Thermal Modeling of Multiple-Line-Heat Source Guarded Hot Plate Apparatus

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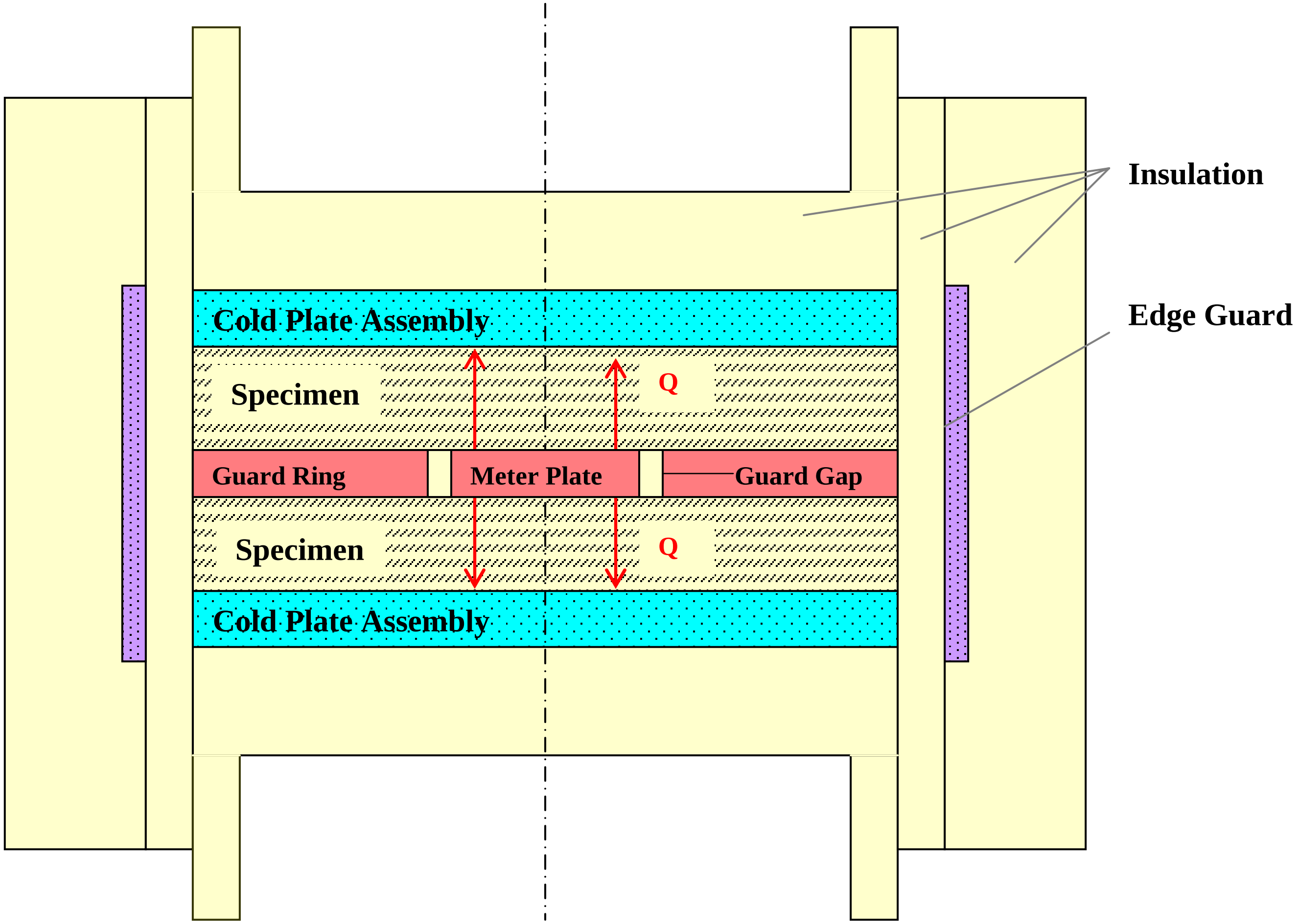
Outline

- Meter Plate
- Cold Plate
- Edge Guard
- Temperature Perturbations

Finite Element Analyses

Lumped Sum Analysis

Cross-sectional Schematic of Guarded Hot Plate Apparatus



Motivation

Evaluate and Minimize Potential Errors in Design

Where do potential errors arise?

λ determined from the heat conduction equation:

1-D heat flow?

$$\lambda = \frac{Q\Delta z}{A\left(T_{hot} - T_{cold}\right)}$$

Any storage or release of heat due to small temperature fluctuations?

Errors in temperature measurement?

Thermal Analysis Objectives

1. Ensure that hot and cold plates are isothermal so that temperature fluctuations are within approximately 0.1 % of ΔT across specimen
   (decrease errors in T measurement)

2. Minimize radial heat flow
   (decrease errors in estimation of Q)

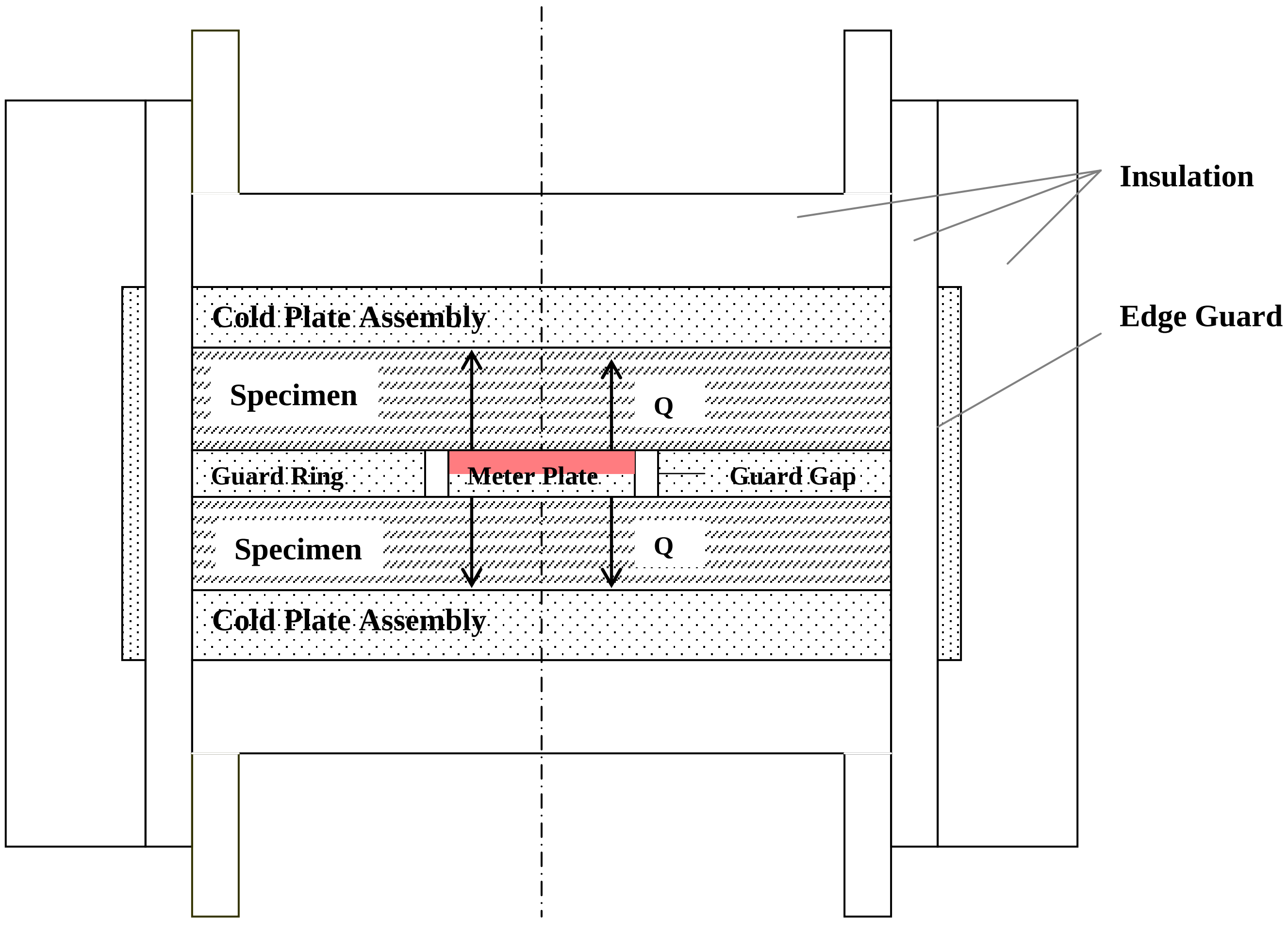
3. Evaluate perturbations in temperature due to imperfect temperature control of meter plate
   (determine errors associated with heat storage)

Analysis Tools

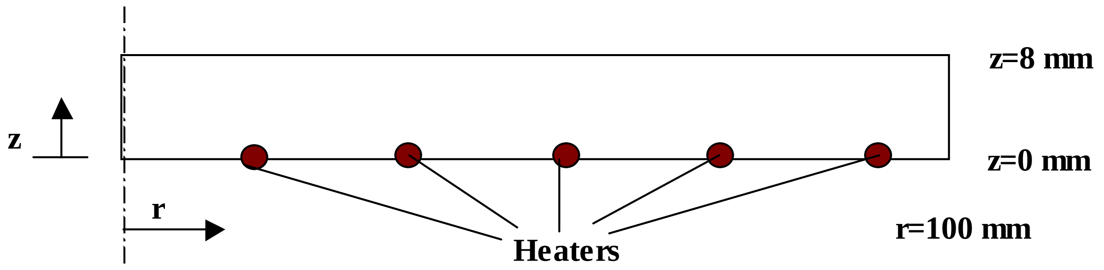
- Initial analyses utilized analytical techniques

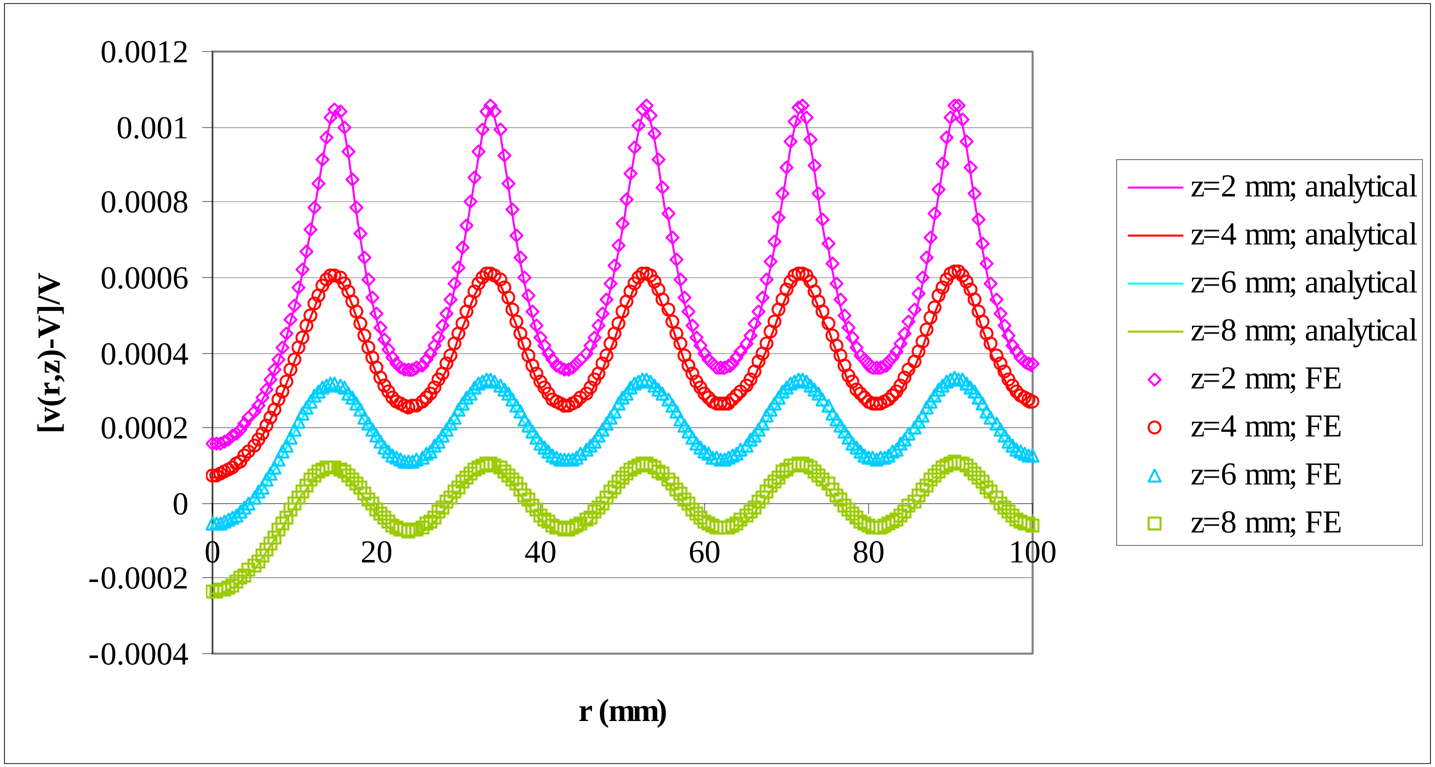
- More complicated geometries required finite element analysis

Meter Plate Modeling

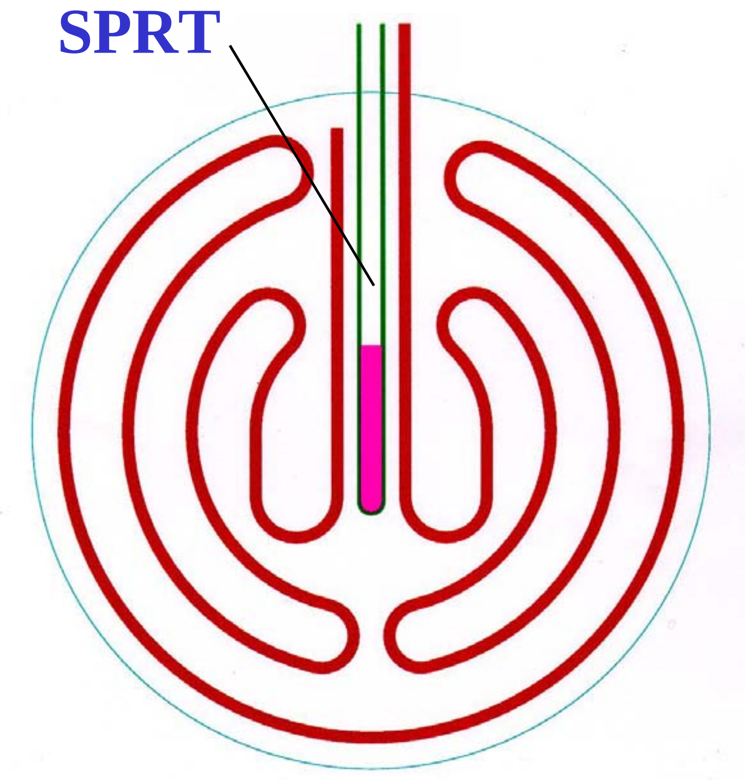


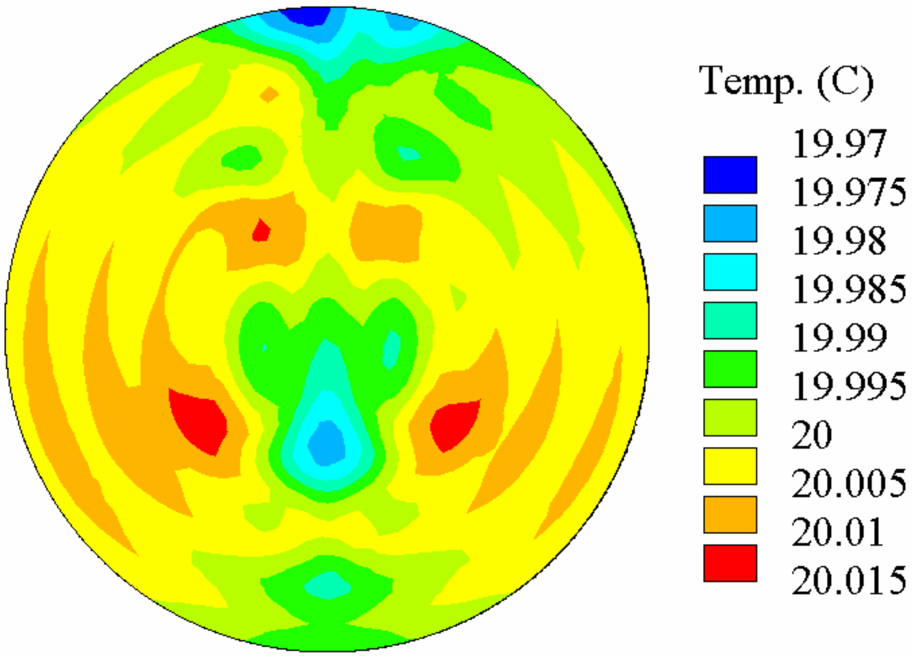
Comparison of Finite Element Solution to Analytical Solution in Meter Plate





Temperature Contours on Surface of Meter Plate (initial heater layout)





Simulation Parameters:

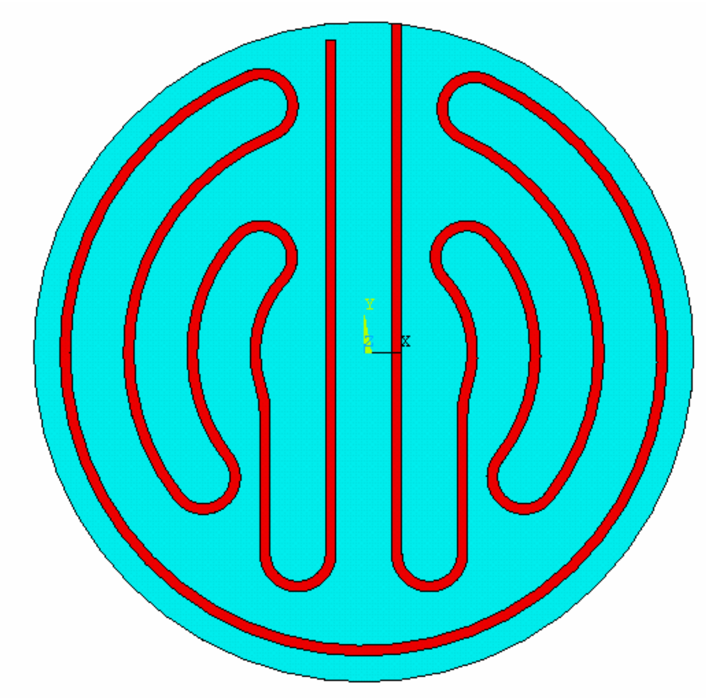
Plate material: **Nickel**

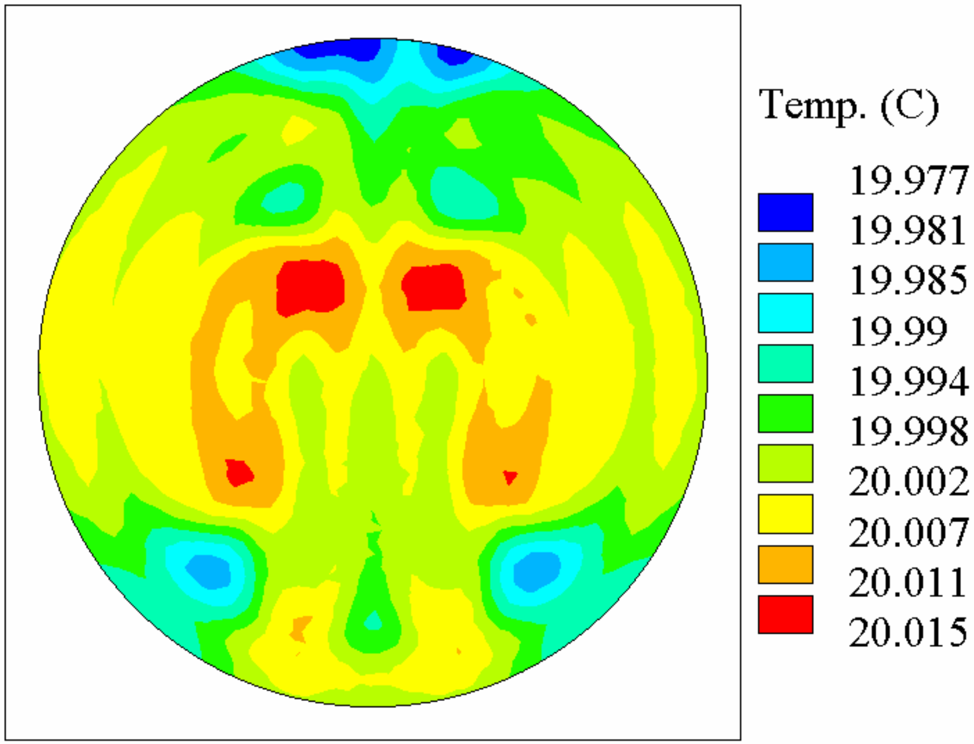
Specimen R-value = **0.125 $m^2 \cdot K/W$**

Cold Plate T = **0 °C**

Heater Power = **5 W**

Temperature Contours on Surface of Meter Plate (modified heater layout)





Simulation Parameters:

Plate material: **Nickel**

Specimen R-value = **0.125 m²·K/W**

Cold Plate T = **0 °C**

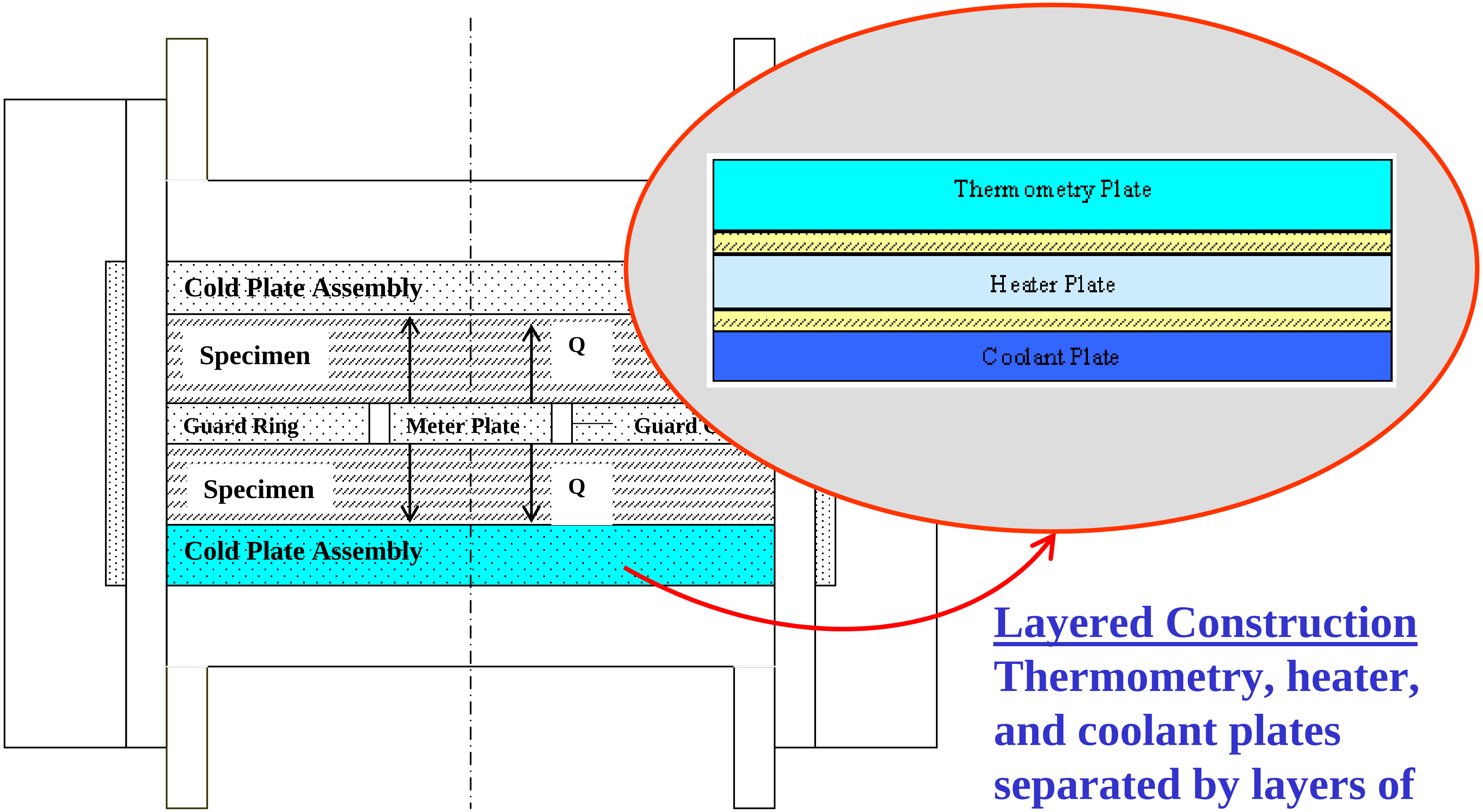
Heater Power = **5 W**

Design Decisions for Meter Plate

Heater layout that:

1) Permits insertion of SPRT
2) Maintains a temperature profile with small variations on surface
3) Provides a temperature field in the region of the SPRT that approximates the average plate temperature

Cold Plate Assembly Modeling

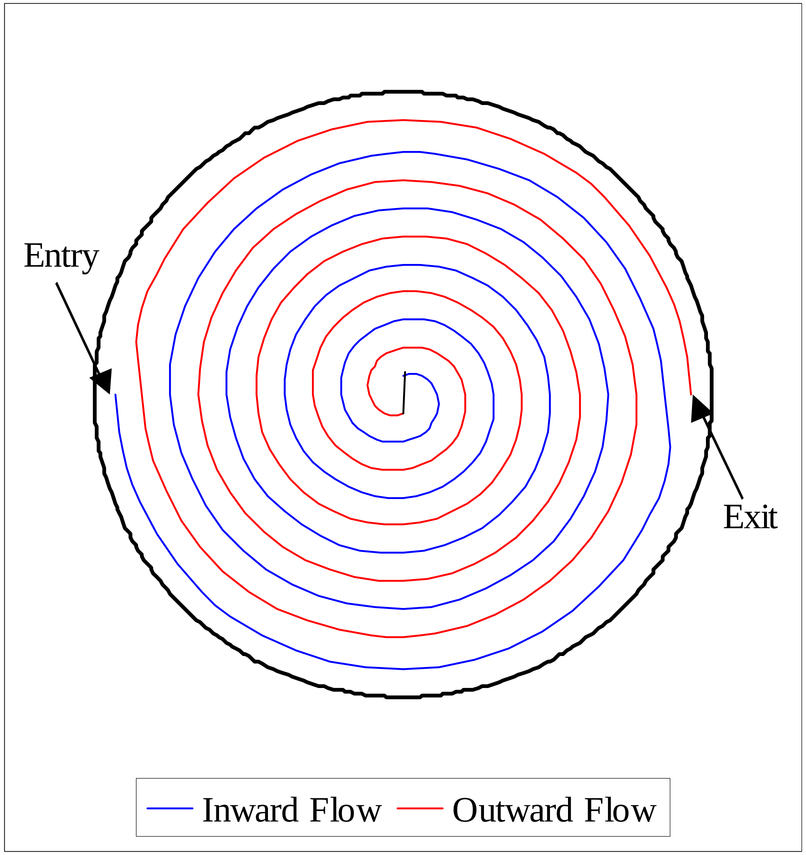


Layered Construction

Thermometry, heater, and coolant plates separated by layers of insulation

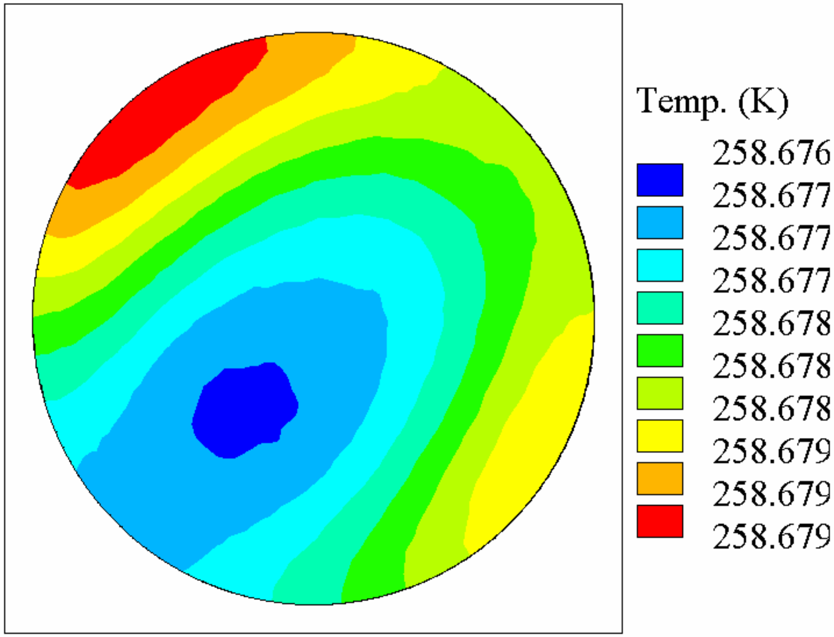
Coolant Plate Modeling

- Design goal: achieve 90 K at surface of thermometry plate
- Goal of analysis: Determine temperature field on surface of thermometry plate resulting from coolant flow in coolant plate
- Operation: Coolant (ethanol or nitrogen) flows in bifilar spiral channels in coolant plate

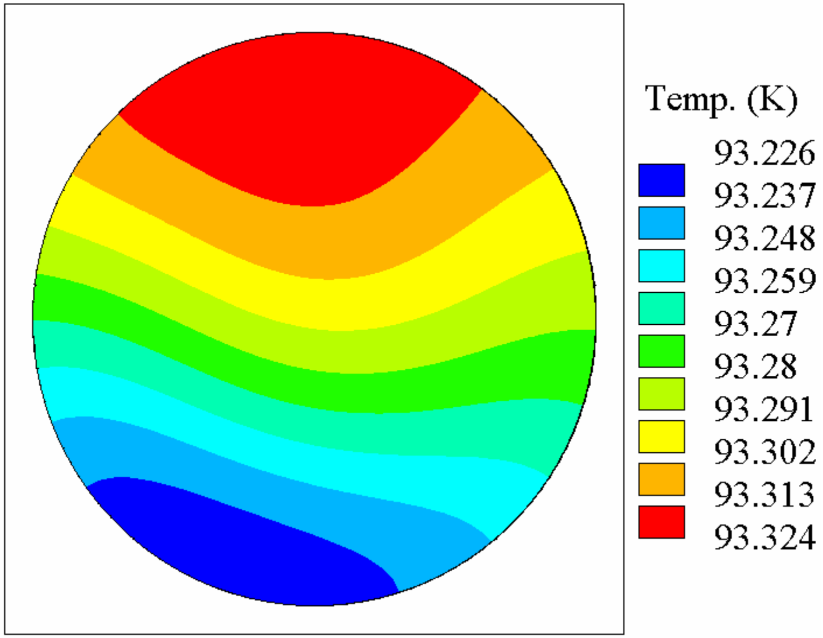


Coolant channel schematic

Temperature Profiles on Surface of Thermometry Plate



Ethanol



Nitrogen Gas

Simulation Parameters:

Plate material: **Nickel**

Specimen R-value = **0.125 m²·K/W**

Ambient T = **297 K**

Hot Plate T = **270 K *or* 100 K**

Auxiliary insulation R-value = **0.7 m²·K/W**

Design Decisions for Cold Plate Assembly

Operating regimes:

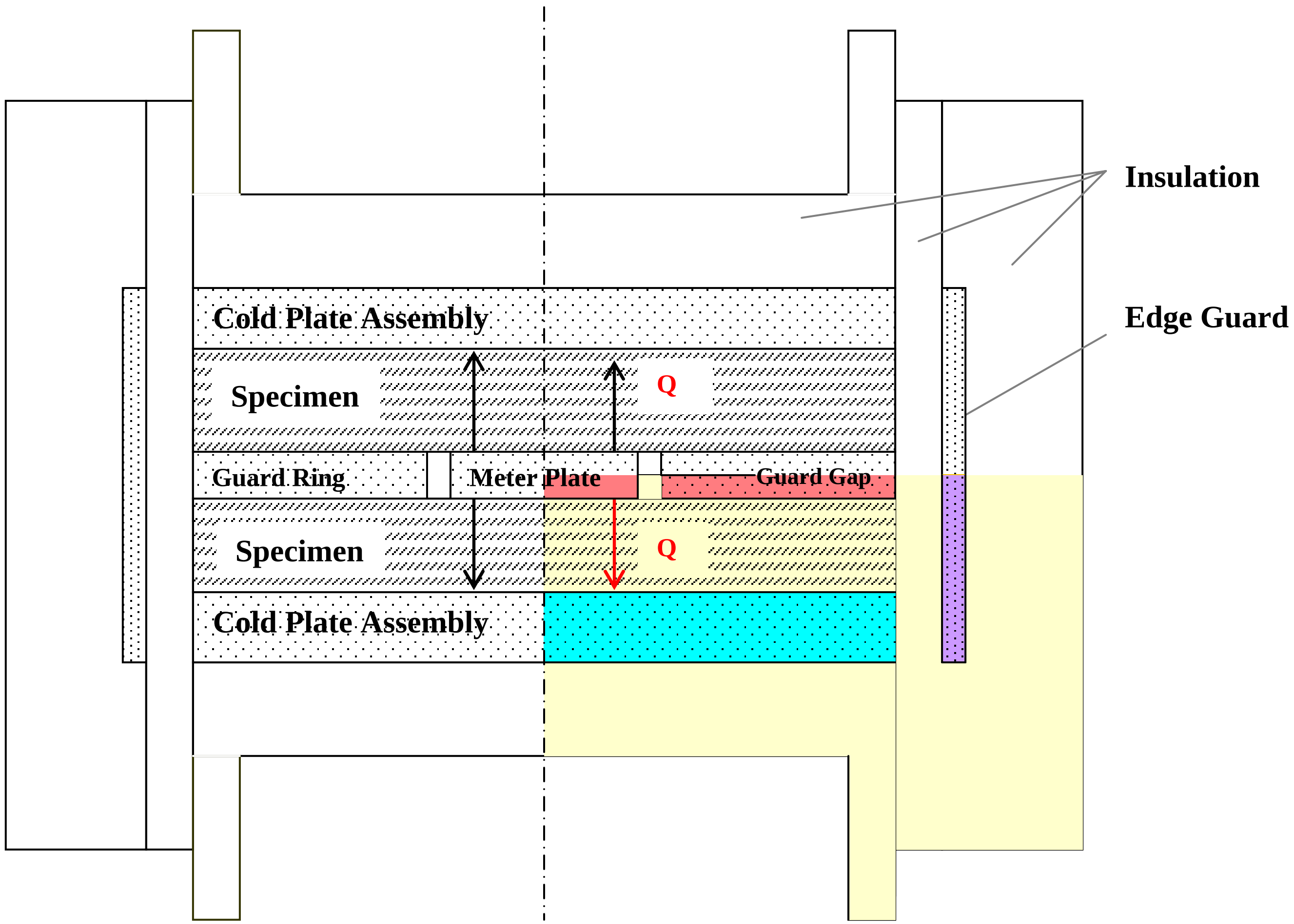
1) From room temperature down to ~210 K:

    Ethanol

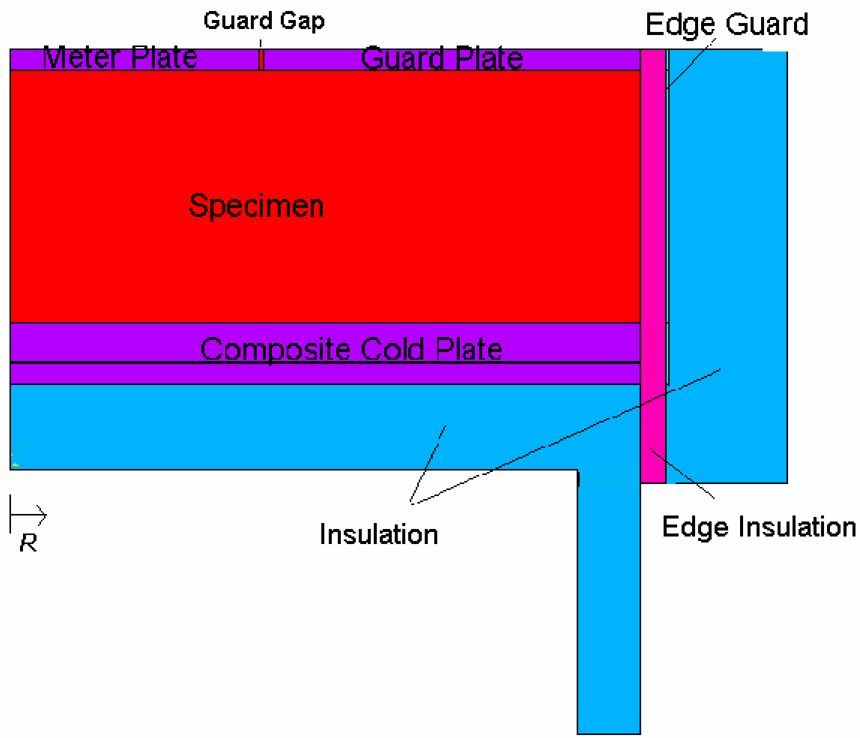
2) From 90 K to ~210 K:

    Liquid Nitrogen + heat

Edge Guard Modeling



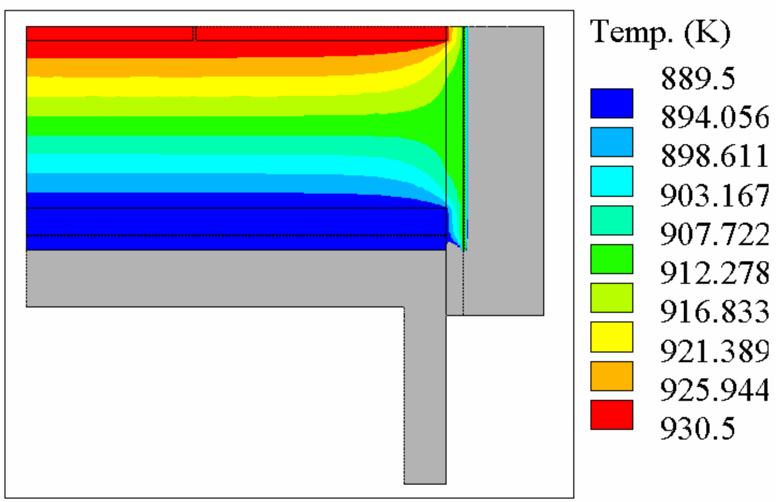
Edge Guard Modeling



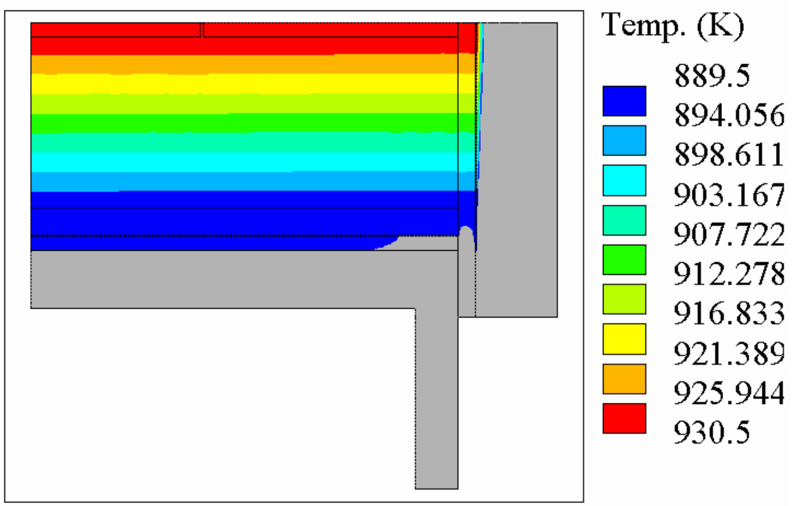
Model used in finite element analysis (to scale)

- Edge guard surrounds specimen to minimize heat transfer to or from environment
- Two design options considered:
  (1) linear temperature
  (2) isothermal
- Goals of analysis: check radial heat flow in specimen, predict errors in λ, examine plate surface temperatures
- 2-D model, axisymmetric, uniform generation in plate areas

Temperature Profile Within Specimen for Both Control Strategies



Isothermal



Linear

Simulation Parameters:

Plate material: **Nickel**

Specimen $\lambda \approx$ **0.13 W/(m · K)**

Specimen thickness = **100 mm**

Hot Plate T = **270 K *or* 100 K**

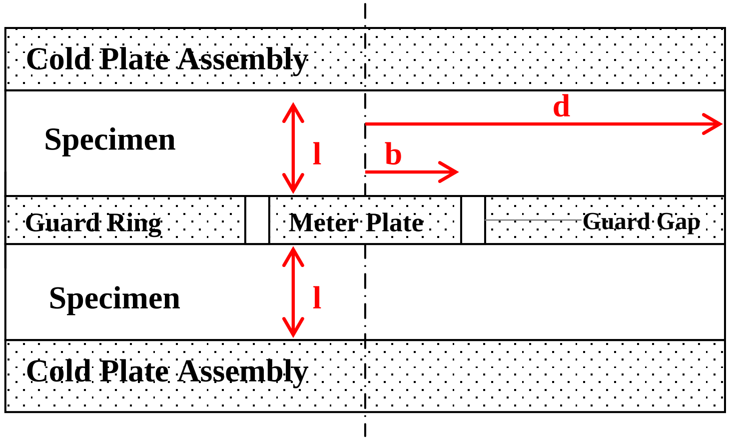
Auxiliary insulation $\lambda \approx$ **0.12 W/(m · K) (@ 600 K)**

Ambient T = **300 K**

Despite visual differences, errors in λ caused by edge effects were less than 0.2 % for both cases.

Design Decisions for Edge Guard

- Both a “linear” and an “isothermal” edge guard provide sufficient guarding for a guarded hot plate apparatus having these aspect ratios

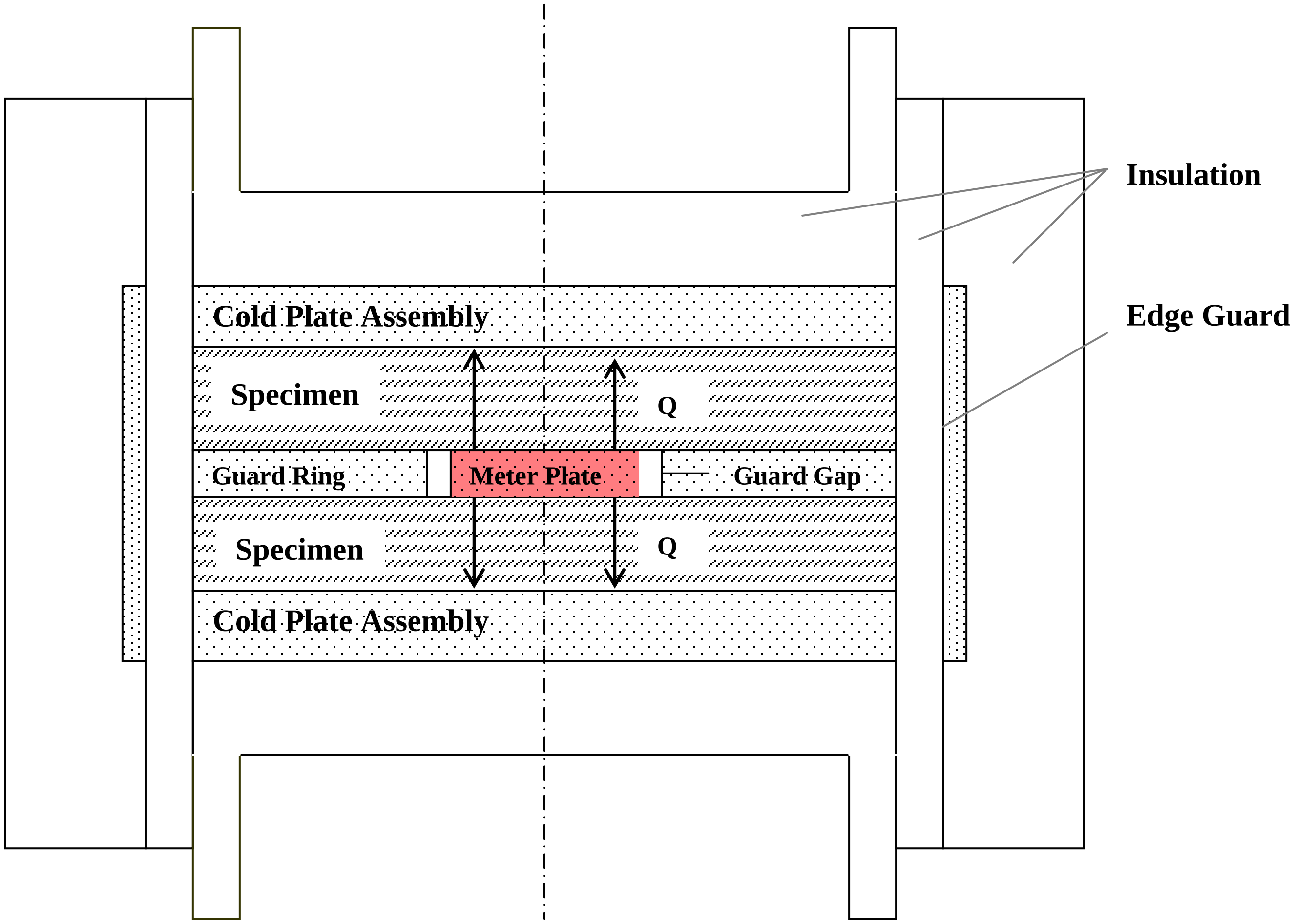


d/b = 2.5

2b/l = 5 *to* 38

- Isothermal design was chosen because of simpler construction

Determining Effects of Temperature Perturbations in Meter Plate



Effects of Temperature Perturbations in Meter Plate

- Heat storage in meter plate leads to error in determination of Q:

$$Q_{heater} = Q + Q_{st} \longrightarrow Q_{st} = lA\rho C_p \frac{dT}{dt}$$

- Goal: Q_{st} less than 0.1 % of Q

Maximum allowable temperature variations in meter plate with specimen ΔT = 10 K

Temperature	Specimen R-value [$m^2 \cdot K/W$]	Plate ($l \cdot \rho \cdot C_p$) [$J/(m^2 \cdot K)$]	$(dT/dt)_{max}$ [K/h]
90 K	4 (in air)	28 300	6.4×10^{-4}
90 K	40 (evacuated)	28 300	6.4×10^{-5}
900 K	2 (in air)	64 900	5.5×10^{-4}

Conclusions

- Analytical solutions and finite element analysis enhanced design process
- Heater and coolant layout should provide a sufficiently uniform surface temperatures
- Guarding should minimize unwanted heat flow into or out of meter section from the environment
- Plate temperature control requires tight tolerances to prevent errors related to heat storage in meter plate