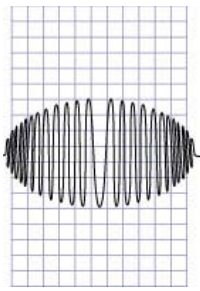

Final Report

for

COMPOTOOL LTD

THERMAL CONDUCTIVITY MEASUREMENTS OF CT850 TOOLING BOARD SPECIMENS

July 23, 2014

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PURCHASE ORDER NUMBER
PO-0012

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THERMAL CONDUCTIVITY MEASUREMENTS OF CT850 TOOLING BOARD SPECIMENS

WORK CONDUCTED FOR COMPOTOOL LTD
PURCHASE ORDER NUMBER PO-0012

July 23, 2014

Precision Measurements and Instruments Corporation (PMIC) measured the thermal conductivity of CT850 Tooling Board specimens. The measurements were performed with a guarded-comparative-longitudinal heat flow technique based on ASTM standard E-1225.

Specimen Description

CompoTool Ltd provided the following specimens:

Specimen ID	Description	Width	Depth	Thickness
1	CT850 Tooling Board	≈101.6mm	≈101.6mm	≈ 50.8mm
2	CT850 Tooling Board	≈101.6mm	≈50.8mm	≈50.8mm

The specimens were tested in the depth direction.

Test Procedure

- Specimen Check-In

The specimens were hand delivered at the SAMPE Seattle show. The specimens were inspected for damage. No damage was observed. The specimens were labeled and stored in a secure environment (**Figure 1**).

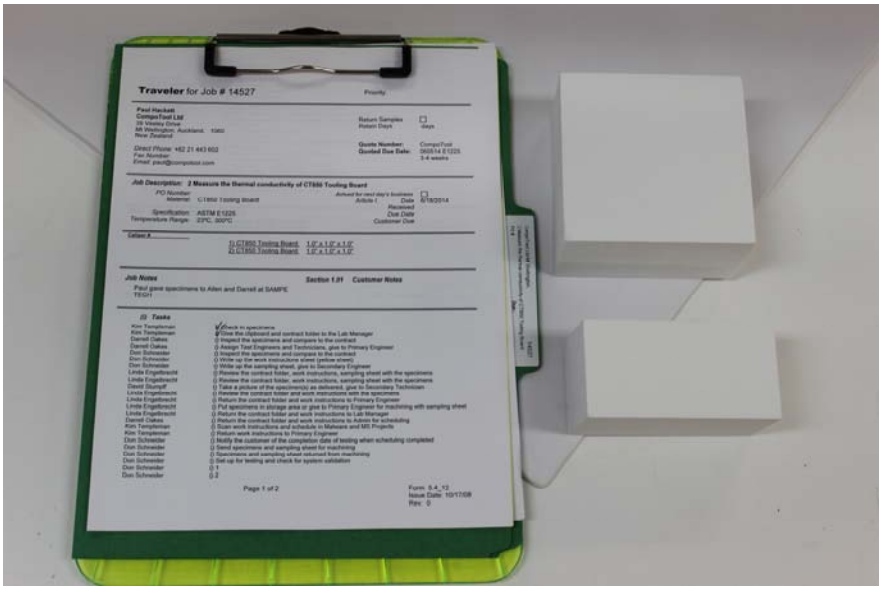


Figure 1: Calcium Silicate samples at check-in

♦ Specimen Preparation

Two thermal conductivity specimens were cut from the 101.6mm x 101.6mm x 50.8mm sample piece. The test specimens were cut to approximately 25.4mm x 25.4mm x13mm and flat sanded to improve the flatness, parallelism and thickness uniformity. Holes with a diameter of ≈0.838mm (#66 bit, .033") for thermocouples were drilled on one face of the specimens. (See **Figure 2**).

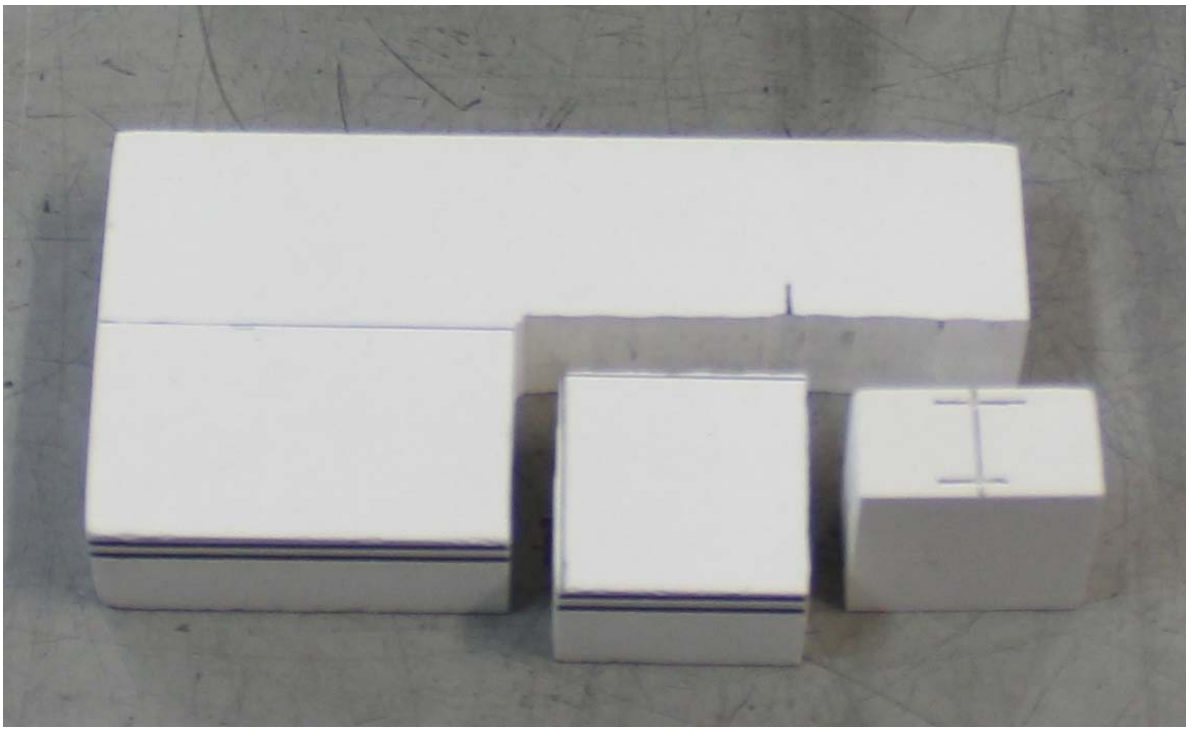


Figure 2: Cutting of sample test material

♦ Specimen Conditioning

Prior to testing the specimens were stored in a vacuum oven at 60°C for at least 24 hours.

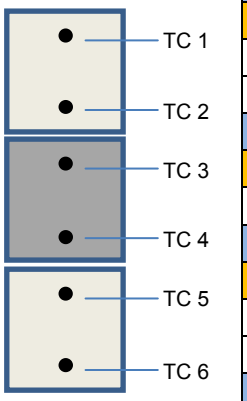
♦ Thermal Conductivity Measurements

The thermal conductivity of the specimens was measured at nominal temperatures of 23°C and 300°C. Pyroceram meter bars fitted with thermocouples, were used for heat flux measurement. K-type thermocouples were placed in the appropriate holes for temperature measurement. A small quantity of thermal grease was applied to the tip of each thermocouple to improve thermal grounding to the specimen or meter bars. A thin film of thermal grease was also applied at each interface, between the specimen, meter bars and hot and cold plates. A uniform compressive load was maintained on the specimen stack during testing. The test apparatus was ramped to the desired temperatures and held for sufficient time to reach steady state. The setup details are given in **Table 1**.

The thermal conductivity-testing apparatus was verified with Pyroceram 9606. Data recommended by TPRC (Thermophysical Properties Research Center, Thermal Conductivity, Volume1, Plenum, New York, 1970) for the reference material were used for the verification. A test was run under identical conditions using a fused quartz reference

material in place of a specimen, to validate the error in thermal conductivity experienced in the testing of the Pyroceram reference material.

Table 1: E1225 measurement setup details



Upper Meter Bar (UMB)* PC-3		Thermocouple Type: 36ga, K-type	
Material: Pyroceram 9606 (K_{MB})		TC 1 ID: A1	TC 2 ID: A2
Area: 648.673 mm^2		TC distance, L_0: 20.31mm	
Approx. Specimen to MB Resistance ratio:		Thermocouple Type: 36ga, K-type	
≈ R_{spec}/ R_{MB} @ RT:	7.4	TC 3 ID: A3	TC 4 ID: A4
Lower Meter Bar (LMB)* PC-4		Thermocouple Type: 36ga, K-type	
Material: Pyroceram 9606 (K_{MB})		TC 5 ID: E3	TC 6 ID: E5
Area: 287.30 mm^2		TC distance, L_0: 20.31mm	

Environmental conditions	Vacuum level	Temperature points	Purge gas
	≤ 13.33 Pa	23, 300 (˚C)	N/A
Column force or load	0.414 MPa (60 lb loading force)		
ΔT across stack	40°C		

* Thermal Conductivity, K of Pyroceram from TPRC data ($K=C_0+C_1*T+C_2*T^2+...C_6*T^6$)

Tmin	Tmax	C_0	C_1	C_2	C_3	C_4
30	800(°C)	4.12364	- 4.86616E-3*T	+ 1.09483E-5*T^2	- 1.34612E-8*T^3	+ 6.29187E-12*T^4

♦ Analysis

10 minutes of data, after the specimen had stabilized at each desired temperature, were used for the conductivity calculation. The temperature of each specimen and meter bar thermocouple was averaged over this time. The analysis is based on solution of Fourier's First Law of one-dimensional conduction:

$$k = \frac{q}{A} * \frac{dX}{dT}$$

where:

k is the conductivity, W/m-K
q is the heat flow, Watts
A is the cross-sectional area of the specimen, m^2
dX is the specimen length, m
dT is the is the temperature difference across the specimen, ºC or K

Uncertainty

The uncertainty in the measurement was calculated using the following RMS method:

$$\omega_R = \left[\left(\frac{\partial R}{\partial x_1} \omega_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} \omega_2 \right)^2 + \ldots + \left(\frac{\partial R}{\partial x_n} \omega_n \right)^2 \right]^{1/2}$$

where: ω_R is the overall measurement uncertainty
x_i is each measured input
ω_i is the estimated uncertainty of each measurement input, x_i
$\partial R/\partial x_i$ is the weighted contribution of each input, x_i

The estimated uncertainties are:

$k_{calib\ or\ MB} \approx 5\%$
A ≈ 1%
dX ≈ 0.127 m
dT ≈ 0.25ºC

Thermal Conductivity Test Results

The results are presented in **Table 2**. The thermal conductivity is expressed in W/m-K. The actual specimen temperature is listed on the table. The Pyroceram reference material tested to within -2.5% of the TPRC published data at 23°C and -13.8% at 300°C. The estimated uncertainty in the specimen measurements over the temperature range is between 5.9% and 7.1%.

Table 2: Thermal Conductivity Results for Calcium Silicate Samples

ASTM E1225

Specimen I.D. Calcium Silicate blocks	Nominal Temperature (°C)	Actual Temperature (°C)	Thermal Conductivity (W/m-K)
#1	23	23	0.426
	300	301	0.667
#2	23	22	0.418
	300	300	0.633

Please contact our technical staff at (541) 753-0607 if you have any questions or require additional information regarding these measurements.

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Project Engineer

Linda Engelbrecht
Project Engineer

Darrell Oakes
Lab Manager

Precision Measurements and Instruments Corporation hereby claims that test results are obtained by techniques based on relevant ASTM standards, calibrations with NIST standard reference materials and/or published procedures. Thus, we accept no liability for test results beyond the cost of the contract rendered.

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