Materials Science Seminar UAH 2012

Thermophysical Property Measurements and their Application to Materials Processing

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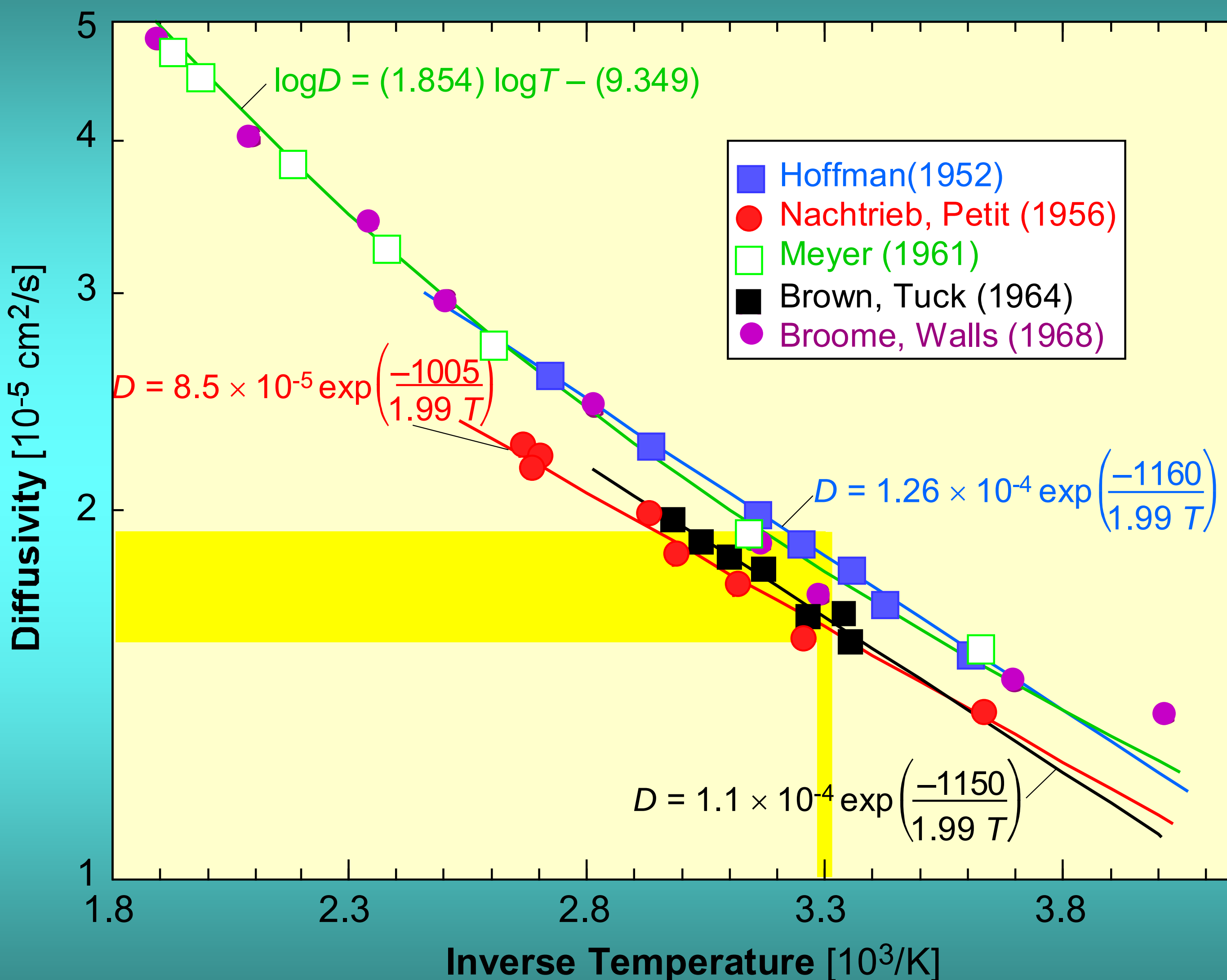
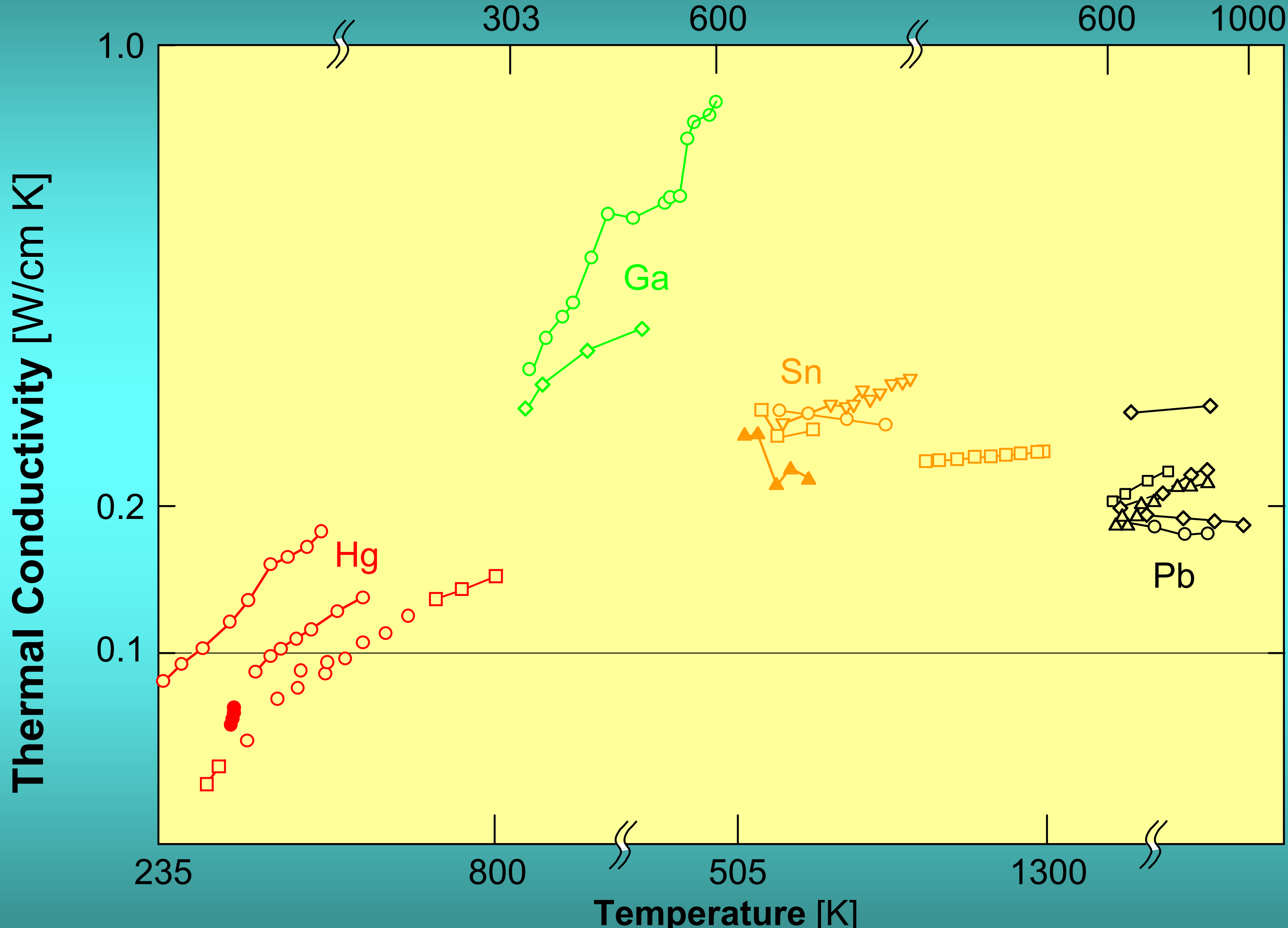
- Introduction
  - Mass Diffusivity: O~10^{-5} [cm^2/sec]
  - Thermal Diffusivity: O~10^{-1} [cm^2/sec]
- Experimental Configurations
  - Mathematical Models
  - long thin cylinder
  - central region heating
  - edge heating with no internal generation
  - edge heating with internal heat generation
- Experimental Results
- Lead free alloys

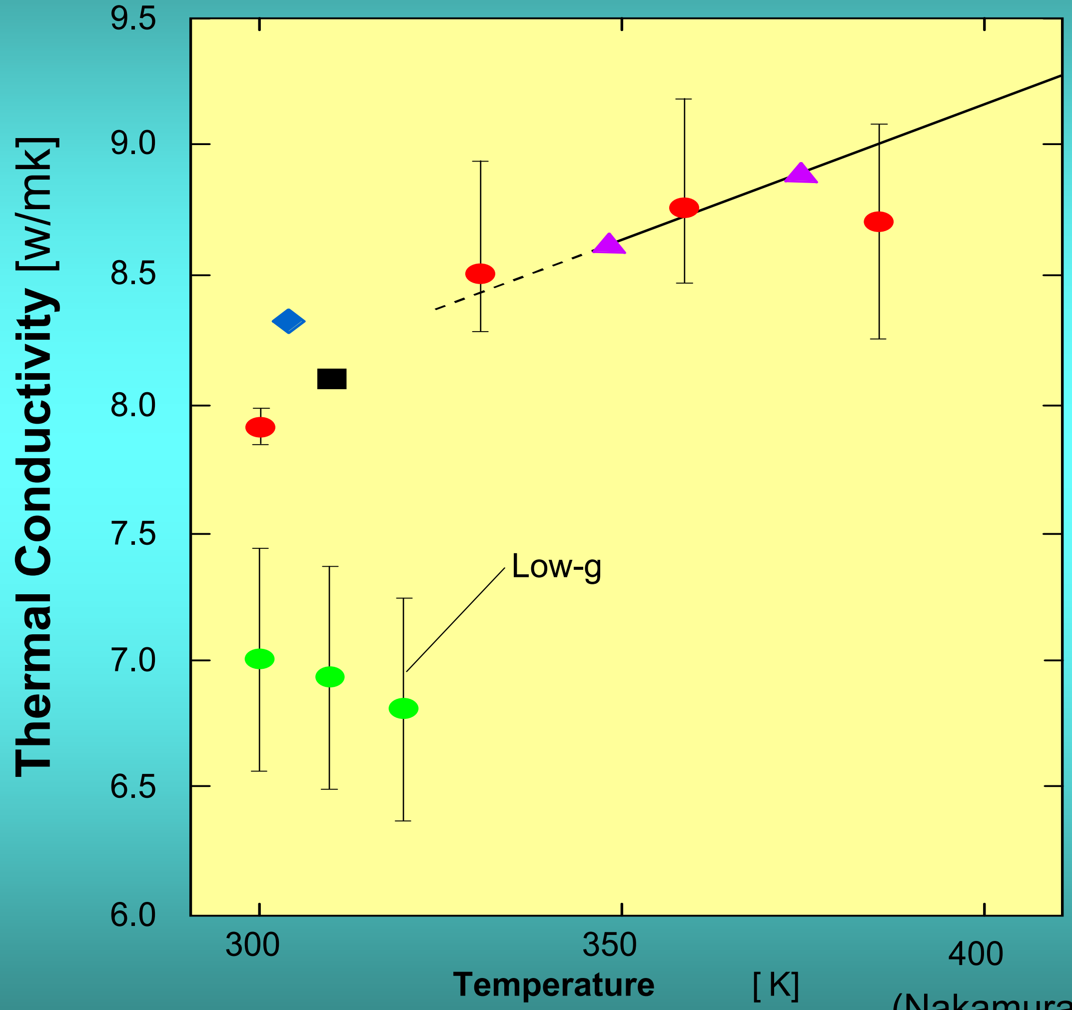
• Self-diffusivity of Mercury – Experimental Data



- **Terrestrial Determinations of Thermal Conductivity**

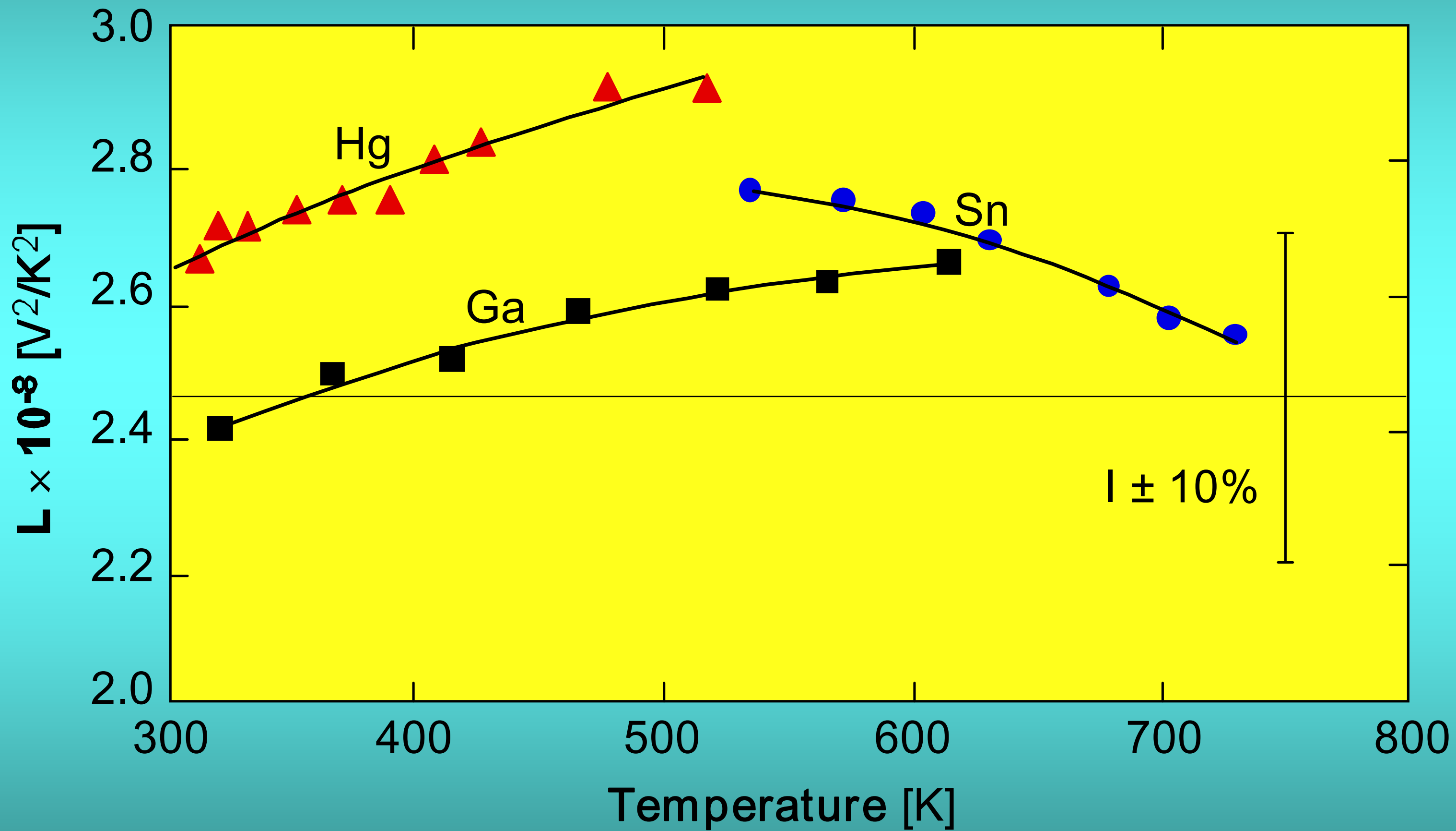


- Thermal Conductivity of Mercury
  - terrestrial and low-gravity



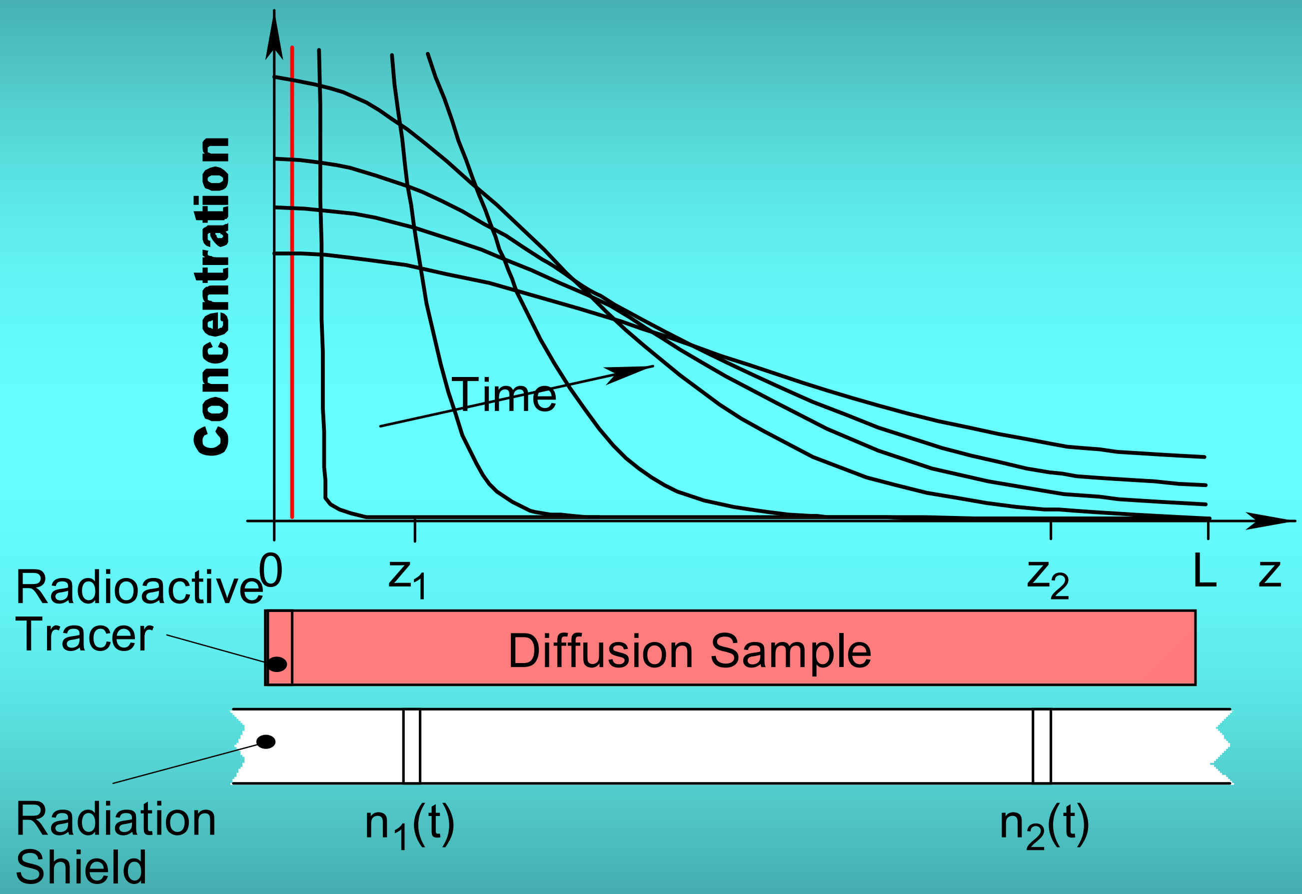
(Nakamura, Hibiya, Yamamoto, and Yokota, 1991)

- Thermal Diffusivity Temperature Dependence
  - Wiedemann Franz Relation

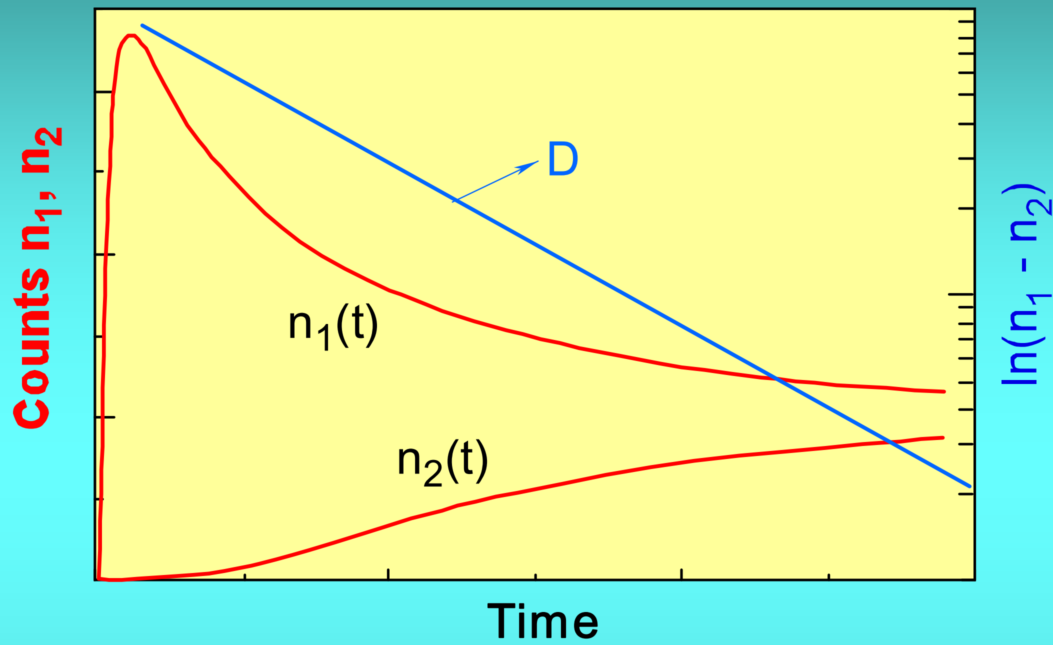


Wakeham and Hix

- Measurement Methodologies
  - Mass Diffusivity – long, thin cylinder



- Measurement Methodologies con't
    - long, thin cylinder con't

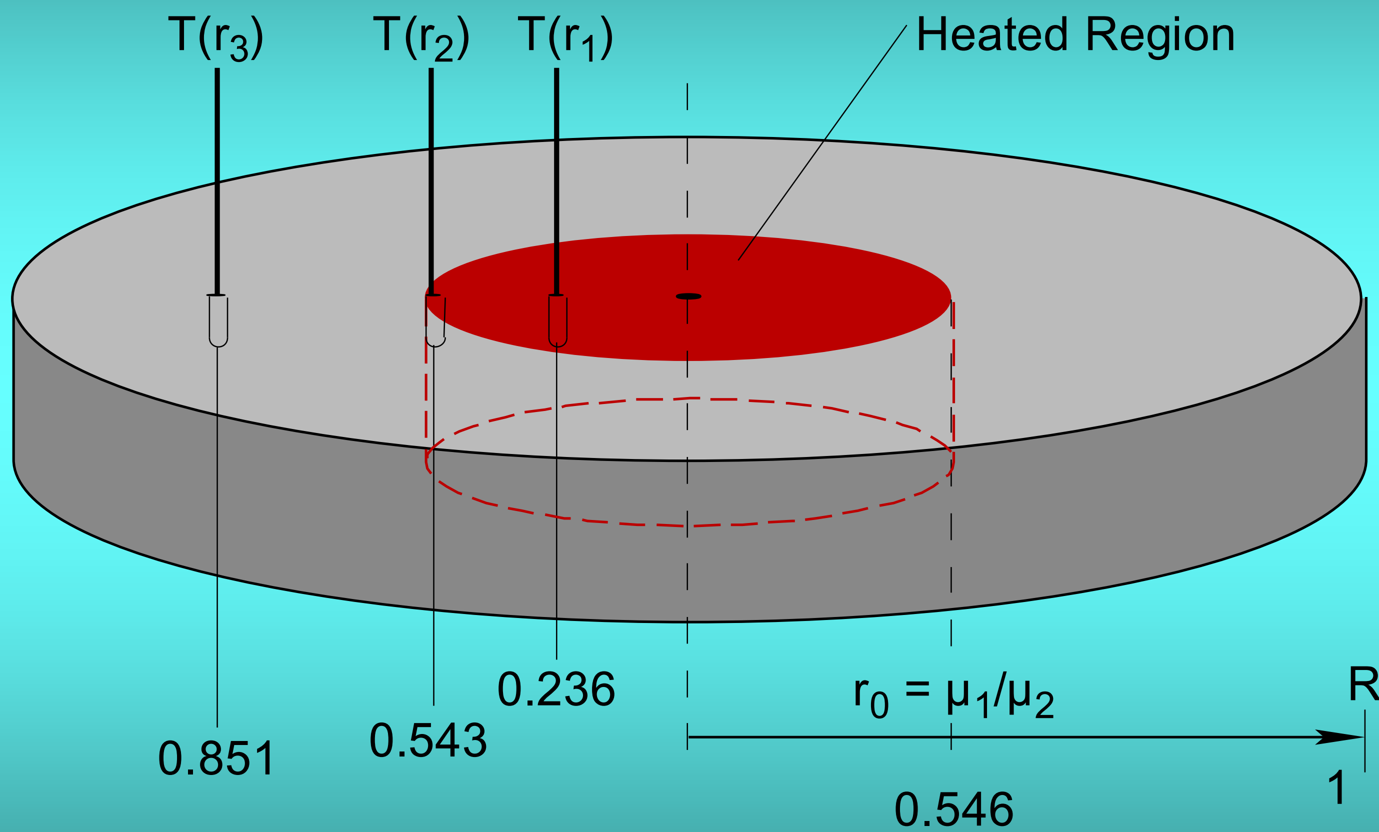


Z_1 = L/6 and Z_2 = 5L/6

$$\ln[n_1(t) - n_2(t)] = \text{const} - (\pi/L)^2 D t$$

Codastefano, Russo and Zanza, *Rev. Sci. Instr.* **48** (1977) 1650

- Measurement Methodologies
  - Disk with central region heating



- Measurement Methodologies
  - Disk with central region heating

$$\frac{r_1}{a} = 0.2364$$

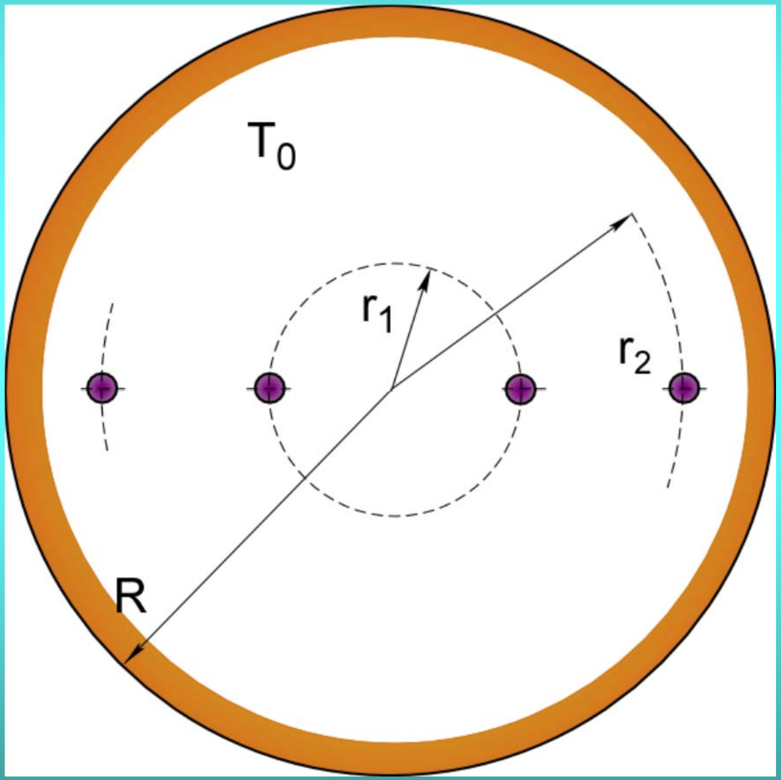
$$\frac{r_2}{a} = 0.5426 \quad \rightarrow \quad \ln(\Delta T_{ij}) = \ln(\beta_{ij}) - \left(\frac{\kappa \mu_1^2}{a^2}\right) t$$

$$\frac{r_3}{a} = 0.8506$$

- fine grained graphite
- boron nitride
  - sensitivity analysis

Thermal Diffusivity Measurement Methodology
Cylindrical Sample with Edge Heating

- Initial Conditions
  - cylinder at initial T_0
  - constant heat flux Q"
  - flux applied $0 < t < t_e$



- Transient form of Heat Equation

$$\frac{1}{r}\frac{\partial T}{\partial r}+\frac{\partial^2 T}{\partial r^2}=\frac{1}{\kappa}\frac{\partial T}{\partial t} \quad .$$

- Boundary condition

  $T(r,0) = T_0$ at $r = R$

$$-k\frac{\partial \mathrm{T}}{\partial \mathrm{r}}=Q^{"}\left[1-h\left(t-t_e\right)\right]$$

Mathematical Model – edge heating con't

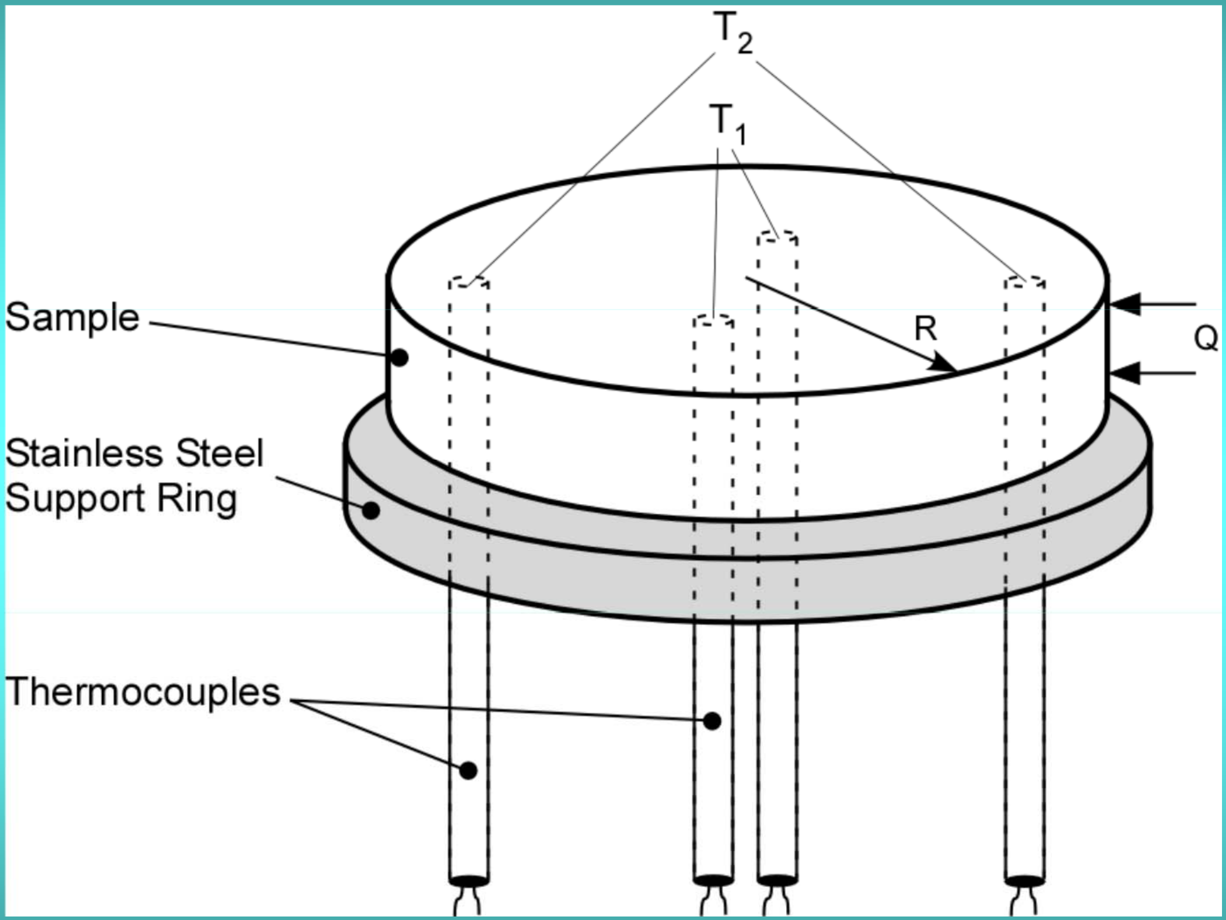
$$\Delta T_{ij} = e^{-\frac{\kappa\alpha_1^2 t}{R^2}} \times \frac{2Q''R}{k}\left(1-e^{\frac{\kappa\alpha_1^2 t_e}{R^2}}\right)\frac{J_0\left(\frac{r_i\alpha_1}{R}\right)-J_0\left(\frac{r_j\alpha_1}{R}\right)}{\alpha_1^2 J_0(\alpha_1)}$$

$$\ln\left(\Delta T_{ij}\right) = -\frac{\kappa\alpha_1^2}{R^2}t + \ln\left(\beta_{ij}\right)$$

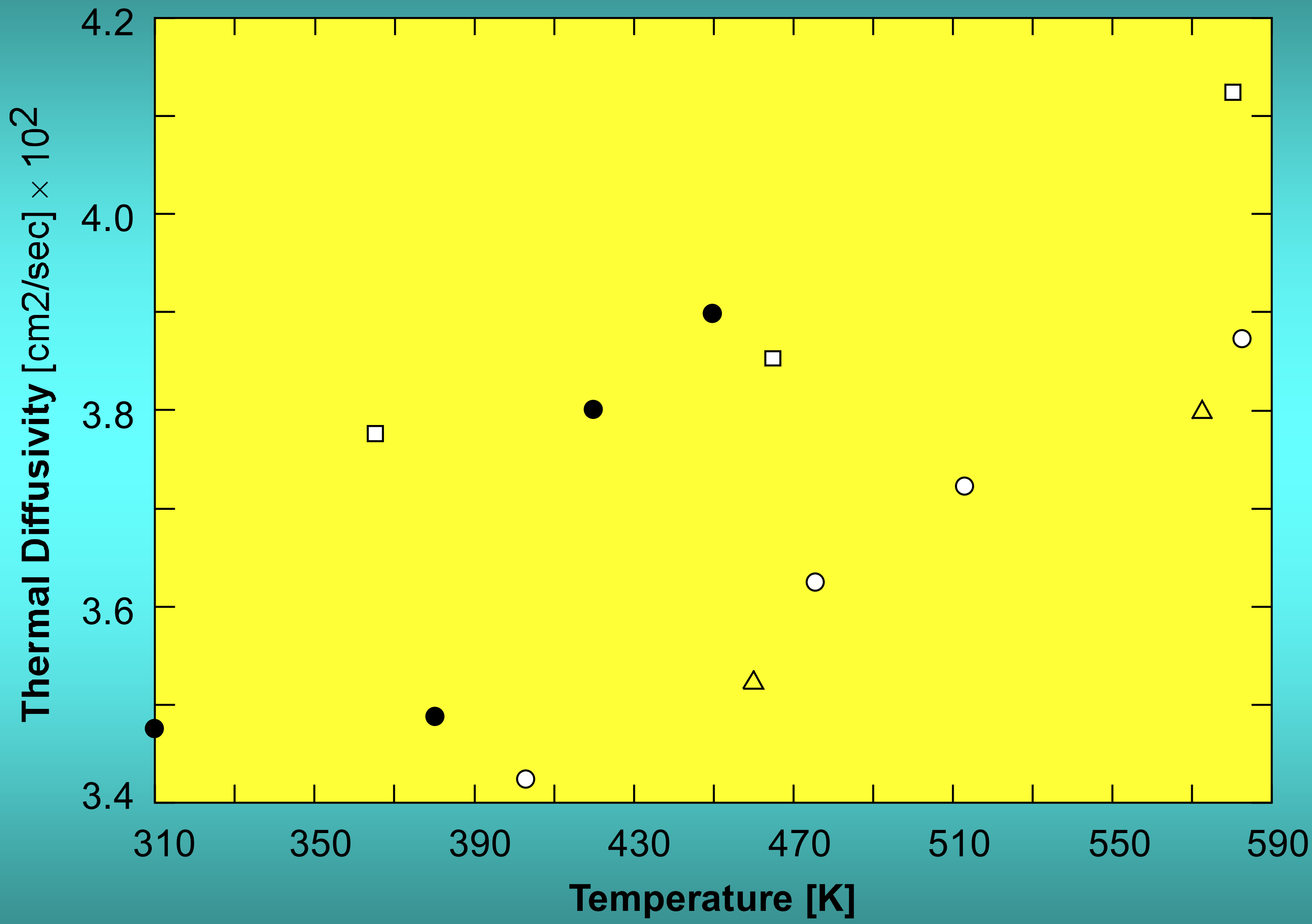
$$\beta_{ij} = \frac{2Q''R}{k}\left(1-e^{\frac{\kappa\alpha_1^2 t_e}{R^2}}\right)\frac{J_0\left(\frac{r_i\alpha_1}{R}\right)-J_0\left(\frac{r_j\alpha_1}{R}\right)}{\alpha_1^2 J_0(\alpha_1)}$$

Note: ln(ΔT) could be nondimensionalized by dividing by 2Q"R/k

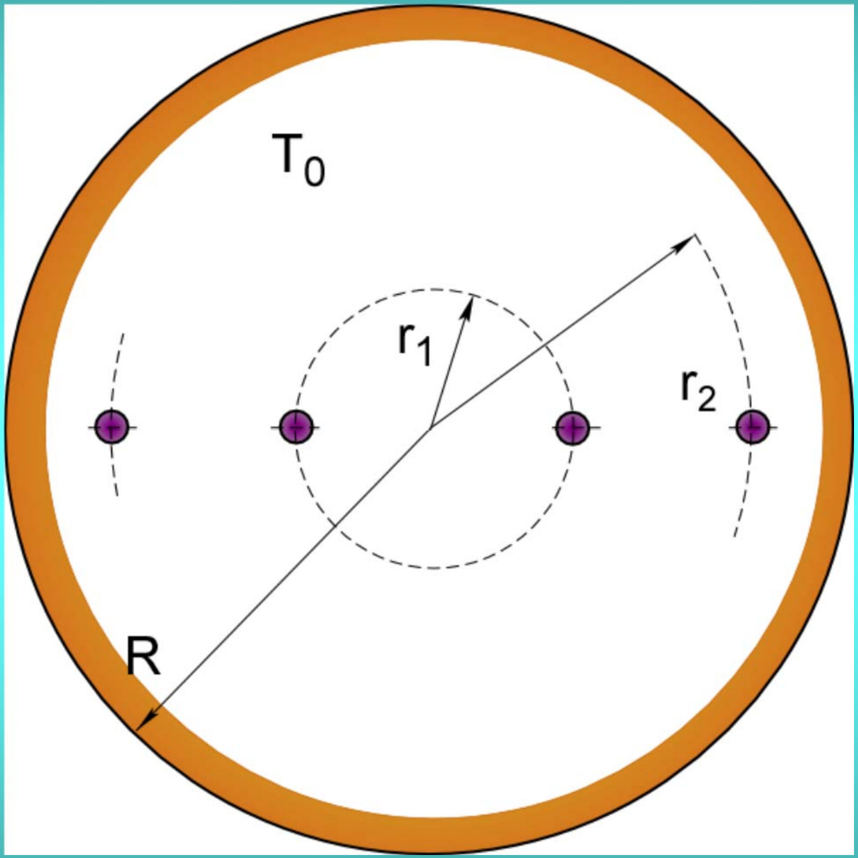
- Experimental Setup



• Experimental Results – 303 Stainless Steel



- Thermal Diffusivity Determinations with Internal Heat Generation
  - Cement Pastes (I-V)



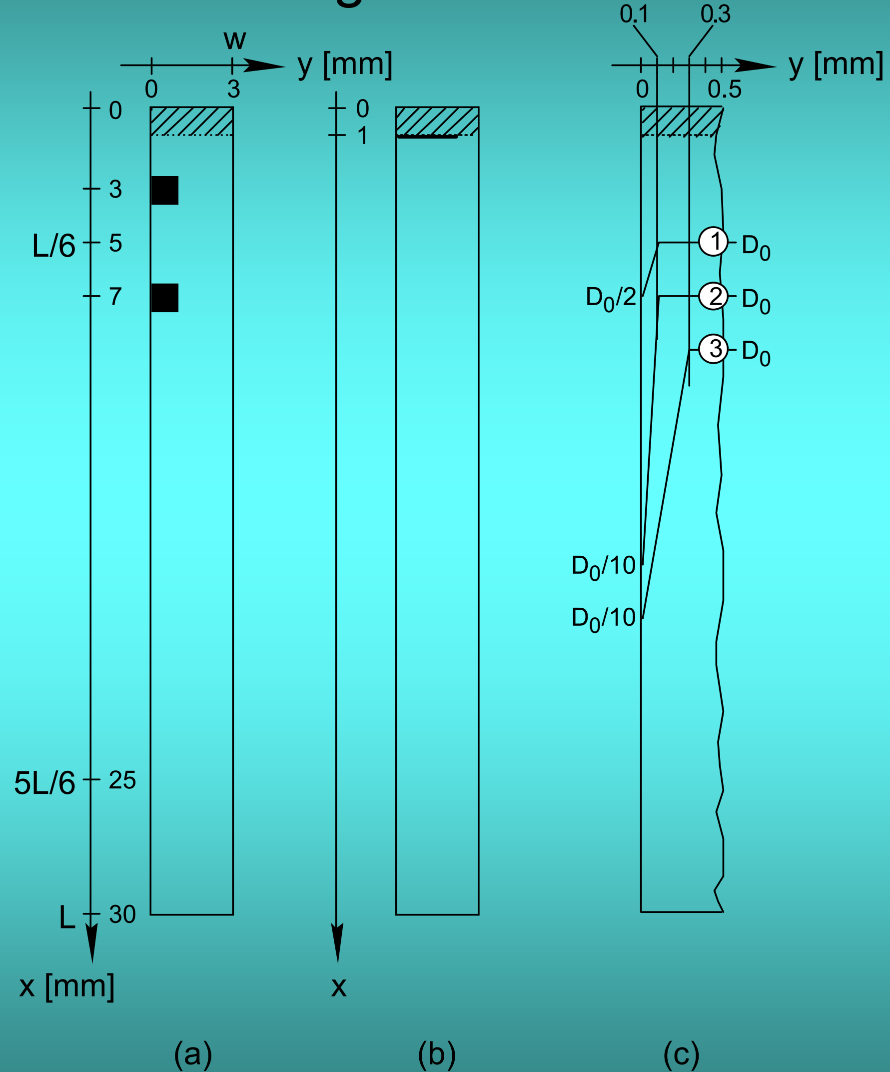
Mathematical Model – edge heating – internal heat generation con't

- Similar simplifications and linearization as before

$$T_i - T_j = \frac{R^2 \Delta T}{\kappa t_e} \left\{ \begin{aligned} & e^{-\frac{\kappa \alpha_1^2 t}{R^2}} \left(\mathrm{e}^{-\frac{\kappa \alpha_1^2 t}{R^2}} - 1 \right) \frac{J_0\left(\frac{r_i}{R}\alpha_1\right) - J_0\left(\frac{r_j}{R}\alpha_1\right)}{\alpha_1^2 J_0(\alpha_1)} \\ & + \phi \frac{\left(\frac{r_i}{R}\right)^2 - \left(\frac{r_j}{R}\right)^2}{4} + \frac{2}{R^3} e^{-\kappa \beta_1^2 t} e^{-\kappa \beta_1^2 t_e} \left(\frac{J_0(r_i \beta_i) - J_0(r_j \beta_j)}{\beta_1^3 J_1(R\beta_1)} \right) \end{aligned} \right\}$$

$$T_i - T_j = C_1 \left[C_2 e^{-\frac{\kappa \alpha_1^2 t}{R^2}} + \left(C_3 + C_4 e^{-\kappa \beta_1^2 t} \right) \right]$$

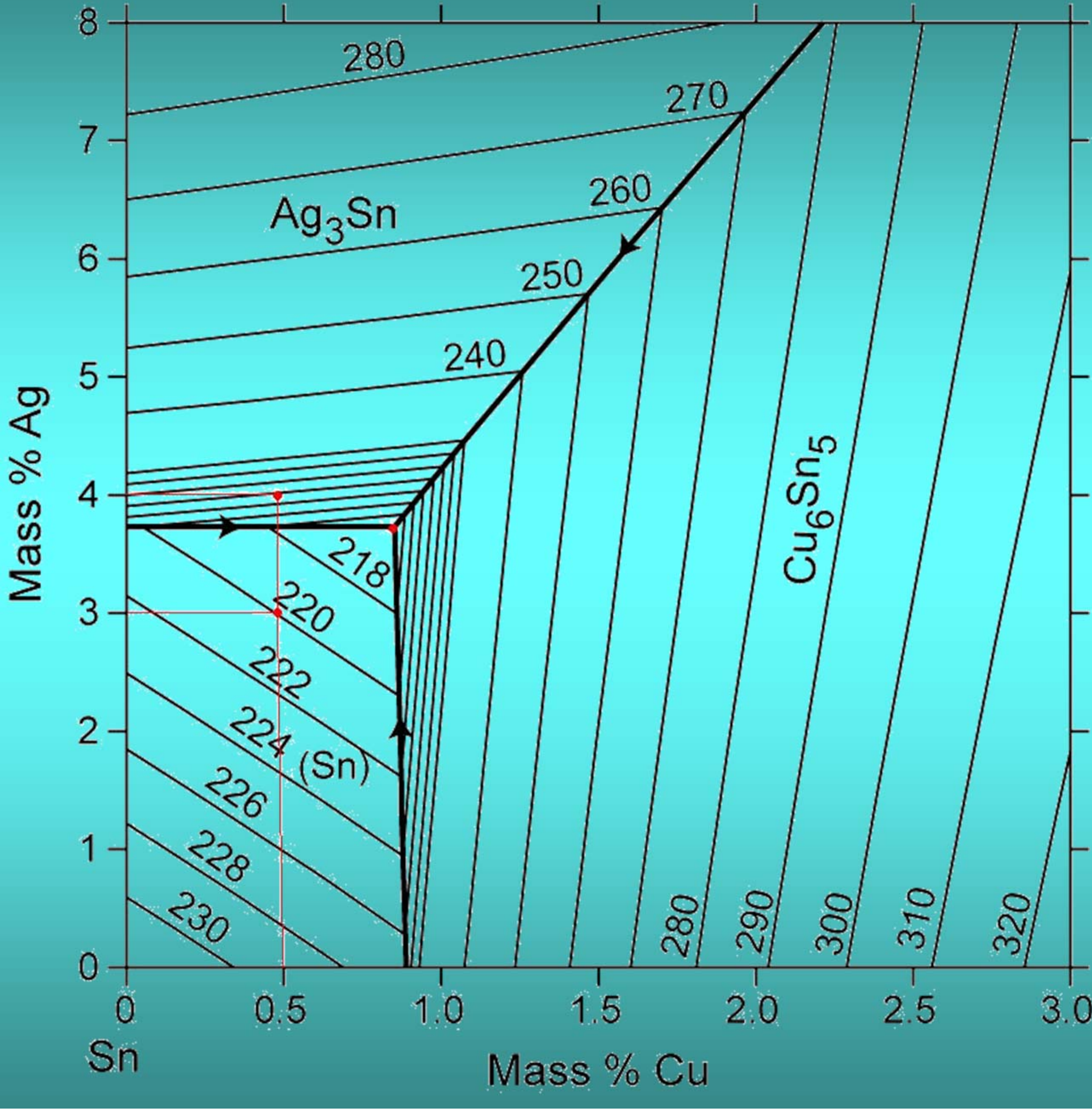
- Insensitivity to Deviations from 1D transport
  - numerical modeling



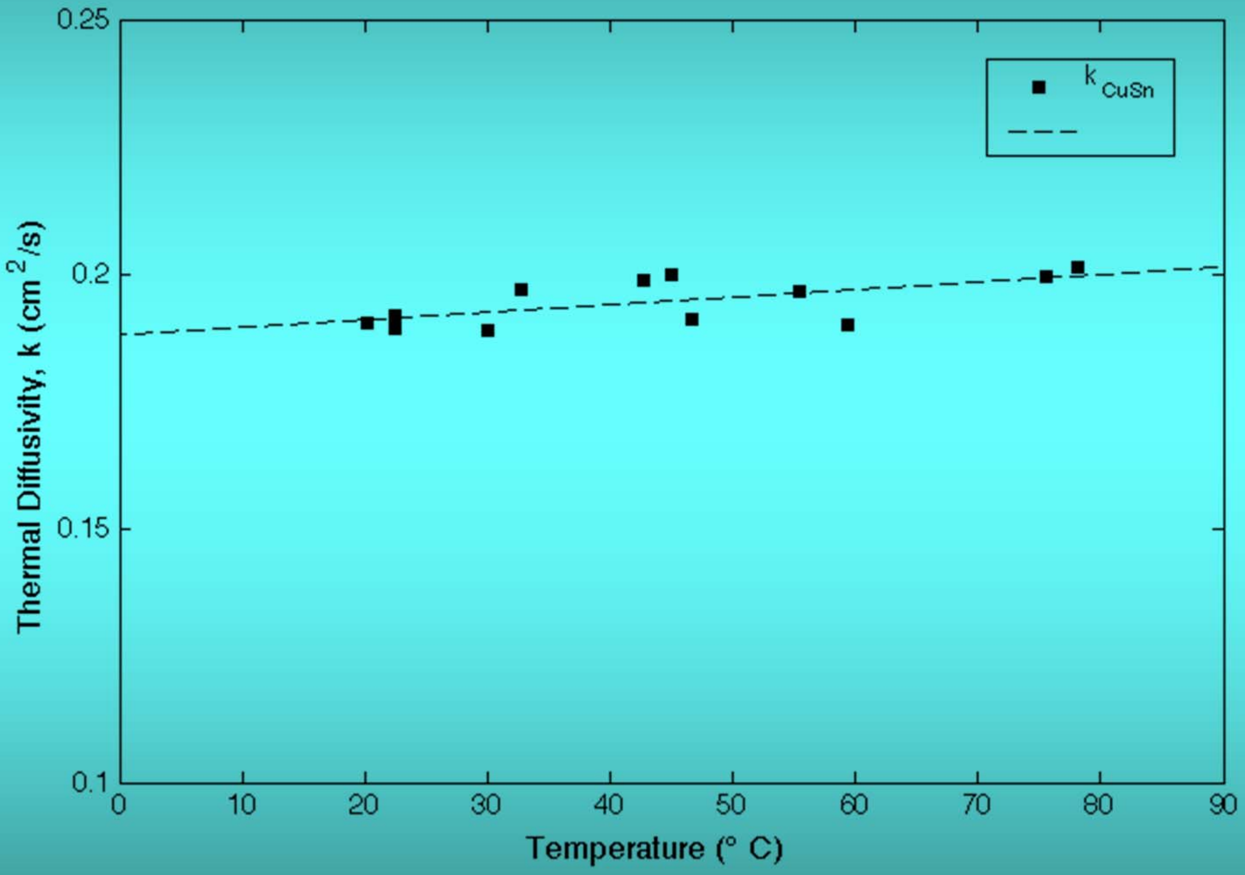
● Summary

→ Methodology is insensitivity to a wide range of perturbations and initial conditions restrictions that are necessary for other measurement methodologies.

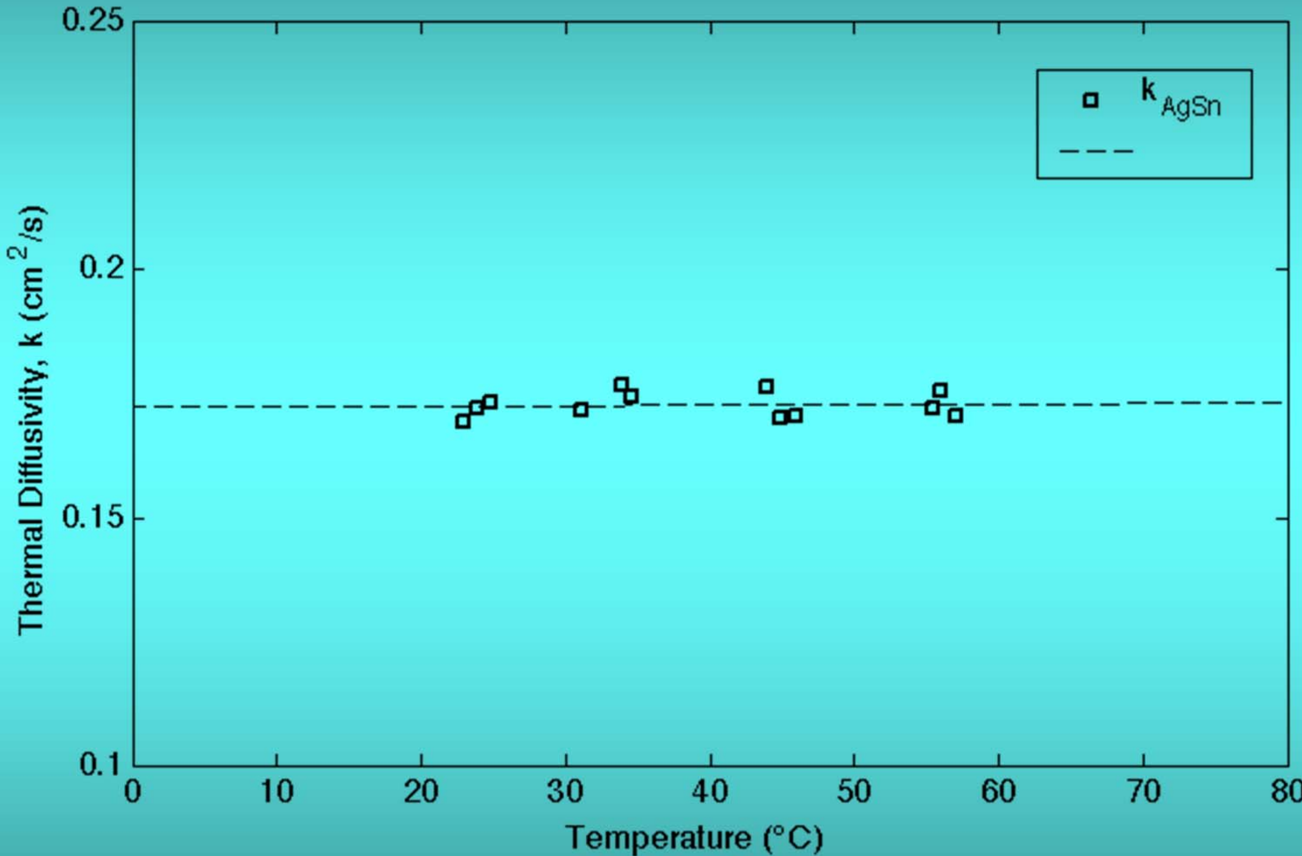
- Thermal Diffusivity Determinations in Lead-free solders



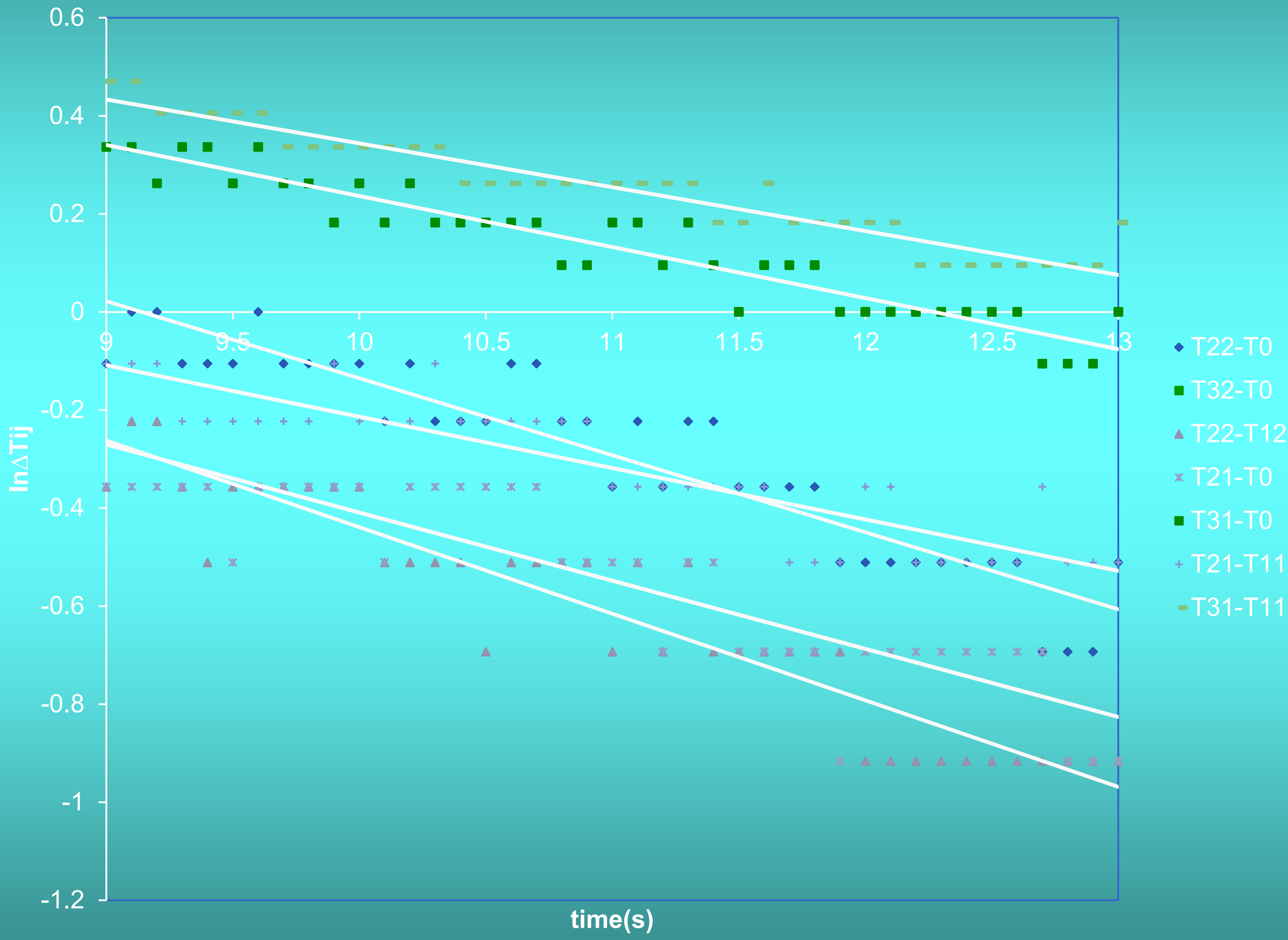
- Thermal Diffusivity – Lead-free alloys
  - Cu_6Sn_5



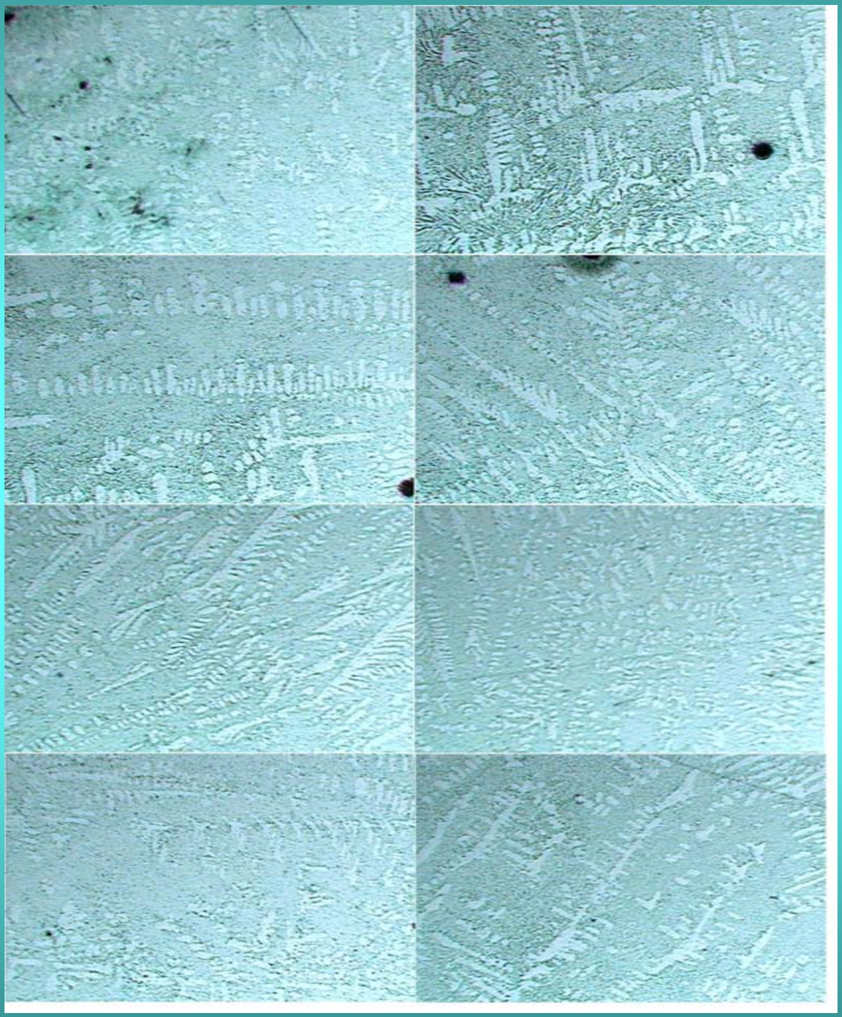
- Thermal Diffusivity – Lead-free alloys
  - Ag_3Sn



● Thermal Diffusivity – Lead-free alloys
- SAC387



- Thermal Diffusivity – Lead-free alloys
  - SAC387



● Thermal Diffusivity – Lead-free alloys

- Numerical Modeling
- Aspect ratio and orientation of second phases
- Lattice mismatch between host lattice and the second phases.

→ Numerical modeling results showed that the driving parameter was the lattice mismatch, and resulting thermal diffusivity mismatch, between the host lattice and the second phases.

● Effect of gold addition on the MP of three SAC alloys.

● Distribution of gold in solidified SAC alloys - Nextek.

Current Research Interest - Funding

- STTR awarded - Contract Negotiations

- Start of consulting agreement with outside company – thermophysical property measurements high temperature melts – pushing to go through UAH and hire a MS student.

- NASA continues to talk about needing diffusion measurements – both for theoretical model development and current Material Science Experiment support.

- Proposal on Mechanical Behavior of Lead Free Alloys

Thank you for your attention!

- Diffusion in Liquids

"If the reader has by now concluded that little is known about the prediction of dense gas and liquid diffusivities, he is correct. There is an urgent need for experimental measurements, both for their own value and for development of future theories."

Bird, Stewart and Lightfoot
Transport Phenomena, p. 515

"Equation [72] will predict the self-diffusion coefficient of several liquid metals to better than an order of magnitude, though good agreement is not obtained."

Edwards, Hucke and Martin
Diffusion in Binary Liquid Metal Systems
Metallurgical Reviews (1968)

- Estimation of Convective Contamination due to Temperature Nonuniformities

$$\overline{W} = \frac{\beta R^3 |\nabla T| L_T g}{15 \pi \upsilon H}$$

Water: $\nu = 0.008\ cm^2/sec$, $\beta = 0.004\ K^{-1}$

$\nabla T = 1K/cm$, $LT = r_3 - r_1$, terrestrial gravity

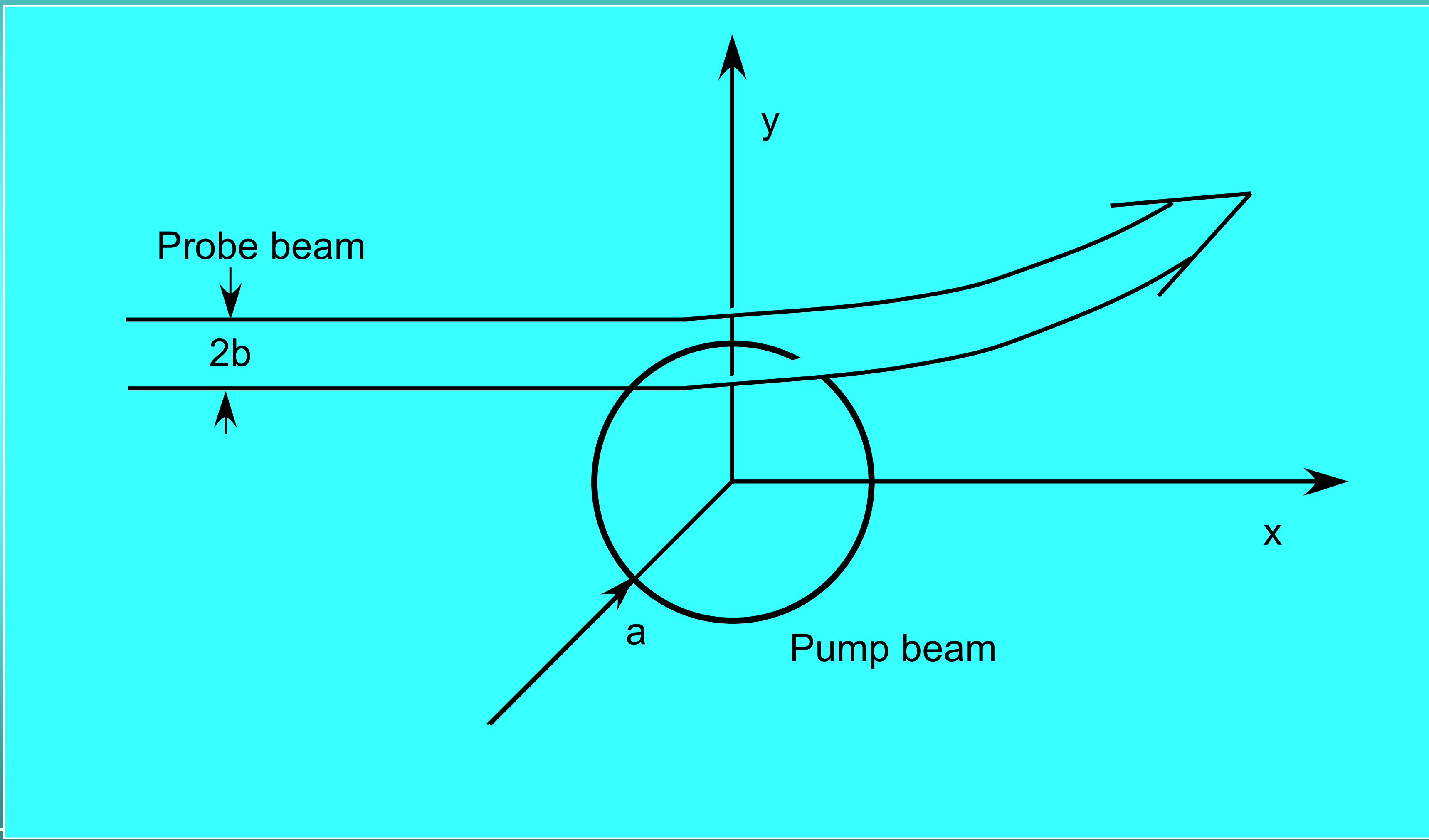
Convective Velocities [cm/sec]

Height/Radius [cm]	2	5
0.4	26	1020
0.6	17	830
0.9	12	450

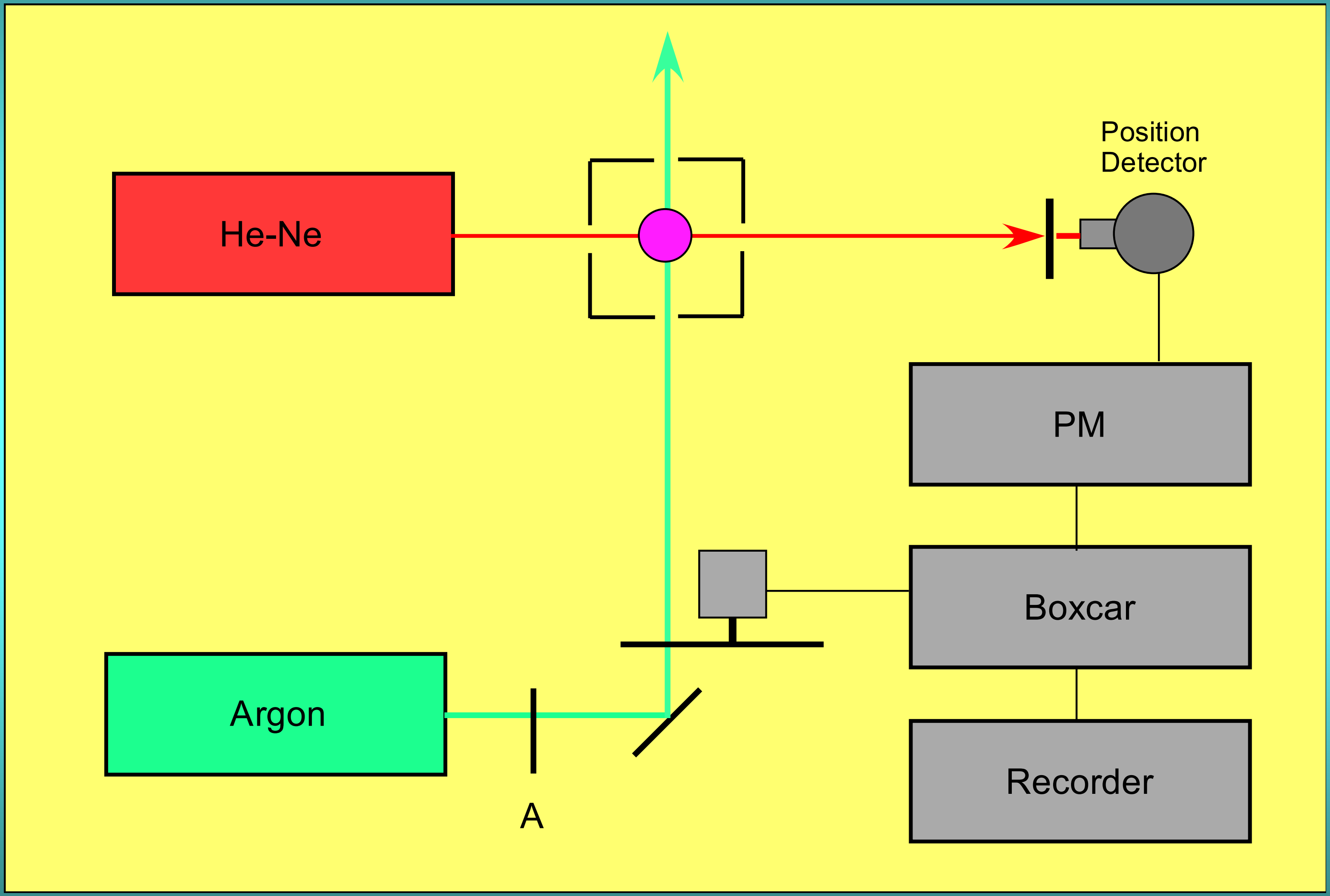
Garandet, et al, Phys Fluids 9 (1997) 510.

- Effect of (Thermal) Diffusivity where you don't expect it

→ Vapor Concentration Measurement in a Crystal Growth Ampoule

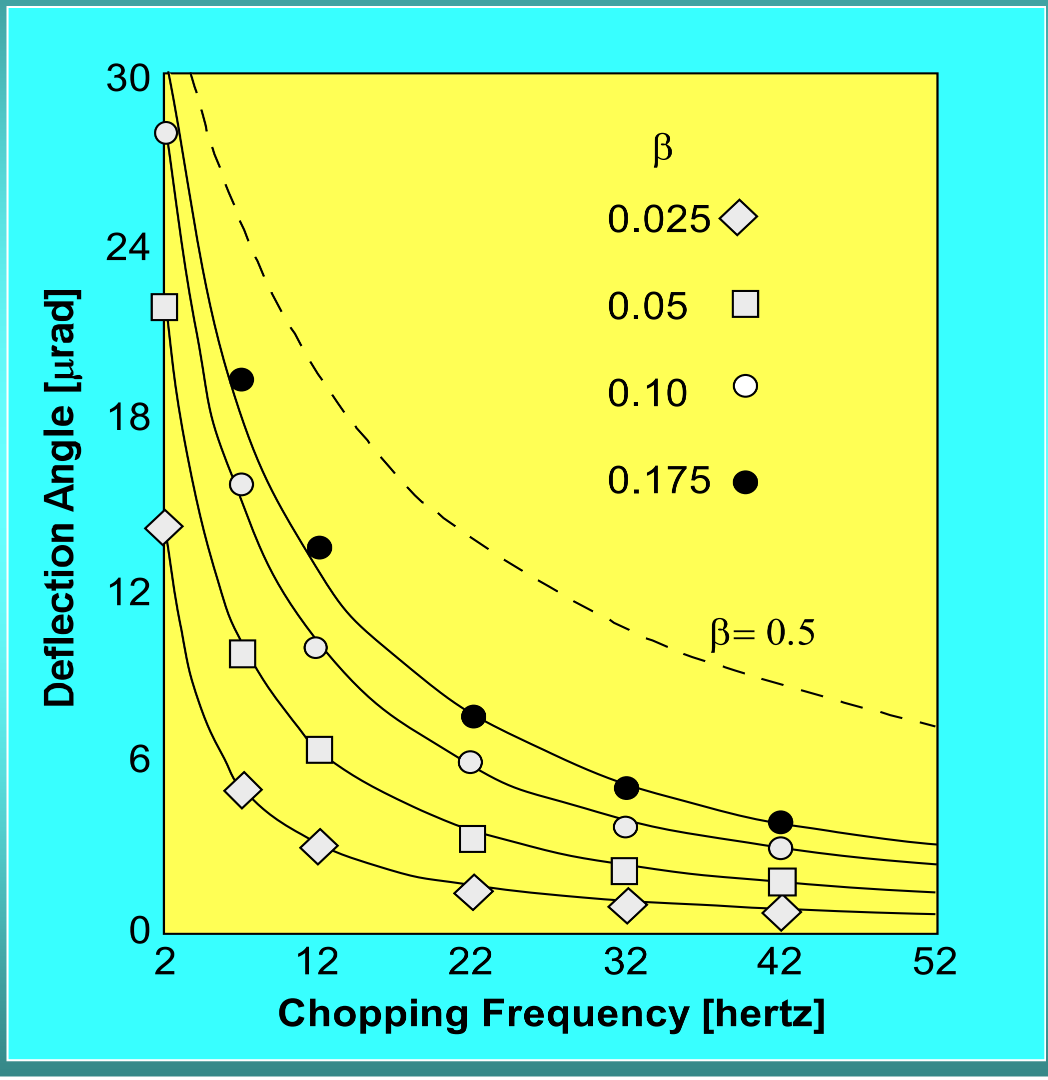


- Schematic Experimental Setup



• Experimental Results

Thermal Diffusivity (of nitrogen) was the “adjustable” parameter



- Mass Diffusivity Experiments –low gravity

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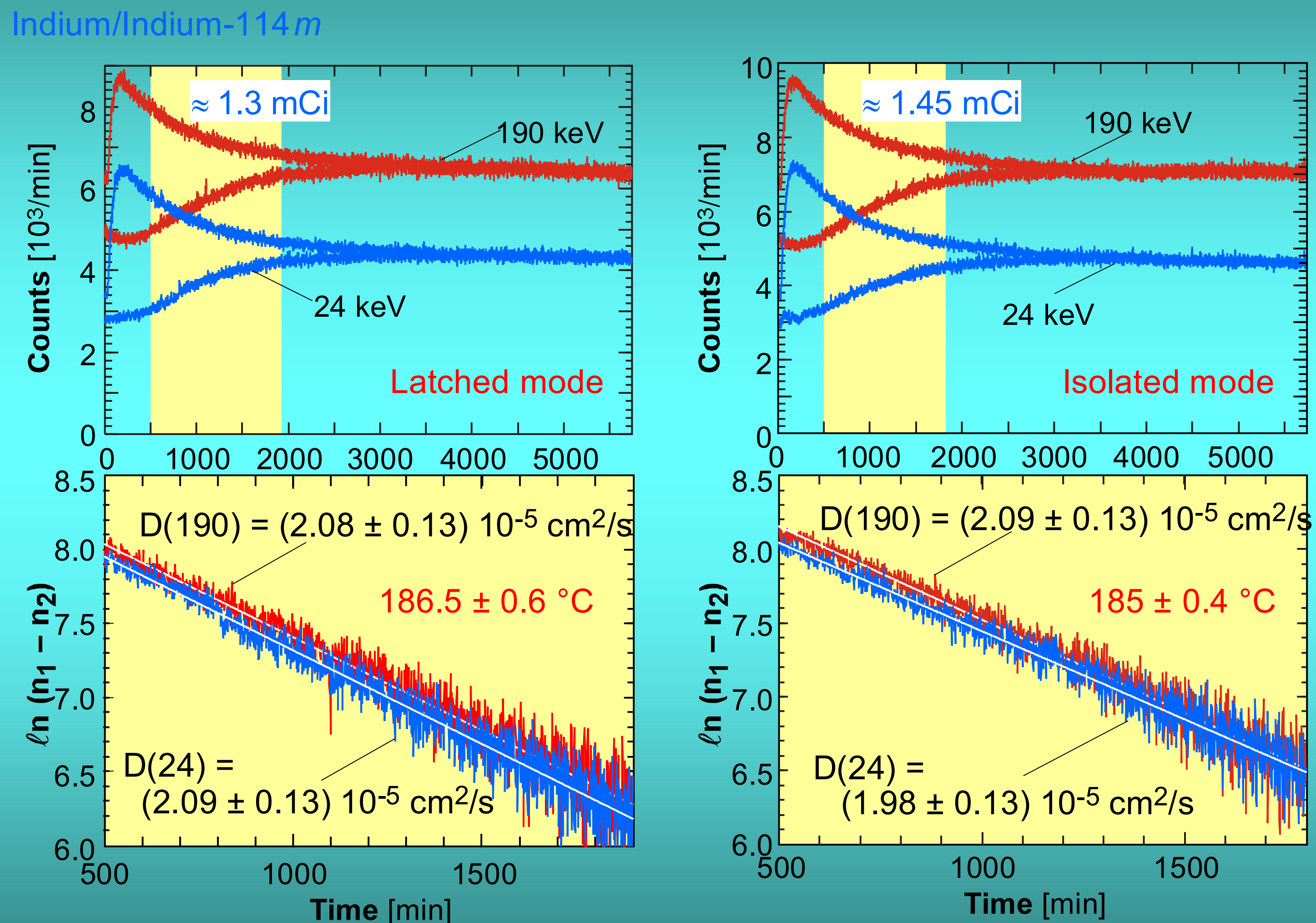
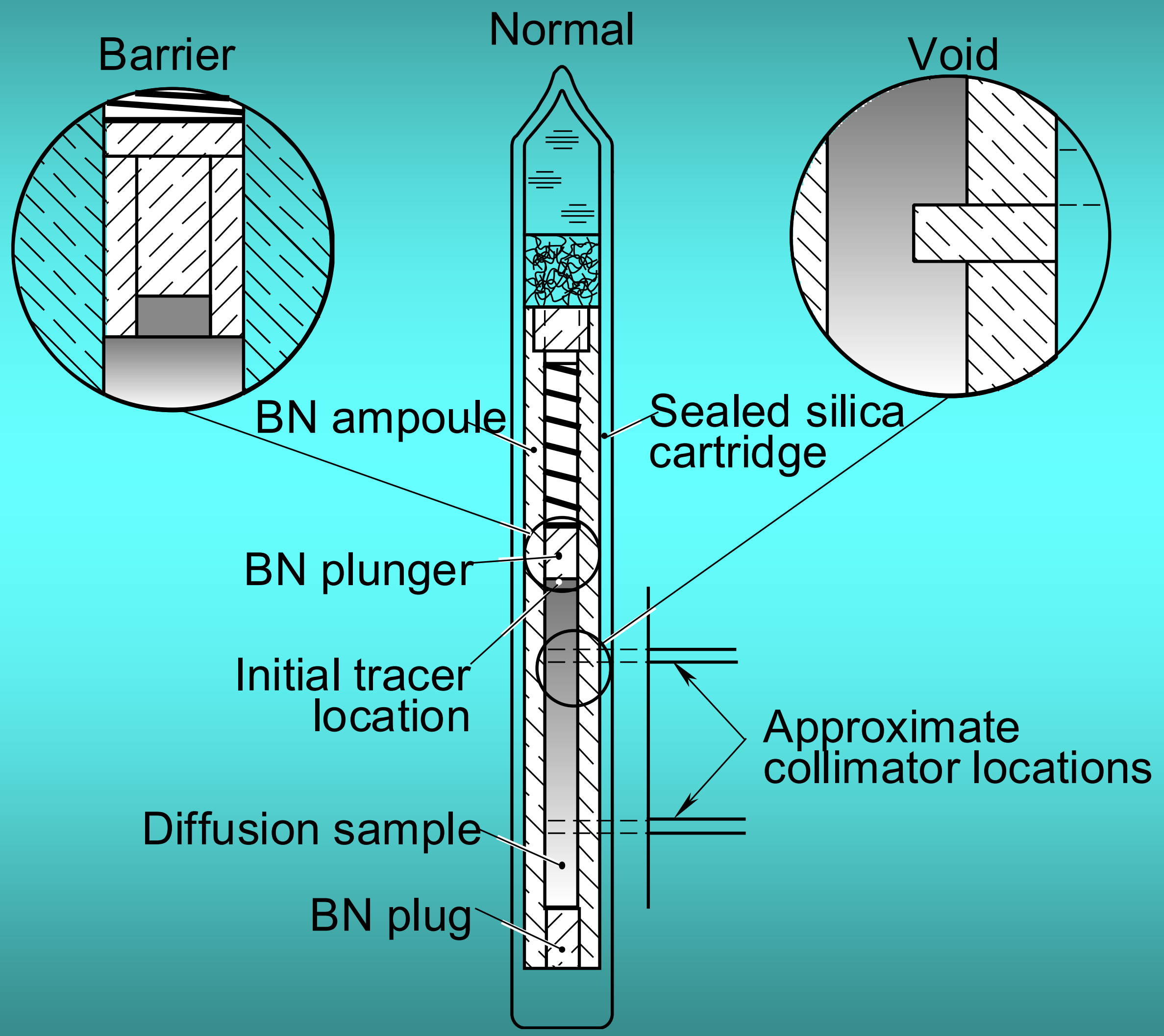
LMD-MIM-Mir Measurements



- Insensitivity to Deviations from 1D transport
  - experimental setup



- D(T) Predictions and Elements used for Confirmation

$A\exp(-Q/RT)$	In, Sn, Hg, Ag, Na
AT^2	In, Sn, Hg, Na, Ga
AT	In, Sn, Ag, Hg, Na, Tl, Zn
$AT^{3/2}$	In (at lower T's), Hg, Na
$AT^{1/2}$	In, Sn, Hg
$AT\exp(-Q/RT)$	In, Sn, Hg, Ag, Na, Pb, Zn, Tl, K, Li
$AT^{-5/2}\exp(-Q/RT)$	Sn, Hg, Pb, Cd
$AT^{1/2}\exp(-Q/RT)$	In, Sn, Hg, Na, Ag, Pb, Ga
$[AR\delta^2T(V-V_0)]/[2VV_0]$	solutes only