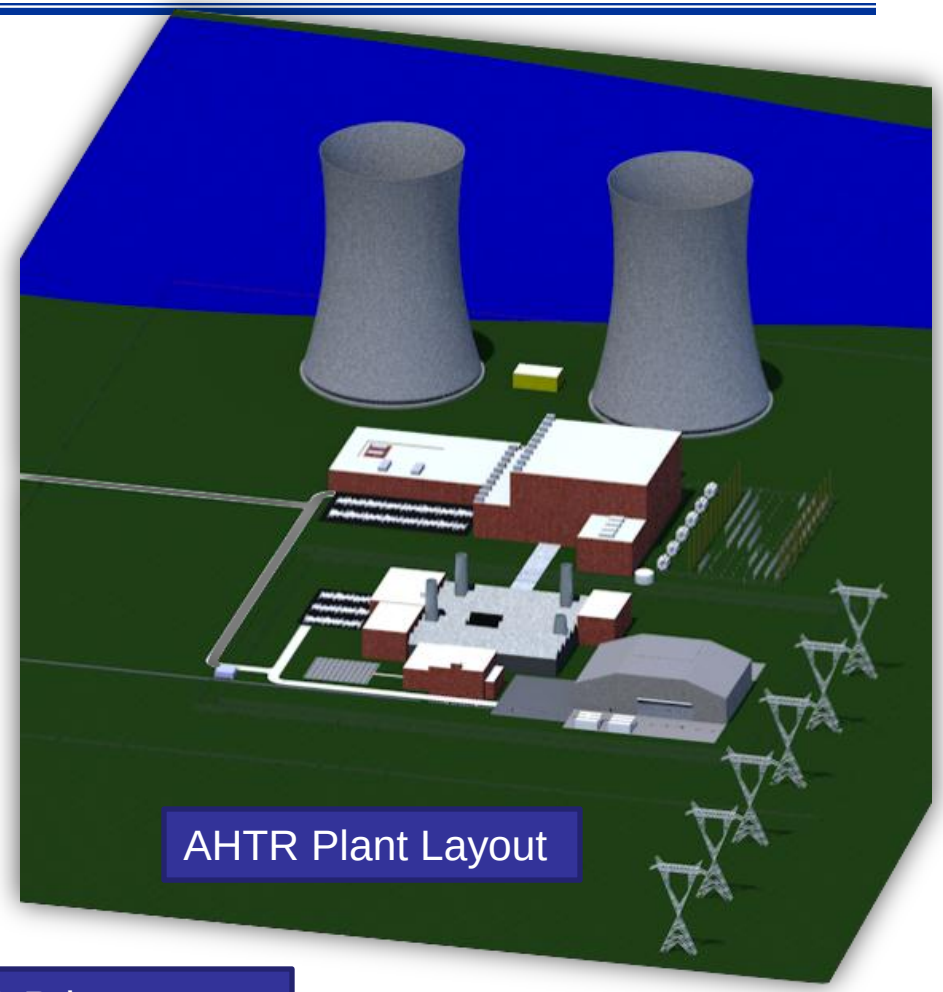
- **Hydraulic design not yet performed**
  - Lower core coolant flow velocity employed to minimize vibration and erosion (1.9 m/s AHTR versus 5.1 m/s PWR)
  - Downcomer has twice flow area as core
  - 1 atm. pressure drop across core

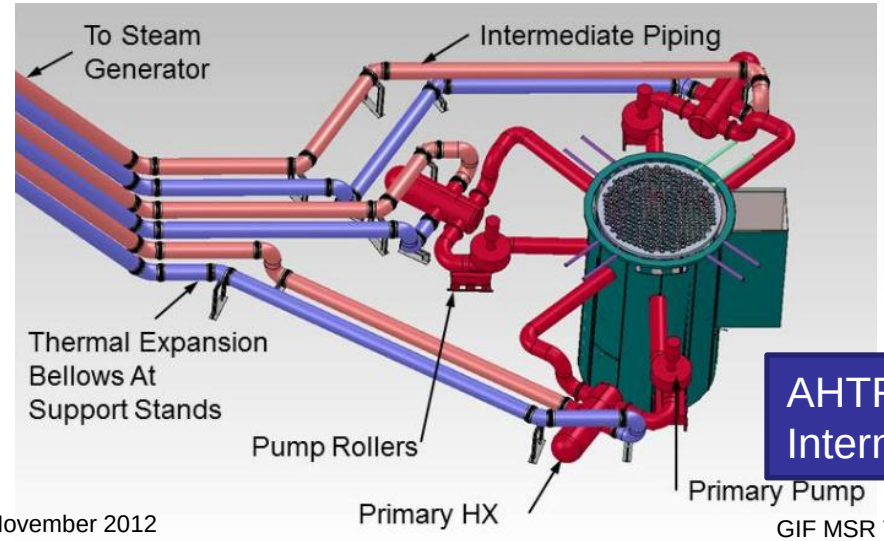


AHTR Properties	
Thermal Power	3400 MW
Electrical Power	1500 MW
Top Plenum Temperature	700 °C
Coolant Return Temperature	650 °C
Number of loops	3
Primary Coolant	$2^{7}LiF\text{-}BeF_2$
Fuel	UCO TRISO
Uranium Enrichment	9%
Fuel Form	Plate Assemblies
Refueling	2 batch 6 month

General AHTR Plant Layout Has Been Developed

- **Below grade siting to minimize aircraft impact vulnerability**
- **Local used fuel storage in dry wells**
- **Turbine building separated from nuclear island**
  - Bellows included on intermediate piping to accommodate thermal expansion
- **Emergency planning zone limited to site boundary**





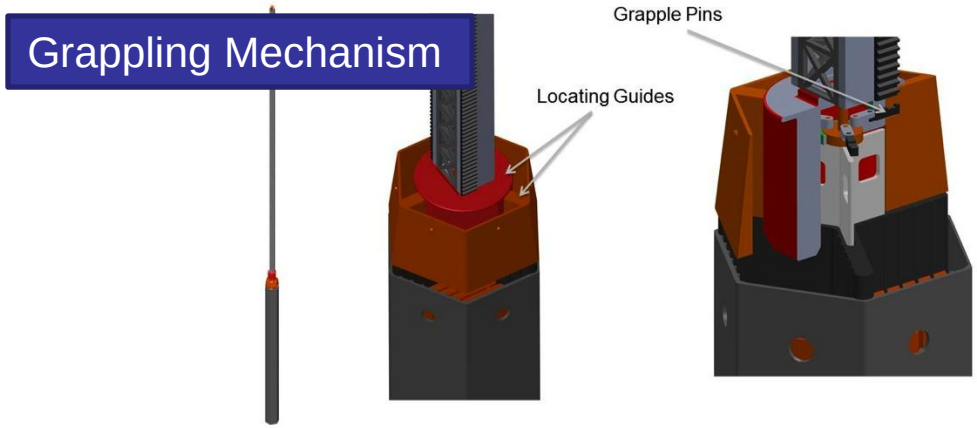
AHTR Primary-Intermediate Piping

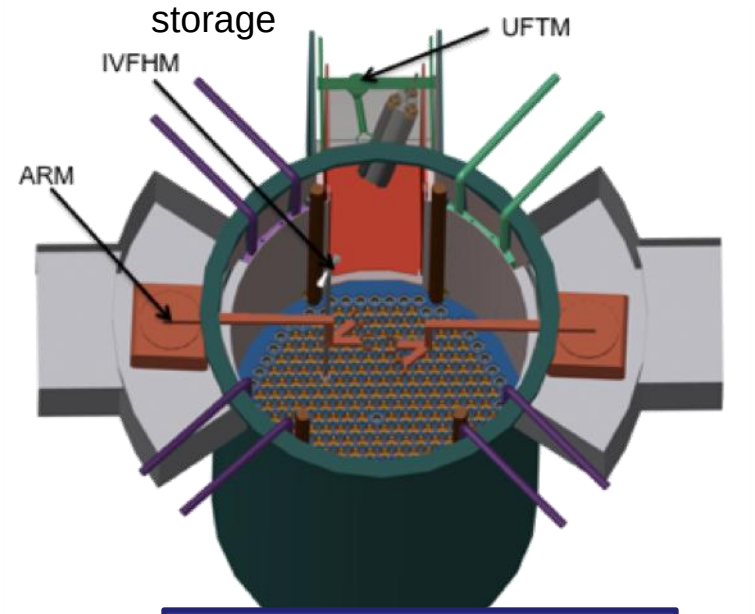
Tritium Release Prevention is the Only Conceptual Viability Issue Identified

- **Tritium is the only radionuclide with significant possibility for release from FHRs**
- **FHRs will generate significantly more tritium than LWRs**
  - Less than HWRs
- **Tritium migrates rapidly through structural alloys at high temperature**
- **Most of the tritium will migrate through the large, thin walled heat exchangers**
- **MSR program intended to trap tritium as a hydride in intermediate loop**
- **Double walled heat exchangers can provide similar tritium trapping**
  - Keeps tritium in reactor building
  - Does not require boron fluorides
- **Lithium-7 metal can be used between the heat exchanger walls to trap tritium**
  - Tritium can be recovered from lithium hydride
  - Lithium-7 leak into primary loop is not operationally significant

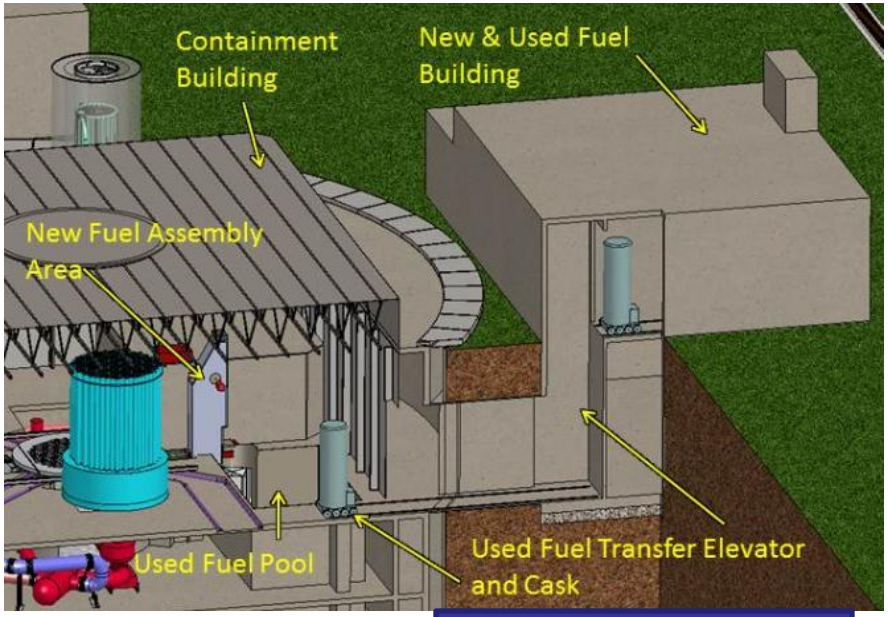
Refueling System Evaluation Was a Significant Area of Emphasis

- **Visually guided fully automated refueling system minimizes refueling outage duration**
- **Used fuel storage 0.5 - 1 year inside containment in used fuel pool**
  - Lower power density combined with high temperature tolerance lowers required liquid immersed cooling time
  - Local dry wells for intermediate term storage





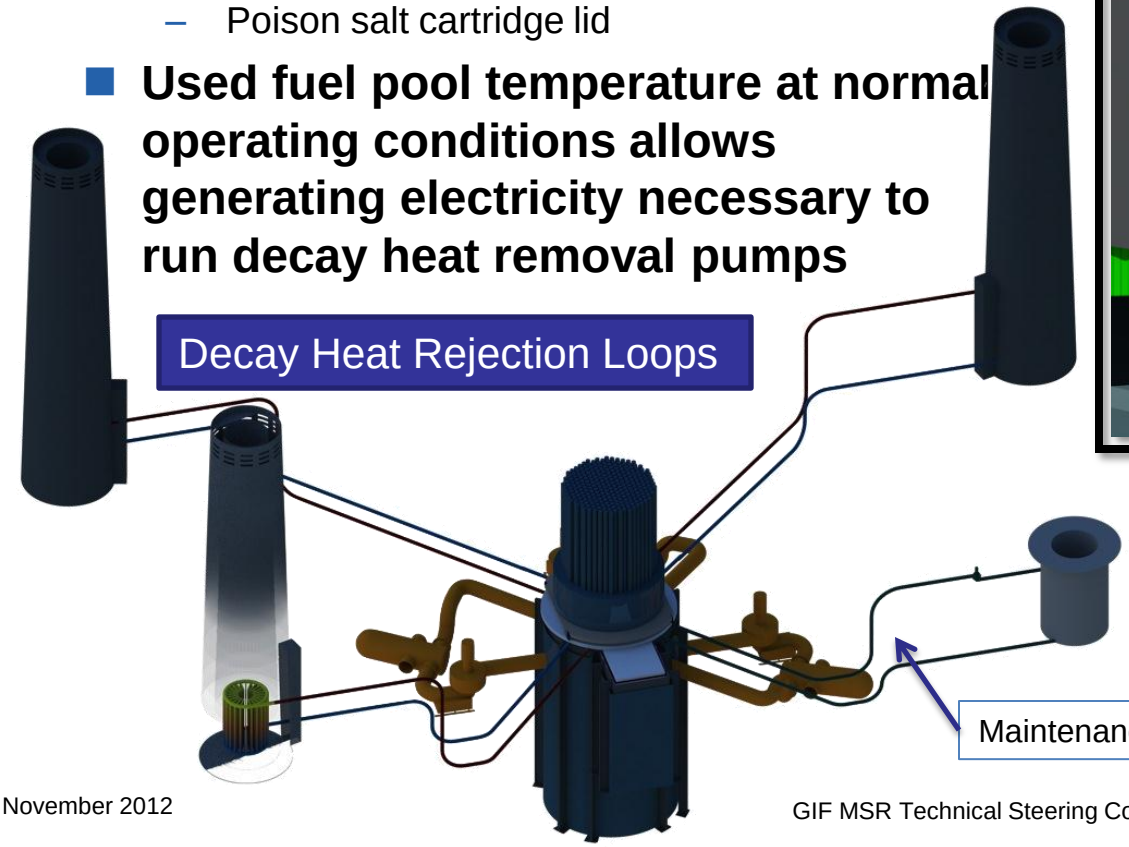
Fuel Handling Machines

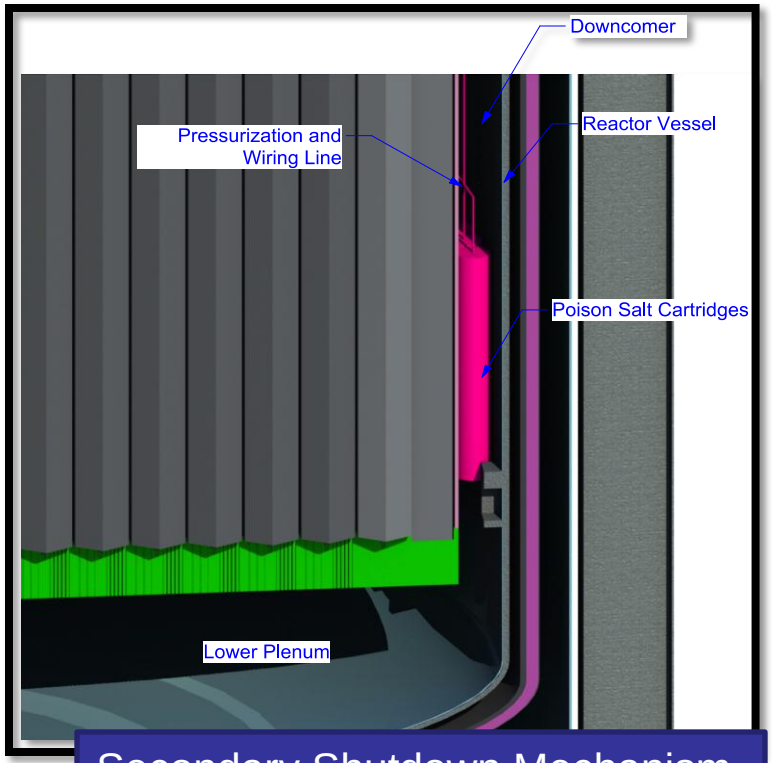


Fuel Transfer Path

Heat Removal and Negative Reactivity Insertion Under Accident Conditions Are Key Design Features

- **Primary coolant temperature rise tolerance enables melt point triggered negative reactivity insertion mechanisms**
  - Link in control blade leader rod
  - Poison salt cartridge lid
- **Used fuel pool temperature at normal operating conditions allows generating electricity necessary to run decay heat removal pumps**

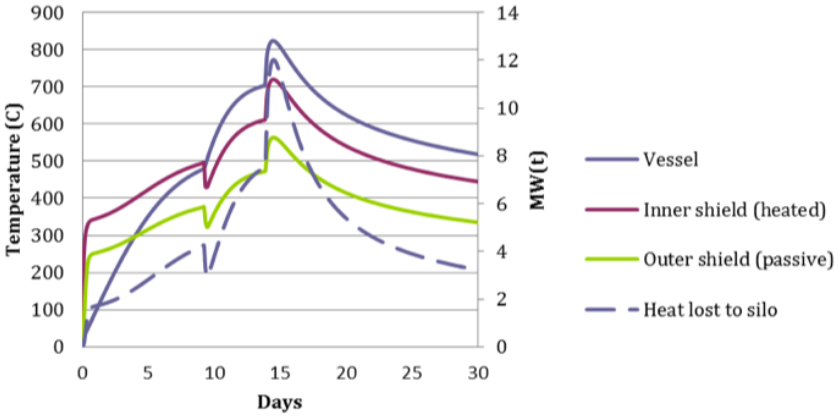




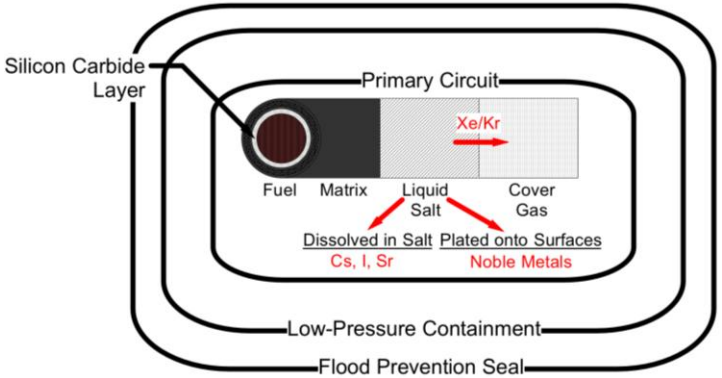
Secondary Shutdown Mechanism

Intended Response To Initial Suite of AHTR Accident Scenarios Described

- **Full suite of accident initiators have not yet been defined**
  - No active response required for any accident scenario identified
  - Accidents investigated include more severe conditions than required for LWRs (e.g. primary vessel failure)
- **Does not require off-site power**
  - Can help restart black grid
- **Robust fuel and large margins to failure may lower the required fidelity of accident simulations**
- **Safety grade reactor cavity cooling system does not appear to be necessary**
  - Temperature begins to decrease a few days after a station blackout accident



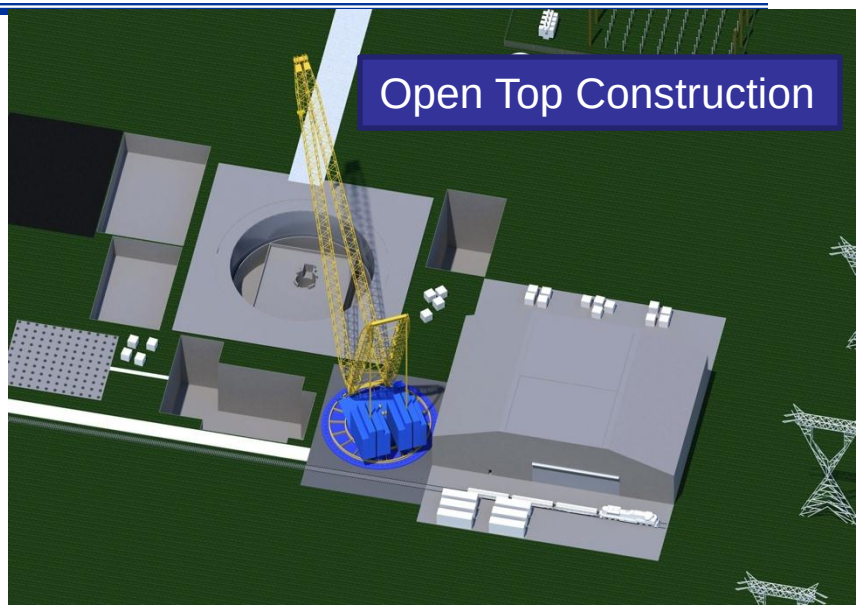
Vessel Temperature Following Loss of Forced Cooling

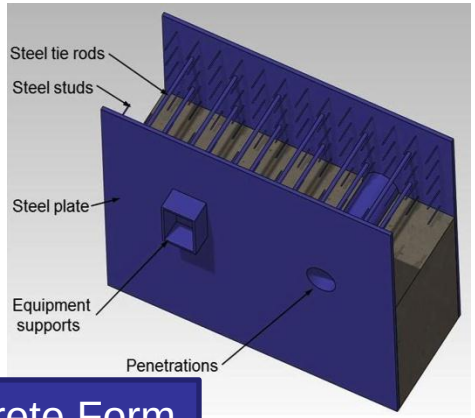


Radionuclide Containment Boundaries

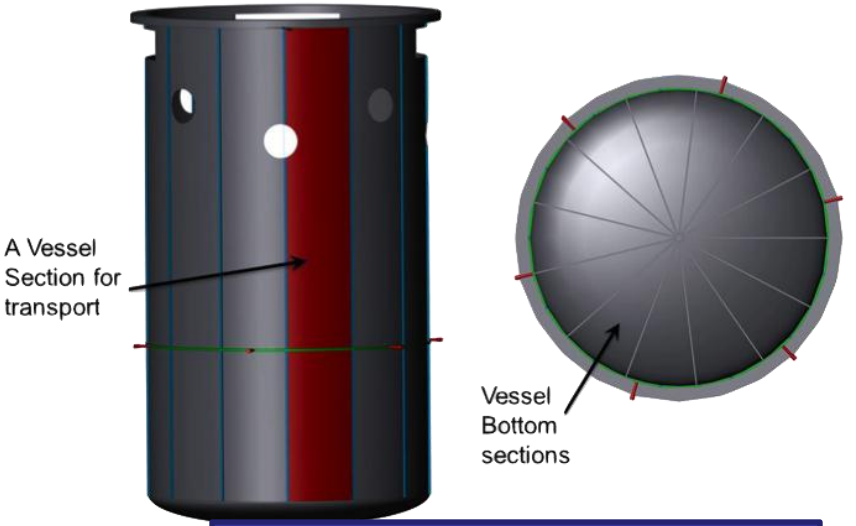
AHTR Concept Includes Focus on Minimizing Construction Time and Cost

- **Reactor building is formed from modules that are factory constructed off-site**
  - AHTR is a large, modular reactor to maximize learning in the construction process
- **All components rail transportable**
  - Smaller components enables more diverse supplier base
  - Thin walls allow on site welding of reactor vessel
  - Truss structure employed to maximize strength
- **Open top construction**
- **Welded steel form walls**
- **On-site workshop employed to minimize work in reactor building**
- **36 months from first nuclear concrete to fuel loading**





Steel Plate Concrete Form



Reactor Vessel Segmentation

FHRs Inherently Include Several Distinctive Design Elements

- **Core power density is significantly lower than that of LWRs necessitating a large vessel and in-vessel structures.**
- **A principal safety requirement is holding the fuel under the coolant surface.**
- **The most vulnerable element in safety analysis is not the fuel, but the reactor vessel.**
  - A guard vessel is employed to provide defense-in-depth.
- **No low vessel penetrations exist avoid potential loss of coolant accidents.**
- **Reactor vessel is hung from its upper flange to minimize thermal expansion stresses.**
- **Piping thermal expansion is accommodated using mechanical bellows on the intermediate heat transfer loops.**

FHRs Inherently Include Several Distinctive Design Elements (contd.)

- **Instrumentation system is primarily visually based with its elements above the salt surface to take advantage of the good transparency of the liquid salt.**
- **High normal operating temperature enables production of back-up power from the used fuel pool.**
- **Intermediate coolant loop is located above the primary loop to provide inflow avoiding need for containment isolation valves.**

FHR Reactor Class Shows Much Promise

Still Requires Significant Research, Development, and Demonstration

- **Tritium release prevention only identified concept viability issue**
  - Double walled primary to intermediate heat exchanger promising approach for tritium containment
- **More complete reactor conceptual design required**
  - Needs to include all of the specialized systems and components
- **Innovative use of vision based measurement and automation necessitates extensive evaluation and demonstration**
- **Replacement industrial scale lithium enrichment**
- **Salt chemistry control system requires basic design**
- **Structural ceramics must become safety grade nuclear engineering materials**
- **Safety and licensing approach must be developed and demonstrated**
- **Layered TRISO fuel must be demonstrated and qualified**