# Development of Conduction, Convection, Spreading and Contact Resistance Models for Microelectronics Applications

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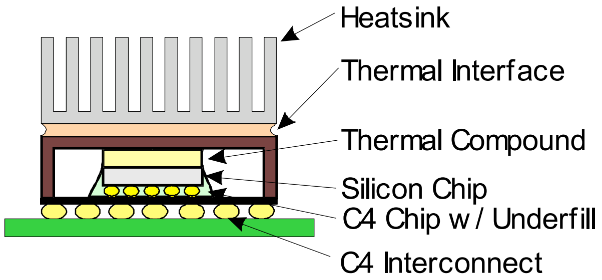
*University of Waterloo*

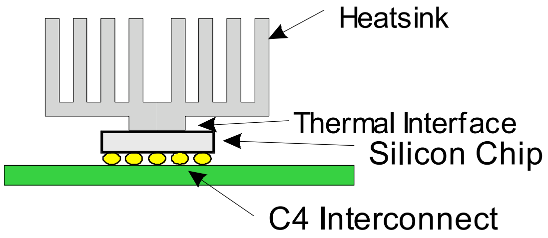
# Outline

- Project Overview
- Objectives
- Year 1 Deliverables
- Design & Analysis Tools
- Personnel
- What Lies Ahead
- Concluding Comments

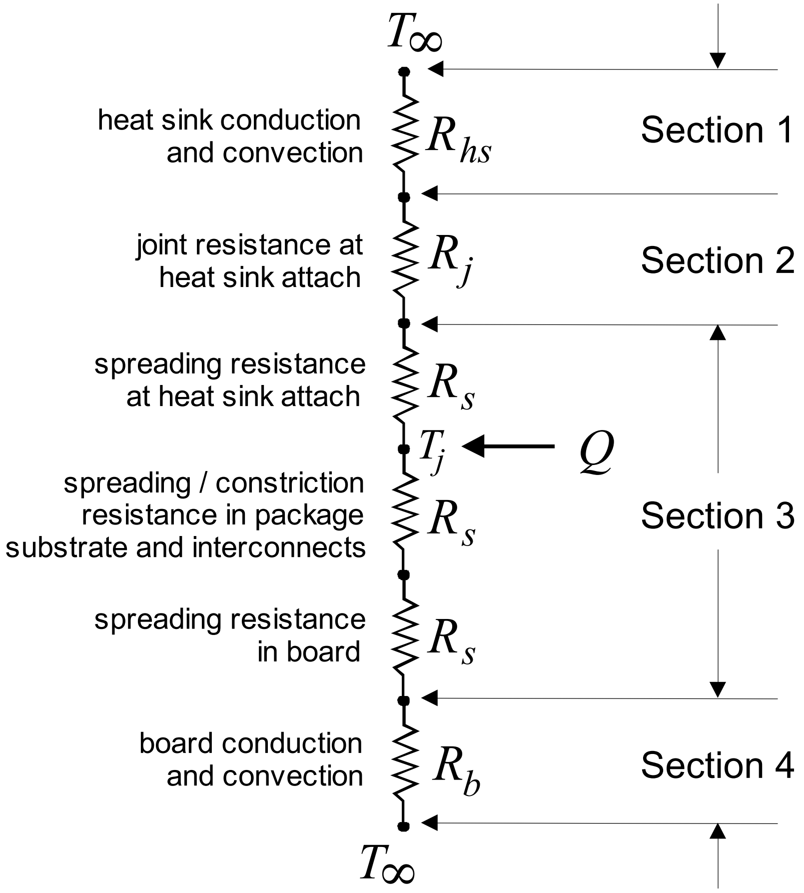
# Project Strategy



BGA with Heatsink



Flip Chip with Heatsink



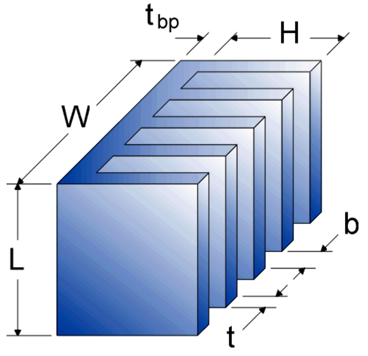
# Objectives

- Thermal model development:
  chip level ⟶ cooling medium

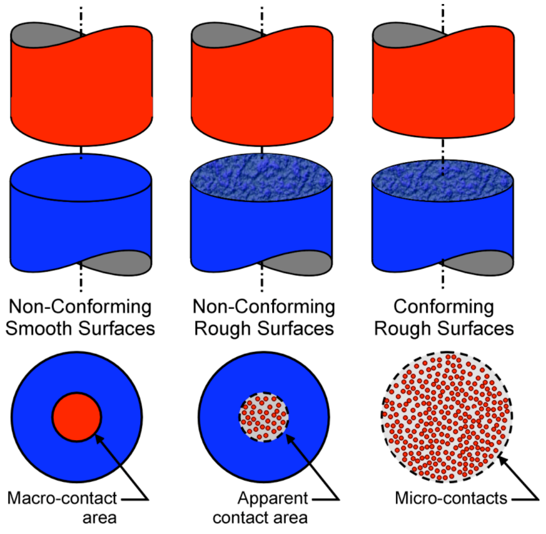
  - ✓ heat sink optimization
  - ✓ modeling & characterization of thermal interfaces
  - ✓ modeling of spreading & constriction resistance
  - ✓ modeling of conduction & convection in PWBs

# Year 1 Deliverables

- Heat sink optimization model
  - ✓ shrouded, air-cooled, plate fin heat sink
  - ✓ interactive web-based modeling tool

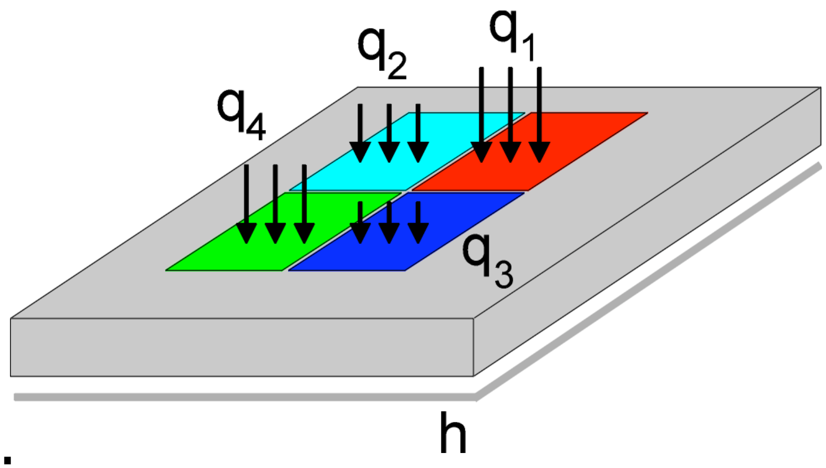


- Thermal resistance models
  - ✓ non-conforming, smooth surfaces
  - ✓ conforming rough surfaces
  - ✓ Excel spreadsheet models



# Year 1 Deliverables

- Spreading resistance model for
  - ✓ multiple discrete sources
  - ✓ isotropic or multi-layered substrate
  - ✓ interactive web-based modeling tool



- Thermal Interface Test Rig
  - ✓ design, build and commission test apparatus

# Heat Sink Optimization

**Analysis Tool** vs. **Design Tool**

- design is known a priori
- used to calculate the performance of a given design,
  i.e. Nu or R vs. Re
- cannot guarantee an optimized design

- used to obtain an optimized design for a set of known constraints i.e.
  given:
  - ✓ maximum temperature
  - ✓ heat input
  - ✓ maximum outside dimensions

find: the most efficient design

# Optimization Using EGM

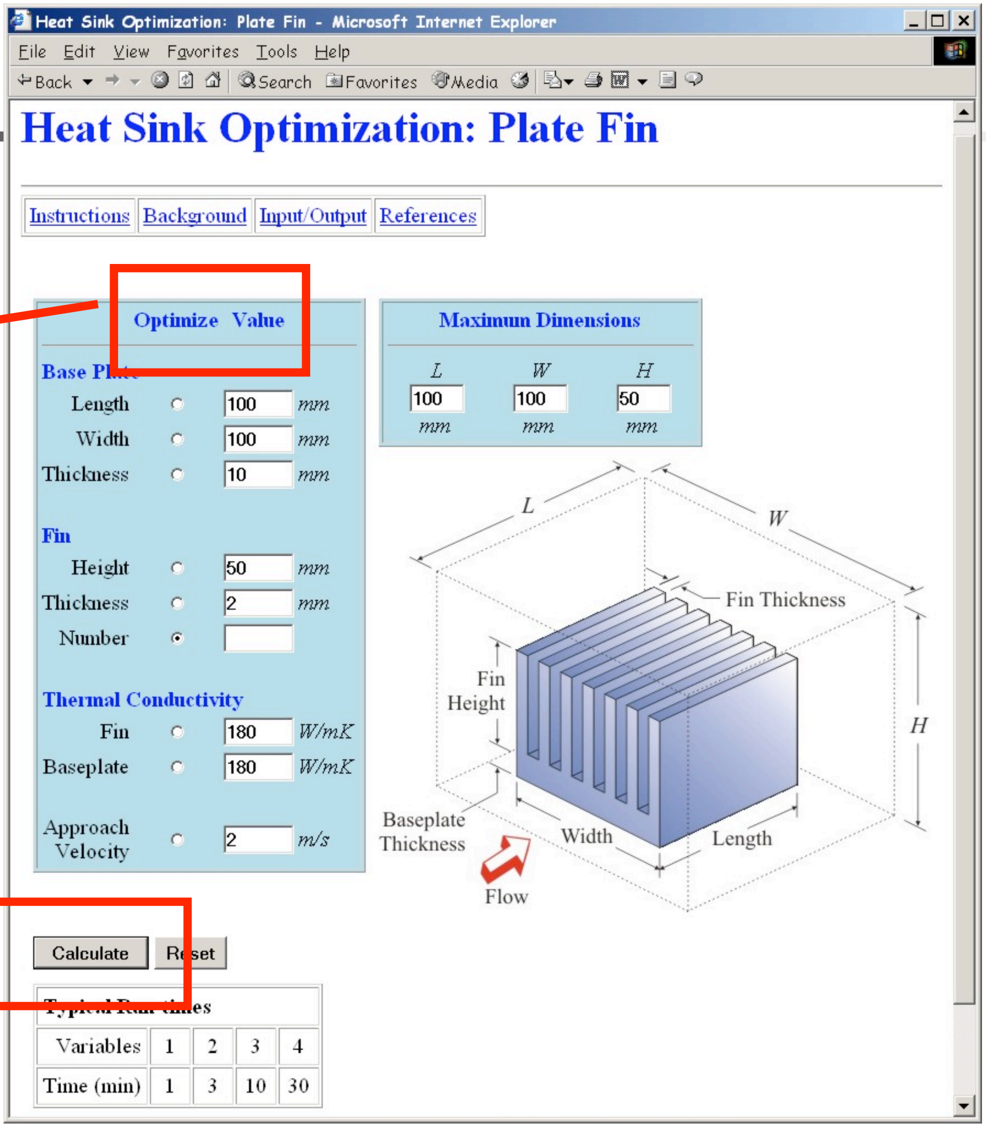
## Why use Entropy Generation Minimization?

- entropy production ∝ amount of energy degraded to a form unavailable for work
- lost work is an additional amount of heat that could have been extracted
- degradation process is a function of thermodynamic irreversibilities e.g. friction, heat transfer etc.
- minimizing the production of entropy, provides a simultaneous optimization of all design variables

Value: provide specific values for constrained parameters

Optimize: indicate parameters to be optimized

Calculate: run optimization code to calculate design parameters for maximum thermal-fluid performance



## Heat Sink Optimization: Plate Fin

Instructions | Background | Input/Output | References

|  | Optimize | Value |  |
|---|---|---|---|
| **Base Plate** |  |  |  |
| Length | ○ | 100 | mm |
| Width | ○ | 100 | mm |
| Thickness | ○ | 10 | mm |
| **Fin** |  |  |  |
| Height | ○ | 50 | mm |
| Thickness | ○ | 2 | mm |
| Number | ● |  |  |
| **Thermal Conductivity** |  |  |  |
| Fin | ○ | 180 | W/mK |
| Baseplate | ○ | 180 | W/mK |
| Approach Velocity | ○ | 2 | m/s |

**Maximum Dimensions**

| L | W | H |
|---|---|---|
| 100 mm | 100 mm | 50 mm |

Typical Run-times

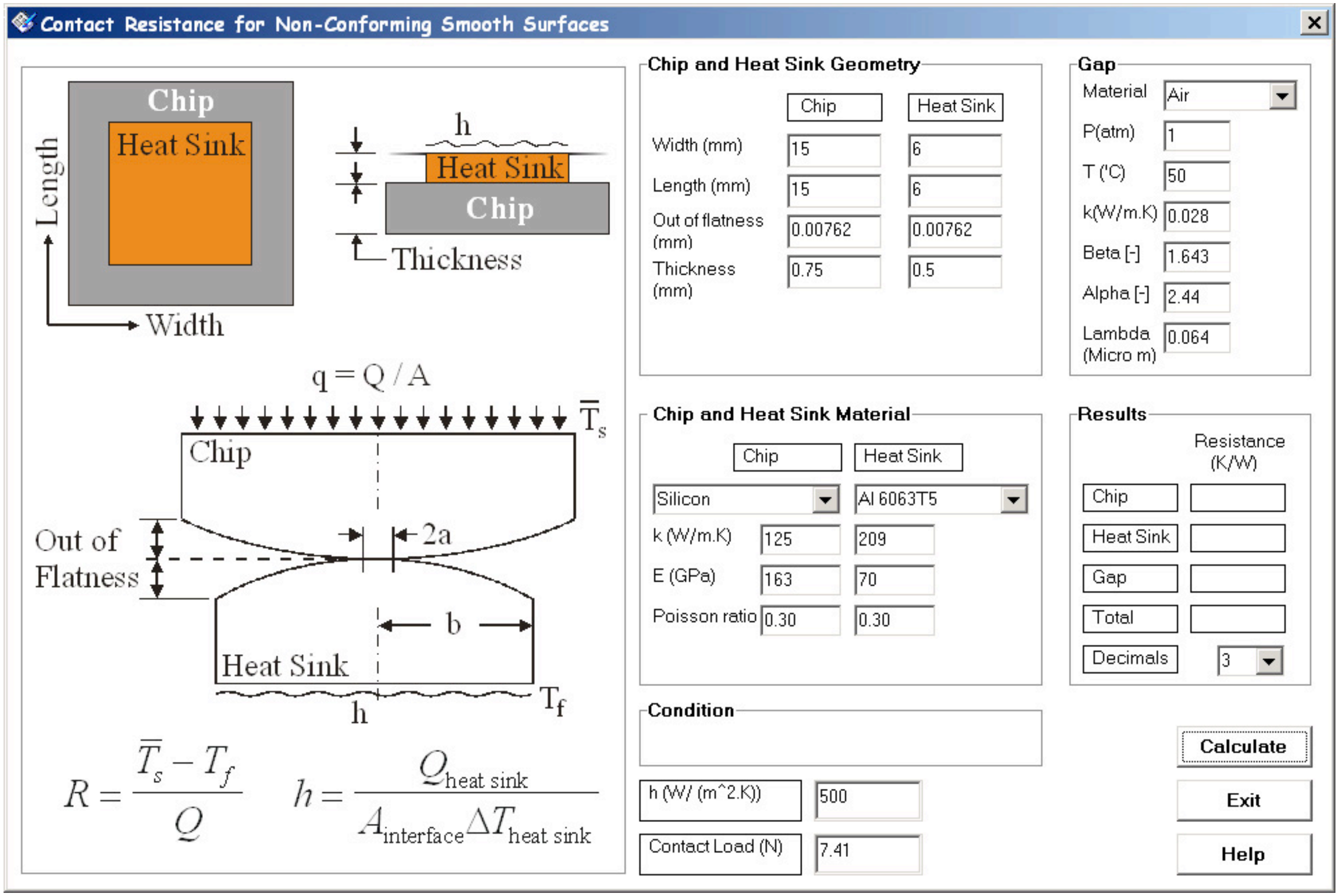
| Variables | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Time (min) | 1 | 3 | 10 | 30 |

Web URL: http://mhtlab.uwaterloo.ca/onlinetools/optimize/index.html

# Contact Resistance Models

- Non-conforming, smooth surfaces:
  - ✓ assume material waviness (out-of-flatness) predominates
  - ✓ microscopic roughness is negligible
  - ✓ example: heat sink on a silicon chip
  - ✓ determine contact, gap and joint resistance
- Conforming rough surfaces:
  - ✓ assume microscopic roughness predominates
  - ✓ out-of-flatness is negligible
  - ✓ example: two machined (lapped or ground) surfaces
  - ✓ determine contact, gap and joint resistance

# Non-Conforming Smooth Surfaces



$$q = Q / A$$

$$\bar{T}_s \qquad T_f$$

$$R = \frac{\bar{T}_s - T_f}{Q} \qquad h = \frac{Q_{\text{heat sink}}}{A_{\text{interface}} \Delta T_{\text{heat sink}}}$$

**Chip and Heat Sink Geometry**

| | Chip | Heat Sink |
|---|---|---|
| Width (mm) | 15 | 6 |
| Length (mm) | 15 | 6 |
| Out of flatness (mm) | 0.00762 | 0.00762 |
| Thickness (mm) | 0.75 | 0.5 |

**Gap**

| | |
|---|---|
| Material | Air |
| P(atm) | 1 |
| T ('C) | 50 |
| k(W/m.K) | 0.028 |
| Beta [-] | 1.643 |
| Alpha [-] | 2.44 |
| Lambda (Micro m) | 0.064 |

**Chip and Heat Sink Material**

| | Chip | Heat Sink |
|---|---|---|
| | Silicon | Al 6063T5 |
| k (W/m.K) | 125 | 209 |
| E (GPa) | 163 | 70 |
| Poisson ratio | 0.30 | 0.30 |

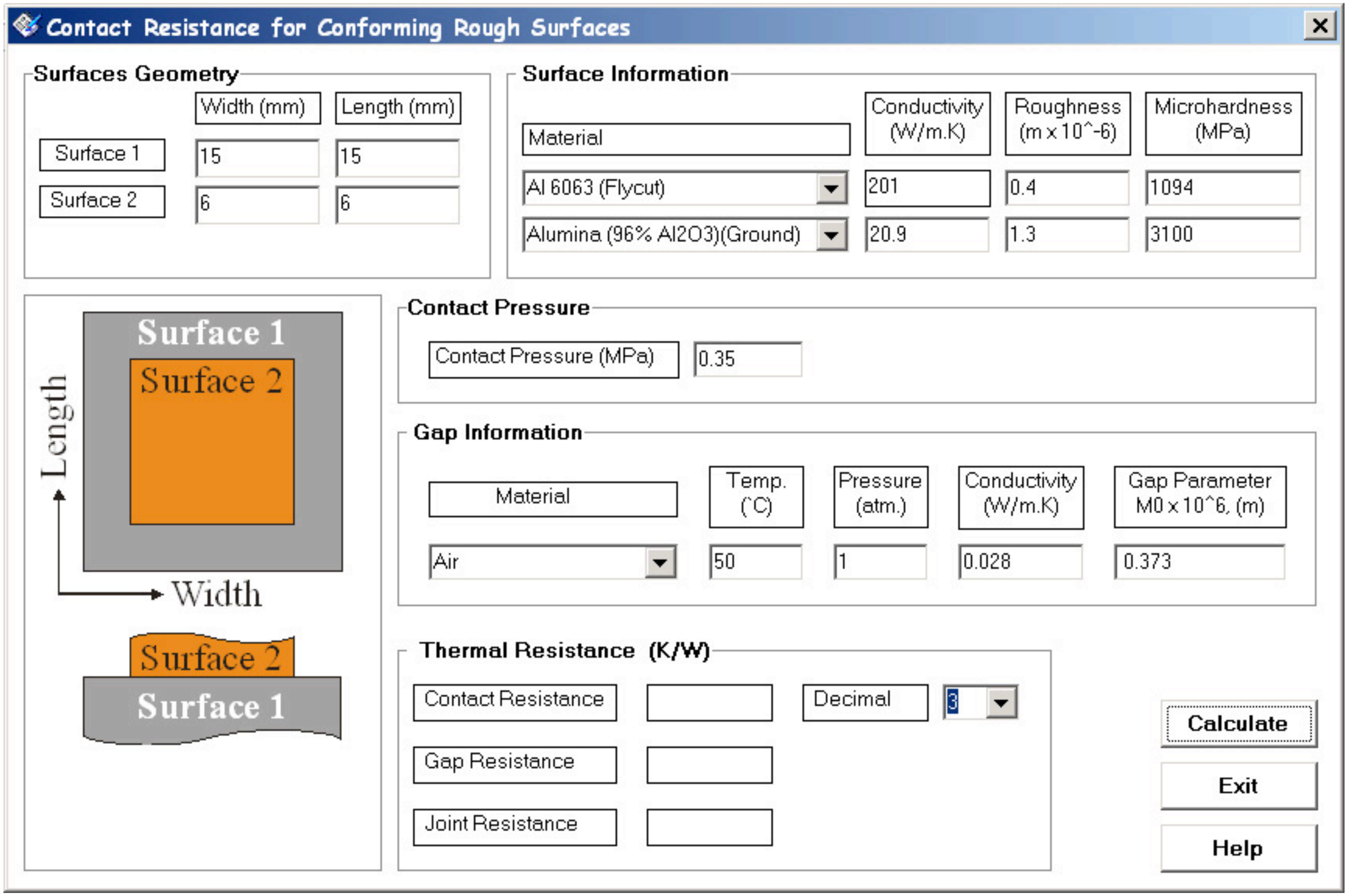
**Results**

| | Resistance (K/W) |
|---|---|
| Chip | |
| Heat Sink | |
| Gap | |
| Total | |
| Decimals | 3 |

**Condition**

| | |
|---|---|
| h (W/ (m^2.K)) | 500 |
| Contact Load (N) | 7.41 |

# Conforming Rough Surfaces



**Contact Resistance for Conforming Rough Surfaces**

**Surfaces Geometry**

| | Width (mm) | Length (mm) |
|---|---|---|
| Surface 1 | 15 | 15 |
| Surface 2 | 6 | 6 |

**Surface Information**

| Material | Conductivity (W/m.K) | Roughness (m x 10^-6) | Microhardness (MPa) |
|---|---|---|---|
| Al 6063 (Flycut) | 201 | 0.4 | 1094 |
| Alumina (96% Al2O3)(Ground) | 20.9 | 1.3 | 3100 |

**Contact Pressure**

Contact Pressure (MPa) 0.35

**Gap Information**

| Material | Temp. (˚C) | Pressure (atm.) | Conductivity (W/m.K) | Gap Parameter M0 x 10^6, (m) |
|---|---|---|---|---|
| Air | 50 | 1 | 0.028 | 0.373 |

**Thermal Resistance (K/W)**

Contact Resistance

Gap Resistance

Joint Resistance

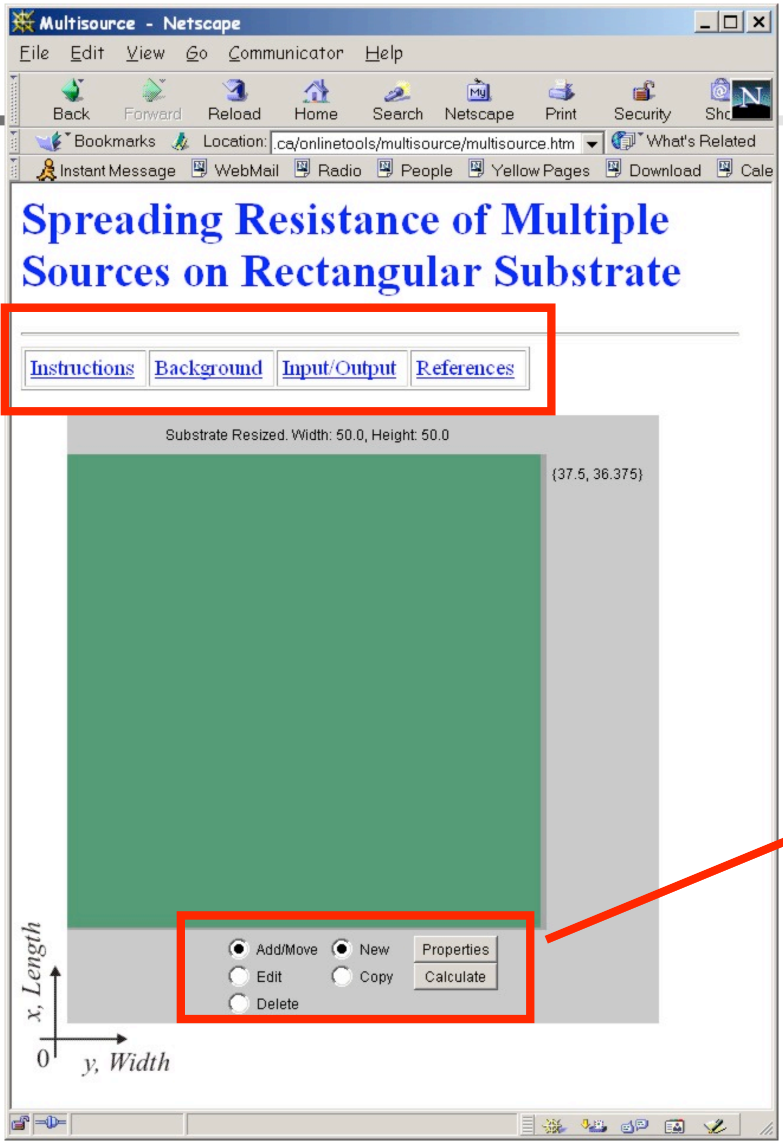
Decimal 3

# Spreading Resistance Model

- Analytical solution for heat sources on a rectangular flux channel
    - ✓ isotropic or laminated substrates
    - ✓ multiple discrete sources

- Model details in:

“Muzychka, Y.S., Culham, J.R. and Yovanovich, M.M., 2000, "*Thermal Spreading Resistance of Eccentric Heat Sources on Rectangular Flux Channels*," ASME IMECE, Orlando, FL, November 5-10.



Spreading Resistance of Multiple Sources on Rectangular Substrate

Substrate Resized. Width: 50.0, Height: 50.0

Instructions: user's guide & sample problem

Background: governing eqns. & model development

Input/Output: data entry & units

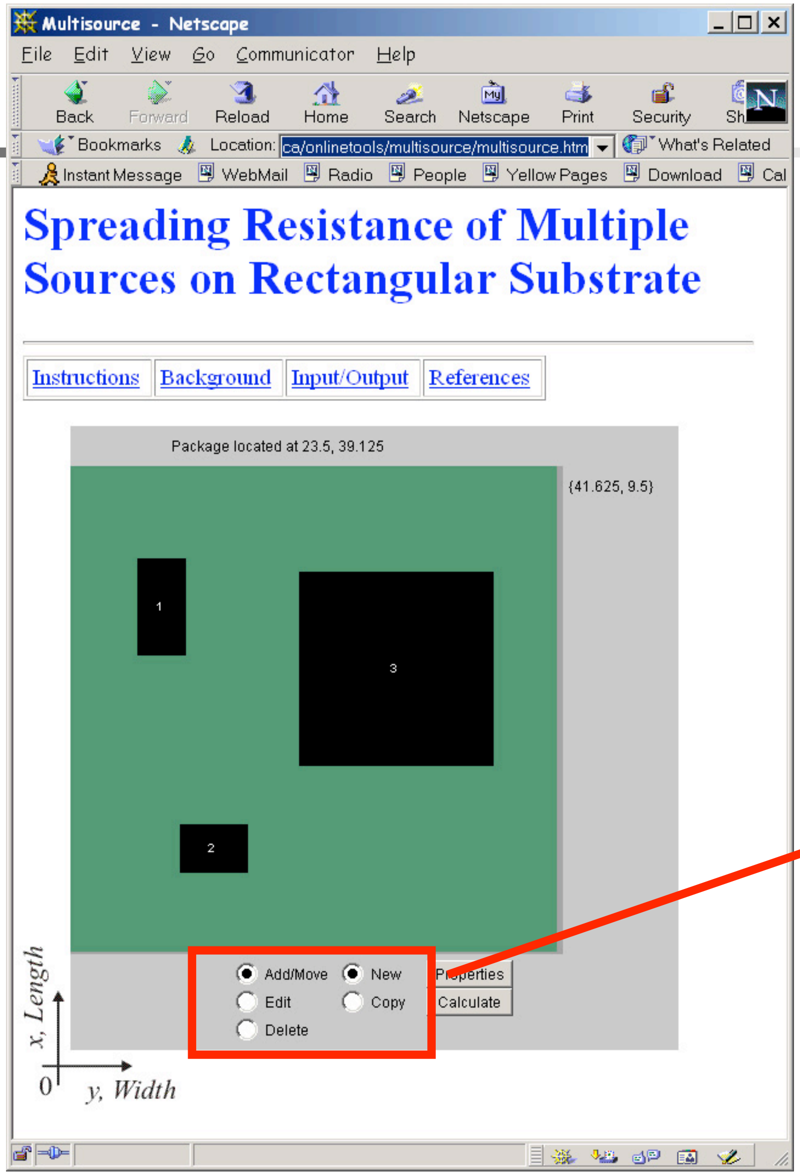
References: publications & sample pdf files

Properties: set substrate & source properties

Add/move, Edit, Delete, New, Copy: on screen package placement

Note: Java source requires Netscape (IE will not work)

Web URL: http://mhtlab.uwaterloo.ca/onlinetools/multisource/index.html



## Spreading Resistance of Multiple Sources on Rectangular Substrate

Package located at 23.5, 39.125

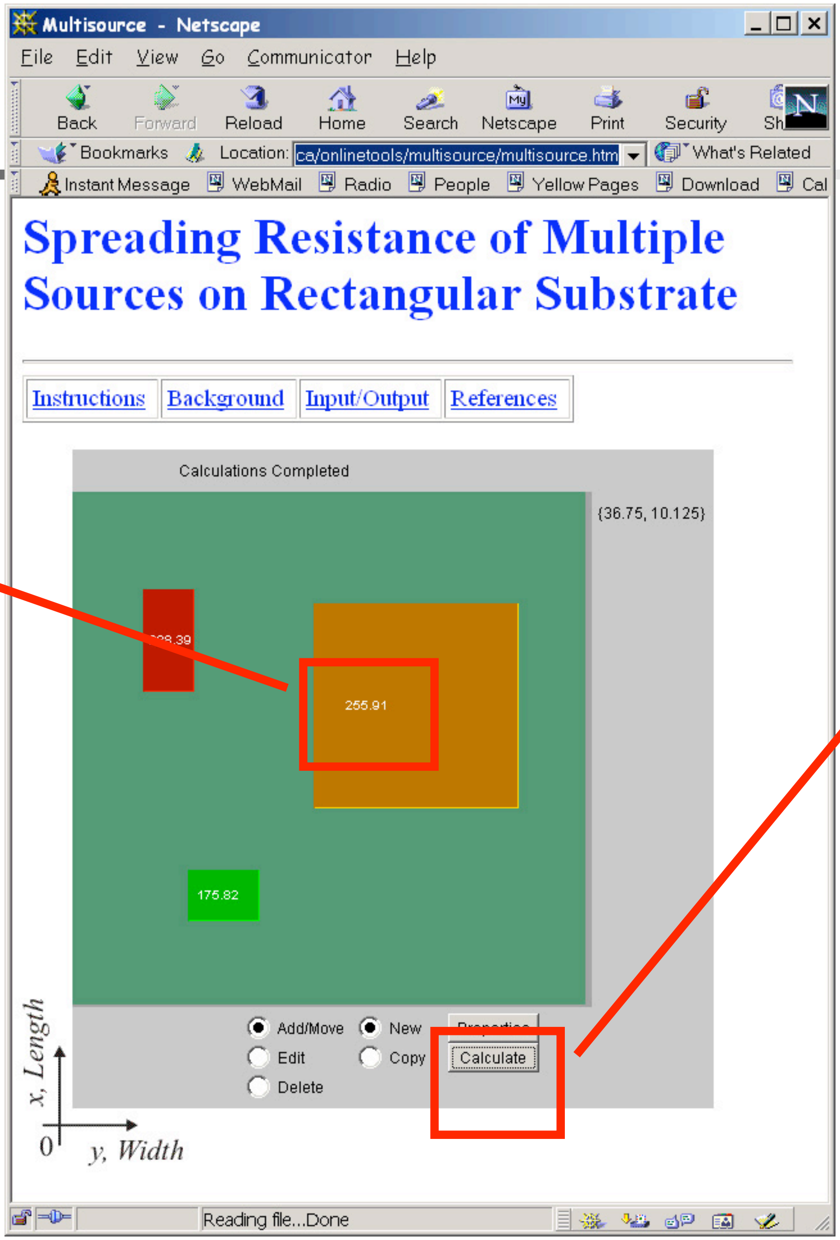
{41.625, 9.5}

● Add/Move ● New
○ Edit ○ Copy
○ Delete

Add a new source: a pop-up window will appear for entering heat source inputs

- click on substrate to place current heat source

Mean source temperature rise - °C



**Spreading Resistance of Multiple Sources on Rectangular Substrate**

Calculations Completed

Reading file...Done

Calculate: click calculate to obtain mean heat source temperature rise for each source

- Java-based code will be executed on local CPU
- typical run times are approximately 10 seconds per source

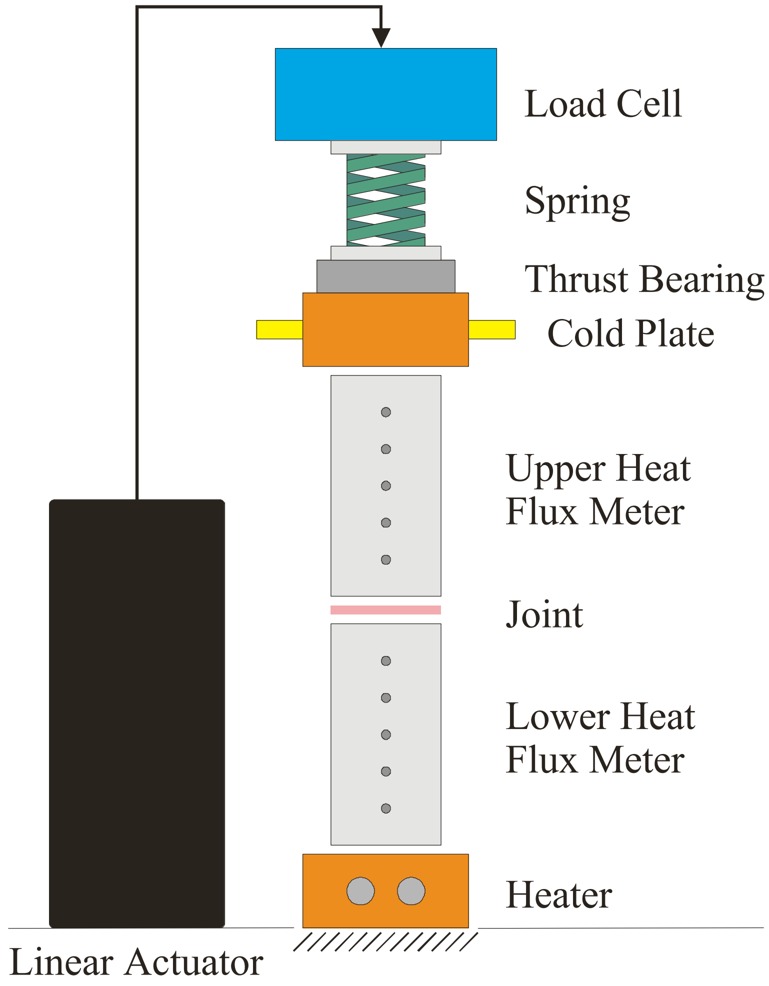
# Thermal Interface Materials

- Design, build & commission test apparatus & data acquisition interface for testing interface materials:
  - ✓ Measure joint resistance and thermal conductivity as function of:
    - interface temperature
    - contact pressure
    - material properties
    - surface characteristics
  - ✓ in-situ thickness measurement: sub micron precision

# Testing Capabilities

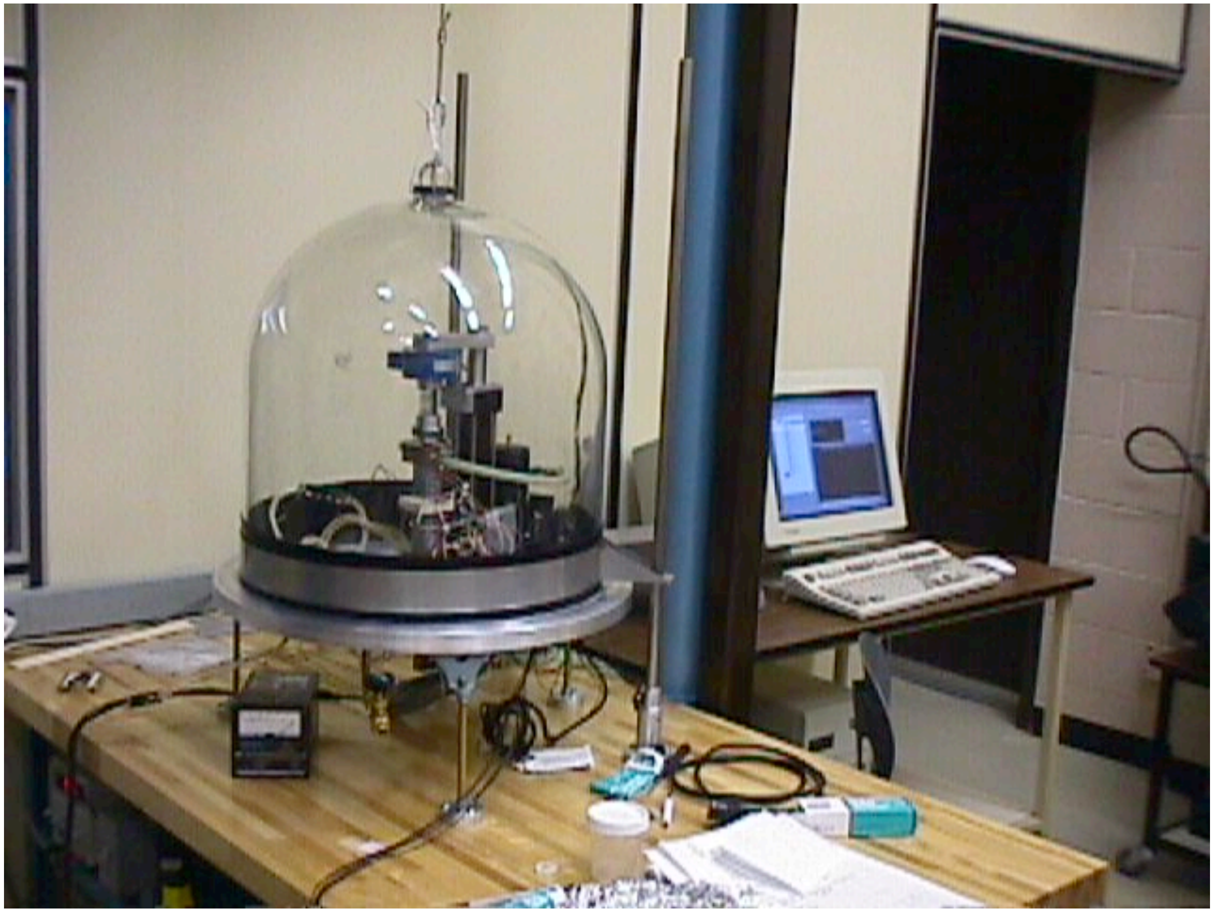
- 4 categories of materials can be tested
  - ✓ materials requiring stops & minimal clamping force
    - grease, liquids, phase change
  - ✓ materials deforming more than 10% under clamping force - compliant materials
  - ✓ materials deforming less than 10%, no stops required - hard rubber
  - ✓ thermally conductive materials requiring high clamping force - ceramics & plastics

# Apparatus

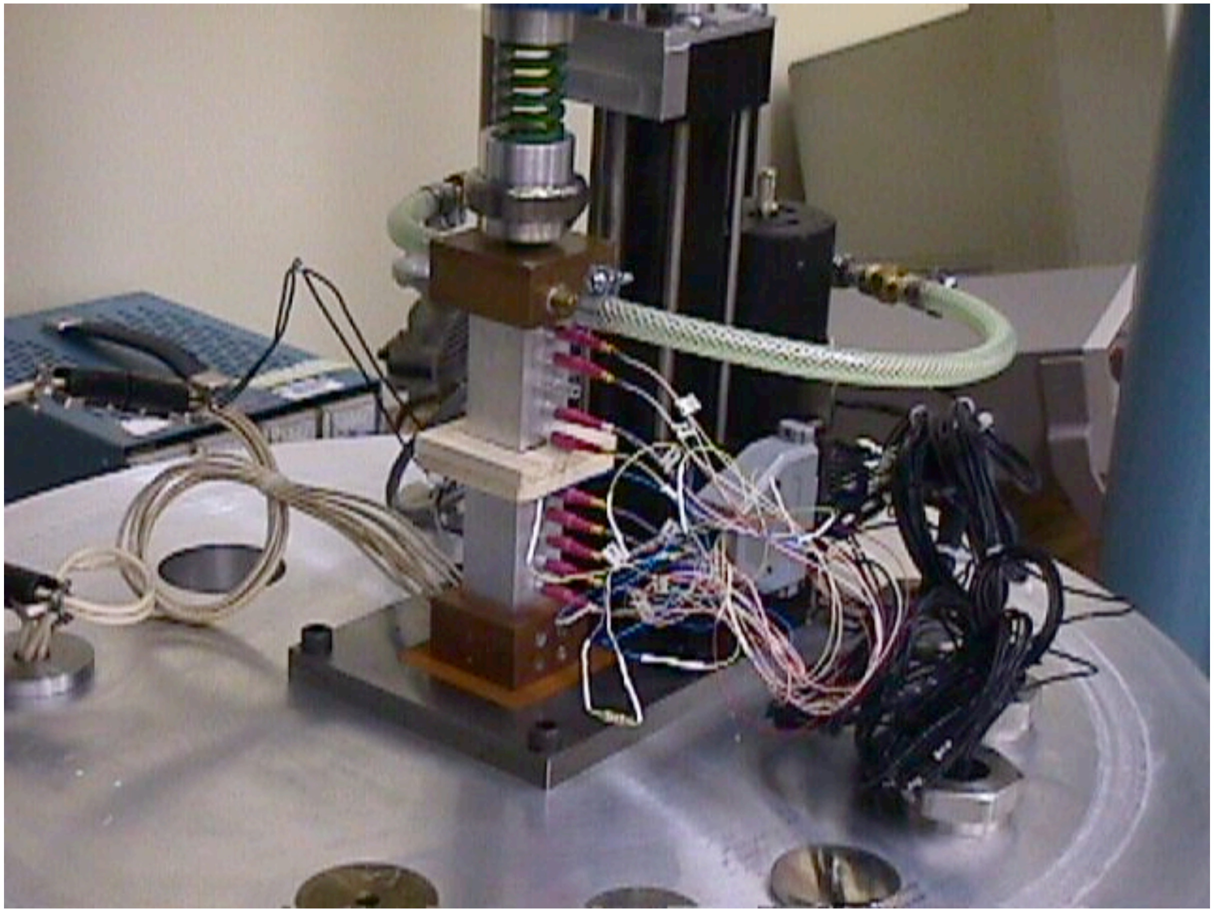


- Load cell
    - ✓ 100 or 1000 lbs
- Spring to compensate for thermal expansion
- Thrust bearing to remove torque loads
- Electric cylinder
    - ✓ digitally controlled stepper motor
    - ✓ 400 steps / rev  0.1” per revolution

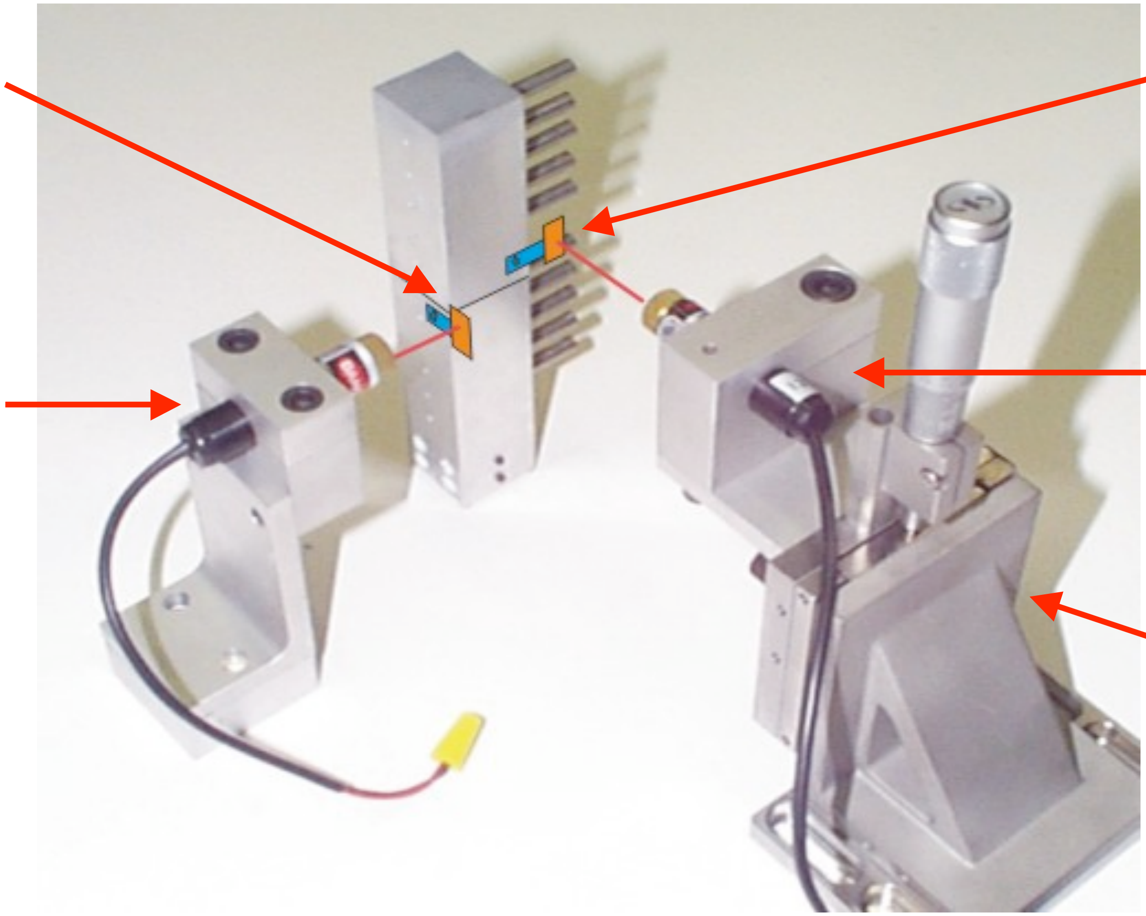
# Thermal Interface Test Apparatus



# Thermal Interface Test Apparatus



# Thickness and Deflection



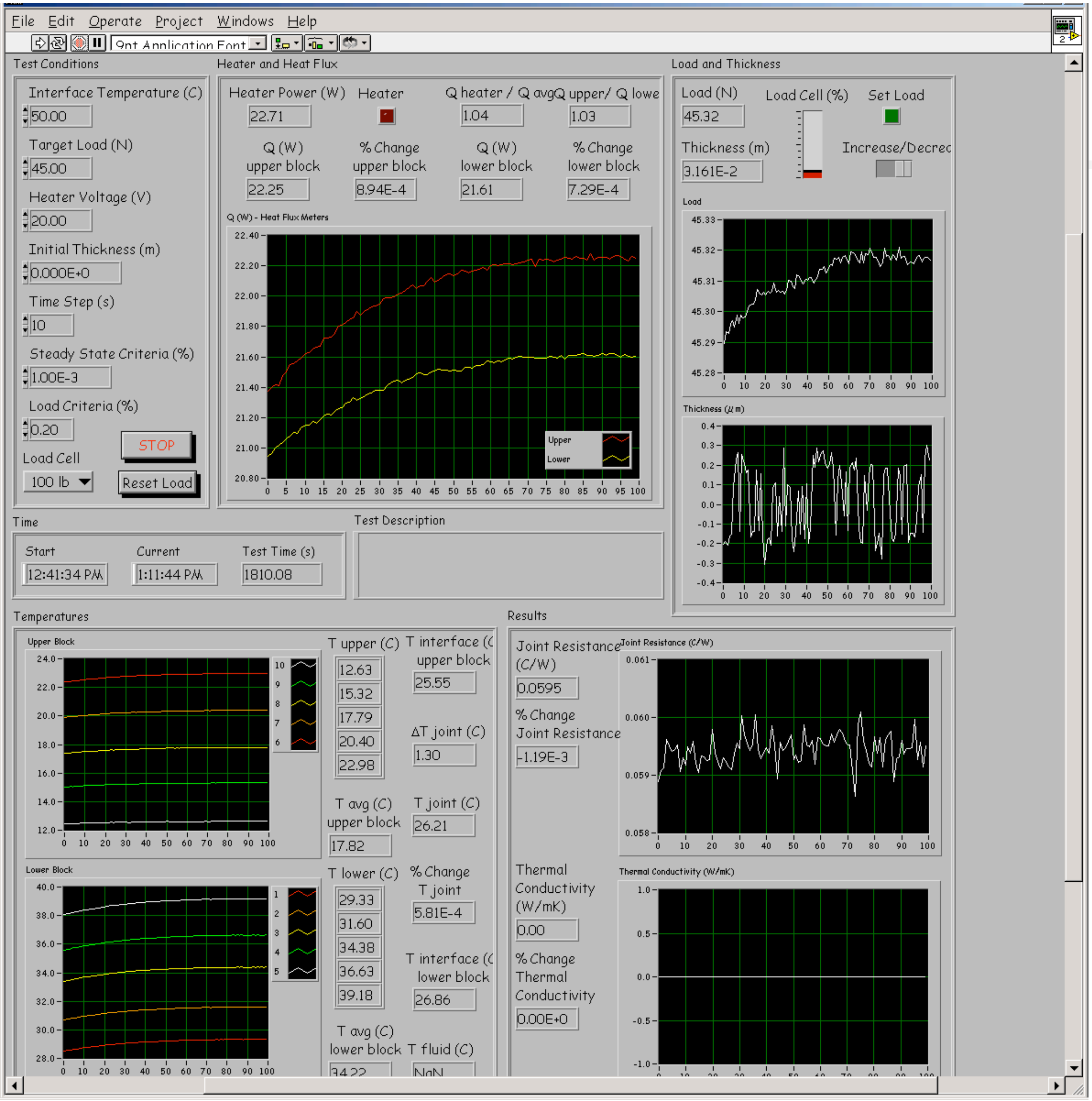
*Detector, Lower Block*

*Laser, Lower Block*

*Detector, Upper Block*

*Laser, Upper Block*

*Translation Stage*



Test Conditions

Interface Temperature (C): 50.00
Target Load (N): 45.00
Heater Voltage (V): 20.00
Initial Thickness (m): 0.000E+0
Time Step (s): 10
Steady State Criteria (%): 1.00E-3
Load Criteria (%): 0.20
Load Cell: 100 lb

Heater and Heat Flux

Heater Power (W): 22.71
Q heater / Q avg: 1.04
Q upper/ Q lowe: 1.03
Q (W) upper block: 22.25
% Change upper block: 8.94E-4
Q (W) lower block: 21.61
% Change lower block: 7.29E-4

Load and Thickness

Load (N): 45.32
Thickness (m): 3.161E-2

Time

Start: 12:41:34 PM
Current: 1:11:44 PM
Test Time (s): 1810.08

Test Description

Temperatures

T upper (C): 12.63, 15.32, 17.79, 20.40, 22.98
T interface (C) upper block: 25.55
ΔT joint (C): 1.30
T avg (C) upper block: 17.82
T joint (C): 26.21
T lower (C): 29.33, 31.60, 34.38, 36.63, 39.18
% Change T joint: 5.81E-4
T interface (C) lower block: 26.86
T avg (C) lower block: 34.22
T fluid (C): NaN

Results

Joint Resistance (C/W): 0.0595
% Change Joint Resistance: -1.19E-3
Thermal Conductivity (W/mK): 0.00
% Change Thermal Conductivity: 0.00E+0

# HQP's

- Graduate Students
  - ✓ Mr. Majid Bahrami
    - Ph.D candidate - *topic*: contact resistance in non-conforming rough surfaces
  - ✓ Ms. Irena Savija
    - M.A.Sc. Candidate - *topic:* modeling and characterization of thermal interface materials
- Summer Students
  - ✓ Mr. Joel Reardon and Mr. Chris Hurley
    - Web tool model development: Java, C, Javascript, CGI
- Senior Undergraduate Projects
  - ✓ Dana Frigula and Matthew Morrissey
    - Laser measurement system

# What Lies Ahead

- Heat sink models for base plate enhancements such as copper inserts, laminates and heat pipes
- Heat sink flow by-pass models
- Joint resistance models for non-conforming rough surfaces
- Thermal interface models: grease, phase change materials and compliant polymers
- Board level modeling

# Concluding Comments

- Thank you to sponsoring companies:
  - ✓ Alcatel
  - ✓ Celestica
  - ✓ Dy4
  - ✓ Coretec
- Cross our fingers for a successful CFI bid in the new year