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RIC 2007
Severe Accident Research and Regulatory Applications

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USNRC

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Flow and heat Transfer for BWR Spent Fuel Assemblies under Loss of Coolant Conditions

Outline

- Objective
- Experimental Approach
- Hardware
- Experiments
- Comparison of Data, MELCOR and CFD calculations
- Summary

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Objectives

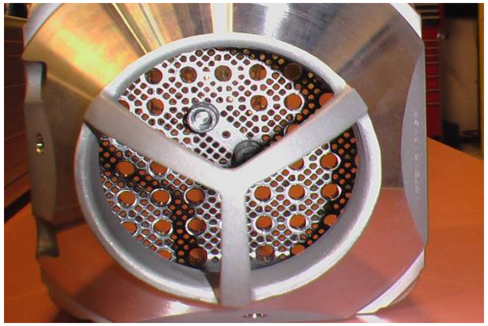
- Air flow conditions
  - Associated with a spent fuel pool complete loss of coolant accident
- Provide prototypic data for **laminar flow** through BWR assemblies
- Provide full-scale data for code validation
  - Hydraulic loss coefficient for: MELCOR, CFD (porous media)
  - Temperature distribution and mass flow rate for code validation (MELCOR).
- Useful to dry cask analysis.

Phased Experimental Approach

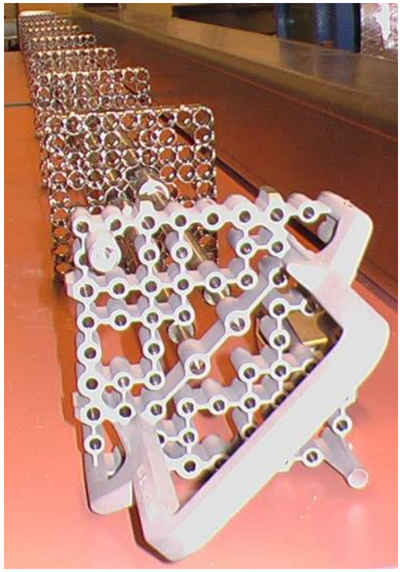
Description	Purpose	Assembly	Rod material
Heater Design	Test electrical heater performance, preliminary data on “zirc fire”	12 rod bundle	Zircaloy
Separate Effects	Hydraulics – Determine form loss and laminar friction coefficients	Single Prototypic Assembly	Stainless Steel
Separate Effects	Thermal hydraulics	Single Prototypic Assembly	Incoloy
Separate Effects	Thermal Radiation	Multi-Prototypic Partial Length Assemblies	Incoloy
Integral Effects	Axial Ignition Propagation	Single Prototypic Assembly	Zircaloy
Integral Effects	Radial and Axial Ignition Propagation	Multi-Prototypic Partial Length Assemblies	Zircaloy

Actual Hardware

- Prototypic GE 9x9 BWR hardware
  - Full length, prototypic GE 9x9 BWR components
  - Rods made of stainless steel (Hydraulics) and Incoloy (Thermal-Hydraulics)



Nose piece & debris catcher



Upper tie plate

BWR channel, water tubes & spacers

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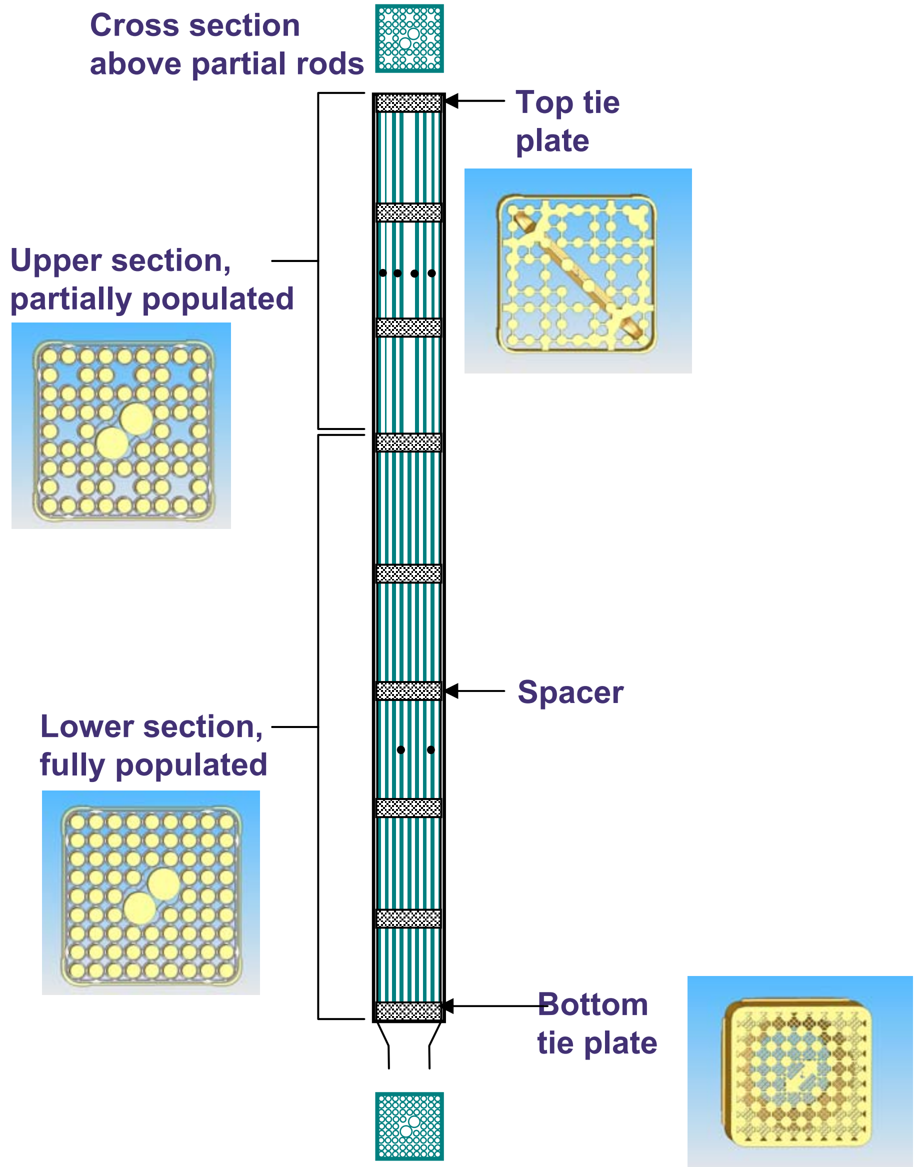
Separate Effects Tests (Hydraulics)

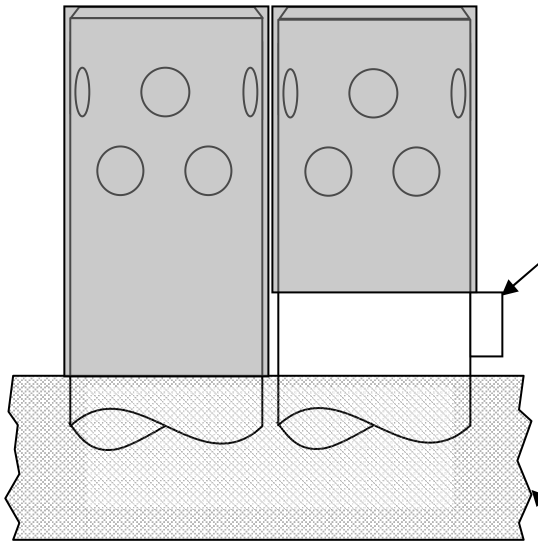
- Single, full length, closely prototypic assembly
  - Unheated, stainless steel rods and pins
  - Prototypic top & bottom tie plates, channel box, water tubes and spacers
  - Force ambient air through assembly
    - Reynolds numbers of 70 to 900 based on bundle hydraulics
      - $Re = (\square \cdot D_{H,bundle} \cdot V_{bundle})/\square$
        - ✓ Typical: $\square = 0.98\ kg/m^3$, $\square = 1.85 \times 10^{-5}\ N \cdot s/m^2$
    - Measure pressure drop across different assembly sections
      - Pressure drops are very low, $O(10\ N/m^2)$
    - Determine form Inertial loss coefficients and laminar friction coefficient

Assembly Hydraulics

- Lower, fully populated bundle section more restrictive than upper section
  - $A_{lower} = 0.93\ A_{upper}$
  - $D_{H,\ lower} = 0.85\ D_{H,\ upper}$
- Spacers local restrictions in assembly
  - $A_{sp,\ lower} = 0.75\ A_{lower}$
  - $A_{sp,\ upper} = 0.79\ A_{upper}$



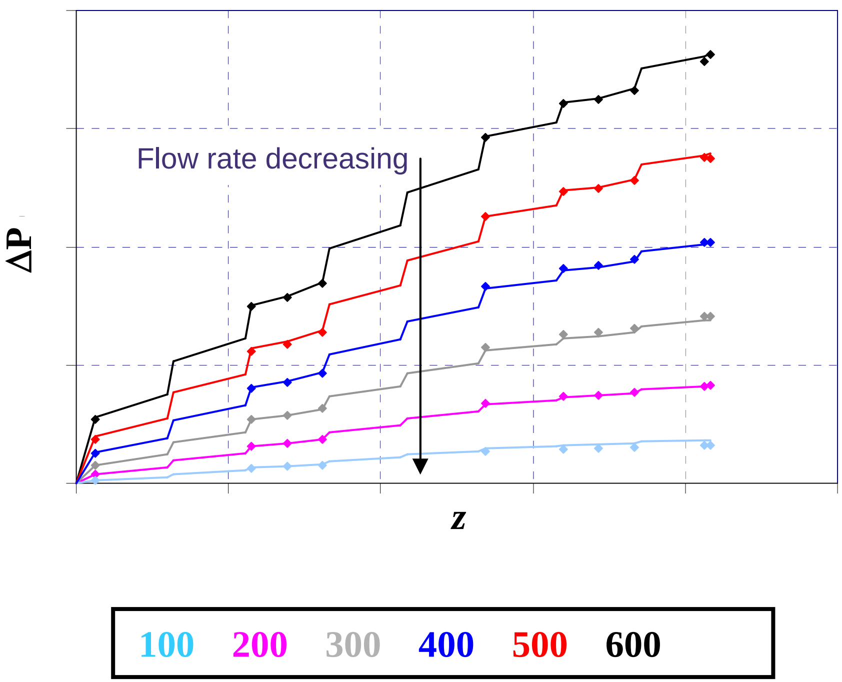
Water Rod Blockage

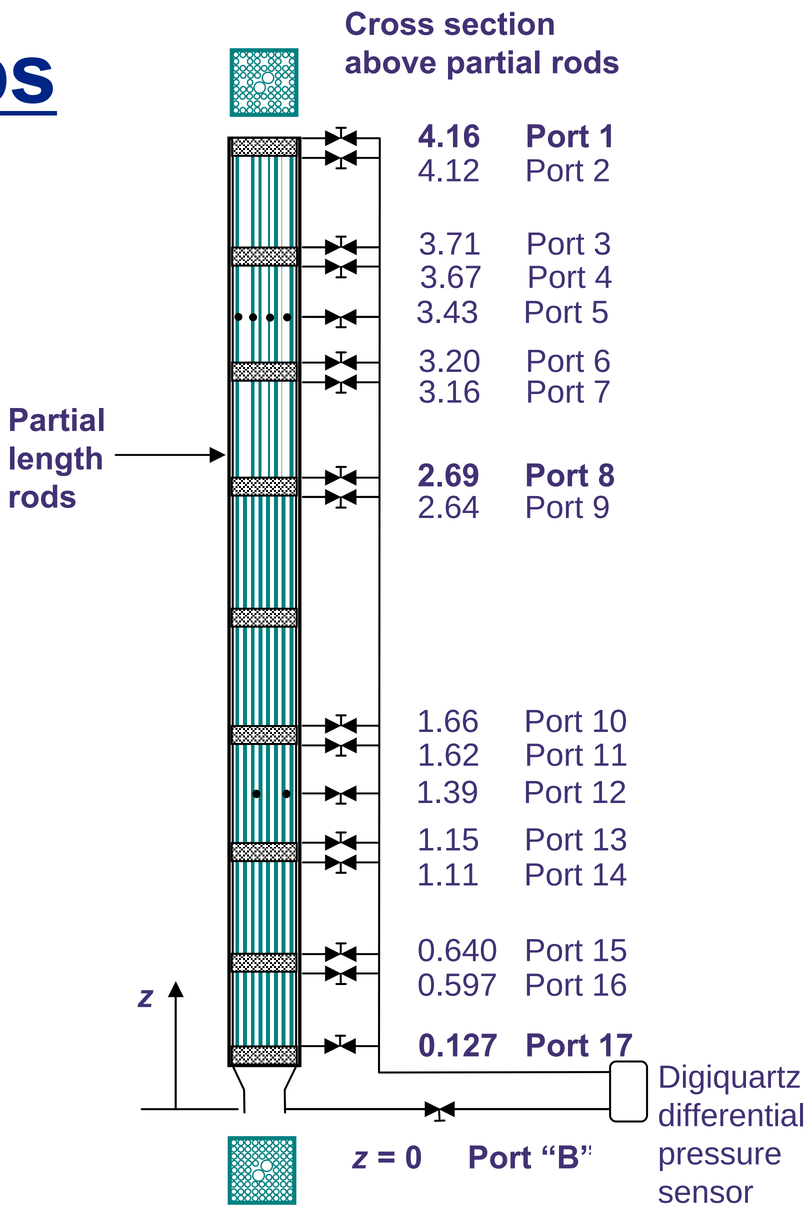


- Acrylic sleeves fitted around exit holes of water rods
- Forces all flow through bundle
  - Pressure drops across bundle runs only
- Removal of blockages
  - Determine actual flow rate fraction through water rods

Measured Pressure Drops

- Pressure measurements conducted on highly-prototypic BWR GE assembly
- Blocked water rods





S_{LAM} and k Analysis

- Major, or viscous, pressure drop

$$\Delta P_{major} = f\left(\frac{L}{D_H}\right)\left(\frac{\rho \cdot V_{bundle}^2}{2}\right) \qquad f = \frac{S_{LAM}}{Re}, \text{ where } S_{LAM} = 64 \text{ (pipe flow)}$$

$$= 100 \text{ (bundle flow)}$$

$$\Delta P_{major} = S_{LAM}\left(\frac{L}{D_H^2}\right)\left(\frac{V_{bundle} \cdot \mu}{2}\right)$$

- Minor, or form, pressure drop

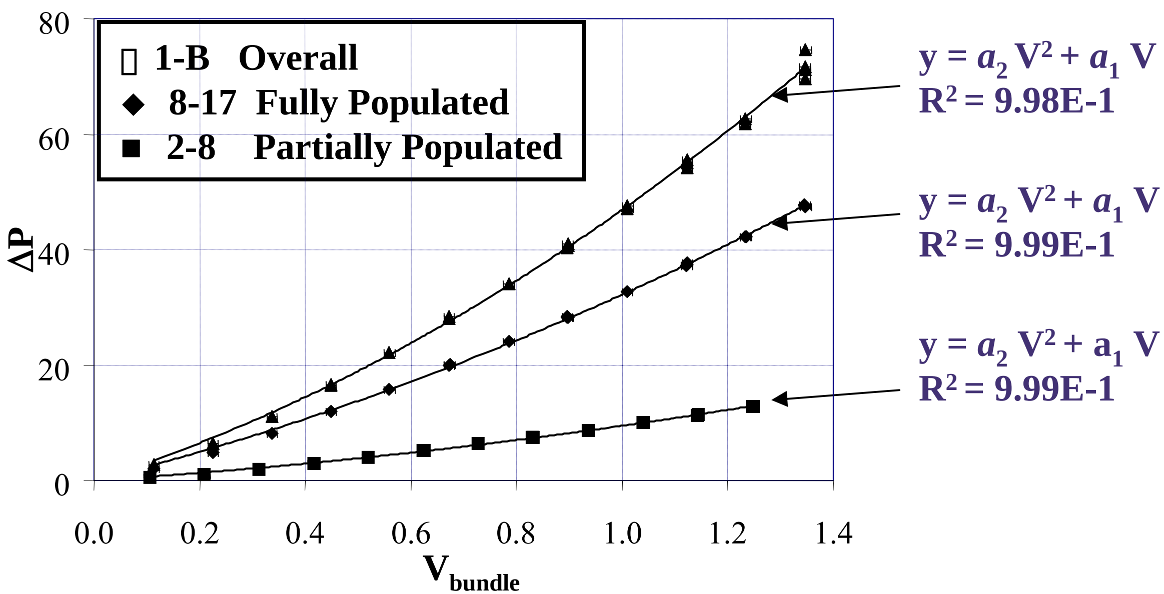
$$\Delta P_{minor} = \Sigma k\left(\frac{\rho \cdot V_{bundle}^2}{2}\right)$$

- Total pressure drop

$$\Delta P_{total} = \Delta P_{minor} + \Delta P_{major} = a_2 \cdot V_{bundle}^2 + a_1 \cdot V_{bundle} \implies S_{LAM} = 2 \cdot a_1\left(\frac{D_H^2}{L \cdot \mu}\right), \quad \Sigma k = \frac{2 \cdot a_2}{\rho}$$

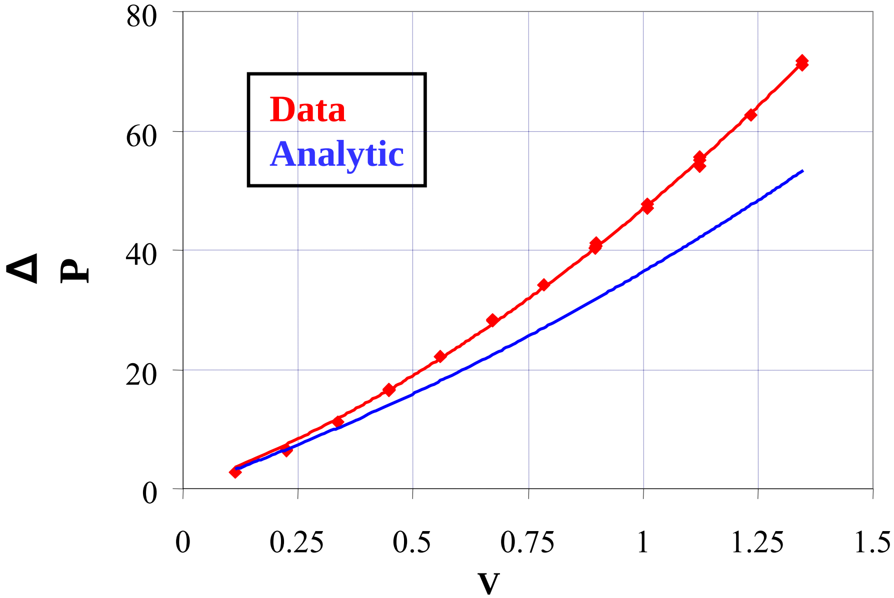
Pressure Drop vs. Velocity

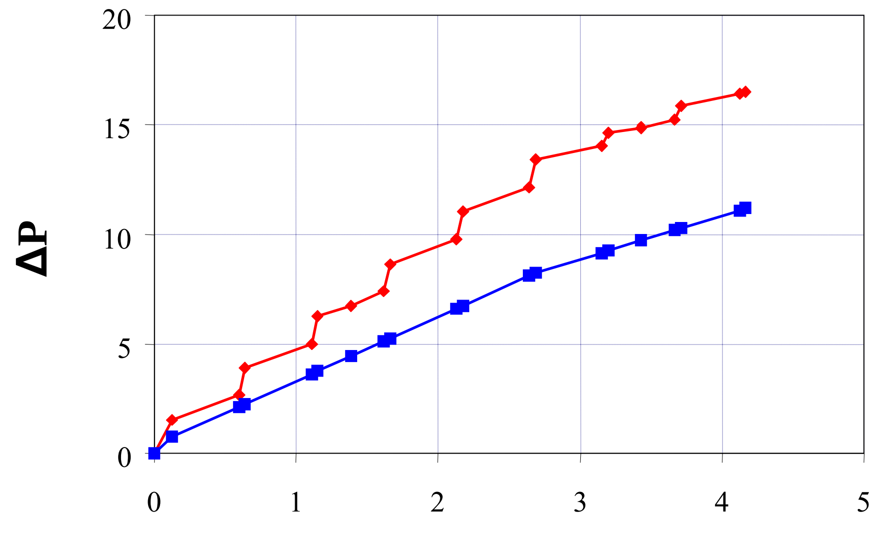
- Blocked water rods
- Uncertainty in velocity □0.01 m/s
  - Mainly due to measurement error of the mass flow controllers
- Quadratic dependence
  - Predicted from analytical equations
- Determine laminar friction coefficient (S_{LAM}) and form loss coefficients (Σ k) from curve fits



Hydraulic Results

- Laminar flow
  - Re = 70 to 900
- “Textbook” values of S_{LAM} and k
  - S_{LAM} = 100, k_{spacer} = 1.4, and k_{bottom} = 7.6
    - Available from vendor data and literature
  - Significantly underestimates pressure drop





S_{LAM} and k Coefficients

Blocked Water Rods

Segment	S_{LAM}	Σ k	# of spacers	k per spacer
1-B	106	37	–	–
2-8	88	7.3	2	3.6
8-17	138	19	5	3.8

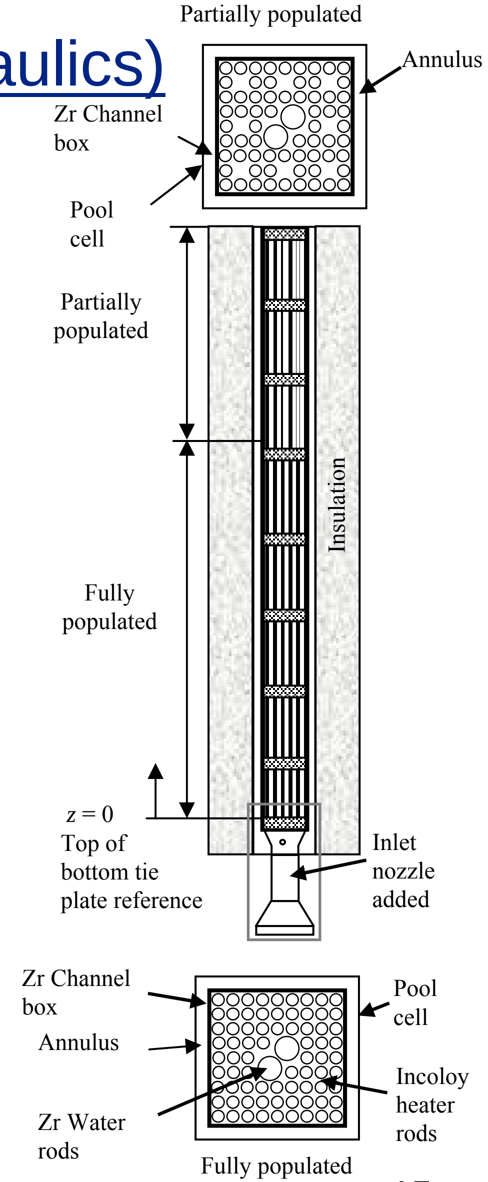
Unblocked Water Rods

Segment	S_{LAM}	Σ k	# of spacers	k per spacer
1-B	96	37	–	–
2-8	80	7.3	2	3.7
8-17	125	19	5	3.8

- Uncertainties determined from curve fit error analysis
  - u_{SLAM} = □5
  - u_k = □1
- Hydraulics for 1-B assumed as fully populated bundle
- Unblocked water rod analysis
  - Assumes all flow through the bundle
  - S_{LAM} ~10 on average lower for each segment
  - k coefficients identical within experimental error

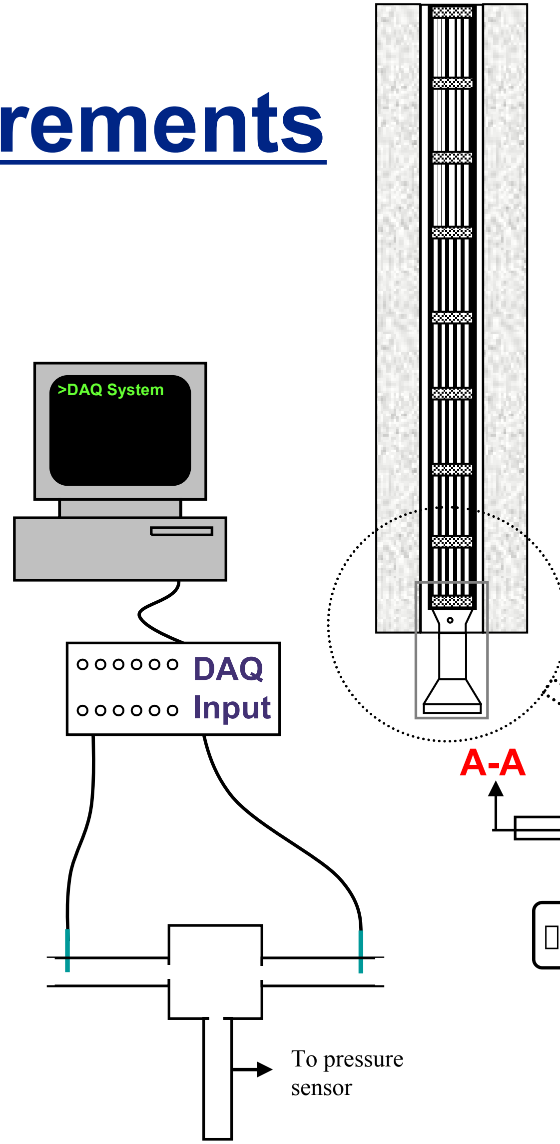
Separate Effects Tests (Thermal-Hydraulics)

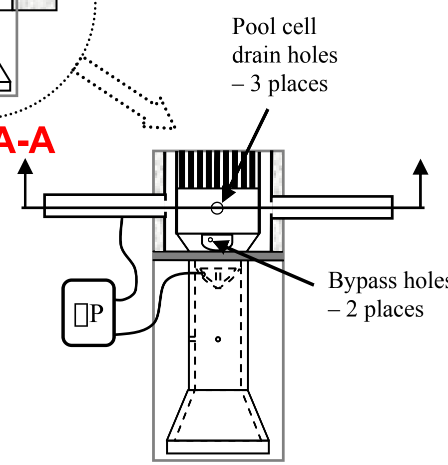
- Single, full length, prototypic Incoloy assembly
  - Inside single prototypic pool rack cell
    - Annular flow characterized
  - Incoloy heater rods
    - 0.430” diameter (0.438” in stainless assembly)
    - Thermocouple instrumented
    - Allows heating to temps around 900 K
      - Avoid Zr component oxidation
  - Repeat some forced flow pressure drop measurements
    - Excellent agreement with unheated stainless assembly
      - When small difference in rod diameter considered
  - Measure naturally induced flow
    - Bundle and annulus
    - Function of assembly power (steady state exit temp)
  - Thermal and hydraulic response highly coupled
    - Delicate balance makes predictions difficult



Annulus Flow Measurements

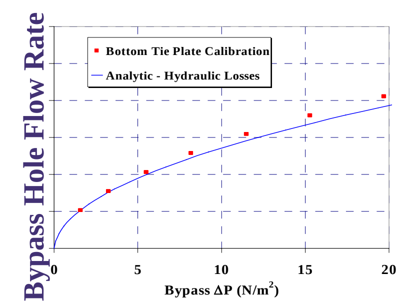
- Annulus flow sources
  - Two bypass holes in tie plate
    - Differential pressure across bypass holes
      - Calibration at Primary Standards Lab
        - ✓ Compares well with analytic analysis
    - Open or closed
  - Two pool cell drain holes
    - Hot wire anemometry
      - Fixed position like Inlet
    - Open or closed





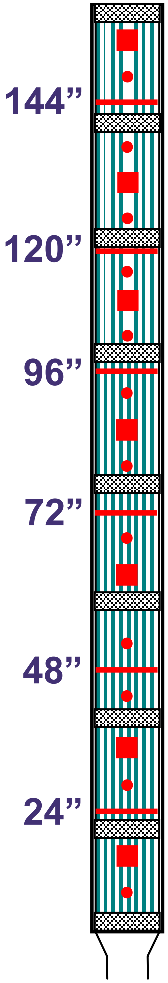
Section A-A

Bypass Hole Flow Calibration



Bypass Pressure Drop

Thermocouple Layout



Internal Thermocouples

Radial Array
24” spacing
11 TC each level
66 TC total (details below)

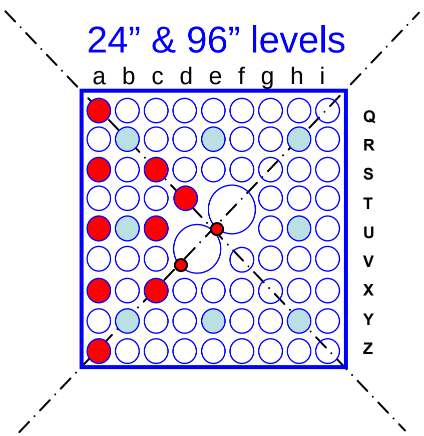
Axial array A1
6” spacing
20 TCs

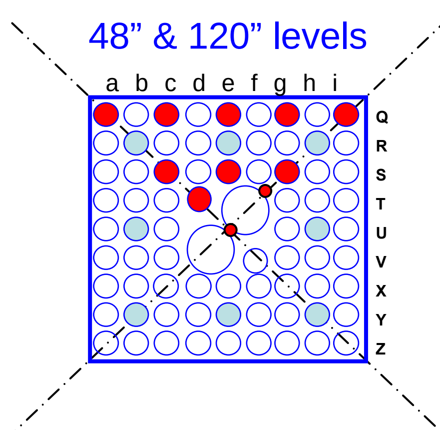
Axial array A2
12” spacing
7 TCs

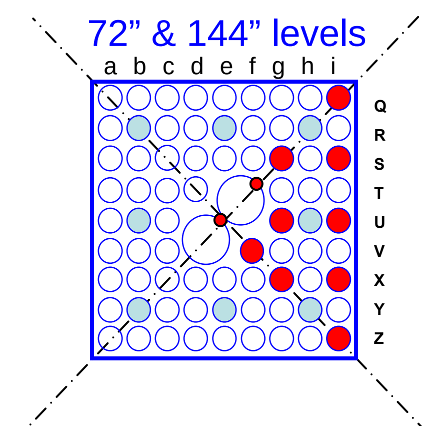
Water rods inlet and exit
4 TCs

Total of 97 TCs

- 97 Total TC’s internal to assembly
- 10 TC’s mounted to channel box
  - 7 External wall
    - 24” spacing starting at 24” level
  - 3 Internal wall
    - 96”, 120”, and 144” levels
- 13 TC’s on outer wall of pool cell
- 6 TC’s measuring air temp
  - 4 Exit air temps
  - 1 Inlet air temp
  - 1 Ambient
- 2 TC’s on outside of insulation







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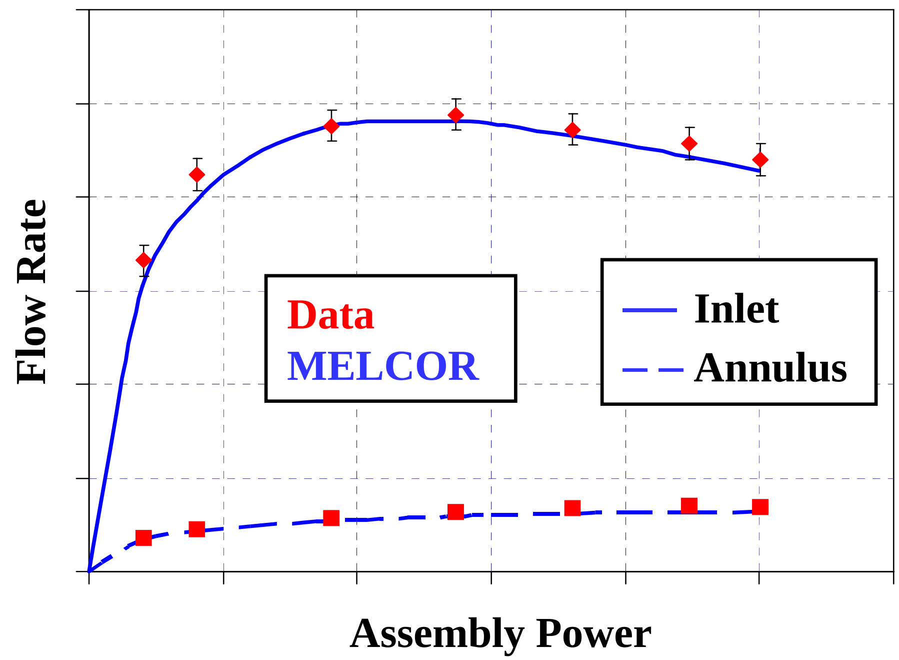
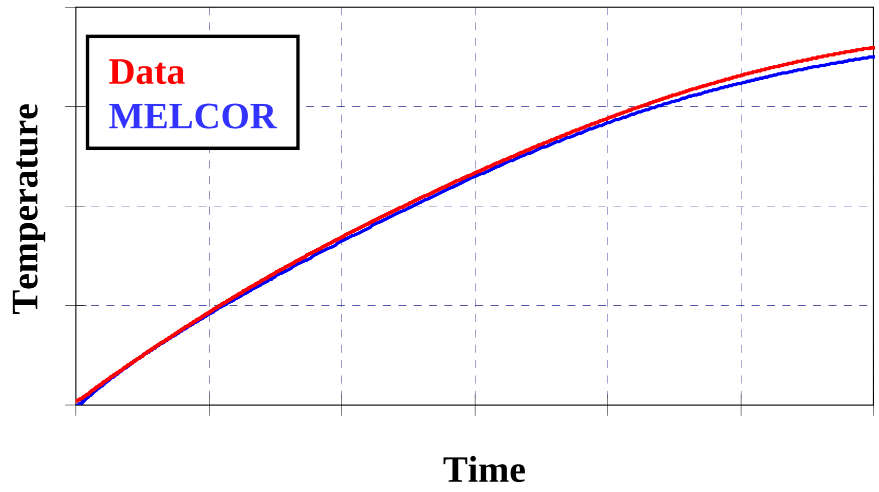
Inlet and Annular Flow Rate Dependence on Assembly Power

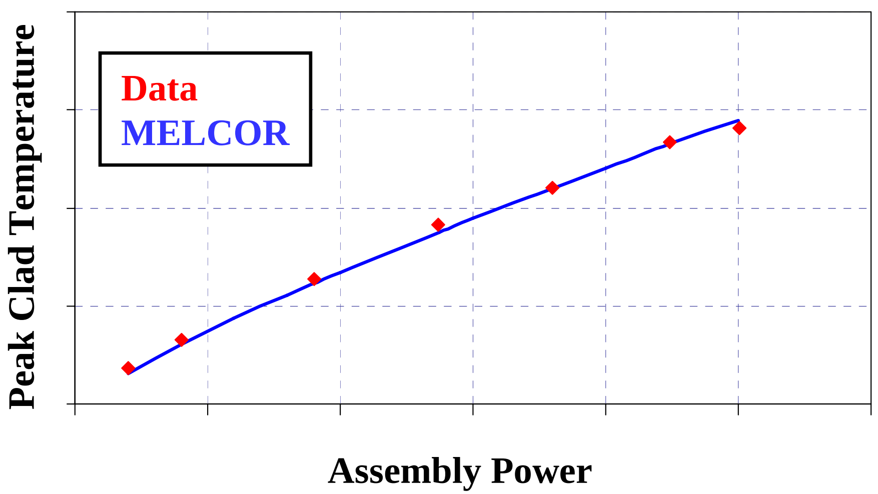
- Inlet flow initially increases with power
  - Slowly decreases after peak
- Excellent agreement between experiments and MELCOR
  - Within experimental uncertainty for majority of data
  - Correct flow prediction required for correct temperature predictions



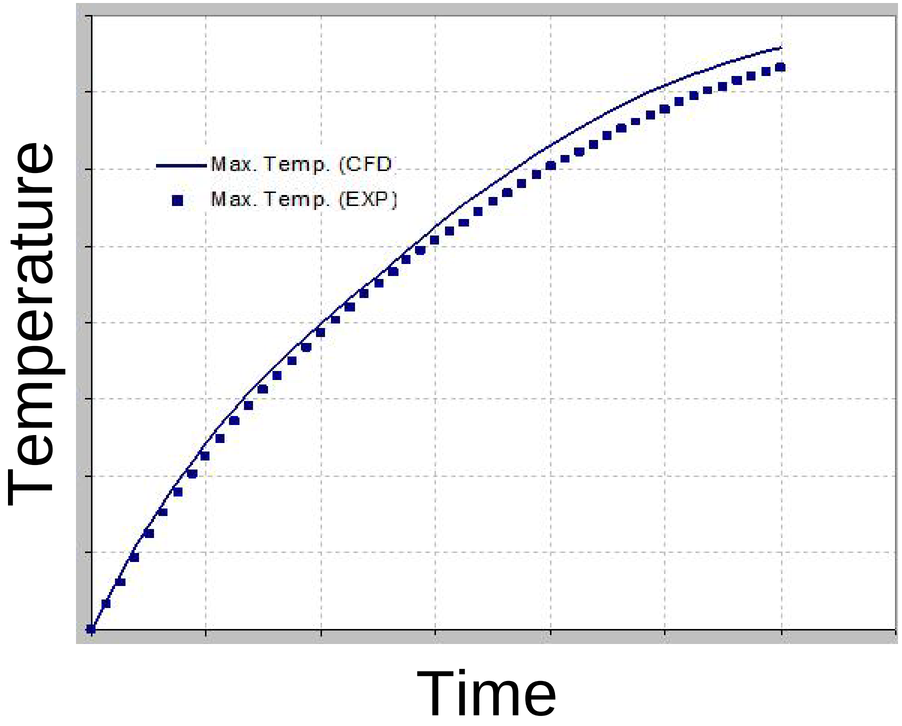
Peak Temperatures

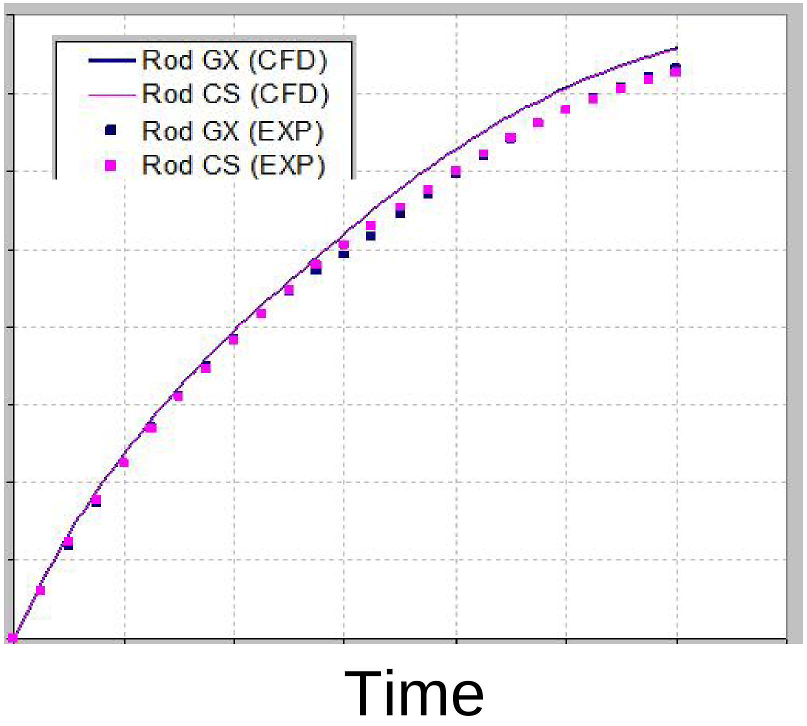
- Transient response
  - Average temperatures at 144” level
  - Excellent agreement with MELCOR (within 3%)
- PCT vs. assembly power at 12 hrs
  - MELCOR within 5% for all cases





Peak Cladding Temperature Comparison (CFD)





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Summary

- Hydraulics of prototypic assembly quantified for *Re* = 70 to 900
  - Loss coefficients determined with highly accurate gages
  - Overall assembly (1-B) with unblocked water rods: S_{LAM} = 96, Σ k = 37 assuming bundle flow only
  - Two regions were used to characterize the flow in the analysis:
    - S_{LAM} = 125, Σ k = 19 (Fully Populated Region)
    - S_{LAM} = 80, Σ k = 7.3 (Partially Populated Region)
  - Significantly different than “textbook” prediction
  - Water rod and bypass flow rates quantified
  - Reynolds of interest for spent fuel calculations (around 100)
- Thermal-hydraulic response of prototypic assembly quantified
  - Induced flow quantified
  - Axial and radial temperature profiles measured
- MELCOR and CFD accurately predicts response of heated assembly
  - Within 5% of PCT for all cases
  - Within experimental uncertainty of induced flow rate.
- Improved Calculation for dry cask analysis.
  - Frictional loss were used in the porous media CFD calculations