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CFD Best Practice Guidelines

for Dry Cask Analysis

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Introduction

- NRC used CFD for confirmatory analysis in dry cask applications.
- CFD is used to analyze dry cask for:
  - Normal storage operation (long-term): Steady state analysis
  - Accident analysis (short-term): Transient analysis, e.g. (Blocked vents scenario, fire analysis, effect of wind direction on air cooling efficiency)
- Dry cask thermal performance should comply with to 10CFR72 requirements.
- Thermal evaluation follows the guidelines of NUREG-1536 and Interim Staff Guidance Memorandum No.11 to demonstrate thermal compliance of the dry cask
- Specifically, some of the requirements are:
  - The fuel cladding temperature for long term storage shall be limited to 400 C
  - The fuel cladding temperature should be maintained below 570 C for accidents.
  - The maximum internal pressure of the MPC should remain within its design pressures for normal, off-normal, and accident conditions.
  - The cask materials should be maintained within their minimum and maximum temperature criteria for normal, off-normal, and accident conditions.
  - The HI-STORM system should be passively cooled

Sources of Errors and Uncertainties

- CFD user introduces errors and uncertainties through the process of performing CFD
- CFD is a knowledge-based activity despite the availability of CFD software
- Initiatives to structure existing knowledge in the form of Best Practice Guidelines (e.g. ERCOFTAC, QNET-CFD, MARNET CFD, CSNI BPG)
- There is no universal classification of errors, but ERCOFTAC BPG adopts the following seven different source of errors and uncertainties:

Error: a recognizable deficiency that is not due to the lack of knowledge

Uncertainty: a potential deficiency that is due to lack of knowledge.

1. Model errors and uncertainties: Models may not be a good model for reality.
   - e.g. **Turbulence Models** (most published).
2. Discretization errors: Difference between exact solution and discretized equations
3. Iteration errors: Difference between fully converged solution and not fully converged.
4. Round-off errors: A computer solves the equation with a finite number of digit
5. Application uncertainties: Imprecise geometry, **BC Uncertainty**, steady vs. transient.
6. User errors: Oversimplification of the problem and mistakes of the user
7. Code errors: Bugs in the software

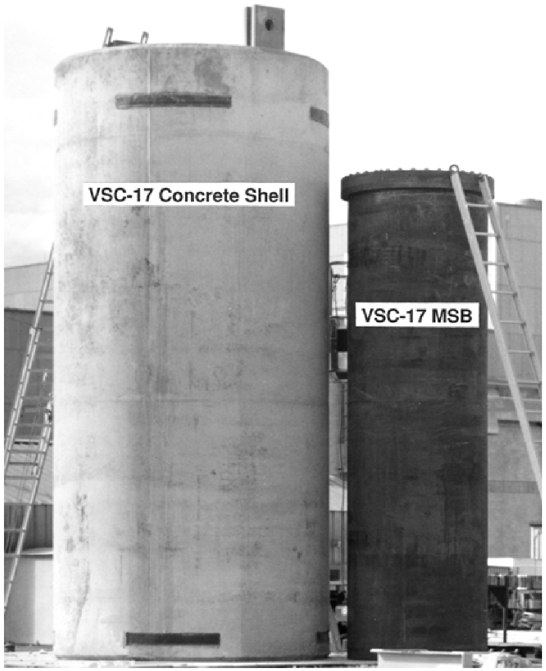
Dry Cask Modeling issues and Validation:

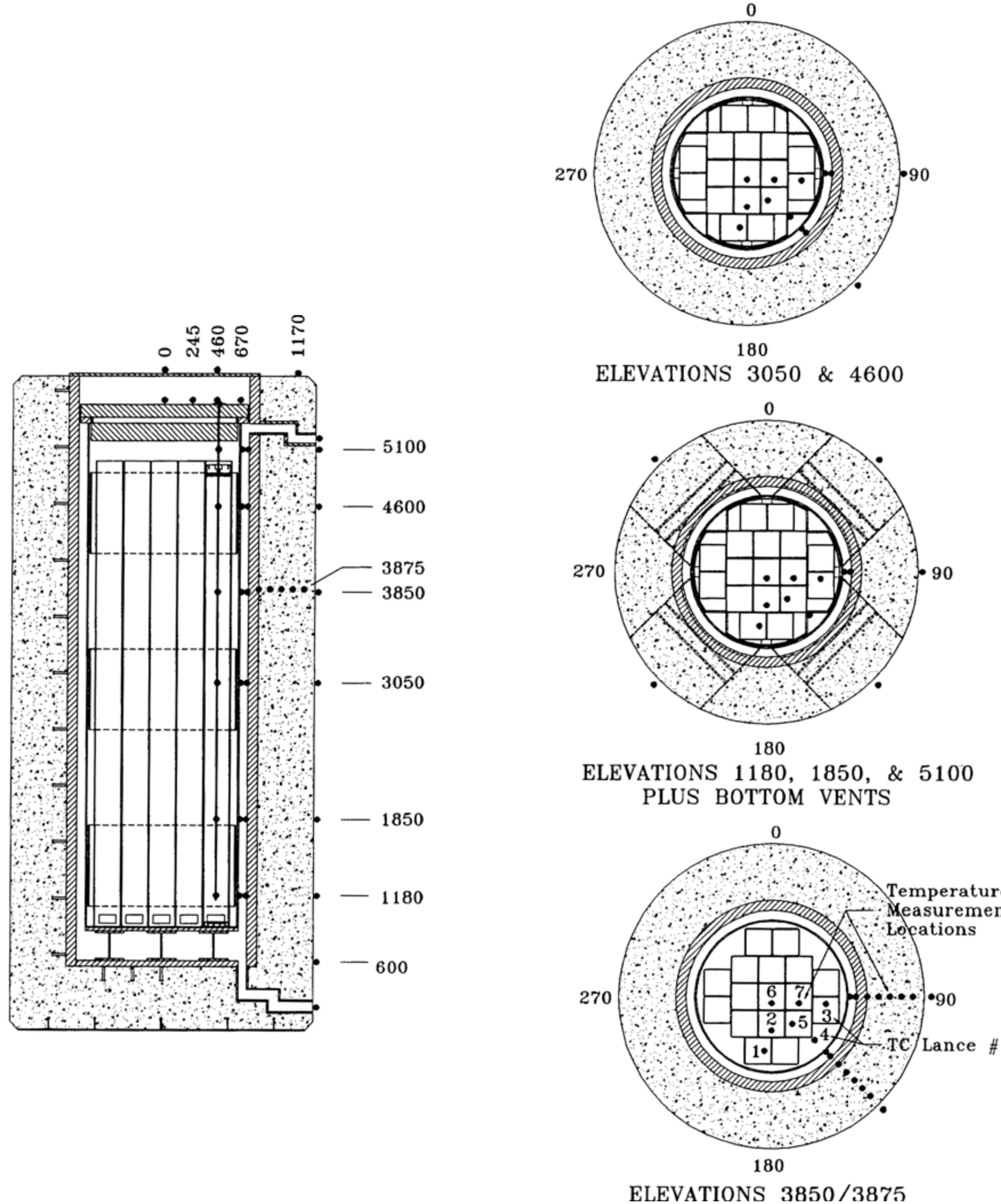
- Porous media was used to model flow through fuel rods to save time and effort
  - Effective conductivity representing radiation and conduction in the porous region
  - Porous media modeling used an equivalent frictional and inertial resistances
- Uncertainty in flow regime modeling
  - Turbulent vs. Laminar
  - Uncertainty in turbulence models
- Uncertainty in Boundary condition
  - Buoyancy driven flow
  - Pressure boundaries: What values?
- The Solution is to validate the CFD model before using it.
- **Validation**: Procedure to test if the model accurately represents reality.

Guidelines on Validation

- Use test data for a similar application with similar flow structures
- Check carefully the quality and accuracy of data used for validation
- The experiment should reflect the relevant Boundary and initial conditions
- Data that are sensitive to Boundary conditions should be reported
- Ventilated Storage Cask (VSC-17) experimental data, collected by INEEL was used
- Similar flow structure and Geometry as the casks presented to NRC for certification

Dry Cask VSC-17

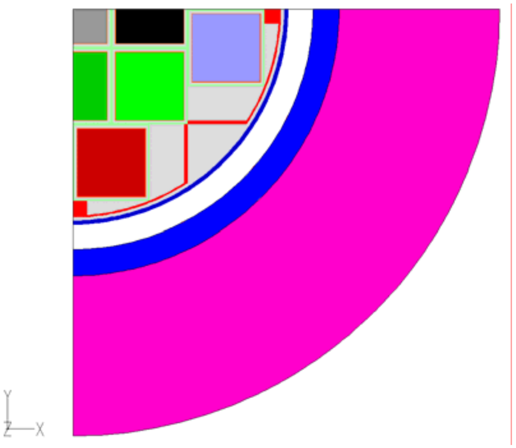


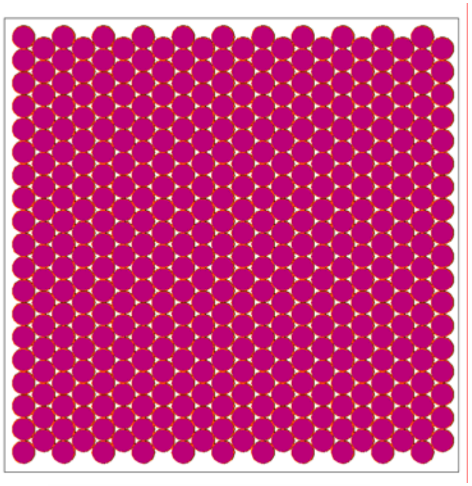


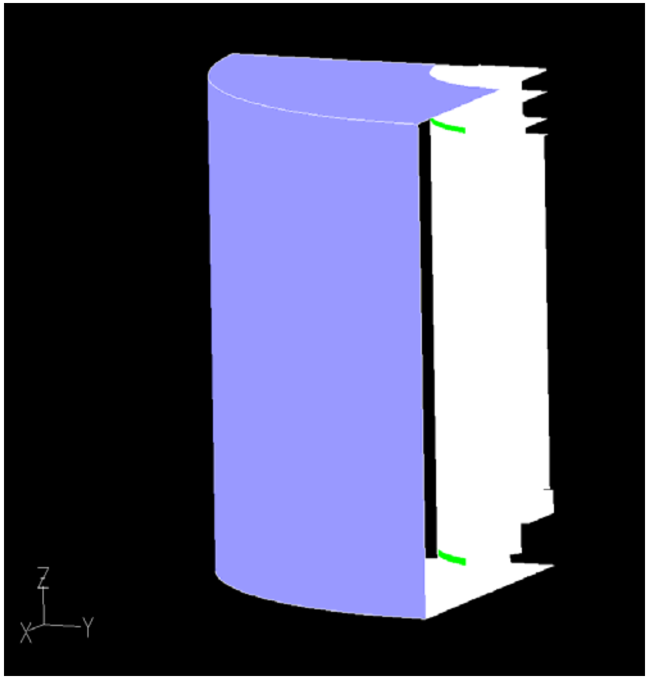
VSC-17 Modeling

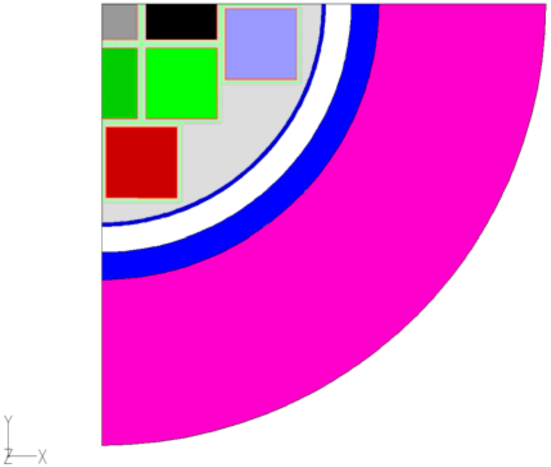
- Inert gas (He) inside the canister. Laminar flow based on the Rayleigh Number
- Air flows in an open system to cool the canister: issues of flow regime.
- **Pressure Boundaries** were used at the inlet and outlet air ducts
- **Regime of the flow**: can under-predict the Peak Clad Temperature (PCT)
- Four turbulence models were used:
  - Low Reynolds std k-ε: requires fine mesh near the wall (y+ ~1)
  - Transitional k-ε SST: requires fine mesh near the wall (y+ ~1)
  - Standard k-ε: requires a mesh near the wall (y+ ~ 30), uses Std wall functions
  - Laminar flow regime: requires fine mesh.
- Consolidated Fuel (410 rods): fuel was modeled by a solid volume with an energy source of 14.9 kW.
- **Porous media** is usually used to model flow through fuel rods
  - Equivalent effective thermal conductivity was found using 2-D CFD analysis
  - Equivalent flow resistances are calculated using 3-D CFD in a single assembly.
- Grid independent solution was found first.

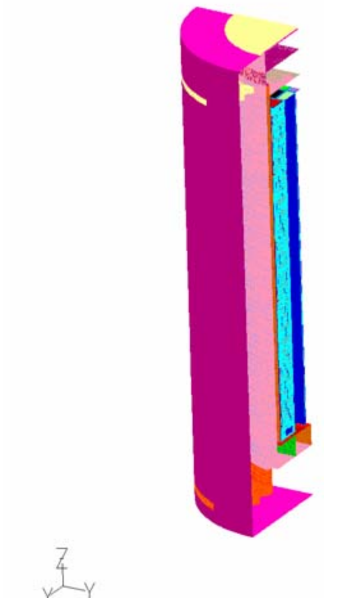
VSC-17 Modeling (Cont)



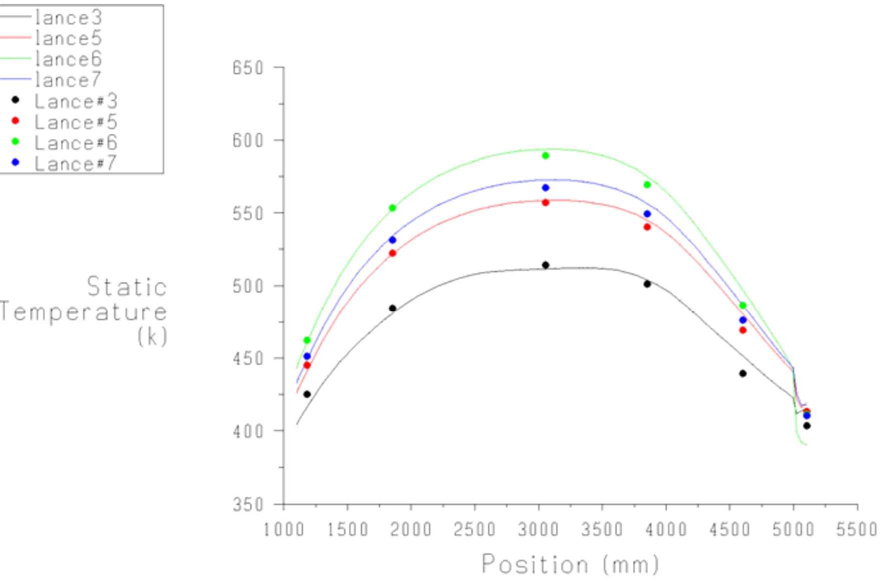




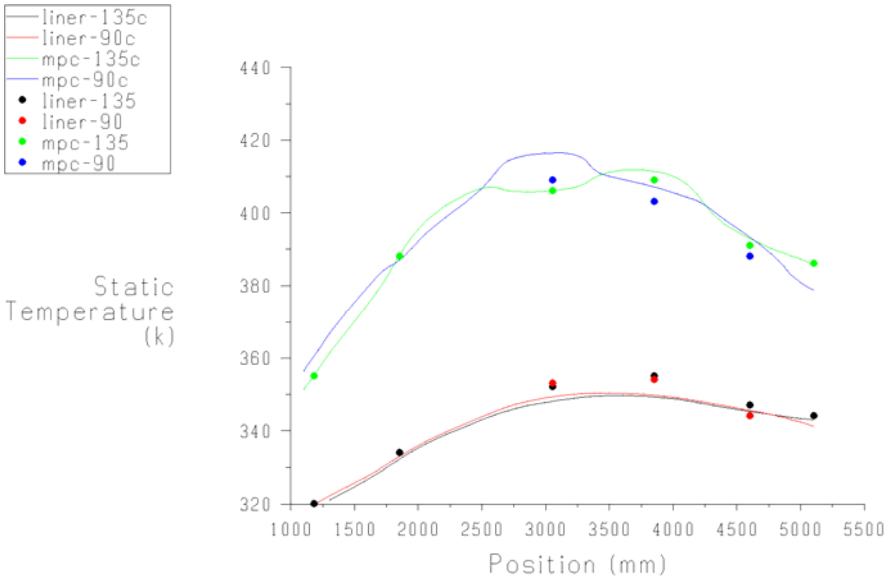




VSC-17 Results (Comparison)

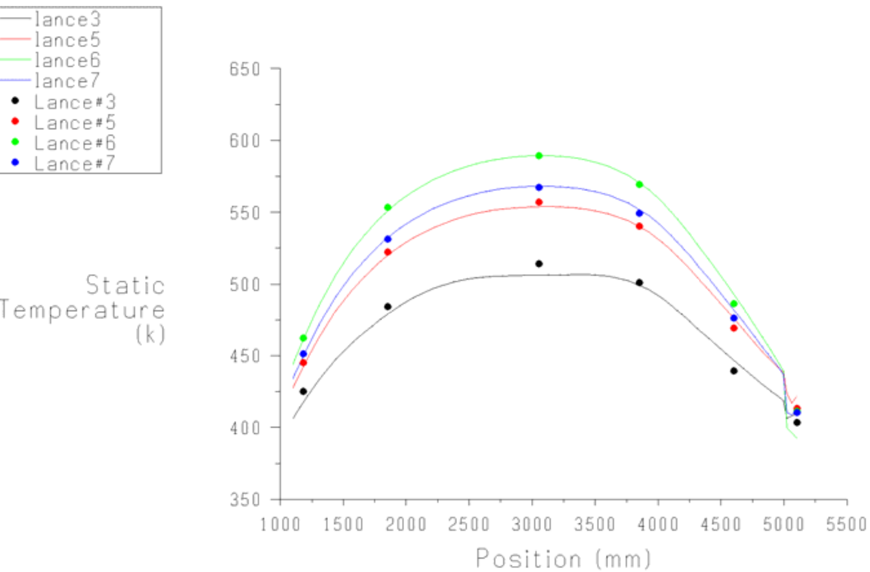


Fuel axial temperature using low Reynolds k-ε turbulence model

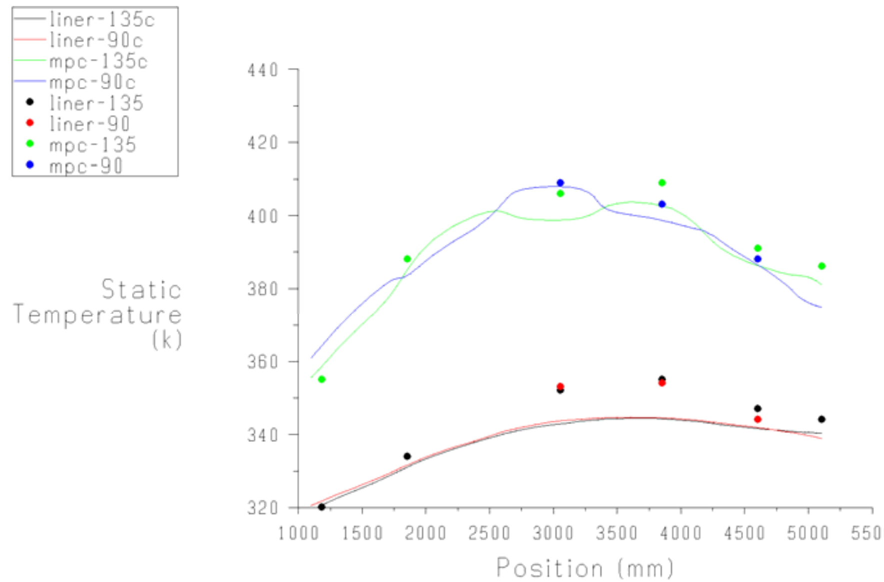


Liner and MPC walls axial temperature using low Reynolds k-ε turbulence model

VSC-17 Results (Comparison)

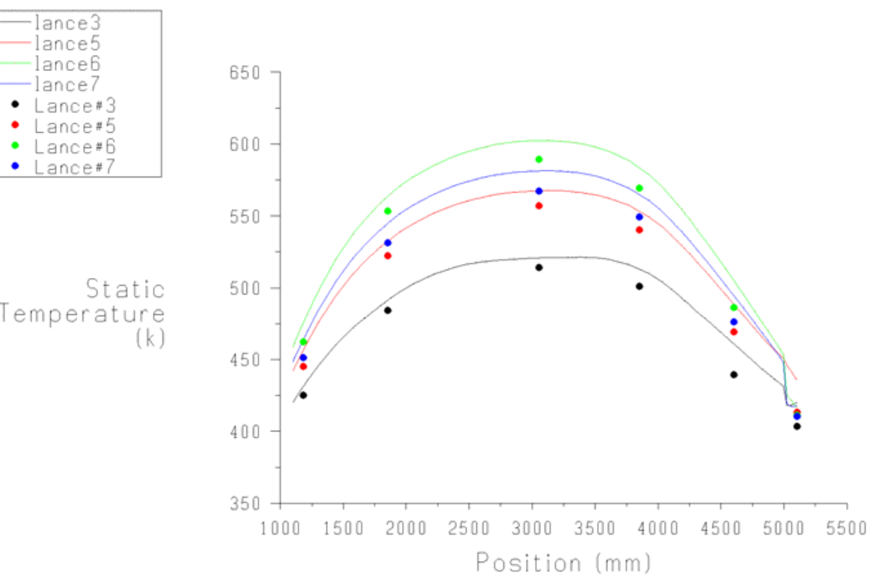


Fuel axial temperature using standard k-ε turbulence model

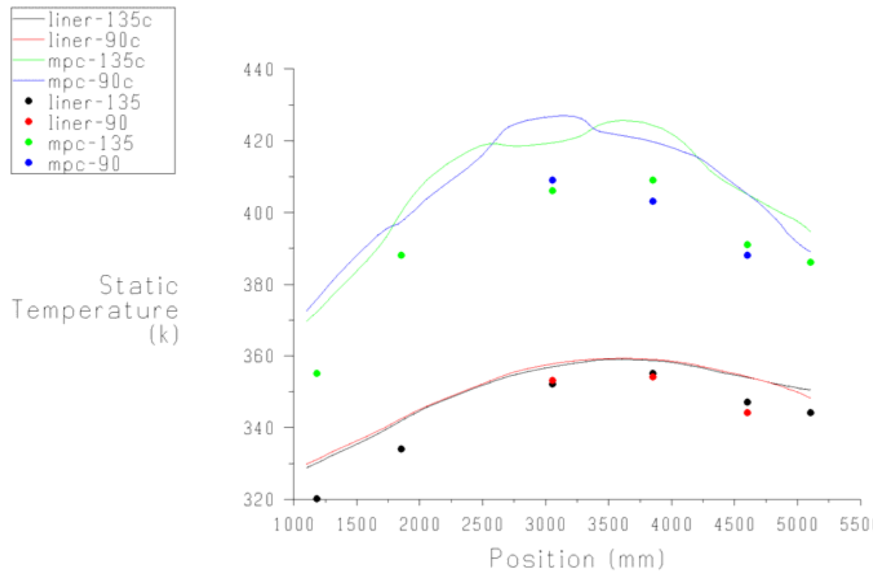


Liner and MPC walls axial temperature using standard k-ε turbulence model

VSC-17 Results (Comparison)



Fuel axial temperature using laminar flow regime



Liner and MPC walls axial temperature using laminar flow regime

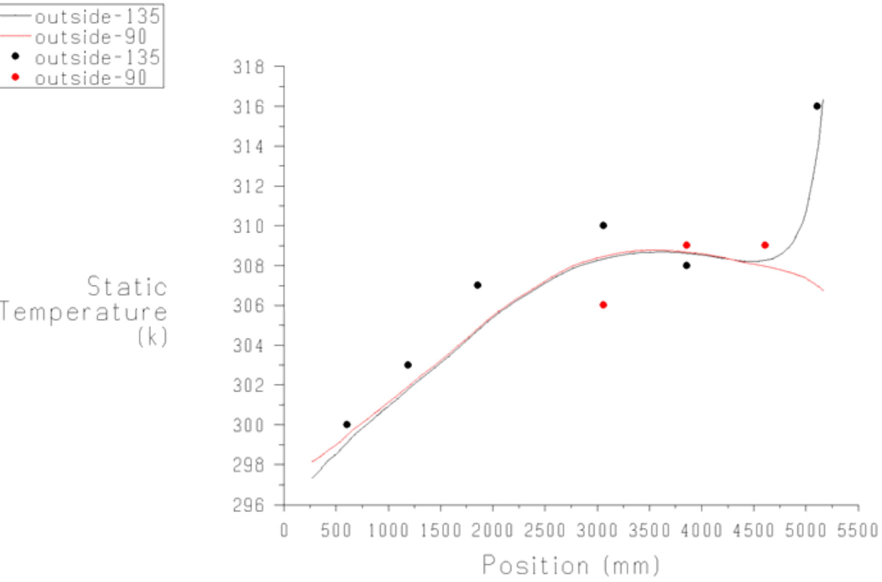
Boundary Conditions:

- Buoyancy driven flow
- Pressure Boundaries were used
- Operating density is needed

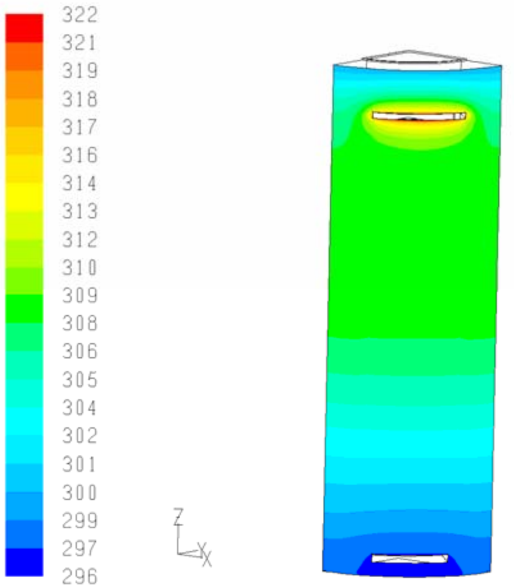
$$P' = P - \rho_0 g x \qquad \frac{\partial P}{\partial x} = \frac{\partial P'}{\partial x} + \rho_0 g \qquad -\frac{\partial P}{\partial x} + \rho g = -\frac{\partial P'}{\partial x} + (\rho - \rho_0) g$$

Control Volume	Operating density (kg/m3)	Peak cladding Temperature (Kelvin)	Air mass flow rate (kg/s)	Heat absorbed by air (Watts)	Air exit temperature (Kelvin)
Dry Cask	1 (inlet)	598	0.238	9284	339
Dry cask	0.92 (avg)	607	0.1272	7816	351
Dry cask + Ambient	1 (inlet, avg, ambient)	599	0.237	9300	338

VSC-17 Results (outside surface)



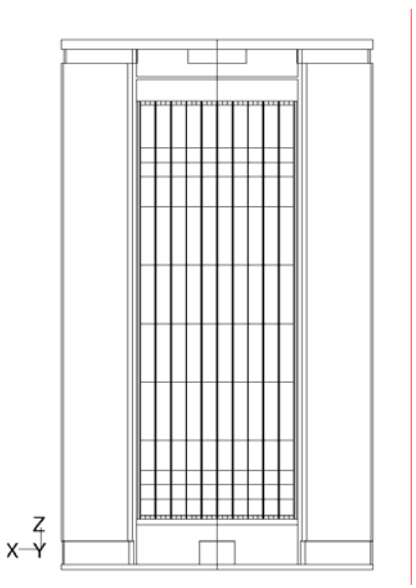
Outside surface temperature using low Re k- ε turbulence model

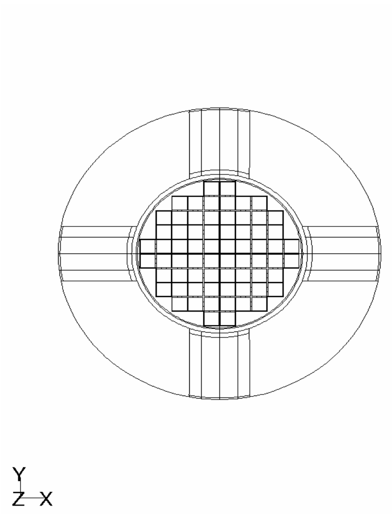


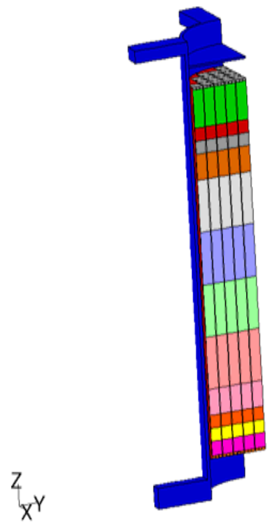
Outside surface temperature contours using low Re turbulence k-ε model

Non Consolidated Fuel Storage Cask

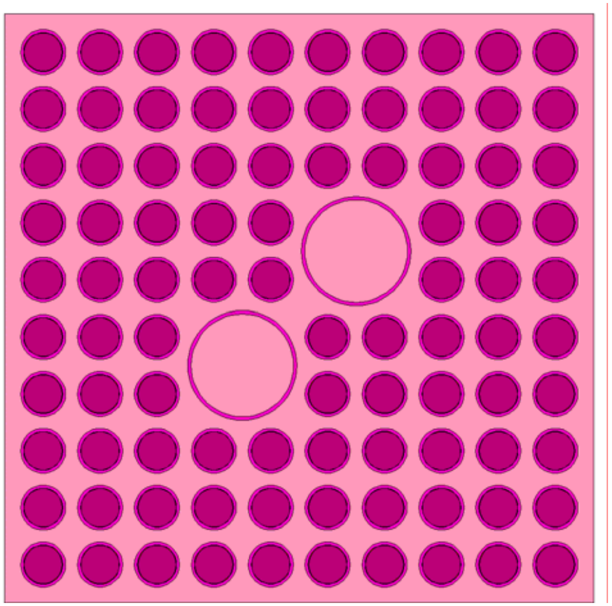
- Porous media is used to model the fuel rod region
- Effective thermal conductivity was obtained using 2D CFD.
- Equivalent flow resistance is used
  - The higher the frictional resistance the higher the PCT
  - Initially, applicants used a friction factor f=64/Re.
  - 3D CFD was used.
  - CFD data were confirmed using experimental data.

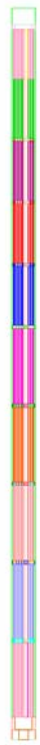


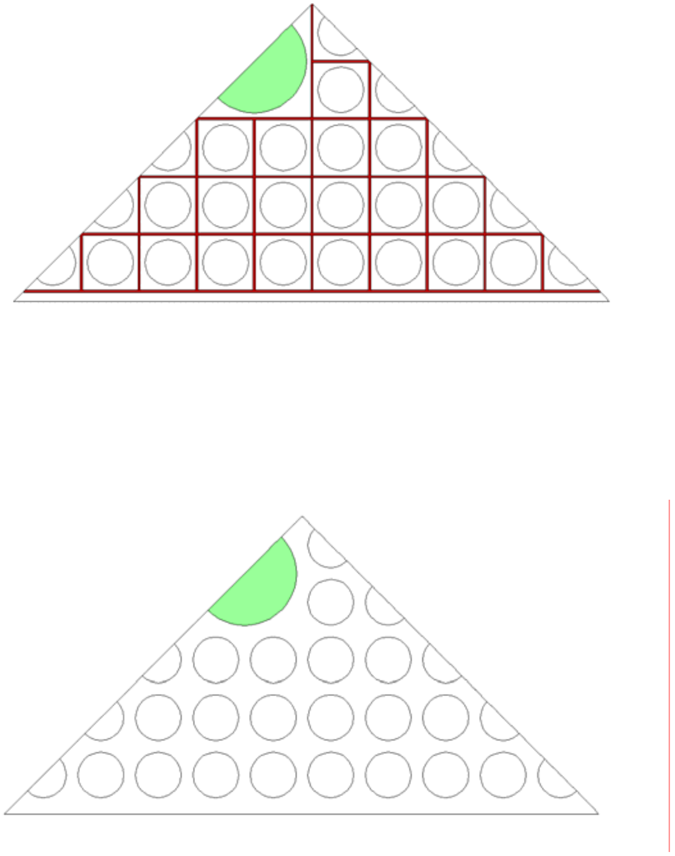




Effective Conductivity and Flow Resistance







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Non Consolidated Fuel Storage Cask Results

Turbulence model in air passage	Turbulence model inside MPC	Peak Clad temperature (Kelvin)	Air mass flow rate (kg/s)	Heat absorbed by air (watts)	Air exit temperature (Kelvin)
Laminar	Laminar	718	0.292	21,032	371
Transitional k-ε	Laminar	704	0.33	22,532	367
Low Re k-ε	Laminar	702	0.34	22,915	367
Std k-ε	Laminar	666	0.344	25,705	370
Std k-ε	Std k-ε	658	0.346	25,760	369

Axisymmetrical analysis

Turbulence model in air passage	Turbulence model inside MPC	Peak Clad temperature (Kelvin)	Air mass flow rate (kg/s)	Heat absorbed by air (watts)	Air exit temperature (Kelvin)
Transitional k-ε	Laminar	645	0.338	24,160	369
Low Re k-ε	Laminar	641	0.33	24,190	369

3-D analysis

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Summary

- Validate your CFD model to ensure that the new model is applicable with confidence
- The more validation tests a model passes with acceptable accuracy, the more generally it can be applied to industrial flows
- Limitations of selected models should be listed and alternatives should be given
- The influence of the assumptions should be tested with a sensitivity analysis
- Modeling errors are the most difficult to avoid; depends on the quality of the available models in CFD package and the experience of the user.
- There is strong interaction between modeling errors and discretization errors. The resolution has to be sufficient for the model selected for the application