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 Delft, Netherlands

November 8, 2011

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FHRs are Central to DOE-NE Advanced Reactor Concepts Program Mission

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

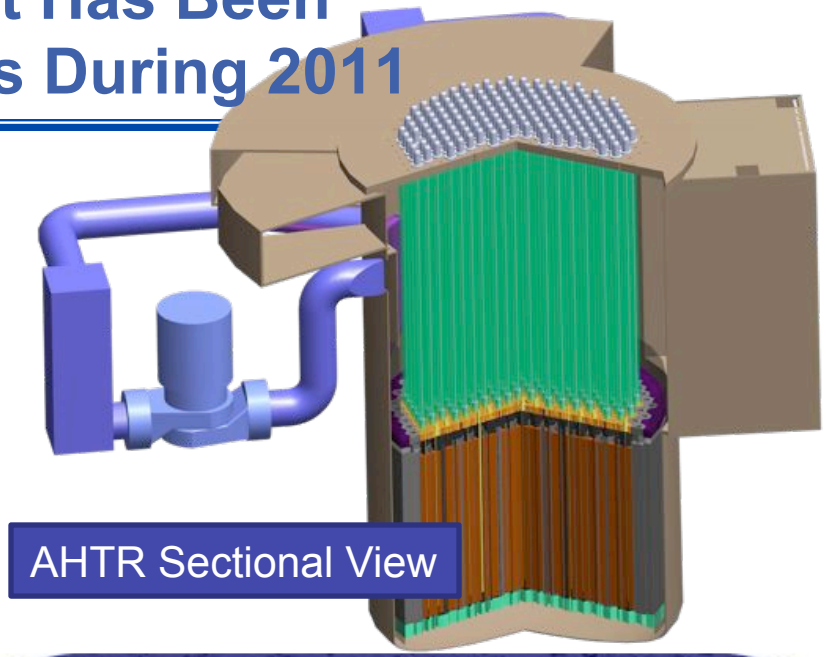
The strategic approach is to:

- **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)*
  - Small Modular Reactors (SMR)*

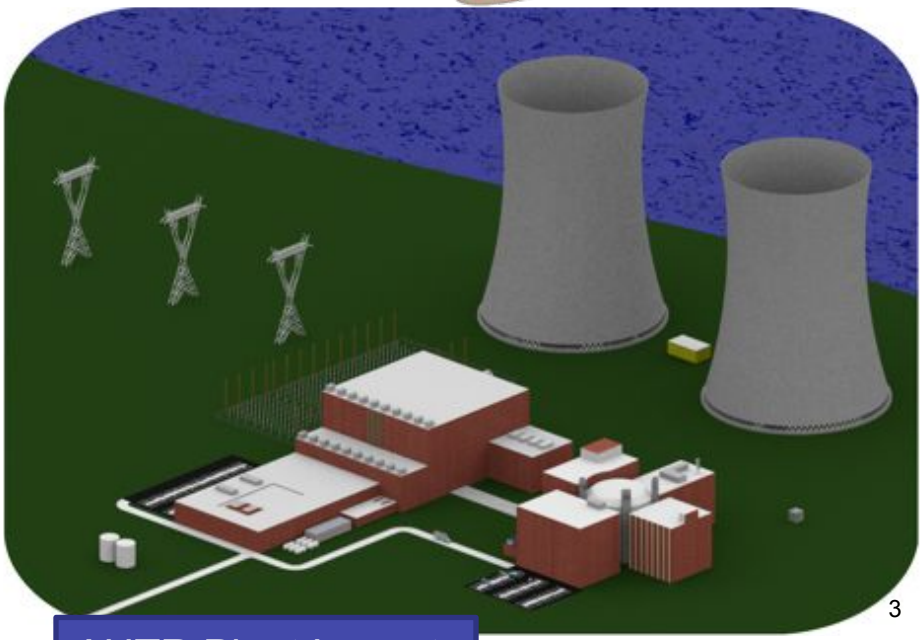
* Not yet started

AHTR Concept Development Has Been Primary FHR Program Focus During 2011

- **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**
- **Significant developments remain in almost all aspects of the reactor**
- **Recent program technical reports are available for download from the DOE Office of Scientific and Technical Information (OSTI)**
  - Core and Refueling Design Studies for the Advanced High Temperature Reactor
  - Advanced High Temperature Reactor Systems and Economic Analysis



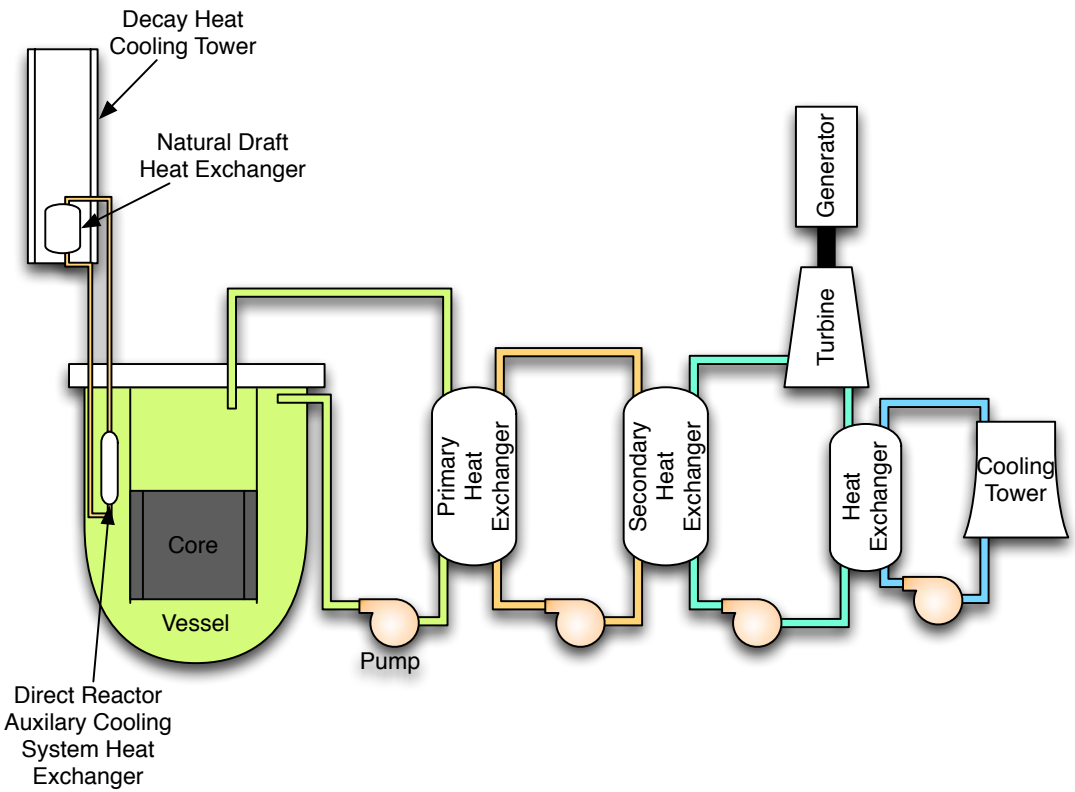
AHTR Sectional View



AHTR Plant Layout

AHTR is Progressing Towards a Preconceptual Design Level of Maturity

Both reactor and power plant systems are included in the modeling



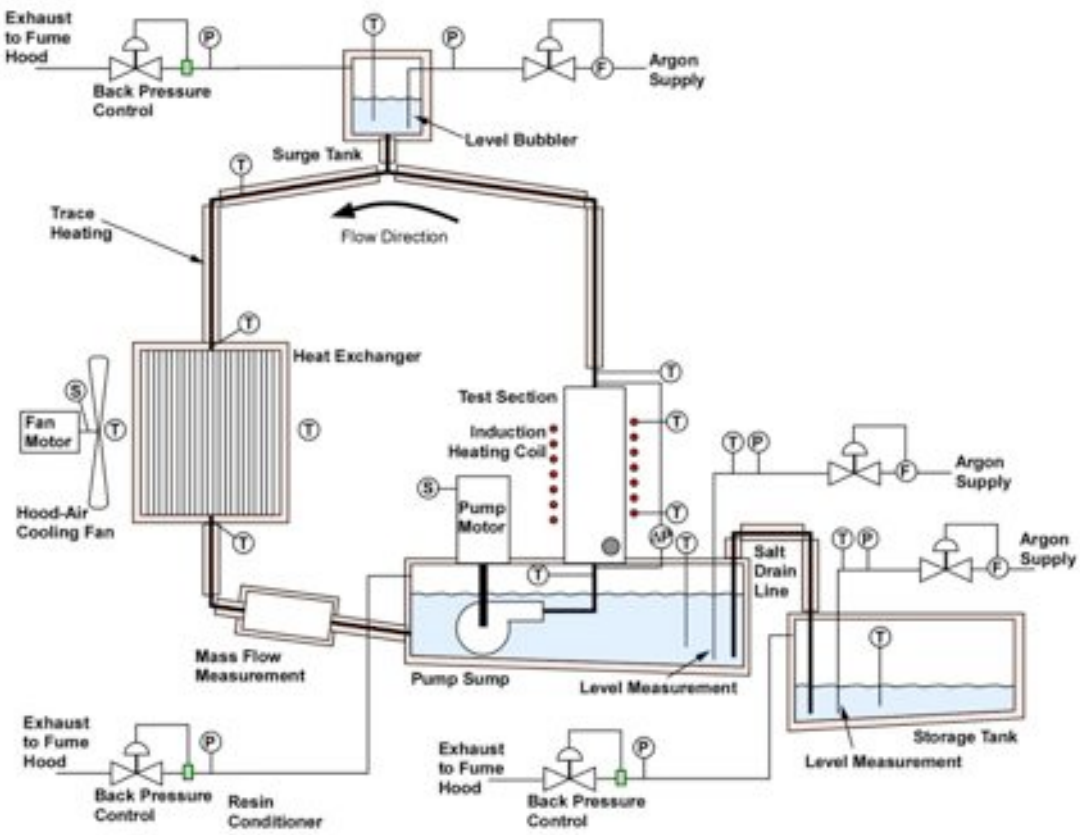
AHTR Properties	
Thermal Power	3400 MW
Electrical Power	1500 MW
Top Plenum Temperature	700 °C
Coolant Return Temperature	650 °C
Number of loops	3
Primary Coolant	$2^7LiF\text{-}BeF_2$
Fuel	UCO TRISO
Uranium Enrichment	9%
Fuel Form	Plate Assemblies
Refueling	2 batch 6 month

FHR Material and Component Design Studies are Continuing

- **Intermediate loop to power cycle heat exchanger is key component for successful FHR deployment**
- **"Feasibility Study of Secondary Heat Exchanger Concepts for the Advanced High Temperature Reactor" recently published (INL/EXT-11-23076)**
  - Will be available for download from INL
- **Assessment of current status of Alloy N for salt reactor deployment recently published – "Considerations of Alloy N for Fluoride Salt-Cooled High Temperature Reactor Applications" ASME 2011 Pressure Vessels & Piping Division Conference**
  - Presentation available at http://info.ornl.gov/sites/publications/Files/Pub31145.pdf
- **Cladding qualified structural alloys is a near-term approach to enable higher temperatures**
  - NGNP program is qualifying higher temperature structural alloys (800H, 617, perhaps 230)
  - "Cladding Alloys for Fluoride Salt Compatibility" recently published (ORNL/TM-2011/95 – available on-line from OSTI)

Liquid Salt Test Loop is Nearing Completion

- Completion scheduled for February 2012
- Major components all either completed or in fabrication
- Loop will provides infrastructure to test high temperature salt components
- Demonstrates inductive heating can be used for liquid salt experimentation
- Demonstrate the use of SiC as a structural material for use in molten salt systems
- Demonstrates performance of a fluidic diode

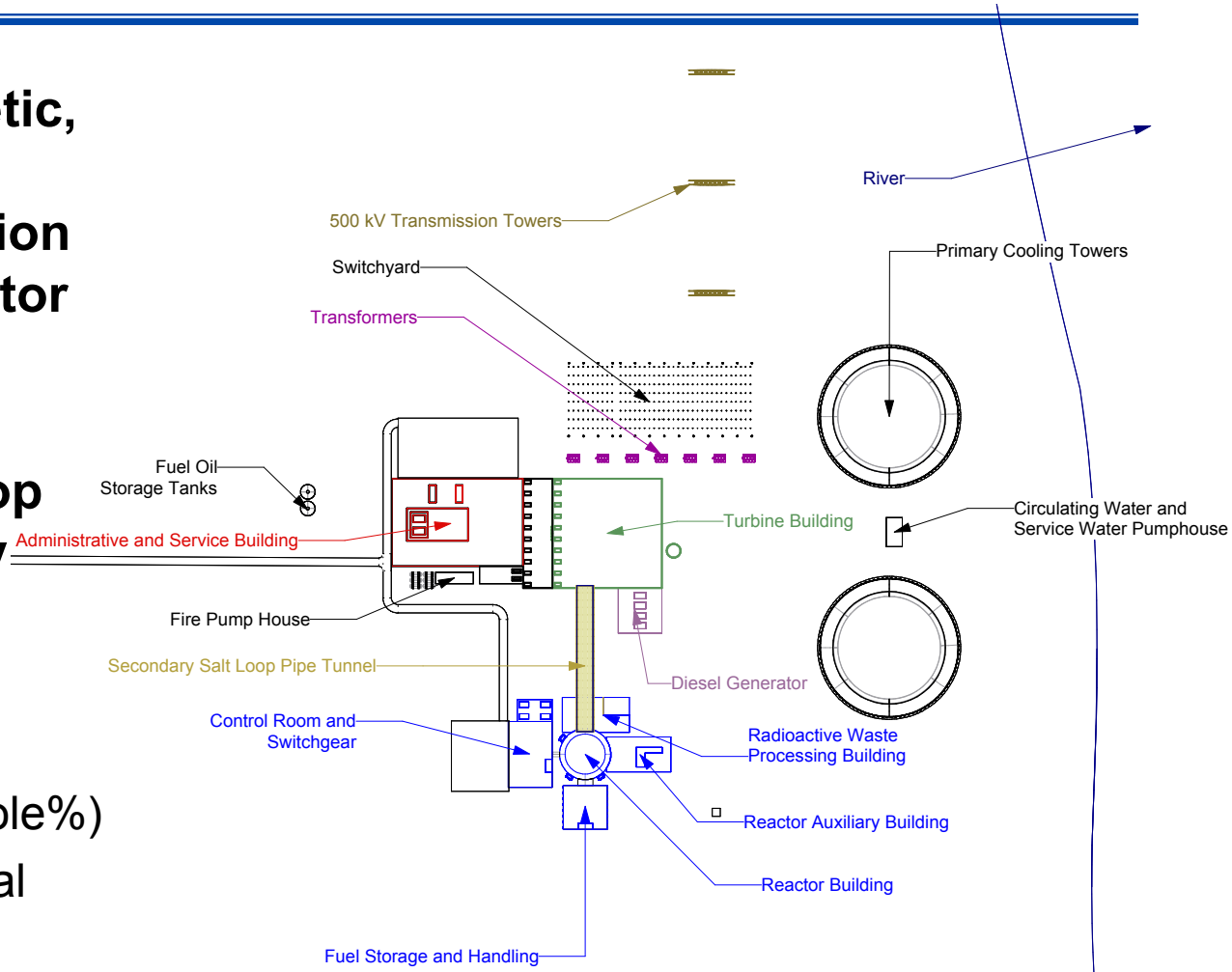


DOE-NE Has Just Awarded an Integrated University Project to Develop an FHR Test Reactor Design

- **Massachusetts Institute of Technology**
  - Pre-conceptual design and material testing at the MIT research reactor
- **University of California at Berkeley**
  - Thermal hydraulics and neutronics
- **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

AHTR Site Layout Isolates Nuclear Island From Power Plant

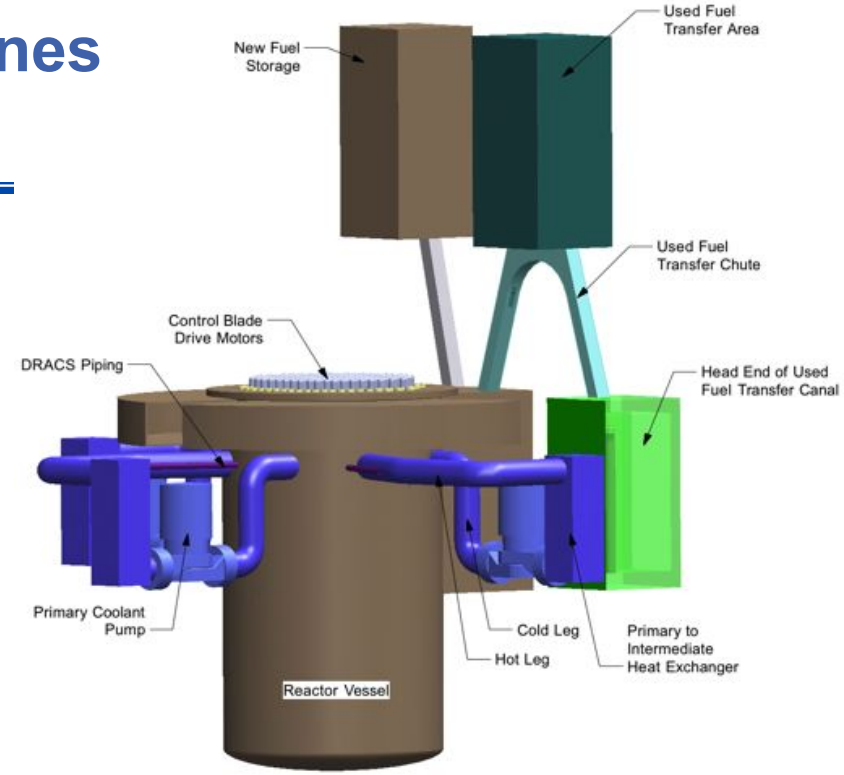
- **Separating energetic, high-pressure electricity generation process from reactor enhances passive safety**
- **Secondary salt loop cost does not vary significantly with length**
  - Thin walled pipe
  - $KF\text{-}ZrF_4$(47-53 mole%)
  - Provides additional length for tritium extraction

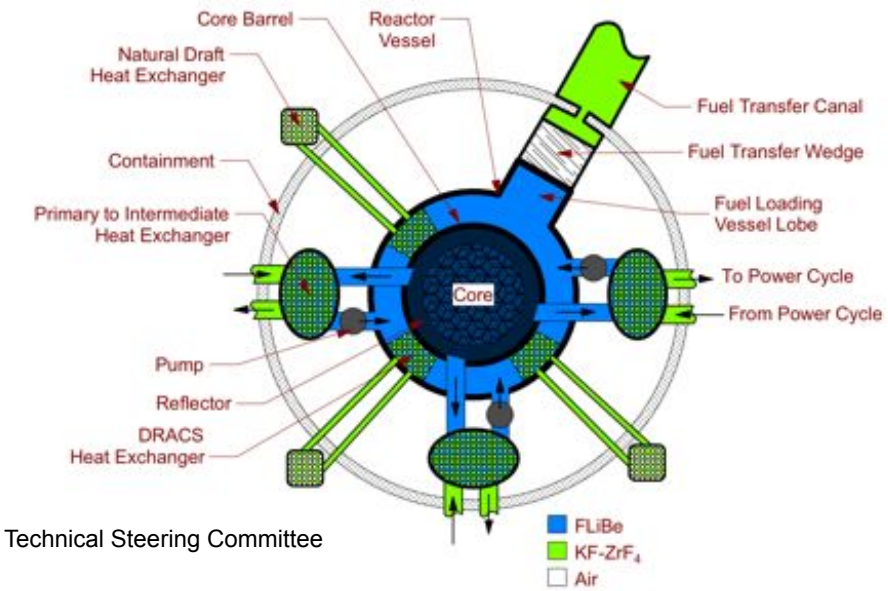


No materials with potential for energetic chemical processes allowed within nuclear island

AHTR Heat Transport Combines Loop and Integral Features

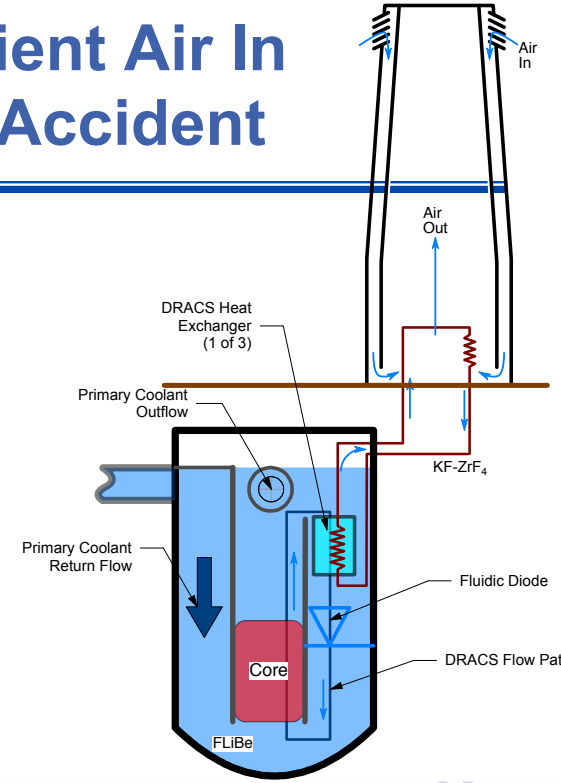
- **Normal operations heat transport is via three loops**
  - Loops have no safety role
  - Primary loop length is minimized to minimize expensive, primary salt volume
  - Primary to intermediate heat exchangers are within containment
- **Decay heat rejection heat exchangers are integral to the reactor vessel**
- **All reactor vessel penetrations are near the top**
- **Refueling occurs with vessel lid in place**

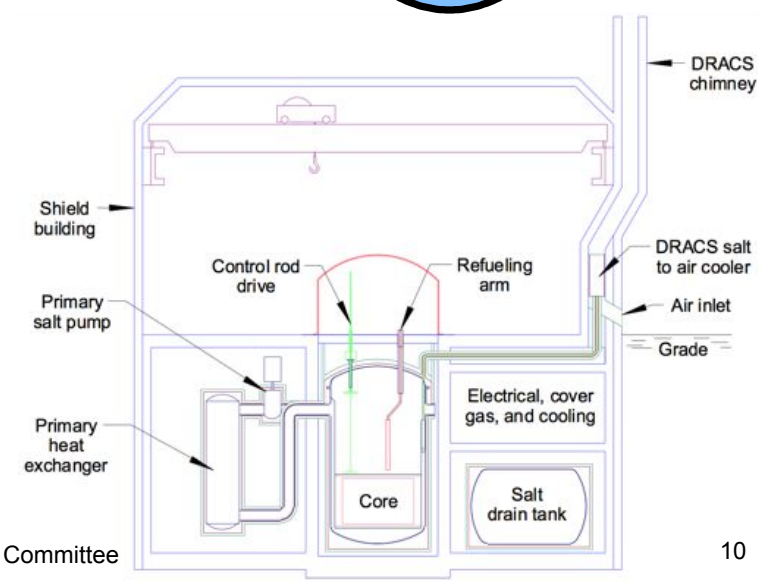




DRACS Rejects Decay Heat to Ambient Air In the Event of a Loss of Forced Flow Accident

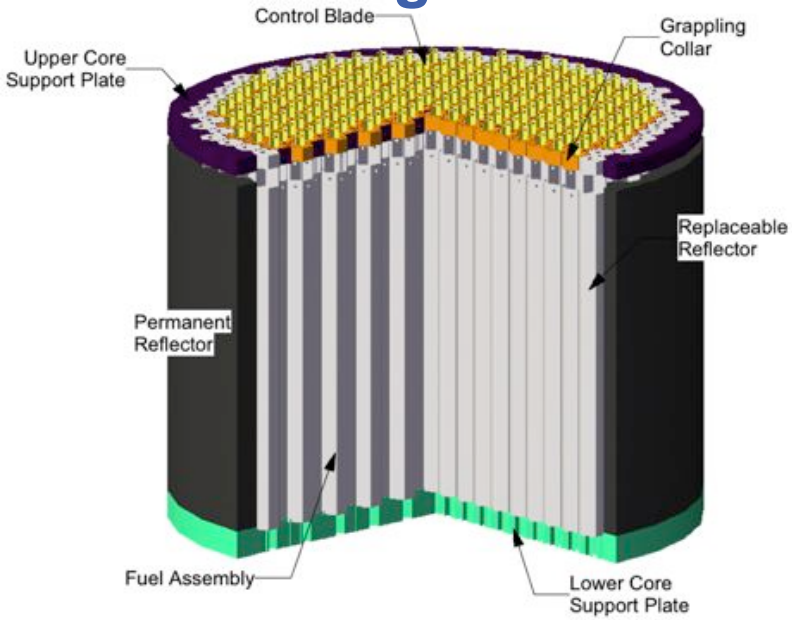
- **Loss of forced flow decay heat removal is via three, independent natural convection driven direct reactor auxiliary cooling system (DRACS) loops**
  - DRACS primary heat exchangers are located in vessel downcomer
  - Bypass flow through DRACS is minimized by fluidic diode below heat exchanger
- **DRACS employs three coupled buoyancy driven loops (FLiBe, KF-ZrF_4, and air)**
- **Each DRACS is sized to reject 0.25% (8.5 MW) full power at operating temperature under fully developed flow**

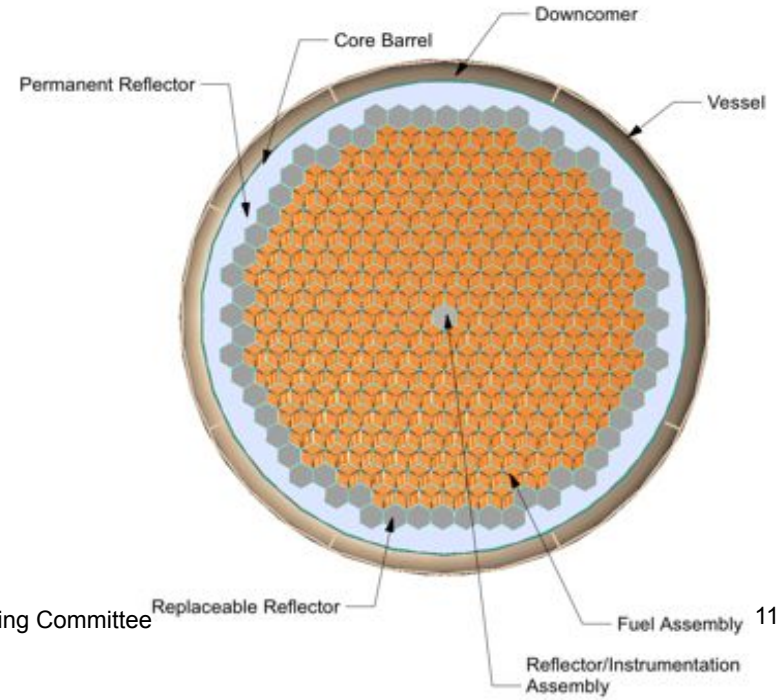




AHTR Core Consists of 252 Identical Hexagonal Fuel Assemblies

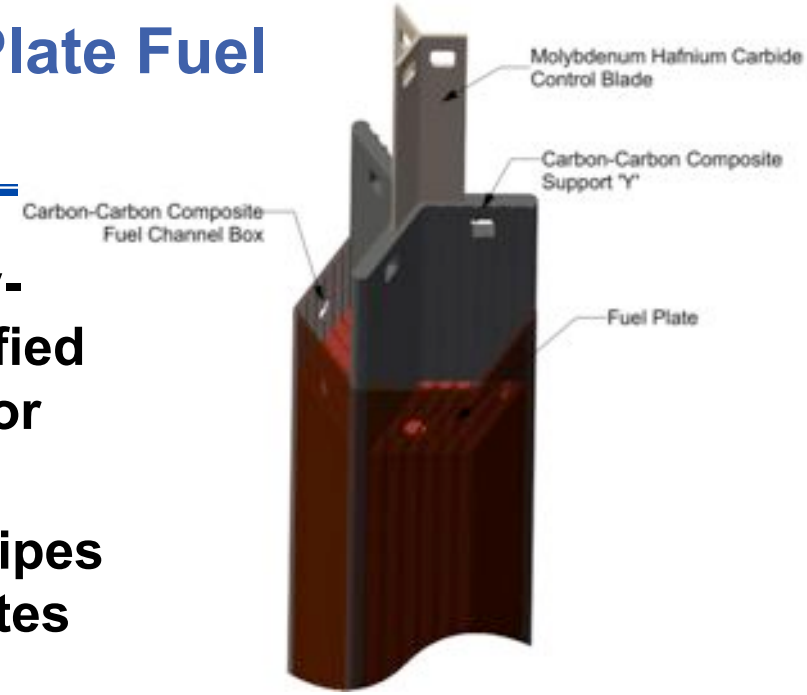
- **Core surrounded by replaceable and permanent graphite reflector columns**
- **Fueled core height 5.5 m**
- **Total core height 6.0 m**
- **Fuel assembly pitch 46.75 cm**
- **Equivalent fueled core diameter 7.81 m**
- **Volumetric power density 12.9 MW/m^3**
- **Core makes extensive use of carbon fiber and silicon carbide fiber composites**
  - Molybdenum alloy control blade is only metallic material in core

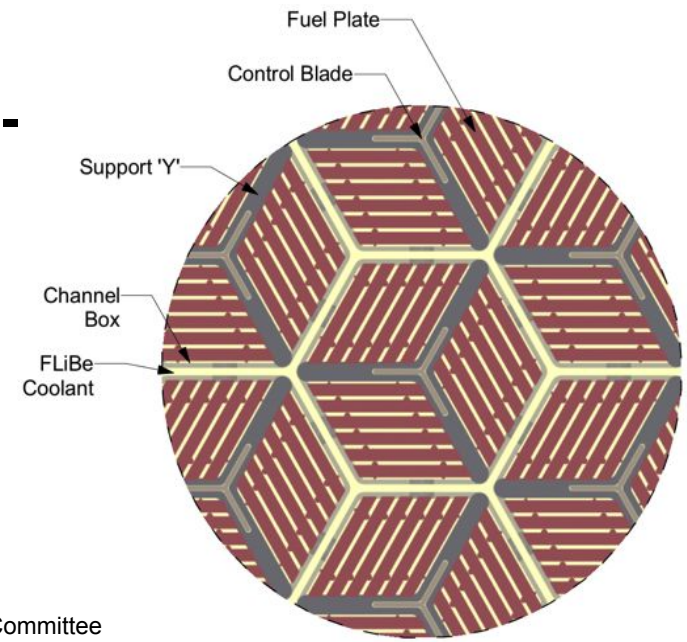


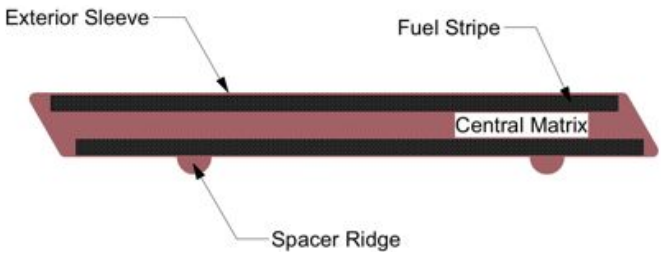


AHTR Uses Coated Particle Plate Fuel Assemblies

- **Coated particle fuel is a uranium oxy-carbide variant currently being qualified under DOE-NE Advanced Gas Reactor (AGR) program**
- **Fuel particles are configured into stripes just below the surface of the fuel plates**
  - Minimizes heat conduction distance to coolant
- **Fuel assemblies are surrounded by a C-C composite shroud to channelize coolant flow**



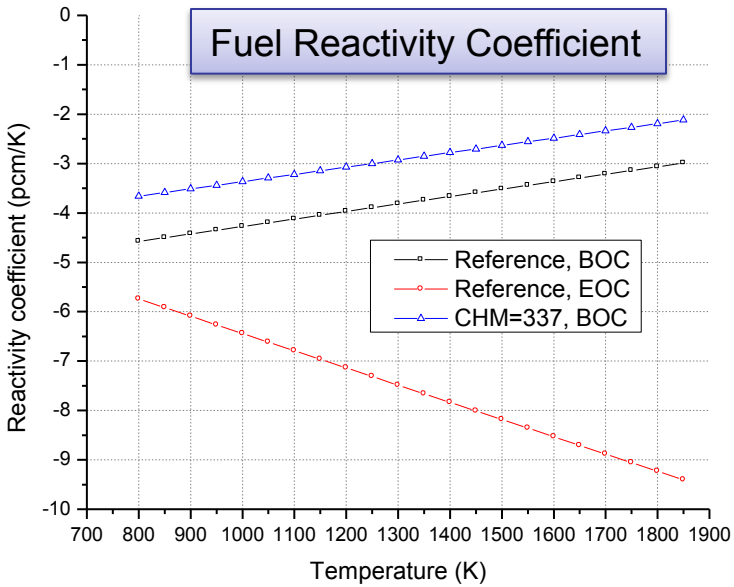


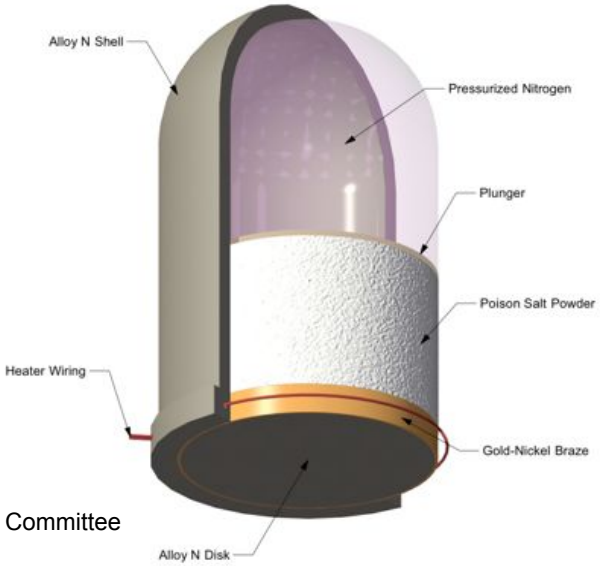


Fuel Plate Cross Section

Reactivity Control is Provided Through Diverse Mechanisms

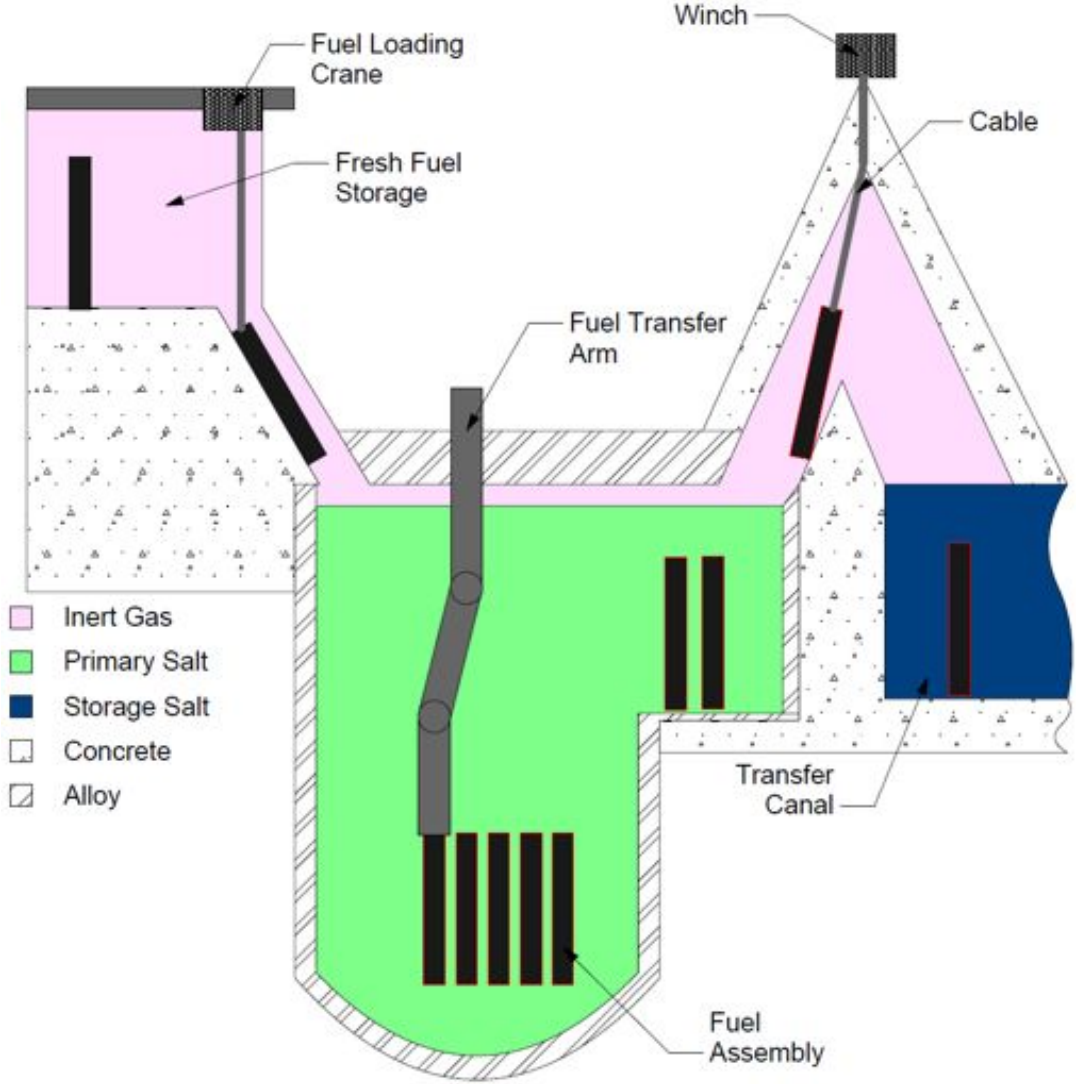
- **Fuel temperature, coolant temperature, and coolant void coefficients are all negative**
  - Magnitude depends on carbon to heavy metal ratio and burnup
  - Impact of burnable poison particles yet to be calculated – anticipated to be beneficial
- **Control blade included in each fuel assembly**
  - Molybdenum hafnium carbide alloy
  - Control blade remains with fuel assembly during refueling to minimize possibility of criticality accidents
- **Thermally triggered poison salt (EuF_3) injection selected as secondary shutdown method**
- **All accident sequences are slow and no known accident requires a control response**





AHTR Fuel Handling Resembles Sodium Fast Reactor

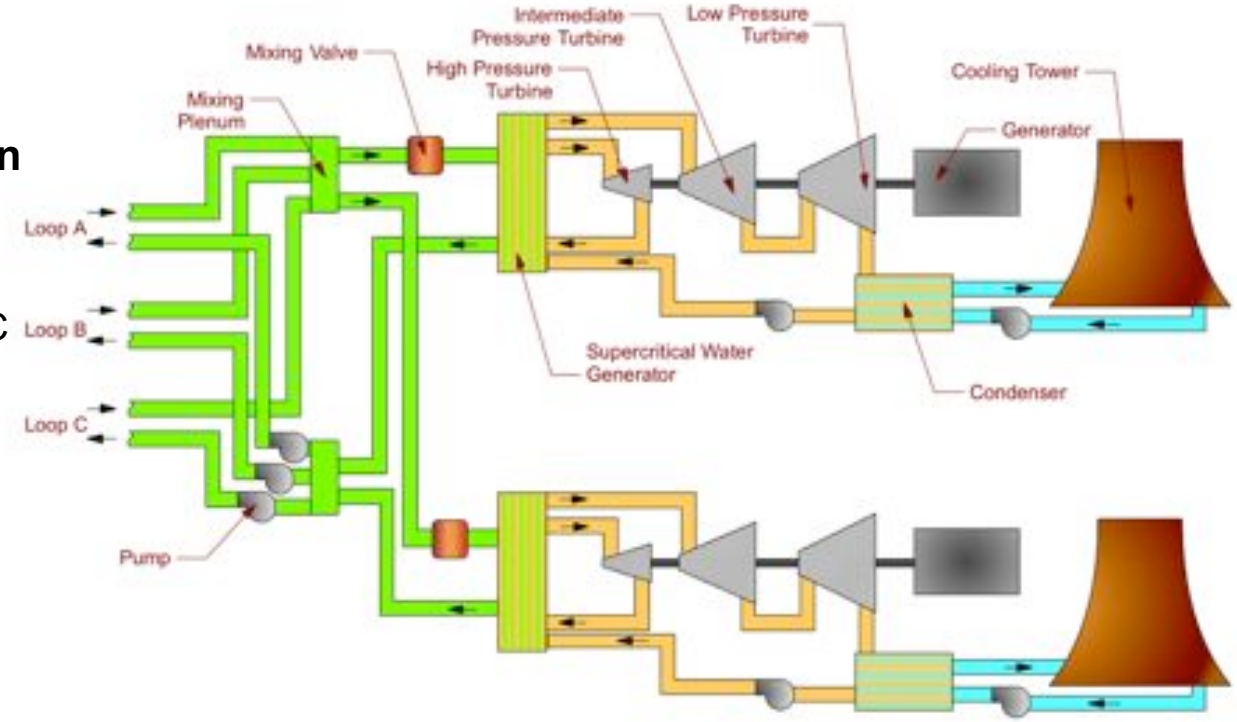
- **Transparent coolant enables visual refueling**
- **Time consuming steps not required**
  - Cooldown
  - Opening head
  - Flooding channel
  - Lifting and storing head and internals
- **Transfer to storage pool salt under cover gas**
- **Several minutes of transfer time before fuel overheats in gas**
- **Refueling shutdown times anticipated to be less than 3 days**



Optimal Power Conversion Cycle is Not Obvious

Reheated Supercritical Water Selected as Baseline AHTR Power Conversion Cycle

- **Supercritical CO_2**
  - Not mature or scaled
  - Corrosion concerns
- **Helium or helium-nitrogen**
  - Large components
- **Open air**
  - Lower efficiency at 700 °C
- **Subcritical steam**
  - Mature
  - Good cost models
- **Supercritical water**
  - Highest proven efficiency
  - Highest pressure



Initial AHTR Economic Model Demonstrates Competitiveness with Large LWRs

- **Significant uncertainties remain in the model data**
- **Economic modeling is performed using the international EMWG Generation IV Excel Calculation of Nuclear Systems (G4-ECONS)**
  - Model estimates Levelized Unit Electricity Cost (LUEC) based upon structured set of capital and operating costs
- **Evaluation utilizes the Energy Economic Data Base (EEDB) prepared by DOE in the 1970s and 1980s for use in comparing costs for different nuclear and nonnuclear systems**
  - Costs escalated to 2011
- **While the preliminary evaluation shows the AHTR's LEUC to be lower than that for a large LWR, sufficient uncertainty remains to prevent drawing conclusions**
  - Higher efficiency of AHTR balances against the higher fuel cycle cost and specialized commodity costs (^{7}Li and Be)

FHR Reactor Class Shows Much Promise

Still Requires Significant Research, Development, and Demonstration

- **More complete reactor conceptual design required**
  - Needs to include all of the specialized systems and components
- **Refueling mechanisms remain to be designed**
- **Replacement industrial scale lithium enrichment**
- **Salt chemistry control system requires basic design**
- **Structural ceramics must become safety grade nuclear engineering materials**
- **Process instrumentation requires further development**
- **Safety and licensing approach must be developed and demonstrated**
- **Plate fuel manufacturing technology must be demonstrated**