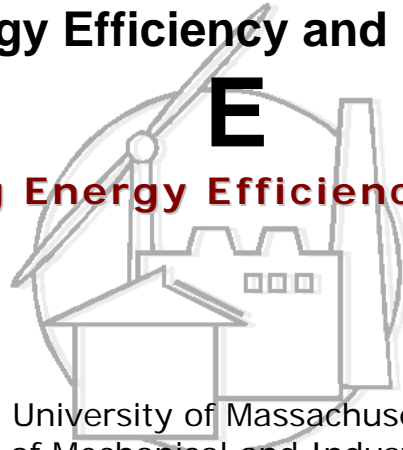


Center for Energy Efficiency and Renewable Energy

C E E R E

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**ANALYSIS OF CTS CALIBRATION DATA SUBMITTED BY ATI AS
A PART OF NFRC RESEARCH PROJECT "CALIBRATION OF
THERMAL TESTING METERING CHAMBERS USING CTS
PANELS"**

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Introduction

This goal of this phase of the project is to determine suitability of internal and external thermocouple locations. Two 2'x4' CTS panels and two 1'x1' CTS panels were constructed. One 2'x4' CTS panel had thermocouples installed in between glass and foam (interior locations), while one 2'x4' CTS panel had thermocouples mounted on the exposed surfaces of glass layers. In both cases, thermocouples were fabricated from 30 gauge wire and permanently attached (soldered) onto the copper shim, which were then in turn attached to glass surfaces using thermally conductive fast bonding adhesive. The two small CTS panels 1'x1' each were constructed with and without the thermocouples. The unit with thermocouples had one thermocouple installed on each side of the CTS (interior location). These two panels were used to determine conductance of the assembled CTS and to investigate if there was any change in conductance due to the presence of thermocouples. The detailed description of the construction of these panels is given in CEERE (2001).

Heat Transfer Analysis

Two 2'x4' CTS panels were run two times each and in each case two runs have produced almost identical results (see appendix), so the detailed analysis is presented for one run each. The flanking loss for the surround panel was determined in a separate run and applied for each CTS run. The conductivity of foam core and conductance of CTS panel was determined separately in a C518 apparatus and the resulting conductivities and conductances with associated analysis are presented here. The Layout of thermocouples on the two CTS's is shown in Figures 2 and 3.

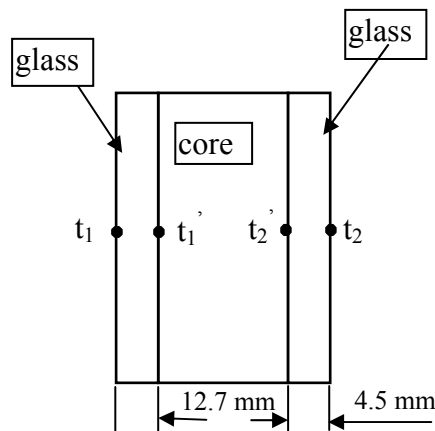


Figure 1. CTS Cross-section Geometry and Materials and Temperature Nomenclature

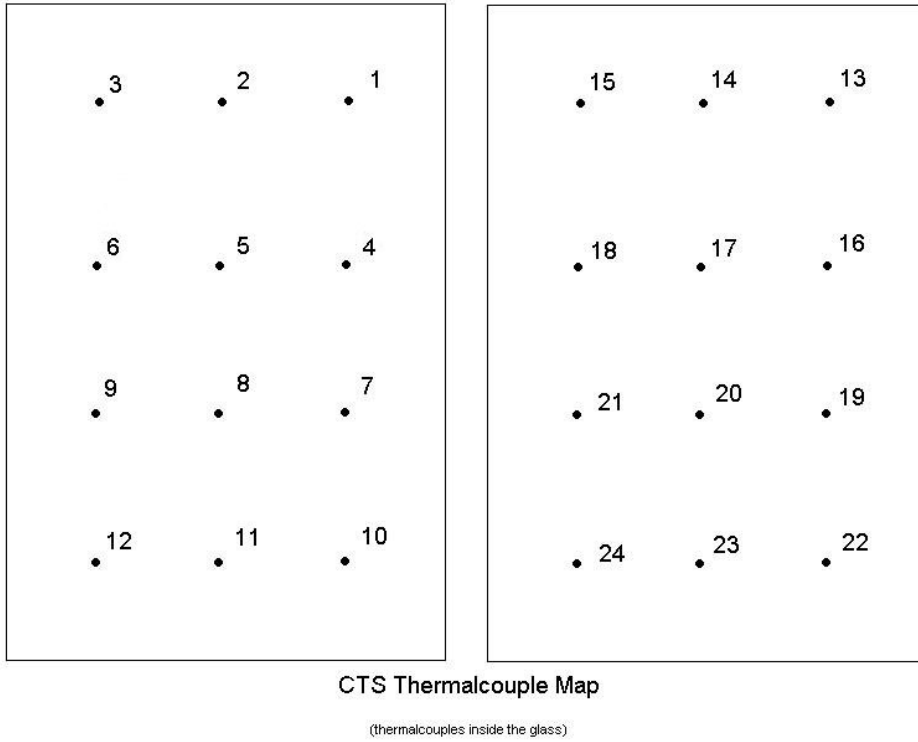


Figure 2. Thermocouple Layout for Mounting Inside the Glass (i.e., Interface of Glass and Foam)

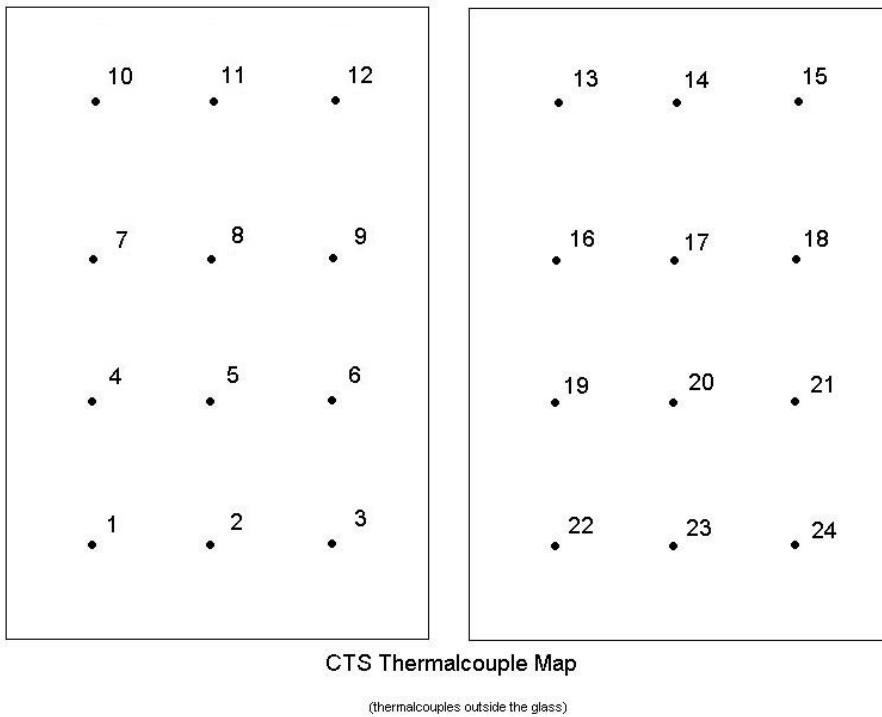


Figure 3. Thermocouple Layout for Mounting Outside the Glass (i.e., Inside and Outside Surfaces)

a) Heat flow through the CTS panel can be calculated from *measured core Resistance, R_{core} and interface temperatures, t_1' , and t_2'* as follows:

$$Q = C_{core} \cdot A_{CTS} \cdot (t_2' - t_1'), \text{ [Energy/Time]}$$

where: $C_{core} = 1/R_{core}$, [Energy/(Time*Length²*Degree Temperature)]

t_1' , t_2' are either measured (internally mounted thermocouples), or calculated from:

$$t_1' = t_1 + Q \cdot d_g / (A \cdot k_g), \text{ [Degree Temperature]}$$

$$t_2' = t_2 - Q \cdot d_g / (A \cdot k_g), \text{ [Degree Temperature]}$$

b) Alternatively, the heat flow through the CTS can be calculated using *measured resistance of the CTS assembly, R_{CTS} and measured surface temperatures, t_1 and t_2* :

$$Q = C_{CTS} \cdot A_{CTS} \cdot (t_2 - t_1), \text{ [Energy/Time]}$$

where: $C_{CTS} = 1/R_{CTS}$, [Energy/(Time*Length²*Degree Temperature)]

t_1 , t_2 can be either measured (external thermocouples) or estimated from:

$$t_1 = t_1' - Q \cdot d_g / (A \cdot k_g), \text{ [Degree Temperature]}$$

$$t_2 = t_2' + Q \cdot d_g / (A \cdot k_g), \text{ [Degree Temperature]}$$

Estimate of equivalent CTS conductivity:

$$k_{CTS} = d_{CTS} / R_{CTS}, \text{ [Energy/(Time*Length*Degree Temperature)]}$$

c) **Additional check** can be done by calculating the conductance of the CTS assembly from the measured conductivity of the core, and temperatures of the exposed surfaces:

$$C_{CTS} = 1 / (d_1 / k_g + d_{core} / k_{core} + d_2 / k_g) = 1 / (2 \cdot d_g / k_g + d_{core} / k_{core}), \text{ [Energy/(Time*Length}^2 \cdot \text{Degree Temperature)]}$$

And recalculating Q , $Q = C_{CTS} \cdot A_{CTS} \cdot (t_2 - t_1)$, [Energy/Time]

where: k_g = conductivity of glass, [Length]

d_g = thickness of the glass layer, [Length]

d_{core} = thickness of the core, [Length]

d_{CTS} = thickness of the CTS panel, [Length]

$$d_{CTS} = 2 \cdot d_g + d_{core}$$

k_{core} = conductivity of the core material, [Energy/(Time*Length*Degree Temperature)]

A_{CTS} = area of the CTS panel, [Length²]

d) The heat flow through the CTS can also be calculated from the *measured surface heat flux data* (additional measurements)

$$Q = q \cdot A_{CTS}, \text{ [Energy/Time]}$$

Data Analysis:

A. Externally Mounted thermocouples:

a) Measured: $t_1 = 5.97$ °F; $t_2 = 51.19$ °F; $Q_{\text{measured}} = 224.111$ Btu/hr. If account for $Q_{\text{fl-CTS}}$ [estimated value $Q_{\text{fl-CTS}} = 2.97$ Btu/(hr·ft)], then $Q_{\text{measured}} = 224.111 - 2.97 = 221.141$ Btu/hr; $R_{\text{core}} = 1.789$ hr·ft²·°F/Btu

Educated estimate: $d_g \{= 4.5 \text{ mm}\} = 0.178$ in (estimated from the measurement of the total CTS thickness); $k_g = 1.0$ W/m·K = 6.93 Btu·in/(hr·ft²·°F);

Calculated:

$$t_1' = t_1 + Q \cdot d_g / (A \cdot k_g) = 5.97 + 221.141 \cdot 0.178 / (2 \cdot 4 \cdot 6.93) = 6.68 \text{ °F } \{-14.07 \text{ °C}\};$$

$$t_2' = t_2 - Q \cdot d_g / (A \cdot k_g) = 51.19 - 213.275 \cdot 0.178 / (2 \cdot 4 \cdot 6.93) = 50.48 \text{ °F } \{10.27 \text{ °C}\};$$

$$C_{\text{core}} = 1/R_{\text{core}} = 1/1.789 = 0.55897 \text{ Btu}/(\text{hr} \cdot \text{ft}^2 \cdot \text{°F}) \{3.1738 \text{ W}/\text{m}^2 \cdot \text{K}\}$$

$$Q = C_{\text{core}} \cdot A_{\text{CTS}} \cdot (t_2' - t_1') = 0.55897 \cdot 2 \cdot 4 \cdot (50.48 - 6.68) = 195.86 \text{ Btu/hr [difference from measured: } \Delta Q = 25.55 \text{ Btu/hr]}$$

b) Measured: $t_1 = 5.97$ °F; $t_2 = 51.19$ °F; $R_{\text{CTS}} = 1.797$ hr·ft²·°F/Btu

Calculated:

$$C_{\text{CTS}} = 1/R_{\text{CTS}} = 1/1.797 = 0.55649 \text{ Btu}/(\text{hr} \cdot \text{ft}^2 \cdot \text{°F})$$

$$Q = C_{\text{CTS}} \cdot A_{\text{CTS}} \cdot (t_2 - t_1) = 0.55649 \cdot 2 \cdot 4 \cdot (51.19 - 5.97) = 201.32 \text{ Btu/hr } [\Delta Q = 19.821 \text{ Btu/hr}]$$

Estimate of equivalent CTS conductivity:

$$k_{\text{CTS}} = d_{\text{CTS}}/R_{\text{CTS}} = 0.856/1.797 = 0.476 \text{ Btu} \cdot \text{in}/(\text{hr} \cdot \text{ft}^2 \cdot \text{°F})$$

c) Measured: $t_1 = 5.97$ °F; $t_2 = 51.19$ °F; $R_{\text{core}} = 1.789$ hr·ft²·°F/Btu

Educated estimate: $d_g \{= 4.5 \text{ mm}\} = 0.178$ in; $k_g \{= 1.0 \text{ W}/\text{m} \cdot \text{K}\} = 6.93$ Btu·in/(hr·ft²·°F); $d_{\text{core}} = 0.5$ in {= 12.7 mm}

Calculated:

$$k_{\text{core}} = d_{\text{core}}/R_{\text{core}} = 0.5 \text{ in}/1.789 \text{ hr} \cdot \text{ft}^2 \cdot \text{°F}/\text{Btu} = 0.2795 \text{ Btu} \cdot \text{in}/(\text{hr} \cdot \text{ft}^2 \cdot \text{°F}); \{= 0.0403 \text{ W}/\text{m} \cdot \text{K}\}$$

$$C_{\text{CTS}} = 1/(2 \cdot d_g/k_g + d_{\text{core}}/k_{\text{core}}) = 1/(2 \cdot 0.178/6.93 + 0.5/0.2795) = 0.543 \text{ Btu}/(\text{hr} \cdot \text{ft}^2 \cdot \text{°F})$$

$$Q = C_{\text{CTS}} \cdot A_{\text{CTS}} \cdot (t_2 - t_1) = 0.543 \cdot 2 \cdot 4 \cdot (51.19 - 5.97) = 196.435 \text{ Btu/hr } [\Delta Q = 24.706 \text{ Btu/hr}]$$

d) Measured: $q = 24.265$ Btu/(hr·ft²) [Average of three surface heat flux sensors]

Calculated:

$$Q = q \cdot A_{\text{CTS}} = 24.265 \cdot 2 \cdot 4 = 194.123 \text{ Btu/hr } [\Delta Q = 27.018 \text{ Btu/hr}]$$

B. Internally Mounted Thermocouples:

a) Measured: $t_1' = 6.57$ °F; $t_2' = 50.43$ °F; $Q_{\text{measured}} = 221.184$ Btu/hr. If account for $Q_{\text{fl-CTS}}$ [estimated value $Q_{\text{fl-CTS}} = 10.84$ Btu/(hr·ft)], then $Q_{\text{measured}} = 221.184 - 2.97 = 218.214$ Btu/hr; $R_{\text{core}} = 1.789$ hr·ft²·°F/Btu.

Calculated:

$$C_{\text{core}} = 1/R_{\text{core}} = 1/1.789 = 0.55897 \text{ Btu}/(\text{hr}\cdot\text{ft}^2\cdot\text{°F}) [3.1738 \text{ W}/\text{m}^2\cdot\text{K}]$$

$$Q = C_{\text{core}}\cdot A_{\text{CTS}}\cdot (t_2' - t_1') = 0.55897\cdot 2\cdot 4\cdot (50.43 - 6.57) = 196.131 \text{ Btu/hr [diff. from measured: } \Delta Q = 22.083 \text{ Btu/hr}]$$

b) Measured: $t_1' = 6.57$ °F; $t_2' = 50.43$ °F; $R_{\text{CTS}} = 1.794$ hr·ft²·°F/Btu; $d_{\text{CTS}} = 0.856$ in, $Q_{\text{measured}} = 221.184$ Btu/hr. If account for $Q_{\text{fl-CTS}}$ [estimated value $Q_{\text{fl-CTS}} = 2.97$ Btu/(hr·ft)], then $Q_{\text{measured}} = 221.184 - 2.97 = 218.214$ Btu/hr.

Educated estimate: $d_g \{= 4.5 \text{ mm}\} = 0.178$ in (estimated from the measurement of the total CTS thickness); $k_g = 1.0$ W/m·K = 6.93 Btu·in/(hr·ft²·°F);

Calculated:

$$t_2 = t_2' + Q\cdot d_g/(A\cdot k_g) = 50.43 + 218.214\cdot 0.178/(2\cdot 4\cdot 6.93) = 51.10 \text{ °F};$$

$$t_1 = t_1' - Q\cdot d_g/(A\cdot k_g) = 6.57 - 218.214\cdot 0.178/(2\cdot 4\cdot 6.93) = 5.87 \text{ °F}$$

$$C_{\text{CTS}} = 1/R_{\text{CTS}} = 1/1.794 = 0.55741 \text{ Btu}/\text{hr}\cdot\text{ft}^2\cdot\text{°F}$$

$$Q = C_{\text{CTS}}\cdot A_{\text{CTS}}\cdot (t_2 - t_1) = 0.55741\cdot 2\cdot 4\cdot (51.10 - 5.87) = 201.690 \text{ Btu/hr } [\Delta Q = 16.52 \text{ Btu/hr}]$$

Estimate of equivalent CTS conductivity:

$$k_{\text{CTS}} = d_{\text{CTS}}\cdot R_{\text{CTS}} = 0.856/1.794 = 0.477 \text{ Btu}\cdot\text{in}/(\text{hr}\cdot\text{ft}^2\cdot\text{°F})$$

c) Measured: $t_1' = 6.57$ °F; $t_2' = 50.43$ °F; $R_{\text{core}} = 1.789$ hr·ft²·°F/Btu.

Educated estimate: $d_{\text{core}} = 0.5$ in {= 12.7 mm}; $d_g \{= 4.5 \text{ mm}\} = 0.178$ in (estimated from the measurement of the total CTS thickness); $k_g = 1.0$ W/m·K = 6.93 Btu·in/(hr·ft²·°F);

Calculated:

$$t_2 = t_2' + Q\cdot d_g/(A\cdot k_g) = 50.43 + 218.214\cdot 0.178/(2\cdot 4\cdot 6.93) = 51.10 \text{ °F};$$

$$t_1 = t_1' - Q\cdot d_g/(A\cdot k_g) = 6.57 - 218.214\cdot 0.178/(2\cdot 4\cdot 6.93) = 5.87 \text{ °F}$$

$$k_{\text{core}} = d_{\text{core}}/R_{\text{core}} = 0.5 \text{ in}/1.789 \text{ hr}\cdot\text{ft}^2\cdot\text{°F}/\text{Btu} = 0.2795 \text{ hr}\cdot\text{ft}^2\cdot\text{°F}/\text{Btu} \{= 0.0403 \text{ W}/\text{m}\cdot\text{K}\}$$

$$C_{\text{CTS}} = 1/(2\cdot d_g/k_g + d_{\text{core}}/k_{\text{core}}) = 1/(2\cdot 0.178/6.93 + 0.5/0.2795) = 0.543 \text{ Btu}/(\text{hr}\cdot\text{ft}^2\cdot\text{°F})$$

$$Q = C_{\text{CTS}}\cdot A_{\text{CTS}}\cdot (t_2 - t_1) = 0.543\cdot 2\cdot 4\cdot (51.10 - 5.87) = 196.479 \text{ Btu/hr } [\Delta Q = 21.73 \text{ Btu/hr}]$$

d) Measured: $q = 24.265$ Btu/(hr·ft²) [Average of three surface heat flux sensors]

Calculated:

$$Q = q\cdot A_{\text{CTS}} = 24.265\cdot 2\cdot 4 = 194.123 \text{ Btu/hr } [\Delta Q = 19.152 \text{ Btu/hr}]$$

References:

CEERE. 2001. "Instruction Manual on Calibration Transfer Standard (CTS) Construction". University of Massachusetts Technical Report. December 2001.

Appendix: Calculation of the Specimen (CTS) Flanking Loss:

Specimen flanking loss (energy transfer) is estimated using 2-D Numerical modeling tool THERM (LBNL 2002). The following procedure is used to calculate flanking energy transfer:

$$q_{\text{CTS-fl}} = (U_{\text{CTS}}^{2\text{-D}} - U_{\text{CTS}}^{1\text{-D}} + U_{\text{SP}}^{2\text{-D}} - U_{\text{SP}}^{1\text{-D}}) \cdot l \cdot (t_{\text{I}} - t_{\text{II}}), \text{ and}$$

$$Q_{\text{CTS-fl}} = L \cdot q_{\text{CTS-fl}}$$

where:

- $U_{\text{CTS}}^{2\text{-D}}$ = heat transfer through the “edge” region of CTS, [Energy/(Time*Length²*Degree Temperature)]
- $U_{\text{CTS}}^{1\text{-D}}$ = heat transfer through the “center” region of CTS, [Energy/(Time*Length²*Degree Temperature)]
- $U_{\text{SP}}^{2\text{-D}}$ = heat transfer through the “edge” region of surround panel, [Energy/(Time*Length²*Degree Temperature)]
- $U_{\text{SP}}^{1\text{-D}}$ = heat transfer through the “center” region of surround panel, [Energy/(Time*Length²*Degree Temperature)]
- l = edge region length, 203 mm (8 in.)
- L = CTS perimeter length, [Length]
- t_{I} = indoor side air temperature, 21 °C (70 °F)
- t_{II} = indoor side air temperature, -18 °C (0 °F)

From the results of THERM simulation, the following results were obtained:

$$U_{\text{CTS}}^{2\text{-D}} = 0.352 \text{ Btu}/(\text{hr}\cdot\text{ft}^2\cdot^{\circ}\text{F}) \{2.000 \text{ W}/(\text{m}\cdot\text{K})\}$$

$$U_{\text{CTS}}^{1\text{-D}} = 0.354 \text{ Btu}/(\text{hr}\cdot\text{ft}^2\cdot^{\circ}\text{F}) \{2.012 \text{ W}/(\text{m}\cdot\text{K})\}$$

$$U_{\text{SP}}^{2\text{-D}} = 0.060 \text{ Btu}/(\text{hr}\cdot\text{ft}^2\cdot^{\circ}\text{F}) \{0.343 \text{ W}/(\text{m}\cdot\text{K})\}$$

$$U_{\text{SP}}^{1\text{-D}} = 0.053 \text{ Btu}/(\text{hr}\cdot\text{ft}^2\cdot^{\circ}\text{F}) \{0.301 \text{ W}/(\text{m}\cdot\text{K})\}$$

so,

$$q_{\text{fl-SP}} = (0.352 - 0.354 + 0.060 - 0.053) \cdot 8/12 \cdot (70 - 0) = 0.247 \text{ Btu}/(\text{hr}\cdot\text{ft}) \{0.238 \text{ W}/\text{m}\}$$

For 2 ft x 4 ft CTS, the total CTS flanking heat flow, $Q_{\text{fl-SP}}$ is:

$$Q_{\text{fl-SP}} = 2 \cdot (2 + 4) \cdot 0.247 = 2.969 \text{ Btu}/\text{hr} \{0.869 \text{ W}\}$$

Note: The above model was done with the use of detailed radiation transfer modeling in THERM, which can explain why the edge heat transfer is lower than center part heat transfer.

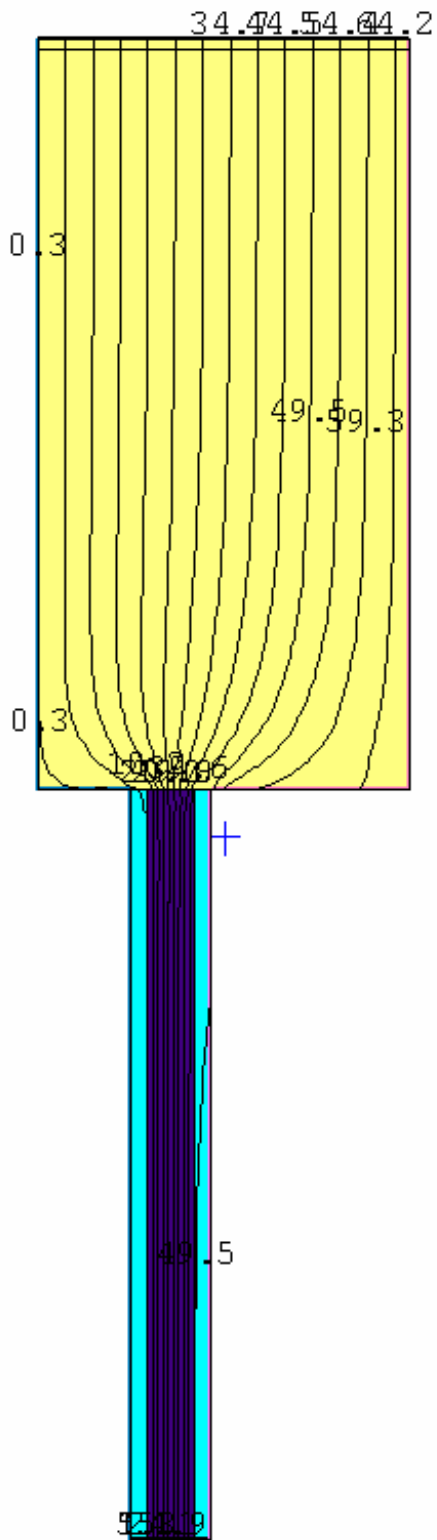


Figure 4. THERM model of edge regions of CTS and Surround Panel