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 OECD Headquarters

Paris, France

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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 are Central to DOE-NE Advanced Reactor Concepts Program Mission

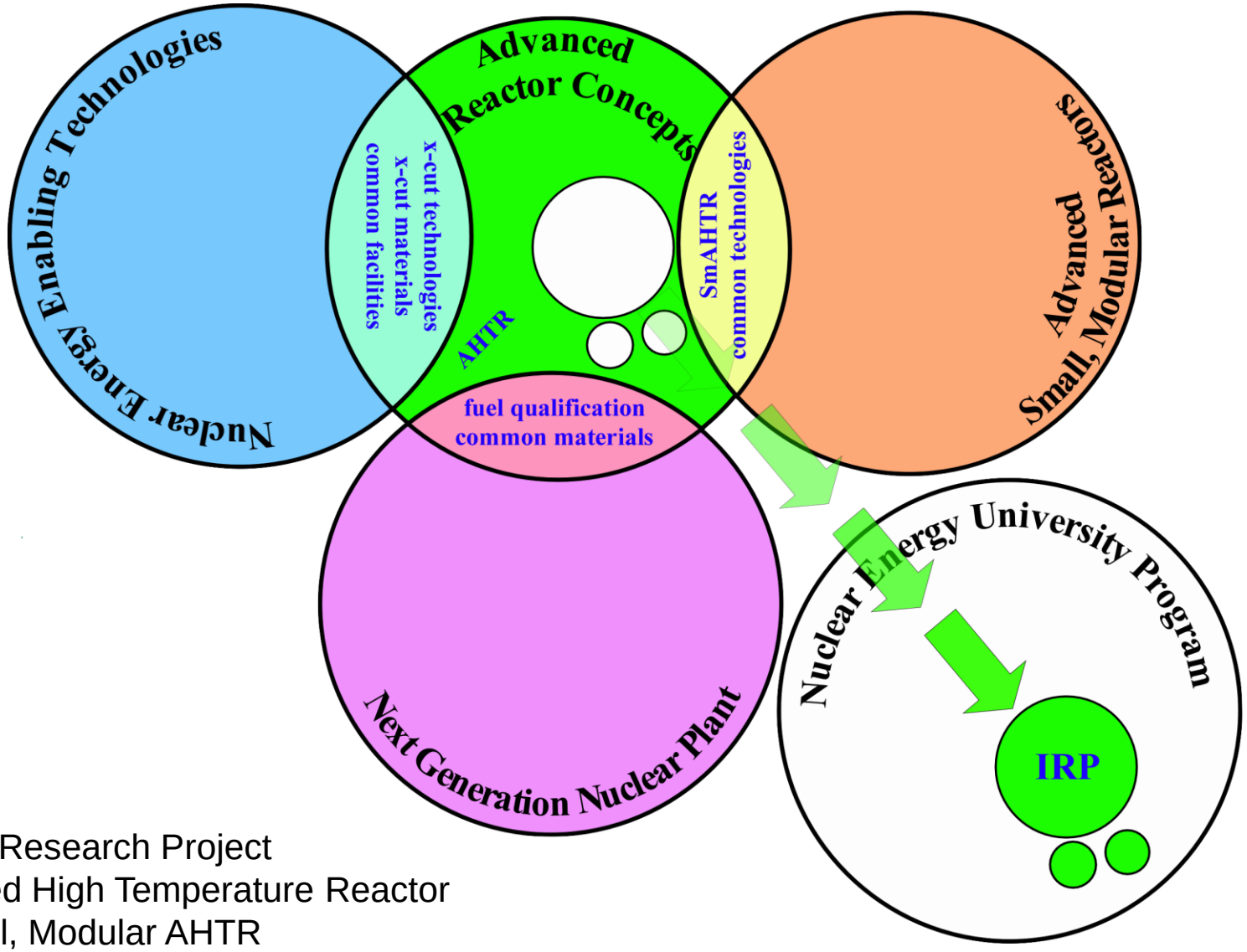
ARC's mission is to develop and refine future reactor concepts that could dramatically improve nuclear energy performance (e.g., sustainability, economics, safety, proliferation resistance)

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)
  - Advanced Small Modular Reactors (aSMR)*

    * Not yet fully started

Advanced Reactor Concepts is the Integrating Organization for FHR Development



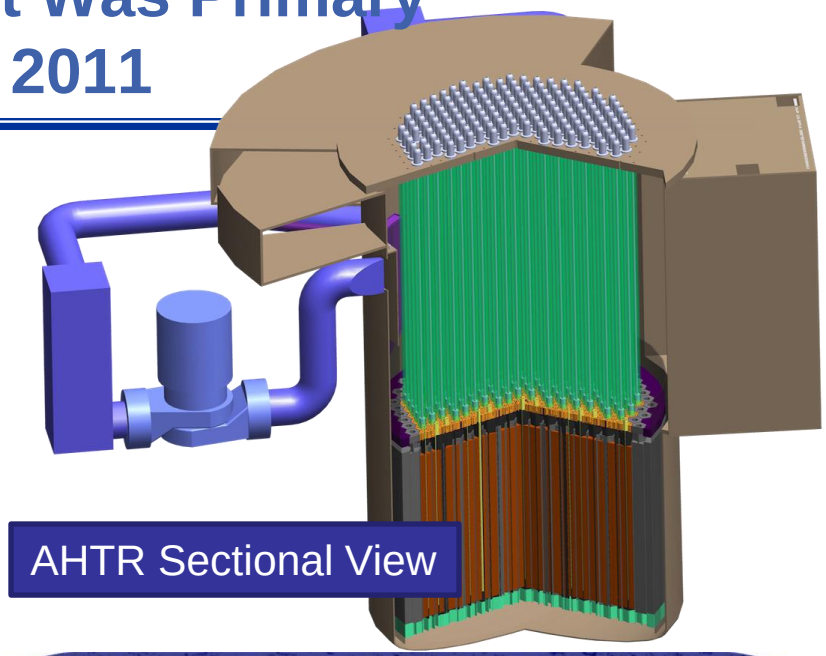
IRP = Integrated Research Project
AHTR = Advanced High Temperature Reactor
SmAHTR = Small, Modular AHTR

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

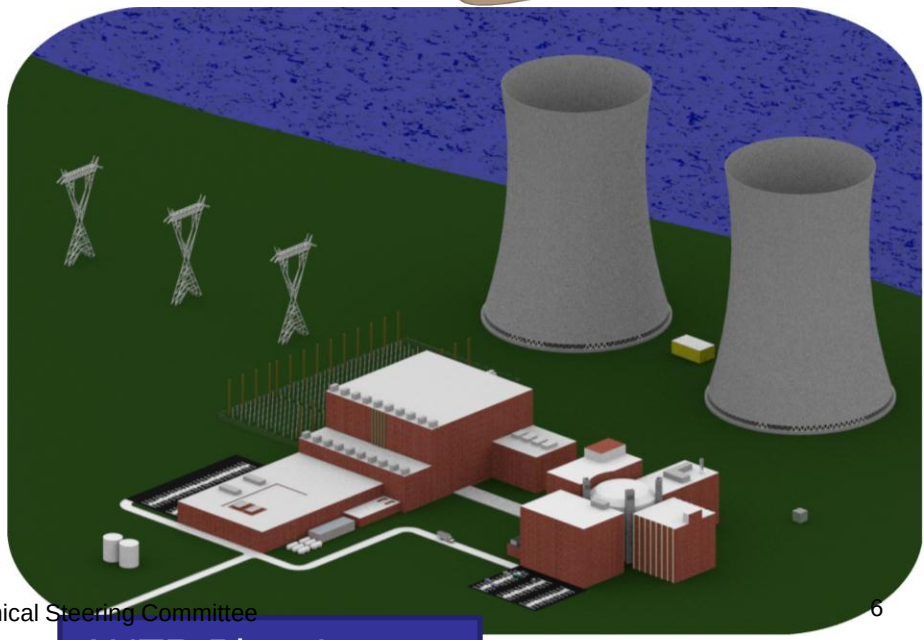
- **Massachusetts Institute of Technology**
  - Pre-conceptual design and material testing at the MIT research reactor
- **University of California at Berkeley**
  - Thermal hydraulics and neutronics
  - Safety and licensing
- **University of Wisconsin**
  - Materials and corrosion
- **Additional individual 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 Concept Development Was 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



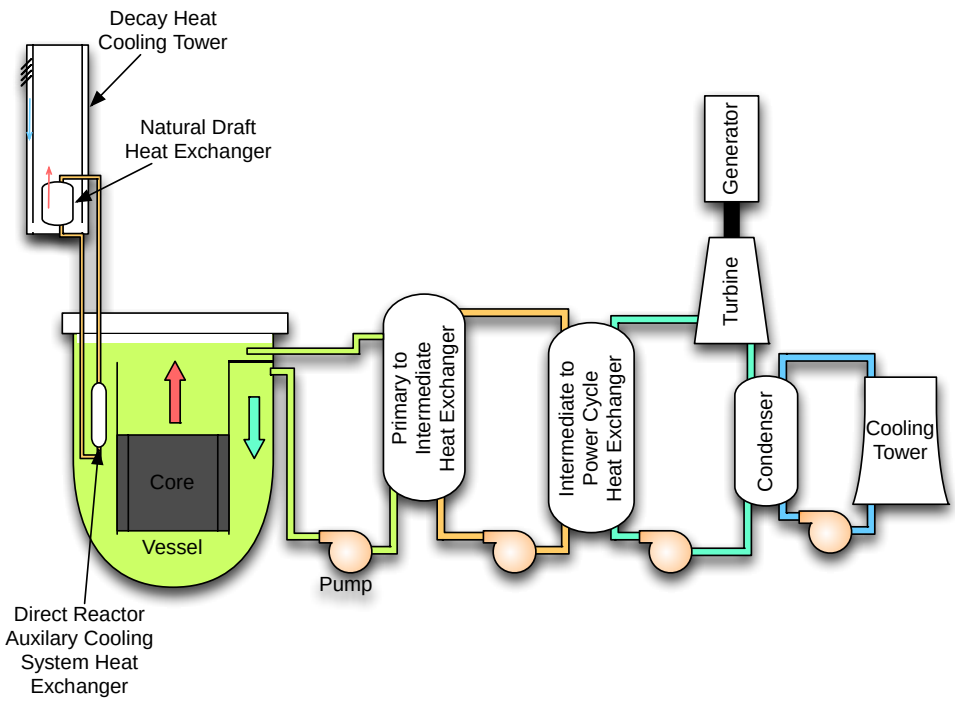
AHTR Sectional View



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

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**
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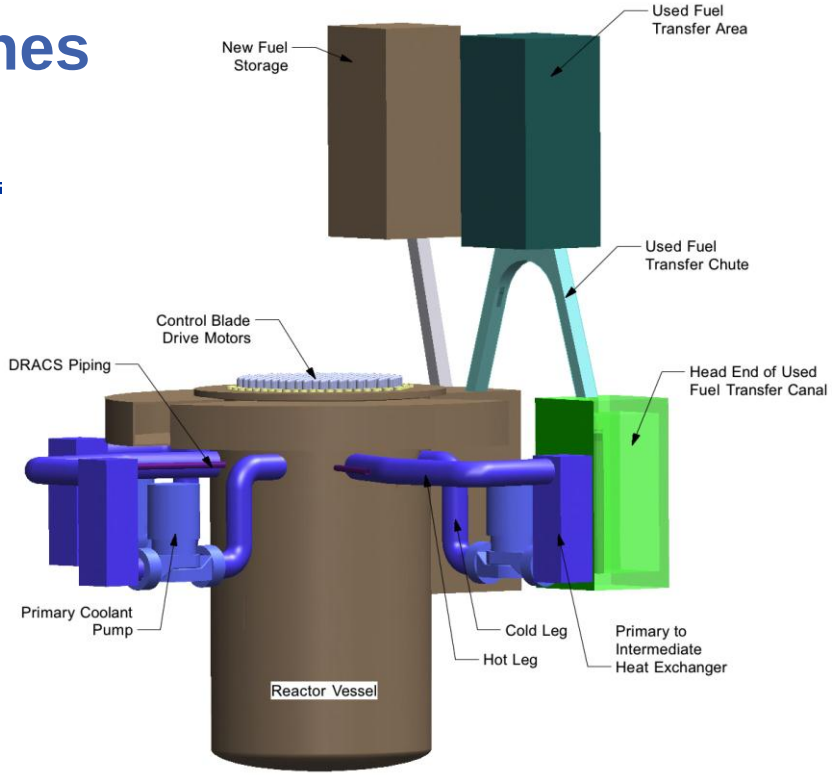
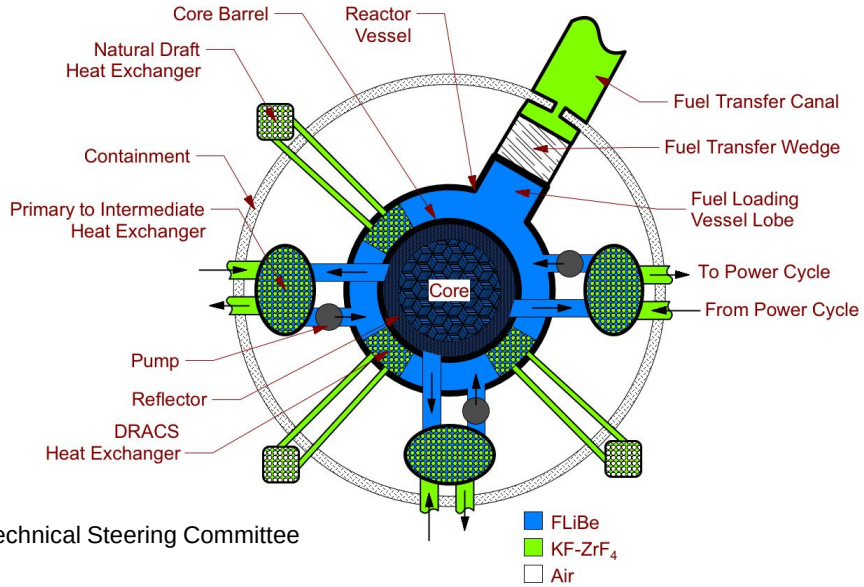
AHTR Heat Transport Combines Loop and Integral Features

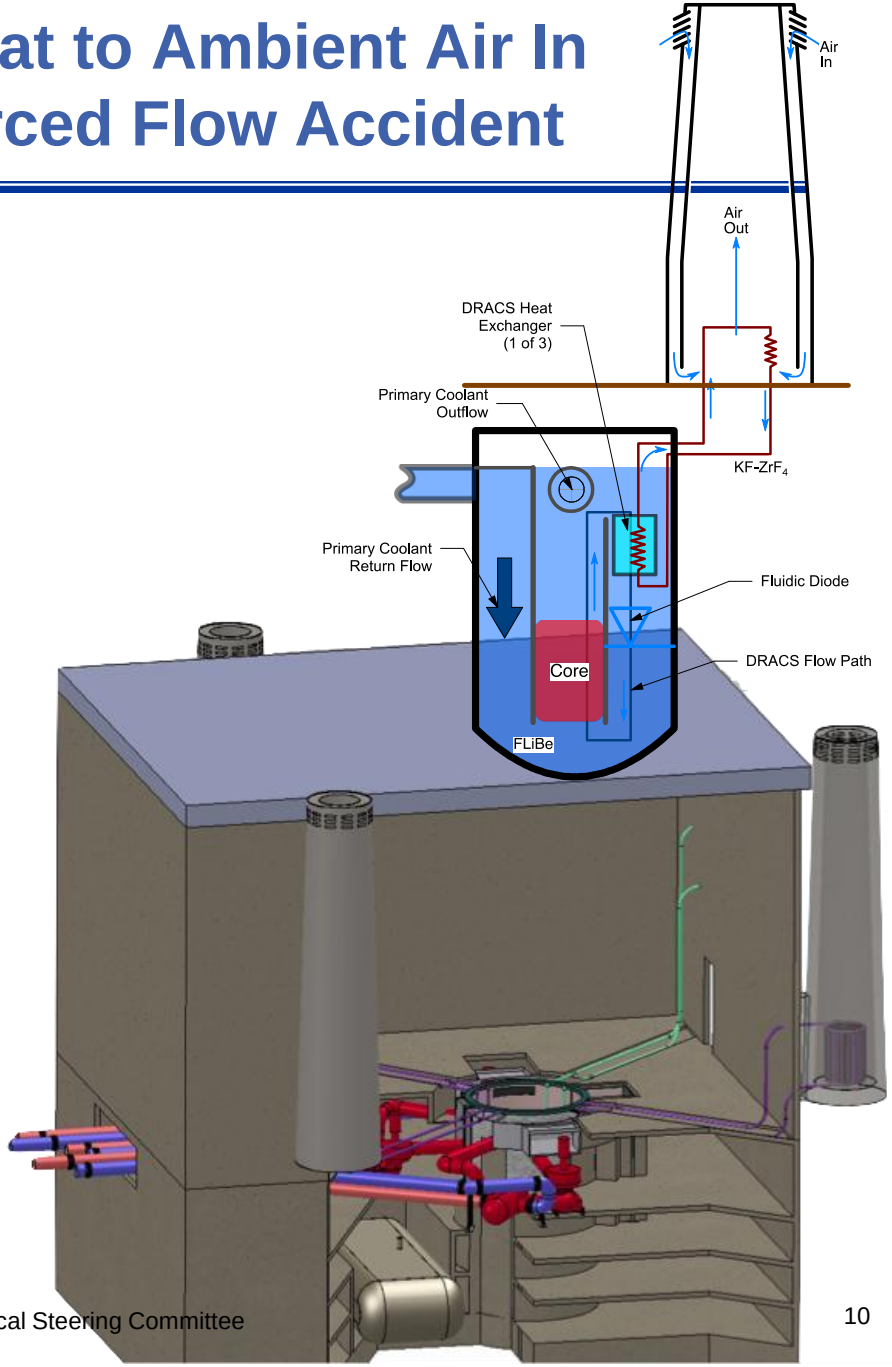
- **Normal operations heat transport is via three loops**
  - Loops have no safety role
  - Primary loop length is minimized to minimize expensive, primary salt volume
  - Primary to intermediate heat exchangers are within containment
- **Decay heat rejection heat exchangers are integral to the reactor 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**



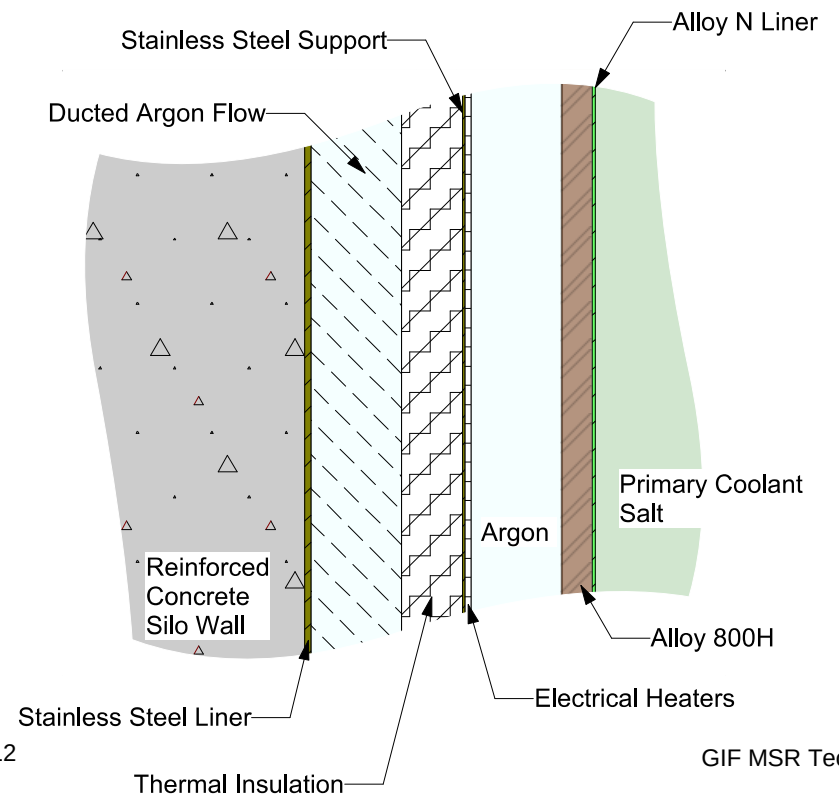
Strong FHR Safety Case Makes Licensing Through Evolutionary Change to NRC Process Possible

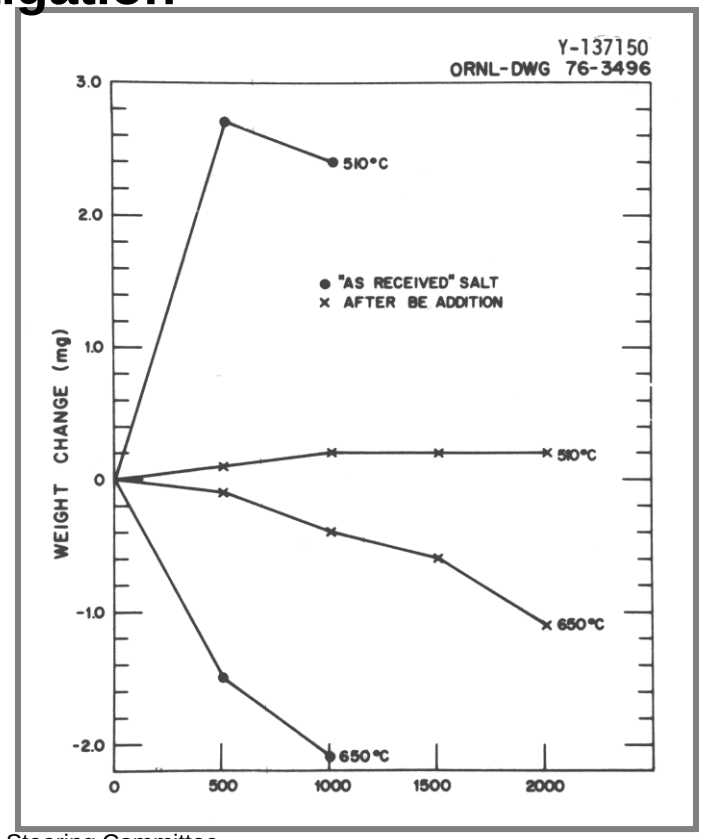
NRC Has Very High Inertia and Revolutionary Change is Unlikely to Succeed

- **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 the FHR customized set of GDCs**
  - Organizing meeting set for immediately following president's reception at the summer 2012 ANS meeting
  - Will require NRC endorsement
  - Will provide guidance on experimental demonstrations required
- **Design specific safety analysis report will show how GDC are fulfilled**
  - E.g. - Fusible links versus buoyancy drive in negative reactivity insertion system
- **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

AHTR Vessel and Piping are Planned to Be Alloy 800H with Alloy N Liner

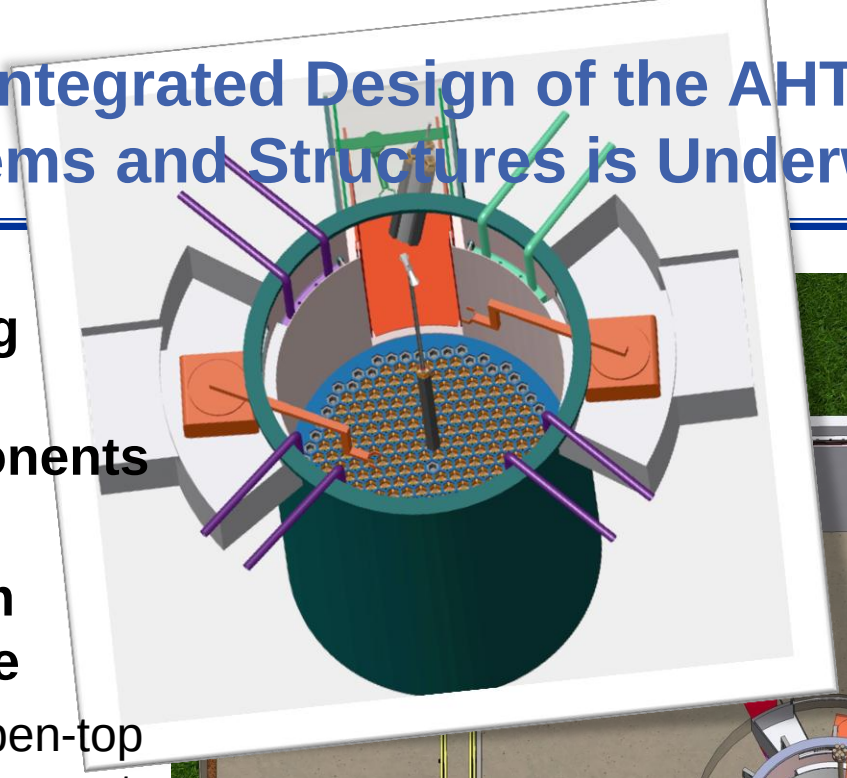
- **Alloy 800H has 60 year ASME BPVC ratings for high temperature nuclear service**
- **Alloy N is chemically compatible with fluoride salts**
- **Redox control is key to corrosion mitigation**

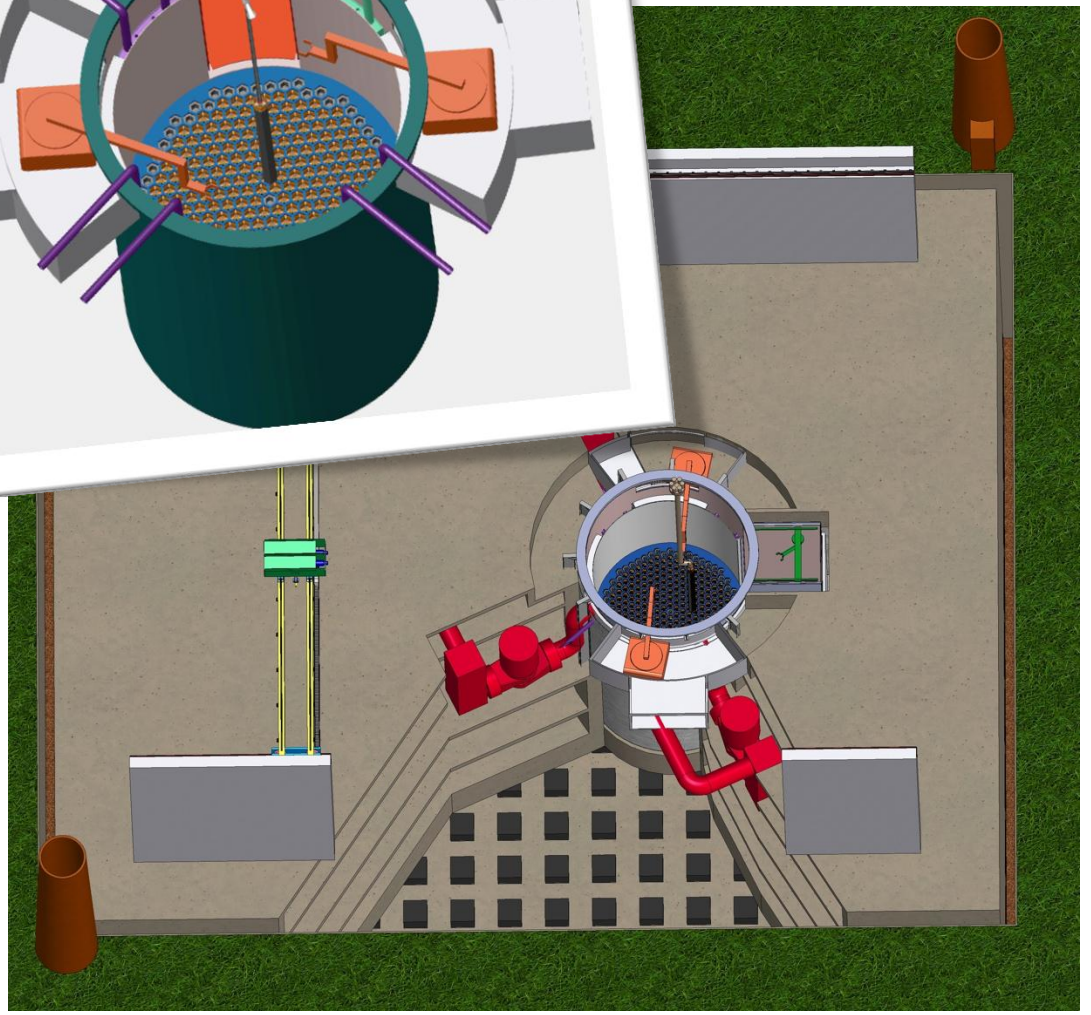




Mechanically Integrated Design of the AHTR Reactor Building Systems and Structures is Underway

- **Focus is on integrating necessary systems, structures, and components**
- **A design focus is on maximizing the system economic performance**
  - Employing modular, open-top construction to minimize cost
  - Availability increased through automated refueling and ease of access for inspection and maintenance
  - Maintaining full passive safety when subjected to severe environmental challenges

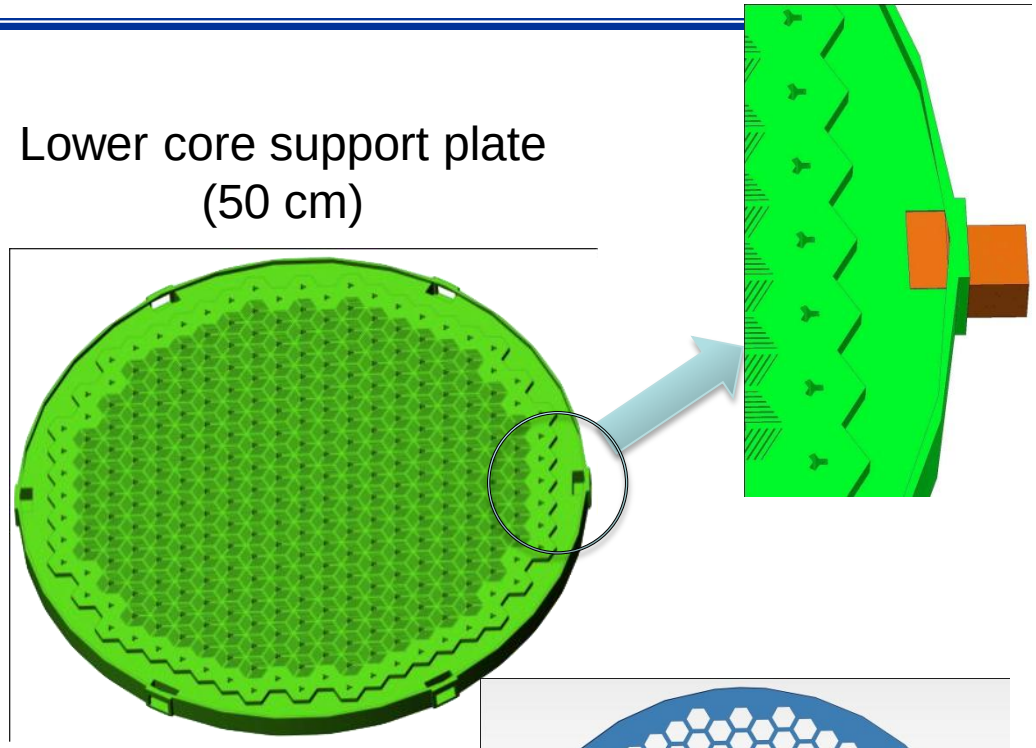




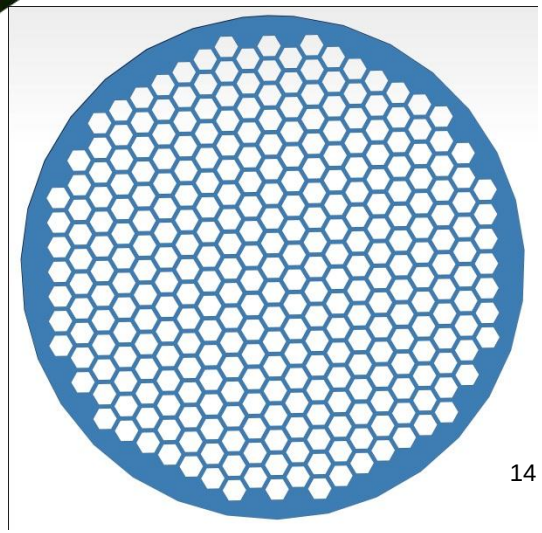
AHTR Employs Ceramic Composite Core Support Plates to Minimize Temperature Impact

- **Lower core support plate anchored to the vessel**
  - Accommodates differential thermal expansion between the vessel and the plate
- **Flow channels are provided through lower core support plate to direct flow into the core**
- **Upper core support plate connected to top flange**
- **Upper core support plate raised during refueling**
- **Both plates are made from SiC-SiC composite**

Lower core support plate (50 cm)



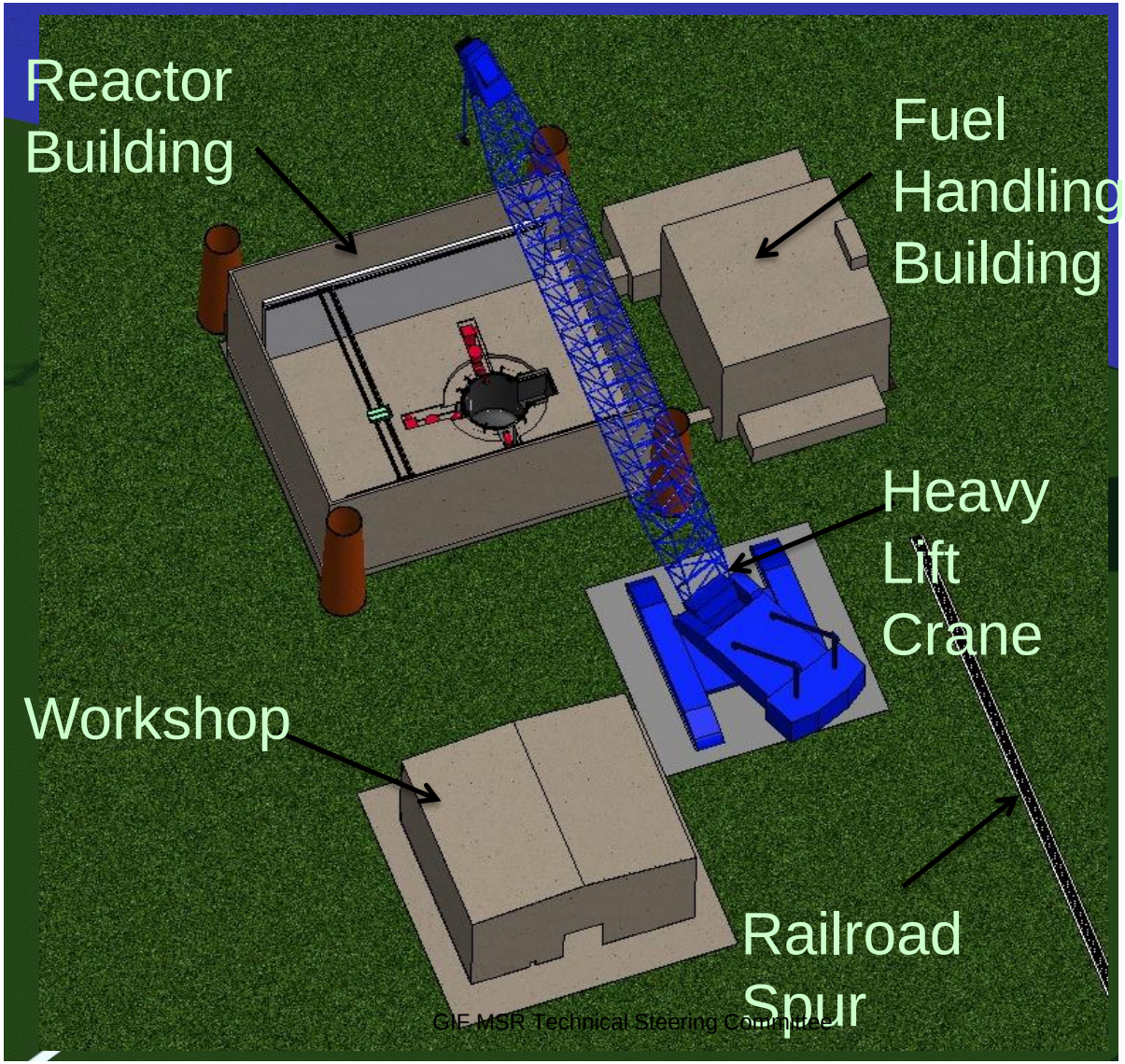
Upper core support plate (30 cm)



Low Pressure Containment is Located Within the Shield Structure

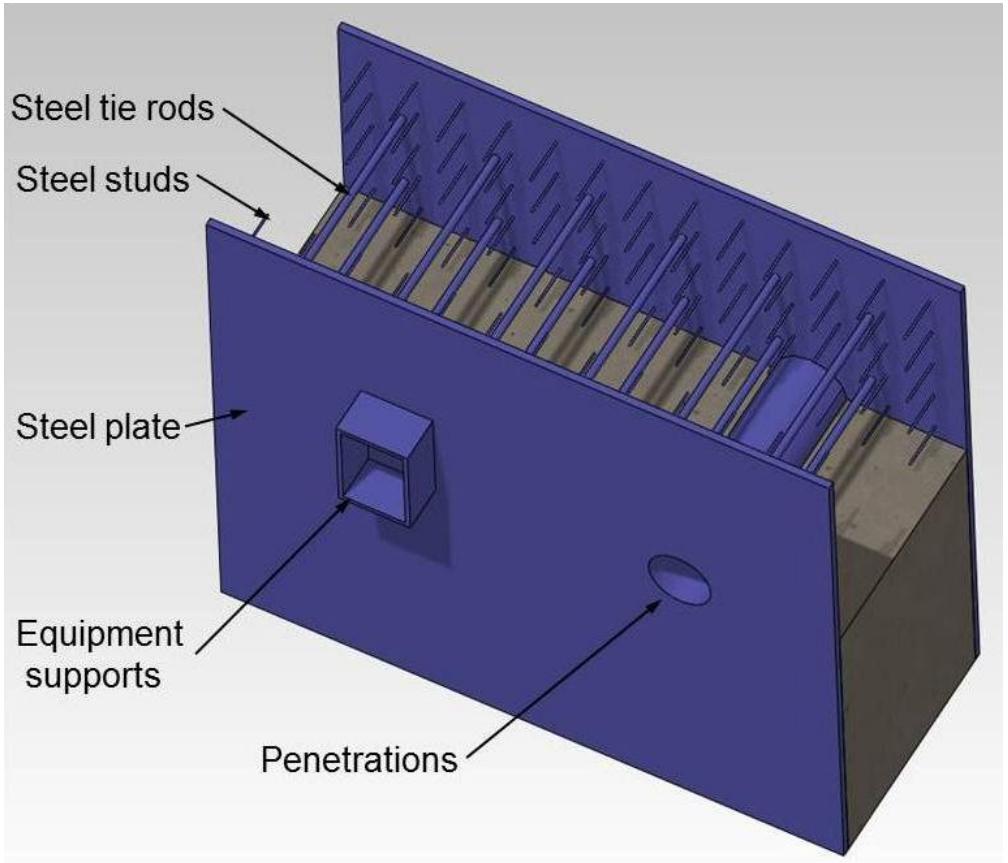
- **Under normal operations the containment building serves as the outer boundary for beryllium and tritium**
  - Under accident conditions containment building provides radioactive material barrier
- **All areas within the containment building have argon atmosphere**
- **Confined areas within the shield structure, not within containment, have dry air atmosphere (e.g. electrical switch panel and manipulator maintenance areas)**
- **Tops of the shield structure and containment building will be opened for construction and for major maintenance**
- **Reactor component cooling system and cavity cooling system will use a forced flow argon system for cooling during normal operations**
  - Heat sink is provided through a chilled nitrogen cooling loop, which passes through containment
- **For loss of forced flow accidents cavity passive cooling will be through the reactor building steel walls to the air trench surrounding the shield building**
  - Cavity heat load is small without pumps operating due to well insulated primary system
- **To avoid the potential to overpressure containment due to phase change, no large-volumes of water will be used within containment**

AHTR Plant Layout Includes Construction Scheduling



Modular Assembly Featuring Steel Plate Concrete Forms Employed to Shorten Schedule

- **Steel plate concrete forms prefabricated off-site will save cost and schedule**
  - Assembled together and welded on-site where concrete is poured
  - No rebar fabrication on-site
- **Much of the site worked performed in local workshop**
  - General Dynamics rule-of-thumb ratios of time as 1:3:9 for factory to workshop to in-situ fabrication

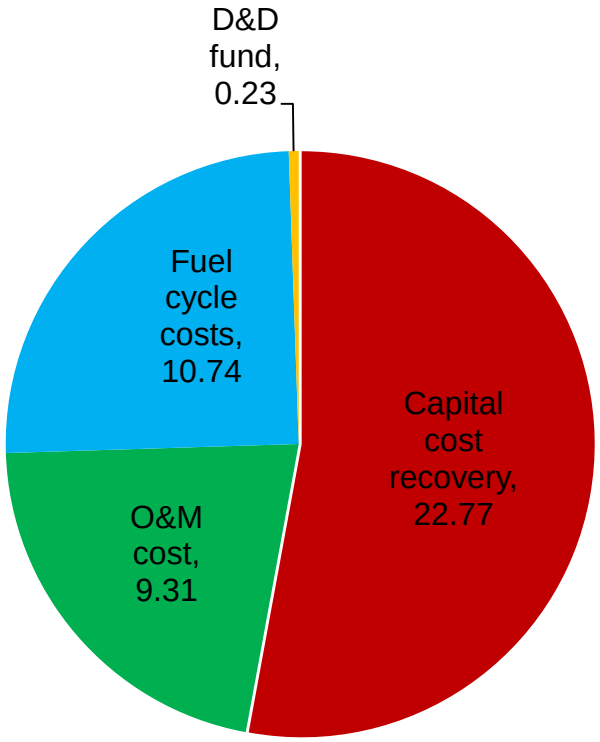


Gen IV – Economic Model Indicates that AHTRs Have the Potential For Lower LUEC than PWRs

Very significant uncertainty remains in the cost estimates

Levelized unit cost output from G4-ECONS (mills/kWh)

Reactor system	PWR 12 better experience	AHTR
Capital cost recovery	29.66	22.77
Operation and maintenance	12.60	9.31
Fuel cycle costs	5.60	10.75
Decommissioning fund	0.32	0.23
Levelized unit cost of electricity	**48.18**	**43.05**
Total capital investment cost, $/kW(e)	**4012**	**3149**

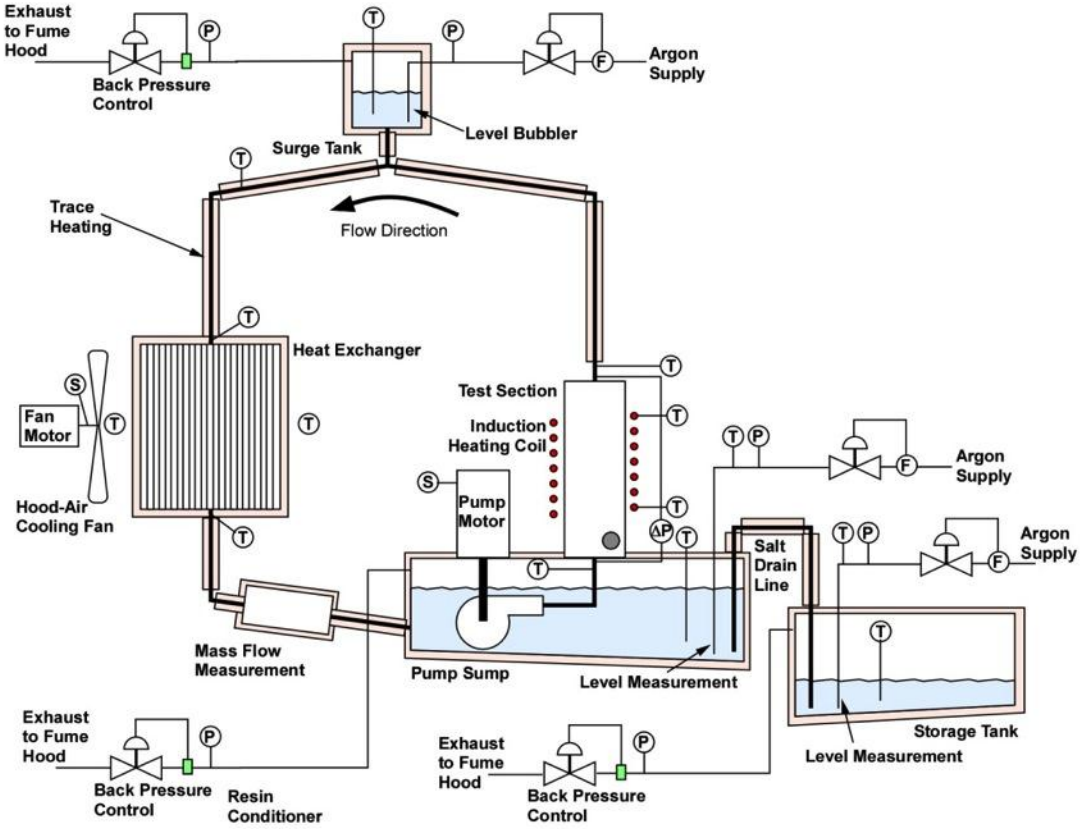


U.S. is Providing Isotopically Selected Fluoride Salt to Czech Republic in Return for Criticality Measurements

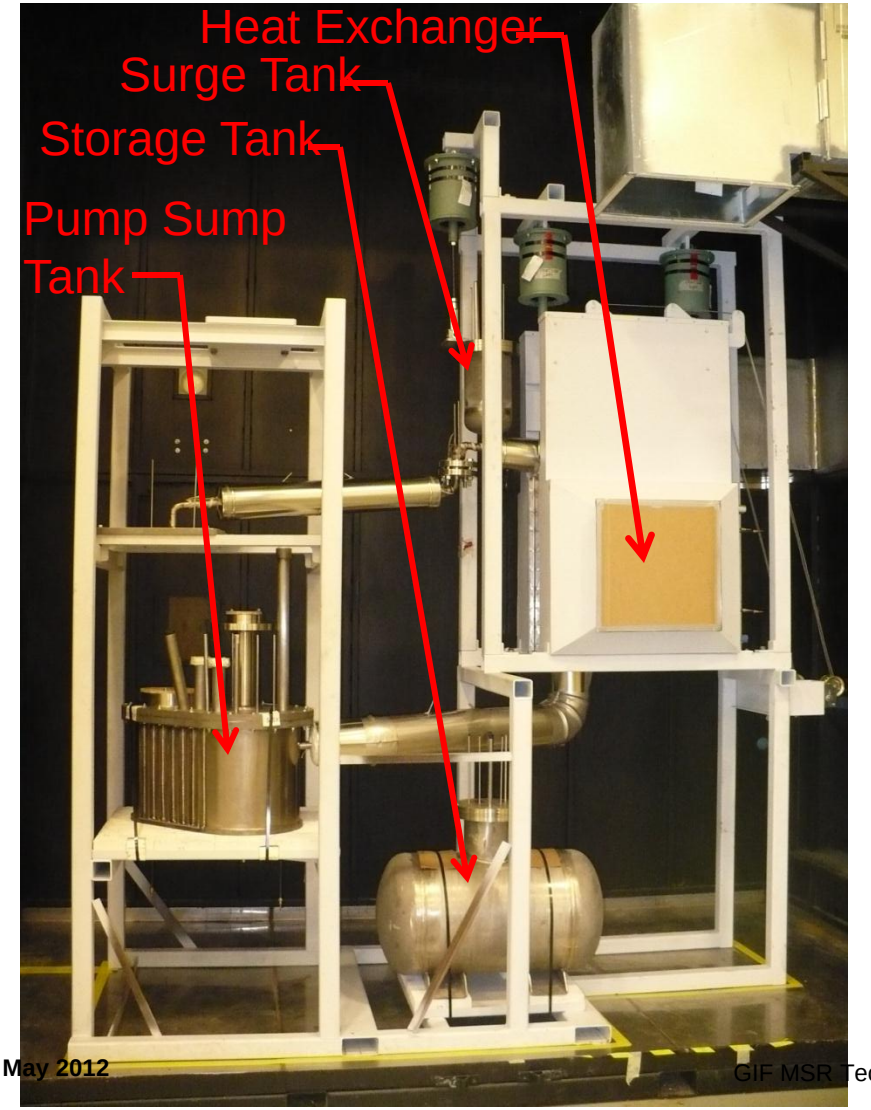
- **Subdivide existing canister of 2^7LiF-BeF_2 of into 75 kg aliquots**
  - Equipment installed
  - Final checkout underway
  - Large salt vessel installed March 30
  - Salt melt initiated mid May
  - Salt transferred by end of May
  - Ready to ship by mid June

Liquid Salt Test Loop is Nearing Completion

- Completion scheduled for September 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



Versatile Liquid Salt Loop Has Been Constructed To Help Develop High Temperature Salt Components



- **Experimental facility will include a salt purification system designed to remove moisture and oxides in the salt to minimize corrosion**
- **A fluidic diode (a leaky check valve with no moving parts) will be tested early in the experimental program**
  - Key decay heat removal component

- **Follow on testing will focus on scaled AHTR components such as:**
  - Fuel heat transfer testing
  - Improved pump designs
  - Salt-to-salt or salt-to-gas heat exchanger
  - Instrumentation
  - Refueling components

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**