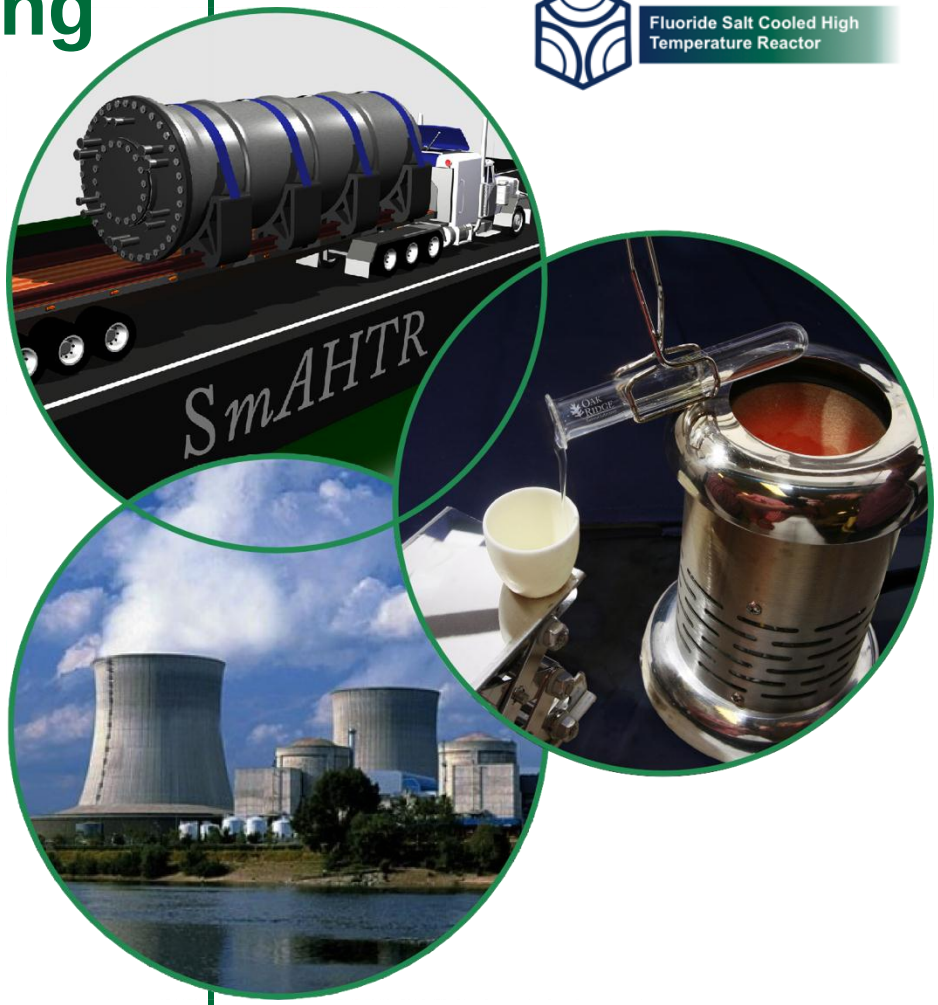
Instrumentation & Controls Technologies for Refueling the AHTR



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U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY

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What Defines an FHR?

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

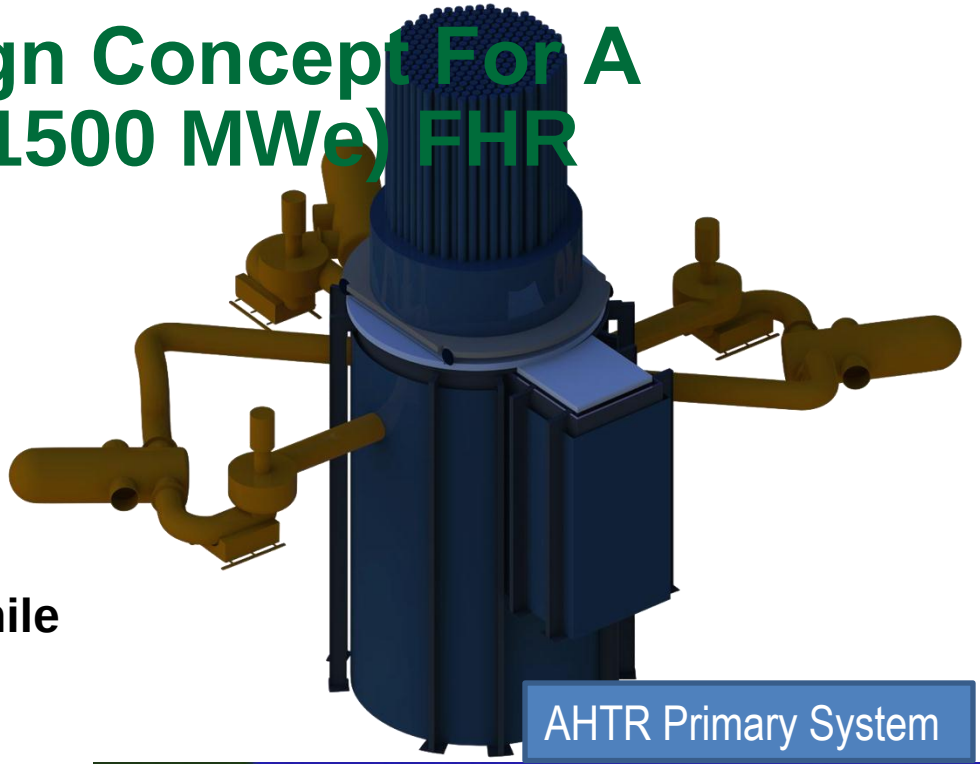
- Use of coated particle ceramic fuel
- Use of fluoride salt as primary coolant
- Use of a low-pressure, pool type primary system configuration
- Delivery of heat at temperatures greater than 600° C
- Strong passive safety features
  - No requirement for active response to avoid core damage or large off-site release following even severe accidents

FHRs Are Important to the World as a Potential Future Primary Electricity and Gasoline Energy Source

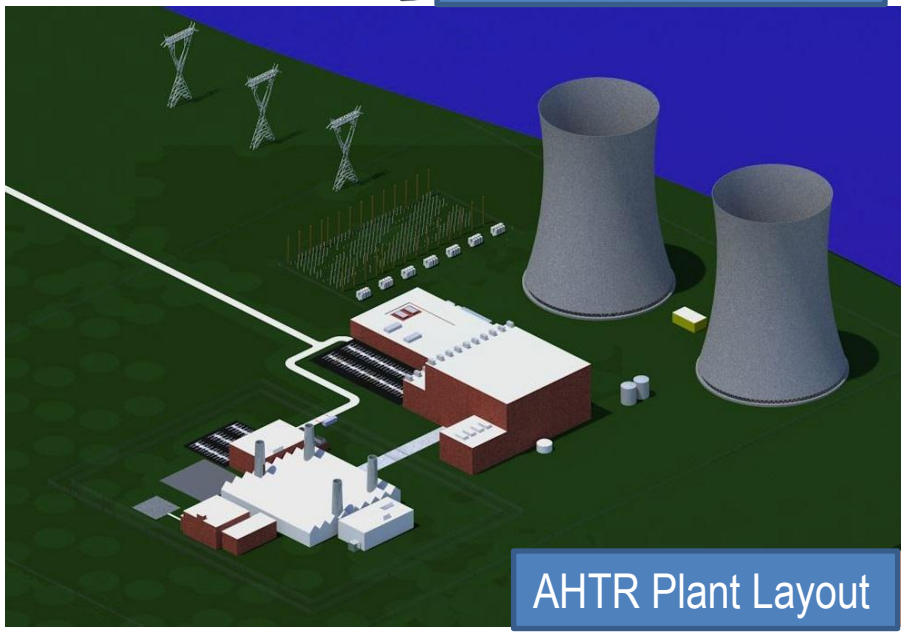
- **Large FHRs have transformational potential to provide lower cost, high efficiency, large scale electrical power**
  - May be cheaper than LWRs due to higher thermal efficiency, low-pressure, and passive safety
- **Small, modular FHRs can be cost effective, local process heat sources**
  - High temperature, liquid cooling enables efficient hydrogen production
  - Domestic oil shale based gasoline production requires large-scale, distributed process heat
- **FHRs have a high degree of inherent passive safety**
  - No requirement for offsite power or cooling water
  - Low-pressure primary and intermediate loops
- **Plant concept and technologies must be matured significantly before the potential for FHRs can be realized**
  - Lithium enrichment must be reindustrialized
  - Tritium extraction technology must be developed and demonstrated
  - Structural ceramics must become safety grade engineering material
  - Safety and licensing approach must be developed and demonstrated
  - Structured coated particle fuel must be qualified
  - …

AHTR Is ORNL's Design Concept For A Central Station Type (1500 MWe) FHR

- **Development is sponsored by U.S. Department of Energy, Office of Nuclear Energy, Advanced Reactor Concepts Program**
- **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



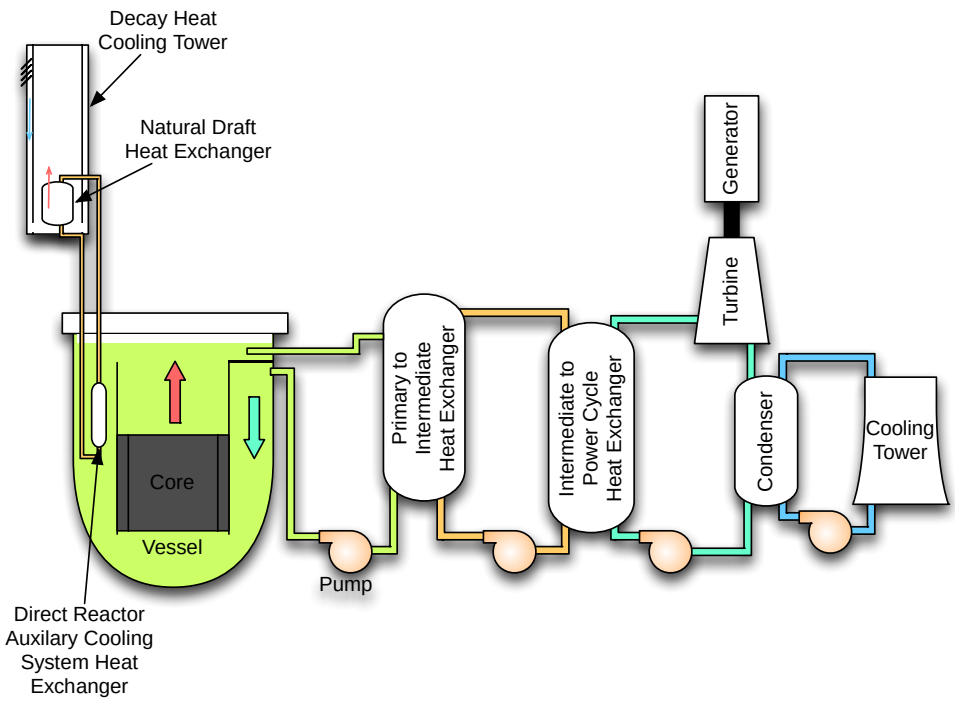
AHTR Primary System



AHTR Plant Layout

AHTR is Progressing Towards a Preconceptual Design Level of Maturity

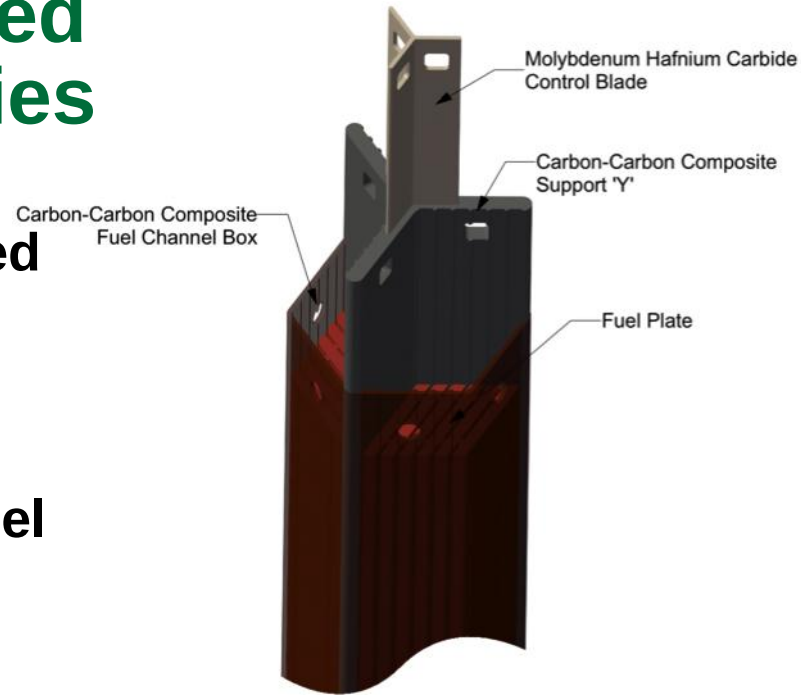
Both reactor and power plant systems are included in the modeling

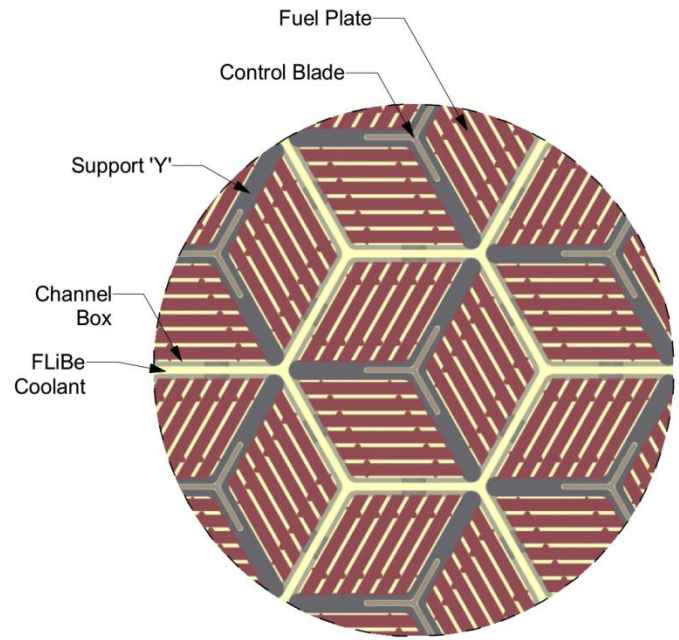


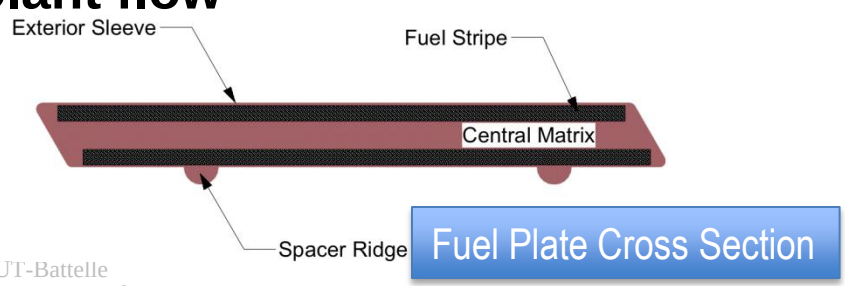
AHTR Properties	
Thermal Power	3400 MW
Electrical Power	1500 MW
Top Plenum Temperature	700 °C
Coolant Return Temperature	650 °C
Number of loops	3
Primary Coolant	$2^7LiF\text{-}BeF_2$
Fuel	UCO TRISO
Uranium Enrichment	9%
Fuel Form	Plate Assemblies
Refueling	2 batch 6 month

AHTR Design Calls for 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 plates have a 5.5 m fueled length
  - Maximum fuel temperature < 1000 ° C
- **Fuel assemblies are surrounded by a C-C composite shroud to channelize coolant flow**

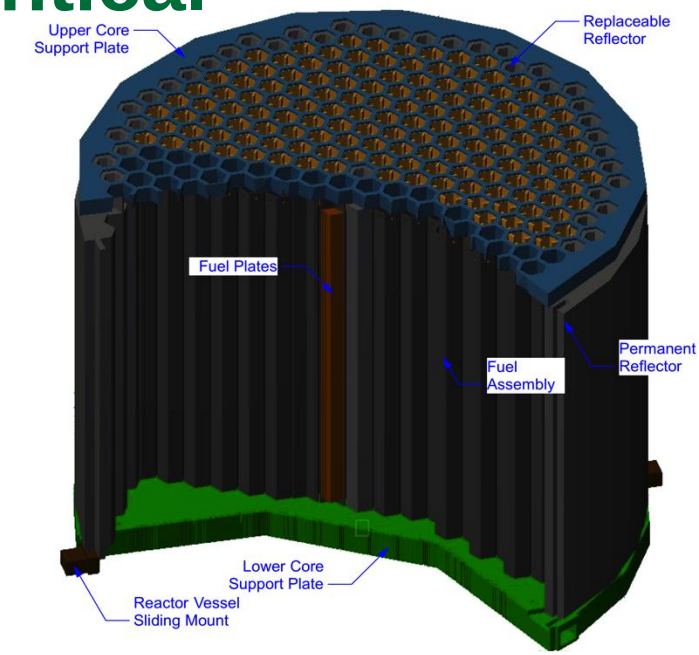


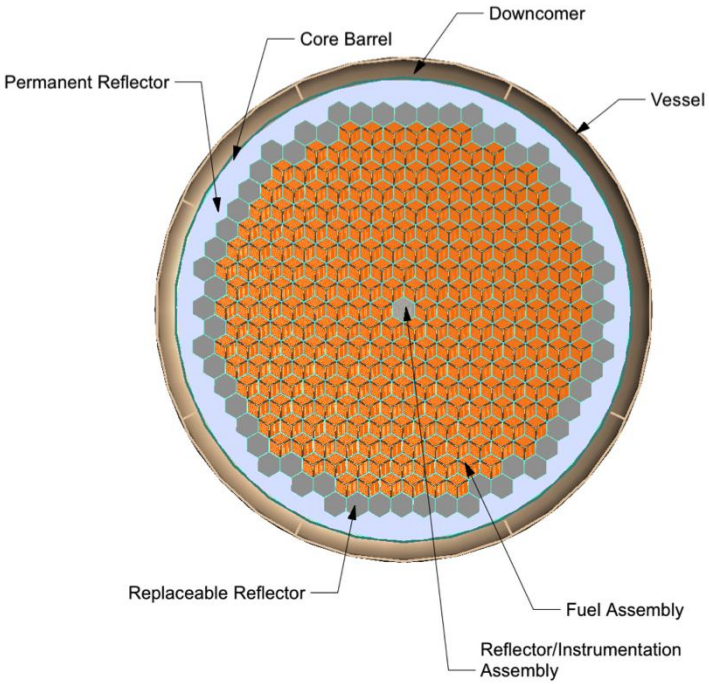




AHTR Core Consists of 252 Identical Hexagonal Fuel Assemblies

- **Core surrounded by replaceable and permanent graphite reflector columns**
- **Total core height 6.0 m**
  - Fueled core height 5.5 m
- **Volumetric power density 12.9 MW/m^3**
- **~73 GWd/MTHM discharge burnup**
- **Core makes extensive use of carbon fiber and silicon carbide fiber composites**
  - Molybdenum alloy control blade is only metallic material in core
- **Fuel assemblies are buoyant in coolant**
  - Control blade makes complete assemblies sink

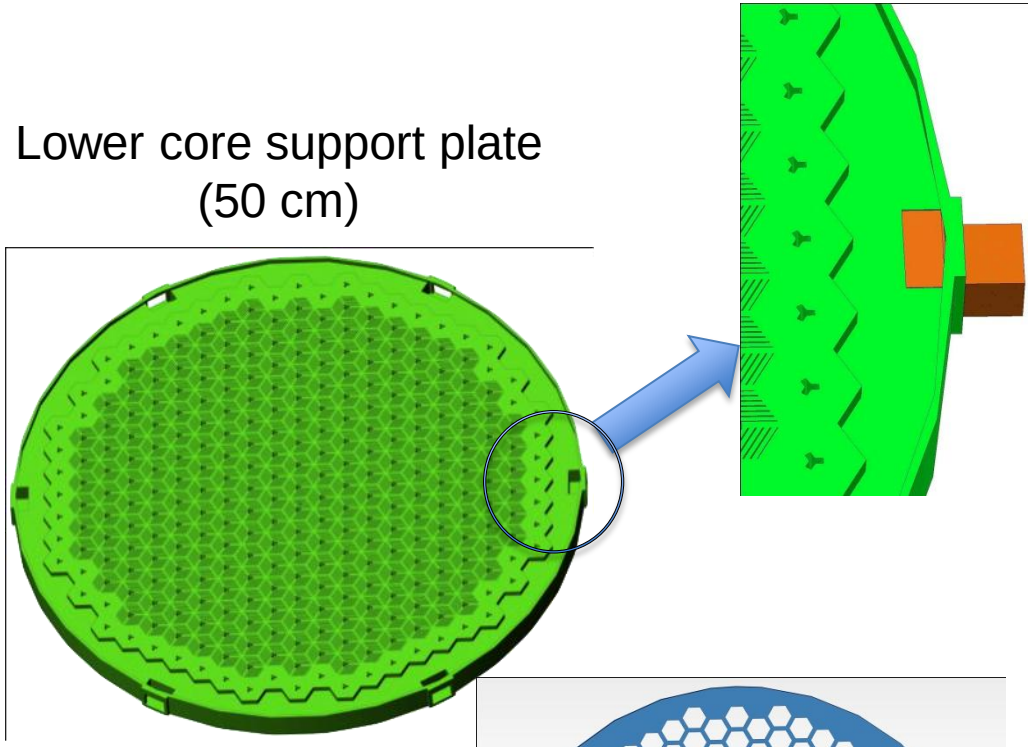




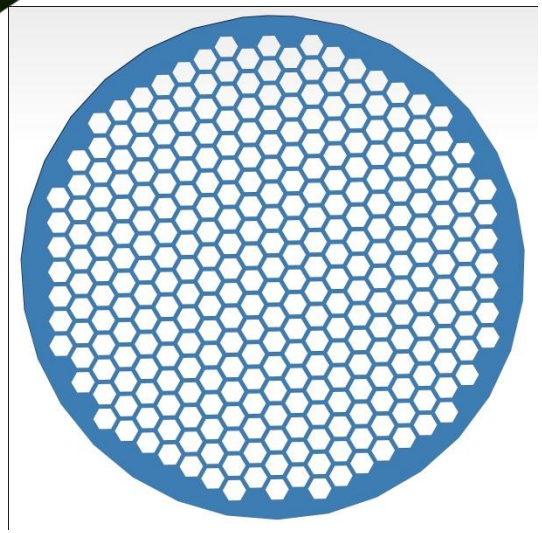
AHTR Design Employs Ceramic Composite Core Support Plates

- **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)

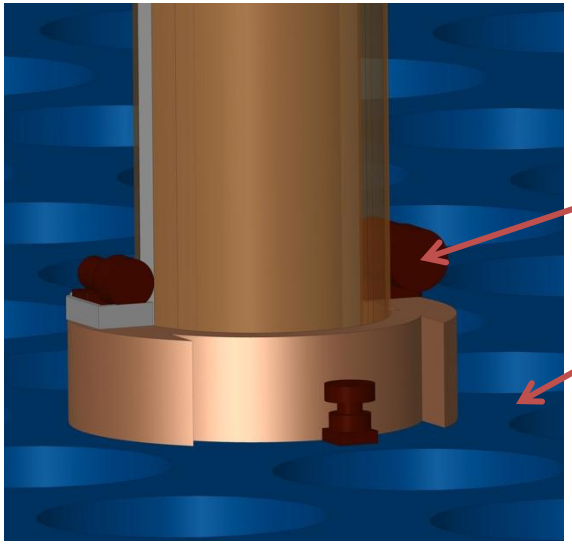


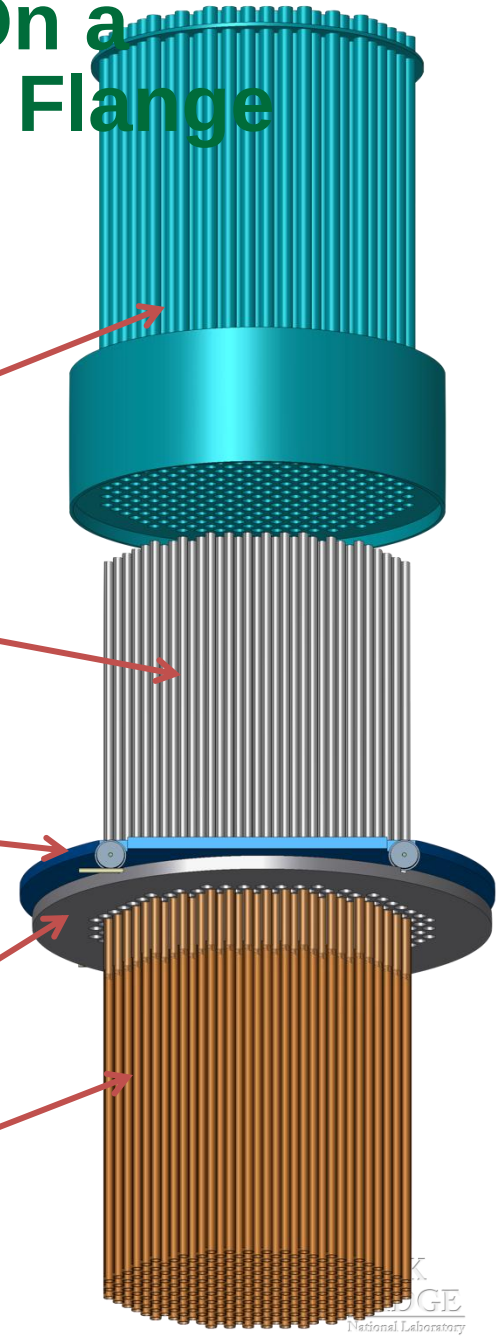
Upper core support plate (30 cm)



Control Blade Drives are Mounted On a Common Plate Above Upper Vessel Flange

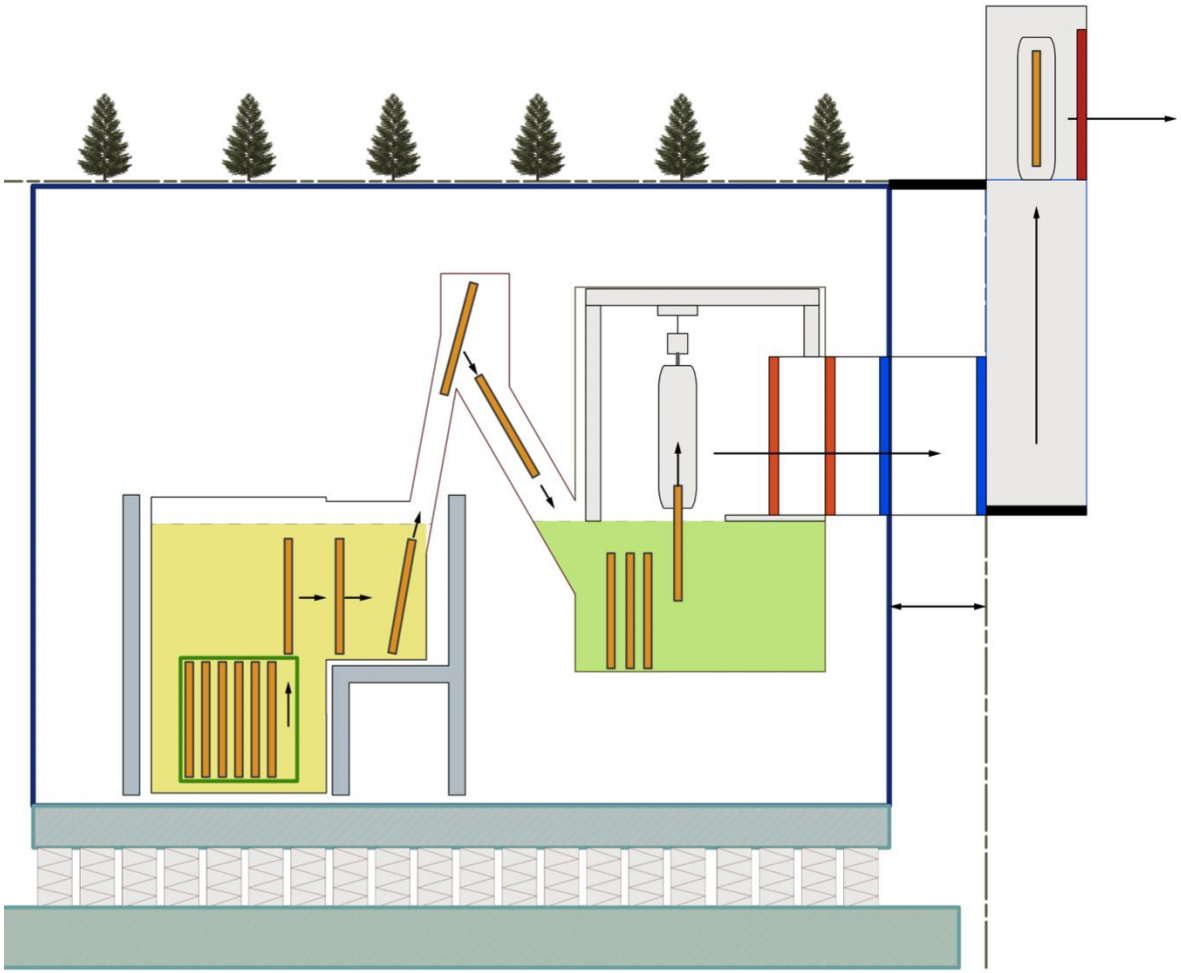
- **Enables removing control drive assemblies as a single piece**
- **Control blades are detached and left with fuel assemblies during refueling**



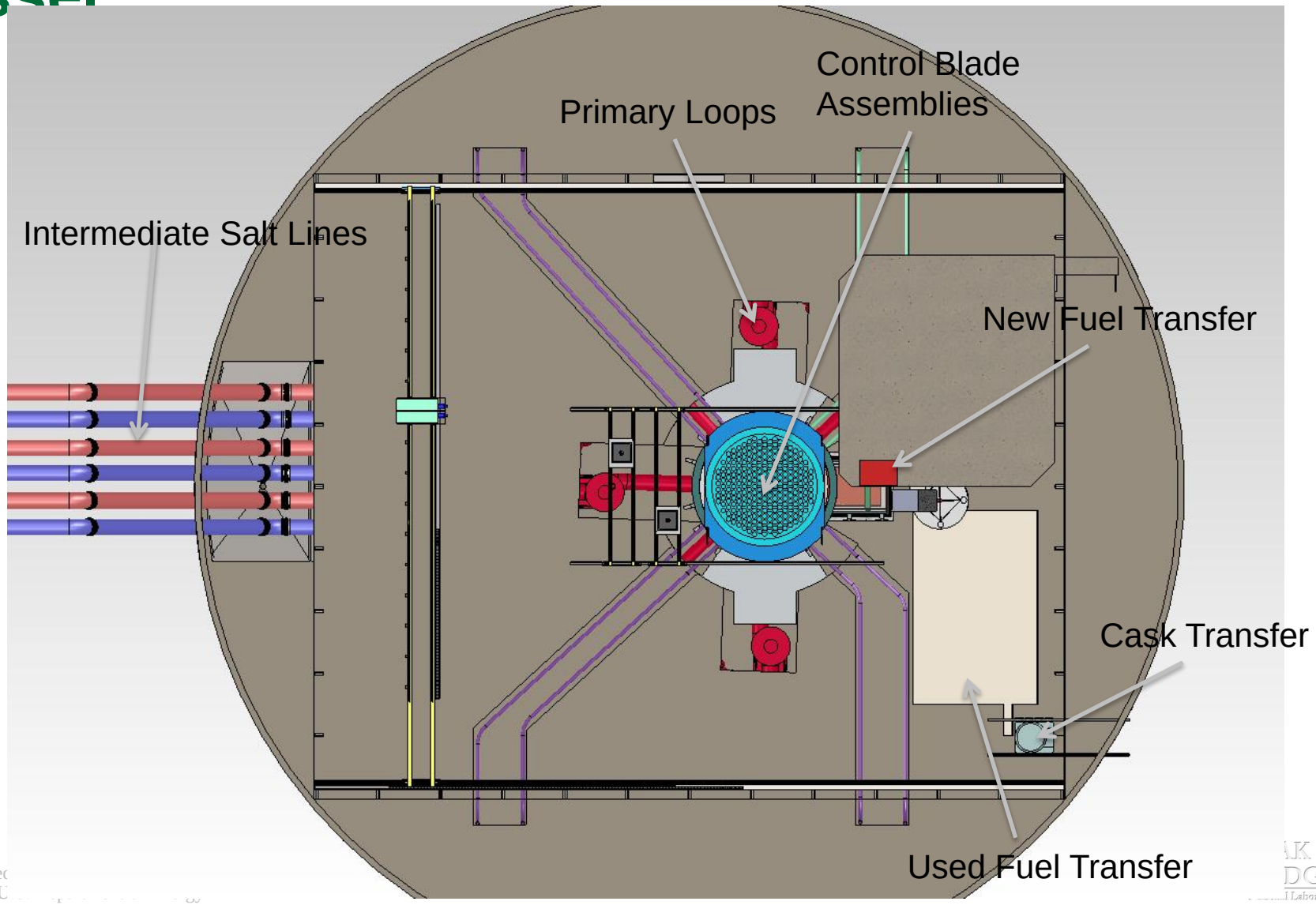


AHTR Fuel Handling Resembles Sodium Fast Reactor

- **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**

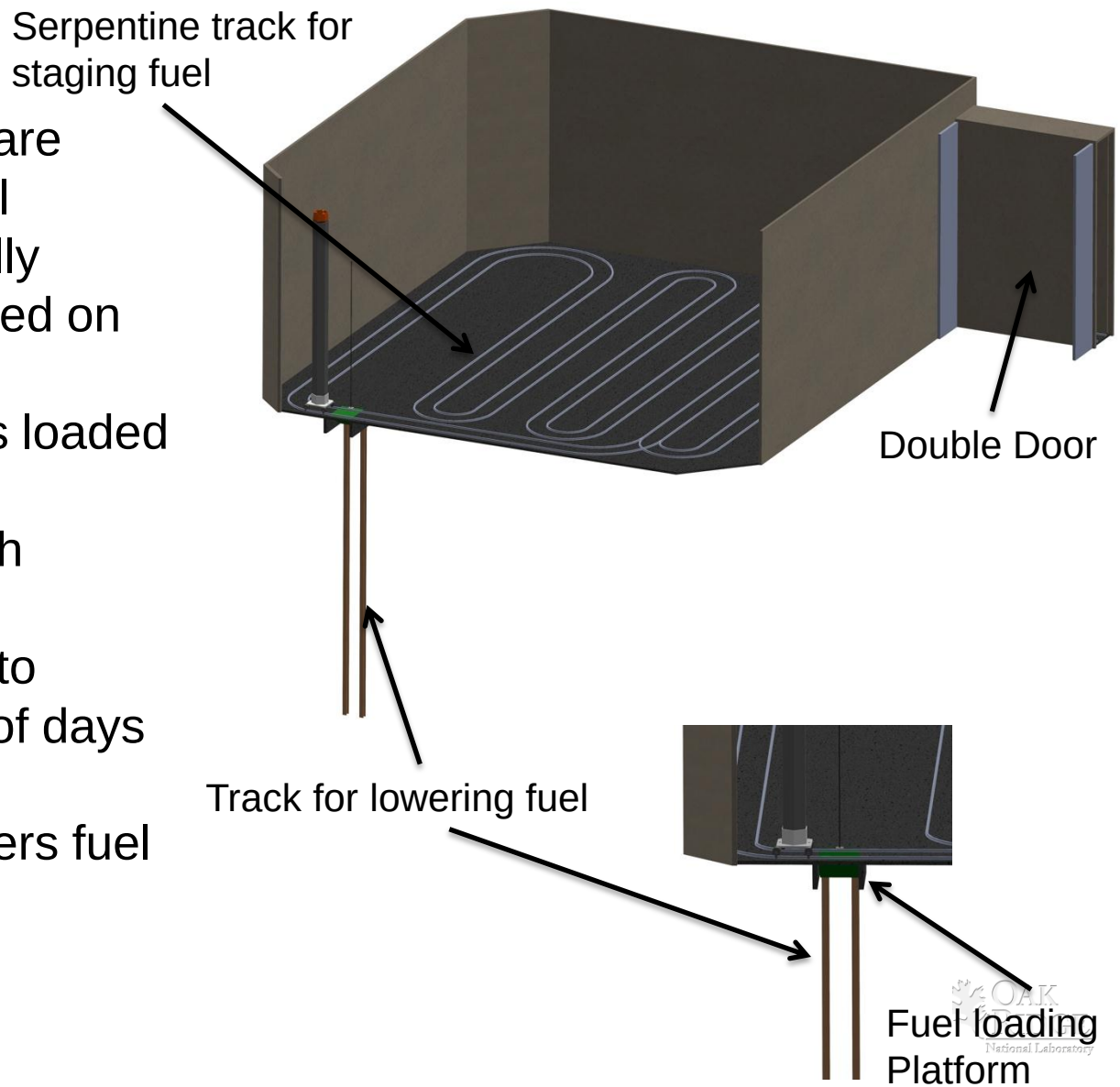


Used Fuel Removed and New Fuel Introduced Through Lobe on Reactor Vessel

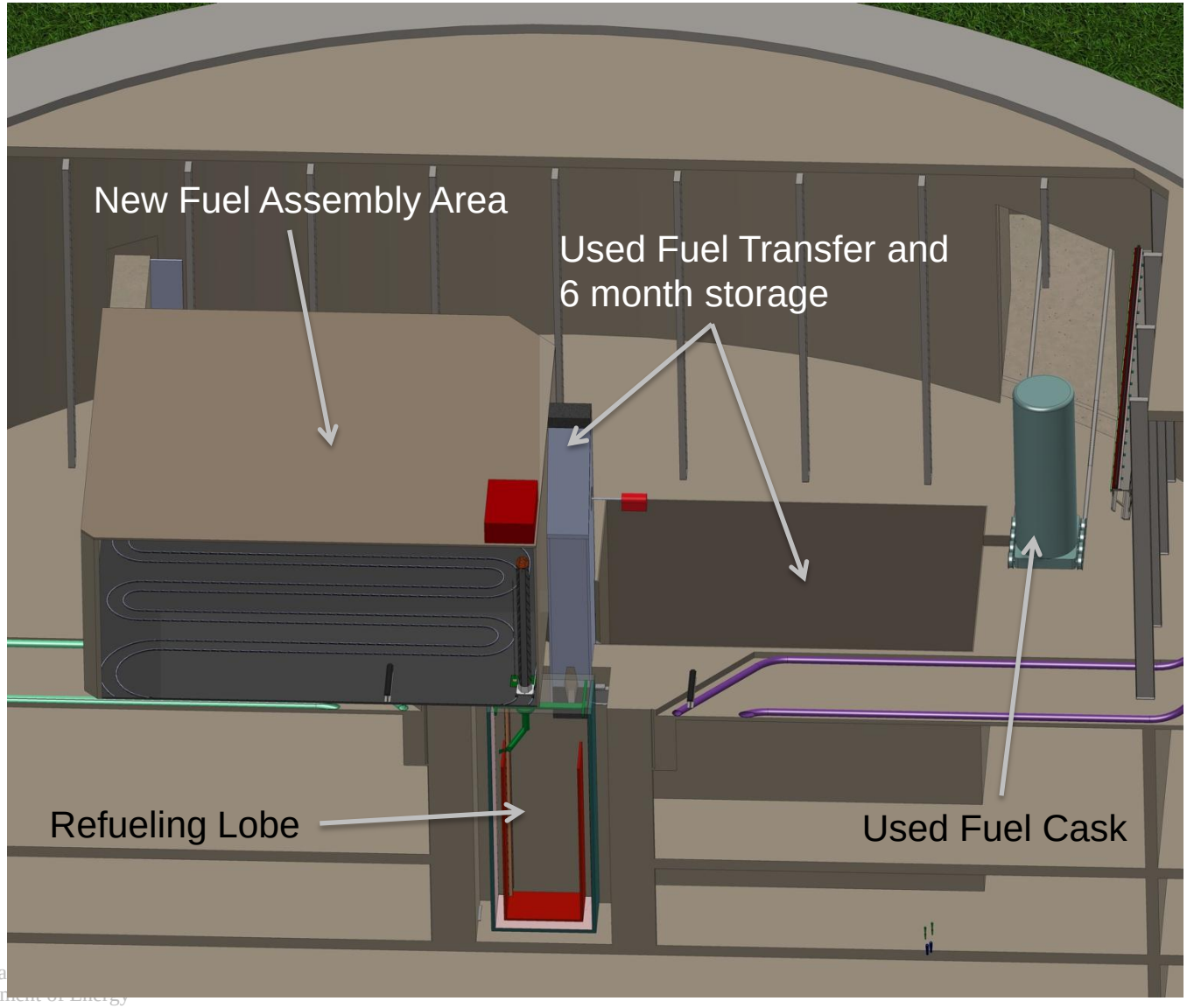


New Fuel is Brought Into Containment and Heated to Remove Moisture

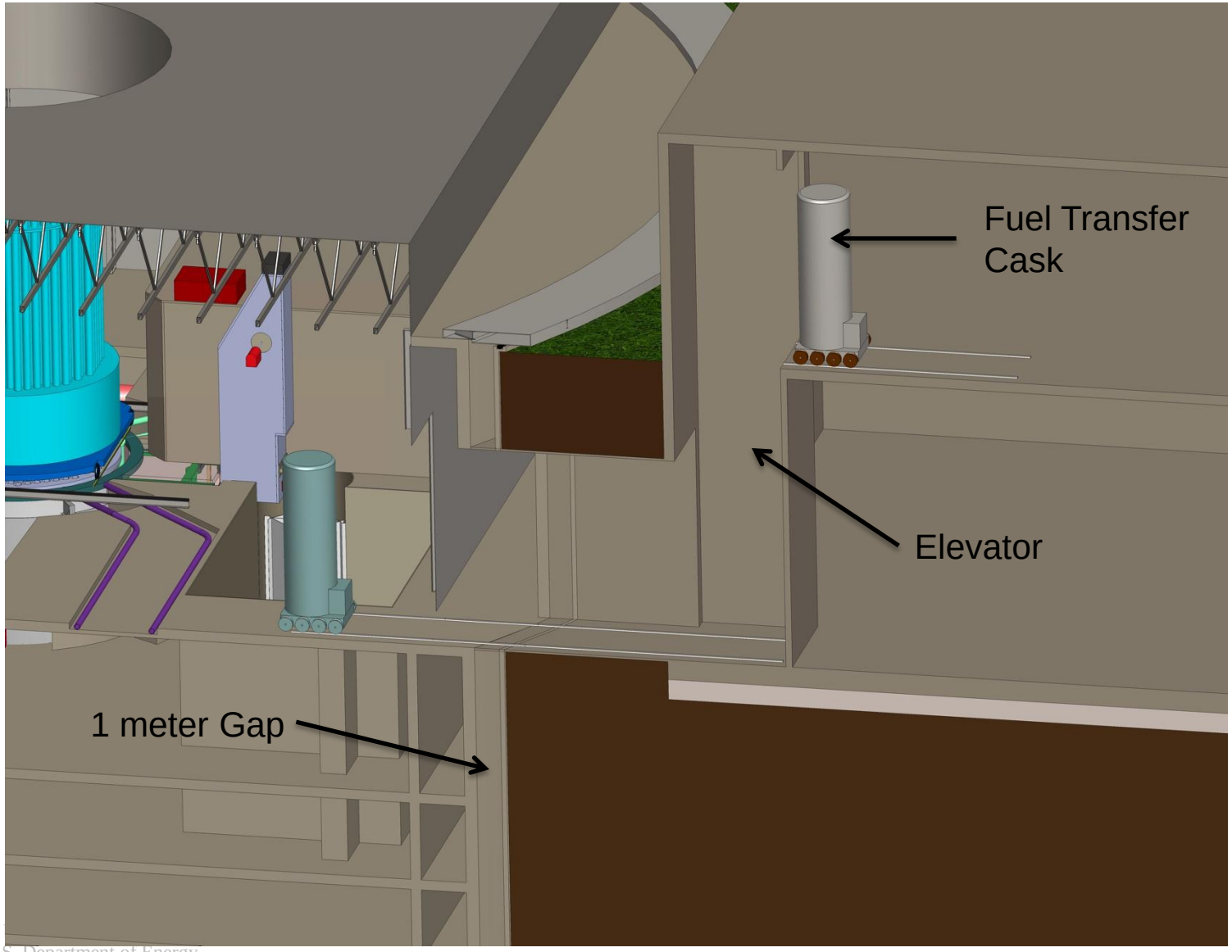
- New Fuel assemblies are brought to the new fuel assembly area manually
- Each assembly is staged on to the serpentine track
  - All 126 assemblies loaded at once
- The area is purged with flowing argon
- Temperature is raised to 1000° C for a couple of days to remove humidity
- A loading platform lowers fuel into the lobe



Lower Core Power Density Enables Smaller In-Containment Used Fuel Storage

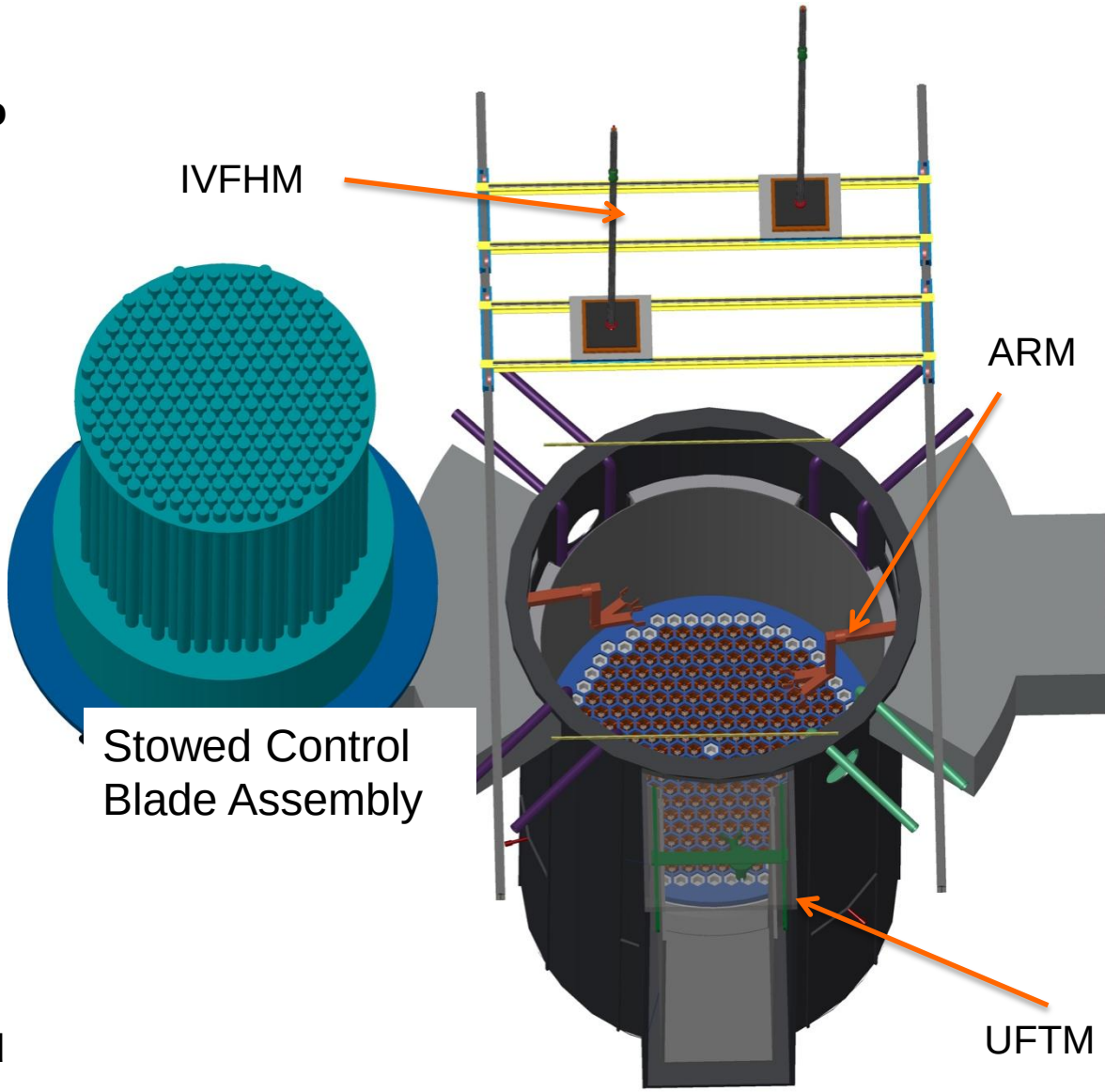


Used Fuel is Transferred Out of Containment Below Grade



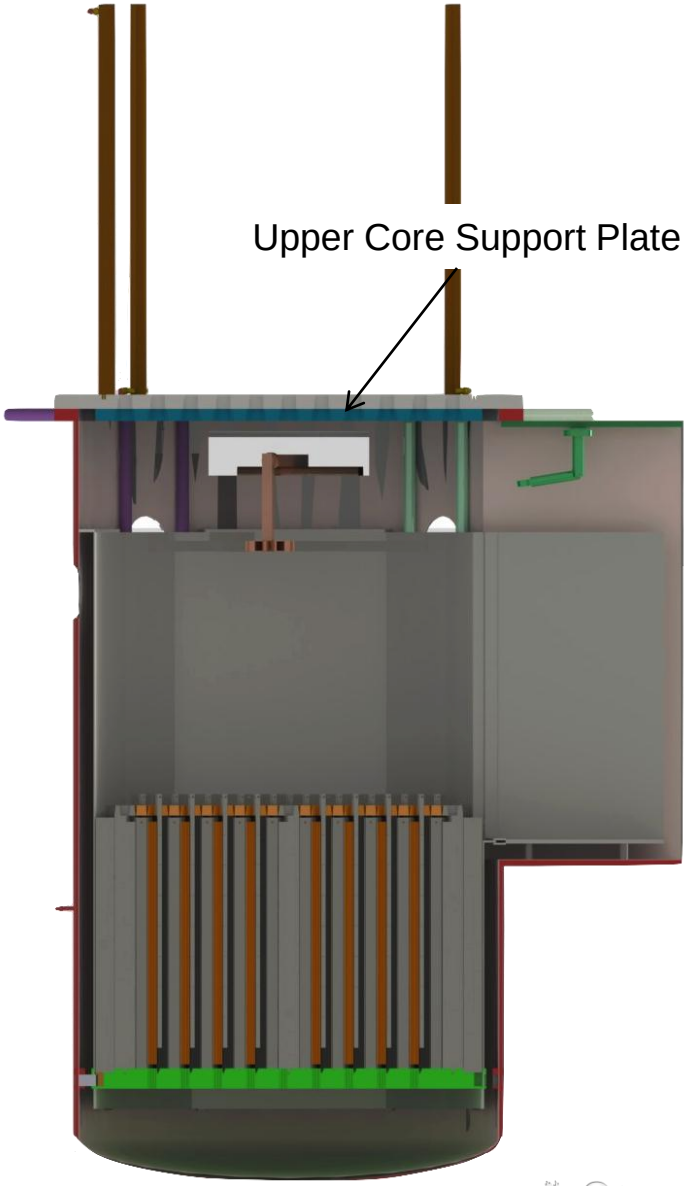
Automatic Refueling Employed to Minimize Outage Time

- **Four mechanisms employed to move fuel from core into fuel transfer canal**
  - In-Vessel Fuel Handling Manipulator raises fuel from core
  - Annular Rolling Manipulator transfers fuel into refueling lobe
  - Used Fuel Transfer Manipulator positions fuel below winch
  - Used Fuel Winch transfers fuel to refueling canal
- **Half of core (126 fuel assemblies) replaced every 6 months**
- **In containment, below grade used fuel storage pool employed for first 6 months to 1 year**
- **Local dry well storage employed for longer term used fuel storage**



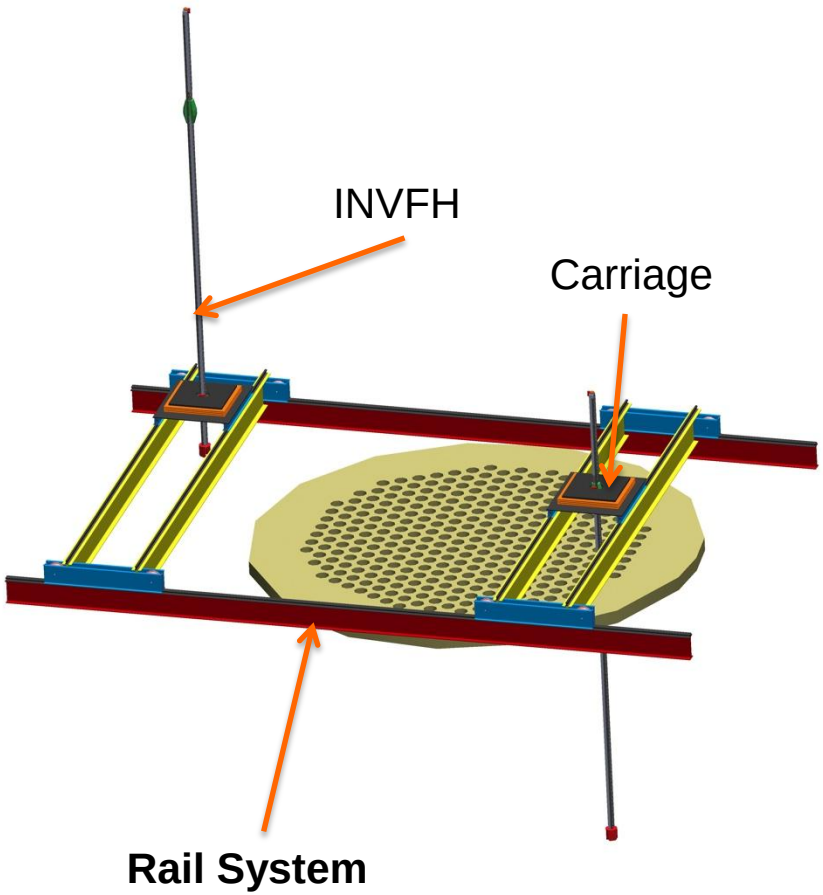
Refueling Process Can Begin Immediately Upon Shutdown

- **The control blades are inserted into all the fuel assemblies**
- **The primary coolant loop pump flow is reduced to about 5% or the maintenance DRACS is brought on-line (forced convection)**
- **Primary coolant temperature is lowered**
  - Materials challenges reduced by the lower temperature and short exposure time
- **Control blades are detached from the leader rods**
- **The control blade leader rods and guide tubes are retracted**
- **The control blade flange is translated laterally**
- **The upper core support plate is raised till it is almost in contact with the top flange**
- **The IVFHM are brought into position**



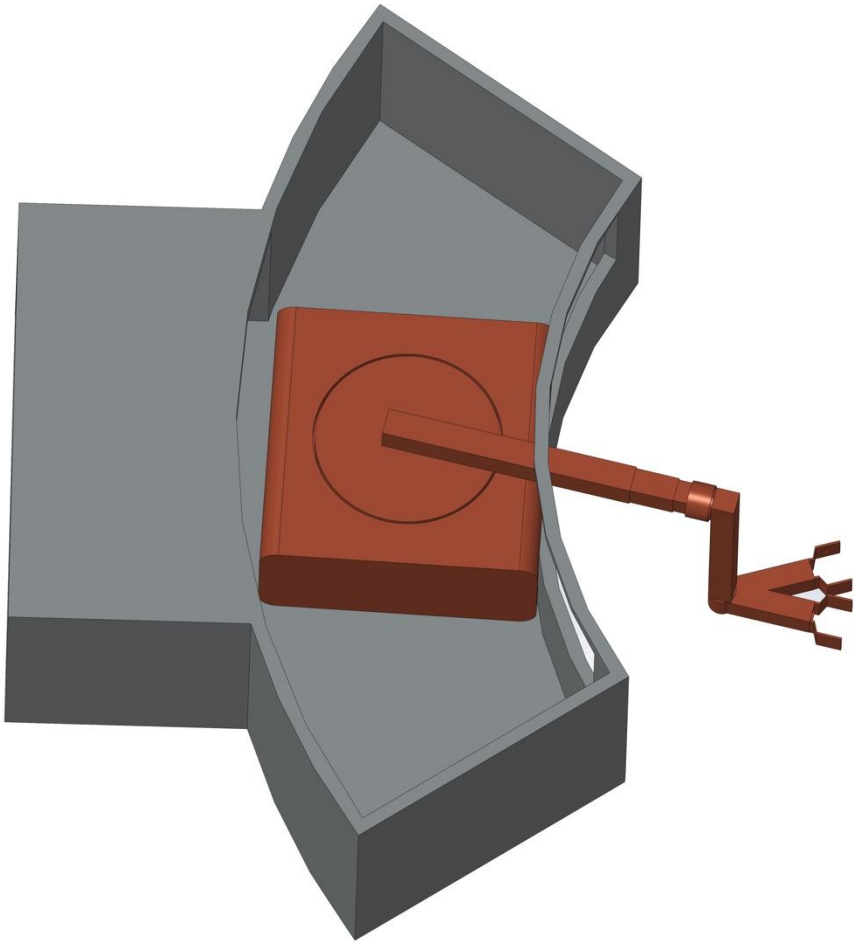
In-Vessel Fuel Handling Manipulator (IVFHM)

- IVFHM are mounted on a low X-Y translating stage above the vessel in the containment area
- Two parallel IVFHMs are employed to reduce refueling outage duration
- IVFHMs are inserted through the corresponding holes for each fuel assembly location at the top flange
- They can also be used for removing temporary reflectors
- The IVFHM can self align with fuel by the lateral compliance provided at the carriage.



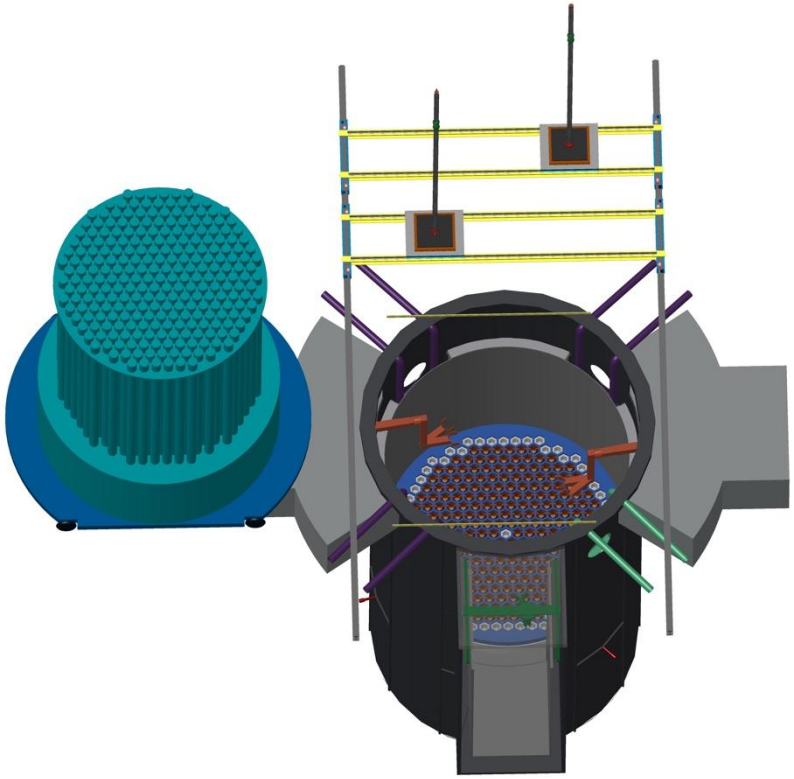
Annular Rolling Manipulator (ARM)

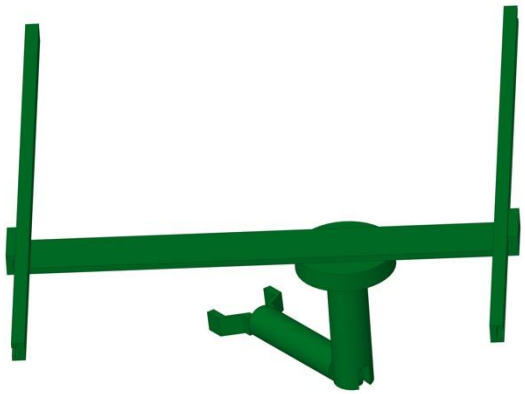
- Two ARM manipulators work in conjunction to cover the entire fueled region
- ARM robots interface with the IVFHM and UFTM
- Reach of each manipulator is slightly greater than half the diameter of the core
- The robot has two grippers to enable replacing a new fuel immediately after withdrawing an old one so as not to starve the fuel core
- For maintenance, the ARM manipulators may be retracted and removed from the coolant salt



Used Fuel Transfer Manipulator (UFTM)

- UFTM is a gantry type manipulator above the salt line in the used fuel lobe
- UFTM interfaces with the ARM
- Both used and new fuel are handled by this robot
- A single UFTM can interface with both ARM robots as the distance it needs to travel is smaller





Fuel Robustness and Slight Negative Buoyancy Minimizes Consequences of Mishandling

- **Fuel remains in a cooled configuration if dropped anywhere in the refueling process**
  - Fuel will gently settle to the bottom of the salt if dropped
  - No mechanical damage anticipated
  - Cooling of the remaining core not prevented if a fuel assembly is dropped across its top
- **Keeping a control blade with each fuel assembly minimizes potential for any criticality accidents**
- **Mechanically robust fuel is difficult to damage**
- **During refueling fuel is only held at the lower core support plate**
  - Upper end of fuel is free to move
  - Overall motion constrained by permanent reflector

Instrumentation and Controls for Refueling AHTR Remain at a Notional Level of Maturity

- **Transparent, low-pressure coolant enables optically based measurements**
- **Technology for automated vision-based mechanical control systems in well defined environments is commercial**
- **Principal technical challenges are**
  - Optical access for vision system
  - Operators maintaining situational awareness
  - Developing adequate confidence in the materials and mechanics in the required environment
  - Responding to failed systems

All Fuel Handling is Performed Under Visual Guidance

- **All sensors and electronics are located above the salt pool**
- **Area above salt is inert and contaminated with BeF_2 and tritium**
  - Human access above vessel is not anticipated for normal refueling sequence
- **Relay lenses in the upper vessel flange provide optical access**
  - Mechanical grasping elements are ~10m long
  - Self aligning mating features decrease required control precision
- **Field of view of lens system will shift with temperature complicating control**
- **First surface lenses will tend to fog with re-solidified salt vapor – primarily BeF_2**
- **The salt surface will include ripples due to coolant flow**

Optically Guided Controls in a Known Environment is Known Technology

- **Camera inputs are compared to that anticipated due to that anticipated from a simulation**
- **Feedback is employed to cause the manipulators to make the real and virtual images concur**
- **Checkpoints within process allow operators to remain engaged**

Operators Supervise Refueling Process

- **Multiple camera views are combined into a virtual reality representation**
- **Operators supervise but do not actively participate in refueling sequence**
  - Operator input can be used as additional verification of proper completion of process steps
- **Principal active role of the operators during refueling is to maintain situational awareness to be able to deal with problems**
  - Respond to instrument or mechanical failures and/or improper operation

Instrumentation and Controls are the Key Technologies to Enable Rapid Refueling of the AHTR

- **Rapidly refueling the AHTR is a key component to achieving high availability and thus economic viability**
  - Fully automated refueling is anticipated to require only a few days of downtime per year
- **While the general components and sequence of actions have been considered, both component and system technologies require substantial development**
  - Hydraulic impacts on refueling mechanics are yet to be analyzed
  - Optical access technologies have yet to be demonstrated
  - Multi-physics system simulation is recommended to provide confidence in overall performance