Thermal Analysis of ATR Experiments

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ATR Experiment Design and Analysis

ATR NSUF User's Week Experimenter Course

Idaho National Laboratory

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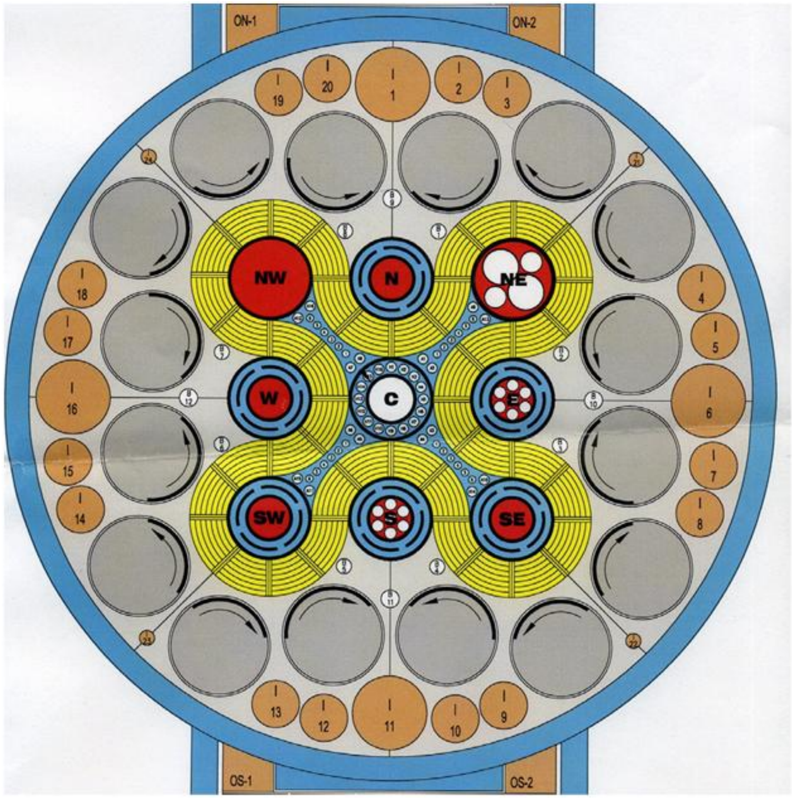
Outline

- Description of the ATR
  - Reactor core arrangement
  - Primary cooling system (PCS)
- Thermal-hydraulic safety requirements
  - Departure from nucleate boiling (DNB)
  - Flow instability (FI)
  - Thermal loads
- Thermal analysis examples
  - Analytical solution to temperature profile in capsule experiments
  - FE analysis of DNB and FI safety limits in capsule experiments
  - CFD simulations of heat transfer in a pressurized water loop

Outline - continued

- Capsule experiments using gas gap temperature control
  - Temperature variations in capsule experiments
  - Static capsule experiments
  - Lead-out capsule experiments
- Capsule experiment examples
  - Temperature data from the TMIST-1 experiment
  - Temperature data from the UCSB-2 experiment mock-up
  - Comparison of measured and calculated temperatures

ATR core cross-section



Primary cooling system

- PCS flow
  - 43,500 gpm (2 pumps)
- Core inlet pressure
  - 360 psig
- Core pressure drop
  - 77 psi (2 pumps)
  - 100 psi (3 pumps)
- Reactor inlet temperature
  - 125°F

Critical heat flux in flow boiling

- Modified form of the CHF correlation due to L. Bernath, " A theory of local-boiling burnout and its application to existing data," Chemical Engineering Progress Symposium Series, Vol. 56, No. 30, 1960

$$q_{chf} = 1.8 \cdot \left(12915 \cdot \frac{d_{hy}}{d_{hy} + d_{he}} + 127 \cdot \frac{v}{d_{hy}^{0.35}} \right) \cdot \left(60 \cdot \ln(P) - 80.8 \cdot \frac{P}{P + 13.5} - 0.25 \cdot v - T_o \right)$$

P	Pressure (psi)
d_{hy}	Hydraulic diameter (ft)
d_{he}	Heated diameter (ft)
v	Velocity (ft/s)
T_o	Temperature (C)
q_{chf}	Critical heat flux (BTU/hr/ft^2)

Thermal-hydraulic safety requirements

- Departure from nucleate boiling ratio (DNBR)
- Flow instability ratio (FIR)

$$\mathrm{DNBR} = \frac{q_{chf}}{q} > 2.0$$

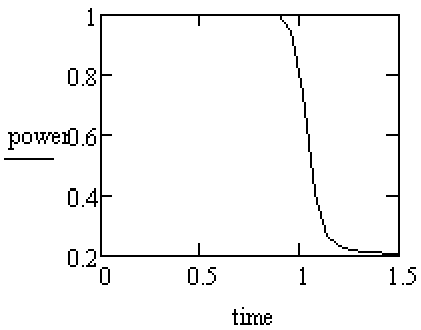
q_{chf}	Critical heat flux in flow boiling
q	Actual heat flux at surface contacting primary coolant

$$\mathrm{FIR} = \frac{\Delta T_c}{\Delta T} > 2.0$$

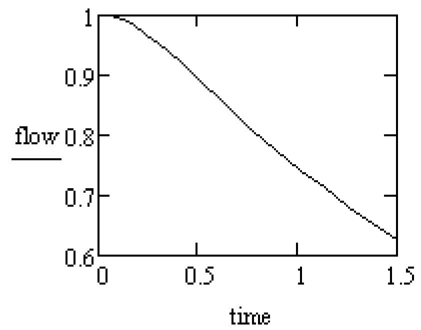
$\Delta T_c = T_{sat} - T_{inlet}$	Critical temperature rise
$\Delta T = T_{outlet} - T_{inlet}$	Actual temperature rise
T_{inlet}	Coolant channel inlet temperature
T_{outlet}	Coolant channel outlet temperature
T_{sat}	Saturation temperature

Thermal loads

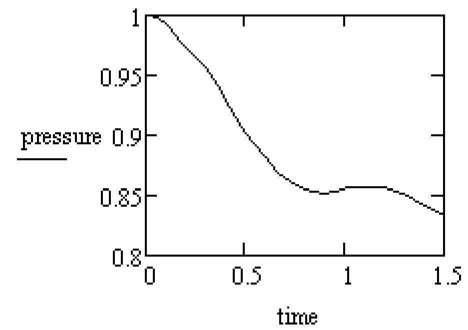
- 25% increase in power (accounting for reactor power variation and instrument uncertainty)
- 25% reduction in flow (primary coolant pump coast-down following loss of power to pumps)
- Power and flow transients (reactor scram at low vessel inlet pressure)



Normalized reactor power vs. time (seconds)



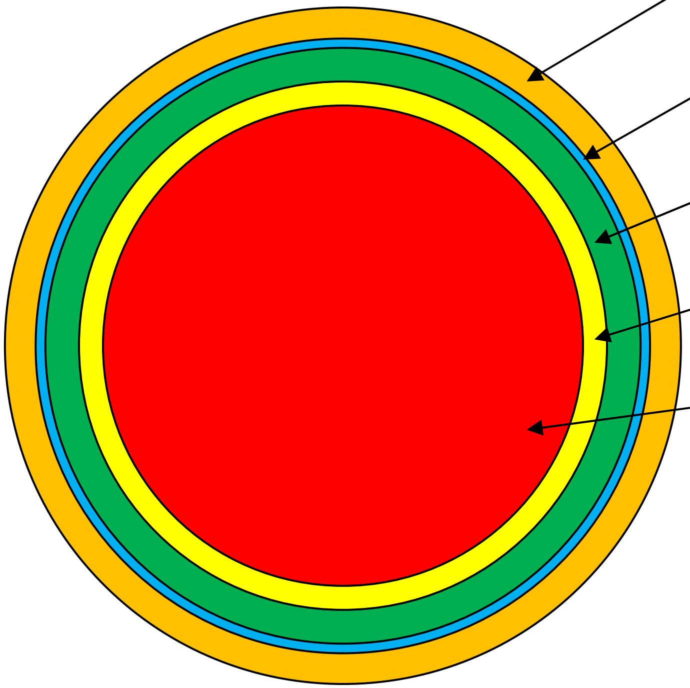
Normalized coolant flow vs. time (seconds)



Normalized inlet pressure vs. time (seconds)

Thermal analysis example 1

- Analytical solution to temperature profile in a capsule experiment



Thermal analysis example 1

- Model inputs

$k_1 = 18.9 \cdot \frac{W}{m \cdot K}$	Thermal conductivity of capsule (stainless steel)
$k_2 = 0.23 \cdot \frac{W}{m \cdot K}$	Thermal conductivity of gas gap (helium)
$k_3 = 18.9 \cdot \frac{W}{m \cdot K}$	Thermal conductivity of specimen (stainless steel)
$h = 33000 \cdot \frac{W}{m^2 \cdot K}$	Heat transfer coefficient at capsule surface (forced convection to primary coolant)
$q_c = 72 \frac{W}{cm^3}$	Capsule heat load
$q_s = 72 \frac{W}{cm^3}$	Specimen heat load
$T_c = 52\,°C$	Temperature of primary coolant
$R_1 = 0.175\ in$	Radius of specimen
$R_2 = 0.193\ in$	Inside radius of capsule
$R_3 = 0.217\ in$	Outside radius of capsule

Thermal analysis example 1

- Solution method

$$\Delta T = \frac{q_s \cdot R_1^{\,2} + q_c \cdot \left(R_3^{\,2} - R_2^{\,2}\right)}{2 \cdot R_3 \cdot h}$$

$\Delta T = 5.2\ °C$ Temperature drop from capsule wall to coolant

$$\Delta T = \left(\frac{q_s \cdot R_1^{\,2}}{2 \cdot R_2 \cdot k_3} - \frac{q_c \cdot R_2}{2 \cdot k_3}\right) \cdot R_2 \cdot \ln\left(\frac{R_3}{R_2}\right) + \frac{q_c \cdot R_3^{\,2}}{4 \cdot k_3} \cdot \left(1 - \frac{R_2^{\,2}}{R_3^{\,2}}\right)$$

$\Delta T = 5.3\ °C$ Temperature drop across capsule wall

$$\Delta T = \frac{q_s \cdot R_1^{\,2}}{2 \cdot k_2} \cdot \ln\left(\frac{R_2}{R_1}\right)$$

$\Delta T = 294.8\ °C$ Temperature drop across gas gap

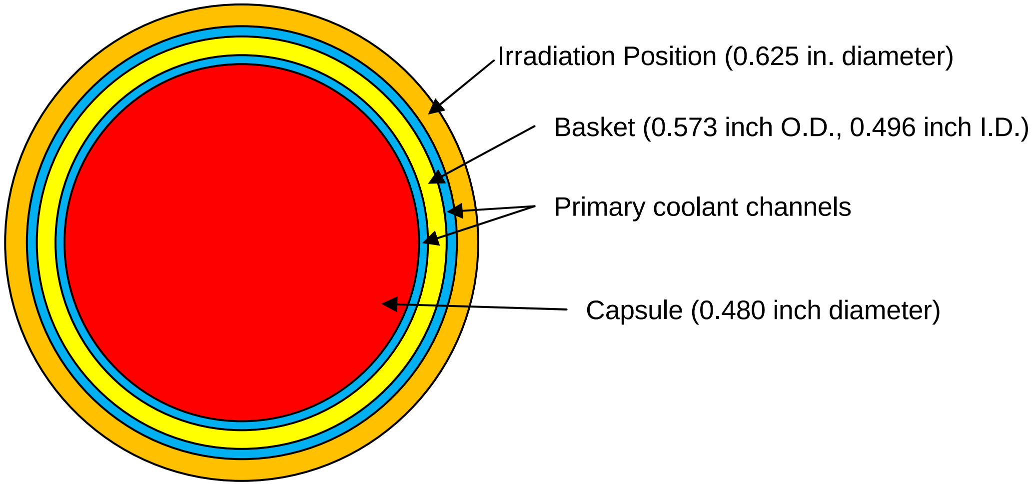
$$\Delta T = \frac{q_s \cdot R_1^{\,2}}{4 \cdot k_1}$$

$\Delta T = 18.8\ °C$ Temperature drop from specimen center to specimen surface

$\Delta T = 324\ °C$ Total temperature drop from specimen center to coolant

Thermal analysis example 2

- Finite element analysis of safety limits in a capsule experiment



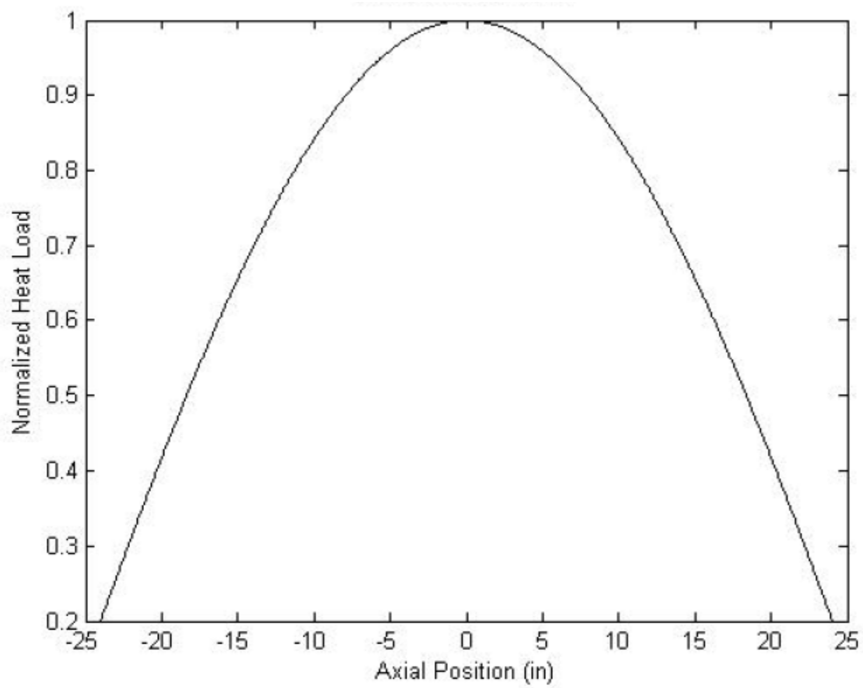
Thermal analysis example 2

- FE analysis of DNB and FI safety limits in capsule experiments
- DNBR > 2.0
  - CHF in flow boiling from modified Bernath correlation
  - Maximum heat flux at capsule surface from FE analysis
- FIR > 2.0
  - Inlet coolant temperature 125°F
  - Saturation temperature 412°F at 285 psig
  - Outlet coolant temperature from FE analysis

Thermal analysis example 2

- Approximate ATR axial heating profile

$P_{norm} = \cos(0.057 \cdot z)$	Normalized axial heating profile
z	Distance from core mid-plane (inches)

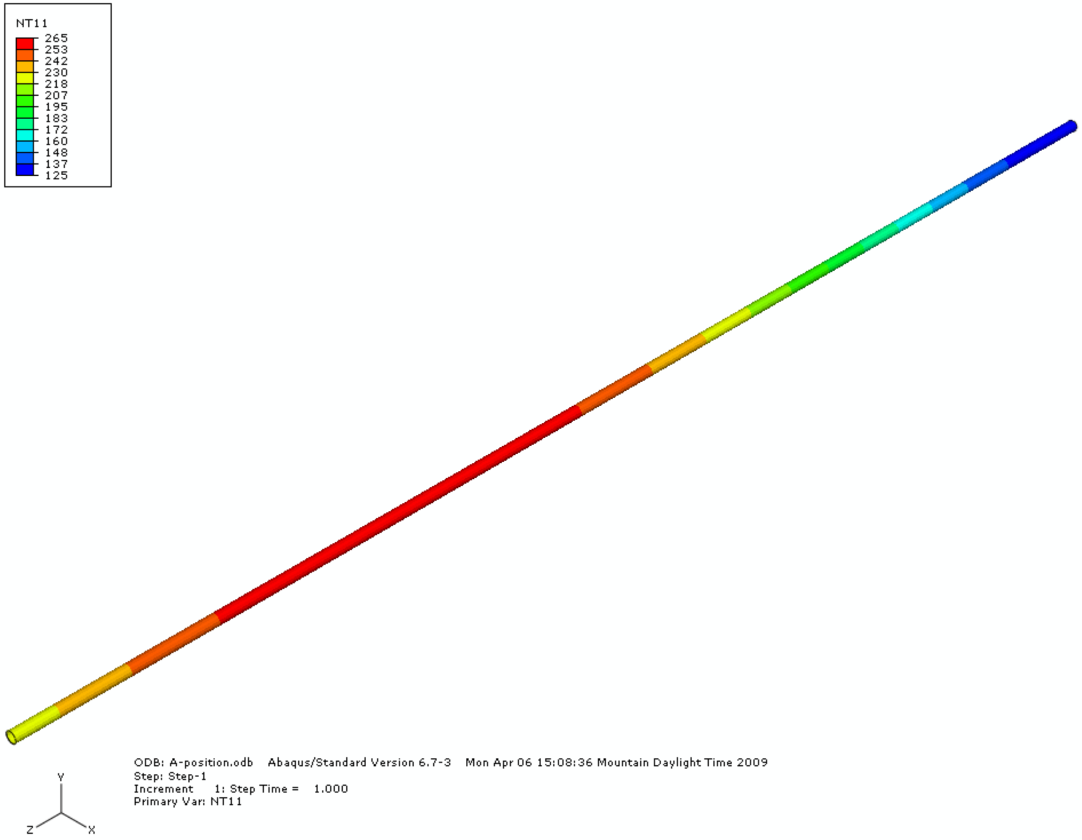


Thermal analysis example 2

- Inner coolant channel
  - Hydraulic diameter 0.016
  - Flow 0.28 gpm
- Outer coolant channel
  - Hydraulic diameter 0.052
  - Flow 2.55 gpm
- Maximum allowable capsule heating to meet safety limits
  - 17,700 W allowable heat load to ensure FIR > 2
  - 220 W/cm^2 allowable heat flux to ensure DNBR > 2

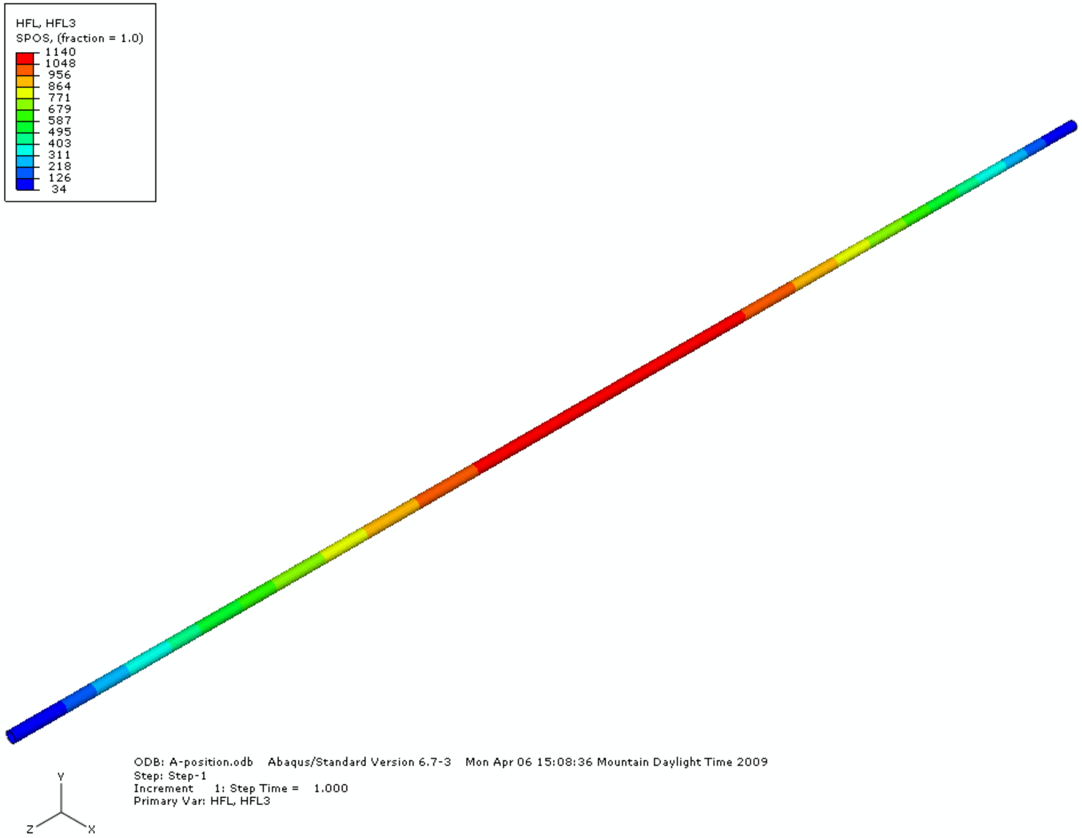
Thermal analysis example 2

- Inner coolant channel temperature distribution (°F)
  - Maximum temperature = 265°F, FIR = 2.0



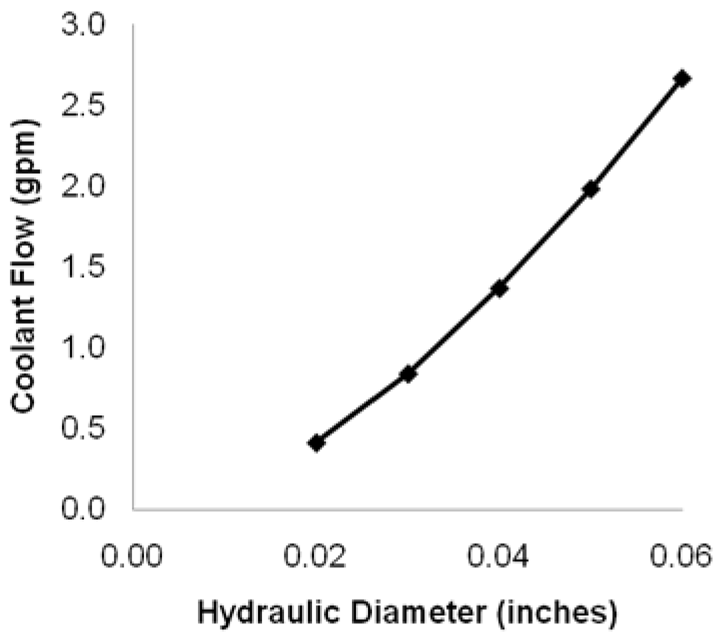
Thermal analysis example 2

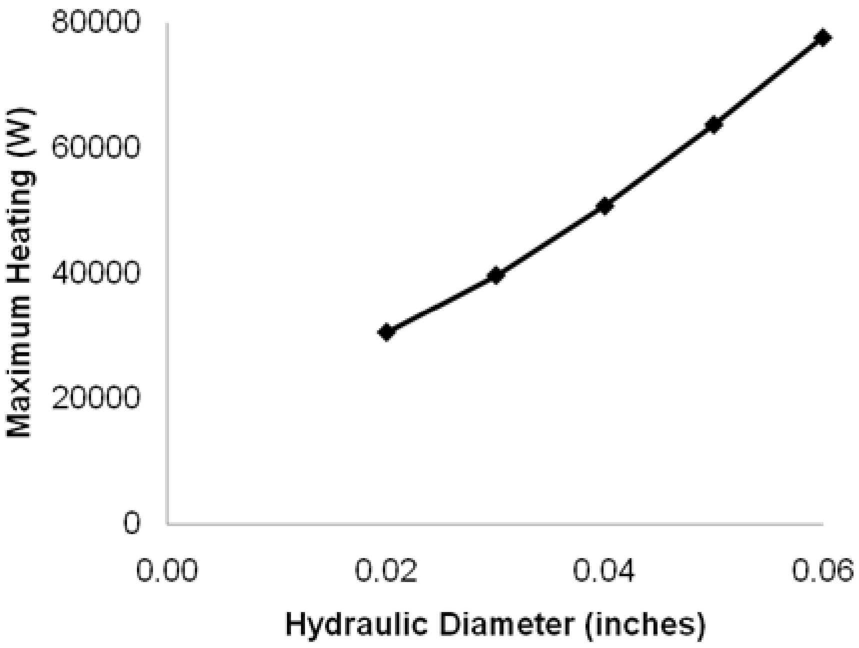
- Capsule surface radial heat flux distribution (BTU/hr/in^2)
  - Maximum heat flux = 1140 BTU/hr/in^2, DNBR = 8.5



Thermal analysis example 2

- Inner coolant channel flow and maximum allowable capsule heating for various hydraulic diameters

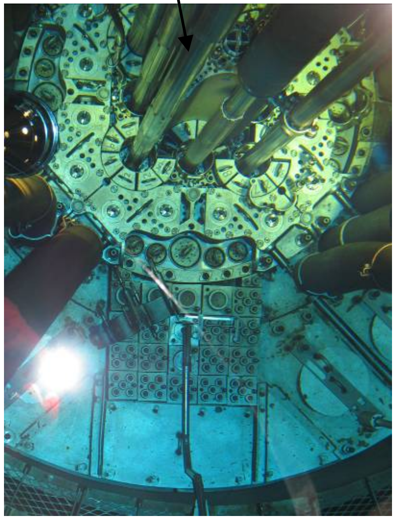




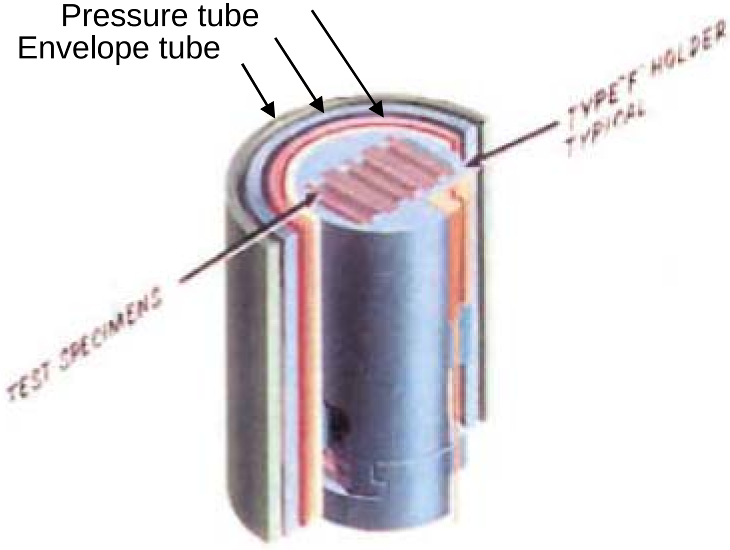
Thermal analysis example 3

- CFD simulations of heat transfer in a pressurized water loop

In-pile tube

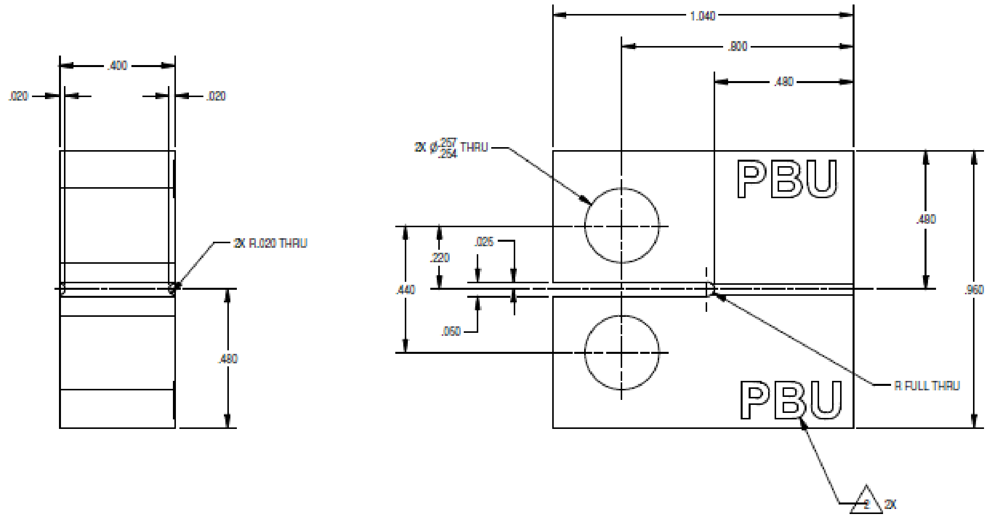


Flow tube
Pressure tube
Envelope tube



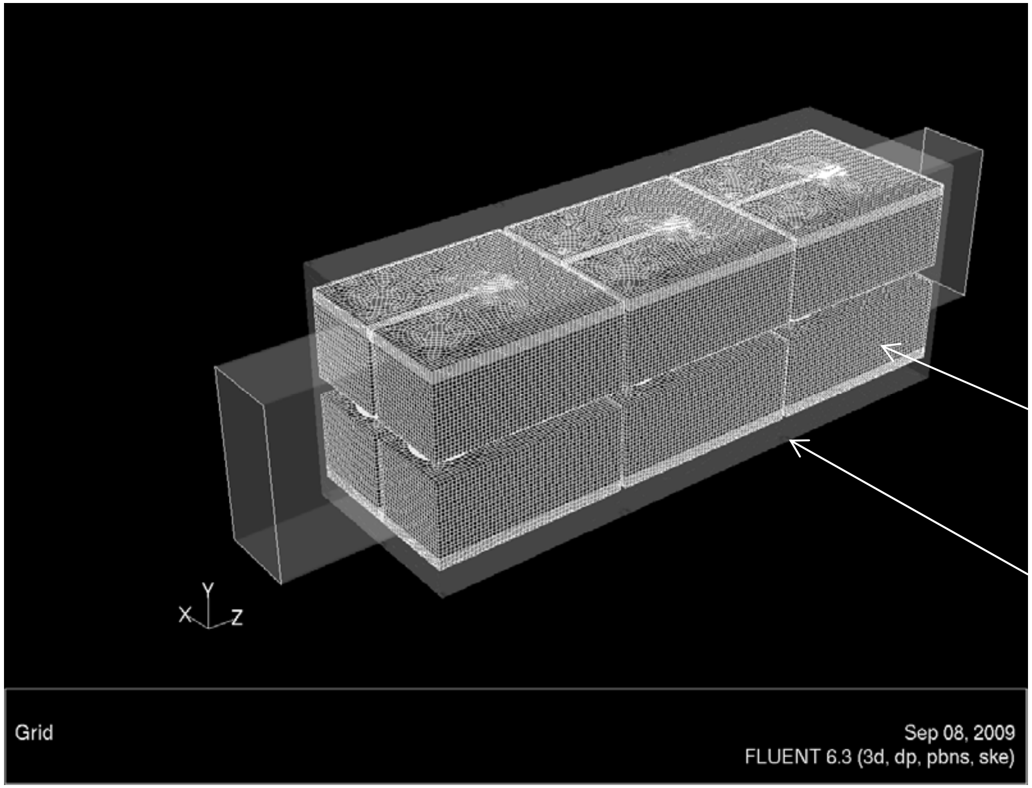
Thermal analysis example 3

- Irradiate 0.4 inch thick stainless steel compact tension (CT) specimens at approximately 288°C
- Coolant flow
  - 10 gpm
- Coolant pressure
  - 2200 psig
- Coolant temperature
  - 230°C
- Reactor lobe power
  - 24 MW



Thermal analysis example 3

- Model geometry



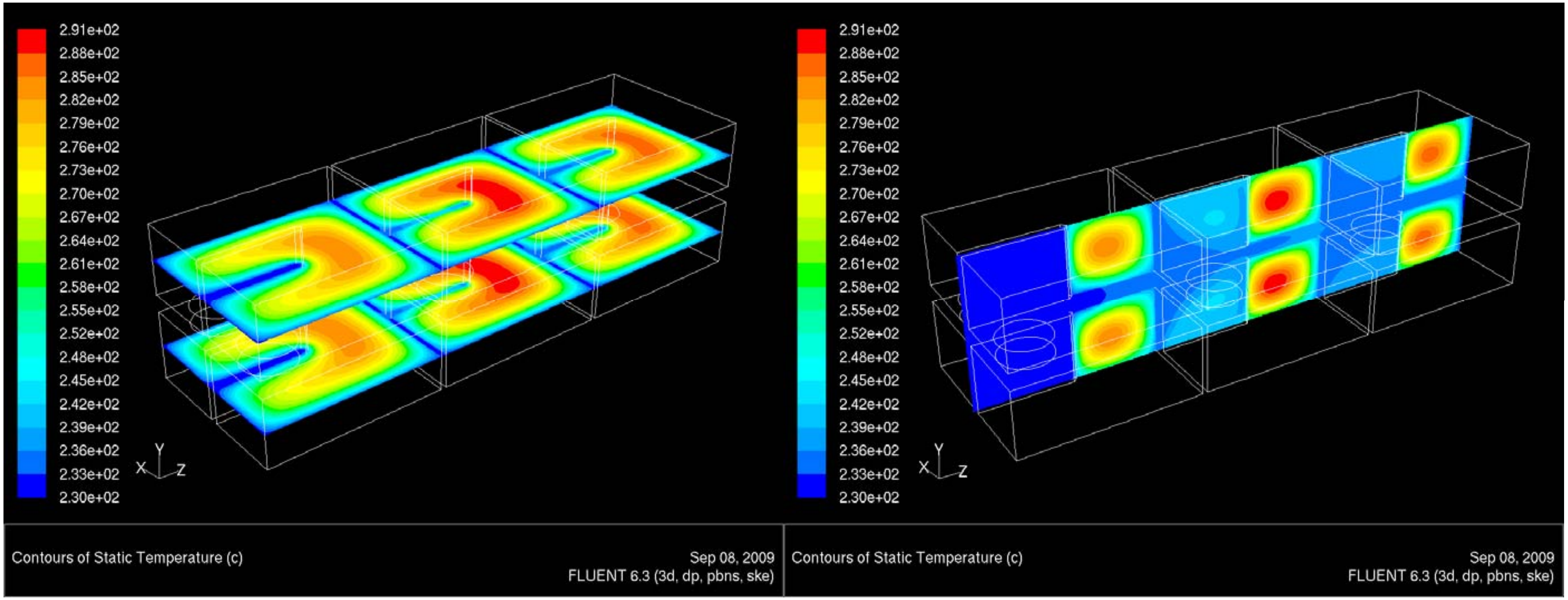
Coolant channels between specimens and holder and between adjacent specimens

CT specimen

Inner wall of specimen holder

Thermal analysis example 3

- Temperature contours (°C) at specimen interior
- Peak temperature is 61°C greater than coolant temperature

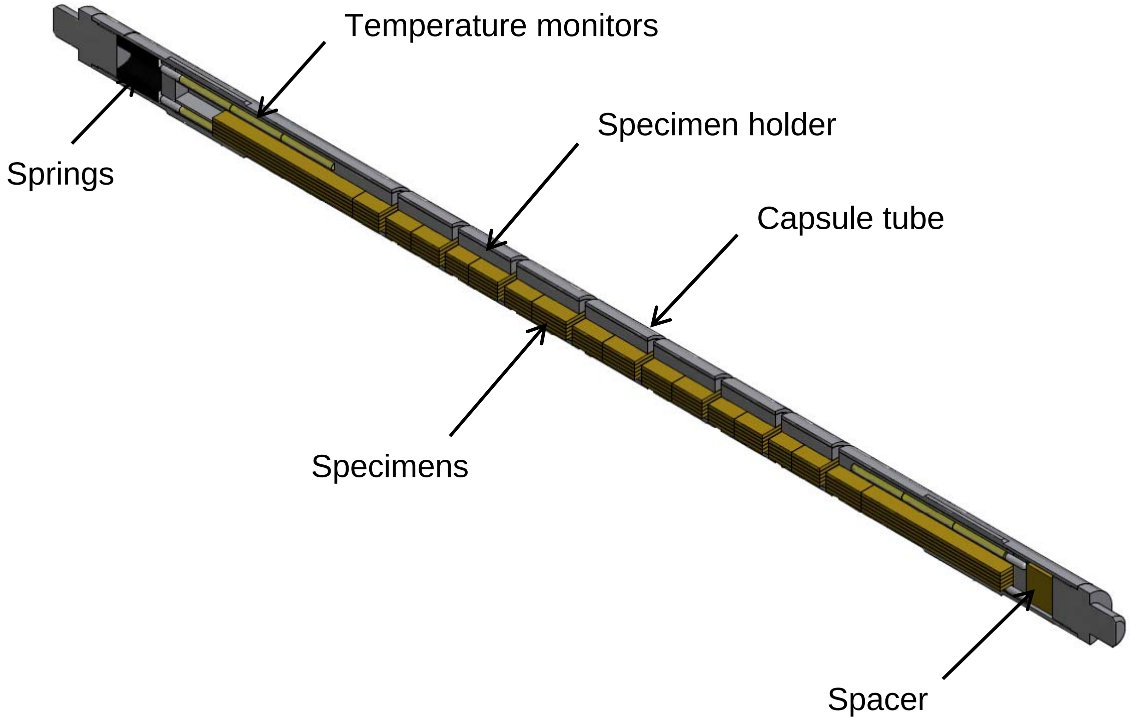


Temperature variations in capsule experiments

- Factors affecting temperature variation
  - Specimen size
  - Gamma heating
  - Gas gap uniformity
  - Axial position in core
  - Reactor power variations
- Methods to control temperature variation
  - Specimen isolation
  - Dimensional tolerances
  - Active temperature control

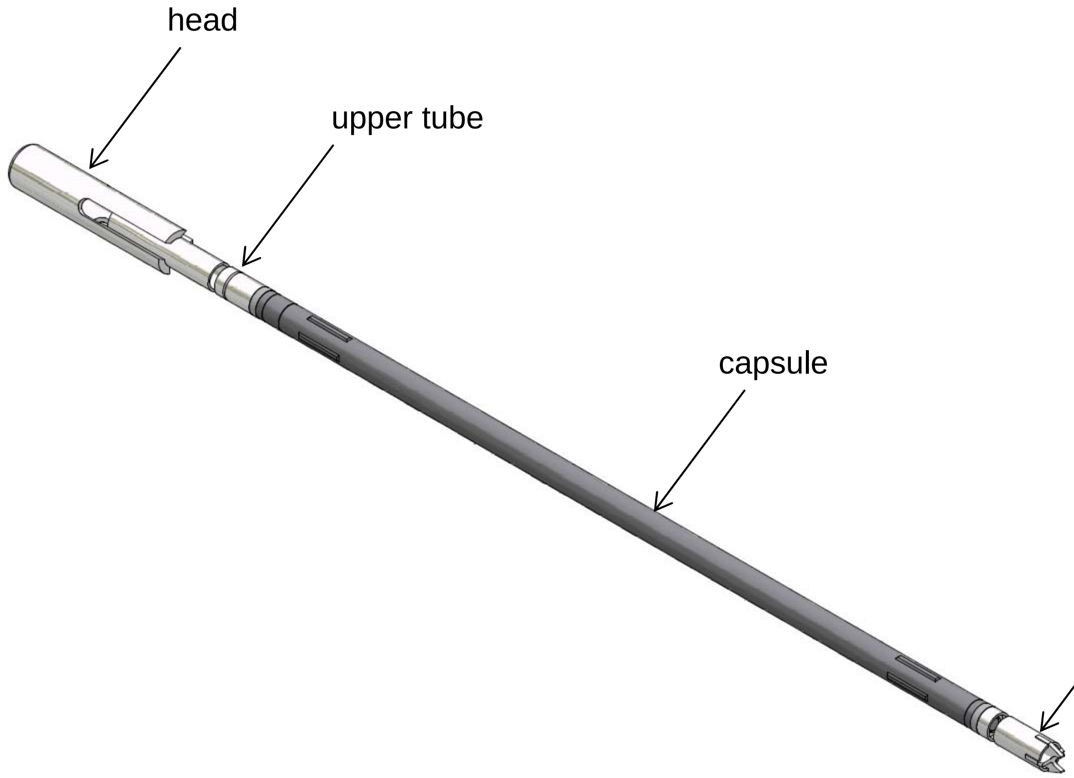
Example 1 – static capsule experiment

- 50 specimens are contained in a stainless steel holder.
- Holder is contained in a helium-filled stainless steel capsule.



Example 1 – static capsule experiment

- Experiment assembly



Example 1 – static capsule experiment

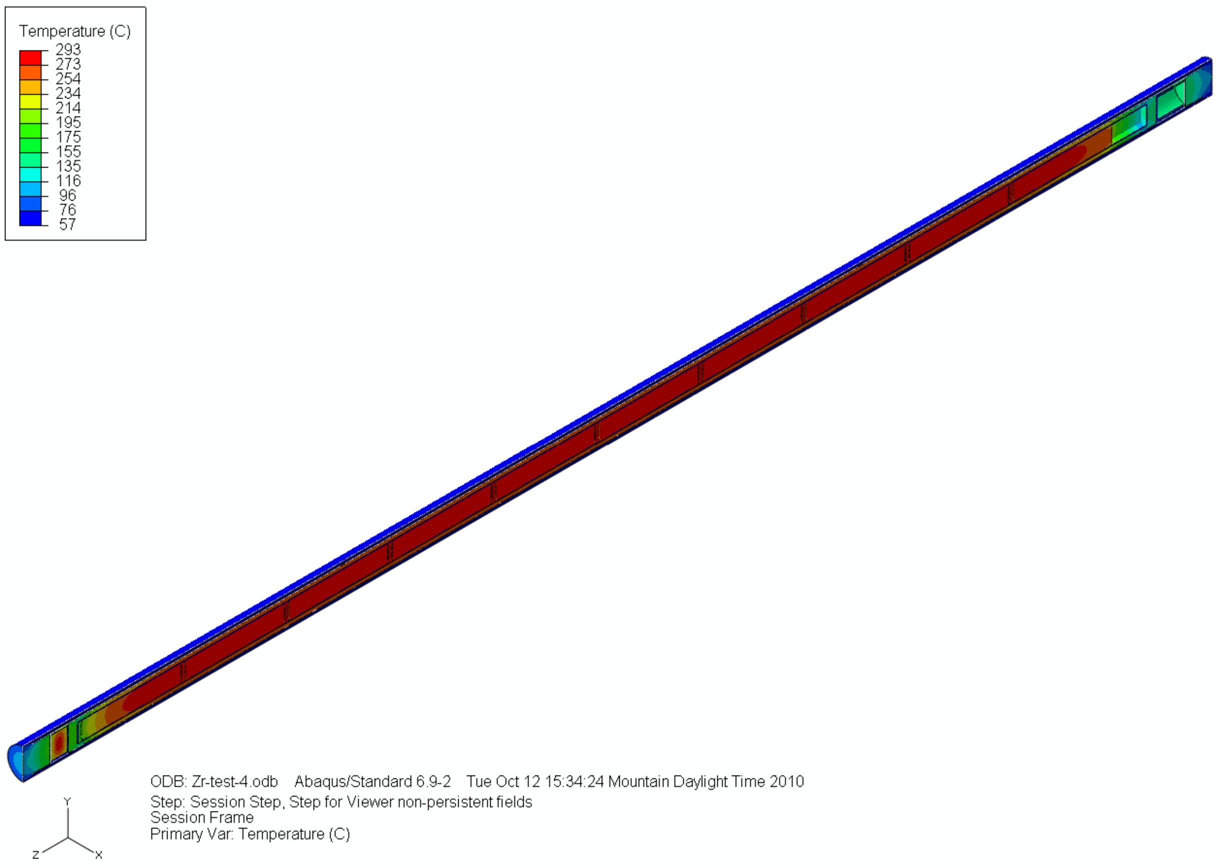
- Experiment capsule, holder, and specimens

Example 1 – static capsule experiment

- Assembling the capsule, holder, and specimens

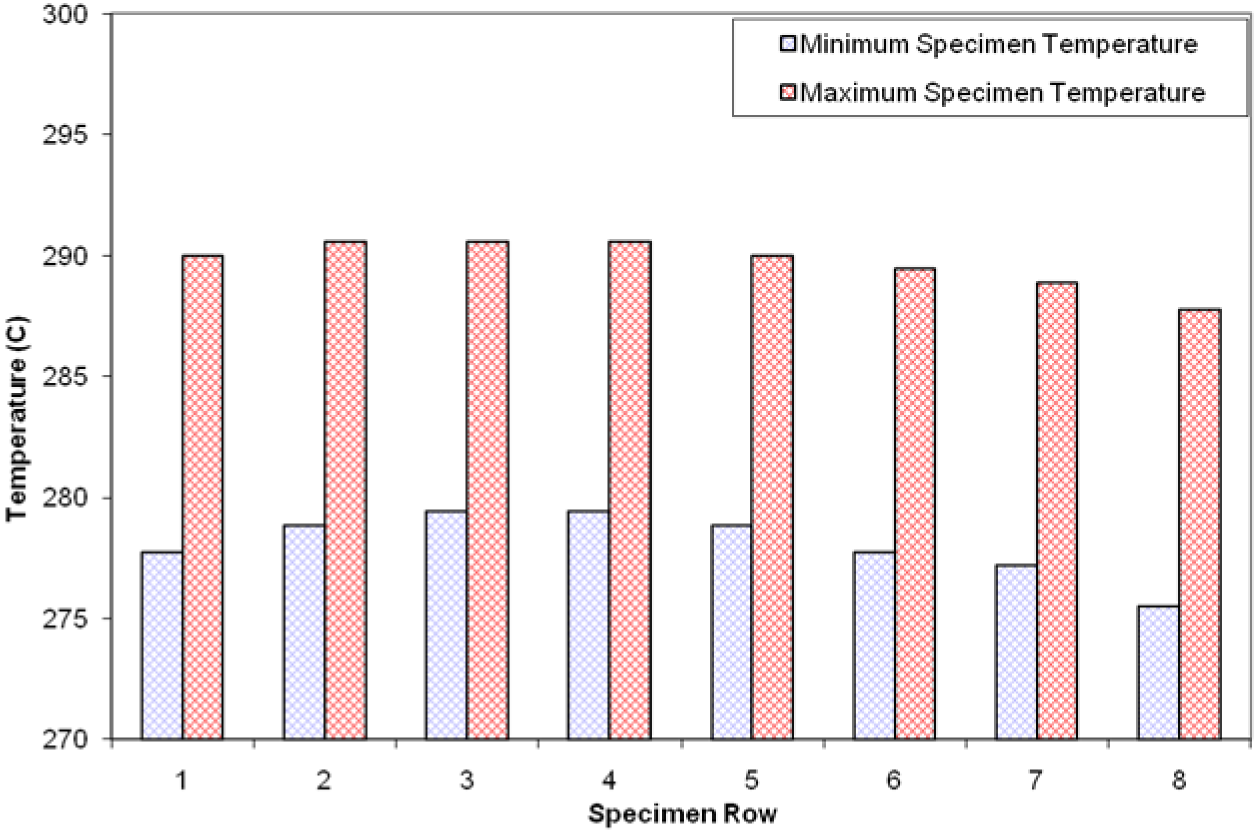
Example 1 – static capsule experiment

- Temperature of capsule assembly



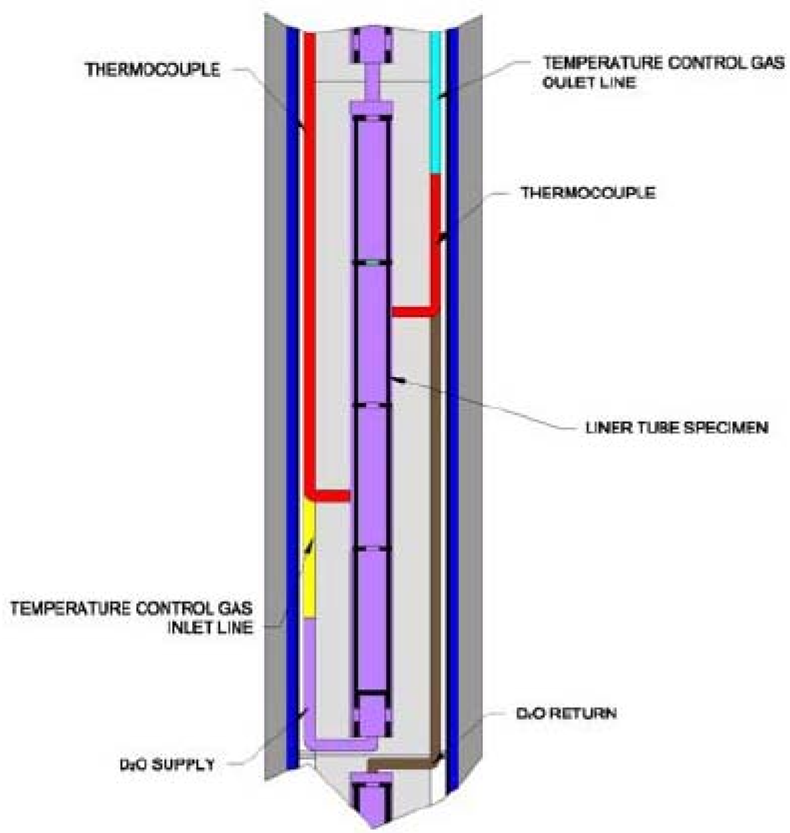
Example 1 – static capsule experiment

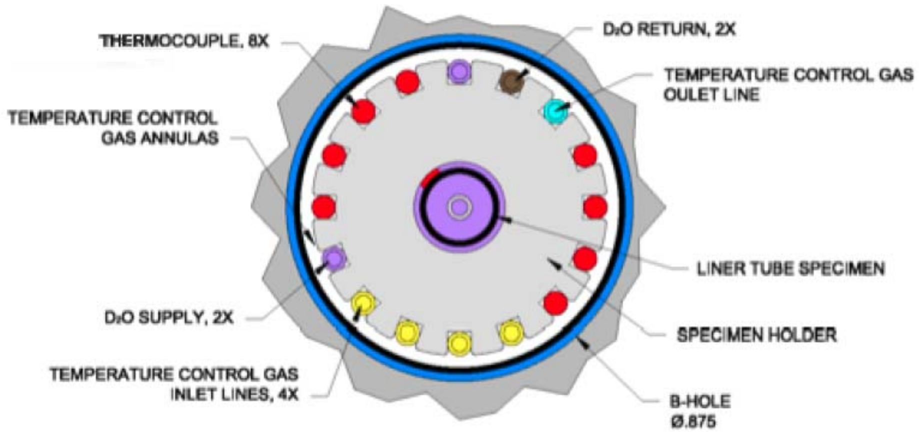
- Range of specimen temperature (40 specimens in the center of stack)
- Target temperature is 285°C ± 10°C



Example 2 – lead-out capsule experiment

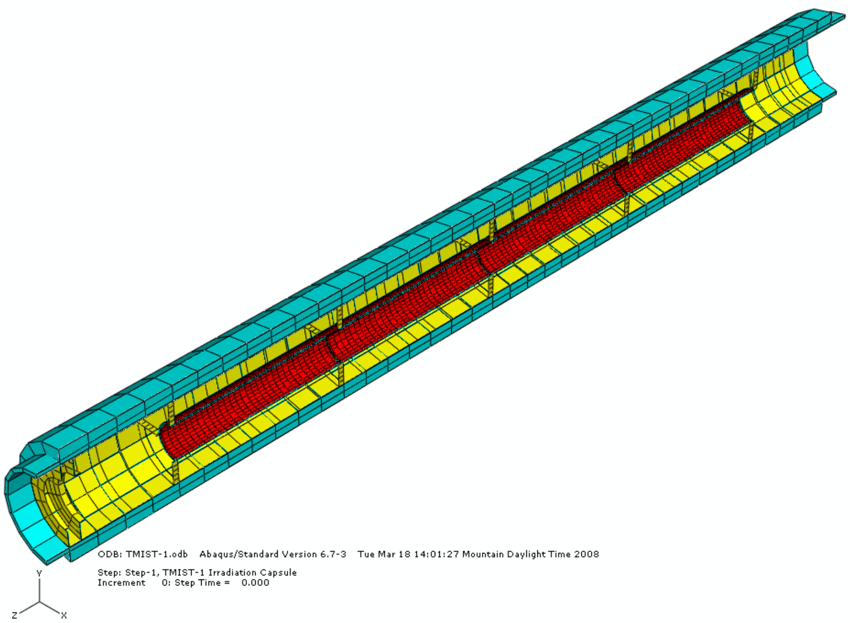
- Experiment design showing gas lines and thermocouples

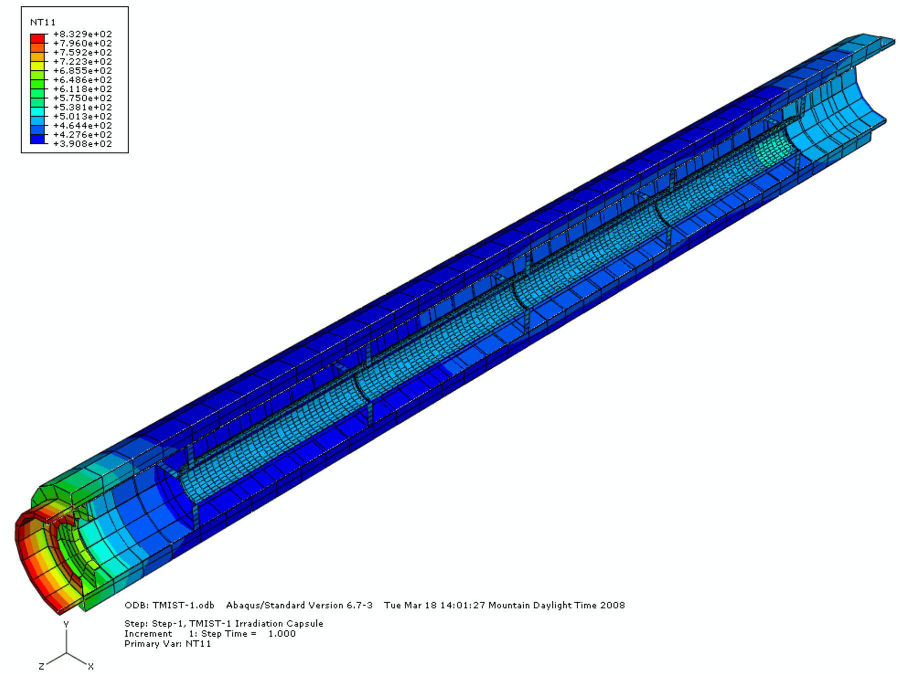




Example 2 – lead-out capsule experiment

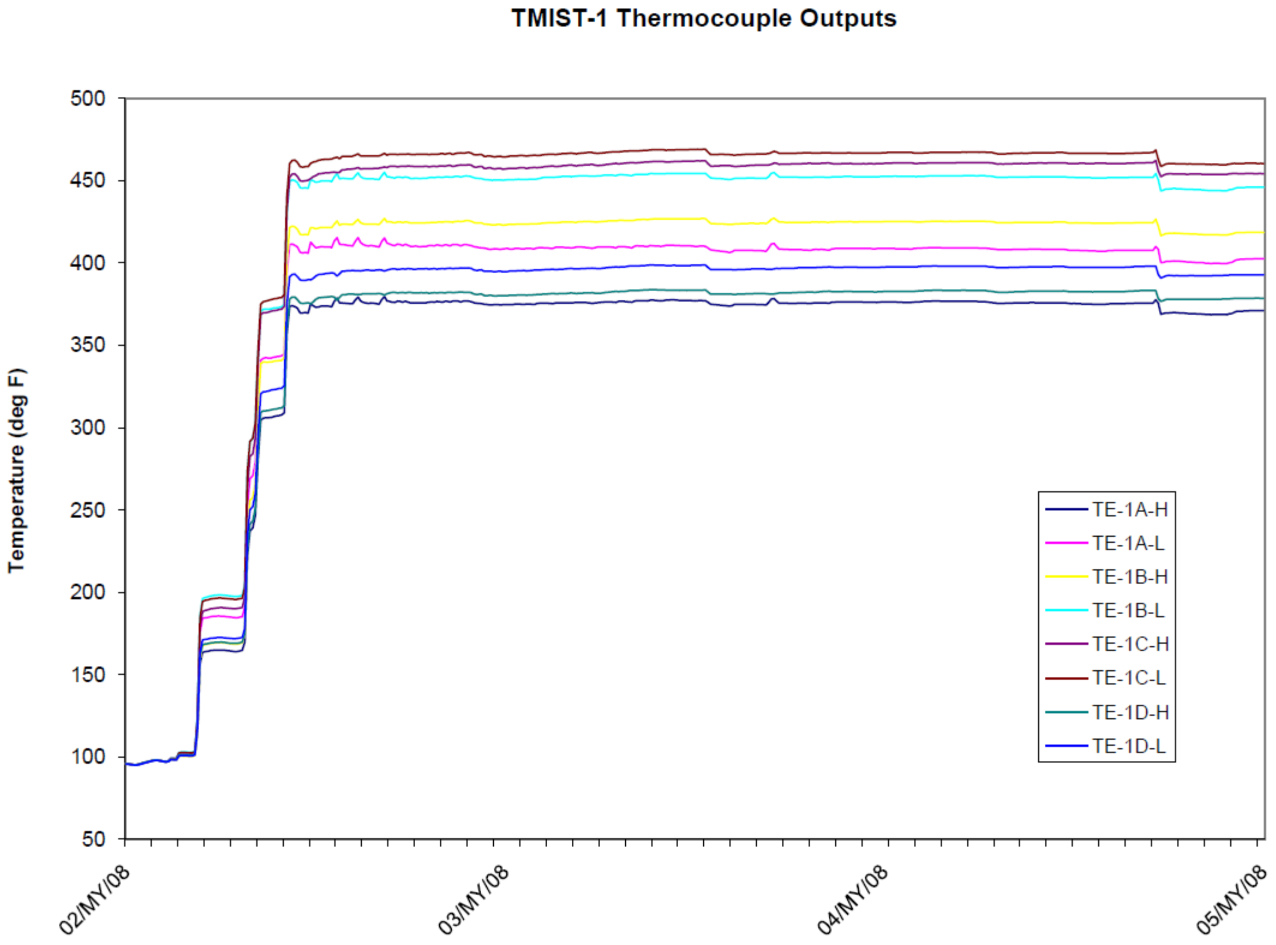
- Finite element mesh and calculated temperature distribution





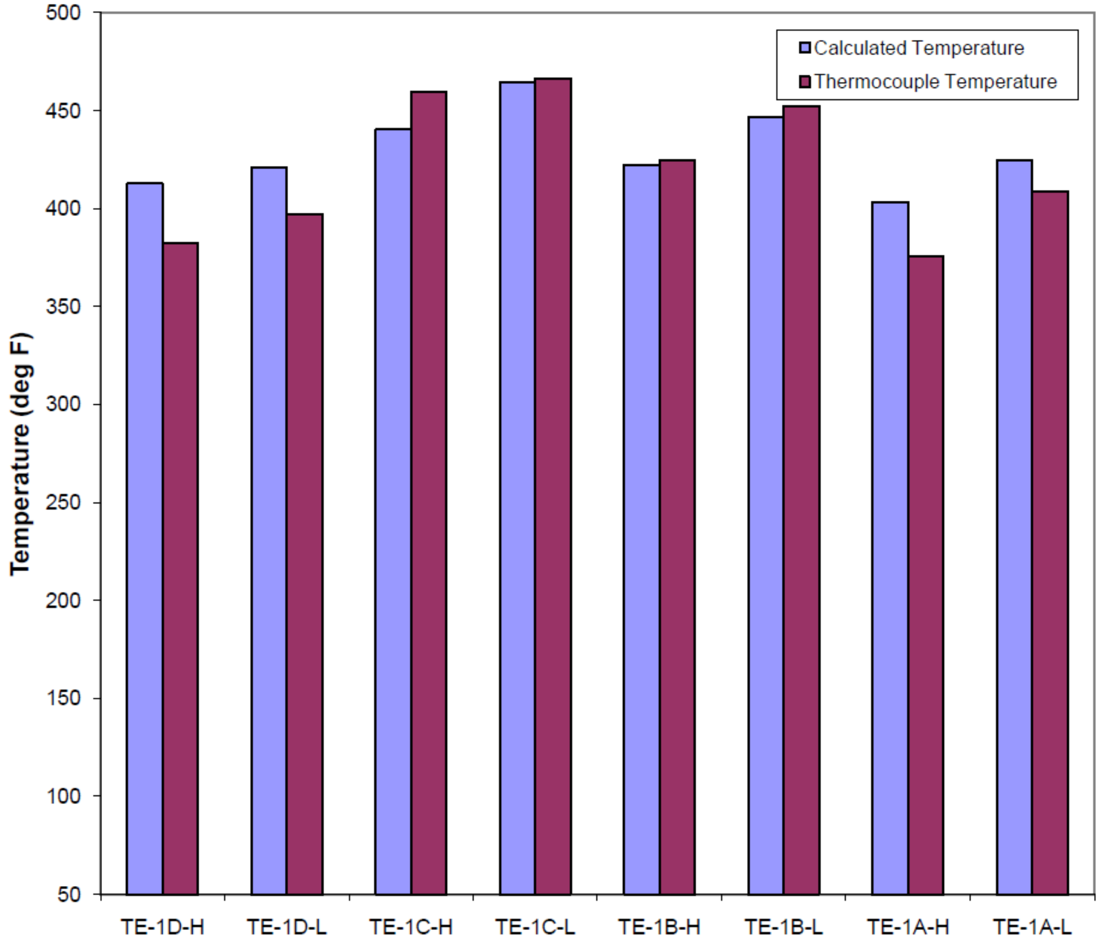
Example 2 – lead-out capsule experiment

- Temperature measured by eight thermocouples located in capsule wall



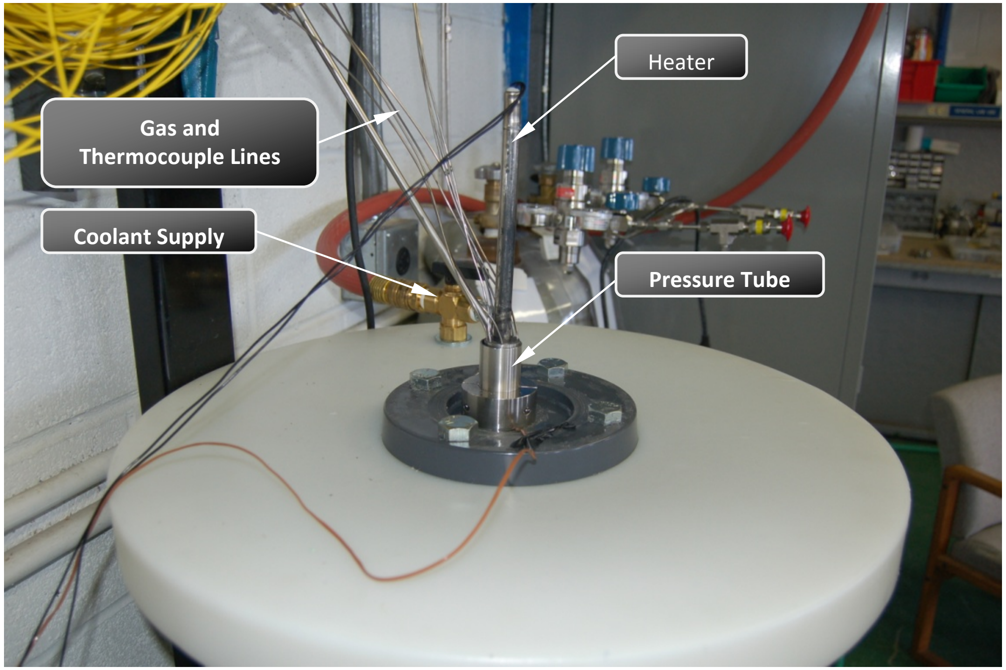
Example 2 – lead-out capsule experiment

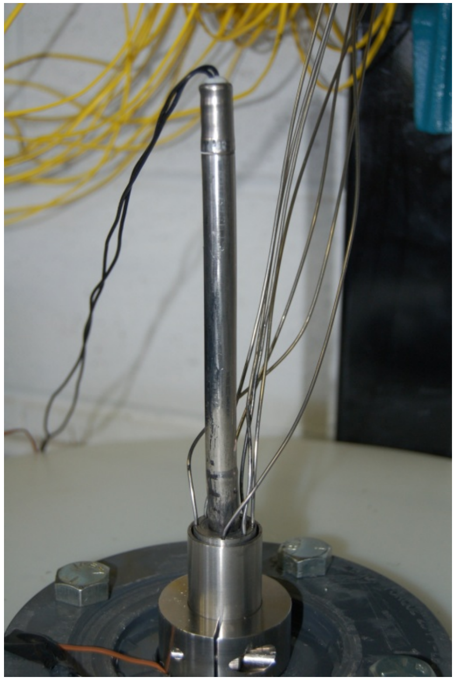
- Comparison of calculated and measured temperatures



Example 3 – lead-out experiment mock-up

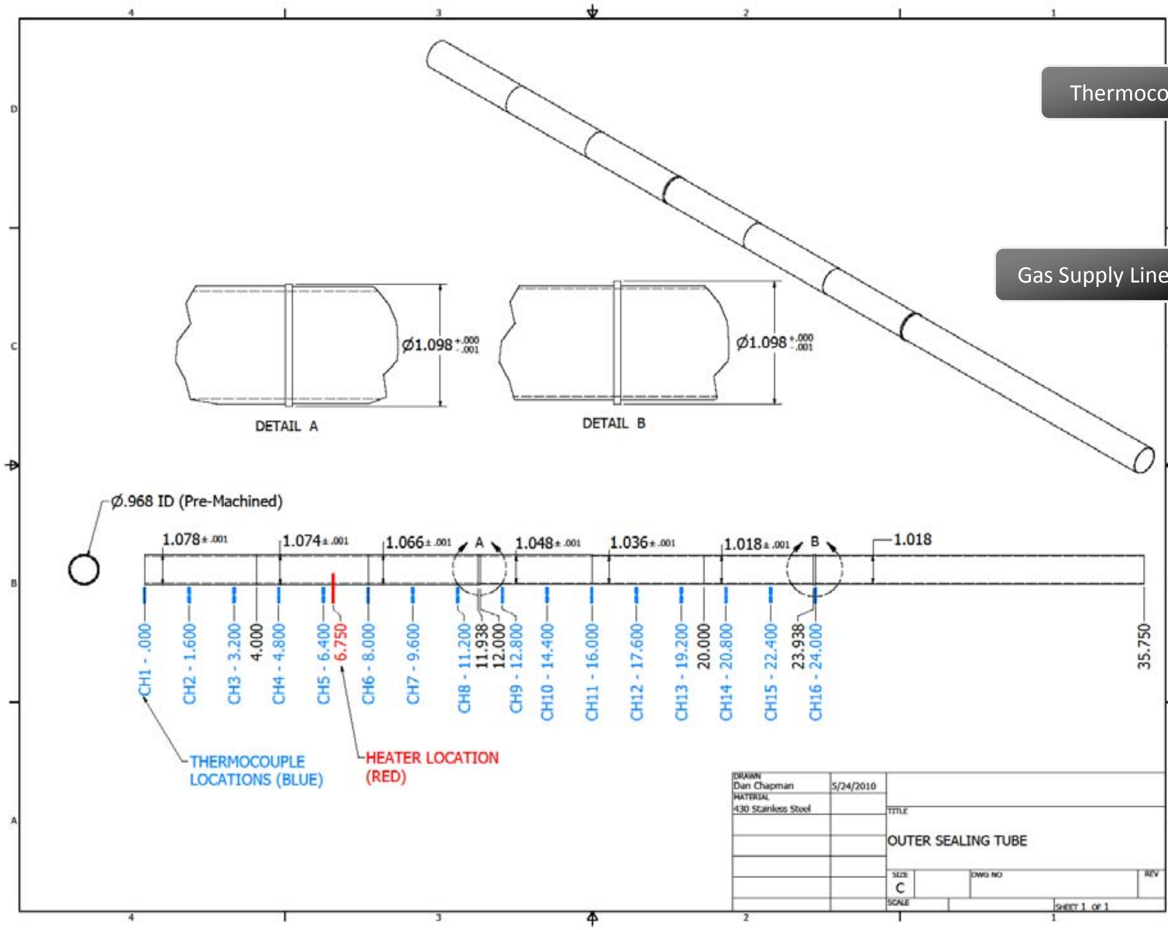
- Electrically heated pressure tube contained in a water tank

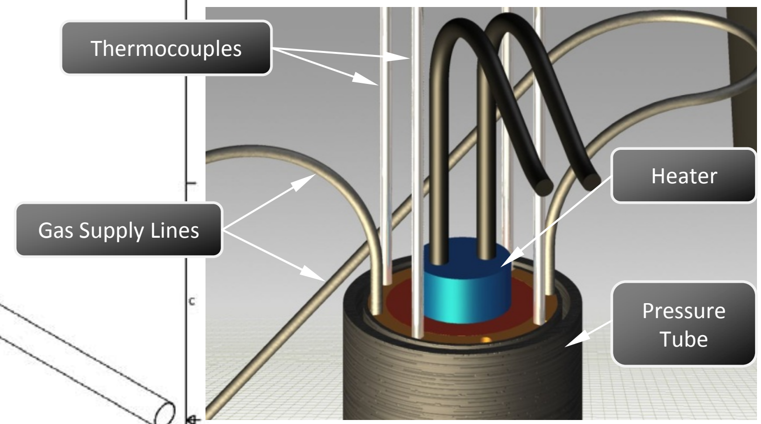




Example 3 – lead-out experiment mock-up

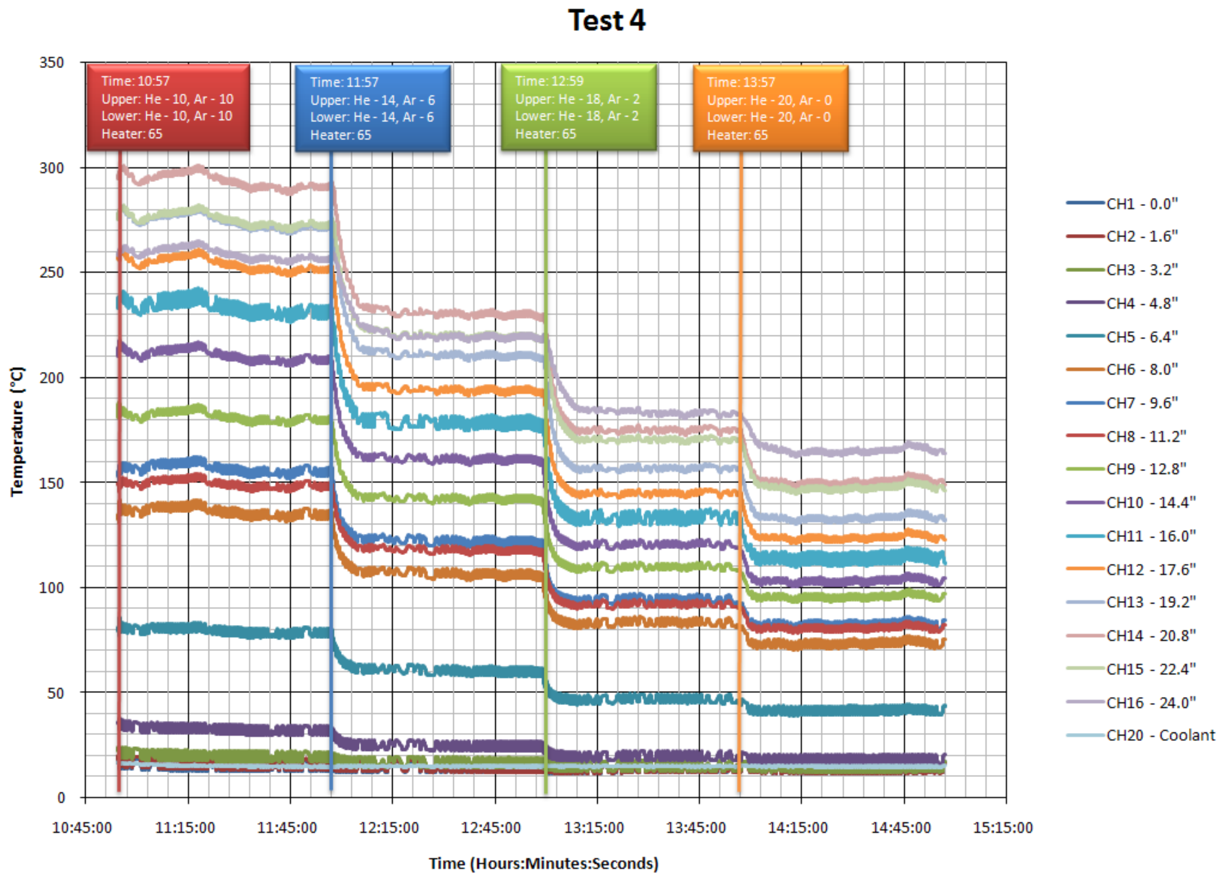
- Location of thermocouples





Example 3 – lead-out experiment mock-up

- Temperature measurements



Example 3 – lead-out experiment mock-up

- Temperature calculations

Example: Calculation of temperature at TC-14 with a heater setting of 65 and a gas mixture of 50% helium - 50% argon

$Q_h = 2000\,W$	Heater power
$L_h = 24\cdot in$	Heated length
$sp = 0.65$	Heater setting
$d_c = 0.040\,in$	Gas gap (cold)

$T_1 = 291\,°C$	Temperature (initially assumed due to nonlinear dependence of radiation heat flux on temperature)
$T_2 = 15\,°C$	Coolant temperature
$\alpha = 1.08\times 10^{-5}\cdot\frac{1}{°C}$	Mean coefficient of thermal expansion
$r = 0.509in$	Radius of tube
$\Delta r = \alpha\cdot(T_1 - T_2)\cdot r$	Radial thermal expansion of the tube
$d_h = d_c - \Delta r$	Gas gap (hot) accounting for thermal expansion
$d_h = 0.038in$	

Example 3 – lead-out experiment mock-up

- Temperature calculations – continued

$\sigma = 5.670 \cdot 10^{-8} \cdot \frac{W}{m^2 \cdot K^4}$ Stefan-Boltzmann constant

$\varepsilon_s = 0.2$ Emissivity of stainless steel

$k = 4.217 \times 10^{-3} \cdot \frac{BTU}{hr \cdot in \cdot R}$ Thermal conductivity of 50% helium - 50% argon mixture

$R_1 = r$ Inside radius of gas gap

$R_2 = r + d_h$ Outside radius of gas gap

$q_s = \frac{sp \cdot Q_h}{L_h \cdot \pi \cdot R_1^2}$ Rate of heat generation

$q_s = 0.063 \frac{BTU}{s \cdot in^3}$

$$\Delta T = \frac{\frac{q_s \cdot R_1}{2}}{\frac{k}{R_1 \cdot \ln\left(\frac{R_2}{R_1}\right)} + \frac{\sigma \cdot (T_1 + T_2) \cdot \left(T_1^2 + T_2^2\right)}{\frac{1}{\varepsilon_s} + \frac{1 - \varepsilon_s}{\varepsilon_s} \cdot \frac{R_1}{R_2}}}$$

Temperature drop across gas gap, due to conduction and radiation

$\Delta T = 276\ °C$

$T_2 + \Delta T = 291\ °C$ Temperature at location of thermocouple, assuming thermal resistance of tubes is negligible in comparison to thermal resistance of gas gap

Example 3 – lead-out experiment mock-up

- Results of temperature calculations

Heater Setting	Helium Percent	Argon Percent	Thermocouple	Calculated Temperature
0.65	0	100	10	422
0.65	25	75	10	298
0.65	50	50	10	213
0.65	75	25	10	153
0.65	100	0	10	106
0.65	0	100	12	478
0.65	25	75	12	341
0.65	50	50	12	246
0.65	75	25	12	178
0.65	100	0	12	124
0.65	0	100	14	549
0.65	25	75	14	399
0.65	50	50	14	291
0.65	75	25	14	212
0.65	100	0	14	148

Example 3 – lead-out experiment mock-up

- Comparison of measured and calculated temperatures