Multiphysics Simulation Of 2nd Generation ^{238}Pu Production Designs Using COMSOL®

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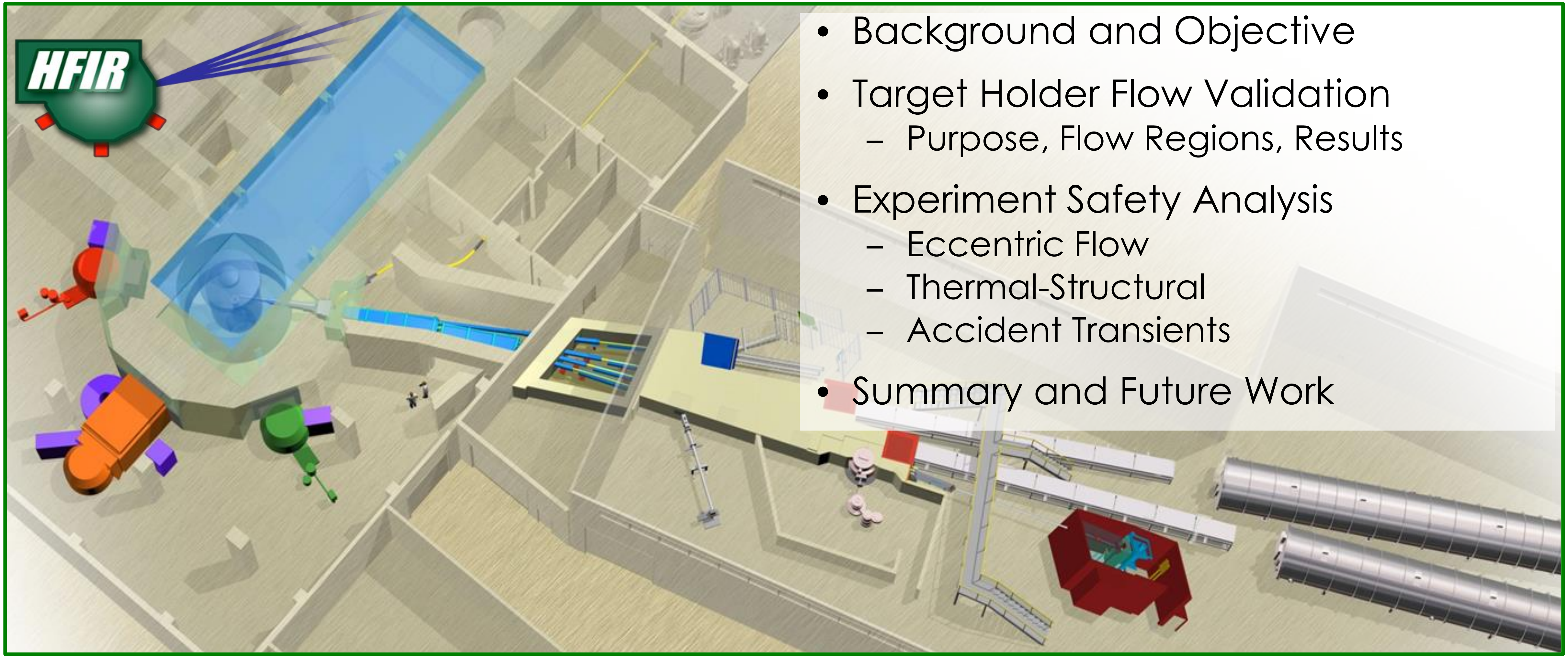
Outline

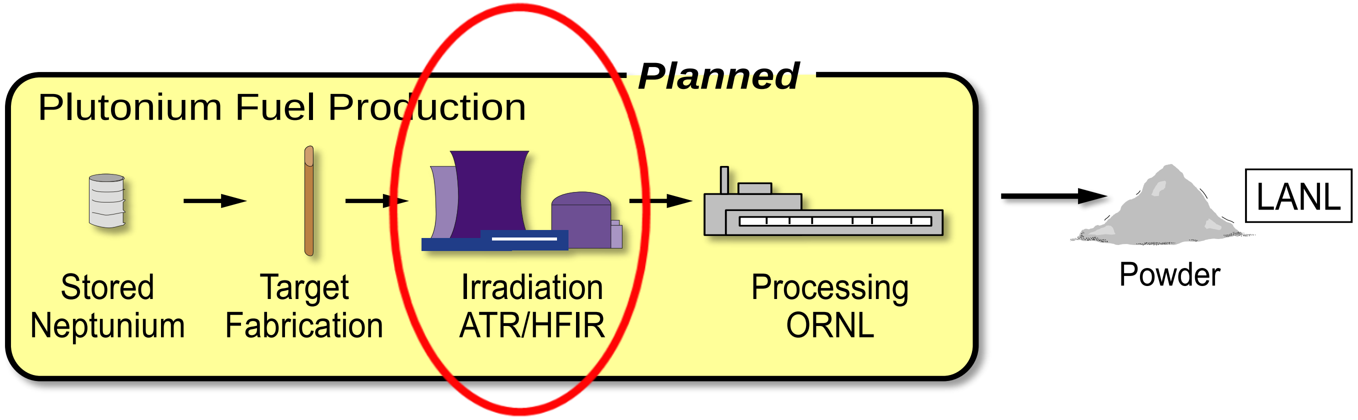


- Background and Objective
- Target Holder Flow Validation
  - Purpose, Flow Regions, Results
- Experiment Safety Analysis
  - Eccentric Flow
  - Thermal-Structural
  - Accident Transients
- Summary and Future Work

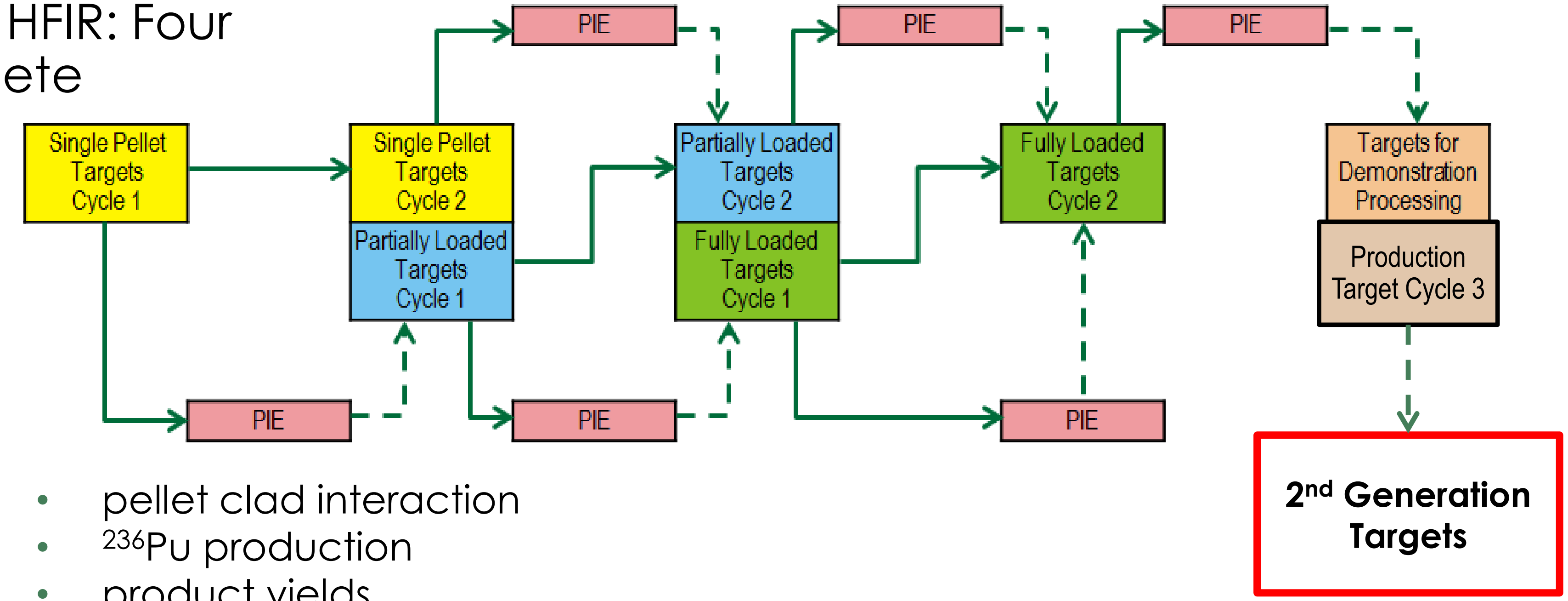
Background and Objective

The ^{238}Pu Supply Project at the High Flux Isotope Reactor

- ^{238}Pu is the fuel source for RTGs that power NASA deep space missions
- This presentation discusses the safety analyses required for irradiation of production targets at the High Flux Isotope Reactor (HFIR) at ORNL



- Target Qualification at the HFIR: Four phase test program complete
  - Post-irradiation examination (PIE) results from each phase serve as a hold point for the following irradiations

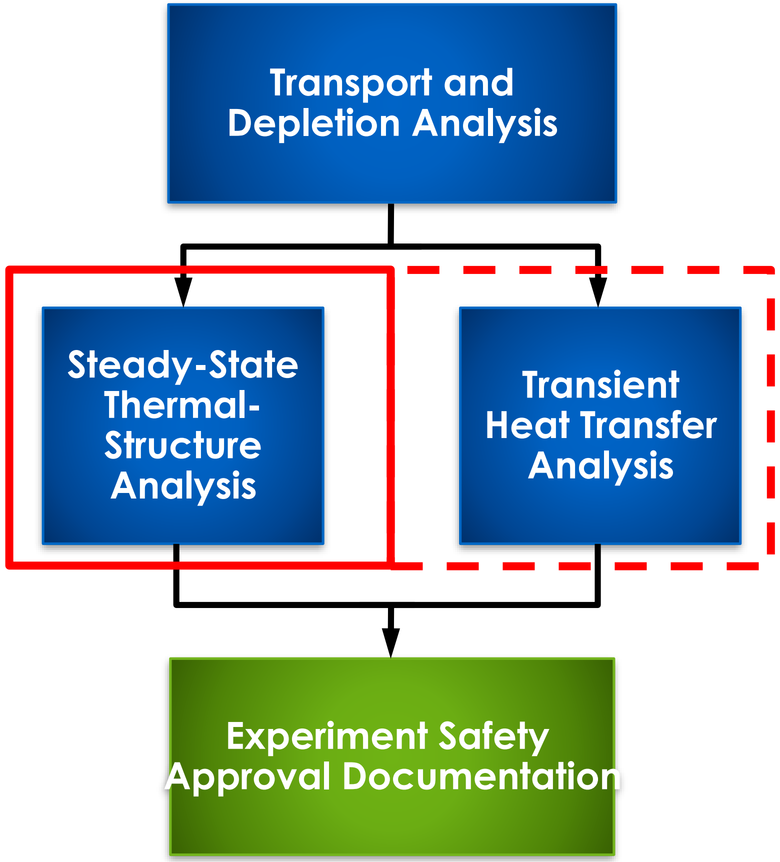


- PIE Characteristics:
  - pellet dimensional changes
  - fission gas release %
  - heat generation rates
  - pellet clad interaction
  - ^{236}Pu production
  - product yields

Background and Objective

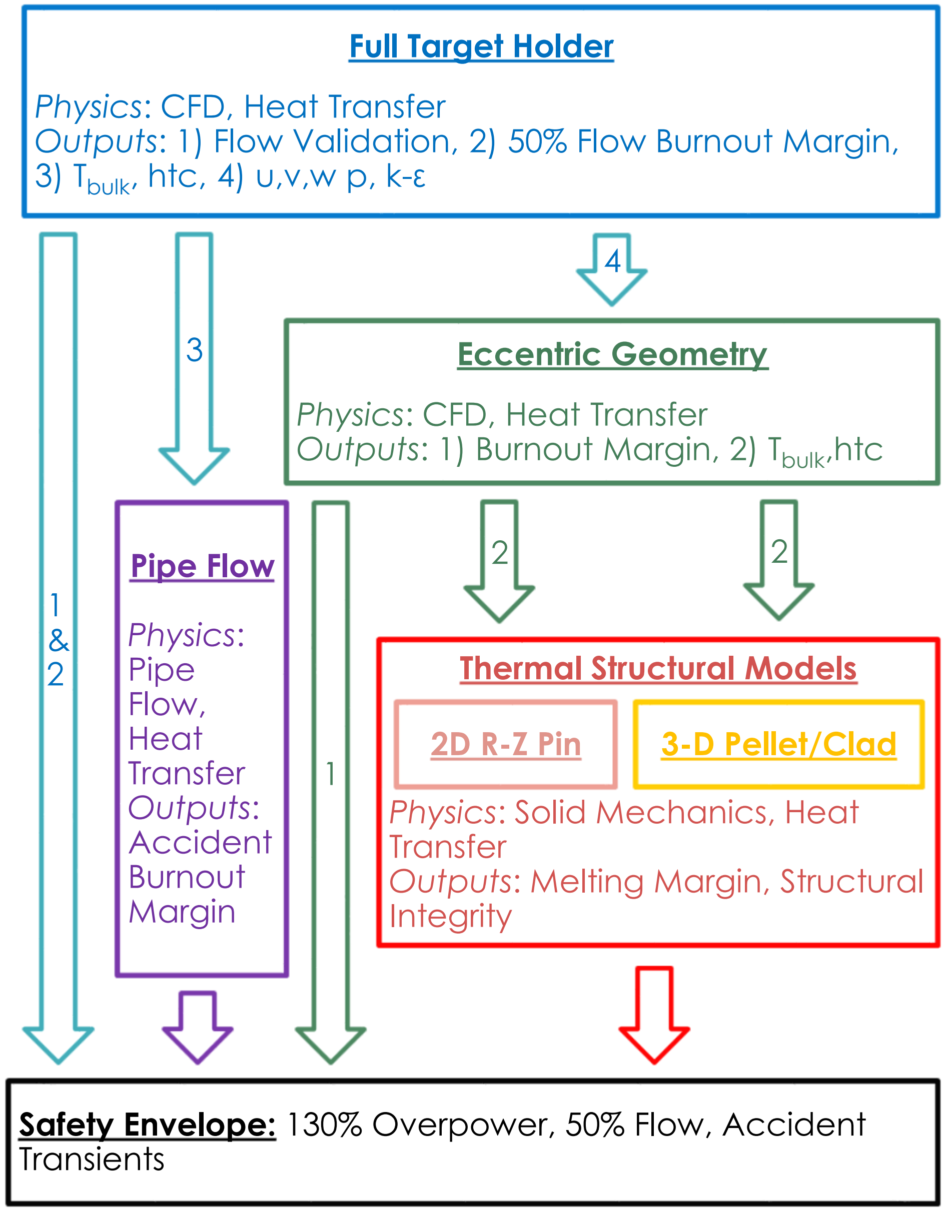
Experiment Qualification at the High Flux Isotope Reactor

- Target qualification at HFIR requires a safety review that assures target cooling in off-normal and nominal reactor operating conditions
- Target cooling is maintained such that:
  - No material melting: $T_{max} < T_{melt}$
  - No surface burnout: $T_{surf\text{-}max} < T_{saturation}$
  - Clad stress/strains below yield: $\sigma_{clad} < \sigma_{yield}$, $\varepsilon_{clad} < \varepsilon_{break}$
  - Target axial forces on welds: $F_{axial} < F_{target\text{-}failure}$
- Off-normal safety review includes the following cases:
  - Steady-State Analysis in COMSOL
    - 50% reduced flow
    - 130% overpower ← Bounding safety condition
  - Transient Analysis (now) in COMSOL:
    - Small break LOCA ← Bounding safety condition
    - Loss of offsite power (LOOP)



Background and Objective
Overview of COMSOL Models

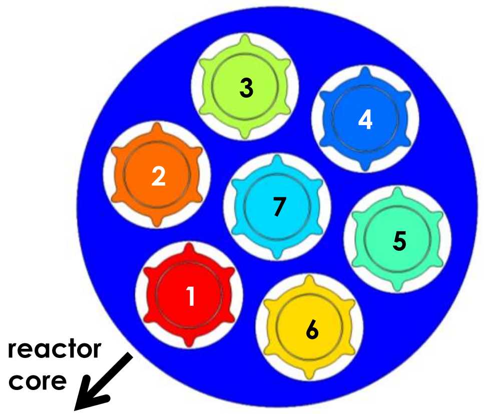
- Five models include physics interfaces of computational flow dynamics (CFD), heat transfer, solid mechanics, and pipe flow
- Additional equations for flow coupling operators, gap/contact conductance, fission gas release, irradiation-driven dimensional changes
- Two thermal hydraulic models (CFD & Heat Transfer)
  - Full Target Holder used for Flow Validation
  - Eccentric Geometry for asymmetric flow positions
  - Address steady-state surface burnout
- Two thermal-structural models (Solid Mechanics & H.T)
  - 2-D R-Z model of entire target pin
  - 3-D model of limiting pellet and adjacent clad
  - Address steady-state melting and structural integrity
- Transient model (Non-Isothermal Pipe Flow & H.T.)
  - Address accident transient surface burnout

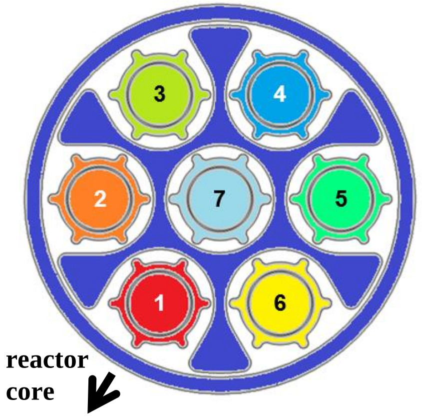


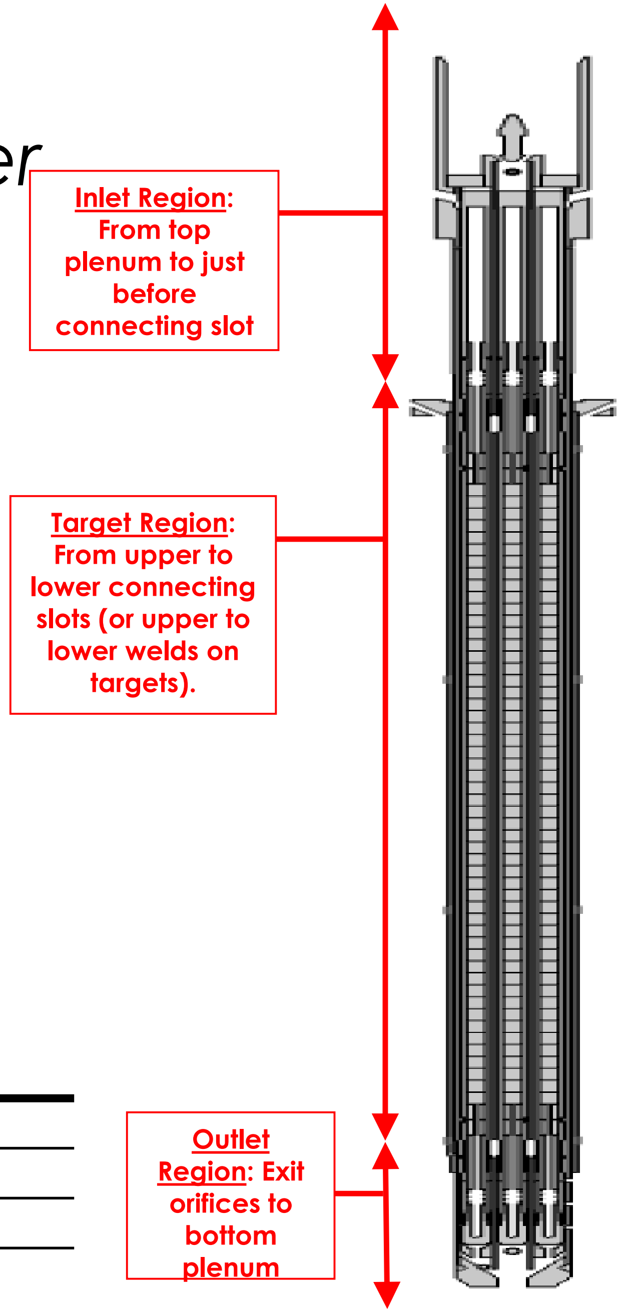
Target Holder Flow Validation Model

Flow Impact of New 2nd Generation Target Holder

- Compute the 3-D Flow Distributions in 2nd Generation Target Holder
  - Import CAD geometry and use COMSOL features to simplify flow paths (see target holder, right)
  - Slice geometry to take advantage of holder symmetry
  - Address asymmetric flow channels (see right)
  - Multiple flow rate cases to compare to conducted flow test measurements (see table below)
  - Cases to optimize existing design drawings for orifice flow control and connecting slot size/location







Model	Case	Description	Flows (gpm)
Flow Test	Nominal	Flow Test Geometry	10,20,30,34
	Constricted	Case Run with Constricted Slot	10,20,30,33
Design-Basis	Nominal	Design Drawings	10,20,30,38
	Design Study	Study to Determine Optimized Flow Control	35

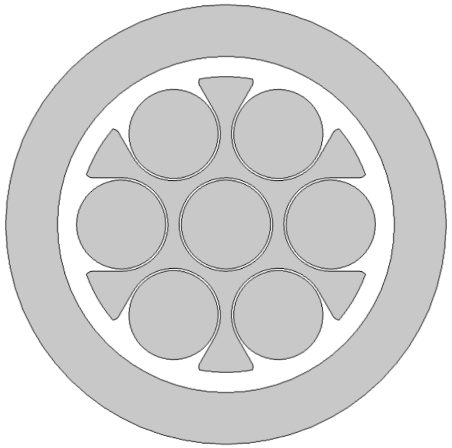
Target Holder Flow Validation Model

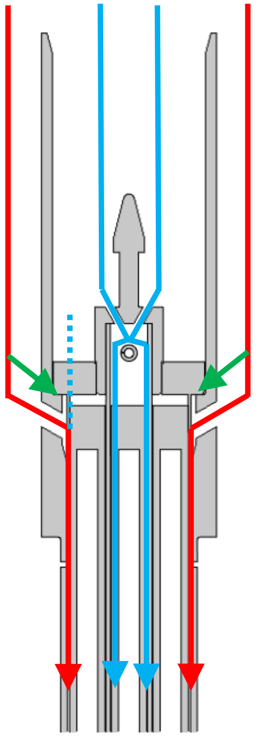
Inlet Flow Region

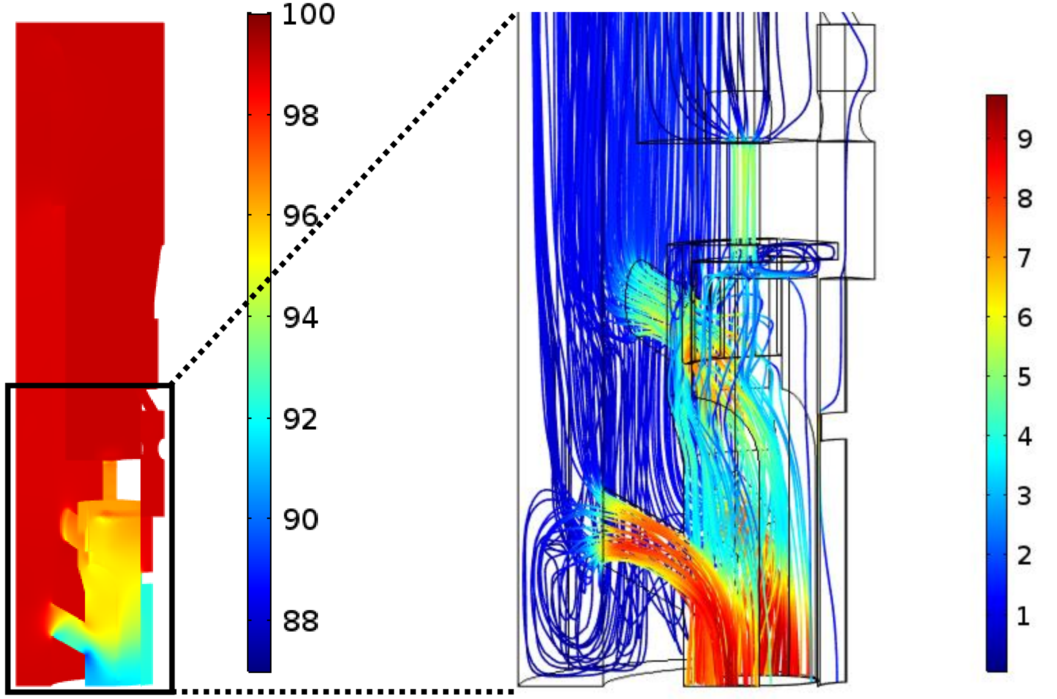
- Inlet Flow Region
  - 1/6th slice geometry
  - Central target inlet restricted
  - ~10 psi drop
  - Side inlets to periphery
- Finned Flow Region
  - 1/6th slice geometry
  - Connecting slot size/location chosen to allow sufficient flow to central target
  - Asymmetric flow in periphery channel
- Outlet Flow Region
  - 1/3rd slice in outlet region
  - End cap geometry on test vs. design requires reduced orifice diameter

X-Y Flow area at top end caps (right)

Flow Velocity Streamlines (bottom right)







Target Holder Flow Validation Model

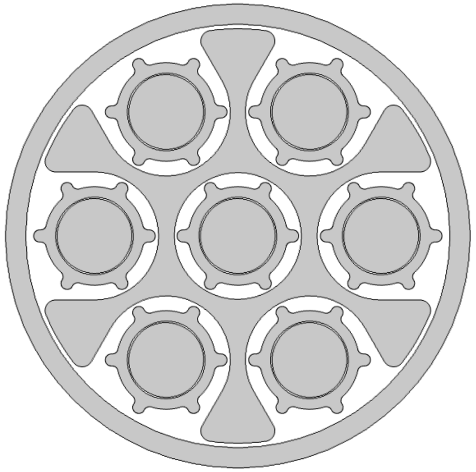
Finned Target Flow Region

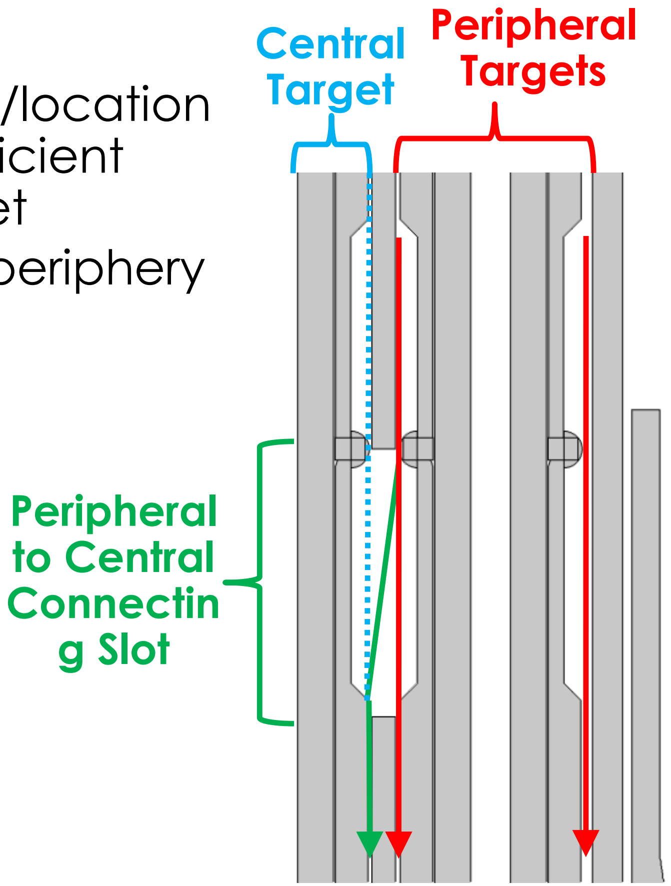
- Inlet Flow Region
  - 1/6th slice geometry
  - Central target inlet restricted
  - ~10 psi drop
  - Side inlets to periphery
- Finned Flow Region
  - 1/6th slice geometry
  - Connecting slot size/location chosen to allow sufficient flow to central target
  - Asymmetric flow in periphery channel
- Outlet Flow Region
  - 1/3rd slice in outlet region
  - End cap geometry on test vs. design requires reduced orifice diameter

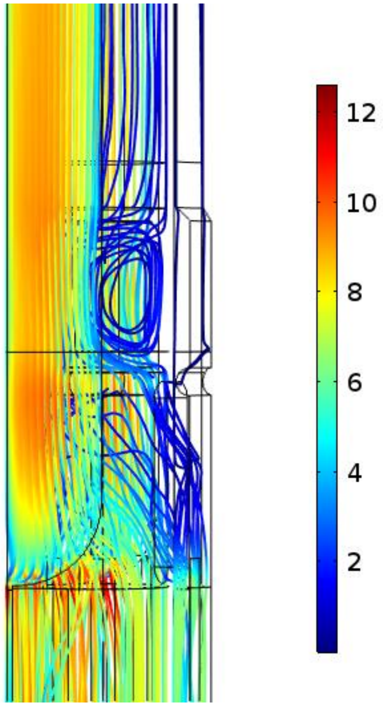
X-Y Flow area at finned region (right)

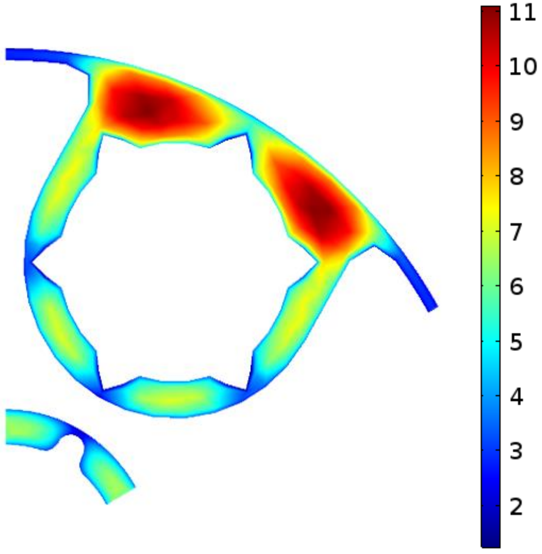
Streamline velocities at connecting slot (bottom)

Velocity Profile (bottom right)









Target Holder Flow Validation Model

Outlet Flow Region

- Inlet Flow Region
  - 1/6th slice geometry
  - Central target inlet restricted
  - ~10 psi drop
  - Side inlets to periphery
- Finned Flow Region
  - 1/6th slice geometry
  - Connecting slot size/location chosen to allow sufficient flow to central target
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  - 1/3rd slice in outlet region
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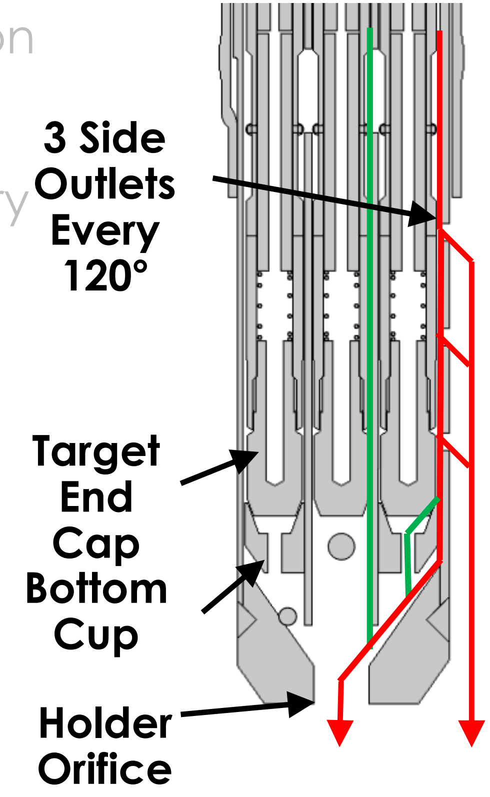
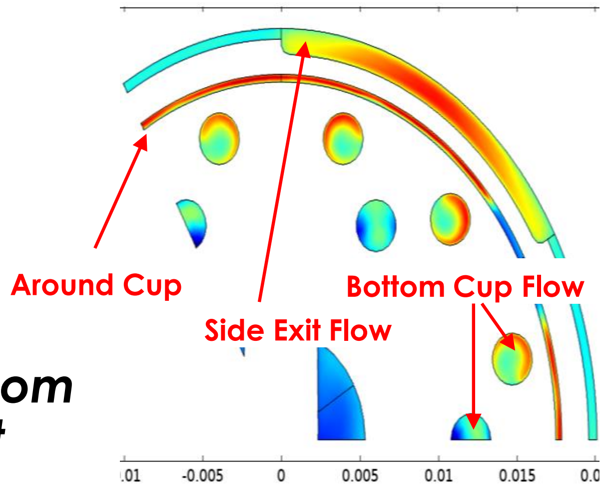
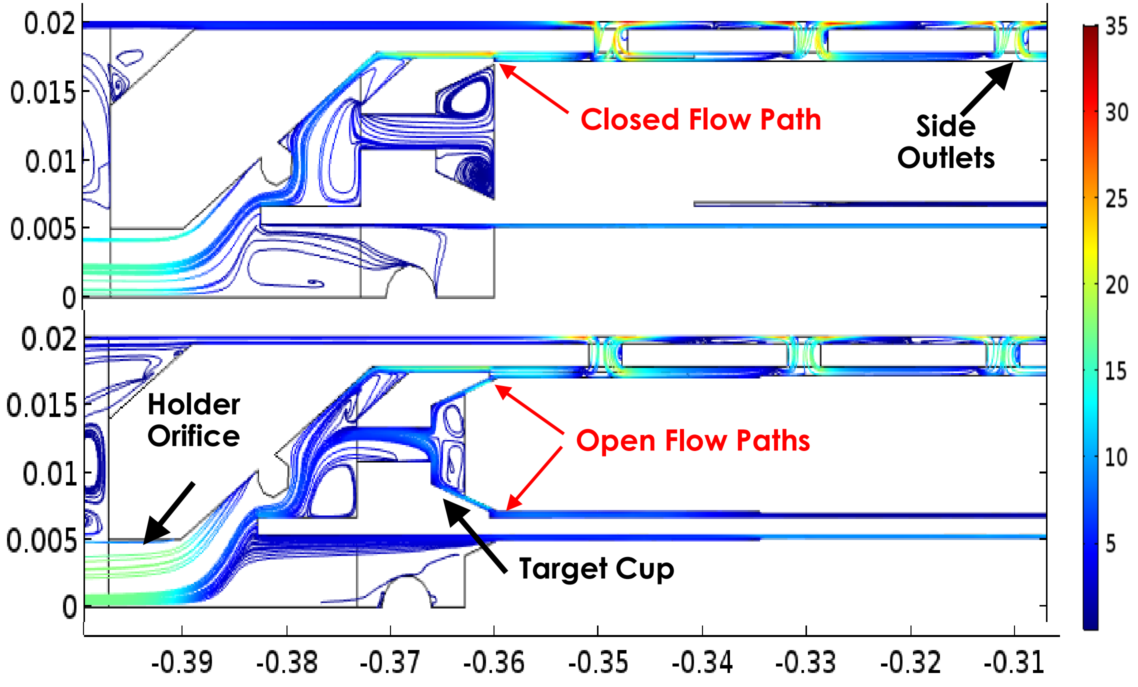


X-Y Outlet Flow Velocity & Paths (right)



Flow Velocity Streamlines (bottom right) for flow test and design



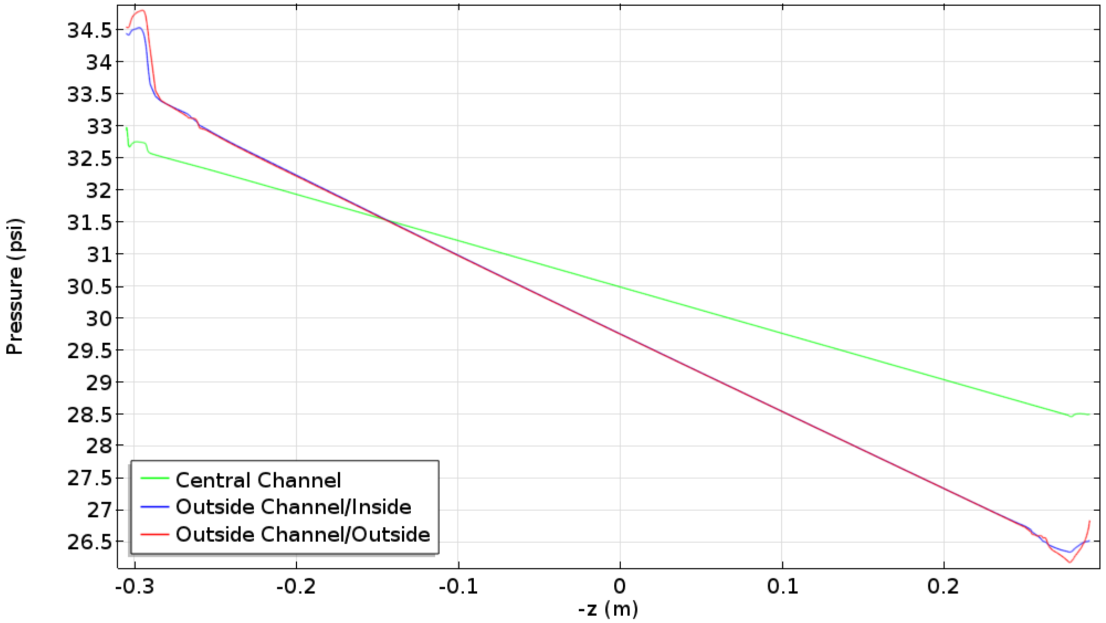
Target Holder Flow Validation Model

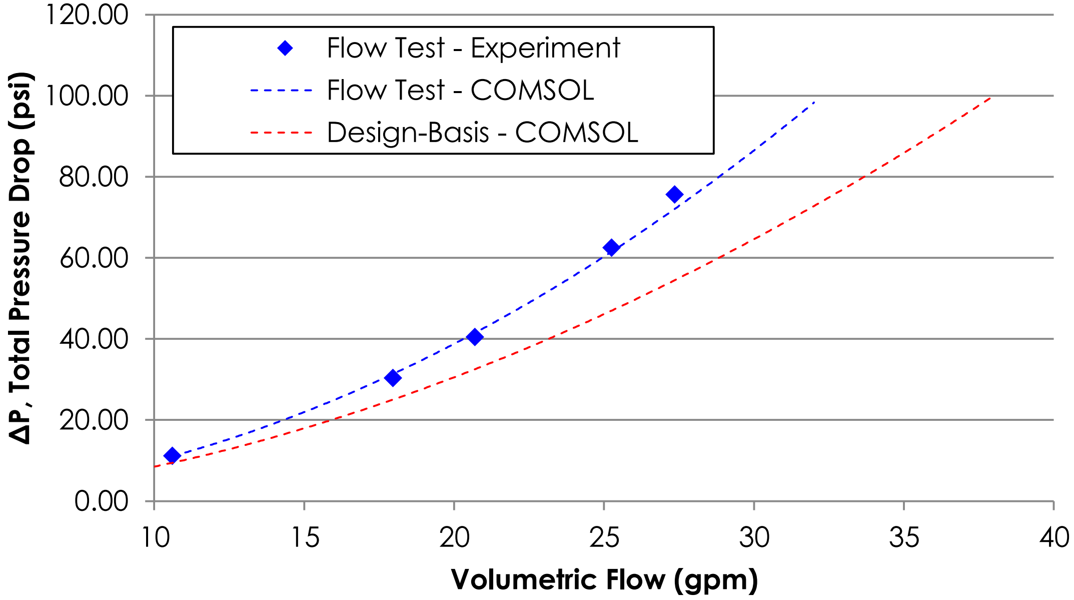
Validation Results

- Comparison to Flow Test Results
  - Flow test measured pressures and holder flow
  - Model results compare well against the experiment results
  - Flow degradation in central target for reduced connecting slot size confirmed
- Design-Study
  - Assessed effect of connecting slot size and locations
  - Assessed increased flow for updated design
  - Prescribed orifice diameter for desired design flow

Flow degradation in central channel (top right)

Pressure drop vs. flow comparison (bottom right) for flow test and models

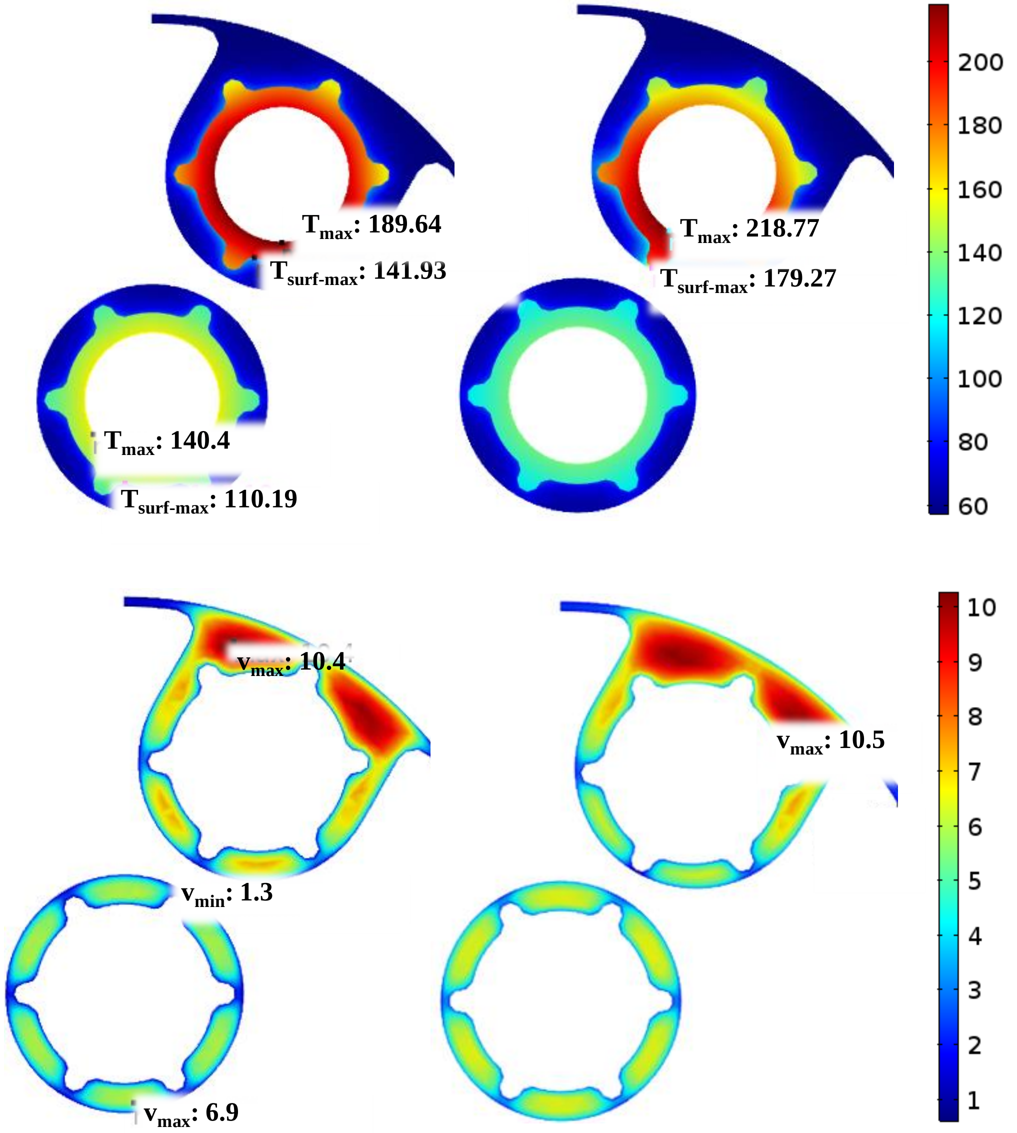




Experiment Safety Analysis

Thermal-Hydraulic Models

- Thermal hydraulic analysis
  - Non-isothermal flow multiphysics coupling of turbulent flow and heat transfer interfaces
  - Solved for k-ε and k-Ω turbulence models
  - 1.3 – 4.4 million mesh
- Full target holder
  - Solved at EOC-1 and EOC-3 for nominal and 50% flow conditions at 100% power
- Eccentric model
  - Fully revolved finned region, extrusion coupling operators used to transpose boundary flow conditions
  - Four eccentric flow positions analyzed for central and "hot pin" or pin 1 peripheral target at 130% overpower conditions
  - Limiting steady-state burnout results identified at pin 1 eccentric flow position shown on right

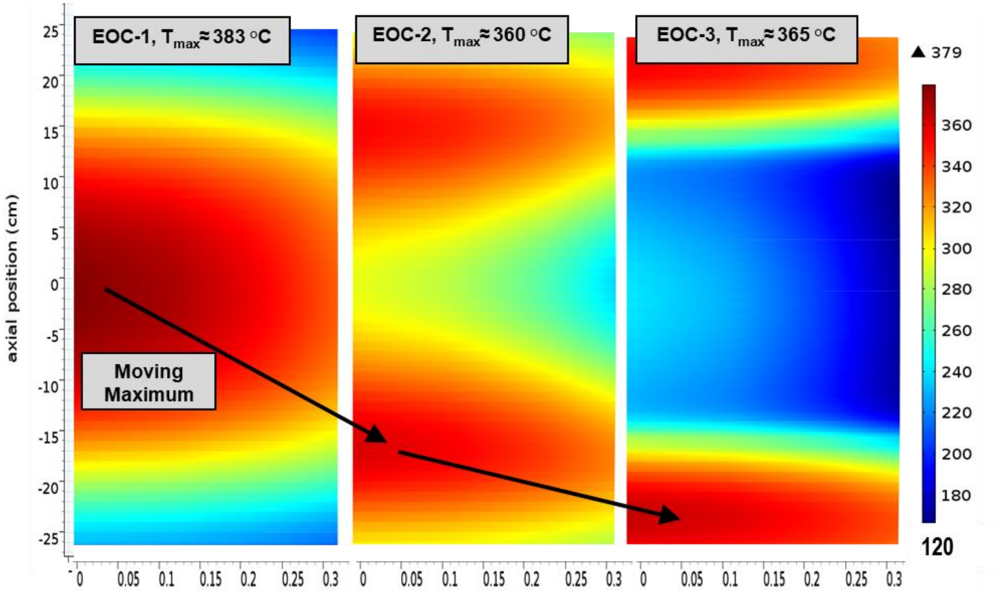


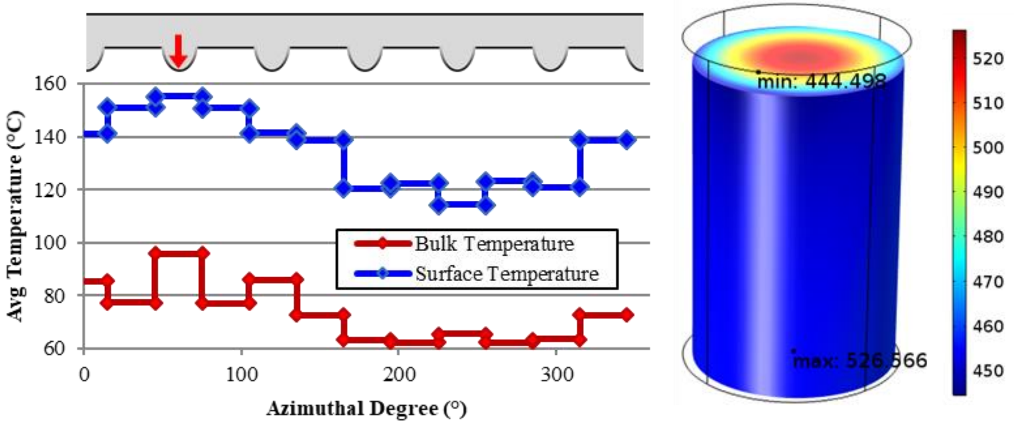
Temperature (top) and velocity (bottom) profiles for nominal (left) and eccentric (right) flow position cases.

Experiment Safety Analysis
Thermal-Structural Models

- Two thermal-structural models developed
  - 2-D R-Z representation of entire target pin
  - 3-D of limiting pellet and adjacent clad (to incorporate asymmetric flow)
  - Address steady-state overpower melting and structural integrity limits
- 2-D R-Z Target Pin
  - Simulations ran at EOC-1, 2, and 3 for pins 1 and 7
  - Pin 1 is limiting, where burnup-driven swelling/densification drives temperature maxima and stress
- 3-D Pellet/Clad
  - Pin 1 symmetric convective cooling inputs used as function of azimuthal angle
  - Small decrease in safety margin from 2-D R-Z reference
  - 1-2 million DOF

Pellet Stack Temperature Profiles





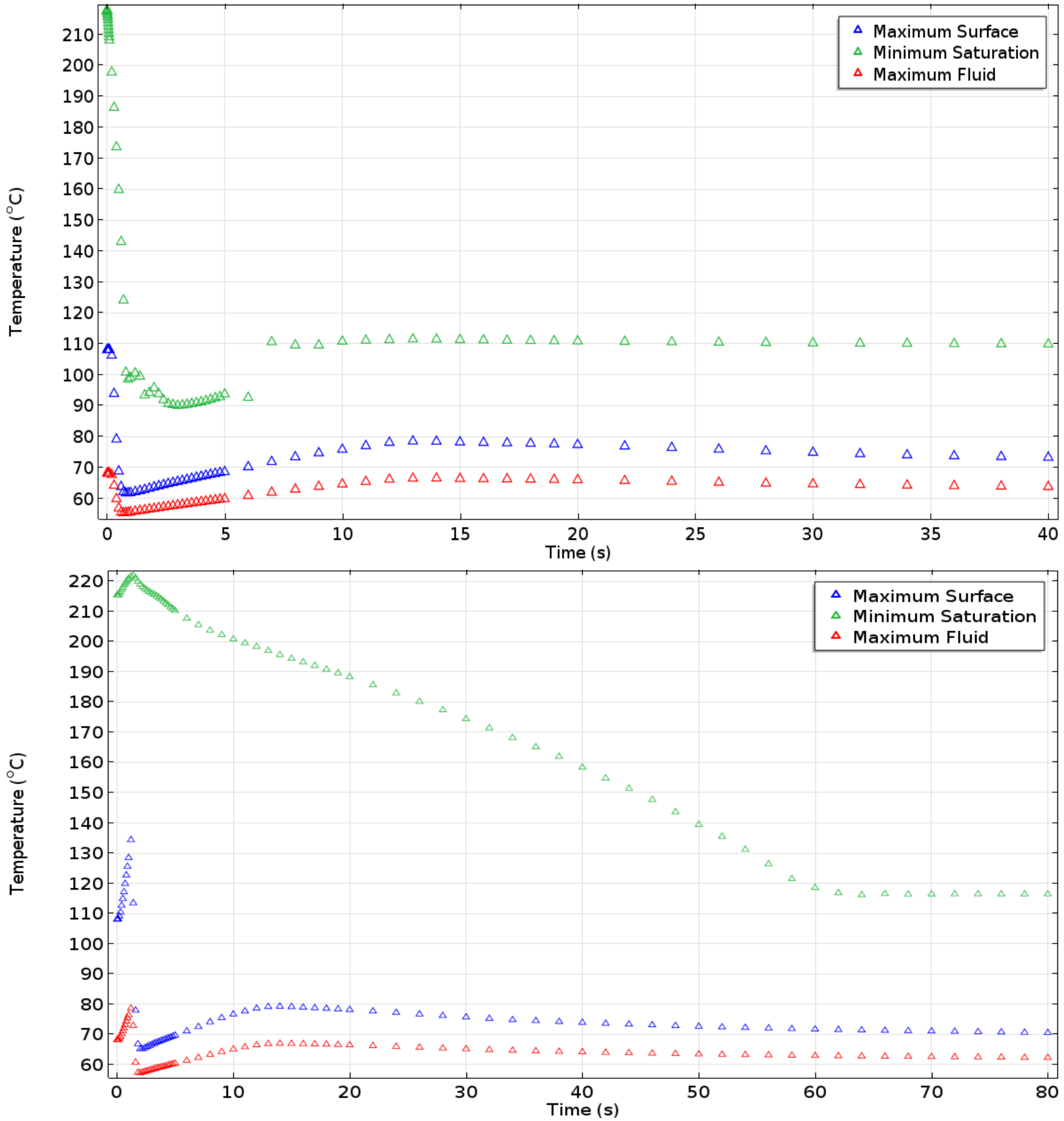
Asymmetric convective cooling (left) and 3-D pellet temperature profile (right)

Experiment Safety Analysis
Transient Analysis

- Uses non-isothermal pipe flow (1-D target holder flow paths) and heat transfer in solids (3-D target cladding)
- Coupled using general extrusion operators and antiderivate approximation

$$F(x) = \int_a^x u(x')dx' = \int_a^b u(x') * [x' \leq dest(x)]dx'$$

- Accident transients include SBLOCA and LOOP (see right, top and bottom, respectively)
- Use plant model time-dependent boundary conditions
- SBLOCA, Pin 1 is more limiting, compares well to previous analysis in 1-D thermal hydraulics code RELAP5



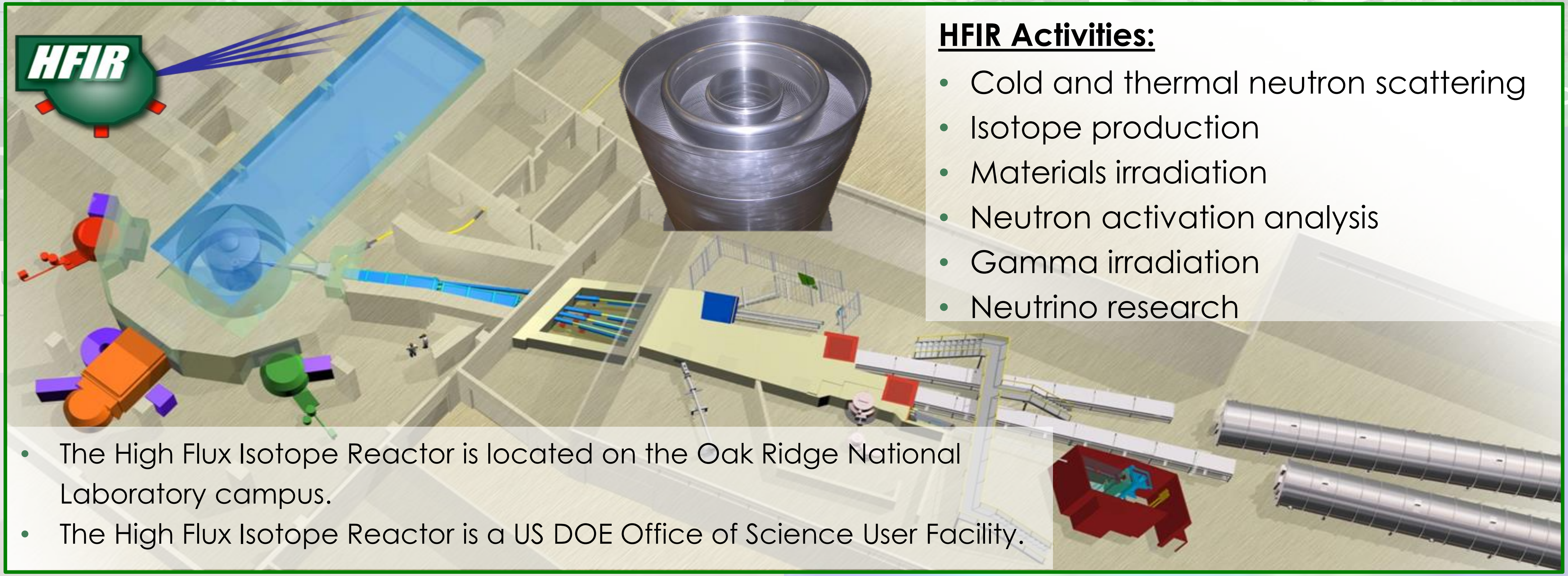
Transient results of SBLOCA (top) and LOOP (bottom) accidents for surface burnout.

Simulation Models of 2nd Generation Target

Summary and Future Work

- Conclusions
  - Five high fidelity models developed spanning four COMSOL physics modules
  - Good comparison of COMSOL CFD simulations to experiment flow tests
  - Characterization of 3-D CFD allowed asymmetric flow channels
  - Utilized pipe flow module and new use of coupling operators
  - Target cooling and structural integrity maintained for steady-state and transient conditions
- Future COMSOL work in the ^{238}Pu Project
  - Assess conservatisms in safety analysis models and utilize further to:
    - Increase neptunium loading
    - Allow reduced target holder flow (for flow diversion)
  - Thermal-structural analysis of permanent beryllium (by M. Crowell)
    - Assess optimized permanent beryllium design for ^{238}Pu production
    - Investigate end-of-life flow degradation

Thank you!



HFIR Activities:

- Cold and thermal neutron scattering
- Isotope production
- Materials irradiation
- Neutron activation analysis
- Gamma irradiation
- Neutrino research

- The High Flux Isotope Reactor is located on the Oak Ridge National Laboratory campus.
- The High Flux Isotope Reactor is a US DOE Office of Science User Facility.

Questions?