Thermal Analysis of ATR Experiments

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ATR Irradiation Testing

ATR NSUF User Week Experimenter Course

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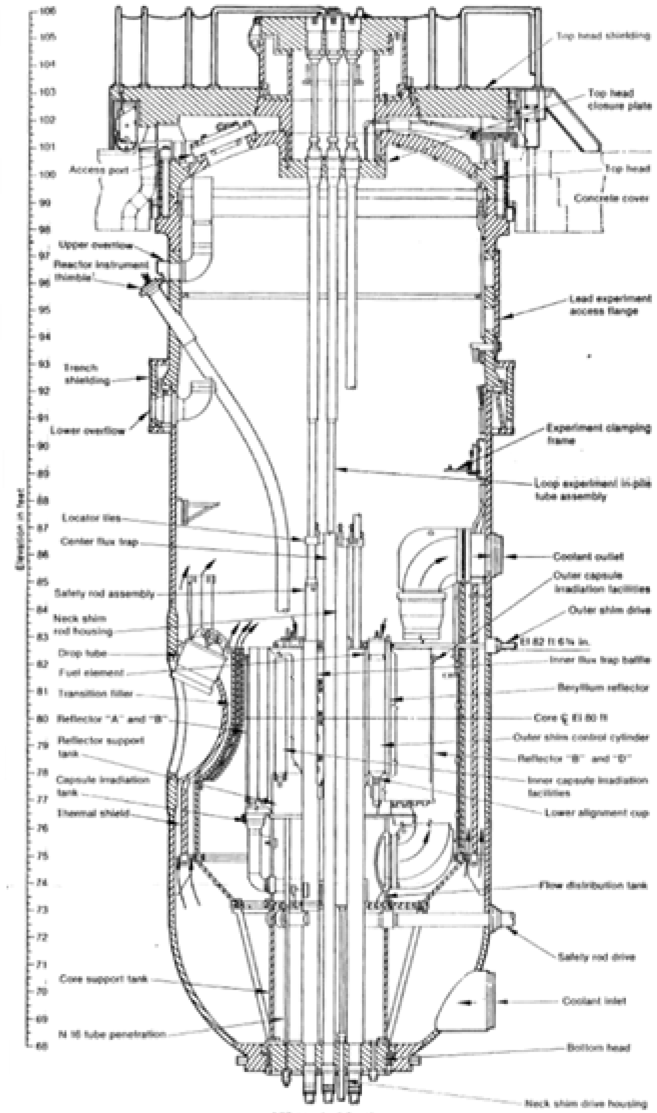
Outline

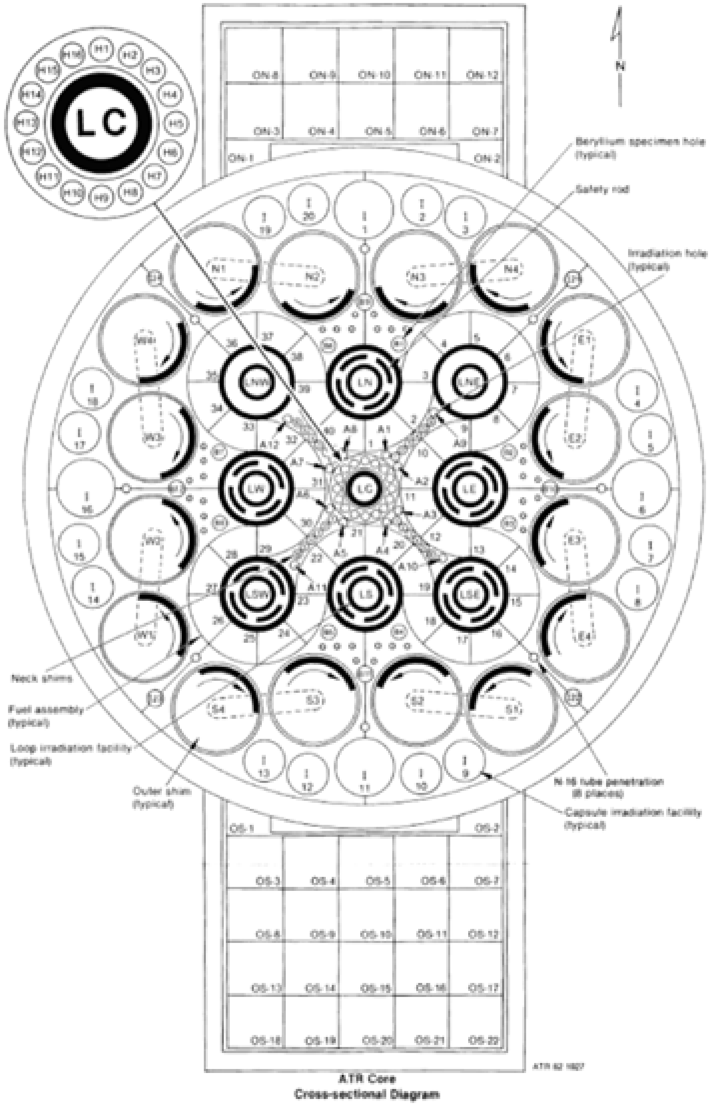
- Description of the ATR
  - Reactor vessel and core arrangement
  - Primary cooling system (PCS)
- Thermal-hydraulic safety requirements
  - Departure from nucleate boiling (DNB)
  - Flow instability (FI)
  - Thermal loads
- Thermal analysis examples
  - Analytical solution to temperature profile in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

ATR vessel vertical section



ATR Vertical Section

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)
- 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)

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

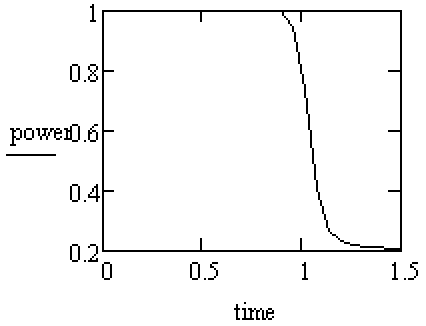
q_{chf}	Critical heat flux in flow boiling
q	Actual heat flux at surface contacting primary coolant

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

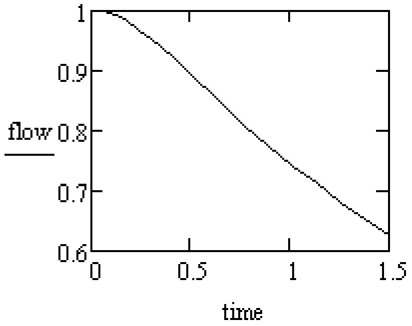
$\Delta T_c = T_{sat} - T_{inlet}$	Critical temperature rise
$\Delta T = T_{outlet} - T_{inlet}$	Actual temperature rise
T_{inlet}	Coolant channel inlet temperature
T_{outlet}	Coolant channel outlet temperature
T_{sat}	Saturation temperature

Thermal loads

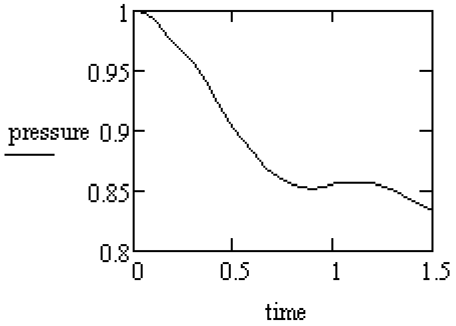
- Nominal operating power and nominal flow
- 25% increase in power (reactor power variation and instrument uncertainty)
- 25% reduction in flow (primary coolant pump coast-down following loss of power to pumps)
- Power and flow transients (reactor scram at low vessel inlet pressure)



Normalized reactor power vs. time (seconds)



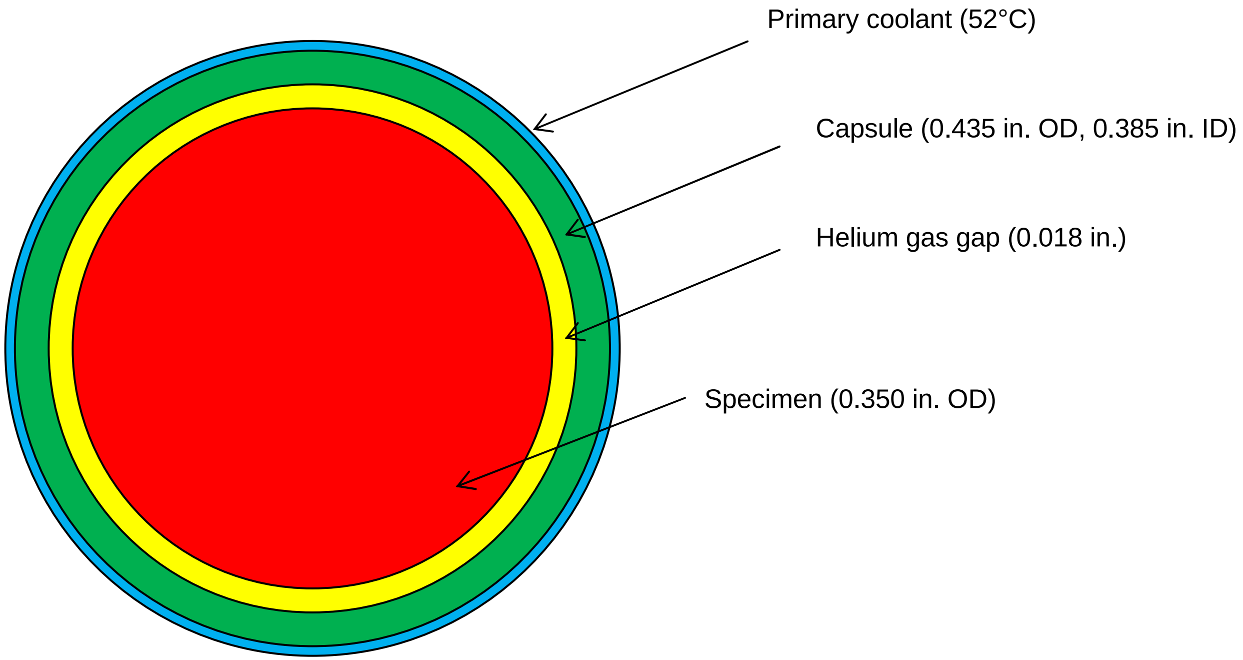
Normalized coolant flow vs. time (seconds)



Normalized inlet pressure vs. time (seconds)

Thermal analysis example 1

- Analytical solution to temperature profile in capsule experiments



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

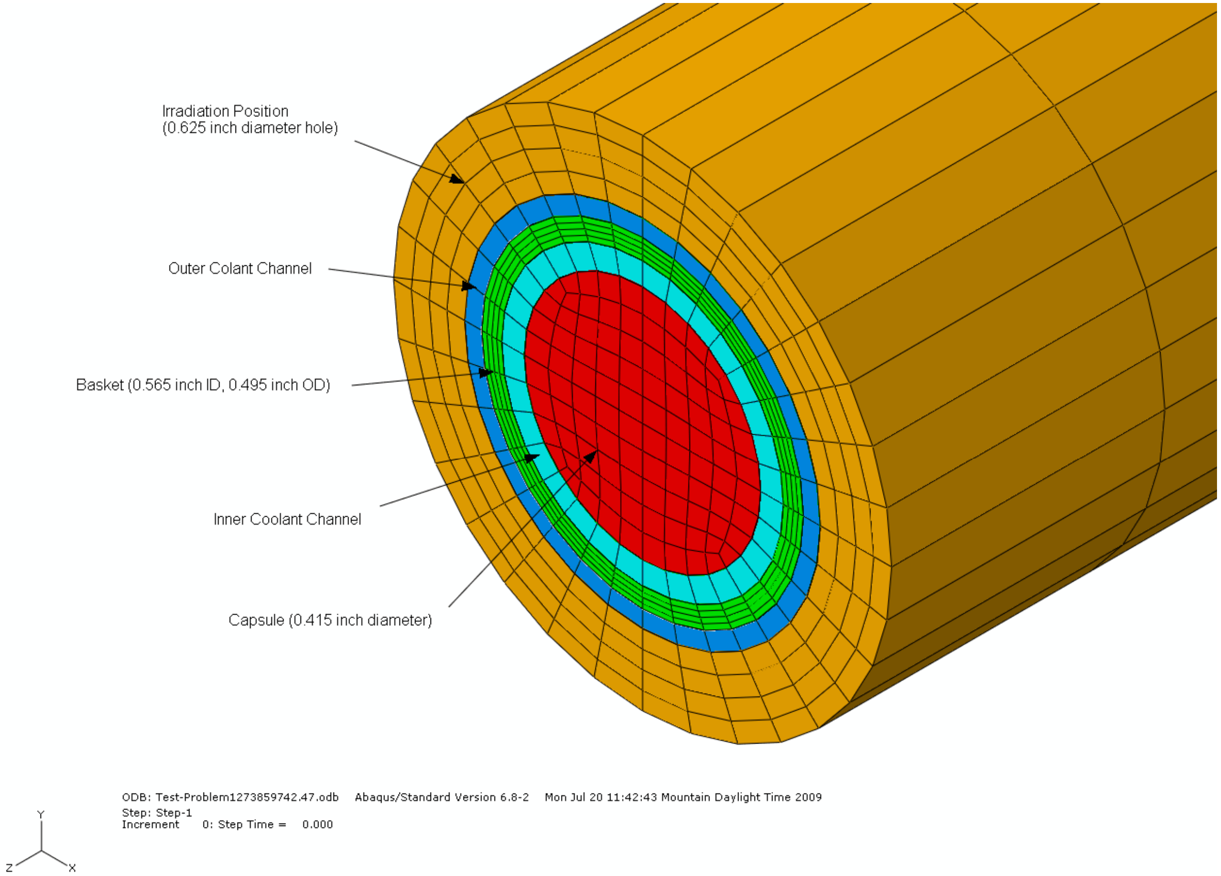
$\Delta T = 324\ °C$ Total temperature drop from specimen center to coolant

Thermal analysis example 2

- 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 saturation pressure 285 psig
  - Outlet coolant temperature from FE analysis

Thermal analysis example 2

- Finite element model of a capsule experiment

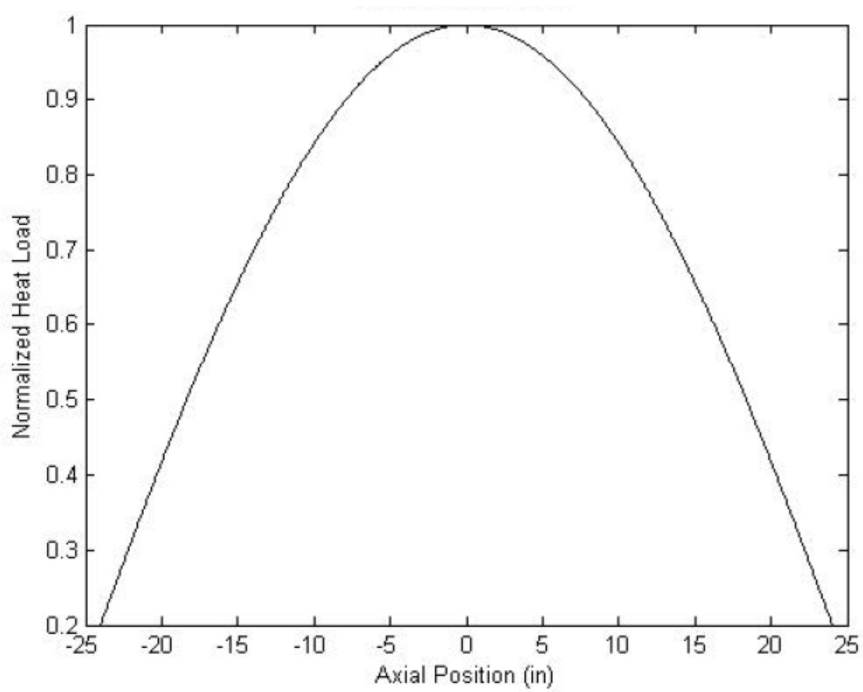


Thermal analysis example 2

- Approximate ATR axial heating profile

$P_{norm} = \cos(0.057 \cdot z)$ Normalized axial heating profile

z Distance from core mid-plane (inches)

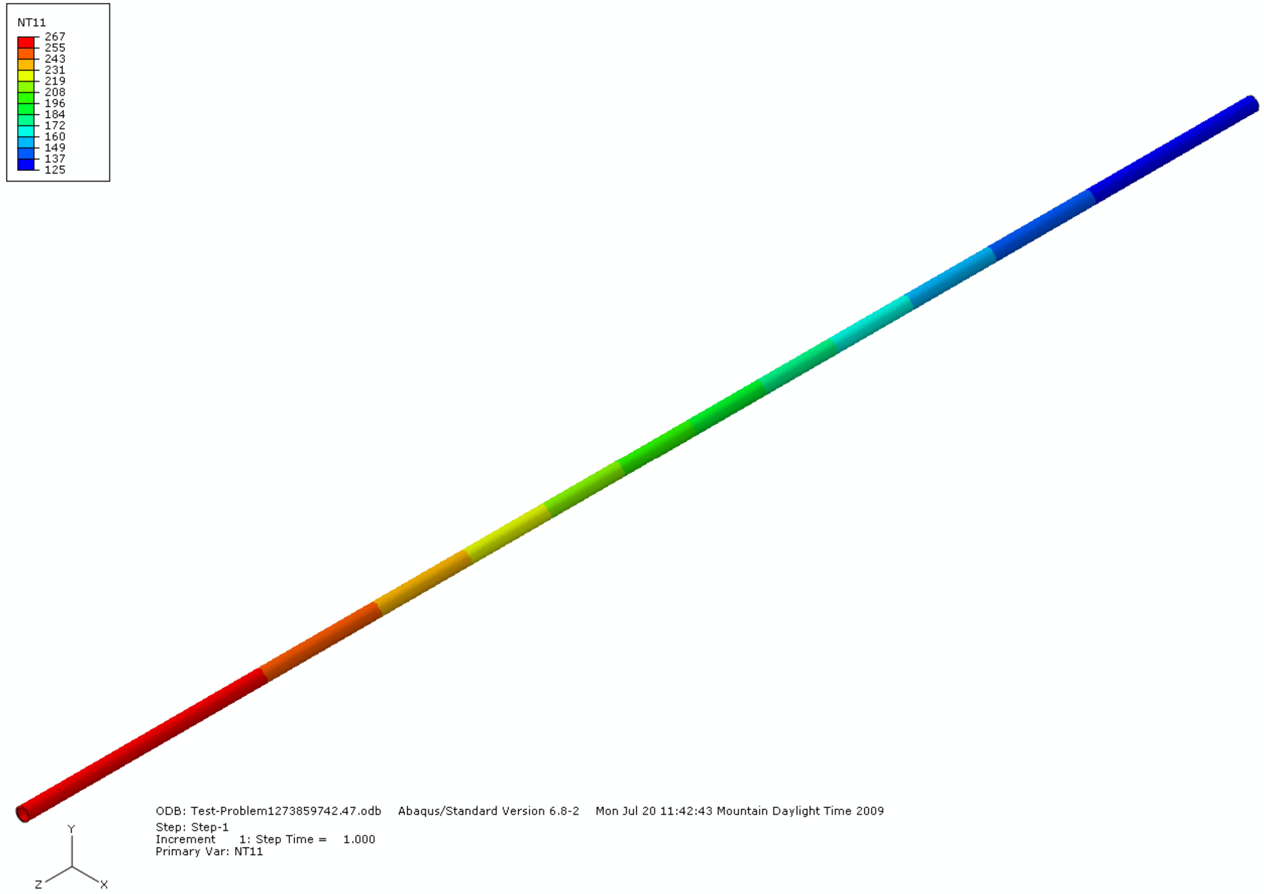


Thermal analysis example 2

- Inner coolant channel
  - Hydraulic diameter 0.080
  - Flow 3.25 gpm
- Outer coolant channel
  - Hydraulic diameter 0.060
  - Flow 2.52 gpm
- Capsule (maximum heating to meet safety limits)
  - Heating 19,730 W/in^3 at core mid-plane
- Basket
  - Heating 445 W/in^3 at core mid-plane
- Water
  - Heating 482 W/in^3 at core mid-plane

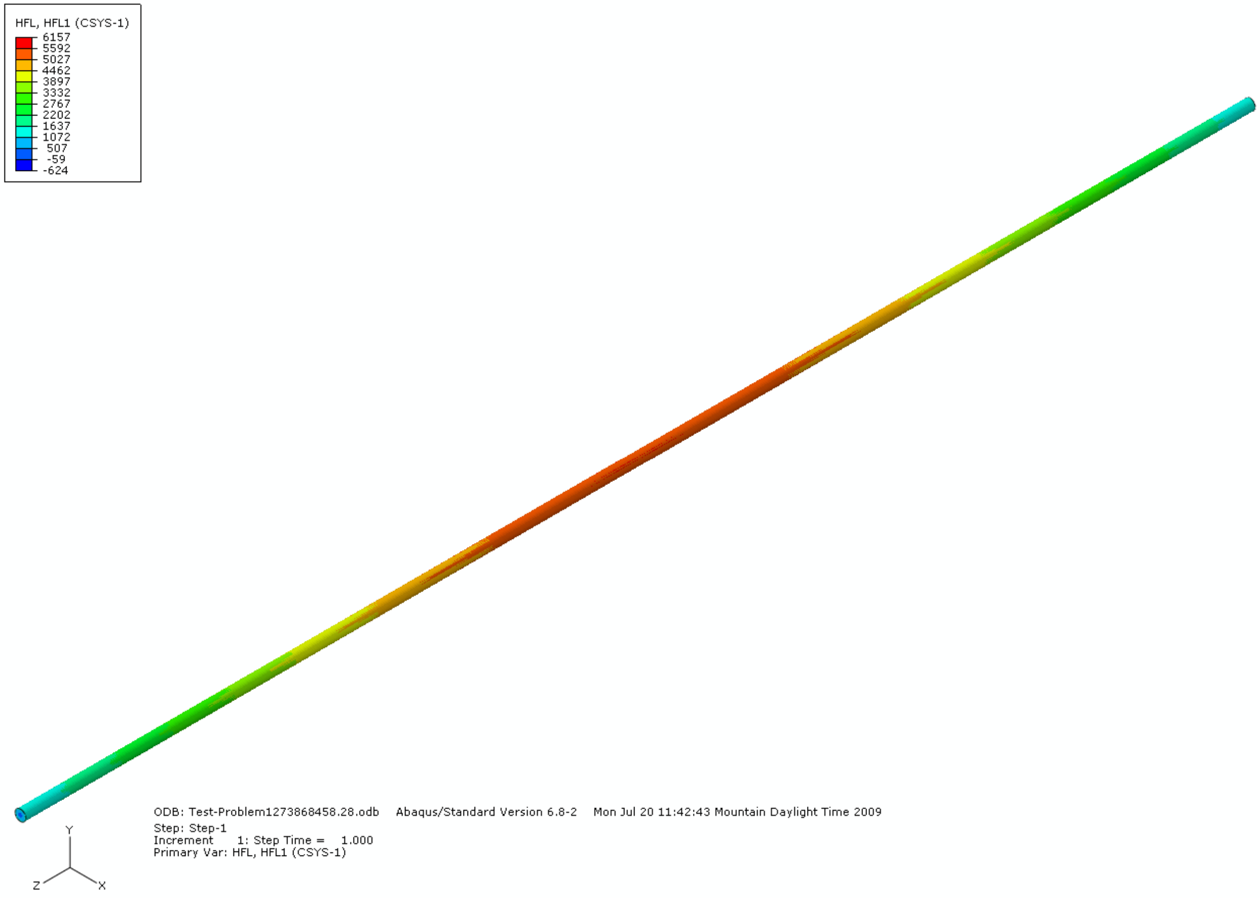
Thermal analysis example 2

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



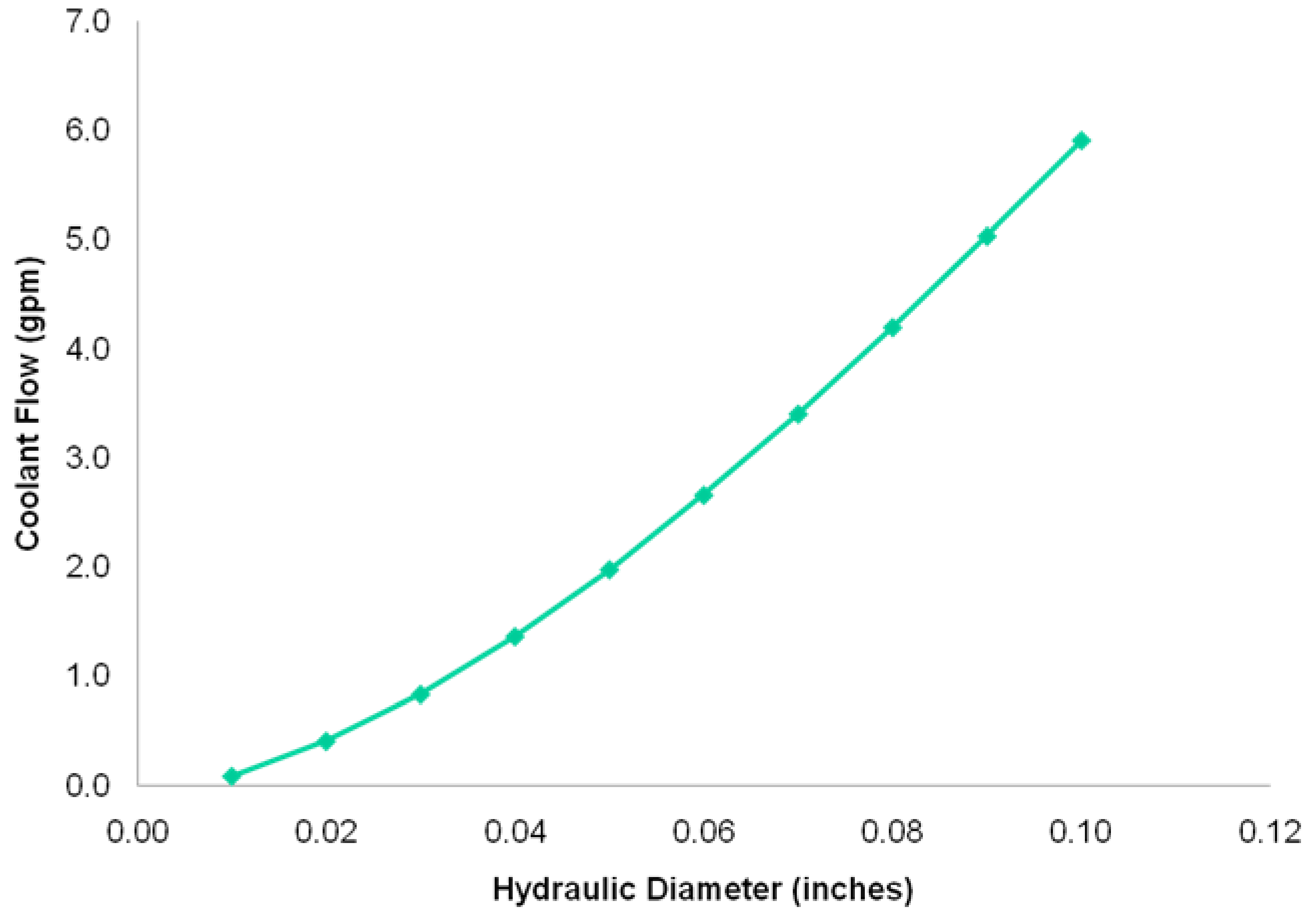
Thermal analysis example 2

- Capsule surface radial heat flux distribution (BTU/hr/in^2)
  - DNBR = 5.2



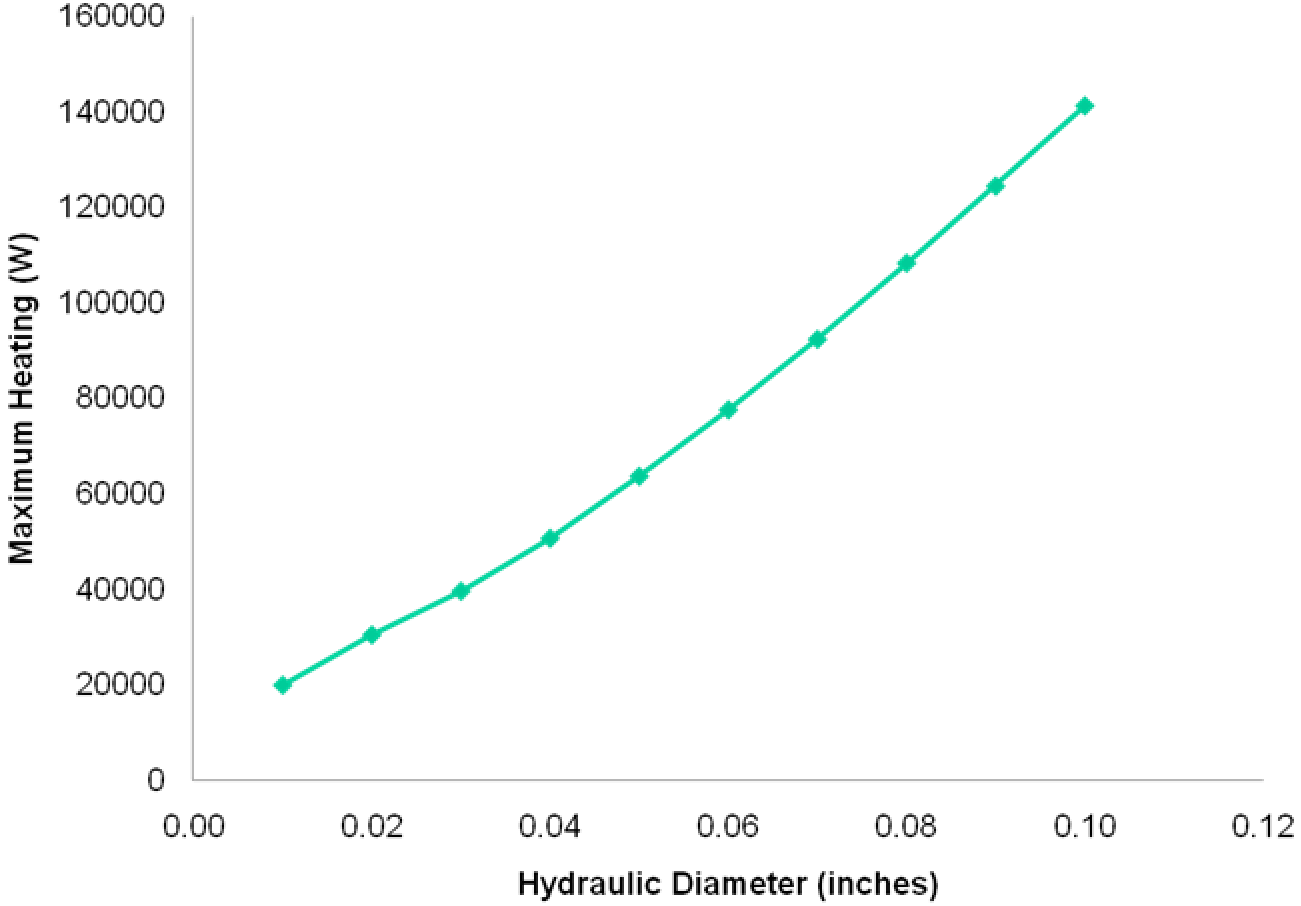
Thermal analysis example 2

- Inner coolant channel flow for various hydraulic diameters



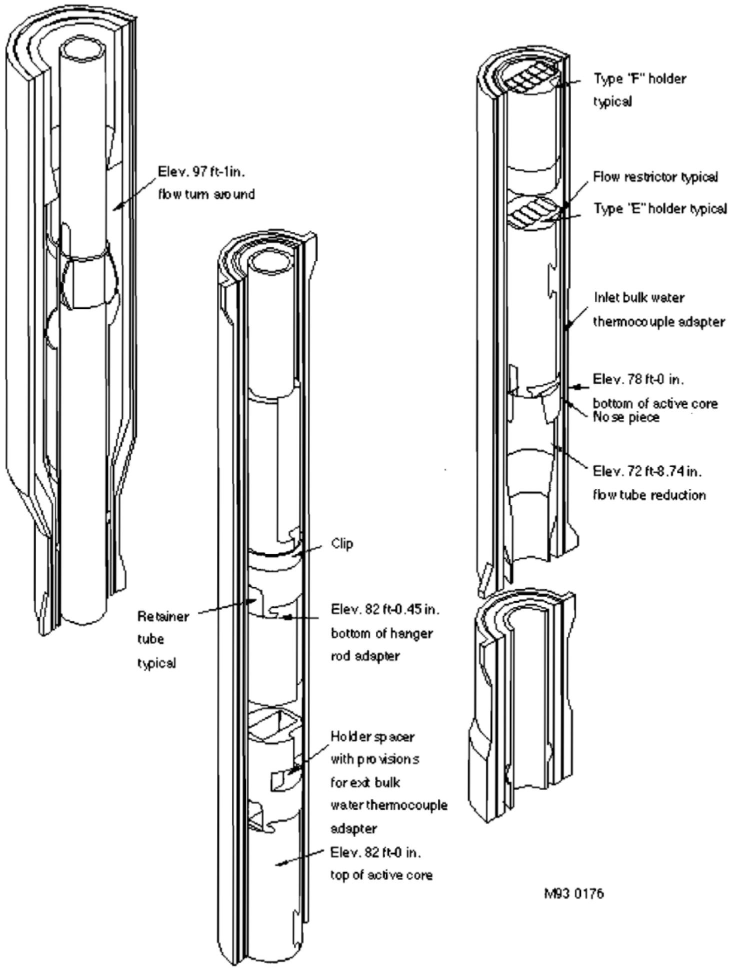
Thermal analysis example 2

- Maximum allowable capsule heating for various hydraulic diameters



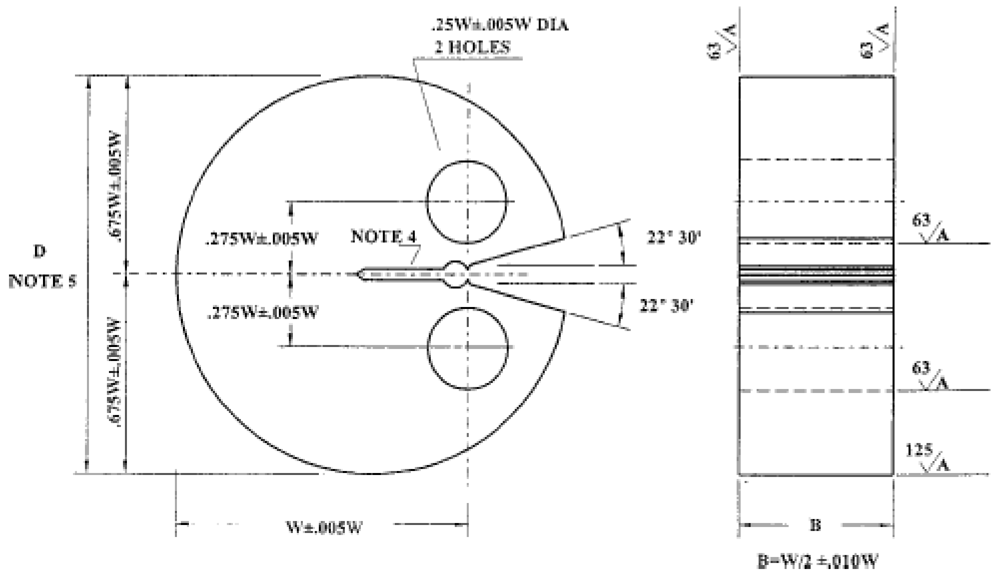
Thermal analysis example 3

- CFD simulations of heat transfer in a pressurized water loop (PWL)



Thermal analysis example 3

- Irradiate 0.5 inch thick stainless steel compact tension (CT) specimens at 288°C

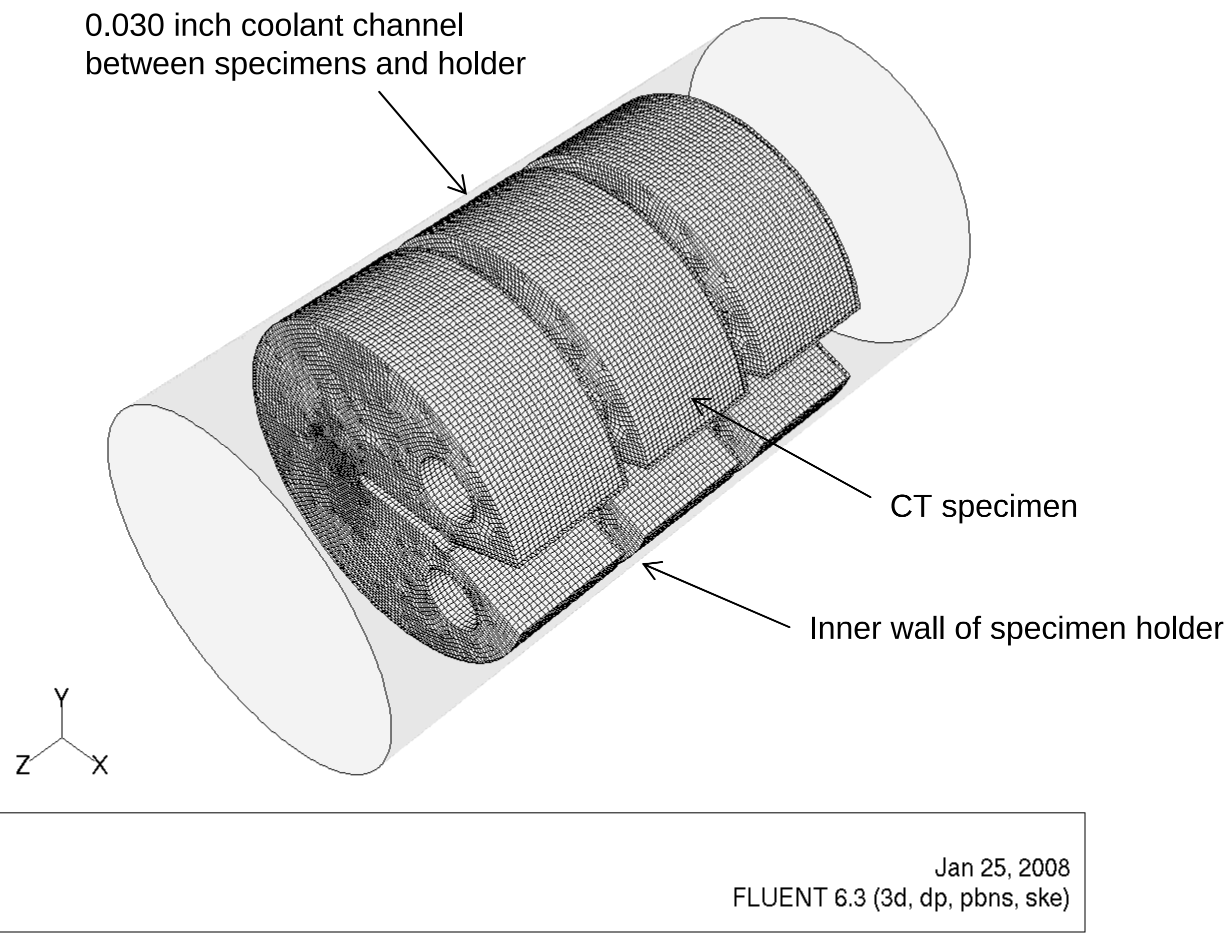


Thermal analysis example 3

- PWL flow
  - 10 gpm (through specimen holders)
- Inlet pressure
  - 2200 psig
- Inlet temperature
  - 226°C
- Reactor lobe power
  - 24 MW

Thermal analysis example 3

- Model geometry



Thermal analysis example 3

- Temperature contours (°C) at specimen interior