Idaho National Engineering and Environmental Laboratory

Beryllium-Steam Reaction in Ceramic Blanket

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University of Wisconsin, Madison

Presentation Overview

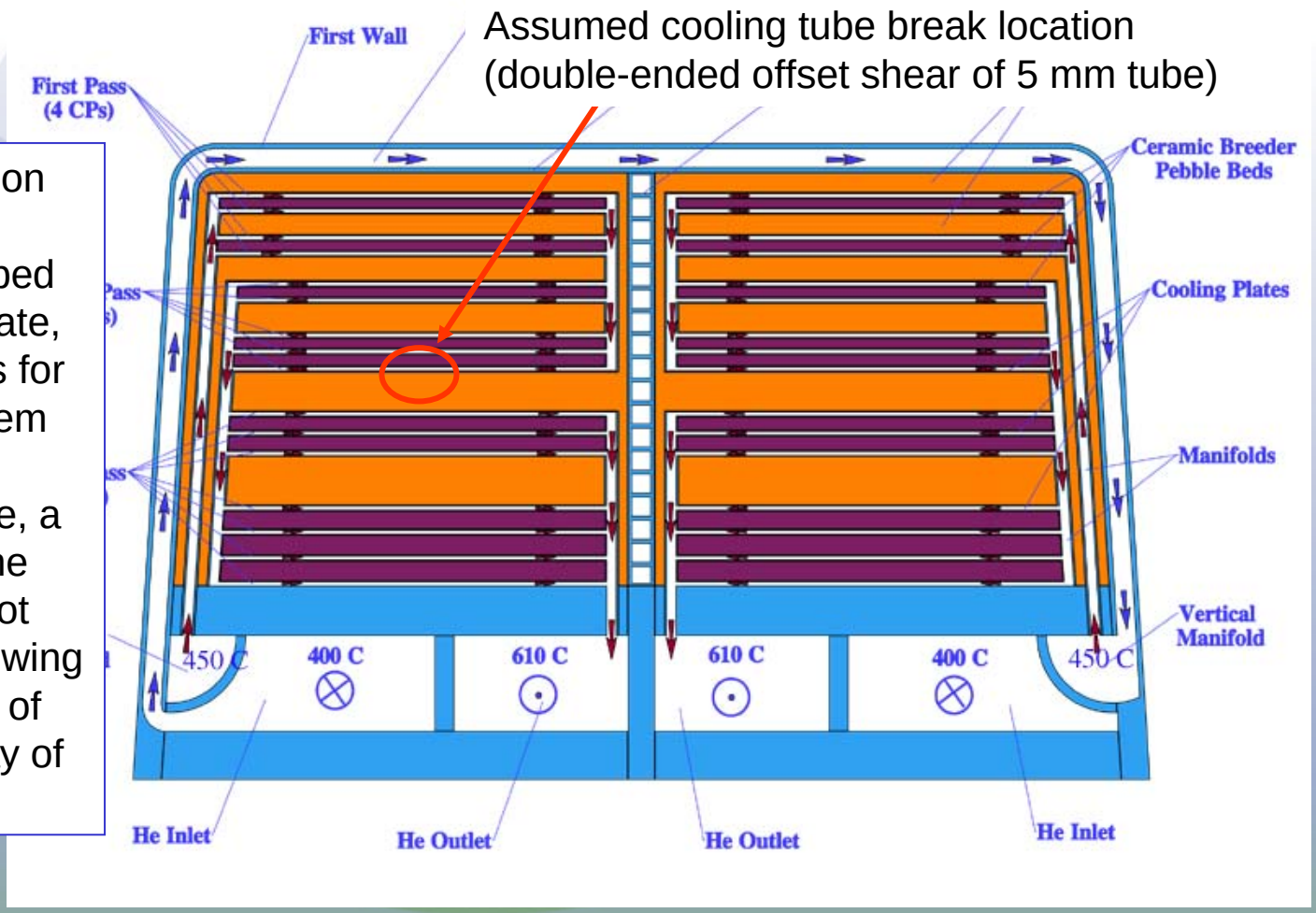
- Background discussion of double tube failure accident for helium cooled pebble bed (HCPB) blanket module design
- Description of the double tube failure accident progression for the ARIES HCPB concept
- Details of MELCOR model developed to analyze this accident for an ARIES HCPB module
- MELCOR results
- Summary and future work

Background of this Safety Issue

- The safety concern with this accident is the beryllium-steam reaction producing chemical heat that propagates additional module failures, and producing hydrogen with the potential of hydrogen explosions failing confinement boundaries
- A double tube failure accident scenario begins with the failure of a blanket helium cooling tube that results in the over-pressurization and failure of a blanket module; then a steam generator (SG) tube also fails, allowing steam to enter the failed module and react with the beryllium multiplier pebbles
- Based on fission SG safety studies, this accident is most likely the result of independent tube failure events; that is, the failure of the first tube does not result in a condition for the second tube that is outside of the second tubes' design envelope
- Based on LWR and HTGR failure data, the probability of this event occurring was estimated at 5×10^{-10} /year
- This probability value indicates that the double tube failure is a Beyond Design Basis Accident (BDBA), and would remain a BDBA even if the severe SG tube conditions produced by this accident where 1000 times more likely to fail the tube than fission data indicates

ARIES Pebble Bed Blanket Module

- Module construction results in each beryllium pebble bed zone being separate, parallel flow paths for tritium purge system gas
- As a consequence, a break into the zone indicated would not result in steam flowing into other regions of the module by way of the purge system

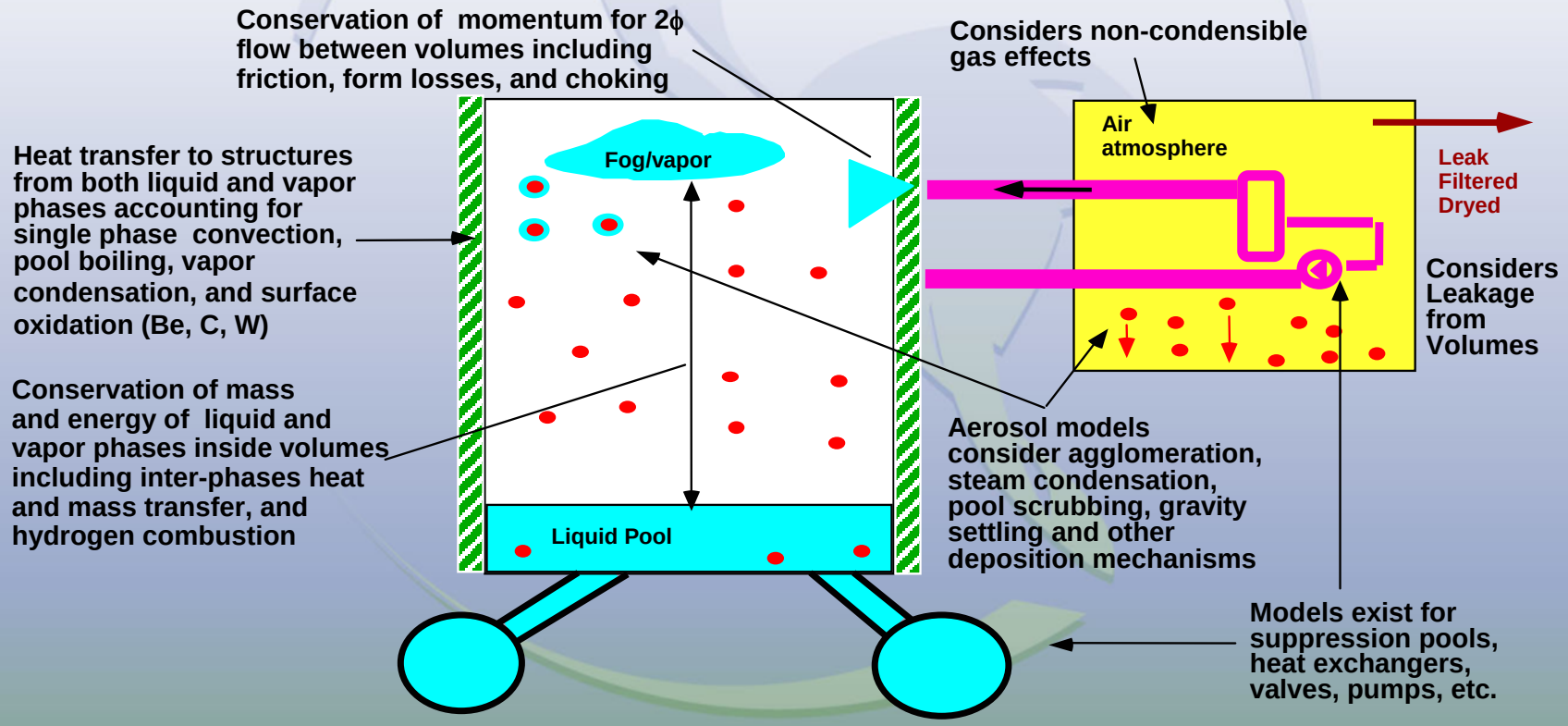


Double Tube Accident Progression

- Module cooling tube breaks and helium leak pressurizes tritium extraction system, then this helium vents from tritium extraction system
- Primary system depressurization to 70 atm occurs over several minutes, giving ample time to shutdown reactor prior to a complete cooling loss
- A steam generator tube eventually breaks and re-pressurizes the cooling primary system
- Inlet channel to broken tube bank will experience choked flow (sonic velocity) since it is the minimum area in the break flow path
- Choked flow could also occur at the tube break since the pebble bed pressure will be less than the break pressure
- Steam flow will continue until mass in the steam generator cools to 100ºC due to flashing (evaporative cooling); at 19,000 kg of H_2O it should take hours for a single tube break vent this steam
- Radioactive decay and steam-beryllium reactions will heat the module
- Steam flow will provide convective cooling to the module

MELCOR Code used for this Accident Analyses

MELCOR is a engineering-level computer code that models the progression of severe accidents in light water reactor (LWR) nuclear power plants, including reactor cooling system and containment fluid flow, heat transfer, and aerosol transport. (Developed by SNLA, fusion modifications by INEEL)



MELCOR Beryllium-Steam Reaction Equations

- Stoichiometric equation

$$Be + H_2O \rightarrow BeO + H_2 \; ; \; Q_R = -370 \, kJ/mol\text{-}Be$$

- ITER reaction rate (kg-Be/m^2) of MELCOR
  - Dense beryllium

$$R_{OX_1} = 1.933 \, x10^6 \, e^{-25850/T} \; ; \; T < 1173 \; K$$

$$R_{OX_2} = 31.837 \; e^{-12830/T} \; ; \; T > 1173 \; K$$

  - Porous beryllium (88% dense)

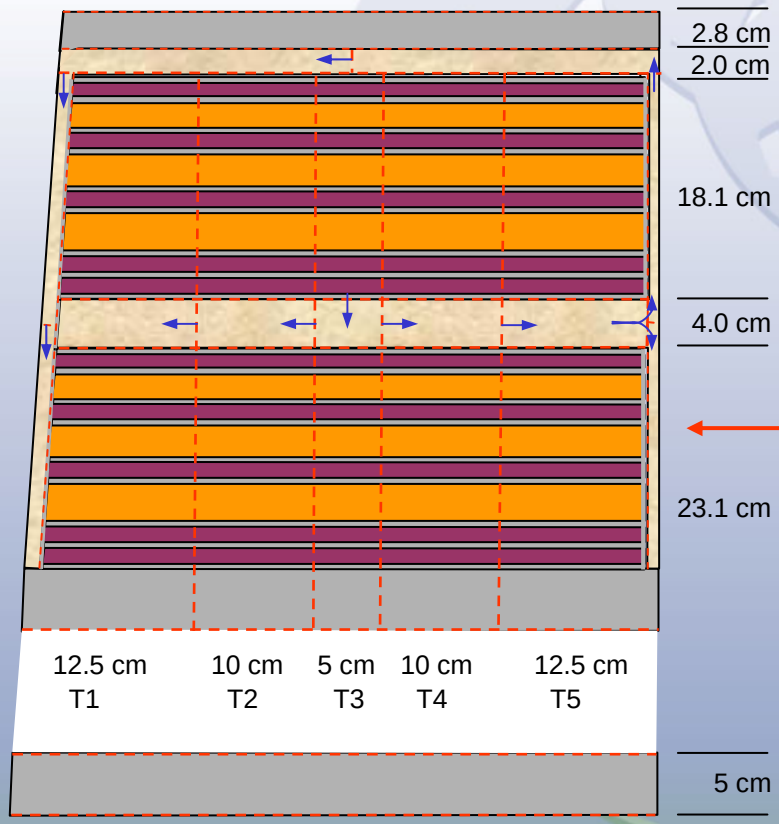
$$R_{OX_3} = 49.533 \; e^{-12500/T}$$

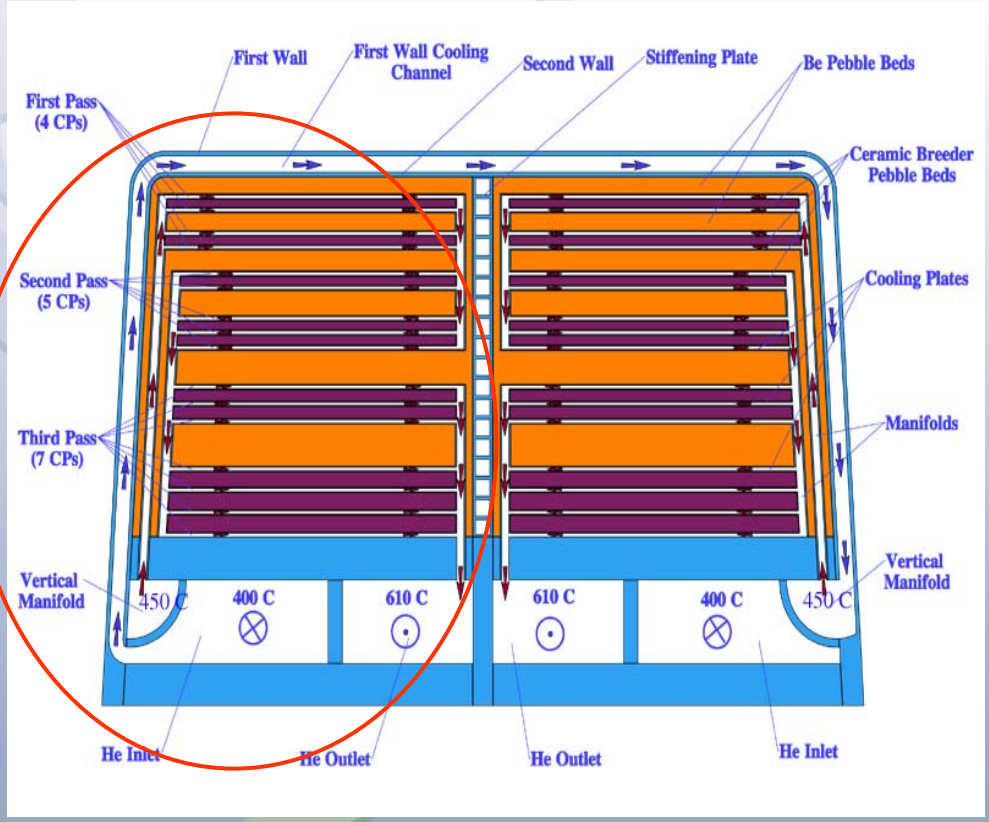
  - Geometric mean rate accounts for beryllium radiation damage (p_m is a multiplier that compensates for H_2O pressure)

$$R_{OX} = p_m \sqrt{R_{ox_{1,2}} R_{ox_3}}$$

MELCOR Model Schematic of One Quarter of ARIES Pebble Bed Blanket Module

Toroidal cross-section





Radiant heat transfer at back of module with other outer surfaces assumed adiabatic

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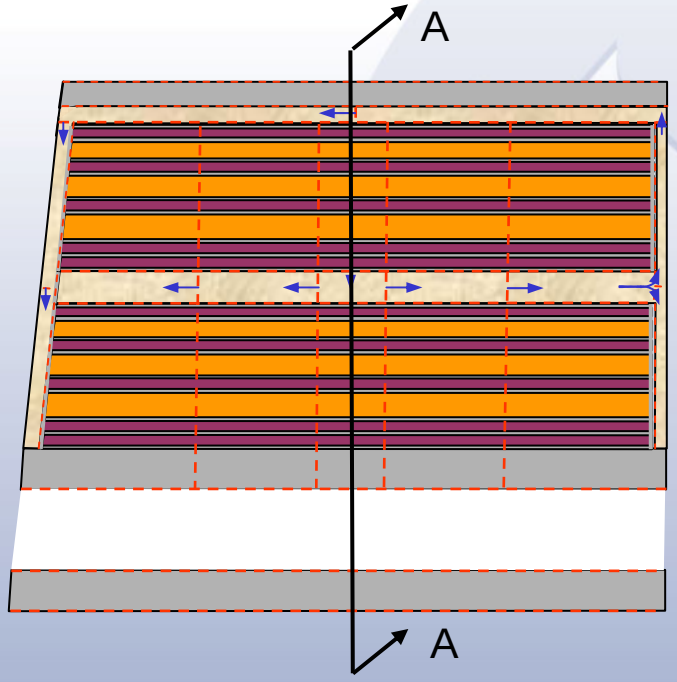
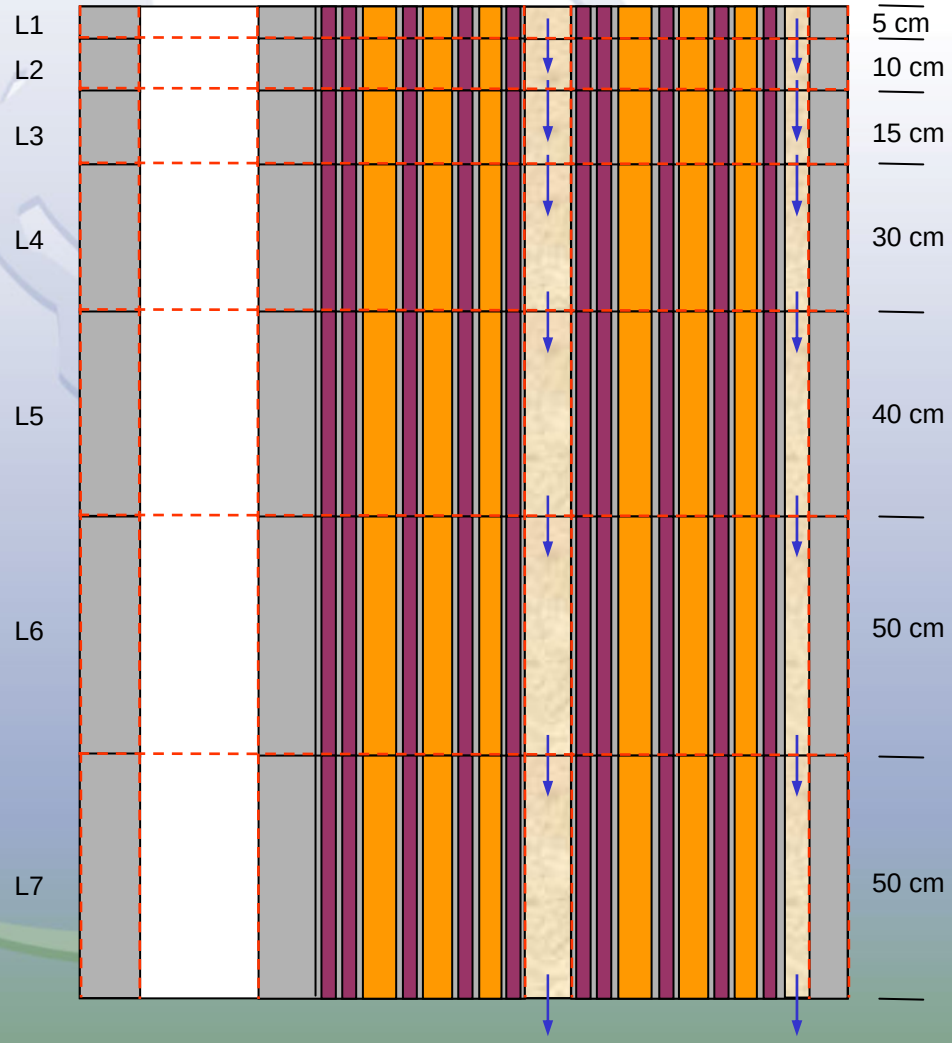
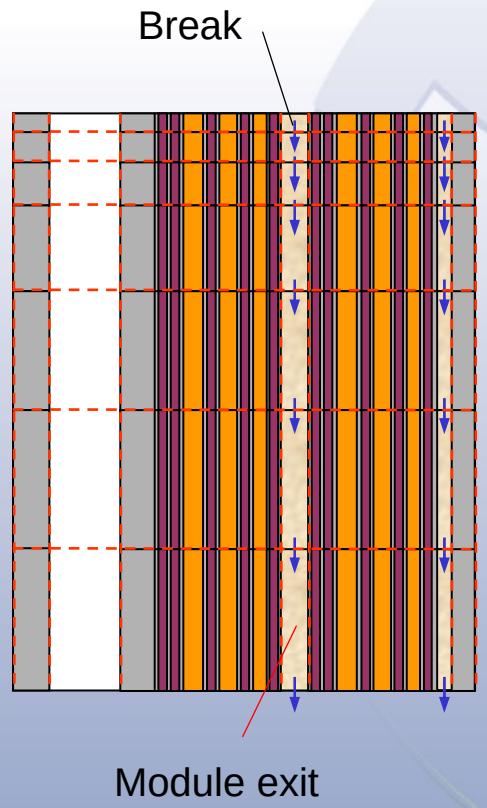


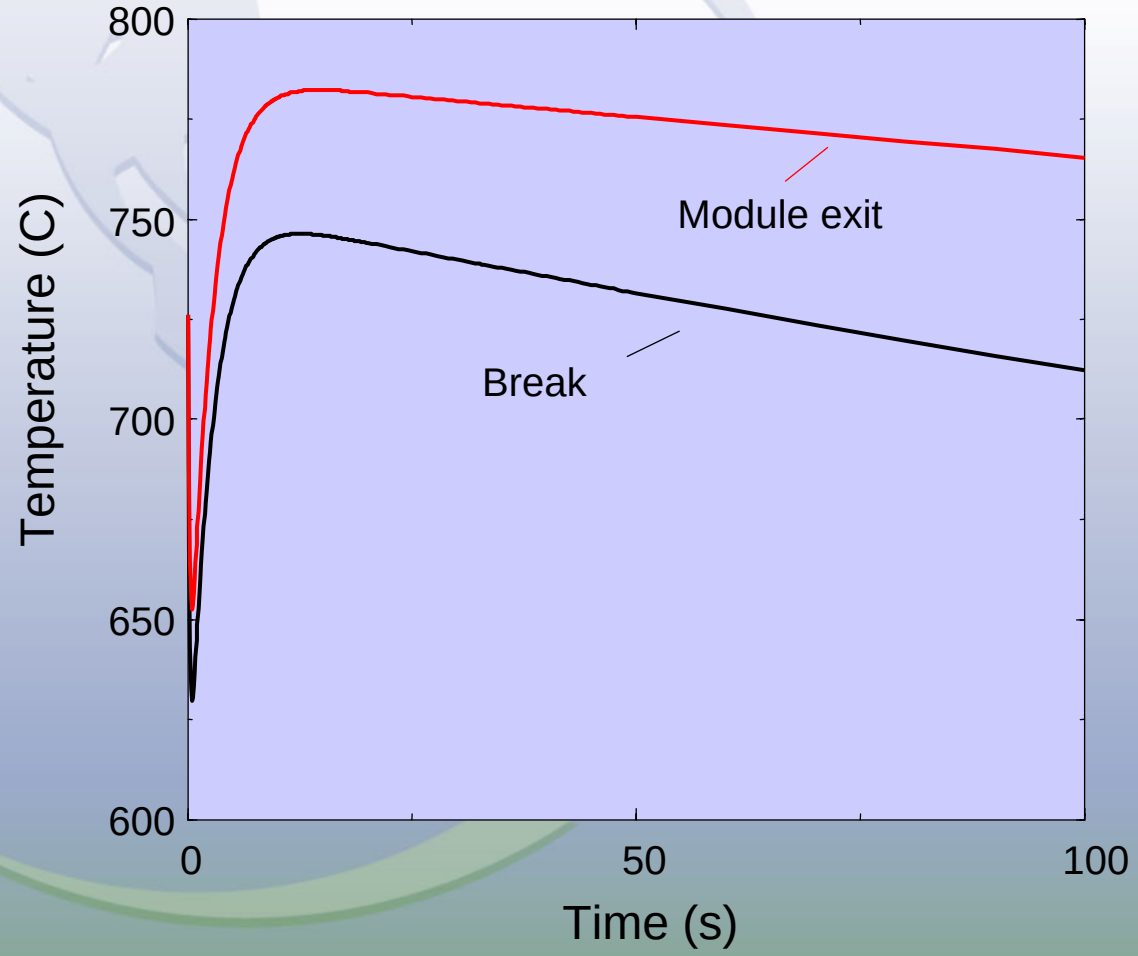
Poloidal cross-section (A-A)



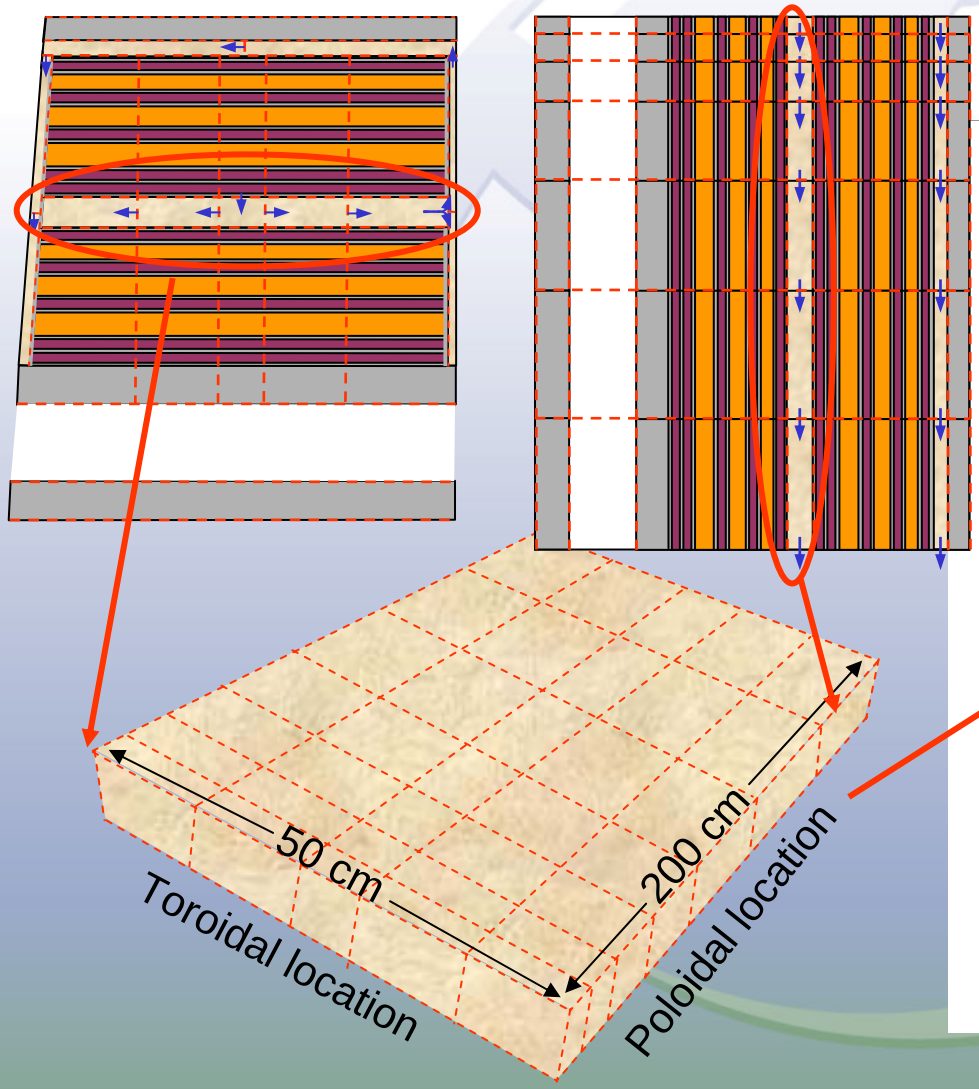
Model is 2-1/2D flow and 3D heat conduction for the beryllium/steam interaction zone and multiple 1D heat conduction simulating the unaffected blanket zones

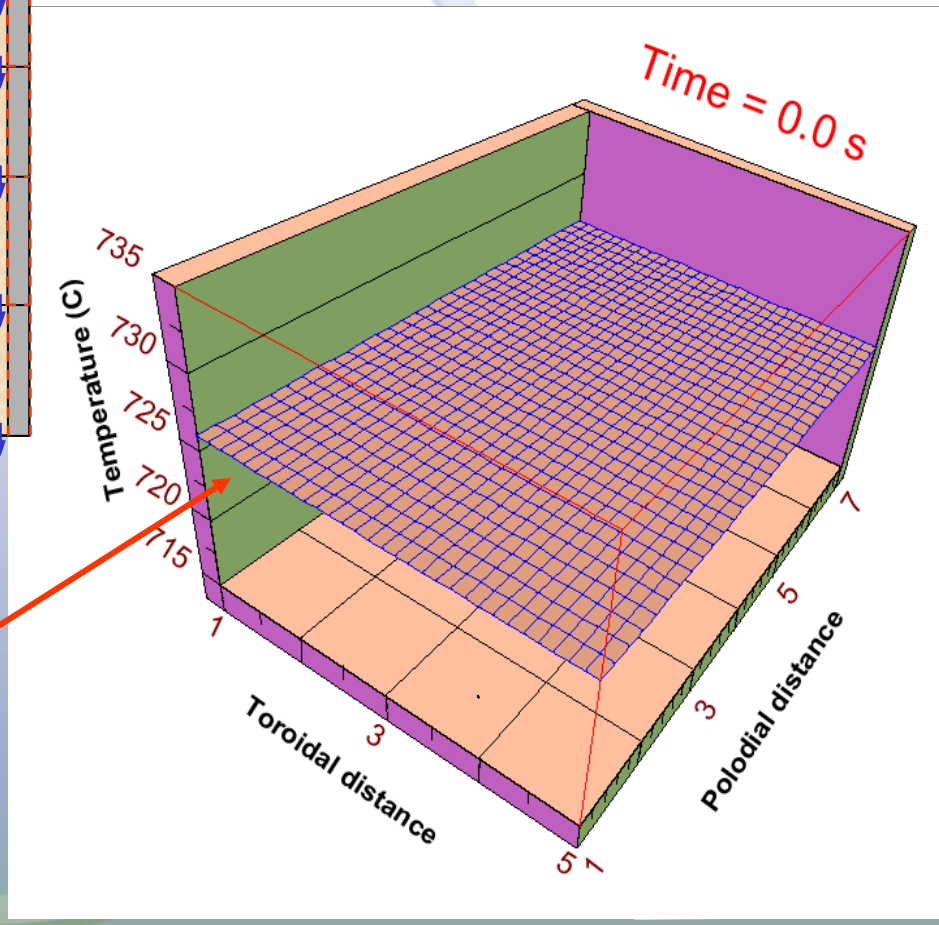
Mid-zone Beryllium Temperature History
(No Decay Heat)





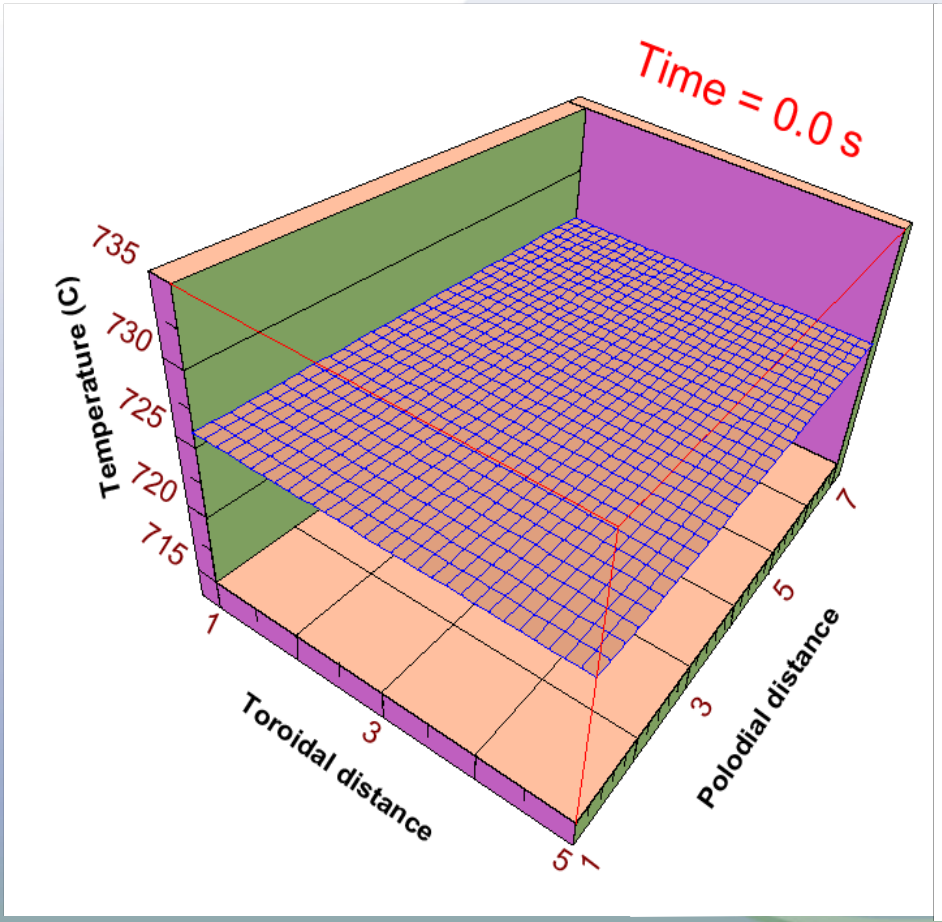
Mid-zone Beryllium Surface Plot Locations

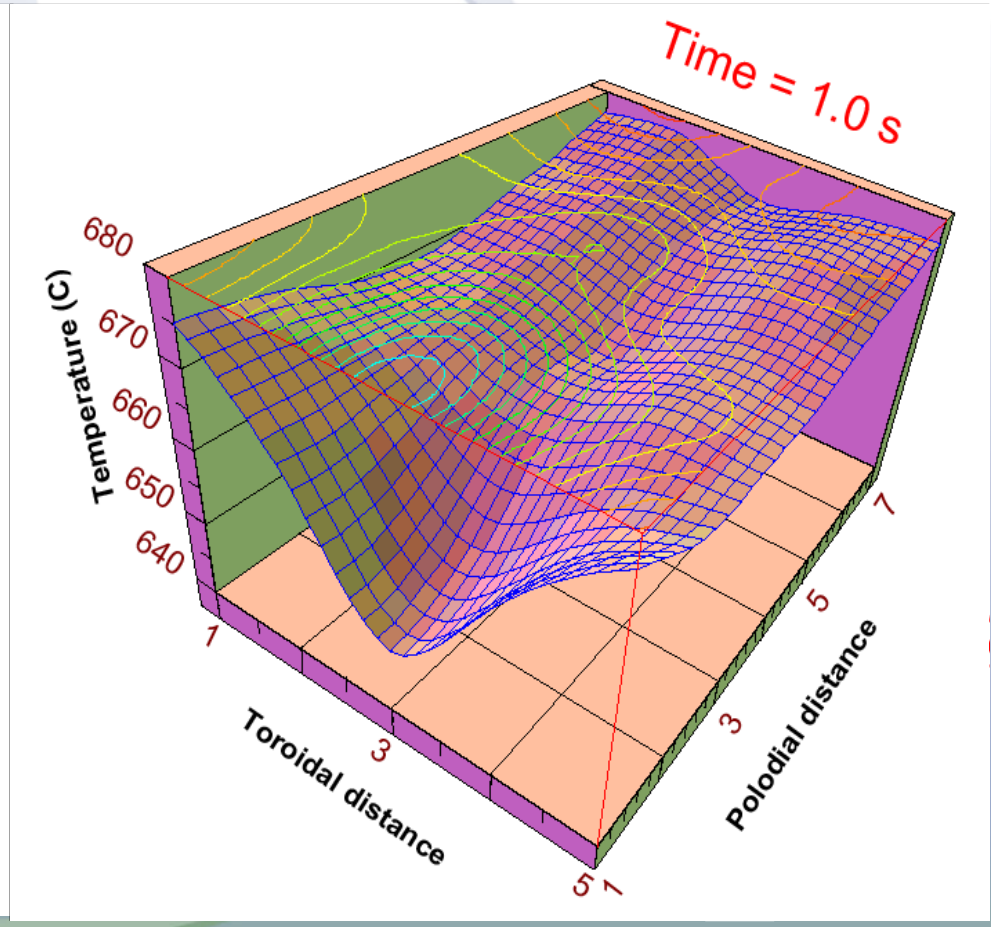




Mid-zone Beryllium Temperatures

(No Decay Heat)





Mid-zone Beryllium Temperatures

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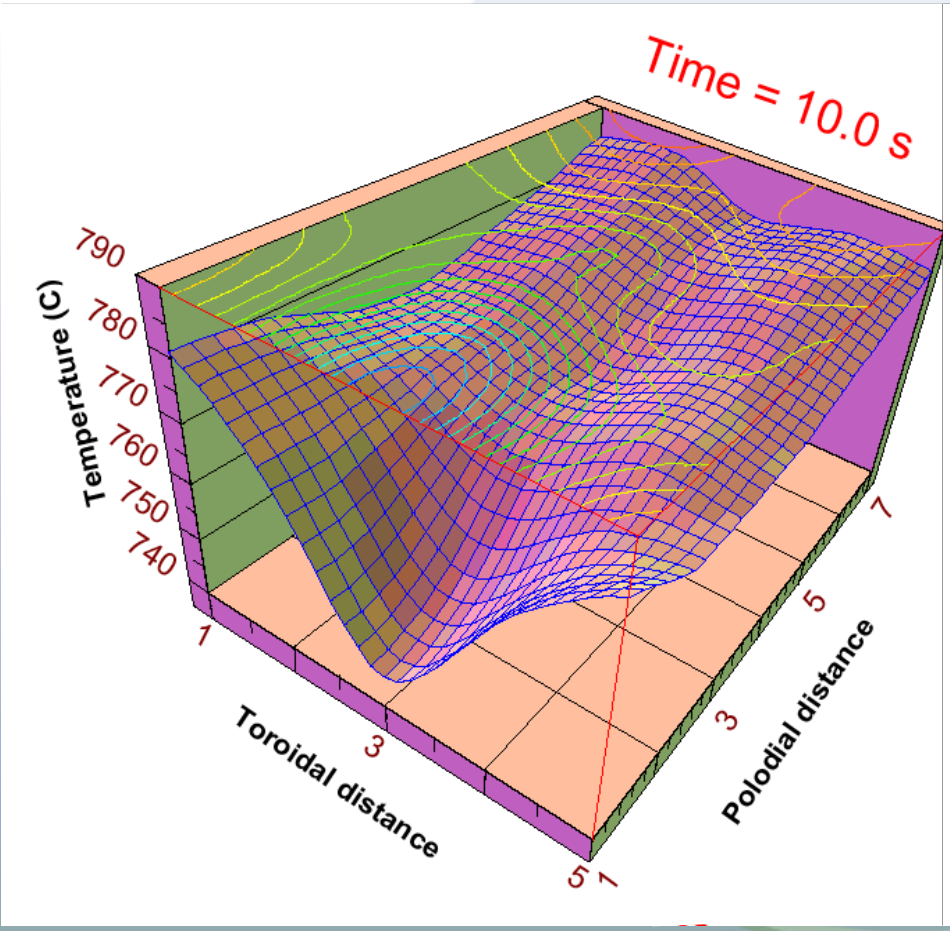
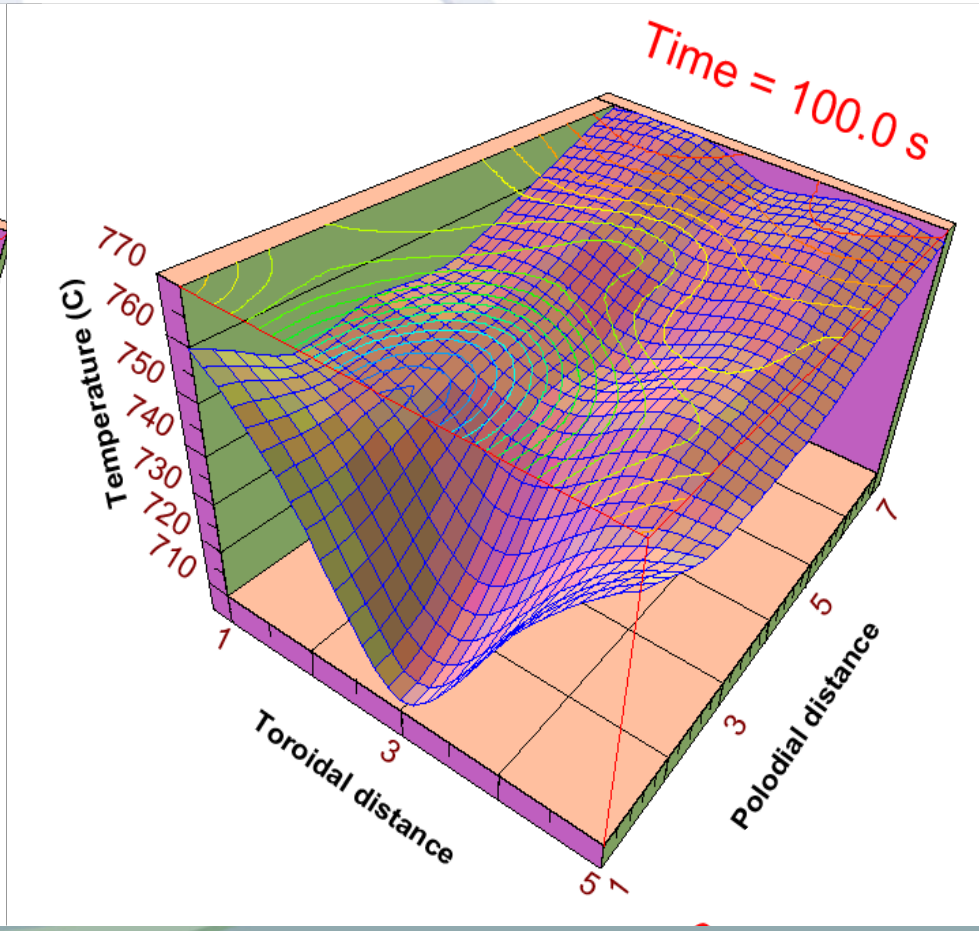


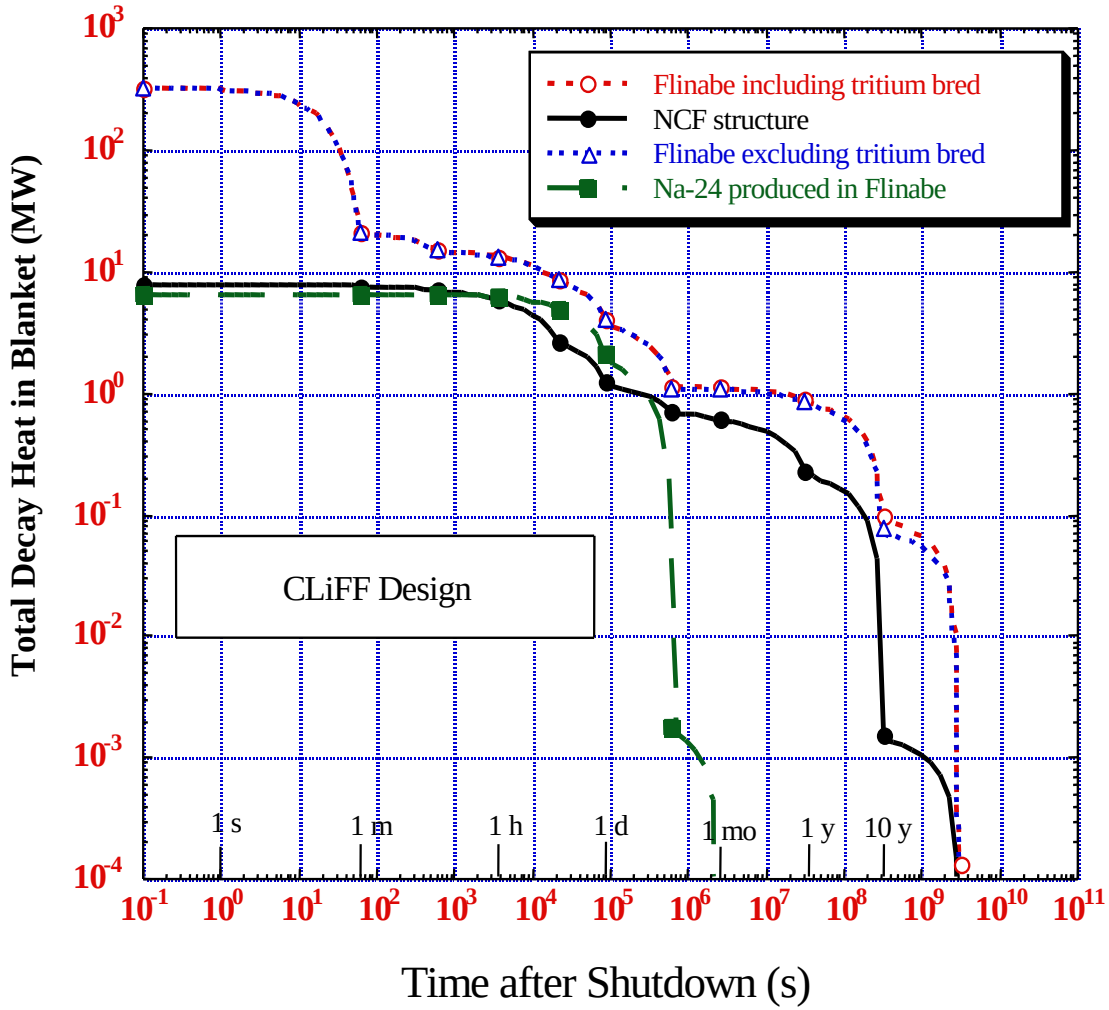


Why A Thermal Runaway Didn't Occur
(Back of the Envelope Check)

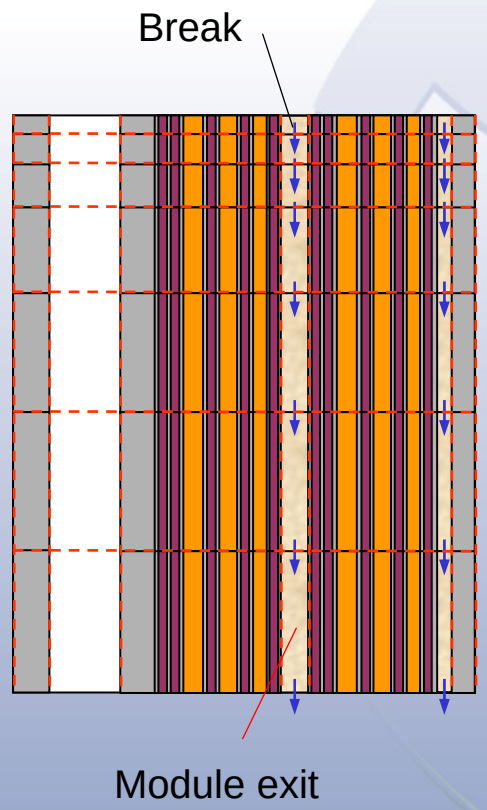
- The quantity of beryllium in the interaction zone of the quarter module modeled is ~ 0.14 m^3
- For 4 mm pebbles, the number of pebbles is 32,550 with a total surface area of ~1.6 m^2
- If all of these pebbles were at the maximum beryllium temperature predicted by MELCOR, then the oxidation rate would be 9.2×10^{-5} kg-Be/s
- At this reaction rate the heat produced would be 6.2 kW, and after 100 s only 2 gm of H_2 would be generated
- The break flow rate of steam is predicted to be ~100 g/s, and given the temperature rise through the module this steam removes ~33 kW of heat, therefore no thermal excursion
- However, decay heat could change this result

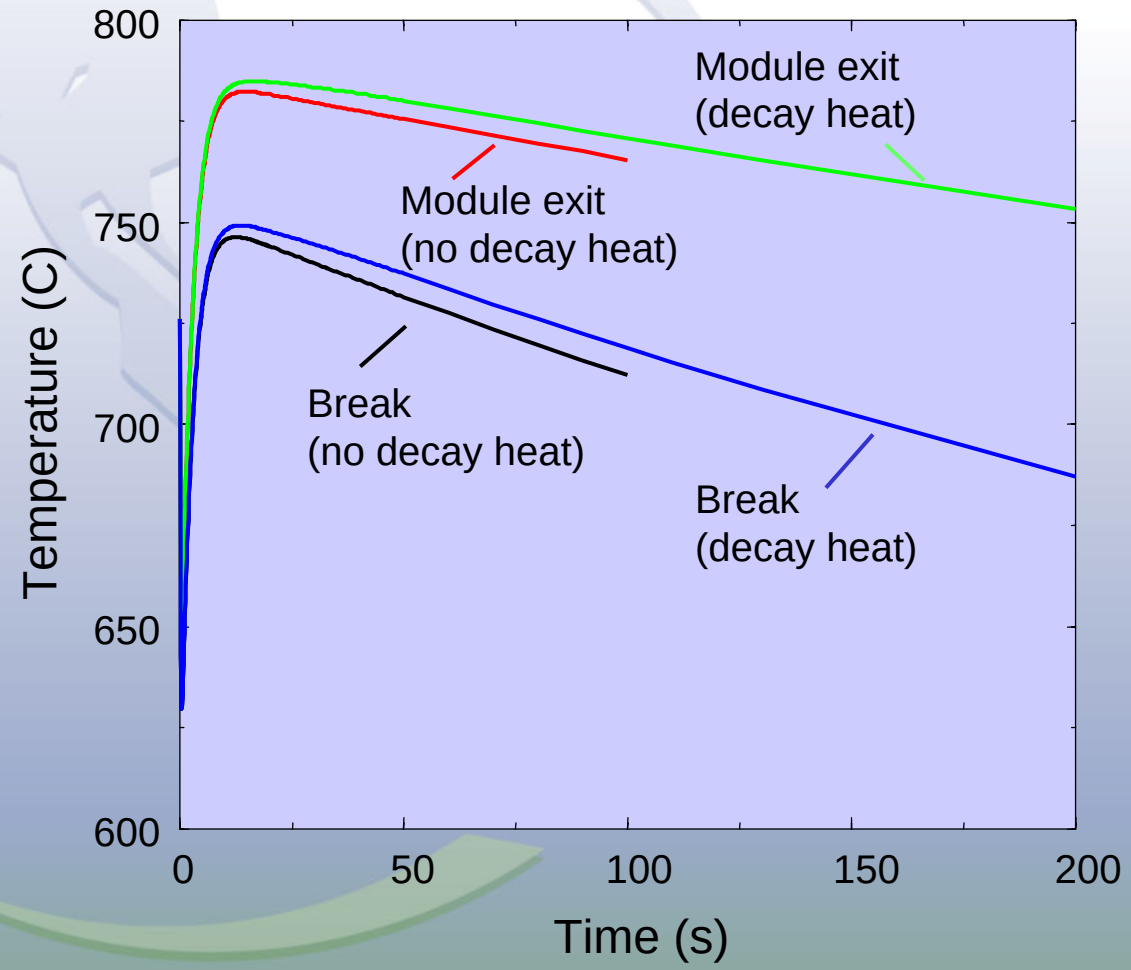
Decay Heat Approximation

- Module decay heat was approximated for this module by adapting decay heating from an APEX molten salt blanket design
- Decay heat was scaled by area (APEX at 555 m^2 to 1 m^2 for quarter module), giving 0.6 MW at shutdown and 36 kW after 60 s
- Should be a conservative estimate because APEX neutron wall loading is 7 MW/m^2 and the rapid decay of F-18 dominates heating during the first minute after shutdown

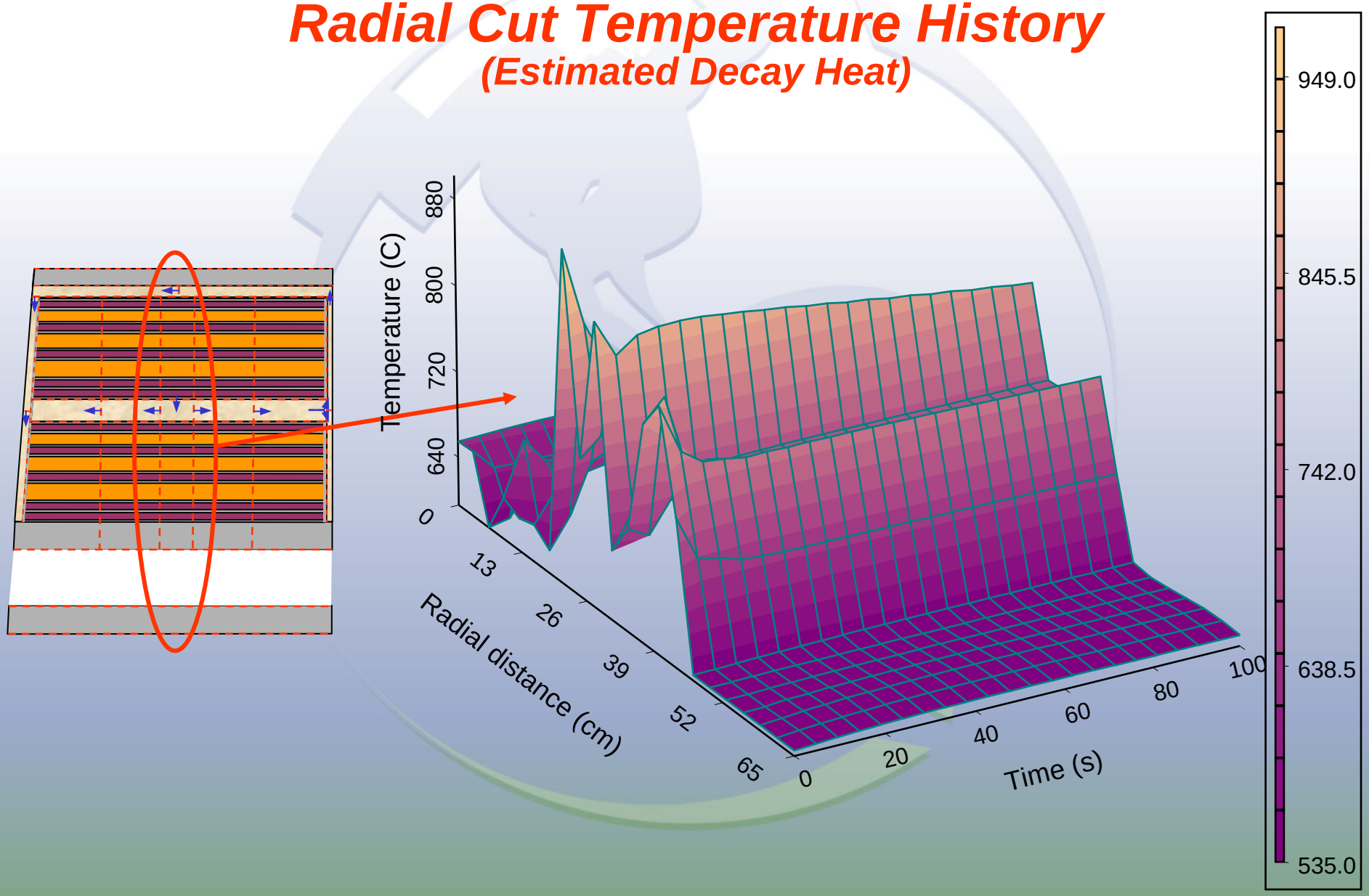


Mid-zone Beryllium Temperature History
(Estimated Decay Heat)



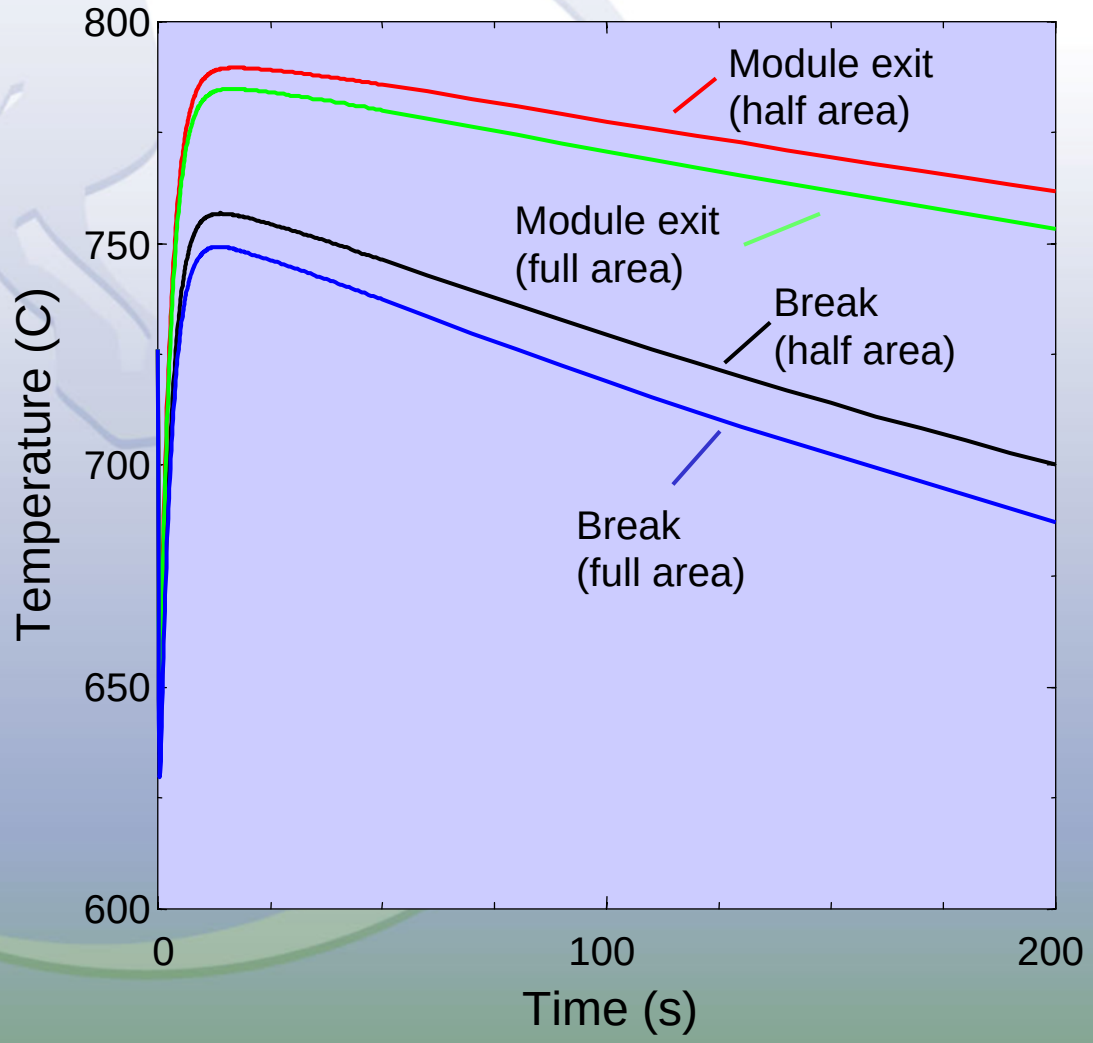


Radial Cut Temperature History
(Estimated Decay Heat)



Influence of Tube Break Size

- Accident analyzed with a break area that is half of that of a double-ended offset shear tube break
- Break flow (downward fraction) only decreased from 95 g/s to 70 g/s because pressure behind break increased from 32.6 atm to 48.7 atm
- There should be a lower limit on break size at which the break becomes a leak controlled by helium makeup (1%/day?,< 0.1 g/s)
- For the double-ended offset shear 5 mm tube break the helium flow rate is 190 g/s; taking ~450 s to depressurize to 70 atm and ~1 hour to completely depressurize



Summary and Future Work

- A multi-dimensional MELCOR fluid flow/heat conduction model was developed for one-quarter of an ARIES HCPB module to analyze a double tube failure event in this blanket design
- Preliminary results suggest that the convective cooling of the steam entering the failed beryllium pebble bed zone will remove more heat than produced by the beryllium-steam reaction, and as a result propagation of this failure to other modules by chemical heating alone is not likely
- The impact of decay heat on these results was investigated with scaled decay heating from a different blanket design and found not to change this conclusion
- More accurate decay heat and pebble bed friction/heat transfer coefficients will be included in the existing MELCOR model for future analyses