Thermal Conductivity Testing Report

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OBJECTIVE

The objective is to determine the thermal conductivity of the provided thermal paint samples at ambient temperature.

APPARATUS

As detailed in Appendix 1, a C-Therm TCi Thermal Conductivity Analyzer (above) was used in this study to perform all the thermal conductivity and thermal effusivity measurements. The C-Therm TCi Thermal Conductivity Analyzer is a modular system with a range of sensors available to accommodate a diverse range of samples. When operated with a Modified Transient Plane Source sensor (left), it is an integrated solution for thermal conductivity and thermal effusivity measurement and operates in compliance with ASTM Standard D7984-16. When operated with the Transient Line Source sensor (right), it operates in compliance with applicable international standards for the testing of polymer melts, soils, soft rock and unconsolidated solids, including ASTM Standard D5334, ASTM Standard D5930, and IEEE Standard 442-1981.

In the case of these samples, the C-Therm TCi Thermal Conductivity Analyzer was used in the Modified Transient Plane Source (MTPS) configuration, which is suited to the analysis of solids, liquids, powders, pastes, textiles, and similar materials. The system was operated in accordance with ASTM D7984. The aerogels calibration was employed for sample testing. In accordance with established test procedures for aerogels, no contact agent was employed and a 3 second test was used. Density (measured via a volumetric-gravimetric method) and specific heat (obtained from literature for Isonem paint) were input to the data analysis algorithm to ensure maximum accuracy of the aerogels test method.

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SAMPLES

Sample provided by the client are pictured below:

Sample were used as provided; two layers were required for Thermal Paint 3cm and 2cm samples in order to prevent the sensor heat pulse from reaching the far end of the material. The final sample, Isonem Thermal Paint (not pictured) was shipped with insufficient thickness for accurate testing. This paint will be tested after appropriate sample machining and the final report shall be issued.

RESULTS

The results for samples are summarized in Table 1 and graphically in Figure 1. Note: RSD is relative standard deviation and k is thermal conductivity in W/mK

Table 1. Thermal conductivity test results of 2cm samples and 3 cm samples

Sample	**Thermal Paint 2cm**		**Thermal Paint 3cm**	
Test	**k (W/mK)**	**RSD (N=5)**	**k (W/mK)**	**RSD (N=5)**
1	0.039	0.6%	0.039	1.0%
2	0.039	0.9%	0.040	0.5%
3	0.040	1.6%	0.040	1.1%
Average	0.039	1.5%	0.039	1.6%

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Table 2. Thermal conductivity test results of 5cm and uncut samples.

Sample	Thermal Paint 5cm		Thermal Paint Uncut	
Test	**k (W/mK)**	**RSD (N=5)**	**k (W/mK)**	**RSD (N=5)**
1	0.031	2.7%	0.033	1.2%
2	0.032	0.5%	0.034	0.5%
3	0.033	1.2%	0.033	1.2%
Average	**0.032**	**2.8%**	**0.033**	**1.4%**

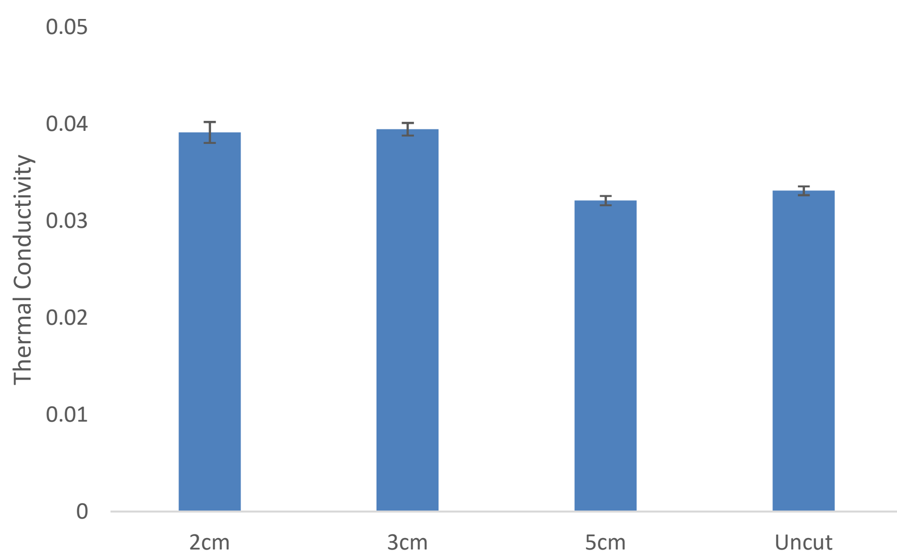

Figure 1: Graphical Comparison of the Samples' Thermal Conductivity

CONCLUSION

The thermal conductivity of the samples provided were characterized using the modified transient plane source (MTPS) method. The Thermal Paint 3cm sample has the highest thermal conductivity. The 5cm and Uncut samples had lower thermal conductivity.

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APPENDIX 1 – C-Therm TCi Thermal Conductivity Analyzer

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SIMPLIFYING

Thermal Conductivity (*k*)

FAST, ACCURATE TESTING
0 to 500 W/mK in seconds

WIDE TEMPERATURE RANGE
-50 ˚C to 200 ˚C
With option to extend to 500 °C

NO SAMPLE PREPARATION
Unlimited sample size

NON-DESTRUCTIVE
Leaves sample unaltered

EASY-TO-USE
No user-calibration required

HIGHLY VERSATILE
Tests solids, liquids, powders and pastes

MODULAR
Configurable to meet a range of needs and budget.
Option to pair with C-Therm Dilatometer.

C-THERM TCi™
Thermal Conductivity Analyzer

ALSO PROVIDES: EFFUSIVITY | DIFFUSIVITY | HEAT CAPACITY | DENSITY

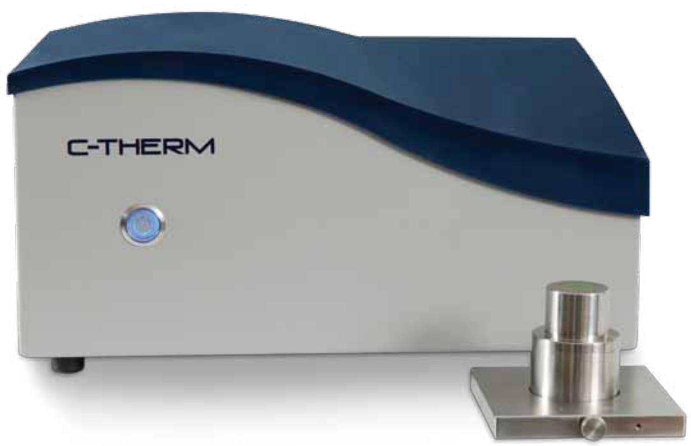
SIMPLIFYING

THERMAL CONDUCTIVITY

C-Therm's patented sensor technology makes thermal conductivity simpler and more accessible to measure. There is simply no faster or easier way to measure thermal conductivity and effusivity.

With the C-Therm TCi there is no complex regression analysis necessary as with other transient methods. No special sample preparation is required and there is no need to measure additional sample material properties such as heat capacity.

The TCi is provided with one versatile sensor for testing all types of materials; including solids, liquids, powders and pastes. A second sensor can be added for increased capacity.



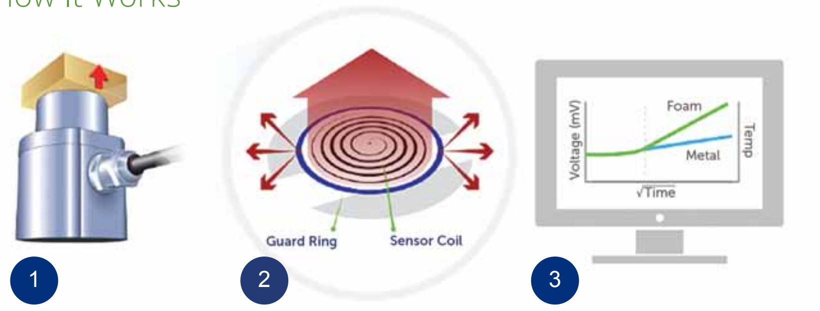
The testing procedure is noninvasive; samples remain unaltered and reusable. The system offers users exceptional versatility in being able to operate in a variety of environments, including thermal chambers, high pressure vessels and glove boxes. Fast and accurate testing made easy!

Principles of Operation

The C-Therm TCi employs the patented Modified Transient Plane Source (MTPS) technique. The one-sided, interfacial heat reflectance sensor applies a momentary constant heat source to the sample. Thermal conductivity and effusivity are measured directly, providing a detailed overview of the thermal characteristics of the sample.

MTPS GUARD RING TECHNOLOGY

How It Works



The TCi is factory-calibrated for directly measuring both thermal conductivity (k) & thermal effusivity:

k Thermal Conductivity & **Effusivity** $= \sqrt{k\rho c_p}$

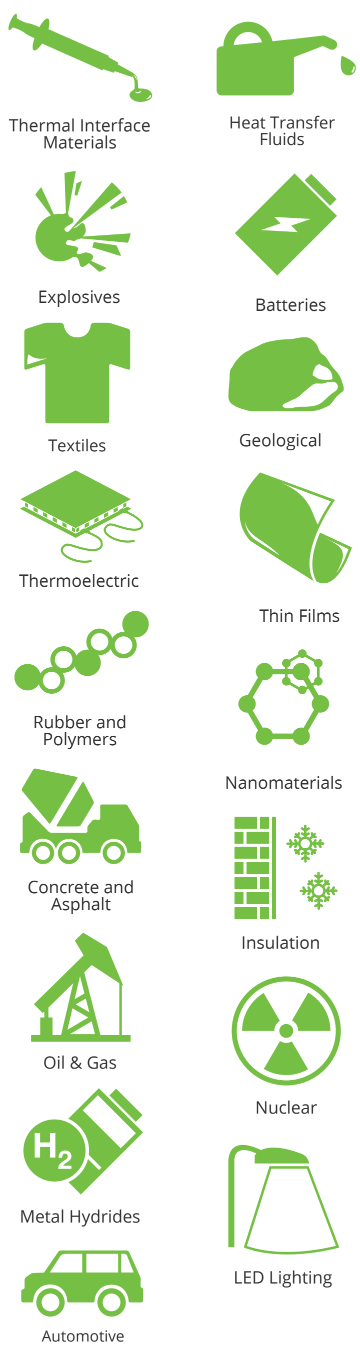
Where:
k = thermal conductivity (W/m • K)
ρ = density (kg/m³)
c_p = heat capacity (J/kg • K)

1. A known current is applied to the sensor's spiral heating element, providing a small amount of heat.
2. The sensor's guard ring is fired simultaneously supporting a one-dimensional heat exchange between the primary sensor coil and the sample. The current applied to the coil results in a rise in temperature at the interface between the sensor and sample, which induces a change in the voltage drop of the sensor element.
3. The increase in temperature is monitored with the sensor's voltage and is used to determine the thermo-physical properties of the sample. The thermal conductivity is inversely proportional to the rate of increase in the sensor voltage (or temperature increase). The voltage rise will be steeper for lower thermal conductivity materials (e.g. foam) and flatter for higher thermal conductivity materials (e.g. metal). Results are reported in real-time making thermal conductivity measurement fast and easy.

VERSATILE

EASILY TEST SOLIDS, LIQUIDS, POWDERS AND PASTES

APPLICATIONS



Solids: Conductive Polymers

C-Therm has provided a breakthrough in the characterization of critical performance attributes of conductive polymers used in electronics and automotive industries. The main advantage the technique offers is the flexibility to test a wide range of sample geometries. As an example, clients at a large polymer producer use the test samples from their tensile testing regimen to also test the in-plane and through-plane thermal conductivity with the C-Therm TCi. There is no longer the need to destructively machine or form specific sample sizes/dimensions to test thermal conductivity!

Powders: From Explosives to Ink Toners

The C-Therm TCi is being used to safely test the stability, degradation, and shelf life of explosives because it is the only instrument engineered for evaluating the thermal conductivity of powders safely. Sample volumes are as small as 1.25 ml. This is also critical to a rapidly growing client base in metal hydrides, where materials are expensive and available in low quantities. The technology is also migratable to manufacturing environments as a cost-effective way to monitor powder processes for moisture and homogeneity.

Pastes: Keeping the Hottest Electronics Cool

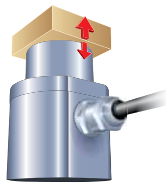
The faster and smaller microprocessors become, the more heat they generate. C-Therm's TCi is providing vital insights into the development of all materials that contribute to the overall thermal budget, including thermal interface materials such as thermal grease and gap pads. These materials are typically compressible and the thermal conductivity varies with changes in the densification of the material. Clients use the C-Therm Compression Test Accessory (CTA) to precisely control the compaction of the sample in producing results reflective of the actual application conditions for the material.

Liquids: Under Pressure

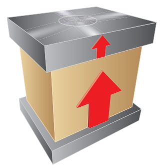
The C-Therm TCi is helping manufacturers improve the heat transfer properties of liquids. C-Therm is unique in offering the capability to accurately measure the thermal conductivity of liquids; the short test time (<1 second) and small sample volume requirements negate the convective errors typical in liquid testing with traditional techniques. As an example, clients in the Oil & Gas field use C-Therm's High Pressure Cell (HPC) accessory in measuring the impact of elevated atmospheric conditions and temperature on the thermal conductivity of fluids.

COMPARISON

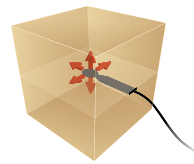
FASTER, EASIER, MORE VERSATILE



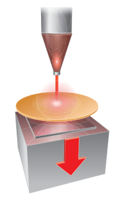
C-Therm TCi
(Modified Transient Plane Source)



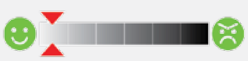
Guarded Hot Plate



Transient Plane Source



LaserFlash Diffusivity

	C-Therm TCi	Guarded Hot Plate	Transient Plane Source	LaserFlash Diffusivity
SPEED & FLEXIBILITY				
Sample Preparation	None Required	Extensive	Some	Extensive
Testing Time	Seconds	Hours	Minutes	Hours*
Training Time	Minimal	Moderate	Significant**	Extensive
Non-Destructive	Yes	No	No	No
Method Development				
RANGE				
k-Range (W/mK)	0 – 500	0 – 2	0 – 100 (100 – 500 requires C_p)	0 – 500 (requires density & C_p)
Temperature Range (°C)	-50 °C to 200 °C With option to extend to 500 °C	-100 °C to 1400 °C	-100 °C to 700 °C	-150 °C to 2800 °C
SAMPLE CONFIGURATION				
Minimum	0.67” diameter (17 mm)	6” x 6” (150 x 150 mm)	Two Identical Samples 1” x 1” (25 x 25 mm)	0.5” diameter (12.4 mm) 0.004” thick (1 mm)
Maximum	Unlimited	24” x 24” (600 x 600 mm)	Two Identical Samples Unlimited	0.5” diameter (12.4 mm) 0.004” thick (1 mm)
Material Testing Capabilities	Solids, Liquids, Powders, Pastes	Solids	Solids, Liquids	Solids
PRICING	$	$ $	$ $	$ $ $

1 Based on publicly available information and feedback from users.
* Calculation of thermal conductivity from Laser Flash Diffusivity Measurement requires the additional following material properties: heat capacity (C_p) density, and coefficient of thermal expansion.
** Traditional Transient Plane Source requires iterative testing to obtain the correct experimental parameters in terms of power flux, test time, and sizing of sensor necessary to obtain accurate results.

MODULAR

SCALABLE SOLUTIONS

ACCESSORIES

Compression Test Accessory (CTA)

Compression of sample material increases the density and impacts the effective thermal conductivity of the material. It is important that the level of compaction is controlled and representative of the application conditions of the material. C-Therm's Compression Test Accessory (CTA) enables researchers testing such materials to precisely control the densification in providing highly reproducible results that better reflect the effective thermal conductivity. The CTA is particularly recommended to users testing textiles/fabrics, insulation batting, thermal interface materials, and powders.

High Pressure Cell (HPC)

C-Therm offers a range of high pressure cells to safely characterize the thermal conductivity of samples under elevated pressure environments up to 2000 PSI (~138 bar). C-Therm's HPCs are popular with researchers in the Oil & Gas, Nuclear and Fuel Cell industries.

Tenney Jr. Thermal Chamber

The TPS Tenney Jr. Thermal Chamber is recommended to users who wish to measure the thermal conductivity at non-ambient temperatures, from -50 ºC to 200 ºC. C-Therm's TCi software enables direct control of the thermal chamber, bypassing manual operation and allowing users to pre-program their desired temperature profile and walk away!

Small-Volume Test Kit (SVTK)

The Small-Volume Test Kit was originally developed with the US Navy Surface Warfare Division specifically for testing energetic materials. The effectiveness of the accessory in reducing convection effect on testing samples make it ideal for characterizing the thermal conductivity of liquid samples. The SVTK is commonly applied in testing nano and heat transfer fluids, as well as emulsions.

DILATOMETRY MODULE

Dilatometry provides key expansion and shrinkage properties of materials under defined temperatures.

TEMPERATURE RANGE	Room Temperature to 1600 °C
TEMP. RESOLUTION	0.1 °C
MAX DISPLACEMENT	4 mm
ΔI RESOLUTION	1.25 nm/digit
ATMOSPHERE	Air, Vacuum, Inert Gas
SAMPLE DIMENSIONS	10 to 50 mm long x max ϕ12 mm
SAMPLE HOLDER	Fused Silica, Alumina
CONFIGURATIONS	Single or Dual Rod LVDT System 1200 °C or 1600 °C furnace
HEATING ELEMENT	FeCrAl, SiC
RATE OF INCREASE (ºC)	1 ºC/min up to 50 ºC/min

C-Therm's latest generation TCi offers an innovative new option to pair the controller with an optional dilatometer. This offers researchers significant savings in leveraging commonalities of the TCi control electronics while expanding the platform's capabilities to dilatometry.

THERMAL EXPANSION • FIRING • PHASE TRANSITION
SHRINKAGE • SINTERING

Conforms to all major standard methods for dilatometry, including ASTM E228.

PROVEN

For over a decade, C-Therm's innovative sensor technology has been pioneering the way for many of the world's most prominent manufacturers, research facilities, and academic institutions to test and measure thermal properties of materials.

WINNER

The technology behind the C-Therm TCi represents a paradigm shift in thermal conductivity measurement and earned the inventor behind the technology the Manning Innovation Principle Award and an R&D 100 Award. These coveted awards are given to the top global innovators, and place C-Therm in the distinguished company of such other winners as the developers of the ATM, Polaroid™ and anti-lock brakes.

Since its launch, C-Therm's unique technology has evolved to new levels of accuracy, speed, and flexibility. Today, it is being used around the globe for R&D, quality control, and on-line production monitoring in a wide range of industries.

C-THERM TCI SPECIFICATIONS	
Thermal Conductivity Range	0 to 500 W/mK
Test Time	0.8 to 3 seconds
Minimum Sample Testing Size	17 mm diameter
Maximum Sample Testing Size	Unlimited
Test Method	Modified Transient Plane Source (MTPS)
Minimum Thickness	Nominally 0.5 mm, dependent on thermal conductivity of material
Maximum Thickness	Unlimited
Temperature Range	-50 °C to 200 °C With option to extend to 500 °C
Precision	Typically better than 1%
Accuracy	Better than 5%
Extra Hook-Ups Required	None
Software	Intuitive Windows®-based software interface. Easy export to Microsoft Excel®. Additional functionality offers indirect, user-input capabilities for a number of other thermo-physical properties including: • Thermal Diffusivity • Heat Capacity • Density
Input Power	110-230 VAC 50-60 Hz
Certifications	FCC, CE, CSA

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COMPANIES AND ORGANIZATIONS USING C-THERM'S PATENTED TECHNOLOGY:

NASA

University of California (Berkely)

Philips

Kodak

Avery

3M

Philip Morris

Astra Zeneca

US Navy

Patheon

Universidade de Aveiro

Raytheon

Corning

Engelhard

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Dow Corning

Exxon Mobil

Hewlett Packard

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Liberec University

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Petrobas

Henkel

Nanocomposix

Canadian Explosives Research Lab

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APPENDIX 2 – Reference Material Test Results

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Reference Material Results

An accuracy check was performed on the instrument prior to running any tests on the standard reference materials of the calibrations to be used and confirmed the instrument was performing well within the stated accuracy specification of 5%. The accuracy of the measurements conducted under specific environmental conditions can be examined by measuring reference materials with externally certified thermal conductivity values. In comparing the observed measurements of the materials with the known thermal conductivity values of the materials, the accuracy of the measurements for unknown samples can be evaluated. The results for the reference accuracy check for the measurements carried out in this study are listed in the table below.

Table A1 – Reference Material Test

Reference Material	Measured Thermal Conductivity (W/m·K)	Avg. of the Measured Thermal Conductivity	RSD (%)	Expected Thermal Conductivity (W/m·K)	Bias (%)
LAF6720	0.062	0.062	0.2	0.0609	1.2
	0.062				
	0.062				
	0.061				
	0.062				