Categorization, Testing, and Selection of Thermal Interface Materials for Semiconductor Test

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Tutorial

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Agenda: Thermal Interface Materials

I. Importance of Thermal Interface Materials for semiconductors and test

II. Categorization methodology for thermal interface materials

III. Identification of TIM categories useful for semiconductor test

IV. TIM industry testing methodologies and practices

V. Recent developments of new materials in new TIM categories

VI. Identification of TIM categories useful for semiconductor liquid immersion test systems and immersion fluid compatibility

VII. Selected References

Note: This tutorial is intended primarily for materials useful for semiconductor test and test heads. In addition, many TIM types described may be selected to meet other applications in test systems.

Importance of Thermal Resistance: Power Semiconductor Example

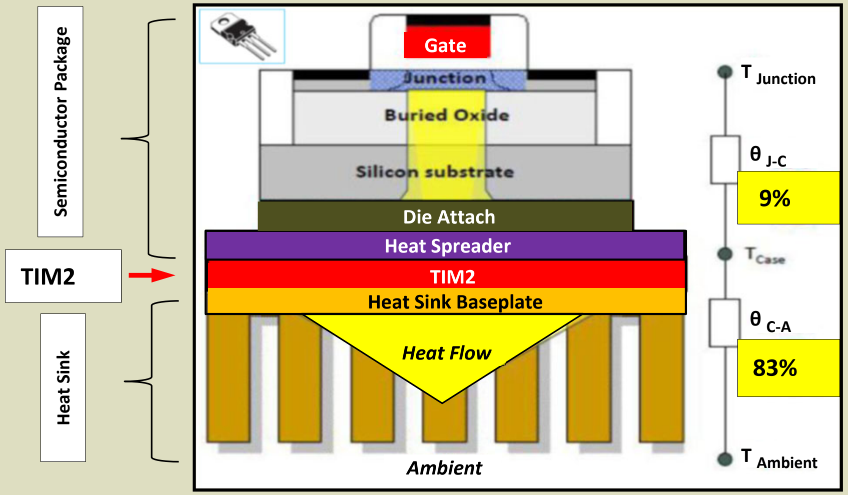


Figure 2 – TO-220 Thermal Resistance Stack

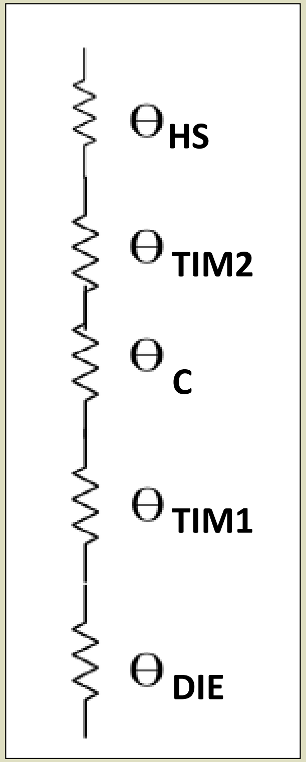
Empirical Analysis, TO-220 Package Materials Thermal Resistance Contribution

Material Layer	BLT (µm)	λ (W/mK)	Percent of Total (%)
Die (Si)	100	150	6
Die Attach (Solder)	20	50	3
Substrate (Cu)	200	380	2
TIM2 (Thermal Grease)	100	5	71
Heat Sink (Al)	2000	180	10
Other	-	-	8
Total	-	-	100

Data Source: Berliner Nanotest und Design GmbH (Germany). Used with permission.

Overview: Thermal Interface Material Function

System thermal management is the sum of a series of thermal resistances:



Heat sink: Inherent bulk material property – typically aluminum or copper (heat sink, liquid cold plate, vapor chamber)

TIM2: *External* to semiconductor package; θ_{T2} is determined by material resistance, which consists of bulk value plus (2) contact resistances (case surface, heat sink)

Case (or lid): Inherent bulk material property – typically nickel-plated copper*

TIM1: *Internal* to semiconductor package; $\theta_{T1\text{-}C}$ is determined by the material resistance which consists of bulk value plus (2)contact resistances (die surface, lid interior surface);

or, **TIM0**: Semiconductor package without lid ("bare die" package)

Die: Inherent bulk material property (Si, SiC, GaN, GaAs, other)

Note: Aluminum for low-power IC packages; aluminum or nickel-plated copper for "paddle" for TO-style power semiconductors and "top-side cooled" power semiconductor modules.

Overview: Thermal Interface Material Function

The primary performance value for a thermal interface material is thermal resistance per unit area (previously referred to as thermal impedance):

° $C\text{-}in^2/W$ or ° $C\text{-}cm^2/W$ (also commonly used, ° $C\text{-}mm^2/W$)

- *Vendor data sheet performance values* are typically expressed as thermal resistance versus clamping force applied (range, typically 0-100PSI).
- In a performance graph, thermal resistance appears on the Y-axis versus clamping force on the X-axis.
- Increased clamping force has a large impact on thinning a TIM and improving (*lowering*) the thermal resistance value.
  - Values are typically asymptotic.
  - General function of a TIM is heat transfer across an interface.

Overview: TIMs for Specific Semiconductor Segments

TIMs are critical for semiconductor test across different semiconductor segments:

- RF power semiconductors and modules
- Power semiconductors in a wide range of package and module configurations
- Integrated circuits – single die, multiple die, SoC, HIR
- Memory

Overview: TIMs for Specific Semiconductor Segments

Current IC industry roadmaps are creating significant new difficulties for TIM performance and application requirements, specifically:

- Heterogeneous integration packaging
- AI processor multiple-die packaging, warpage, power dissipation
- Single- and two-phase liquid immersion
- Quantum processor temperatures

Certain of these challenges *place extreme performance requirements on TIMs that are not necessarily yet resolved* with new TIM developments.

Overview: TIMs for Specific Semiconductor Segments

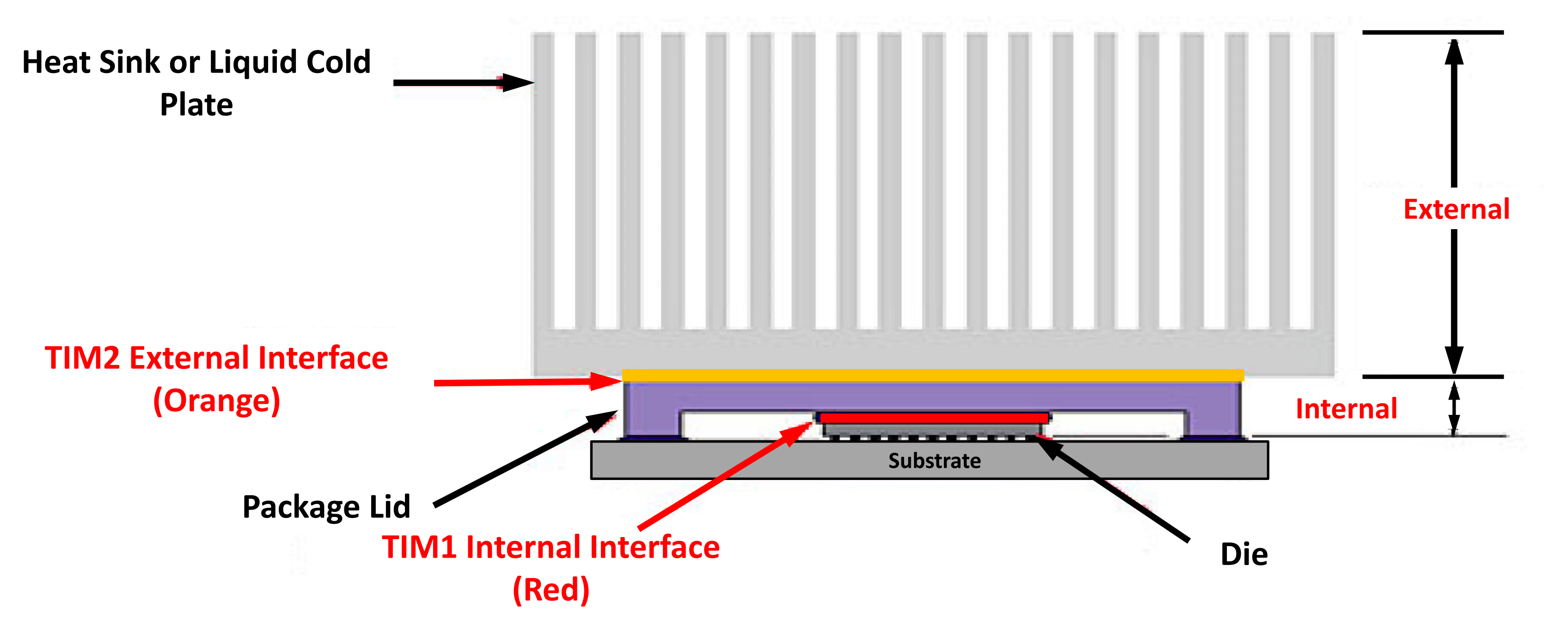
Many different semiconductor package and module types are utilized across industry:

- Semiconductor segment, type, and package or module type will impact specific materials requirements for functional test requirements;
- Cost and through-put is critical to semiconductor test;
- Individual market segments have widely varying module and cost limits (tolerances):
  - Example: Military X-band radar modules have extremely high cost and test is critical at different stages of module assembly, with reworkability a critical requirement – which drives TIM selection criteria;
  - Extremely high cost and low volume production impacts decisions for test and test cost, as compared to high-volume/low cost tolerance processor test requirements.

TIM Terminology

Proper use of terminology is important:

- All applications *external to the semiconductor package* are TIM2:

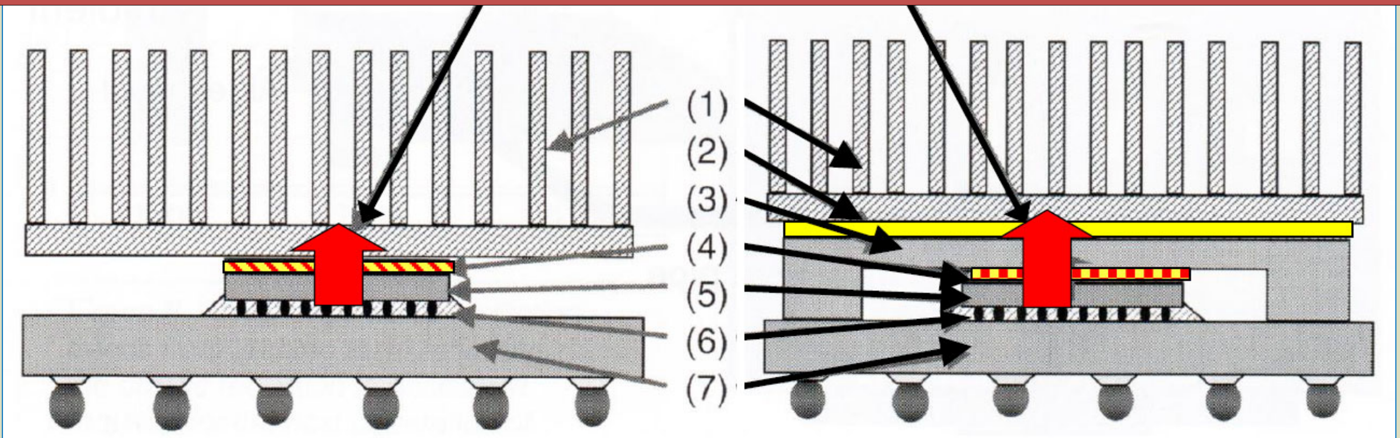


Note: The earlier term adopted as "TIM 1.5" was replaced with "TIM 0" twenty years ago. The three standard terms are TIM0, TIM1, TIM2.
Source: Boteler, L., "Thermal Design of Power Electronics," US Army RDECOM Army Research Laboratory, APEC 2019 Conference, Tutorial (March 2019).

TIM Terminology

Heat Flow Path and Relevant TIM Placement: Common Integrated Circuit Applications

Primary heat transfer path from semiconductor die through TIM/heat sink/ambient air



Key:
(1) Thermal Solution (Heat Sink)
(2) TIM2 🟨
(3) Package Lid
(4) TIM:
  A. Bare die package: TIM0 ▨
  B. Lidded package: TIM1 ▨
(5) Semiconductor die
(6) Interconnect and Underfill
(7) Package Substrate

TIM Terminology

Thermal Interface Material Terminology		
Package Level	**Generally Accepted Definition**	**TIM Terminology**
1	Semiconductor die to heat sink (external, bare die package)	TIM0
1	Semiconductor die to package lid (internal, lidded package)	TIM1
2	Semiconductor lid, case, or baseplate: external to the package, conducting heat to a heat sink, liquid cold plate, or metal component	TIM2
3	PCB or PCB-mounted components or enclosure sheet metal: conducting heat from the PCB or components mounted on the PCB to a large heat sink or metal component (the primary use for gap-filler TIMs). Thickness > 0.10”/250µ (typ.)*	Gap-filler*⁺
4	Platform or subassembly level, conducting heat from the case of a power supply or other large module, large heat sink, metal component*	Gap-filler*⁺

Notes: ** Traditional terminology and definitions*
⁺ Sheet form, die-cut preform, or dispensed

TIM Terminology

Proper use of terminology is important:

- Die attach materials are not categorized as TIMs (although there are limited examples of Ag-filled DA pastes used as TIM1).
- Intel/AMD use of *reflowed indium solders* for TIM1 (within the semiconductor package) is a separate category of TIM application.
  - The term “Solder TIM (STIM)” is appropriate only to these packages.
  - The term “STIM” is *not appropriate* for use in other TIM applications and only creates confusion.
  - A *Solder TIM* has different formulation and requirements than a *liquid metal TIM*.
  - *Liquid metal TIM* and/or *PCMA TIM* are not defined as an STIM.
- Solders are otherwise not categorized as TIMs.

Note: All solders and die attach materials generally have thermal characteristics and provide a heat flow path -- but are not considered in the general terminology usage as thermal interface materials (TIMs). Solders and die attach materials are selected by different criteria as the primary function is <u>electrical interconnect</u>. In very limited cases, a die attach gel has been used as a TIM1.

Thermal Management Technologies - Specific to Semiconductor Test

System Thermal Management Technologies							
Thermal Management Technology	**Accuracy and Stability**	**Temperature Range Capability**	**Thermal Efficiency**	**Heat Flux Range (W/cm^2)**	**Dynamic Response**	**Cost**	**Environmental and Ergonomic**
Refrigeration	Very High	Wide (Cooling)	Very High	(Very High)	Very Fast	Very High	Use of low-GWP refrigerants; Condensation
TEC + Liquid Cooling	High	Wide (Cooling and Heating)	Moderate to High	<250	Fast	Moderate	Condensation (requires insulation)
Liquid Immersion	High	Wide	High	<350	Slow	Moderate	None
Two-Phase Dielectric Liquid Cooling	High	Wide (Above Ambient Temperatures)	High	<350	Fast	High	Condensation*
Fan + Heat Sink	Low	Narrow (Cooling)	Moderate	<50	Slow	Very Low	Fan Noise , Vibration
Heat Sink	Low	Narrow (Cooling)	Low	<10	Slow	Very Low	None

*Notes: Very generalized statements; many system variables to consider. * Depending on temperature differential and dew point. Source: DS&A LLC, modified from Kulicke & Soffa (USA) .*

Essential Factors for TIM Performance and Selection: General

TIM performance is never measured by a single factor:

- Bulk thermal conductivity value alone is highly misleading

Multiple factors must be evaluated for selection of a TIM:

- Thermal resistance at designed clamping force level
- Clamping force applied
- Co-planarity of mating surfaces
- Surface wetting percentage
- Material formulation and performance over time and temperature, including potential for polymeric bake-out, pump-out, or silicone migration
- Surface flatness, surface roughness
- Other long-term reliability factors

Essential Factors for TIM Performance and Selection: Specific

Factors that are increasingly critical in specific categories of TIM application:

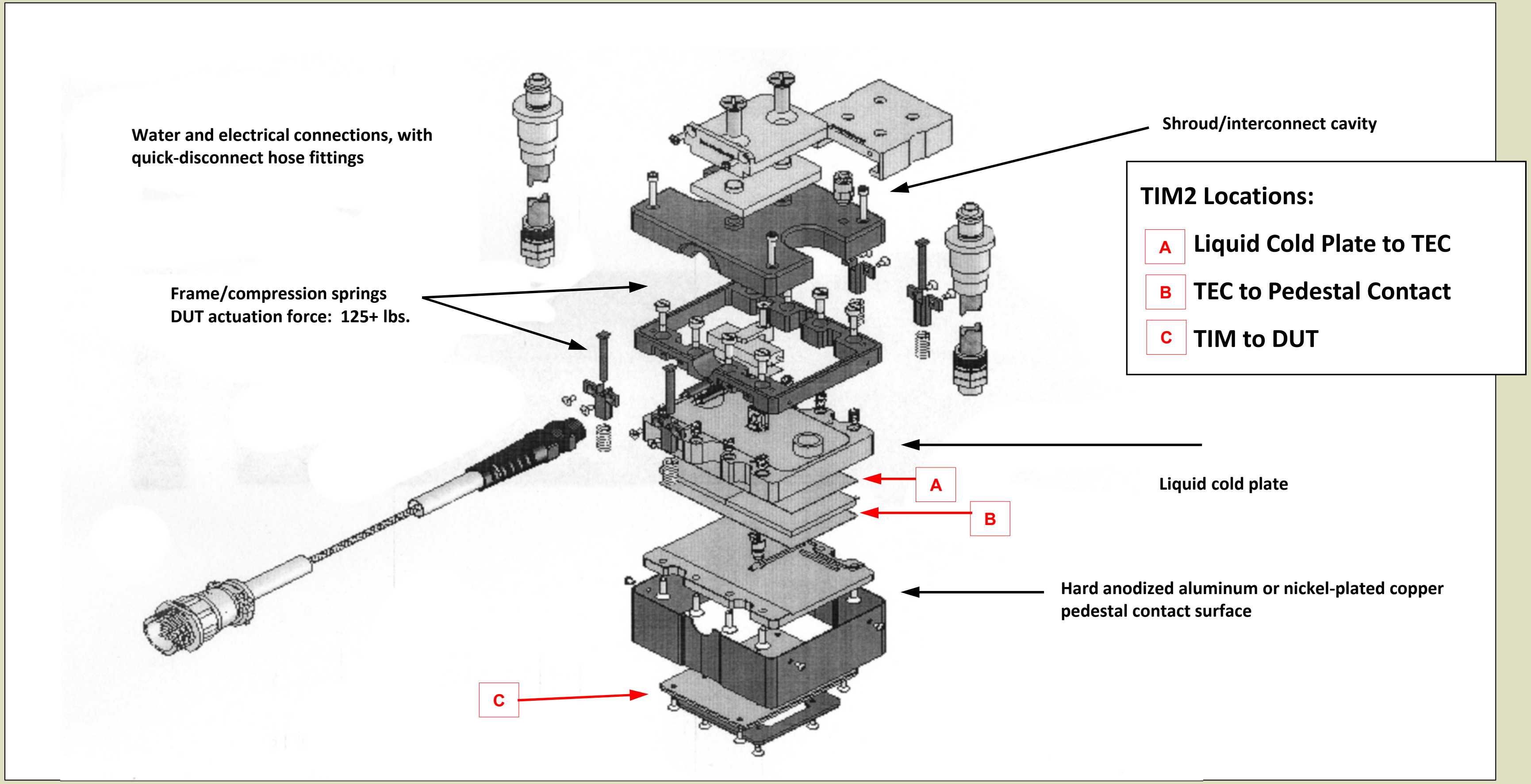
- *Operating and storage temperature tolerance* (-60C to + 600C), depending on specific application type
- Die warpage (0 to $\geq$ 300μ) across die or contact surface area X
- Humidity
- Mating surfaces and potential for corrosion or intermetallic formation
- Erosion due to fluid chemistry and/or boiling action in liquid immersion
- Surface metallizations and reflow process temperature for TIM1 STIM
- Cryogenic temperature performance and reliability factors for quantum

TIM Applications Specific to Semiconductor Test

Proper testing and evaluation is critical to proper selection for a specific package type and application requirements from thousands of TIMs:

- For semiconductor test, specifically:
  - Determine TIM application requirements for test, such as:
    - No marking of DUT, no flaking or detritus;
    - Durability, ability to bend or fold to test head, no cracking;
  - Does a selected TIM meet temperature, assembly process, reworkability?
  - Is a selected TIM suitable for semiconductor test? -- *The most challenging application requirements for TIMs are found in semiconductor test*.
  - Does the TIM selected meet durability and reliability requirements for semiconductor test?

TIM Applications Specific to Semiconductor Test

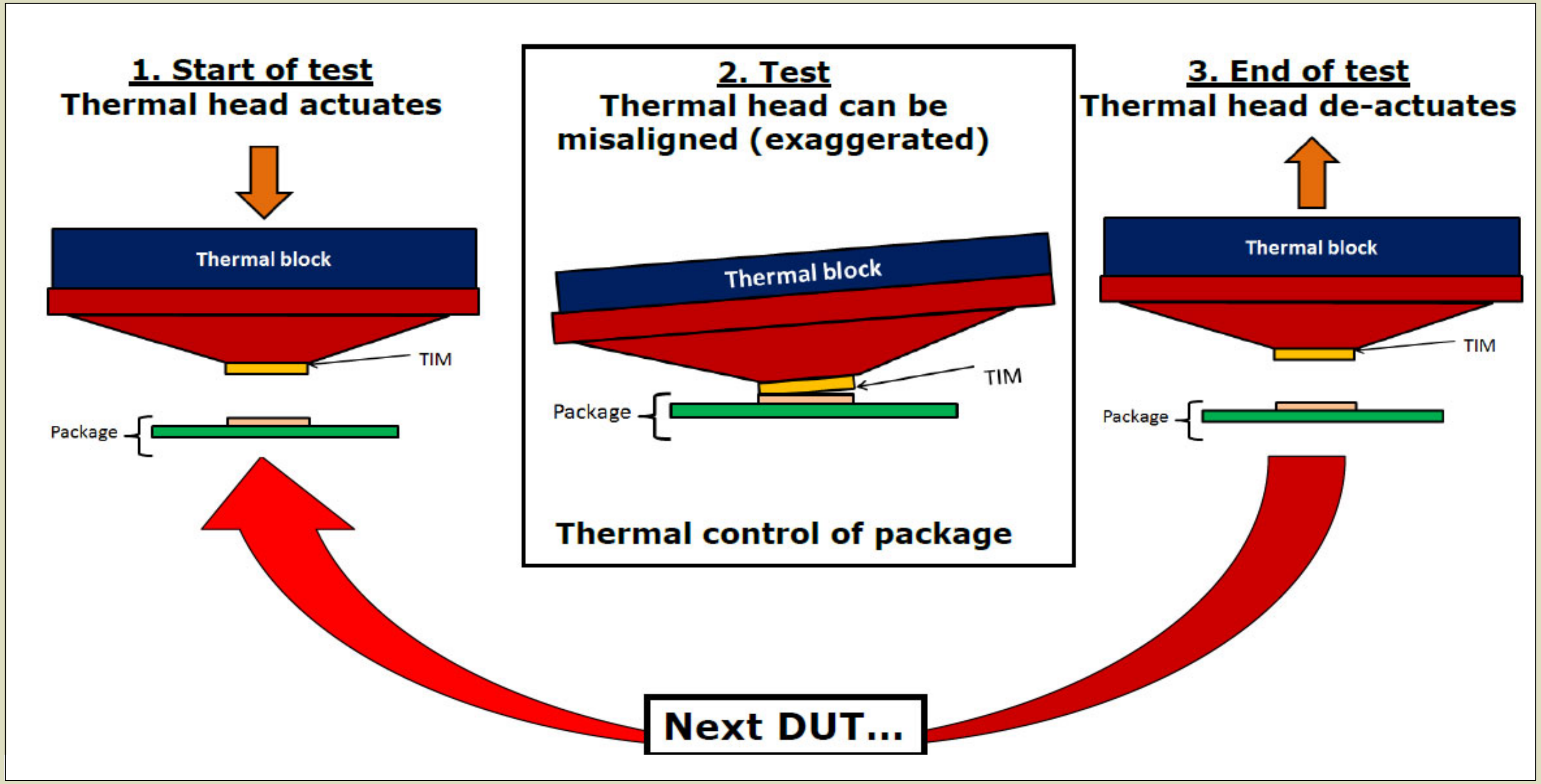


TIM2 Locations:

- A Liquid Cold Plate to TEC
- B TEC to Pedestal Contact
- C TIM to DUT

Source: Antares Advanced Test Technologies (USA) (with modifications and labels added). Note that performance requirements for TIM2 "C" only are DUT contact.

TIM Applications Specific to Semiconductor Test



1. Start of test
Thermal head actuates

2. Test
Thermal head can be misaligned (exaggerated)

Thermal control of package

3. End of test
Thermal head de-actuates

Next DUT…

Source: J. Sanchez, Intel ATTD, Chandler AZ USA

TIM Categorization, Testing, and Material Selection

TIM Categorization System

Purpose:

- Identify differences between TIM types
- Distinguish differences in significant application requirements: material thickness, dispensability, carriers
- Identify major types as solid preforms, pastes, gels, compounds
- Identify adhesives versus categories requiring mechanical fasteners
- Identify dielectric versus non-dielectric materials

TIM Categorization System

General Functions and Categories of Thermal Interface Materials

Adhesive Types

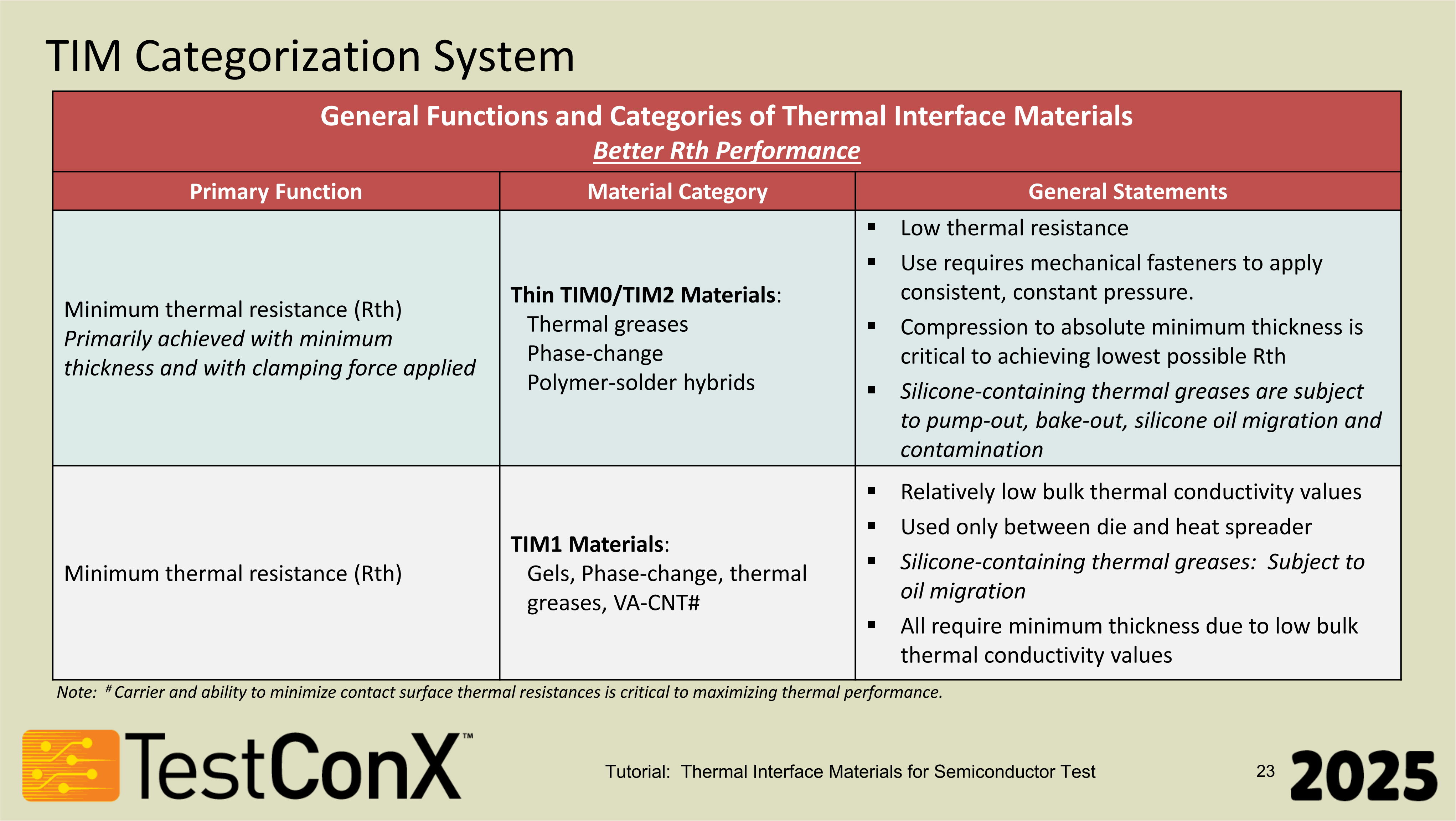
Primary Function	Material Category	General Statements
Adhesive TIM attachment Heat sink fastening Reduced thermal resistance Shock dampening	**Thermally-conductive adhesives (TCA)***: Pressure sensitive preforms Curable or two-part dispensed	▪ Generally very poor thermal performance ▪ Provide adhesive attachment of a heat sink or other component ▪ No mechanical fasteners required ▪ Dispensable TCA are highly desirable in very high volume automotive module applications
Minimum Rth, heat spreading, with CTE control; adhesive	**TIM1 Materials:** Die-Attach Adhesives used as TIM1	▪ Relatively good bulk thermal conductivity and low thermal resistance ▪ Applied between die and heat spreader ▪ Dispensable Ag-filled adhesives ▪ May be difficult to rework

Note: ** Pressure-sensitive adhesives (PSAs) preforms may be manufactured with a carrier, with adhesive coating on two surfaces.*

TIM Categorization System

General Functions and Categories of Thermal Interface Materials *Poor to Moderate Rth Thermal Performance**		
Primary Function	**Material Category**	**General Statements**
Reduce thermal resistance (Θ_{CS} or Rth) versus air over large gaps (i.e., $\geq$ 0.254mm/0.010”)	**Gap-fillers** ▪ **Traditional sheet forms** ▪ **Die-cut preforms** ▪ **Newer dispensable gap-fillers**	▪ Very thick, compressible for large air gaps and differing component heights ▪ Relatively low thermal performance due to moderate bulk thermal conductivity values and significant thicknesses ▪ Often heavy in large sheets; often tacky ▪ *Silicone-containing: Subject to oil migration* ▪ *Single programmable dispensing system can be used for wide range of applications* ▪ Carbon fiber versions may require *limiting compression percentage ($\leq$ 5%) to maintain Rth*
Large-area heat dissipation, temperature control, temperature modulation	**Graphite Sheets** **Elastomeric Sheets**	▪ Wide range of materials ▪ Wide range of Rth values and cost
Electrical insulation with minimized thermal resistance	**Electrically-Isolating**	▪ Less common, higher cost ▪ Dielectric layer seriously impedes Rth values

*Note: * Relative to thin, very high performance TIMs.*



TIM Categorization System

General Functions and Categories of Thermal Interface Materials

Better Rth Performance

Primary Function	Material Category	General Statements
Minimum thermal resistance (Rth) *Primarily achieved with minimum thickness and with clamping force applied*	**Thin TIM0/TIM2 Materials**: Thermal greases Phase-change Polymer-solder hybrids	▪ Low thermal resistance ▪ Use requires mechanical fasteners to apply consistent, constant pressure. ▪ Compression to absolute minimum thickness is critical to achieving lowest possible Rth ▪ *Silicone-containing thermal greases are subject to pump-out, bake-out, silicone oil migration and contamination*
Minimum thermal resistance (Rth)	**TIM1 Materials**: Gels, Phase-change, thermal greases, VA-CNT#	▪ Relatively low bulk thermal conductivity values ▪ Used only between die and heat spreader ▪ *Silicone-containing thermal greases: Subject to oil migration* ▪ All require minimum thickness due to low bulk thermal conductivity values

Note: # Carrier and ability to minimize contact surface thermal resistances is critical to maximizing thermal performance.

TIM Categorization System

General Functions and Categories of Thermal Interface Materials ***Best Rth Performance***		
Primary Function	**Material Category**	**General Statements**
Critical minimum Rth for high heat flux; reworkability highly desirable	**Carbon-Based Arrays:** Carbon Fiber-based Arrays: Vertically-aligned Carbon Fiber Arrays (VA-CNF)	▪ Lowest Rth polymeric materials commercially available currently ▪ Higher cost ▪ Require mechanical fastening
	Carbon Nanotube-based Arrays: Vertically-Aligned CNT (VA-CNT)	▪ Lowest Rth (projected) as commercial polymeric materials (future) ▪ Contact resistances are the major challenge for lowest Rth values ▪ Significantly higher cost ▪ Require mechanical fastening

TIM Categorization System

General Functions and Categories of Thermal Interface Materials ***Best Rth Performance***		
Primary Function	**Material Category**	**General Statements**
Critical absolute lowest Rth for high heat flux die *TIM1: w/CTE Control*	**Reflowed Solders, Liquid Metals, Liquid Metal Hybrids (TIM1, with CTE control)** **PCMA (Phase-change Metal Alloys) (TIM0, TIM2)** **Metallic Preforms (TIM2)** **Graphitic Preforms w/high Z-direction thermal conductivity (TIM2)**	▪ Lowest (best) Rth commercially available currently ▪ Variety of metal alloys and patterns available; variety of graphitic and "graphene-enhanced" graphitic TIMs ▪ Higher cost ▪ Indium alloy solders require reflow process ▪ *Preforms require mechanical fastening and clamping force applied* ▪ *Reflowed solders require contact surface (die, lid) metallization* ▪ Liquid metals require retention mechanism

TIM Categorization System

Thermal Interface Material Categorization and Evaluation

Prioritized TIM Requirements	Property	Typical Value		Alternative/Opposing Value	
1. Electrical	Dielectric Properties	Electrically Conductive		Electrically Non-Conductive	
2. Mechanical	Fastening	Mechanical Fasteners	Adhesive	Mechanical Fasteners	Adhesive
	Thickness	Minimum	Maximum	Minimum	Maximum
	Surface Roughness, Flatness	Minimum	Maximum	Minimum	Maximum
3. Application Process	Dispensing/Placement	Automated	Manual	Semi-Auto	Manual
4. Thermal	Thermal Resistance	Minimum	Maximum	Minimum	Maximum
	Operating Temperature Range	Minimum	Maximum	Minimum	Maximum
	UL Flammability Rating	UL V-0	UL V-0	--	--
5. Cost	Material only/application process/total cost	Material only	Application process only	--	--
6. Environmental/ Health/Safety	Constituent analysis: silicones, toxicity, environmental, H&HS	Government, industry, company regulations			

TIM Performance – General Statements

Determining performance for selecting an appropriate TIM:

- Clamping force uniformly applied is intended to achieve:
  - Maximized surface wetting;
  - Thinnest possible TIM thickness (to minimize bulk thermal conductivity);
- Degree of surface wetting achieved is critical to overall performance, to minimize contact thermal resistance at each of two contact surfaces.
  - *Contact resistance dominates TIM bulk resistance for most materials.*
  - *Achieving the thinnest possible thickness with highest clamping pressure is critical to achieving minimum thermal resistance.*
- Relatively good bulk thermal conductivity is necessary when very limited clamping force (e.g., $\leq$ 30PSI) is available.

TIM Evaluation

Thermal performance is not the only criteria for selection of a TIM.

- A *holistic application view* frequently will result in an application process or a specific reliability requirement influencing selection;
- As a result, the single *lowest thermal resistance* material or the material having the *highest bulk thermal conductivity* may not be selected.
- A material must meet thermal resistance as well as all other requirements: material compatibility, wetting, compression, rheology, assembly procedures, reliability, product life.

TIM Evaluation

A large number of criteria must be established for developing a TIM:

- Important to be aware of the number of criteria and how these individually affect performance of a given TIM;
- The following table is a snapshot of these development parameters, which constitute a complex science.
- Certain of these factors (such as filler percentage by volume) can impact the ability of a TIM to move and not suffer “run-out” (highly thixotropic), affecting relative *thermal performance* and *reliability over time*.
- Selection of a TIM for an application will require certain of these development criteria, but not all.

TIM Evaluation

TIM Typical Development and Evaluation Characteristics	
Thermal Impedance	Dielectric Strength**
Bond Line Thickness Post-Assembly: Compressability	Cut-Through Resistance**
Clamping Force Applied	Thermal Cycling
Wettability	Power Cycling
Bulk Thermal Conductivity	Humidity and Bake
Thixotropicity	HAST
Dispensing/Placement Process Automation	Shock and Vibration
Cure Schedule*	Flammability
Adhesion, Peel Test*	Working Life
Contaminants	Storage/Transit Temperature Range (As Supplied)
Modulus of Elasticity	Shipment/Storage Temp Range (Complete Assembly)
Material Stability	Removability and Rework Process
Silicone Stability	Environmental and Recycling Process
Flammability	Cost

*Notes: *Applies only to adhesive TIMs. **Applies only to dielectric TIMs.*

TIM Evaluation

Basic performance criteria for a TIM characterized as “well-performing”:

- ✓ Required thermal resistance value;
- ✓ Suitable per applicable surface flatness, roughness, clamping force;
- ✓ Suitable per anticipated operating environment;
- ✓ Required product life and reliability:
  - *No* compound run-out or dry-out of a carrier due to temperature, or outgassing
  - *No* compound pump-out due to mechanical stress
- ✓ Suitable cost and delivery format;
- ✓ Suitable assembly process, handling, storage.
- ✓ All of the above measured against specific application requirements.

Thermal Test Performance Terminology

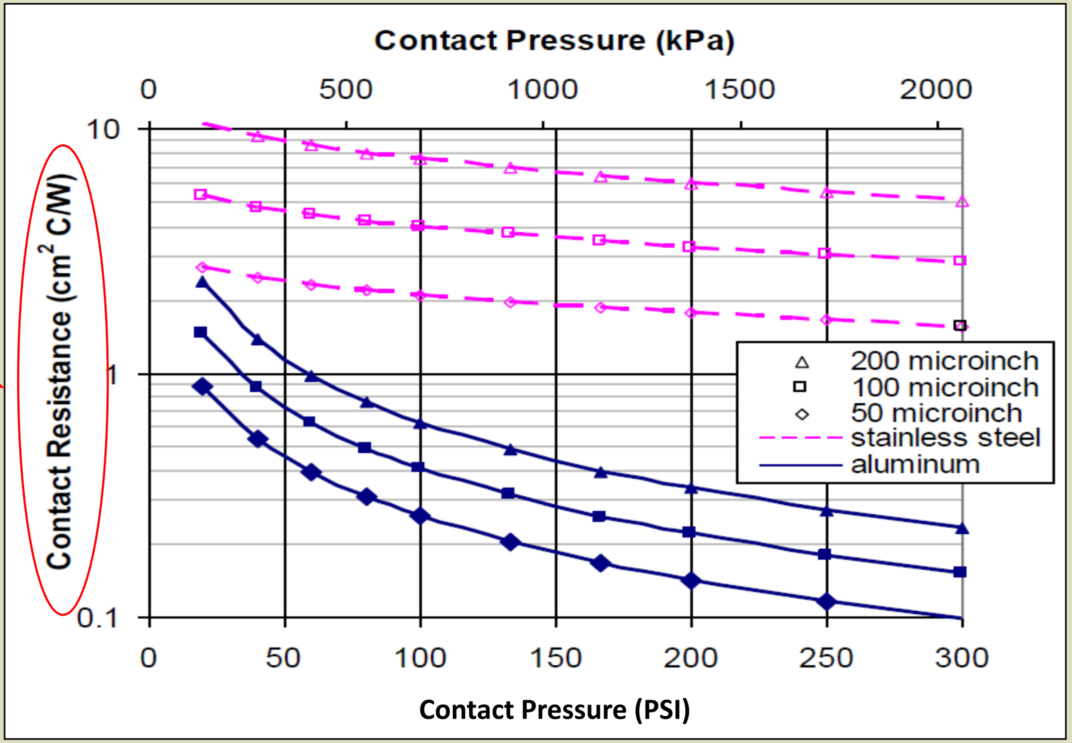
Thermal Interface Material Terminology		
Term	**Generally Accepted Definition**	**Value (Typ.)**
Thermal Resistance (Bulk)	Barrier to flow of heat from heat source through a material or component	°C/W
Thermal Resistance (Interfacial)	Barrier to the flow of heat at the surface of a component	°C/W
Thermal Resistance (Contact)	Alternative term for interfacial thermal resistance (per above)	°C/W
Thermal Resistance (per unit area)*	Barrier to the flow of heat through a material, per unit area (most useful value for selecting a TIM)	°C-in^2/W (or) °C-cm^2/W
Thermal Impedance	Alternative term for thermal resistance per unit area	°C-in^2/W (or) °C-cm^2/W
Heat Flux (Heat Density)*	Amount of power dissipated per unit area (e.g., from a point on the surface of a processor die or across the baseplate of a GaN RF device)	W/in^2 (or) W/cm^2

Note: The above terminology may be used casually and identifying the most useful term is important for selecting a TIM to propose for a given application. The most important term for determining performance of a TIM is thermal resistance per unit area, marked above with an asterisk (*).

Comparative Thermal Resistances

Metal-to-metal surface contact resistance – comparison of two metals, three surface finishes (roughness), under load:

The primary function of a TIM is to minimize thermal contact resistance between two mating surfaces



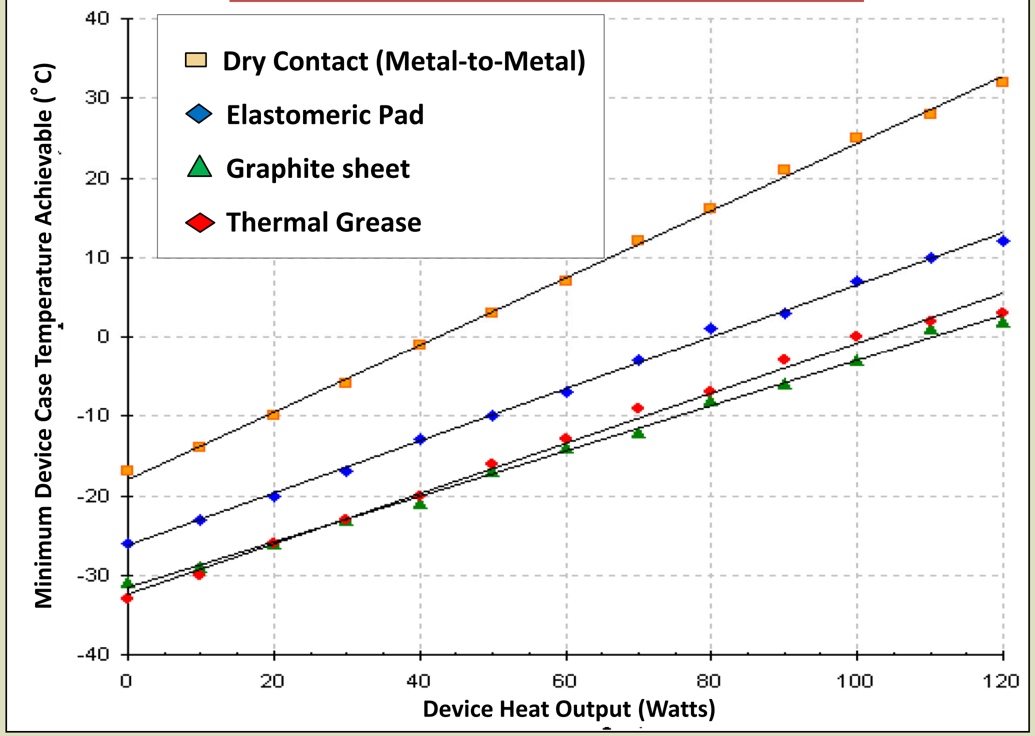
Source: M. Yovanovich, et al., "Calculating Interface Resistance", Electronics Cooling Magazine, *May 1997, Vol. 3, No. 2. Note: Values are RMS values. 100 microinch = 2.54 microns.*

Comparative Thermal Resistances

Impact of a TIM versus dry contact on device operating temperature:

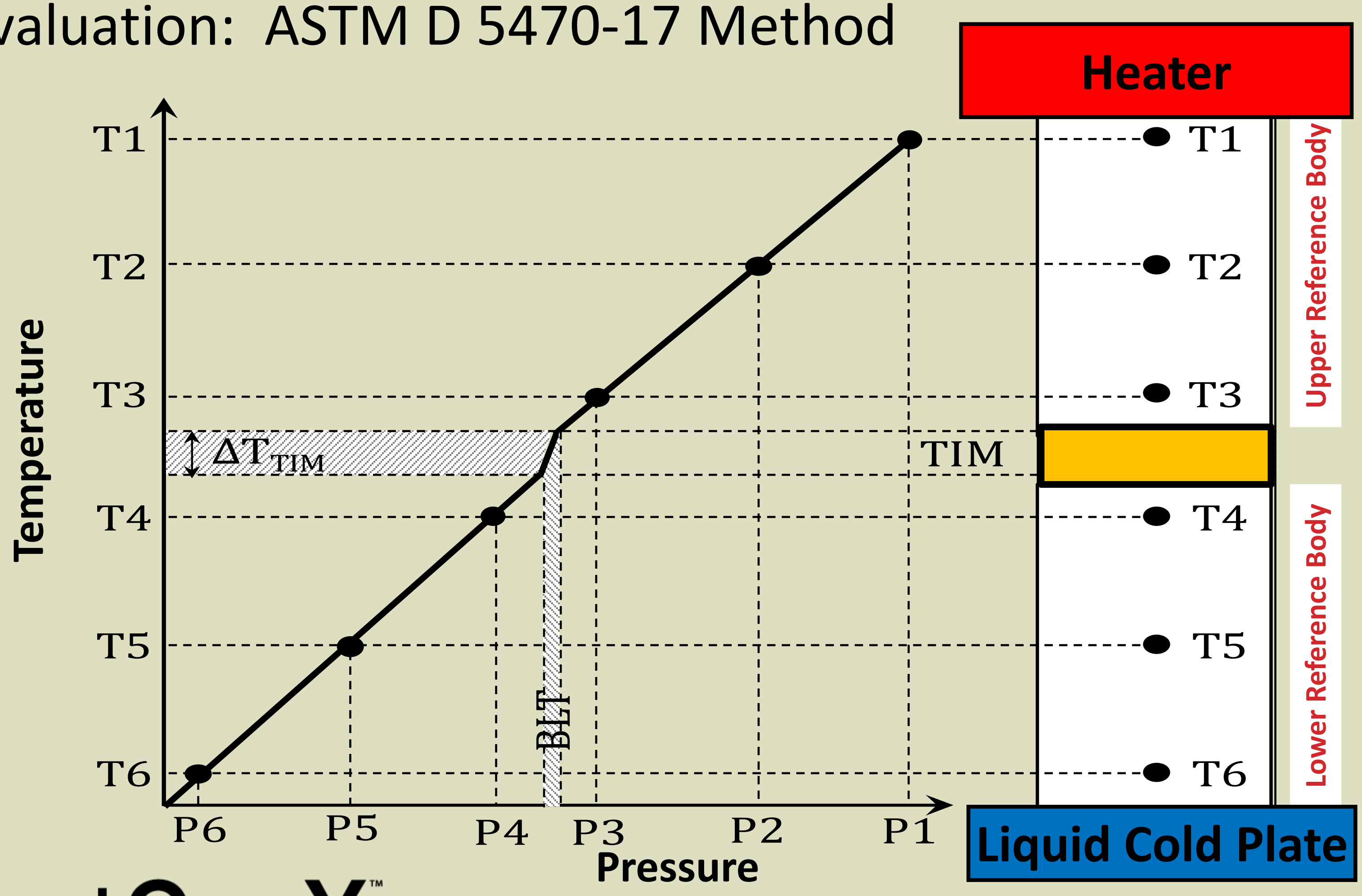
- Three different classes of TIM applied to the test hea for a semiconductor test system, showing impact of three different TIM types versus dry contact:

Example: Impact of TIM Selection



Source: K. Moody, R&D Manager, Kulicke & Soffa (USA). Note: All other conditions held equal.

TIM Evaluation: ASTM D 5470-17 Method



Note: ASTM D 5470-12 methodology may be purchased for a nominal fee from ASTM International. Information can be found at www.astm.org

TIM Evaluation: ASTM D 5470-17 Method

Standard TIM test stand: Berliner Nanotest TIMA5:

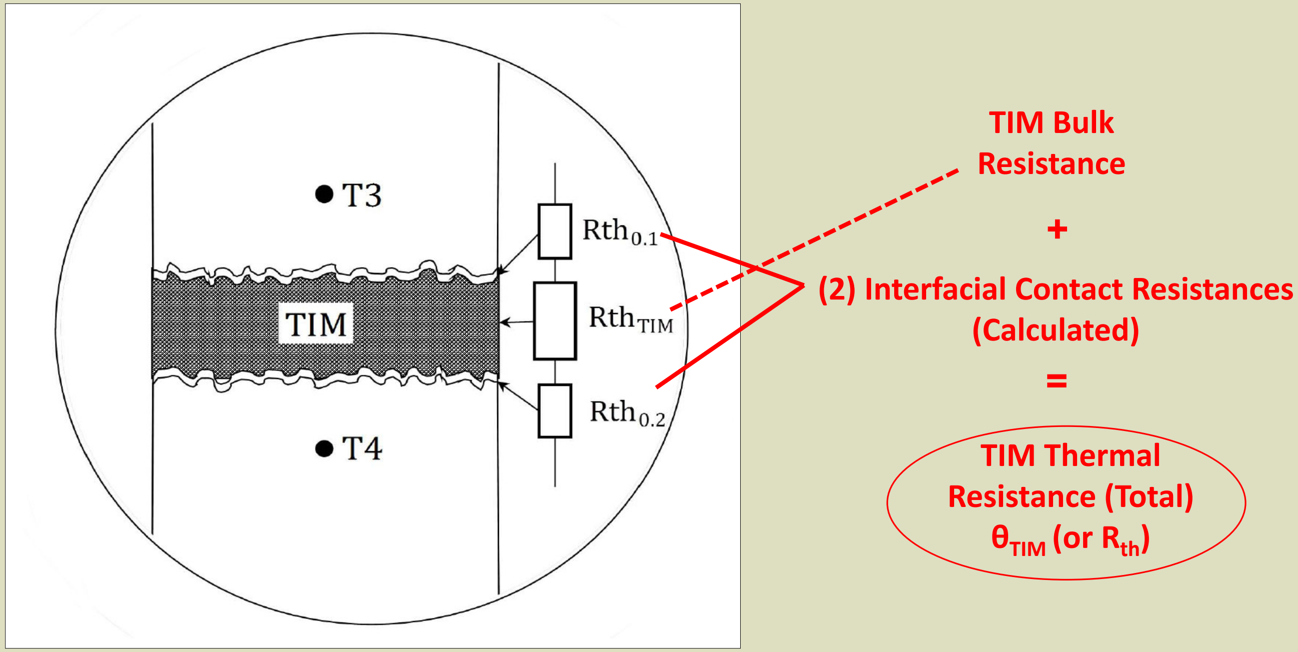
- Designed per ASTM D 5470-12, the industry-standard TIM test methodology for comparative material testing;
- System measures force applied, power (heat), thickness, thickness – with uniform heat flow.
- Measures thermal conductivity, calculated thermal resistance values w/error bars.
- Servo motor controls allow:
  - Extreme precision in measuring placement and thickness
  - Automation of functions (i.e., repeated contact/release cycle testing, to test for TIM durability for semi test.

Photograph: Berliner Nanotest und Design GmbH, Berlin, Germany. Nanotest TIMA5 ASTM D 5470-17 test stand.

TIM Evaluation: ASTM D 5470-17 Method

ASTM D 5470-17 describes a methodology to provide measurement of a thermal resistance value that is the sum of three constituent values:

- TIM thermal resistance *total* (θ_{TIM} or R_{th}) is the important value, in practice.



TIM Bulk Resistance

+

(2) Interfacial Contact Resistances (Calculated)

=

TIM Thermal Resistance (Total) θ_{TIM} (or R_{th})

TIM Development – Test Equipment Manufacturers

Selected TIM Test Equipment Manufacturers		
Company	**Test Stand General Type**	**Status**
Berliner Nanotest und Design GmbH Berlin, Germany	TIMA® ASTM D 5470-17 (Modified)	Production
	LaTIMA® In-Plane Bulk Thermal (X-Y) Conductivity Test Stand	Production
	Thermal Test Die, Thermal Test Wafers, Thermal Test Vehicles (TTVs)	Production
	Three-Omega Method Liquid/Gel Thermal Conductivity Test Stand	Production
Microsanj LLC, Fremont CA USA	Thermoreflectance Test Systems	Production
Siemens (Mentor Graphic Mechanical Analysis Division)	"T3Ster" Structure Function Transient Test Stand; DynTIM™ Test Head	Custom
Thermal Engineering Associates, Inc. Santa Clara CA USA	TIM Test Stand per ASTM D 5470-12 (Modified)	Discontinued

Source: DS&A LLC. Selected vendors shown.

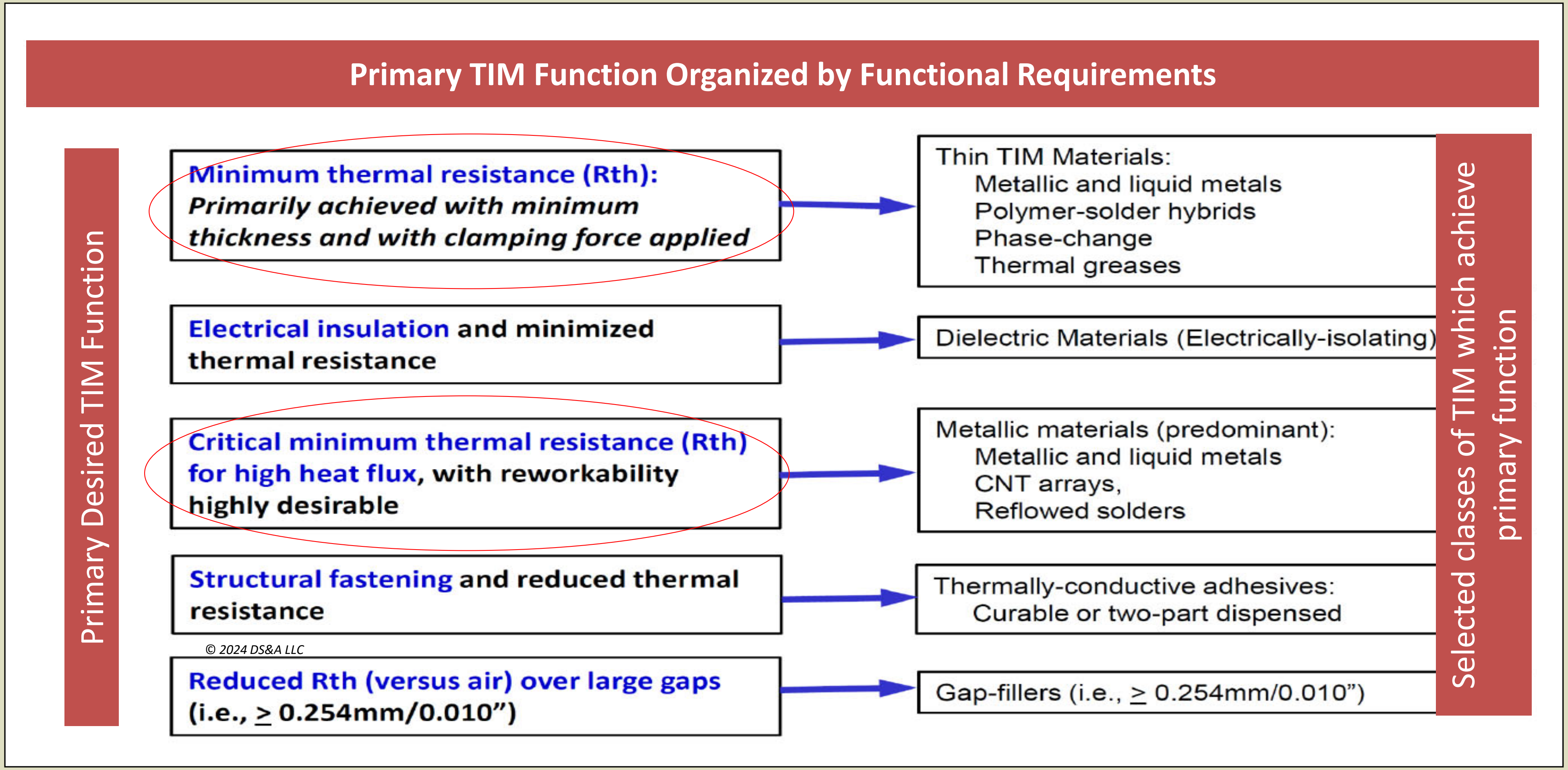
TIM Selection Methodology

Selecting from thousands of TIM products for a single application can be an arduous and time-consuming task.

The following slides illustrates a logical selection process.

1. Identify primary function(s) necessary for a TIM application, in order to begin separating out applicable types.
   a. An adhesive is required if no mechanical fastening is available;
   b. An electrical insulation requirement will preclude numerous types of greases and compounds;
2. Select a secondary TIM function, if any;
3. Select from appropriate TIM categories.

TIM Selection Methodology



Primary TIM Function Organized by Functional Requirements

Primary Desired TIM Function

Minimum thermal resistance (Rth): ***Primarily achieved with minimum thickness and with clamping force applied***

Electrical insulation and minimized thermal resistance

Critical minimum thermal resistance (Rth) for high heat flux, with reworkability highly desirable

Structural fastening and reduced thermal resistance

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Reduced Rth (versus air) over large gaps (i.e., ≥ 0.254mm/0.010")

Thin TIM Materials:
Metallic and liquid metals
Polymer-solder hybrids
Phase-change
Thermal greases

Dielectric Materials (Electrically-isolating)

Metallic materials (predominant):
Metallic and liquid metals
CNT arrays,
Reflowed solders

Thermally-conductive adhesives:
Curable or two-part dispensed

Gap-fillers (i.e., ≥ 0.254mm/0.010")

Selected classes of TIM which achieve primary function

TIM Selection Methodology

Selecting an appropriate thermal interface material:

- *Degree of surface wetting* achieved is critical to overall performance, to minimize contact thermal resistance at each of two contact surfaces.
  - Contact thermal resistances dominate TIM total thermal resistance value for most materials that are thin by design;
    - Exception: Gap-filler bulk thermal resistance will dominate over contact thermal resistance, due to intentional extreme thickness;
  - Driving to *highest wetting* and *thinnest clamped* thickness is *critical to successful TIM selection* in traditional TIM applications.

TIM Selection Methodology

Clamping force (uniformly applied) is intended to achieve:

- Maximized surface wetting;
- Thinnest possible TIM thickness (to minimize influence of bulk thermal conductivity, which is normally low);
- Metal-to-metal contact for surfaces.

Relatively good bulk thermal conductivity is most important when maximum surface wetting is not obtainable:

- Above statements apply for applications for lowest thermal resistance.
- Surface wetting is *not* desirable for semiconductor test applications, due to need to avoid residue and/or DUT marking.
  - Increasing the need for high bulk thermal conductivity for test.

TIM Test Methodologies: Overview

Performance Property	Property Parameter	Method/Value
Thermal Resistance	Through-plane (primary) bulk + contact = total thermal resistance	ASTM D 5470-17 (Steady-state, unidirectional controlled heat flow) JEDEC JESD 51-14 (In-situ, Transient with structure function calculations from electrical resistances) Thermal Test Vehicle (TTV, in-situ)
Thermal Conductivity	Homogeneous, bulk (isotropic)	ASTM D5470-17 (Steady-state) JEDEC JESD 51-14 (Transient) Laser flash (Homogeneous materials) 3Ω Characterization
	Non-homogeneous, bulk (through-plane)	ASTM D5470-17 (Steady-state, unidirectional flow) JEDEC JESD 51-14 (Transient) 3Ω Characterization
	Non-homogeneous, bulk (in-plane)	Berliner Nanotest LaTIMA (Steady-state, in-plane flow) Scanning pulsed laser

Note: Not all test methods are suitable for testing certain categories of TIMs such as anisotropic and/or non-homogeneous structures (examples are compounds coated on a dielectric carrier or multilayer TIMs.)

TIM Test Methodologies: ASTM D 5470-17 and Transient

ASTM D 5470-17 and transient methods are the primary test methods for determining bulk thermal conductivity and thermal resistance values.

- *TIM vendor data sheet values should be developed utilizing ASTM D 5470-17* for comparative values generated under:
  - *Controlled surface conditions*
  - *Unidirectional heat flow conditions*
  - *Parallel contact surfaces*
  - *Precisely known clamping forces*

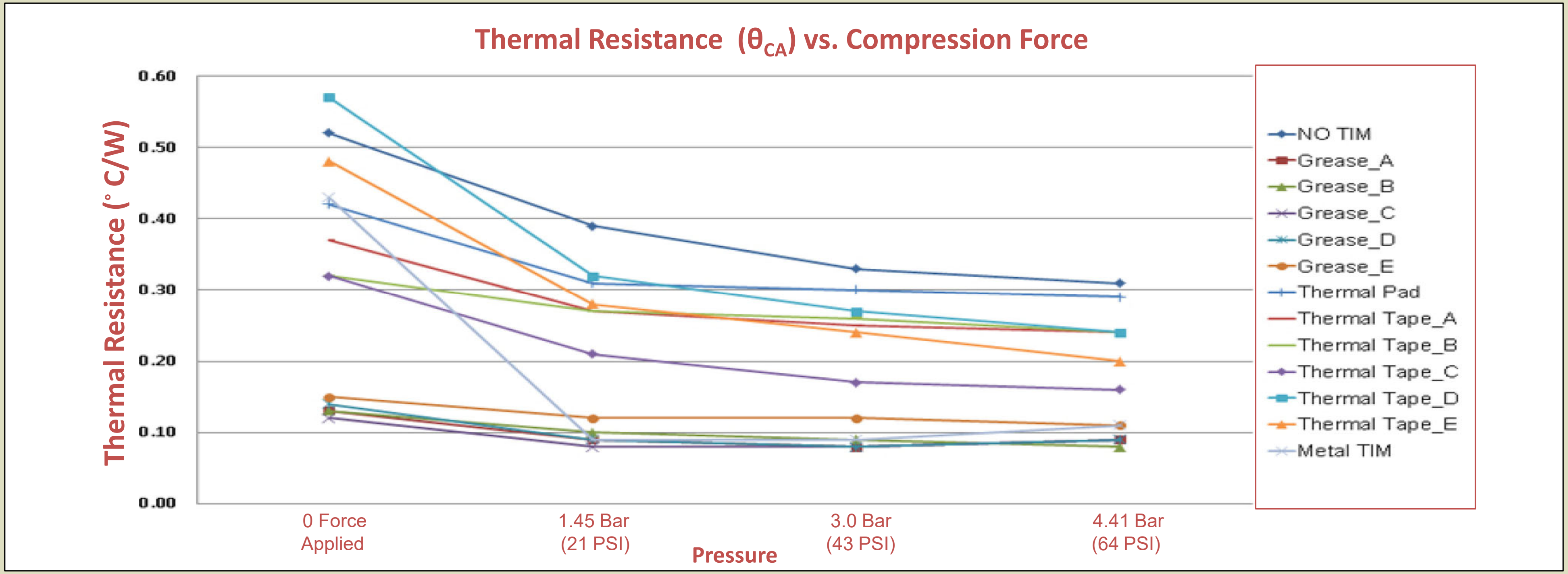
ASTM D 5470 Purpose: Develop comparative test data under identical conditions with all extraneous factors (such as die warpage or non-co-planar contacting surfaces) removed.

- Use of JESD 51-14 transient methodology *follows after* ASTM D 5470 testing. Goal is to develop *in-situ* performance test values with a specific package surface, clamping mechanism, other variables.
- Transient methods use electrical characteristics of a DUT, such as a power semiconductor, in-situ.
- These two methods are complementary: *One does not replace the other*.

TIM Test Methods: ASTM D 5470-17

ASTM D 5470-17 test methodology -- Example of comparative test data generated:

- Application of specified pressures significantly improves thermal resistance of many TIM types;
- Properly-designed test stand provides apples-to-apples comparative data, all factors equal.

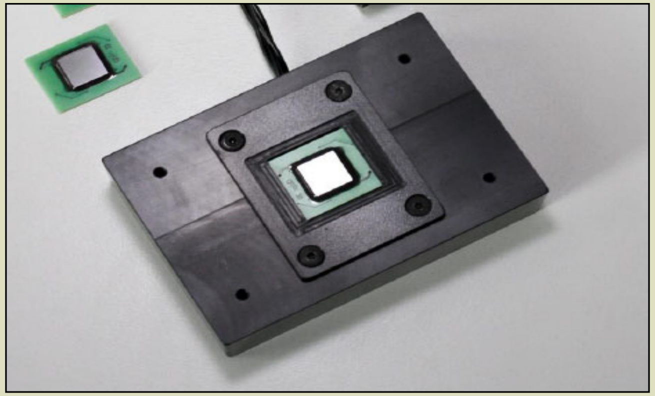


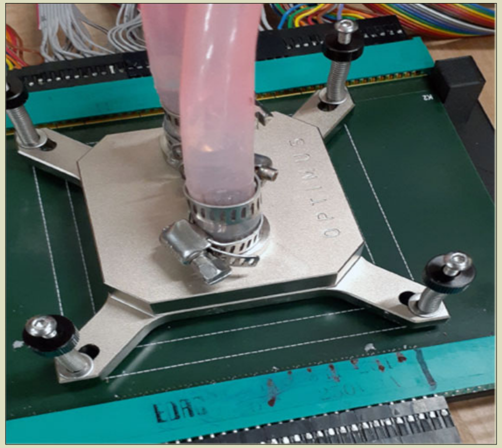
Note: Specific TIM materials are not identified by vendor and vendor product identification. "Metal TIM" is indium metal flat foil.
Source: Ng Hooi Hooi, Thermal Test Solutions, Inc.; "Introduction to Thermal Interface Materials," BiTS Test Workshop, Mesa AZ USA, March 5-8. 2017.

TIM Test Methods: Thermal Test Vehicles (TTV)

Thermal test vehicles are used for examining TIM performance in in-situ applications to measure:

- Performance of a TIM2 with a production semiconductor package;
- Performance of a TIM0 or TIM1 in contact with a die, to evaluate performance:
  - Given specific die warpage
  - With contact to lid (TIM1) or liquid cold plate/heat sink assembly (TIM0)
  - When well-designed, a tool that can provide very useful and detailed analytical capabilities for *in-situ* measurement for applications with a specified package type.



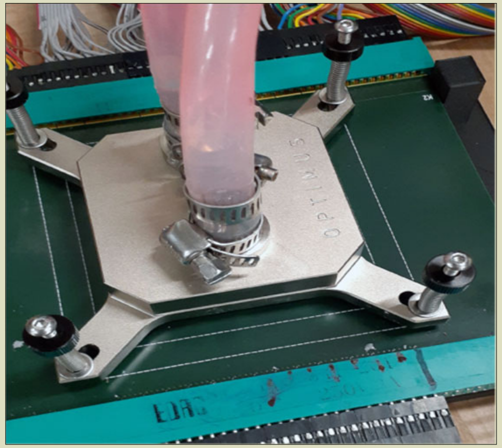


Sources: (Left) TTV, Berliner Nanotest und Design GmbH; (Right) High-performance all-copper liquid cold plate applied to bare die TTV on engineering test board (ETB). (Photograph, DS&A LLC, January 16, 2024.)

TIM Test Methods: Thermal Test Vehicles (TTV) and HIR Die Warpage

Thermal test vehicles have become *critical for evaluation of multiple characteristics of TIM performance* in-situ with test packages given two industry-critical trends for integrated circuits:

- Heterogeneous integration (HIR) package design incorporates multiple die on single substrate:
  - Placement of multiple *processor die (high heat sources) in close proximity to highly temperature sensitive stacked memory (HBM) die – potential for thermal cross-talk*;
  - Design requirements for single TIM0 to protect all die surfaces on substrate;
- Expansion of processor multi-die placement (sub-10µ spacing), expanding die contact area to ≥ 100mm;
  - *What is the definition of "die area" in use?*
- *Rapid worsening of critical die warpage* – across increasing rapidly increasing die contact area;
- TTV of sufficient die size with proper attachment generates thermal test data showing a combination of the impact of die heating, die area, die warpage:
  - Generates thermal performance map across surface.

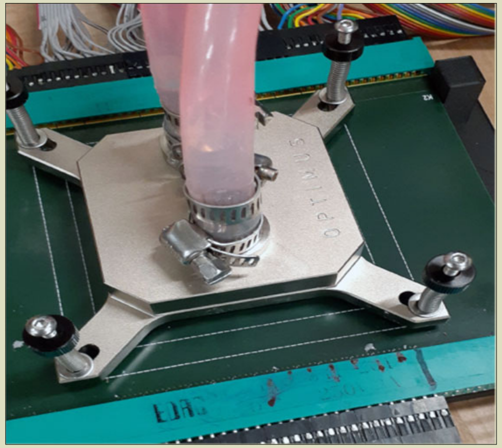


Source: Liquid cold plate applied to bare die TTV on engineering test board (ETB). (Photograph, DS&A LLC, January 16, 2024.)

TIM Test Methods: Thermal Test Vehicles (TTV) and HIR Die Warpage

Thermal test vehicles have become *critical for evaluation of multiple characteristics of TIM performance* in-situ with test packages given two industry-critical trends for integrated circuits:

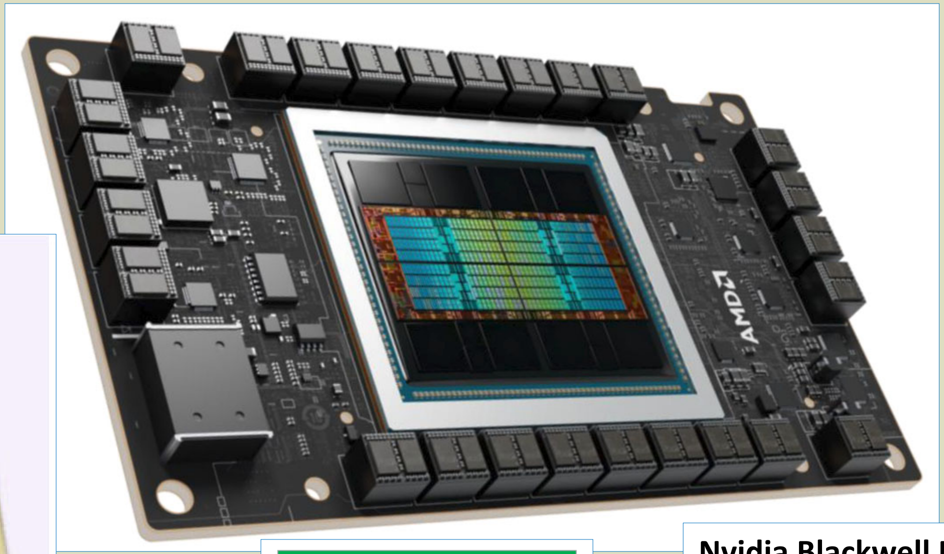
- Heterogeneous integration modules such as AI processor modules incorporate multiple processor, memory, and support ICs on a single complex substrate;
- Placement of multiple processor die with absolute minimum (<10µ) separation;
- "Single-die processor" may refer to two, four, or six processors placed on a single complex substrate;
- Total die area may therefore be termed as "5X reticle" or "6X reticle";

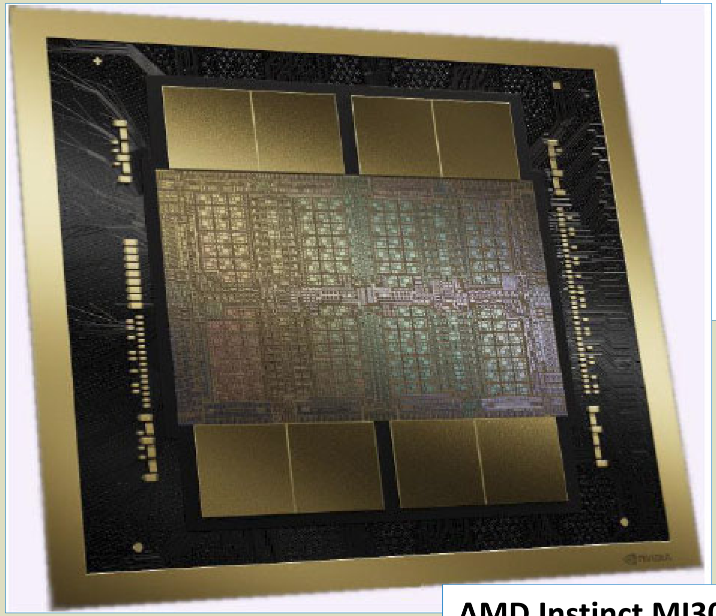


Source: Liquid cold plate applied to bare die TTV on engineering test board (ETB). (Photograph, DS&A LLC, January 16, 2024.)

TIM Test Methods: Thermal Test Vehicles (TTV) and HIR Die Warpage

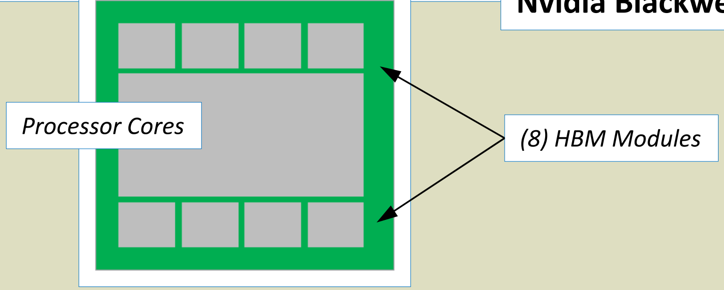
Die and package warpage and resulting temperature mapping may be accomplished with a large-die TTV.





AMD Instinct MI300X

Nvidia Blackwell B200



Processor Cores

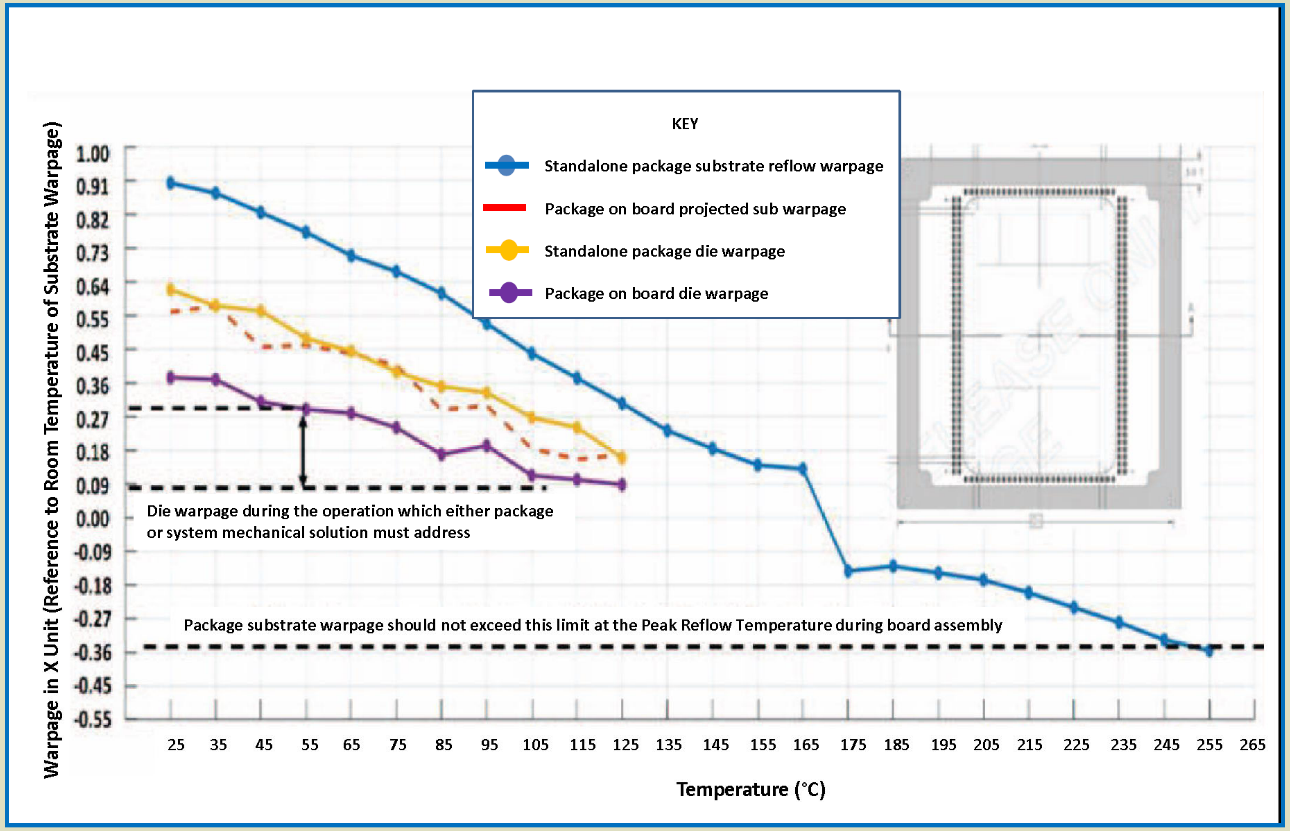
(8) HBM Modules

Source: Kini, G., AMD, "Thermal Landscape for Data Center GPUs," Binghamton University/IBM Research/GE Global 35th Electronics Packaging Symposium 2024, Vestal NY USA, September 4-5, 2024. See presentation for references to prior sources incorporated.

TIM Test Methods: Thermal Test Vehicles (TTV) and HIR Die Warpage

Die and package warpage for large area HIR processor packaging raises significant challenges for TIM1:

- Bond line thickness post-processing
- Coverage of multiple die
- Potential die movement due to temperature-induced substrate and die stress.

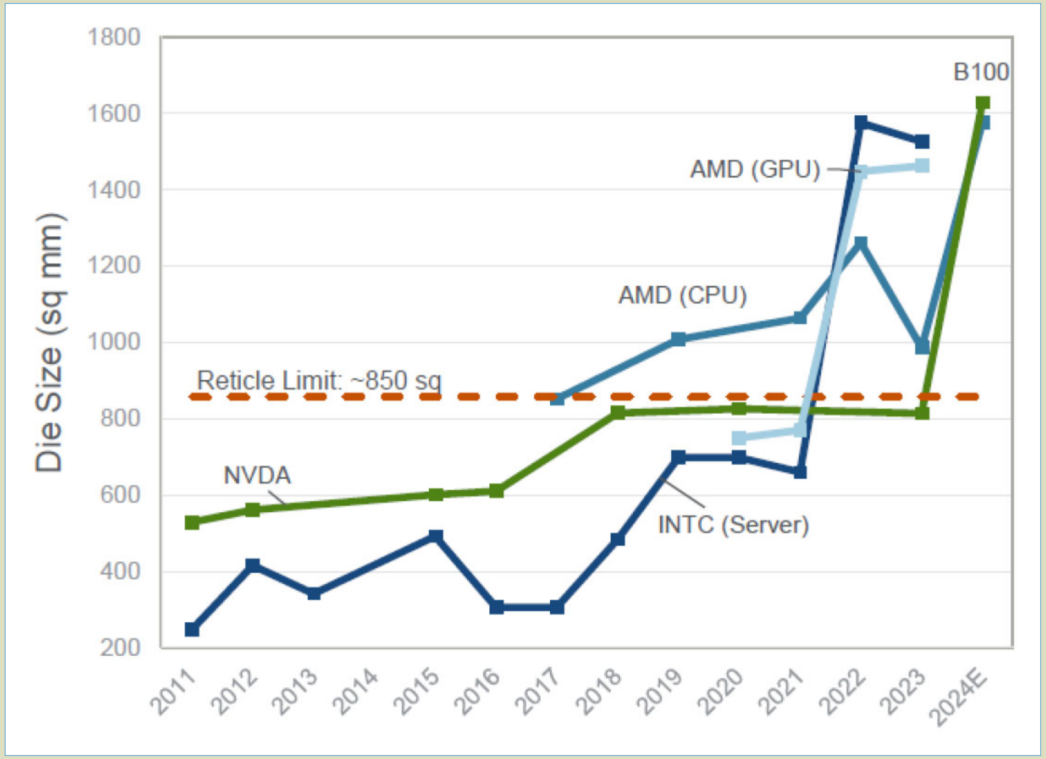


Source: Refai-Ahmed, G.; Do, H.; Islam, M. M.; Strader, J.; Arefeen, Q.; Huttenen, J.; "Roadmap and Challenges on the Next Generation of Thermal Interface Material for High Warpage Heterogeneous Package," 2022 IEEE 24th Electronics Packaging Technology Conference , Singapore, December 7-9, 2022.

TIM Test Methods: Thermal Test Vehicles (TTV) and HIR Die Warpage

Die and package warpage for large area HIR processor packaging raises significant challenges for TIM1:

- "Die size" now significantly exceeds reticle size limit;
- Total area for TIM coverage (as TIM0 or TIM1) now exceeds $1600mm^2$.



Source: Kini, G., AMD, "Thermal Landscape for Data Center GPUs" Binghamton University/IBM Research/GE Global 35th Electronics Packaging Symposium 2024, Vestal NY USA, September 4-5-2024. See presentation for references to prior sources incorporated.

TIM Test Methods: Thermal Test Vehicles (TTV) and HIR Die Warpage

Die and package warpage for large area HIR processor packaging raises significant challenges for TIM1:

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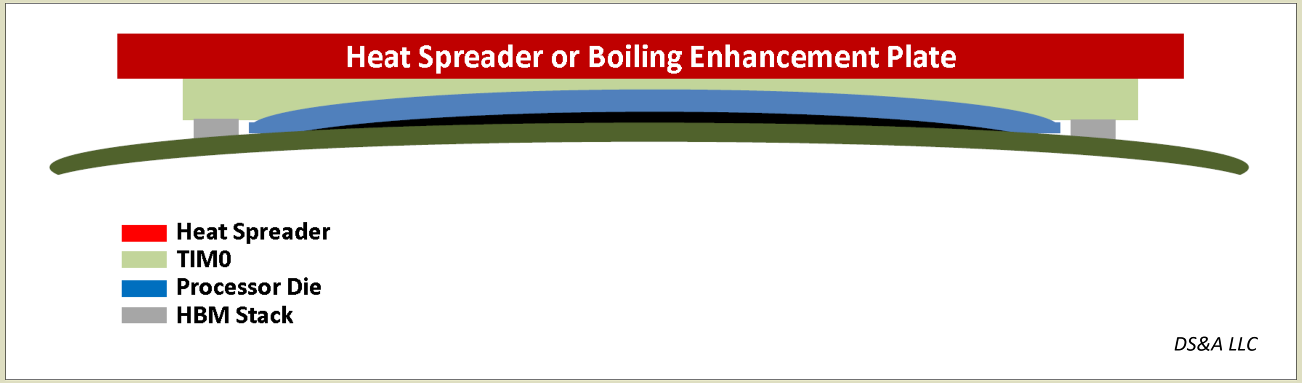
- Adequate TIM coverage of multiple die
- Potential die movement due to temperature-induced substrate and die stress.



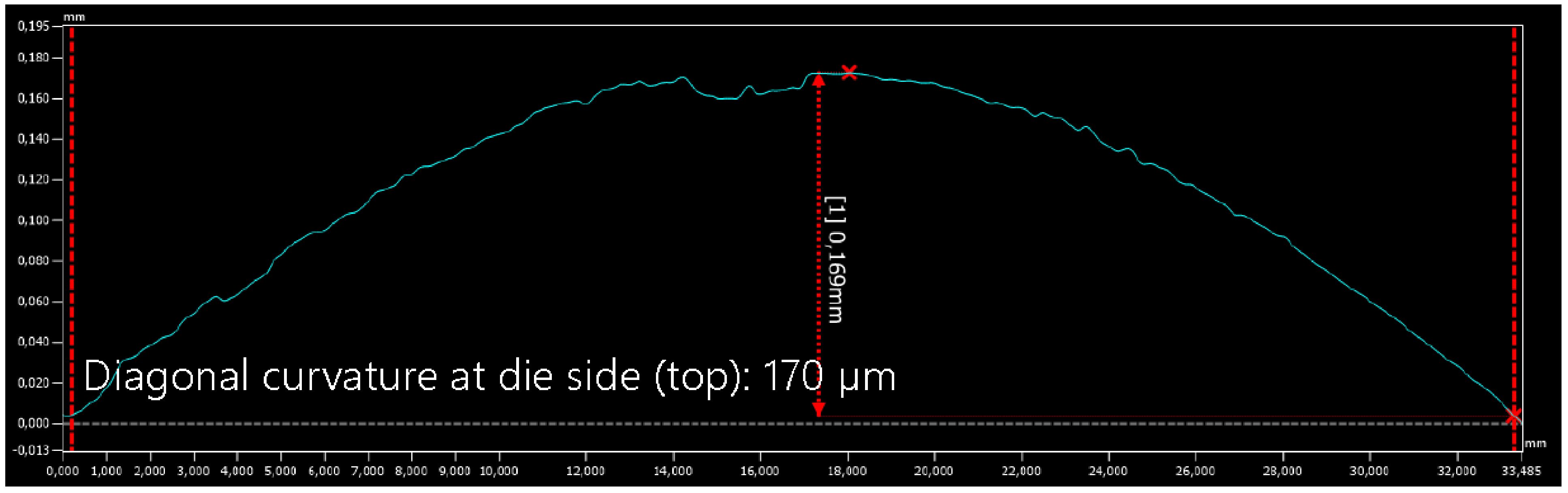
DS&A LLC

- A large-die TTV is a very useful tool for evaluating temperatures at selected points across the die under test

Source: Refai-Ahmed, G.; Do, H.; Islam, M. M.; Strader, J.; Arefeen, Q.; Huttenen, J.; "Roadmap and Challenges on the Next Generation of Thermal Interface Material for High Warpage Heterogeneous Package," 2022 IEEE 24th Electronics Packaging Technology Conference , Singapore, December 7-9, 2022.

TIM Test Methods: Thermal Test Vehicles (TTV) and HIR Die Warpage

Measured die warpage (diagonal) for large area HIR processor package – Example:



Diagonal curvature at die side (top): 170 µm

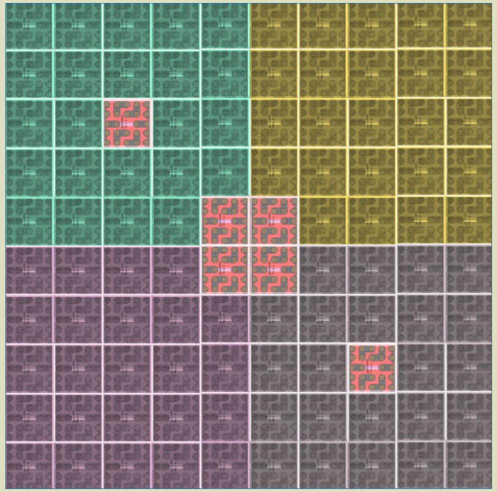
- Reported warpage values for selected semiconductor vendors: ≥ 300µ

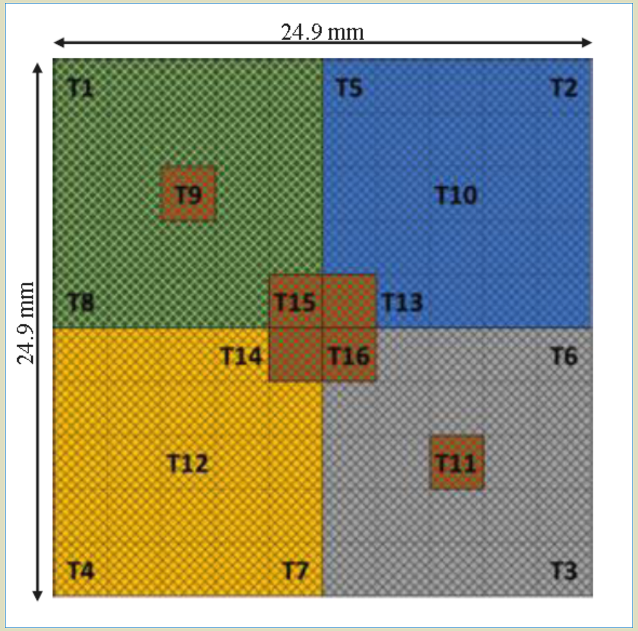
Source: Abo Ras, M., "Thermal Test Vehicle for Investigation of Thermal Path in Large Die Area Packages by Thermal Transient Impedance Analysis" SEMI-THERM 40 Symposium, San Jose CA USA, March 2024.

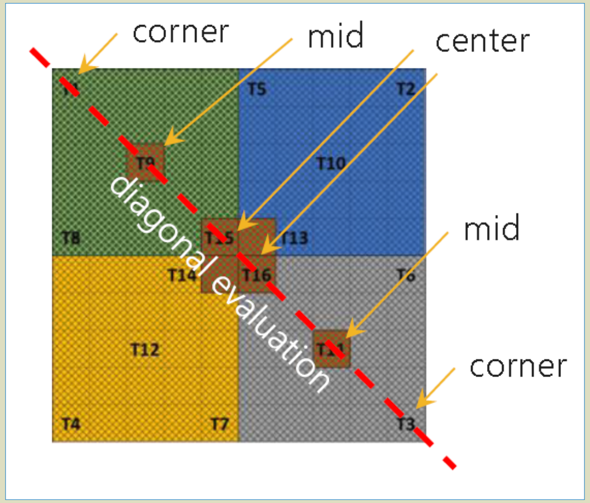
TIM Test Methods: Thermal Test Vehicles (TTV) and HIR Die Warpage

Large-die TTV construction:

- 10x10 cells in 24.9 x 24.9mm (620mm^2) die area
- 60x60 maximum substrate area
- (4) heater zones, (16) RTDs
- Power density to 10W/mm^2



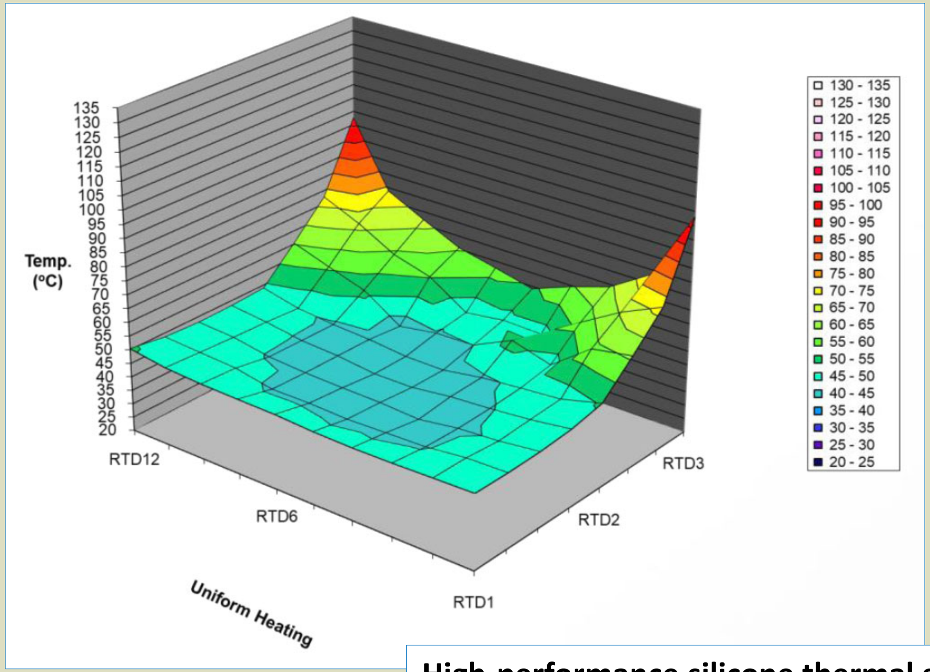




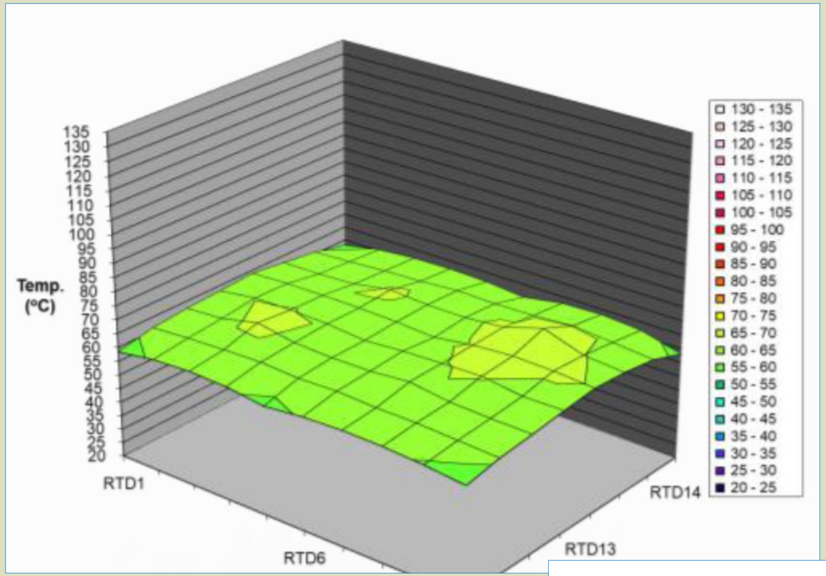
Source: Abo Ras, M., "Thermal Test Vehicle for Investigation of Thermal Path in Large Die Area Packages by Thermal Transient Impedance Analysis" SEMI-THERM 40 Symposium, San Jose CA USA, March 2024.

TIM Test Methods: Thermal Test Vehicles (TTV) and HIR Die Warpage

Large-die TTV comparative sector performance testing of selected TIM0/TIM1:



High-performance silicone thermal grease



Development PCMA

Sources: Jensen, T., "Metal TIMs for High Performance BGA Packages, SEMI-THERM 40 Symposium, San Jose CA USA, March 2024; Jensen, T., "Metal TIMs for Bare Die Applications" IMAPS Symposium 2024, Boston MA USA, September 30 – October 2, 2024.

TIM Selection and Testing/Evaluation Methodologies

Material Attribute	Value or Type
Automated Placement/Dispensing Formats	Vacuum Roll format Liquid dispensed
Flammability Rating	UL 94 V0
Working Life	X Hours @ X°C
High Temperature Storage (Completed Final Assembly)	Y Hours @ Y°C
High Temperature Storage (as supplied)	Z Hours @ Z°C
Transit Temperature	Maximum
Low Temperature Transit/Storage	Minimum
Material Stability	% loss of tack permissible; Dimensionally stable; durable; no fretting/detritus No moisture sensitivity during processing
Outgassing	% Permissible

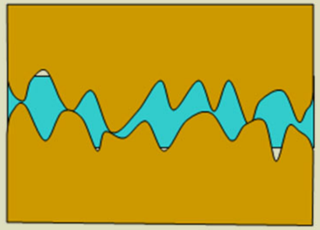
Major TIM Categories for Semiconductor Test

Gap-Fillers: Where Are These Needed?

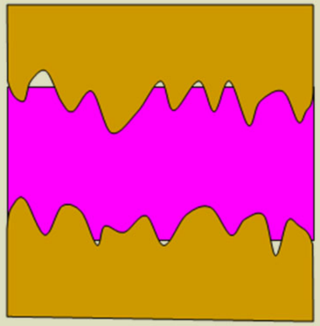
One general definition for TIMs versus gap-fillers:

- Thermal Interface Materials: Replace air in an interface that would otherwise present due to <u>surface roughness;</u>
- Thermal Gap-fillers: Replace air in an interface that would otherwise be present due to <u>tolerance stack-up.</u>

Note that these are very generalized definitions.



Thermal Interface Material
(TIM)



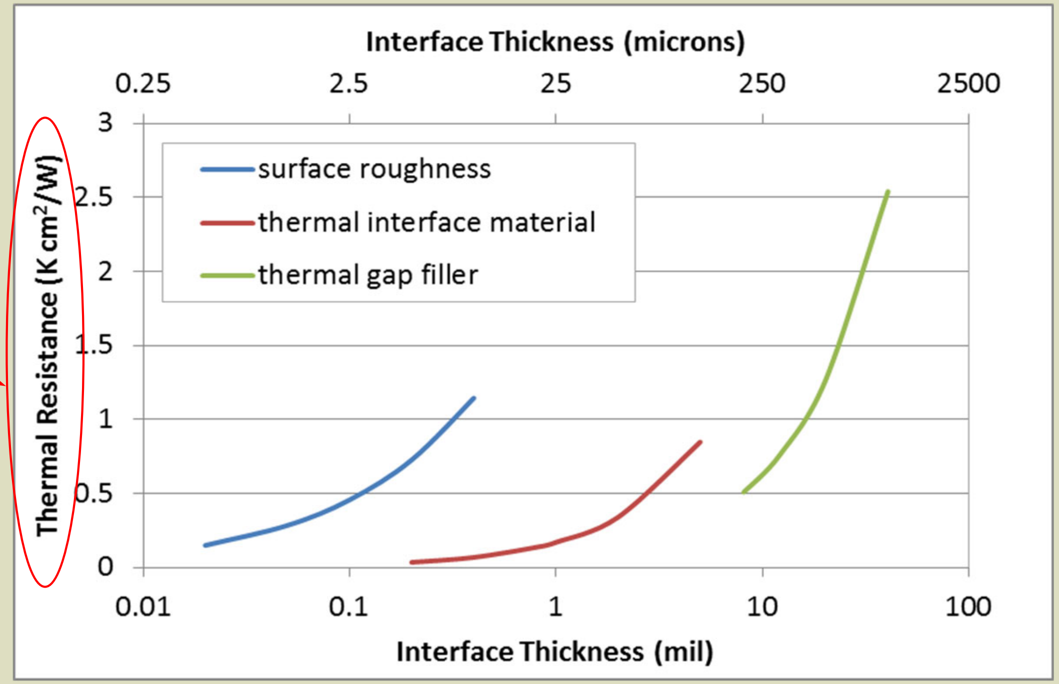
Thermal Gap Filler
(TGF)

Source: Ross Wilcoxon PhD, Engineering Fellow, Advanced Technology Center, Collins Aerospace Inc., Cedar Rapids IA USA. Unpublished; Used with permission.

Gap-Fillers: Where Are These Needed?

Comparison of surface roughness and relative interface thicknesses, to define a *general* application range for TIMs versus gap-fillers, under load:

The primary function of a TIM is to minimize the thermal contact resistance between two mating surfaces.

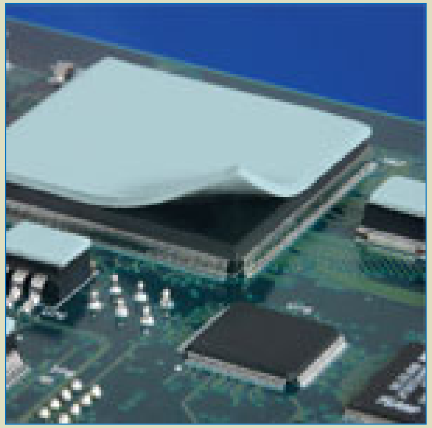


These are rough estimates and values will vary with material properties and contact pressure (clamping force) applied.

Source: Ross Wilcoxon PhD, Engineering Fellow, Advanced Technology Center, Collins Aerospace Inc., Cedar Rapids IA USA. Unpublished; Used with permission. Note: 100 microinch = 2.54 microns. Values are RMS values.

Gap-Fillers: Attributes

Die-cut preform Gap-fillers:



- Generally, higher bulk thermal conductivity than dispensed GF products;
- Higher bulk thermal conductivity is generally achieved with higher loading of fillers;
- Higher filler loading will increase relative stiffness.
- Compression below 50% of initial thickness is not recommended:
    - *Induced failure risk* to solder balls, underfill, or interconnect or package, from excessive force applied to achieve compression;
    - High compression will generally force out carrier fluids, such as silicone oil.

Note: Statements and definitions are imprecise given the very large number of gap-fillers from many vendors and wide range of applications for these types of materials across industry.

Gap-Fillers: Attributes

Die-cut preform Gap-fillers (continued):

- Generally, compression below 50% of initial thickness is not possible or recommended:
  - *Induced failure risk* to solder balls, underfill, or interconnect or package, from excessive force applied to achieve compression:
    - High compression will generally force out carrier fluids such as silicone oil (not desirable in electronic systems);
    - Silicone oil may outgas and redeposit on electrical contacts, impacting solder processing operations and system interconnect performance.
    - Increased surface wetting for gap-fillers can be easily attained by increasing percentage by weight of silicone oil, reducing compression requirement.

Gap-Fillers: Cycling Reliability Testing

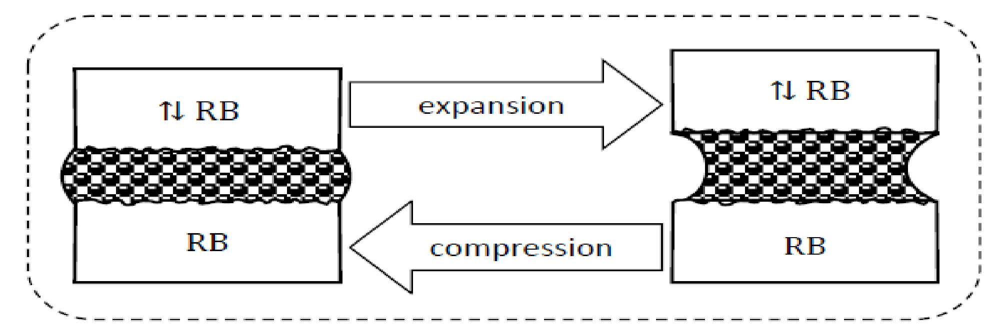
Mechanical cycling and other types of reliability testing over time can demonstrate useful results for evaluating TIMs.

- Previous reliability testing has been undertaken by Berliner Nanotest of “gap-filler” TIMs, examining cyclic compression and relaxation
- Gap-fillers may also be useful for test/burn-in – with different reliability testing requirements.
  - An example is the use of so-called “gap-filler” TIMs for testing with PCBs and other substrates.
  - The same TIM test equipment described has also been used for reliability testing of metallic TIMs with contact/dwell/release cycling, to mimic semiconductor test requirements.

Gap-Fillers: Cycling Reliability Testing

Mechanical cycling and other types of reliability testing over time can be used to examine long-term thermal and mechanical performance of TIMs.

- Example: Mechanical compression/relaxation cycling of gap-fillers:

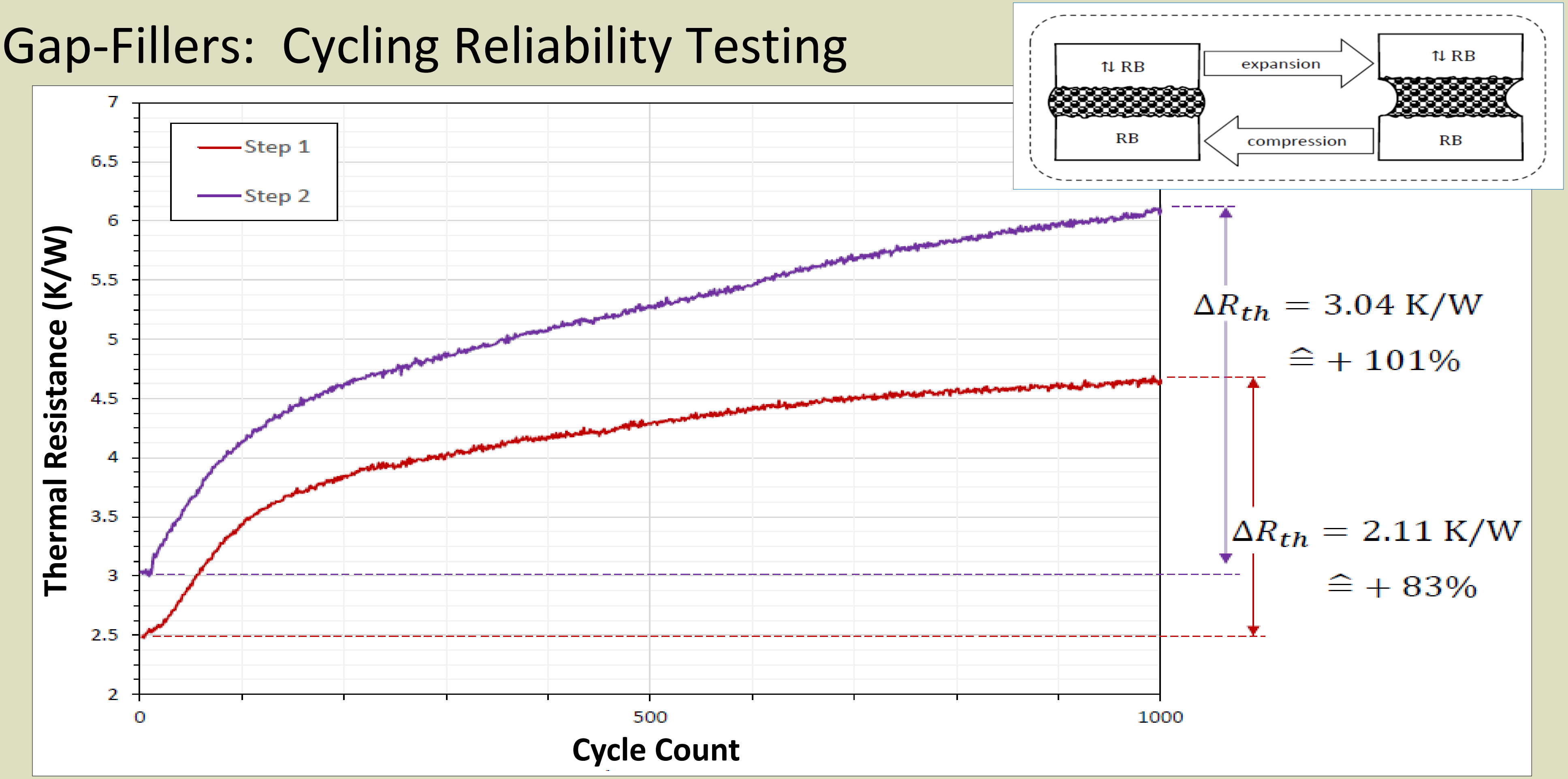


Data analysis indicates increasing thermal resistance over time and cycling:

- Examining time zero thermal resistance values alone is not adequate
- *Increasing thermal resistance over time* and cycling indicates a potential failure mechanism as junction temperature increases.

Source: Berliner Nanotest und Design GmbH. February 16, 2018.

Gap-Fillers: Cycling Reliability Testing



Source: Berliner Nanotest und Design GmbH. February 16, 2018.

High Temperature Applications

Higher operating temperature can severely restrict available thermal solutions:

- May lead to increased focus on TIM *performance,* if the available thermal operating range is reduced*;*
- Requires selection of high-temperature-capable TIMs matched to specific expected application operating temperatures;
- Higher ambient temperature = higher device junction temperature;
- Ambient and junction temperature requirements will dictate TIM *processing temperature* range.

Pressure-Sensitive Adhesives for High Temperature

A key component of many TIMs used for electronics applications is the addition of a pressure-sensitive adhesive. Definition of a PSA:

- Adhesion is achieved when stress is applied (i.e., the application of pressure):
  - Aggressive and permanent tack
  - Adheres with no more than finger pressure
  - Requires no activation energy to adhere
  - Has sufficient ability to hold an adherend
  - Has enough cohesion to hold an adherend
- Adhesives are not as a rule used for test head applications.

Source: Tom Rogers, Technical Director, Polyonics Inc., Westmoreland NH USA. "Thermally Conductive Adhesives," Embedded Tutorial, SEMI-THERM 36 Symposium, San Jose CA USA, March 19, 2018

Pressure-Sensitive Adhesives for High Temperature

Cohesion and shear strength:

- Cohesion is an internal force:
  - An attractive force within a PSA
  - Resistance to separation
- Shear strength measurements
  - Static: ASTM D3654D
    - Weight constant, measured with time to failure
  - Dynamic: ASTM D1002
    - Force increases at rate
  - Shear adhesion failure temperature (SAFT) per ASTM D4498

Source: Tom Rogers, Technical Director, Polyonics Inc., Westmoreland NH USA. "Thermally Conductive Adhesives," Embedded Tutorial, SEMI-THERM 36 Symposium, San Jose CA USA, March 19, 2018

Pressure-Sensitive Adhesives for High Temperature

Two major PSA categories:

- Acrylic-based – two basic types:
  - Co-polymeric
  - Cross-linked
    - Example: polyacrylic acid and hydroxypropyl acrylate
    - *Temperature use: < 125°C*
- Silicone-based – two basic types:
  - Co-polymeric
  - Cross linked
  - *Temperature use: > 125°C*

Source: Tom Rogers, Technical Director, Polyonics Inc., Westmoreland NH USA. "Thermally Conductive Adhesives," Embedded Tutorial, SEMI-THERM 36 Symposium, San Jose CA USA, March 19, 2018

Elastomeric “Silicone Rubber” Preforms

Materials that are manufactured in viscoelastic sheet forms:

- Polymers having both useful viscosity and elasticity properties;
- Low Young's modulus and high failure strain;
- Wide range of softness (measured as Shore A value);
- Typically referred incorrectly as “silicone rubber” preforms and sheets;
- Manufactured from silicones, not silicone rubber;
- Hundreds of “pads” available, many different volume filler percentages:
  - Typically, die-cut to needed shapes, sizes,features (through-holes, etc.);
  - Fillers provide bulk thermal conductivity, typically essentially isothermal;
  - Contact resistances are typically relatively high;
  - Marking and silicone oil contaminants an issue for use with test heads.

Semiconductor Test: Cycling and Reliability

TIMs: Development Specifications for Semiconductor Test

High Performance TIM Material Target Specifications *for Test*	
Material Attribute	**Goal**[1]
Material Stability	No constituent run-out, no mechanical pump-out. Dimensionally stable; no moisture sensitivity during processing or normal operation in specified ambient environmental conditions. No fretting.
Silicone Stability	No silicone content; no dry-out, no silicone oil separation; zero measurable separation by weight (TGA).
Surface Wetting	TIM provides sufficient surface contact to approach 100% surface wetting in clamped condition, including expected warpage and specified surface conditions.

Notes: 1. Generalized statements, applicable to all levels of TIM (TIM0, TIM1, TIM2).

TIMs: Development Specifications for Semiconductor Test

High Performance TIM Material Target Specifications *for Test*	
Material Attribute	**Goal[1]**
Thermal Performance	Target and stretch goals for thermal resistance to meet system maximum heat load and heat flux.
Outgassing	No permissible outgassing per NASA, aerospace applications requirements; no outgassing for medical, optical, optoelectronic applications and systems
Environment	Suitable for shipment, storage, processing, operational temperatures (ambient, junction/module)
Cost	Budget goals met with volume manufactured TIM.

Notes: 1. Generalized statements, applicable to all levels of TIM (TIM0, TIM1, TIM2).

TIMs: Development Specifications for Semiconductor Test

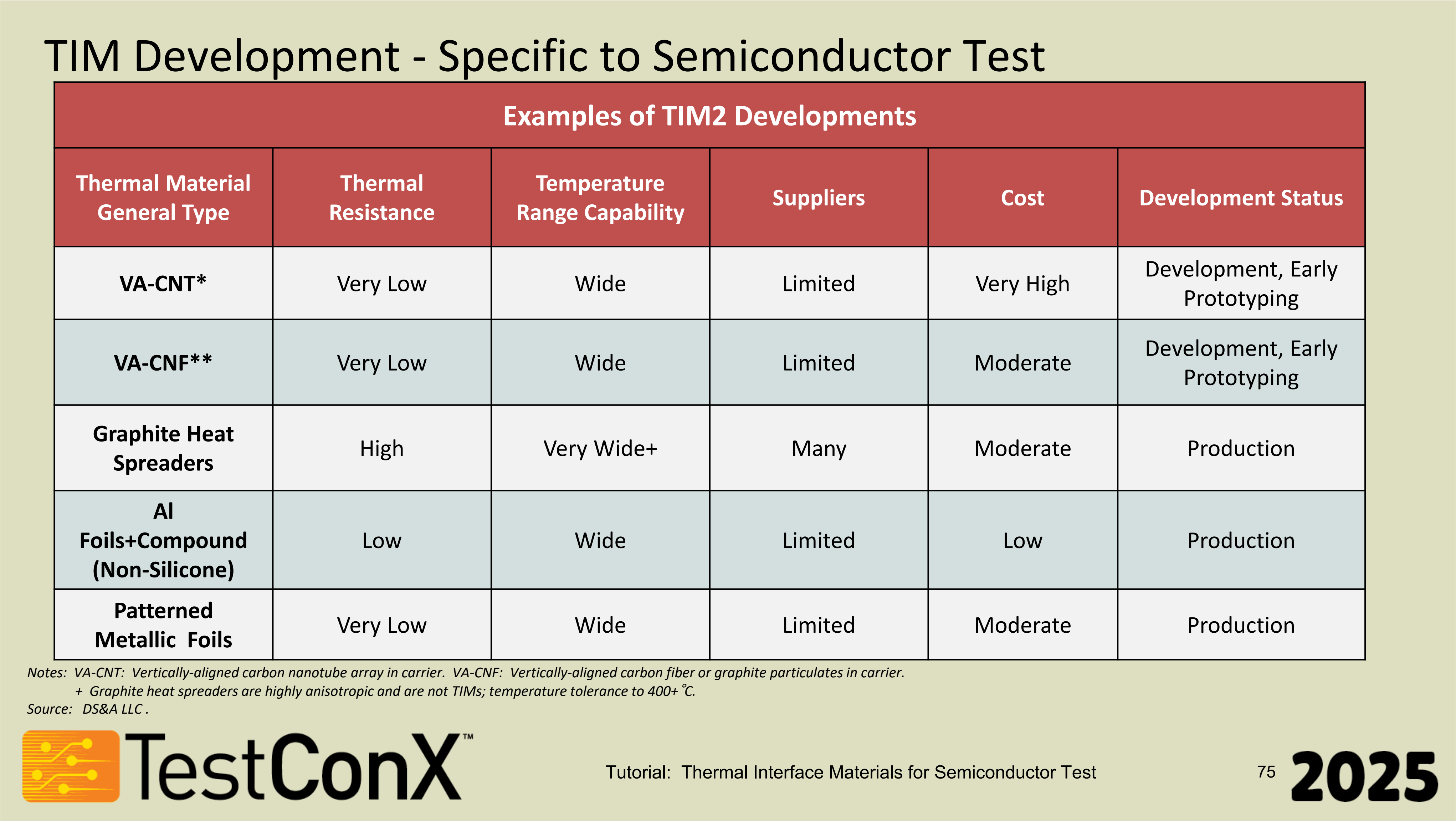
High Performance TIM Material Target Specifications *for Test*	
Material Attribute	**Goal[1]**
Conformability	**Same TIM conforms to different die sizes, lid sizes without damage or change in performance.[2]** **TIM conforms to 90 bending and wrapping around test head/socket lid configuration. [2]**
Particulates	**No permissible loss of particulates, fibers.[2]** **No residue visible, remaining on DUT after contact; no detritus.[2]**
Durability	**Tested cycling survival through X number of repeated contact-and-release cycles. [2]**

Notes: 1. Previous statements are applicable to all levels of TIM (TIM0, TIM1, TIM2).
2. Statements specific to semiconductor test and liquid immersion systems.

TIM Development - Specific to Semiconductor Test

High Performance Commercial TIM Material Target Specification: Test/Burn-In	
Product Attribute	**Goal***
Thermal Resistance	Target: < 0.35°C-cm^2/W @ Minimum clamping force applied Stretch: < 0.15°C-cm^2/W @ 60PSI clamping force applied
Contact, Non-Coplanar Surfaces	Target: 1,000 – 5,000 Cycles Stretch: 5,000 – 15,000
Thermal Conductivity	30W/m-K ■ (Minimum) >100W/m-K ▲ (Ideal)
Operating Temperature	-15°C to 120°C ■ (Minimum) -40°C to 200°C ▲ (Ideal)

*Key to symbols: ▲ Market leading product. ■ Market improvement w/equivalent or better pricing. * Generalized statements. Source: DS&A LLC.*



TIM Development - Specific to Semiconductor Test

Examples of TIM2 Developments					
Thermal Material General Type	**Thermal Resistance**	**Temperature Range Capability**	**Suppliers**	**Cost**	**Development Status**
VA-CNT*	Very Low	Wide	Limited	Very High	Development, Early Prototyping
VA-CNF**	Very Low	Wide	Limited	Moderate	Development, Early Prototyping
Graphite Heat Spreaders	High	Very Wide+	Many	Moderate	Production
Al Foils+Compound (Non-Silicone)	Low	Wide	Limited	Low	Production
Patterned Metallic Foils	Very Low	Wide	Limited	Moderate	Production

Notes: VA-CNT: Vertically-aligned carbon nanotube array in carrier. VA-CNF: Vertically-aligned carbon fiber or graphite particulates in carrier.
+ Graphite heat spreaders are highly anisotropic and are not TIMs; temperature tolerance to 400+ ˚C.
Source: DS&A LLC .

High Performance Metallic TIMs: Indium Foils

Indium flat foils used as TIM2 for decades, for very specific applications:

- Flange-mount RF discrete power amplifiers and modules (telcom, radar, radio communications, satellite communications);
- Standard TIM2 for diode laser arrays[1];
- Reflowed indium solder as a high-volume TIM1 for server processors;
- Current research for high-volume BGA processor packages[2];
- Semiconductor test and burn-in.

Notes: 1. *Koechner, W.,* Solid-State Laser Engineering, *6th Edition (Springer Verlag, 2006).*
2. *Koh, Y. J.; Kim, S.H.; Sohn, E.S.; Khim, J.Y.; Amkor Technology Korea Inc., "Thermal Performance of Advanced TIMs for High-Power FCLBGAs," IEEE ECTC Conference 2022, San Diego CA USA, May 31, 2022.*

High Performance Metallic TIMs: Patterned Metal Alloy Foils

Developments by Indium Corporation for indium and metal alloy foils as TIMs include:

- "Heat-Spring®": Application of patterning to improve gap-filling and improve thermal performance for uneven surfaces;
- Laminated aluminum foil (5µ thickness, typ., one surface) available for:
    - Eliminating "tackiness" of indium metal on contact
    - Eliminate potential for residue in contact cycling for semiconductor test;
- Expansion of range of metal alloys available with above enhancements;
- Applications for gimbaled test heads and higher temperature testing.
- Taller patterns to handle greater die warpage and worse non-flat surfaces.

Note: "Heat-Spring" is a Registered Mark of Indium Corporation. US Patent 7,593,228-B2.

High Performance Metallic TIMs: Patterned Metal Alloy Foils

Comparative test data for indium flat foils versus *patterned* indium foil and two high-performance silicone-based thermal greases:

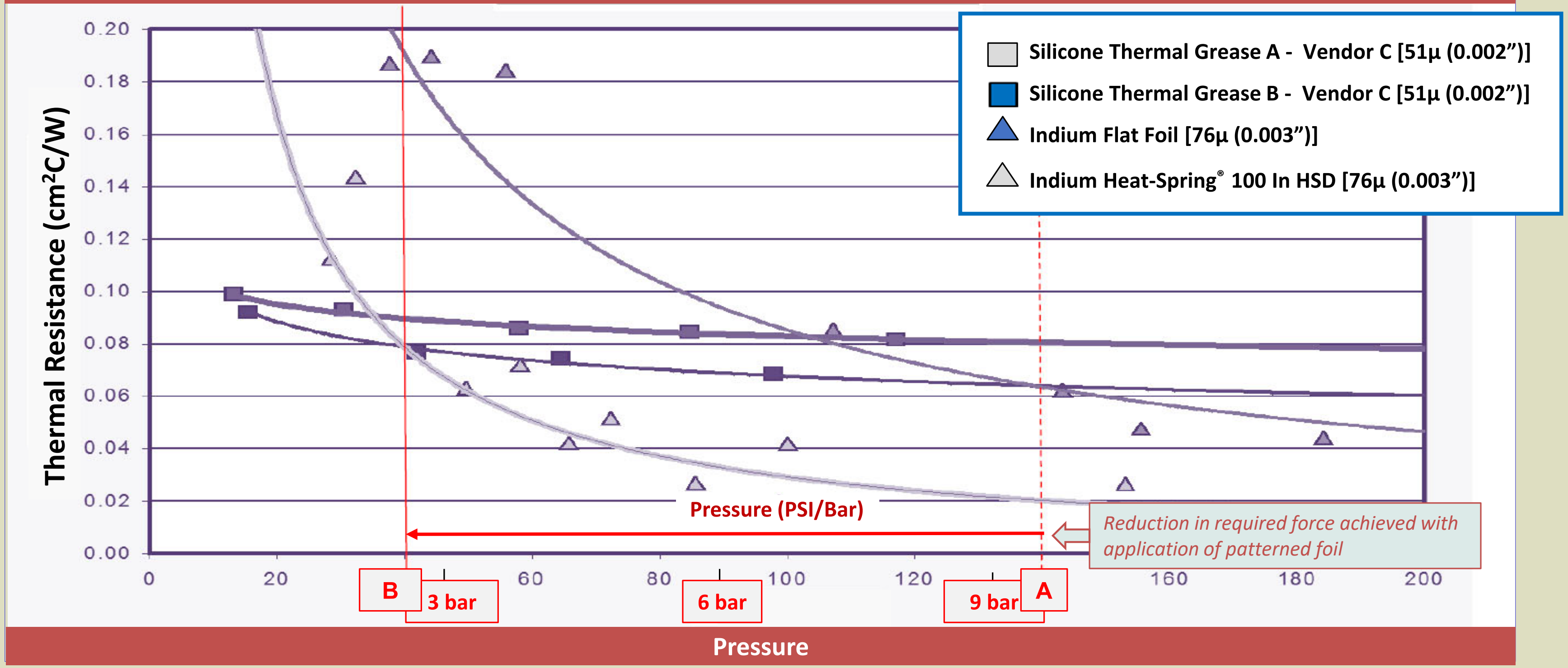
- Patterned metallic foils outperform thermal greases at clamping pressures >35-40 PSI.
- No compound run-out, pump-out, residue, or outgassing;
- Flexible, adaptable formats for easy test head/socket attachment.
- Patterning versus flat foil test data achieves a reduction in force required to match or outperform silicone thermal greases:
  - See following graph, Points B to A.

Patterned Metallic TIMs

Comparative test data: indium flat foils vs. Indium "Heat-Spring" patterned In100 foil and thermal greases:

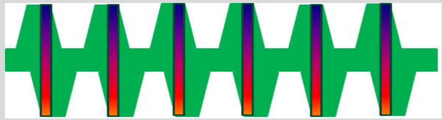
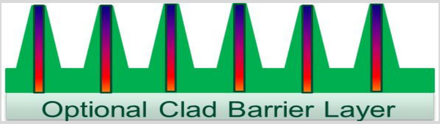
- Improvement: Patterning vs. flat indium foils, greases at ≥ 40PSI (Note force reduction from points A to B)

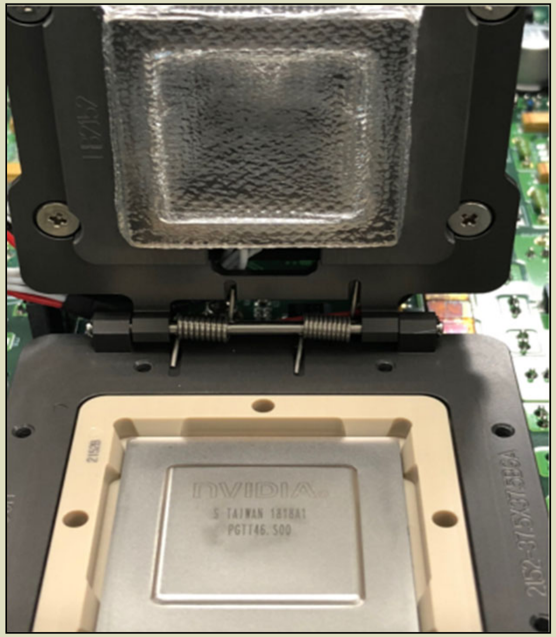
Patterned Metallic TIM versus Silicone Thermal Greases – ASTM D 5470



Data Source: Indium Corporation. DS&A LLC Model 101 ASTM D5470-12 Test Stand. "Heat-Spring" is a registered mark of Indium Corporation.

Patterned Metallic TIMs

Available Patterns for Indium Heat-Spring® Metallic TIMs	
Pattern Type	**Configuration**
Pattern 1: Designed for interfaces with tight surface control for roughness and parallelism.	
Pattern 2: High-profile variant for surfaces w/non-co-planar surfaces or greater warpage. 2X compressibility.	
Pattern 3: Single-sided pattern for clad multiple insertion applications and large surface area applications.	



Example (above):
Heat-Spring® HSK pattern, Al (25µm thickness)

Alloy: 90In10Ag

Clamping force applied: 70 PSI

Tj: 125°C

Device power: 400 - 700W

Burn-in hours: 500 (167 chipsets tested)

Data Source: G. Wilson, Indium Corporation, Milton Keynes UK; M. Lazic, Indium Corporation , Clinton NY USA. US Patent 7,593,228-B2 "Heat-Spring" is a registered mark of Indium Corporation.

Patterned Metallic TIMs

Bulk thermal conductivity and suggested maximum operating temperatures for metallic TIMs:

Maximum Bulk Thermal Conductivity and Suggested Operating Temperature for Metallic TIMs		
Metallic TIM Composition	Bulk Thermal Conductivity (W/mK)	**Suggested Maximum Operating Temperature (°C)**
52In/48Sn Indalloy 1E	34	100
80 In/20 Sn	53	110
100 In	86	125
In/Al Clad	-	125
Sn, “Sn+”	73	200
100 Pb	35	250
100 Cu	395	750

Table shows suggested values for selected metals and alloys; other alloys are possible.

- Characteristics of interface surfaces may affect maximum temperature.

*Notes: * “Indalloy”, “Sn+” are Indium Corporation products. Data Source: R. Jarrett, Indium Corporation , Utica NY USA; Bulk conductivity values, G. Wilson, Indium Corporation, Milton Keynes UK.*

Comparative Thermal Resistances: Reliability Testing

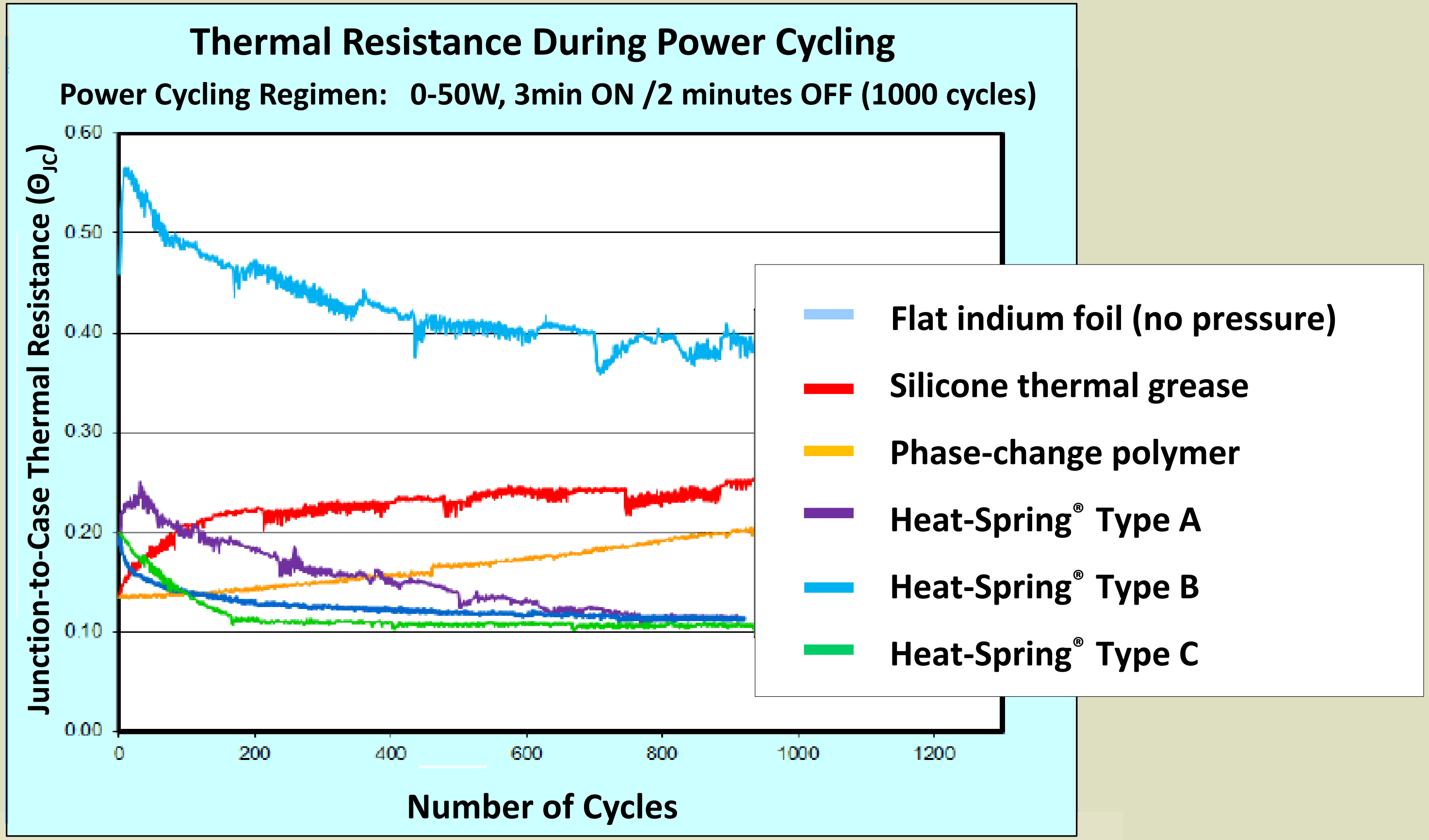
Impact of power cycling and bake testing on TIM types (following slides):

- *Demonstrating the importance of comparative thermal resistance testing beyond time zero*, for material evaluation

✓ Power cycling
  - Increasing thermal resistance values indicates decay in performance over time.
  - Declining thermal resistance values indicate TIM performance is *improving* over time.

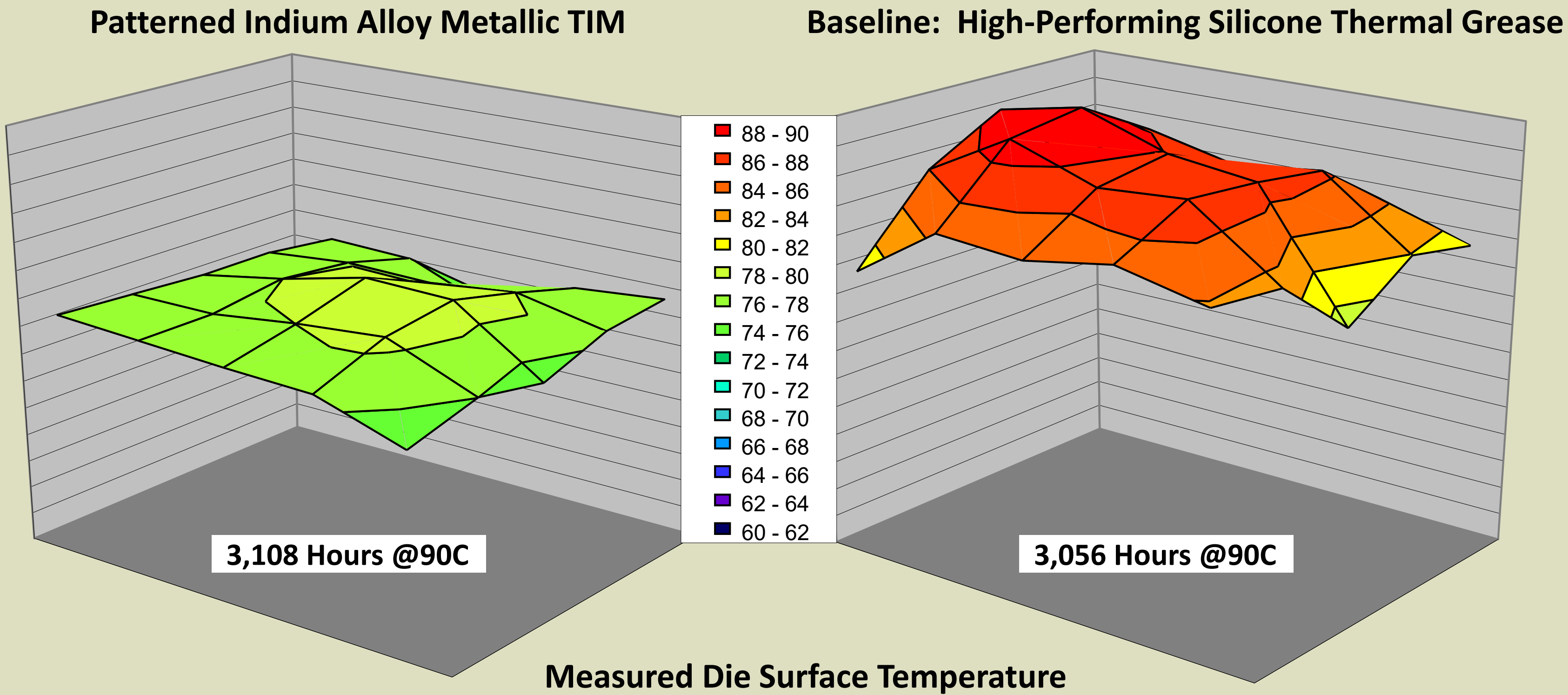
✓ Bake cycling (90C)
  - Declining thermal resistance indicates bake-out of silicone oil carrier from thermal grease.

Comparative Thermal Resistances: Reliability Testing



Source: Indium Corporation

Patterned Metallic TIMs: Reliability



Patterned Indium Alloy Metallic TIM

Baseline: High-Performing Silicone Thermal Grease

Measured Die Surface Temperature

Thermal Test Vehicle Comparative 3,000-Hour Reliability Bake Test

Note: Measured die surface temperature at time zero was shown to be approximately equivalent. Above test data taken after 3,000-hour bake test. Increased die surface temperature for Figure 4B reflects increased thermal resistance due to dry-out of silicone oil in the tested premium silicone-based thermal grease.

Data source: R. Jarrett, Indium Corporation, Utica NY USA.   Die thermal test vehicles: Provided by Intel Corporation.

Metallic TIM Types: New Developments

Examples: Relative bulk thermal conductivity values, development metallic TIMs of different types:

Bulk Thermal Conductivity Values – Metallic TIMs			
Basis[1]	**Category**	**Type (Typical Intended Usage)**	**Value (W/mK, Typ.)**
Indium Based	Solid	Solder TIM (TIM1)	70-86
		Compressible TIMs (Patterned, TIM2)	86
	Phase-Change	Phase-change metal alloy TIMs (TIM2)	40-50
Indium/Gallium[2]	Hybrid Liquid Metal	Indium® m2TIM™ (TIM1)	40-50
		Liquid metal pastes (TIM0, TIM1, TIM)	15-25
Gallium Based[2]	Liquid	Liquid metal TIMs (TIM0, TIM1)	20-45

Notes: 1. Primary metal by percentage. 2. Generalized statements regarding intended usages shown in parentheses. Multiple materials available from suppliers.
Source: Adapted from: Miloš Lazić, Indium Corporation, "Advanced Gallium-Based Thermal Interface Materials," IMAPS New England Symposium 49, Boxborough MA USA, May 2, 2023.

TIM Contact Cycle Reliability Testing for Semiconductor Test

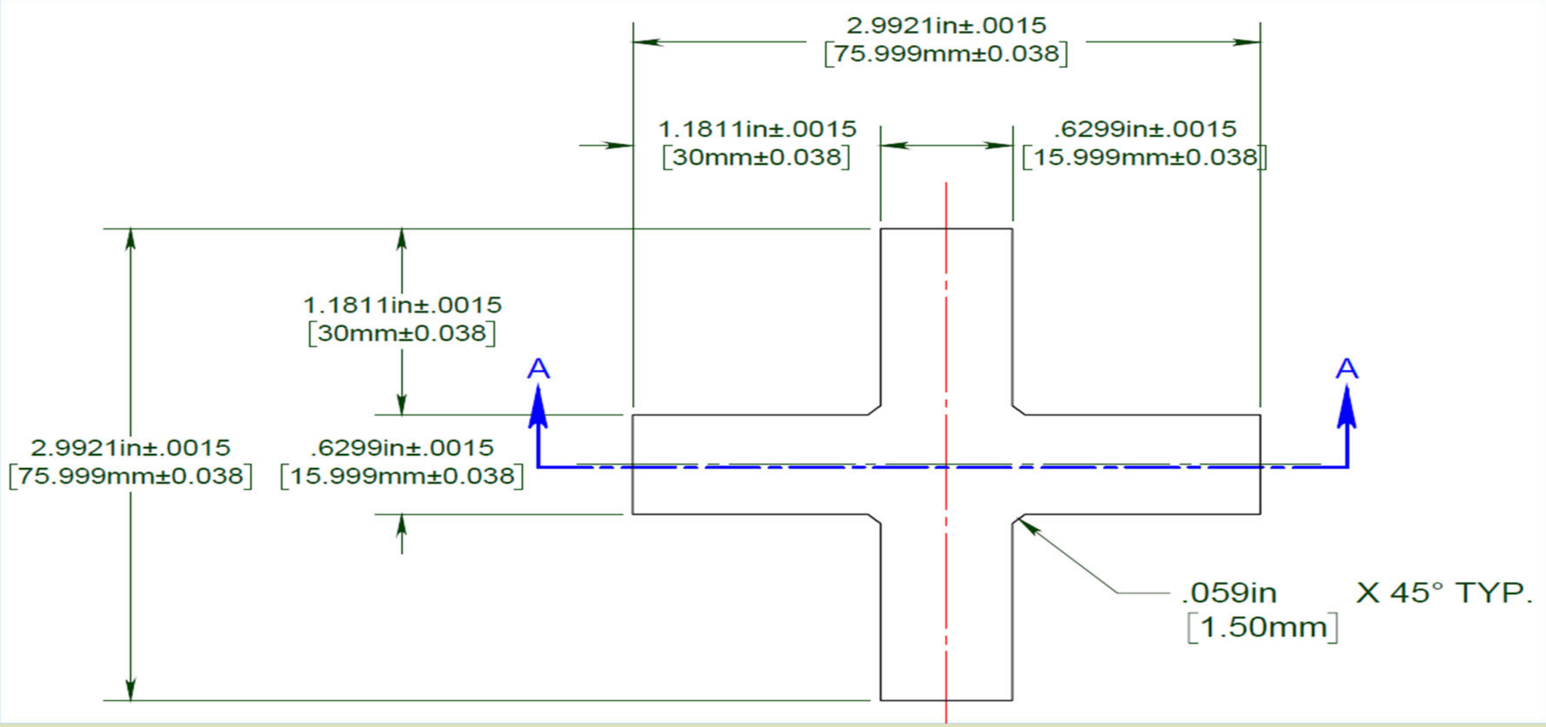
TIM commercial products developed for semiconductor test requirements, included in Phase I test program:

Thermal Interface Materials Tested	
Graph Key	**Description**
CLAD	Indium (99.99%) flat foil, one side only 5µ aluminum cladding
CLAD HSK	Indium (99.99% foil, one side only 5µ aluminum cladding, HSK pattern applied*
Al Foil, One-side coated	Aluminum foil 50µ thickness, coated one side with dry thermal compound**

*Note: * Indium Corporation Heat-Spring® HSK. ** Development material only.*

TIM Contact Cycle Reliability Testing for Semiconductor Test

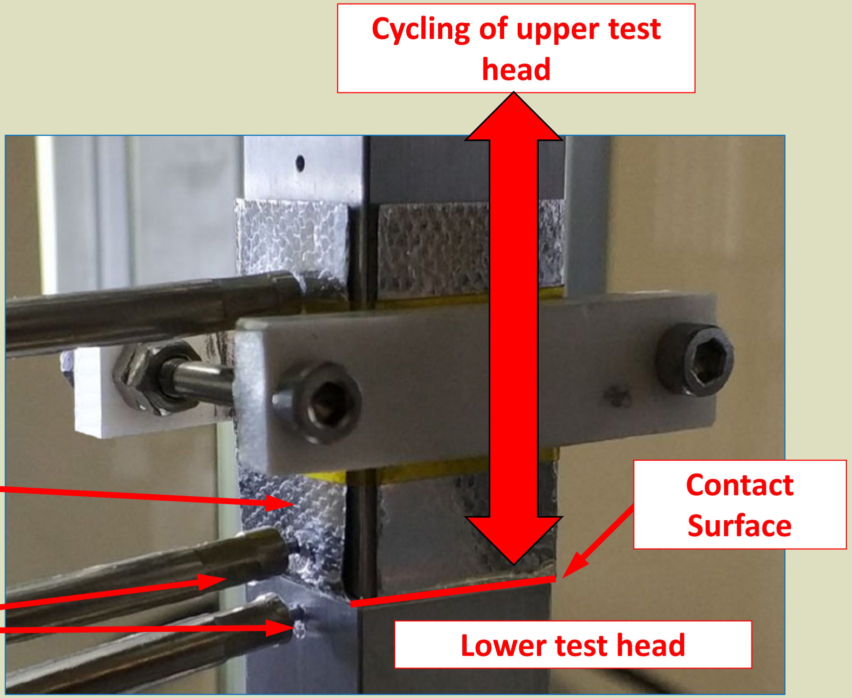
“Red Cross” test material designed for head attachment:



TIM Contact Cycle Reliability Testing for Semiconductor Test

Test heads were adapted for this mechanical cycling test program to fit an existing test stand.

- Test assembly shown with TIM under test applied
- Heat-Spring® HSK aluminum-clad patterned indium alloy TIM applied to upper test head

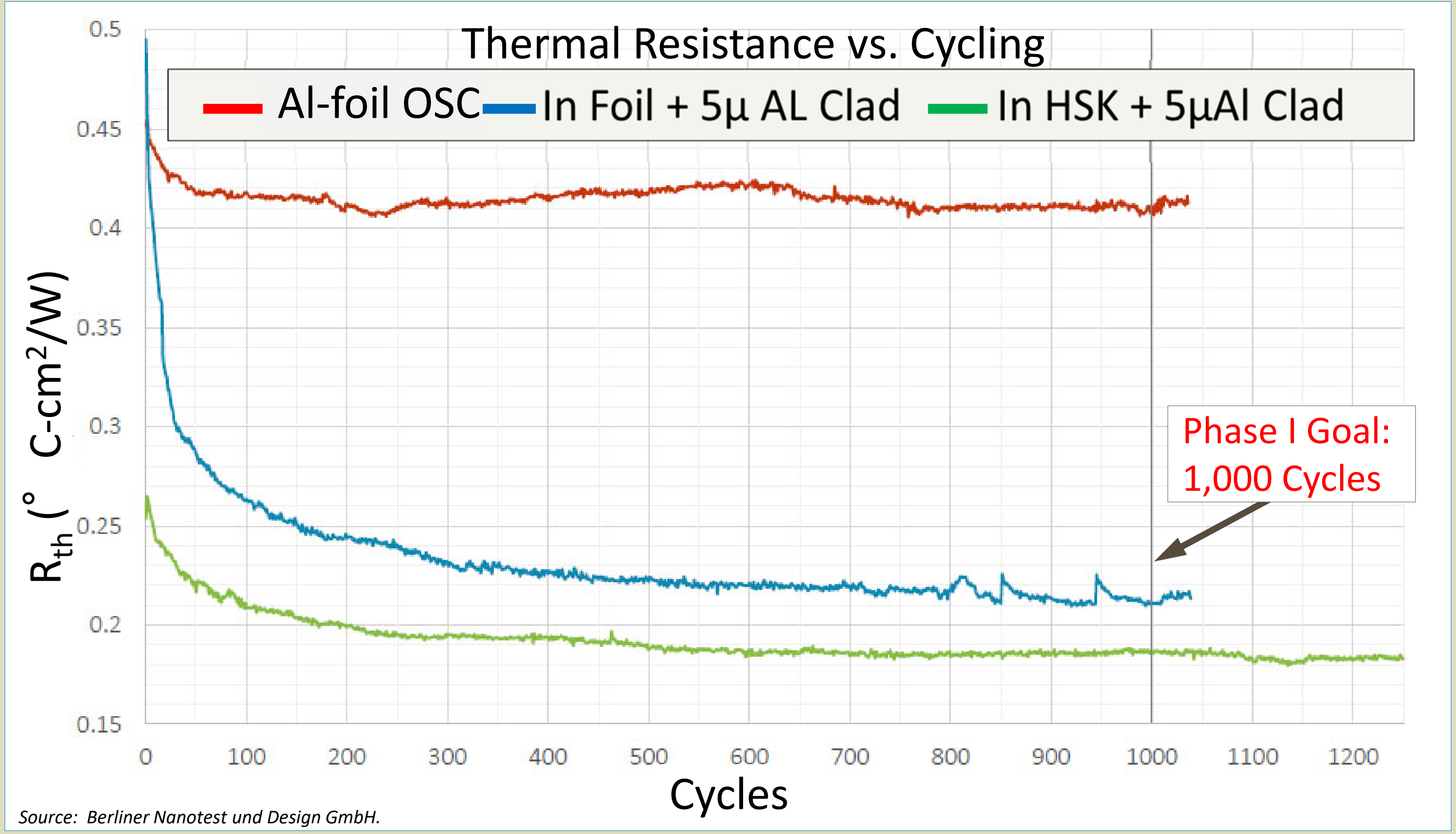


Upper test head with HSK aluminum-clad patterned indium foil TIM applied

RTDs inserted into test heads (3 shown of six total, upper and lower test heads)

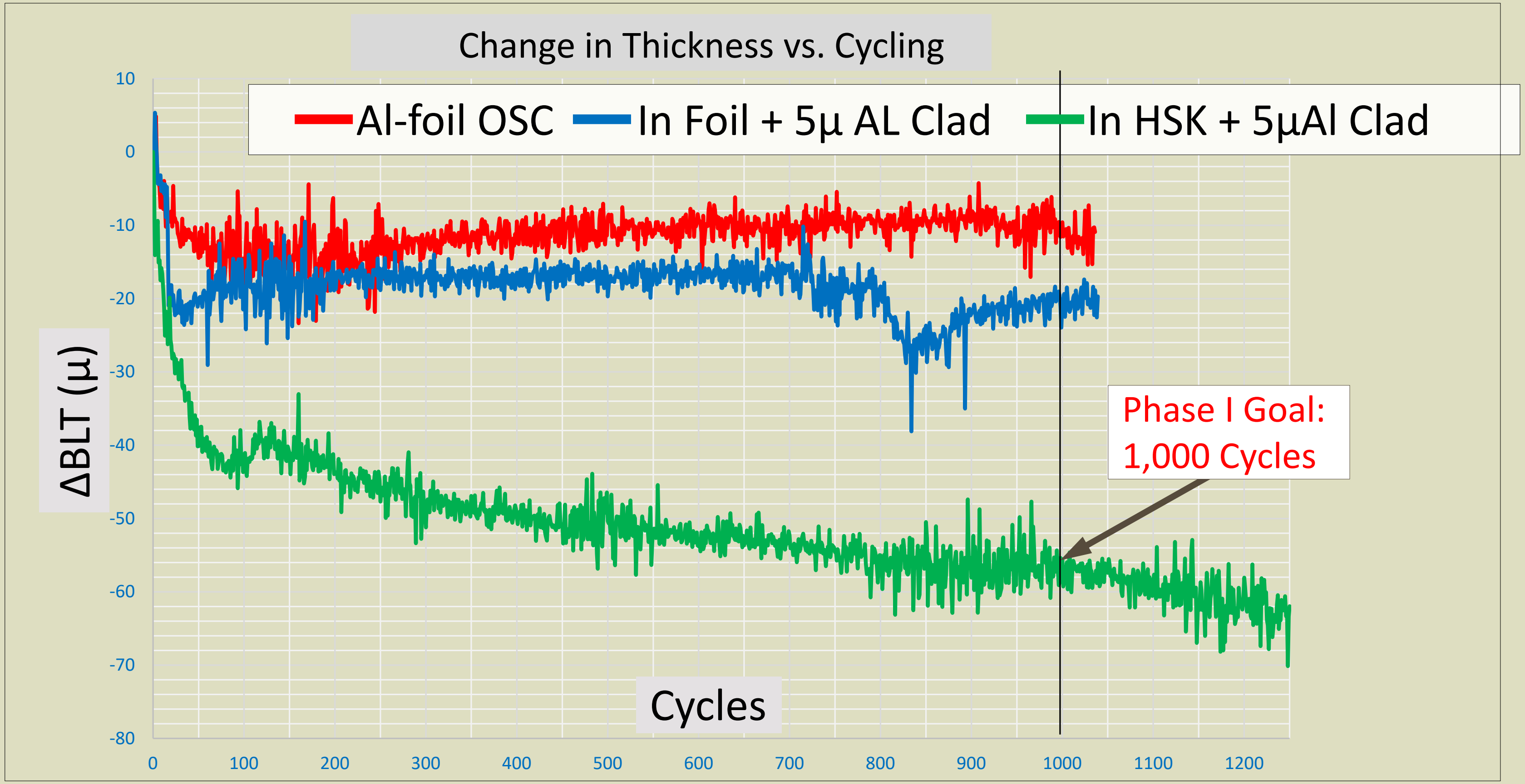
Note: Uniform single clamping force and temperature applied for all materials.

TIM Contact Cycle Reliability Testing for Semiconductor Test



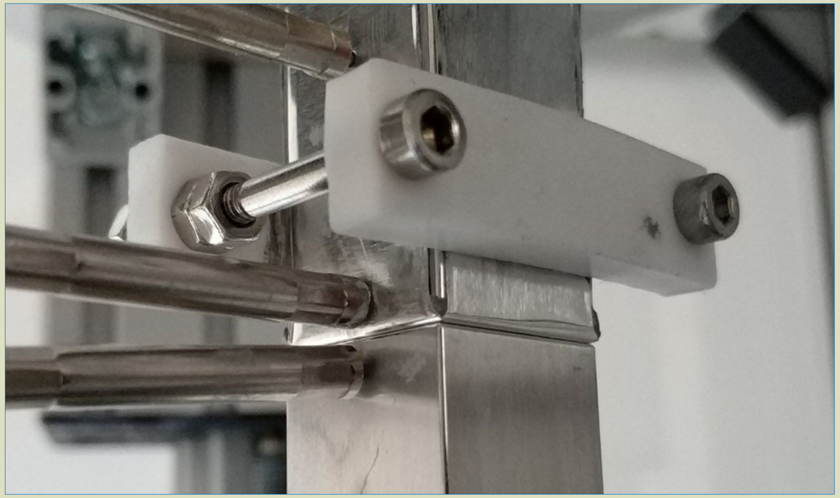
Source: Berliner Nanotest und Design GmbH.

TIM Contact Cycle Reliability Testing for Semiconductor Test

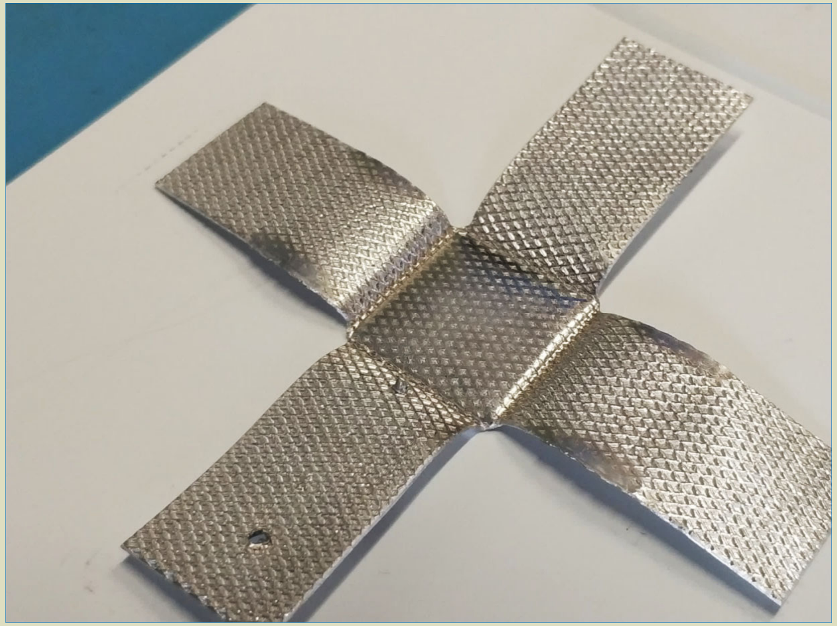


Source: Berliner Nanotest und Design GmbH. Observed variation (>800 cycles) for indium flat foil with al-cladding caused by an error with cold plate water supply. Testing concluded at 1,000 cycles (with exception of patterned In HSK +5µ Al cladding).

TIM Contact Cycle Reliability Testing for Semiconductor Test



Test heads with aluminum-clad (5μ) flat indium foil TIM2 applied.



Appearance of HSK-pattered indium foil with aluminum cladding, after conclusion of >1,000 cycles in testing.

Source: Berliner Nanotest und Design GmbH.

TIM Contact Cycle Reliability Testing: Data Analysis

Phase I testing of all three TIM types successfully passed 1,300 cycles:

- Al-OSC: 0.004” (100μ)-thick aluminum foil, coated one side only with non-silicone thermal compound. Applied with Al surface facing DUT.
- 99.99% flat indium foil [0.012” (300μ) thickness, including clad one side only with 5μ aluminum]. Applied with Al surface facing DUT.
- Indium Corporation Heat-Spring® HSK patterned 99.99% indium foil, clad one side only with 5μ aluminum . Total thickness: 0.0065” (155μ). Applied with bare Al surface facing DUT.

TIM Contact Cycle Reliability Testing: Data Analysis

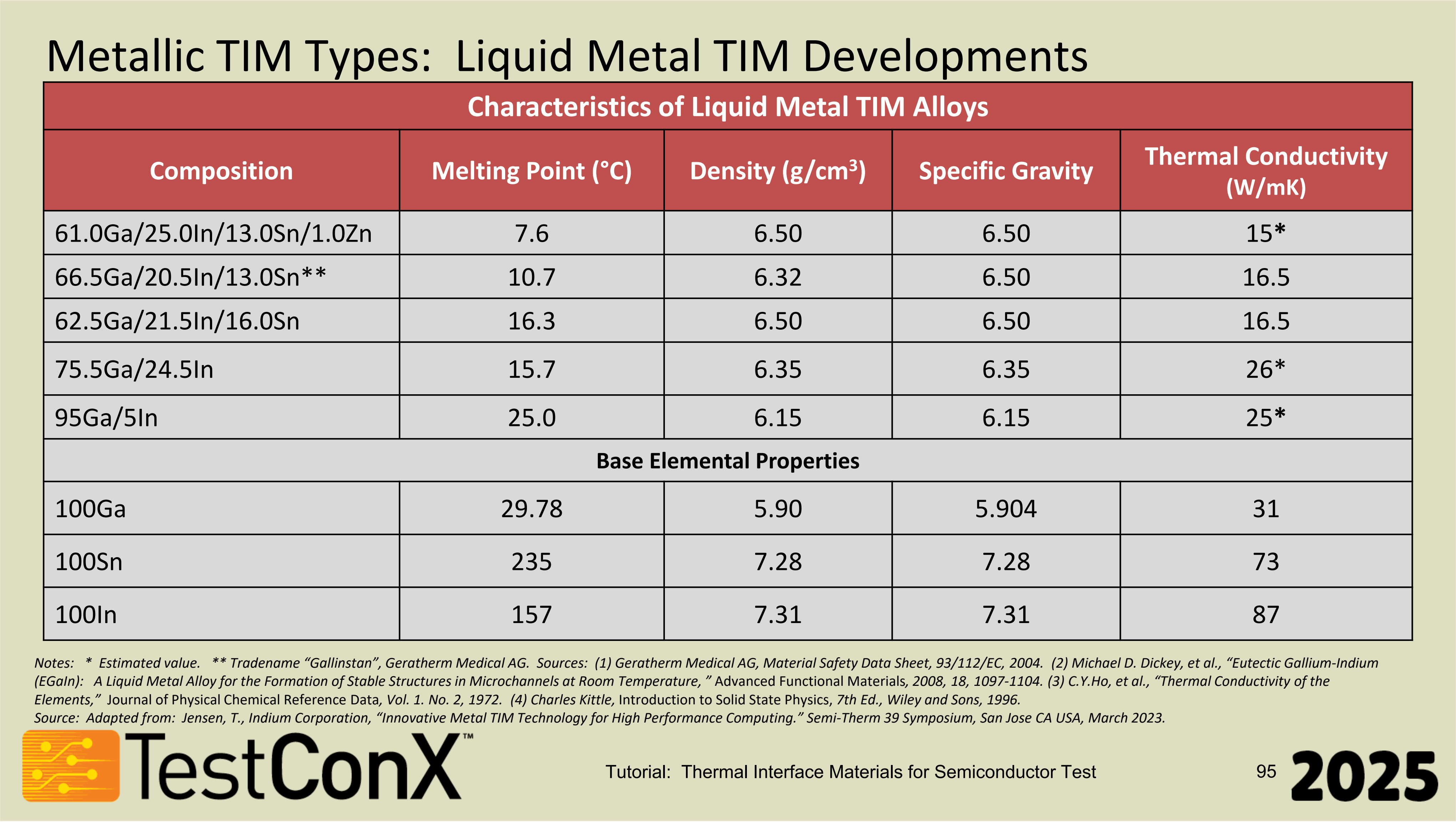
Phase I testing has demonstrated:

- Stable thermal resistance values achieved during mechanical cycling demonstrated required durability for all three baseline materials tested;
- Visual inspection indicated no visible marking and zero residue on lower body test head surface (equivalent to the case or die surface of DUT);
- Stable thermal and thickness values indicate success of each material type for long-term cycling without tearing or marking of DUT.

TIM Contact Cycle Reliability Testing: Next Steps

A test stand designed per ASTM D 5470-17 has been utilized with test heads adapted for a test program in three phases, per requirements for semiconductor test and burn-in applications.

- Phase I baseline test results for a mechanical contact cycling test program have been described. All three materials met the baseline test targets.
- Next steps completed successfully:
  - Phase II – Introduction of strike angle at constant temperature.
  - Phase III – Introduction of strike angle and elevated temperature conditions.
  - Phase IV – Extension to 5,000 contact/release cycles, completed.



Metallic TIM Types: Liquid Metal TIM Developments

Characteristics of Liquid Metal TIM Alloys				
Composition	**Melting Point (°C)**	**Density (g/cm^3)**	**Specific Gravity**	**Thermal Conductivity (W/mK)**
61.0Ga/25.0In/13.0Sn/1.0Zn	7.6	6.50	6.50	15*
66.5Ga/20.5In/13.0Sn**	10.7	6.32	6.50	16.5
62.5Ga/21.5In/16.0Sn	16.3	6.50	6.50	16.5
75.5Ga/24.5In	15.7	6.35	6.35	26*
95Ga/5In	25.0	6.15	6.15	25*
Base Elemental Properties				
100Ga	29.78	5.90	5.904	31
100Sn	235	7.28	7.28	73
100In	157	7.31	7.31	87

*Notes: * Estimated value.   ** Tradename "Gallinstan", Geratherm Medical AG. Sources: (1) Geratherm Medical AG, Material Safety Data Sheet, 93/112/EC, 2004. (2) Michael D. Dickey, et al., "Eutectic Gallium-Indium (EGaIn): A Liquid Metal Alloy for the Formation of Stable Structures in Microchannels at Room Temperature, "* Advanced Functional Materials, *2008, 18, 1097-1104. (3) C.Y.Ho, et al., "Thermal Conductivity of the Elements,"* Journal of Physical Chemical Reference Data, *Vol. 1. No. 2, 1972. (4) Charles Kittle,* Introduction to Solid State Physics, *7th Ed., Wiley and Sons, 1996.*

Source: Adapted from: Jensen, T., Indium Corporation, "Innovative Metal TIM Technology for High Performance Computing." Semi-Therm 39 Symposium, San Jose CA USA, March 2023.

TestConX™

Metallic TIM Types: Liquid Metal TIM Developments

Applicability of liquid metal TIMs for semiconductor test:

- High relative thermal conductivity and excellent wetting characteristics;
- A very thin bond line can be achieved without reflow;
- Liquid metals must be contained, to prevent spread during application;
- Once applied, surface tension will typically hold material as desired;
- Varying metal constituencies will allow tailored melting points as required;
- Metals listed are not known to be toxic but care in handling is required;
- Liquid metals can be jetted to form dots on the intended surface;
- Significant global development interest for TIM0/TIM1 applications;
- Suitability for traditional semiconductor test applications has not been demonstrated, given contact/release and no-marking requirements.

Metallic TIM Types: Liquid Metal Paste TIM Developments

Illustration of thermal resistance for several different liquid metal pastes:

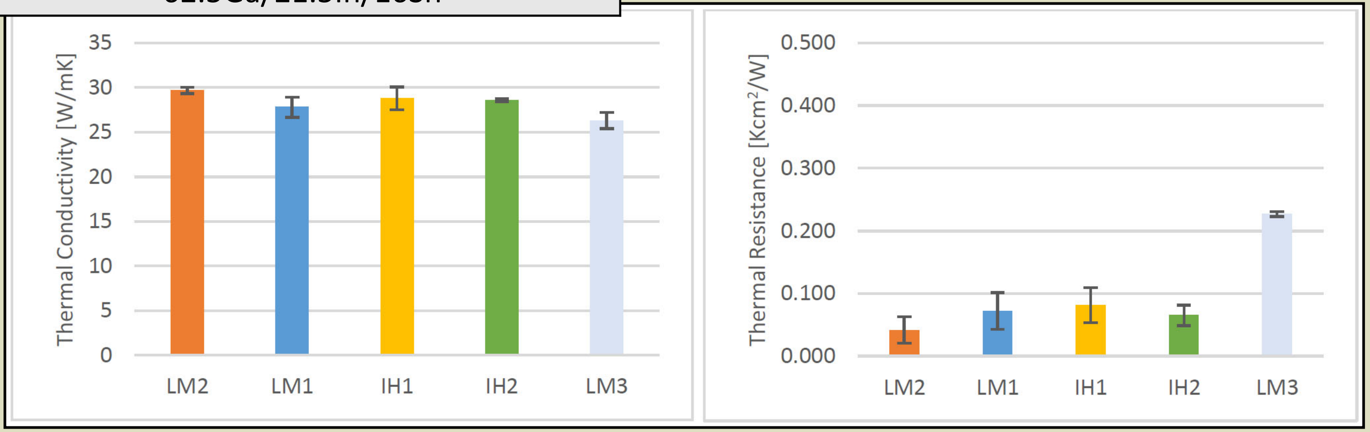
Commercial Gallium-based Liquid Metal Paste TIM Sample Materials Tested

Sample Name	Composition
LM1	68.5Ga/21.5In/10Sn
LM2	Vendor Confidential
LM3	Vendor Confidential
V1	68.5Ga/21.5In/10Sn
V2	62.5Ga/21.5In/16Sn

← *Gallinstan, Vendor A*

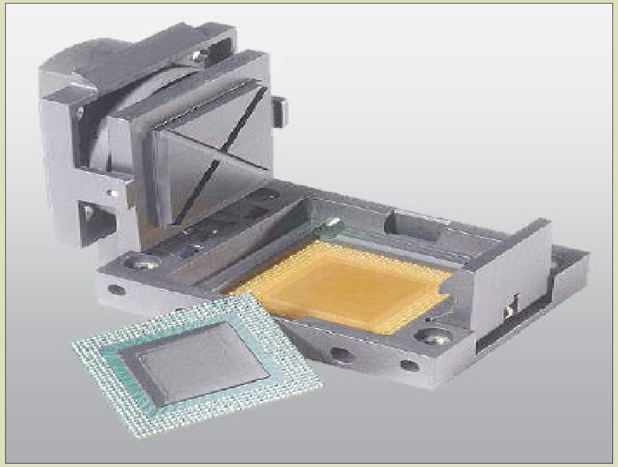
← *Gallinstan, Vendor B*

← *Believed to be ThermalGrizzly Conductonaut*



Source: DuPont (March 2023). DS&A LLC: Notes in red indicating vendor sources for Gallinstan and other; confirmation not available.

Graphitic Materials



Semiconductor test carrier and socket

NeoGraf "Flexible" graphite, highly anisotropic:

- Bulk thermal conductivity:
  - In-plane (X-Y): 1200-1800W/mK
    Through-plane (Z): 1-8W/mK
- Thermal performance improves with higher pressures
- No silicone prone to pump-out or separation – and flexible
- No phase-change temperature required
- Maximum temperature, certain compressible graphite films: 125°C
- Maximum temperature, many traditional graphite films: 400°C
- Disadvantages:
  - Typical minimum thickness: 0.127mm (0.005")
  - Some types are subject to conductive particle flaking
- Development material - compressible to limited degree: NeoGraf eGraf® TG-768
- NeoGraf, Panasonic PGS, Kaneka are leading suppliers.

Source, text and photograph: NeoGraf Solutions LLC data sheets. Note that certain "compressible" graphite films are impregnated with resins that affect maximum operating temperatures, depending on supplier. Refer to individual product data sheets for specific values.

Graphite Sheet Heat Spreaders

Graphite Sheet Heat Spreader Materials

Vendor	Product Designation	Thickness (µm)	Bulk Thermal Conductivity	
			X-Y axis W/mK	Z-axis W/mK
DSN (China)	DSN5017	17	1600-1900	15-20
TTCL (China)	TGS-17	17	1700	15
Panasonic (Japan)	PGS EYG-S-25	25	1600	N/A
NeoGraf (US)	eGraf® SpreaderShield Flexible Graphite SS1500	17	1500	3.4
Panasonic (Japan)	PGS EYG-S-100	100	700	N/A
NeoGraf (US)	eGraf® SpreaderShield Flexible Graphite SS600	127	600	3.5
NeoGraf (US)	eGraf® HiTHERM™ 700	127	240	6

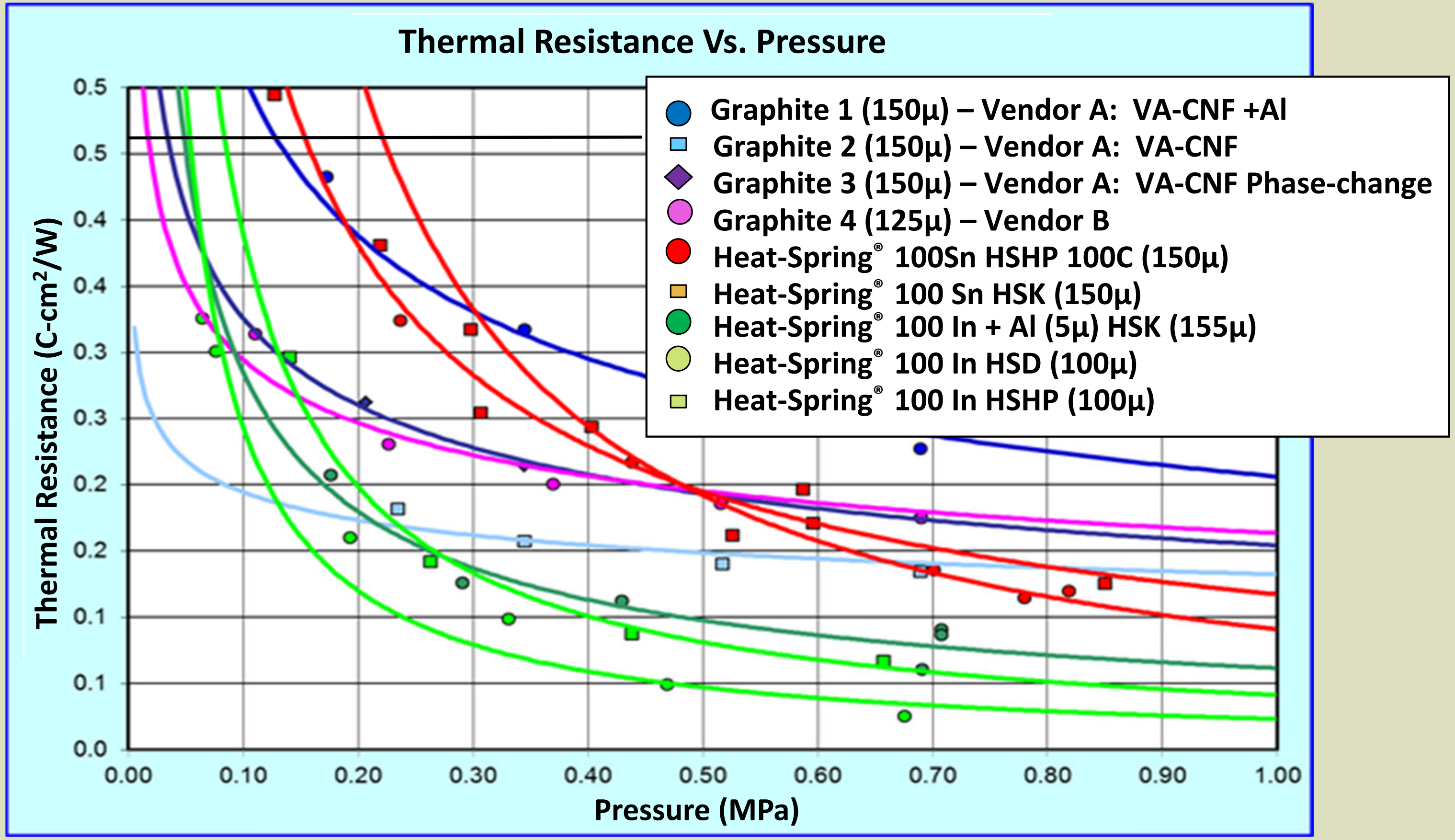
Data Source: Vendor presentations and technical data sheets, DS&A LLC.

Vertically-Aligned Carbon Fiber (VA-CNF) TIMs

VA-CNF				
Vendor	**Product Designation**	**Thickness (µm)**	**Bulk Thermal Conductivity**	
			X-Y axis W/mK	**Z-axis W/mK**
Dexerials (Japan)	EX20200XX Gap-filler	100-200	N/A	15-20
NeoGraf (US)	Grafoil® GTA-005, GTA-030	130-760	140	5.5-7.0
Hitachi (Japan)	TC-001	150-500	N/A	40-90

Data Source: Vendor presentations and technical data sheets, DS&A LLC.

High Performance: Metal Alloy TIMs vs. VA-CNF and Graphite Films

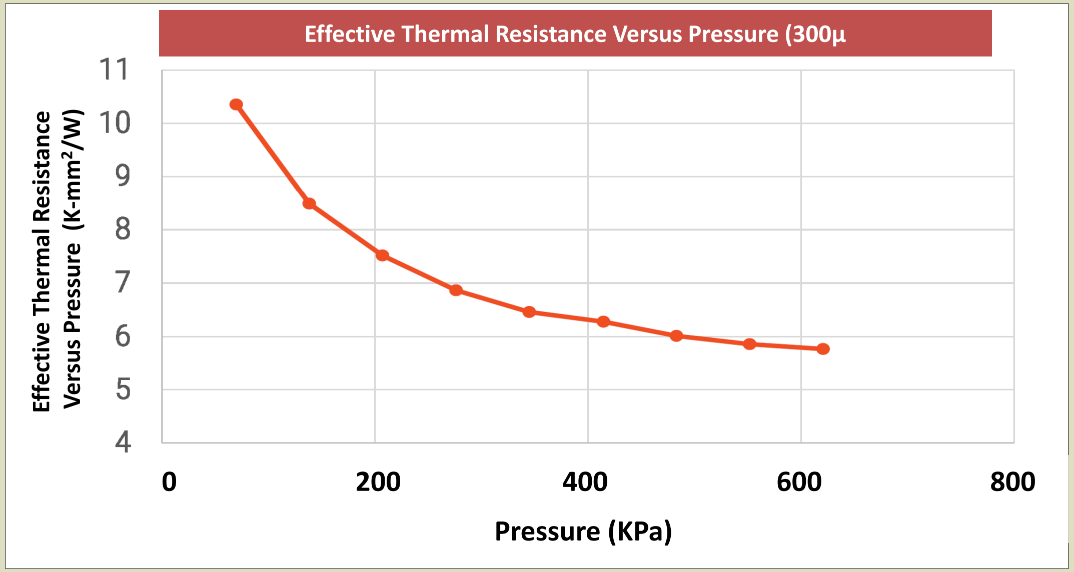


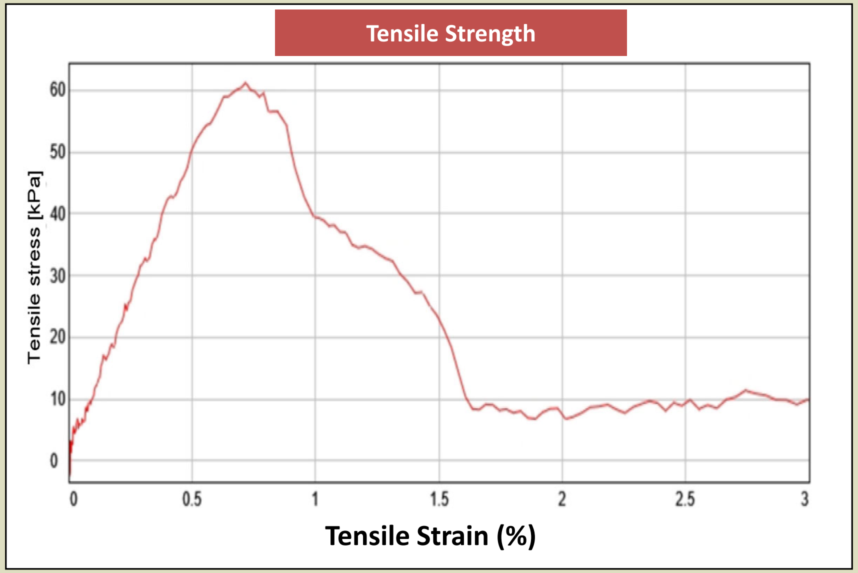
Data Source: Indium Corporation. DS&A LLC Model 101 ASTM D5470-12 Test Stand.

Graphene-enhanced Graphitic Materials

New TIM developments include graphene-enhanced performance of graphite films:

- SHT “FrostSheet” is an example of such a newly-developed thermal material



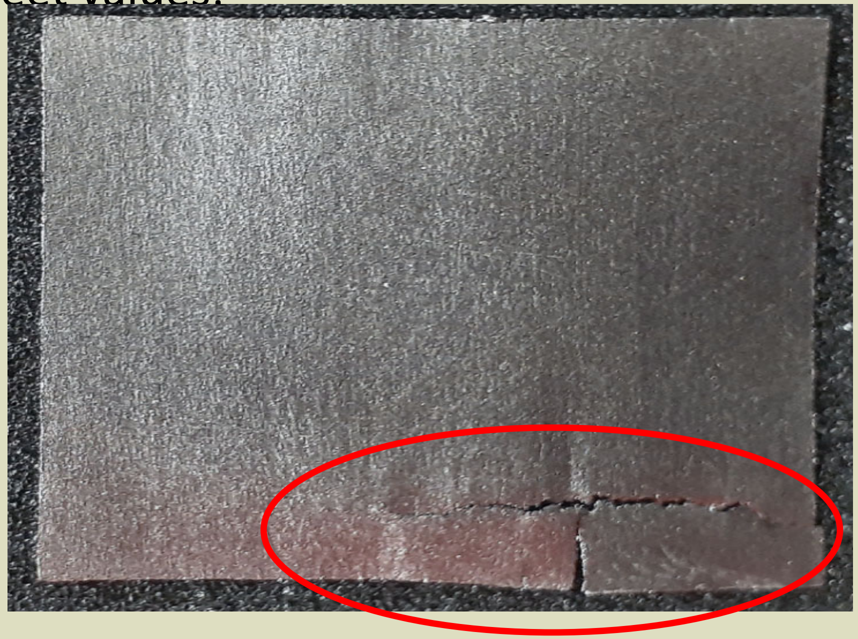


Source: Murugesan, M.; Martinson, K.; Enmark, M.; Zhang, H.; Liu, J.; Almhem, L., “Applications of High Thermal Conductivity Graphene Enhanced Thermal Interface Materials,” SHT AB, IMAPS France Thermal and Micropackaging Workshop 2023, Poitiers, France, March 8-9, 2023.

Graphene-enhanced Graphitic Materials

"Graphene-enhanced" performance of materials such as graphite films:

- SHT FrostSheet is an example of such a newly-developed thermal material;
- Such materials include developments for both TIMs and heat spreaders;
- SHT FrostSheet and GT-TIM GT-90SPRO data sheet values:
  - Bulk through-plane thermal conductivity: 90+/- 10 W/mK
  - Thickness: 300µm (0.012")
  - Fragile, relatively thin graphite materials
  - Subject to easy handling damage
  - No testing to date for repeated contact/release cycling for use in semiconductor test.

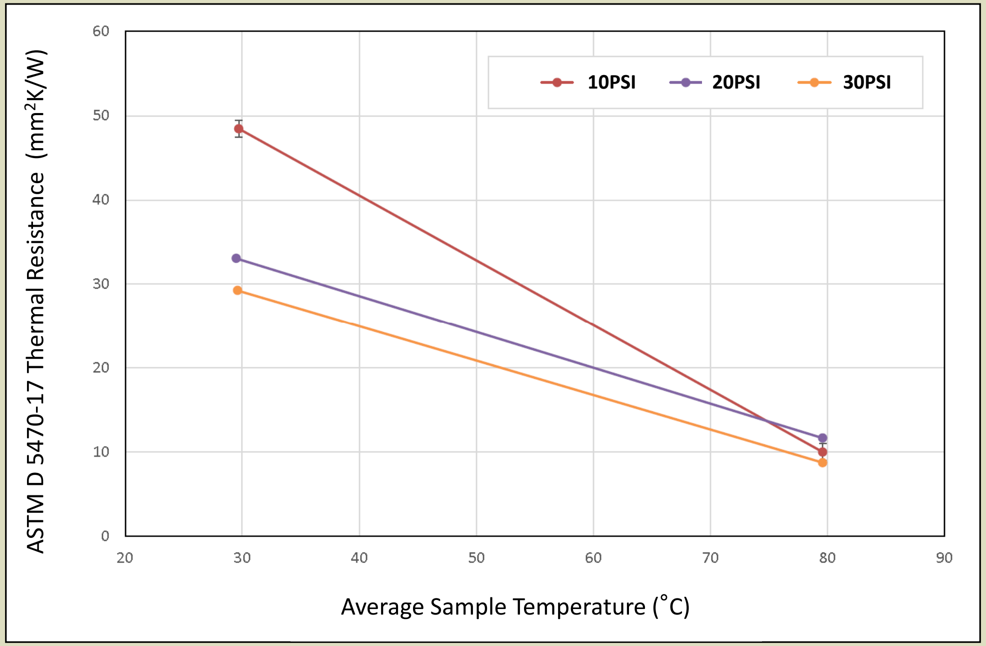


Source: Murugesan, M.; Martinson, K.; Enmark, M.; Zhang, H.; Liu, J.; Almhem, L.; Super High Tech AB, "Applications of High Thermal Conductivity Graphene Enhanced Thermal Interface Materials," IMAPS France Thermal and Micropackaging Workshop 2023, Poitiers, France, March 8-9, 2023.
Photograph: Super High Tech AB (Göteborg, Sweden) "FrostSheet" enhanced graphite film: DS&A LLC (January 16, 2024).

Phase-Change Materials

Phase-change compounds have been manufactured for use as TIMs for more than thirty years and are well-known for TIM2 applications:

- Compounds and pre-forms are available with phase-change temperatures from 45°C to 60°C:
  - Purpose of the phase-change temperature is to achieve thickness change to minimize resistance, at a given pressure (graph)
- Bulk thermal conductivity values are available in a wide range (depending on formulation): 0.6W/mK – 8W/mK
- Not typically utilized for semiconductor test, PCM dispensed compounds and pre-forms will be subject to marking of the DUT (as operating test head temperature approaches the designed phase-change temperature).
- Certain new materials are available that may offer promise for single-side carrier coatings:
  - Aluminum (dead soft)
  - Durable graphite films (certain manufacturers)
  - Dielectric films (i.e., DuPont™ Kapton® MT, MT+)
- Application of a TIM pre-form with single-side coating to face the test head prevents marking or detritus on the DUT.



Source, Graph: Berliner Nanotest und Design GmbH (Berlin, Germany). Well-known phase-change preform TIM (8µm initial thickness, prior to application of pressure).

PCM-Coated Graphite Films and Reliability Testing

Current development of phase-change coated graphite film carriers, developed by Streuter Technologies:

- Data sheet test values per ASTM D 5470.
- Decades of proven compound coating and manufacturing processes for TIM materials, to date;
- Streuter Technologies is now offering different versions of this product type:
  - Single-side phase-change coating on film graphite film for semiconductor test applications;
  - Single- and double-sided coatings in different thicknesses, as required;
  - Multiple combinations of options in performance and durability testing:
    - Carrier (20-, 32-, 40-, 70-micron thicknesses)
    - Coating thickness and custom footprint/offset compound coatings
    - Phase-change temperature (52°C, 60°C)
  - Very high degree of surface wetting achieved – addressing surface warpage and roughness.
  - Certain graphite films are highly durable and have passed significant 90-degree bend testing over tens of thousands of bend cycles – appropriate for semiconductor test.

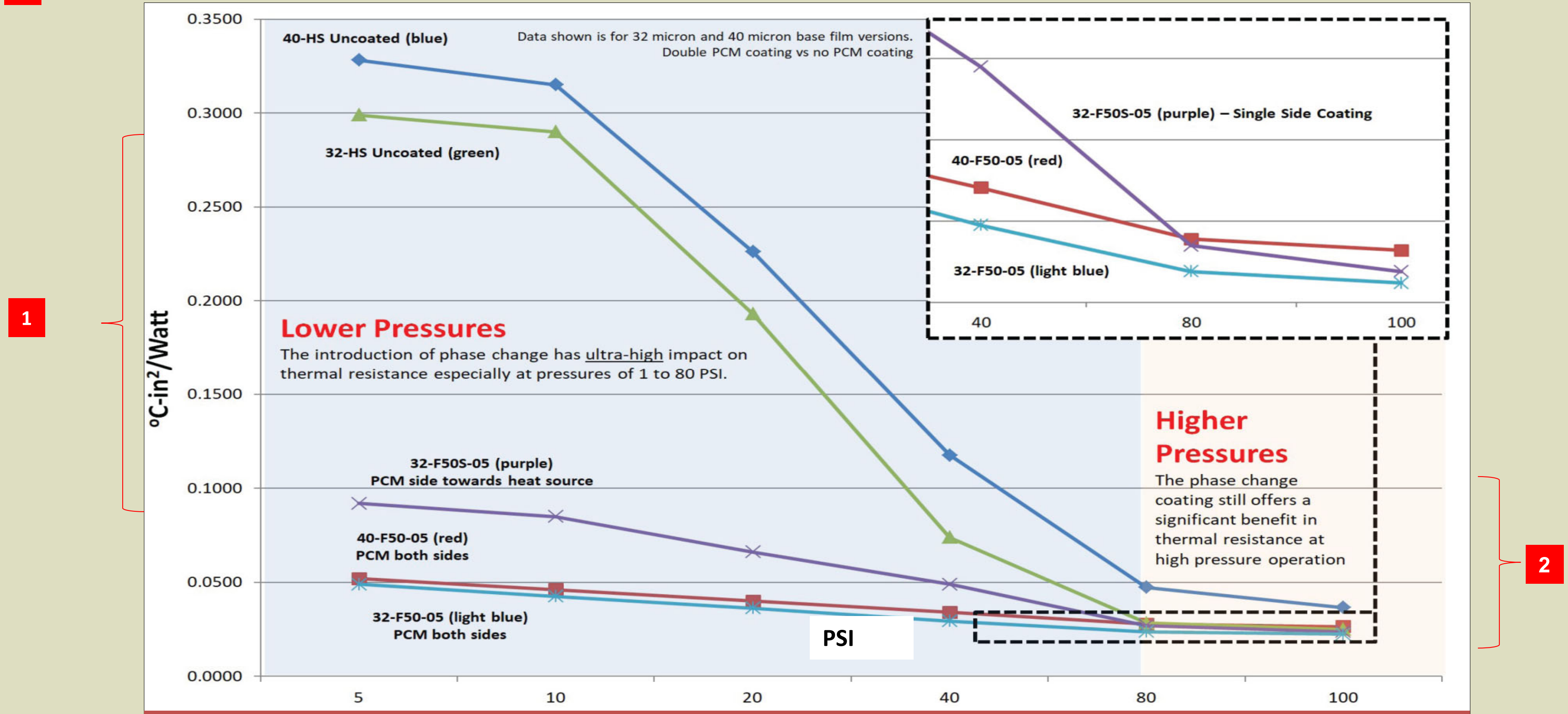
Source: Streuter Technologies, Inc. (www.stretech.com)

TIMtel “Graphenol” PCIM-Coated Graphite Films

Note: Please contact vendor regarding availability of these materials: Streuter Technologies, Inc. (www.stretech.com)

1 **32micron graphite film: 71% Improvement at low pressure (5 PSI), single-side coating vs. uncoated**

2 **40micron graphite film: 70% Improvement at medium (40 PSI) pressure, double-side coating vs. uncoated**



Thermal Resistance, PCM-Coated Graphite Films vs. Uncoated Graphite Films

Carbon Nanotube Materials

Developments with vertically-aligned carbon nanotube TIMs (VA-CNTs):

- Advantages:
  - Perceived high bulk thermal conductivity of CNTs
- Disadvantages:
  - Significant difficulties in developing a manufacturable TIM product
  - Development materials in some cases have very low bulk thermal conductivity
  - High perceived manufacturing cost
- Fujitsu:
  - Tested values to date for bulk thermal conductivity (Z): 10-20W/mK

Summary of New Material Developments

High Performance Commercial TIM Materials - Examples			
TIM Classification	**Vendor**	**Product**	**Status**
Thermal Grease	Shin-Etsu/Japan	Gallium silicone grease	Commercial product
	Sumitomo/Japan	Nanoparticle Ni/Fe grease	(Indeterminate)
Metallic TIM	Enerdyne Corporation/USA	Liquid indium alloy on carrier	(Indeterminate)
	Indium Corporation/USA	Heat-Spring® patterned TIM	Commercial product
		Indium alloy foil	Commercial product
		Phase-change Metal Alloys (PCMA)	Commercial product
	AIM/Canada	Indium alloy foil	Commercial product
	Kester/USA	Indium alloy foil	Commercial product

Summary of New Material Developments

High Performance Commercial TIM Materials - Examples			
TIM Classification	**Vendor**	**Product**	**Status**
Aligned Carbon Fiber/Polymeric Matrix Carrier Preform	Btech Corporation/USA	Graphite fiber/polymeric carrier preform	Commercial product
	DuPont E&C/USA	Carbon fiber vertical array/polymeric carrier preform	Development
	Honeywell Electronic Materials/USA	Graphite fiber/polymeric carrier preform	Commercial product (withdrawn)
	Hitachi/USA	Carbon fiber vertical array/polymeric carrier preform	Commercial product
CNT-Based	SHT AB/Sweden	Vertically-aligned CNT array in polymeric carrier	Development
	Carbice/Georgia Tech/USA	Infinity™ Vertically-aligned CNT-array in polymeric carrier	Commercial product

TIM Design for Single-Phase and Two-Phase Liquid Immersion

Liquid Immersion Systems: General Characteristics

Liquid Immersion Single-Phase Dielectric Fluids: General Characteristics

General Category	Fluid Family	Advantages	Disadvantages
Single-Phase Dielectric Fluids	Synthetic silicate esters	• Good low temperature properties • Tailorable chemistries	• Break down in contact with moisture, forming gels • Moderate dielectric strength
	Organic esters	• Low cost • Excellent dielectric strength • Organic sources: Glycerin and plant seed and vegetable derivatives	• Low to moderate dielectric strength
	Synthetic hydrocarbon oils	• Excellent dielectric strength • Relatively low cost • Minimal impurities • Tailorable chemistries	• Extracts or solvates similar chemistries in system common materials • Requires filtration systems to remove fluid contaminants extracted or solvated from similar system common materials

Liquid Immersion Systems: General Characteristics

Liquid Immersion Single-Phase Dielectric Fluids: General Characteristics

General Category	Fluid Family	Advantages	Disadvantages
Single-Phase Dielectric Fluids	Mineral oils	• Low cost	• Low to moderate dielectric strength • Low AC breakdown voltage • Significant contamination potential: Saturated hydrocarbons with strong chemical affinity for many common materials used in systems: -- Insulation and cabling sheathing -- PSA labels and adhesives -- Silicone oil carriers and silicone gap-fillers -- Silicone thermal greases, gels, thermal compounds • Extracts or solvates similar chemistries in system common materials • High relative levels of impurities • Requires filtration systems to remove fluid contaminants extracted or solvated from similar system materials

Liquid Immersion Systems: General Characteristics

Liquid Immersion Two-Phase Dielectric Fluids: General Characteristics

General Category	Fluid Family	Advantages	Disadvantages
Two-Phase Dielectric Fluids	Perfluorinated fluorocarbons (PFC)	• Excellent boiling point • Highly stable to 300°C • Good low temperature properties • Moderate dielectric strength • Tailorable chemistries	• Extremely high GWP values (not recommended in 2023) • High cost • *Announced discontinuation for some production chemistries (2025)*
	Hydrofluoroethers (HFE)	• Stable to >150°C • Moderate dielectric strength • Moderate AC breakdown voltage • Minimal impurities • Excellent GWP values, zero ODP	• Reduction in dielectric strength in high frequency systems • High cost • *Announced discontinuation for some production chemistries (2025)*
	Fluoroketones (FK)	• No reduction in dielectric strength in high frequency systems	• High cost • Reactive with moisture at RT • *Announced discontinuation for some production chemistries (2025)*

Liquid Immersion Systems: Fluid Evaluation Characteristics

Liquid Immersion Fluids – Key Evaluation Characteristics

Rank	Specific Fluid Characteristic	Value System	Test Standard (English)	Test Standard (SI)
Primary Evaluation Characteristics	Boiling Point (Initial boiling point and range)	°C	ASTM D 1120	ISO R 918, Draft DIS 4626
	Flash Point	°C	ASTM D 92	ISO 2719
	AC Breakdown Voltage	kV (@2.5mm)	ASTM D 1816	IEC 60156
	Dielectric Strength	kV or Vm	ASTM D 877	
	Dielectric Strength (Filtered/degassed liquids)	kV or Vm	ASTM D 1816	
	Relative Density	Kg/l @20°C	ASTM D 1122	(ISO 3675)
	Thermal Conductivity	W/mK	ASTM D 7896	
	Specific Heat Capacity (@20°C)	J/kgK or kJ/kg	ASTM E 1269	
	Kinematic Viscosity (Dynamic Viscosity/Density)	mm^2/s, cSt	ASTM D 445	ISO 3104
	Viscosity Index		ASTM D 445 D 2270	
	Dynamic Viscosity	Pa.s (cP)		
	Pour Point	°C	D 97 (D 5950)	ISO 3016
	Ozone Depletion Potential (ODP)	Value	PNNL 16813	
	Global Warming Potential (GWP)	Value	PNNL 16813	

Liquid Immersion Systems: Fluid Evaluation Characteristics

Liquid Immersion Fluids – Key Evaluation Characteristics				
Rank	**Specific Fluid Characteristic**	**Value System**	**Test Standard (English)**	**Test Standard (SI)**
Additional Evaluation Characteristics	Specific Gravity	Value	ASTM D 4052	
	Color	Hazen	ASTM D 1500, D 5386	ISO 2211
	Appearance	-	Visual	
	Water content	mg/kg or ppm	ASTM D 6304	IEC 60814
	Acidity	mg KOH/g	ASTM D 974 (Modified)	IEC 62021-1, 62021-2
	Biodegradability	Value (%)	MIL-F-24385 BOD (Biological Oxygen Demand)	
	Total Sulphur Content	mg/kg	ASTM D 5185	

Liquid Immersion Systems: Fluid Evaluation Characteristics

Single-Phase Dielectric Immersion Fluids (Sample Listing)

Category	Company	Headquarters	Fluid or Product Name	Chemistry	
Single-Phase Dielectric Immersion Fluids	(Many vendors)		PAO2	Polyalphaolefin 2cSt	SYNTHETIC OIL
	Chevron Phillips Chemical	US	Synfluid PAO6	Polyalphaolefin 6cSt	
	Exxon Mobil Corporation	US	SpectraSyn™ 6	Polyalphaolefin 6cSt	HYDROCARBON OIL
	Engineered Fluids	US	ElectroCool EC-100	Low viscosity hydrocarbon	
	(Many vendors)	-	Mineral oil	Low viscosity hydrocarbon	
	Exxon Mobil Corporation	US	Coolanol™ -20	Synthetic silicate ester	SYNTHETIC ESTER
	Cargill Inc.	US	Envirotemp™ 360	Synthetic organic ester	
	DSI Ventures	US	OptiCool	Synthetic ester	
	Fuchs Petrolub SE	Germany	Renolin FECC 7	Low viscosity hydrocarbon; Inhibited base oil	HYDROCARBON OIL
			Renolin FECC 5		
			Renolin FECC 5 SYNTH		
	GRC	US	ElectroSafe™ Plus	Low viscosity hydrotreated heavy paraffinic oil	
	Shell Nederland	Netherlands	S3X Immersion Fluid	Gas-to-Liquid (GTL) synthetic paraffinic oil	
			S5X Immersion Fluid		
	BP plc	UK	Castrol White Oil 15BP	Low viscosity hydrocarbon	
	BP plc		Castrol DC20		

Sources: Vendor company product data sheets and SDS.

Liquid Immersion Systems: Single-Phase Fluids Available

Single-Phase Dielectric Immersion Fluids (Sample Listing)

Category	Company	Headquarters	Fluid or Product Name	Chemistry	
Single-Phase Dielectric Immersion Fluids	3M Company	US	Novec™ 7300	Hydrofluoroether (HFE)	**HFE**
	Chemours Company FC	US	Vertrel™ XF	Single-phase hydrofluorocarbon (HFC)	**HFC**
	Solvay SA	Italy	Galden® HT110	Perfluorinated Perfluoroether (PFPE)	**PFPE**
			Galden® DO2TS		
			Galden® HT170		

Sources: Vendor company product data sheets and SDS.

Liquid Immersion Systems: Single-Phase Fluids Available

Two-Phase Dielectric Immersion Fluids (Sample Listing)

Category	Company	Headquarters	Fluid or Product Name	Boiling Point (°C)	Chemistry	
Two-phase Dielectric Immersion Fluids	3M Company	US	Novec™ 649	49	Fluoroketone (FK)	**FK**
			Novec™ 7100	98	Hydrofluoroether (HFE)	**HFE**
	Solvay SA	Belgium, Italy	Galden® HT70	70	Perfluorinated Perfluoroether (PFPE)	**PFPE**

Note: 3M Company announcement on December 22, 2022: All 3M production of dielectric liquids will be shut down by December 2025.
Sources: Vendor company product data sheets and SDS.

Liquid Immersion Systems: 1P/2P Fluid Contamination

Liquid Immersion Cooling Systems – Potential Contamination Sources						
Material Source of Contaminant	**Rectifier**	**Server**	**Cabling**	**Tank**	**Example of Component Containing Contaminant**	**Mitigation/Comment**
Electrical isolation pads	•				Power supply transistors and diodes	*
Solder flux	•	•			PCBs	Clean if possible
Heat shrink tubing	•				Wiring, cable assemblies	Minimize
Elastomers				•	Tank o-rings, seals, etc.	Minimize, use cleanest option
Foam rubber		•			Airflow guides or vibration dampeners	*

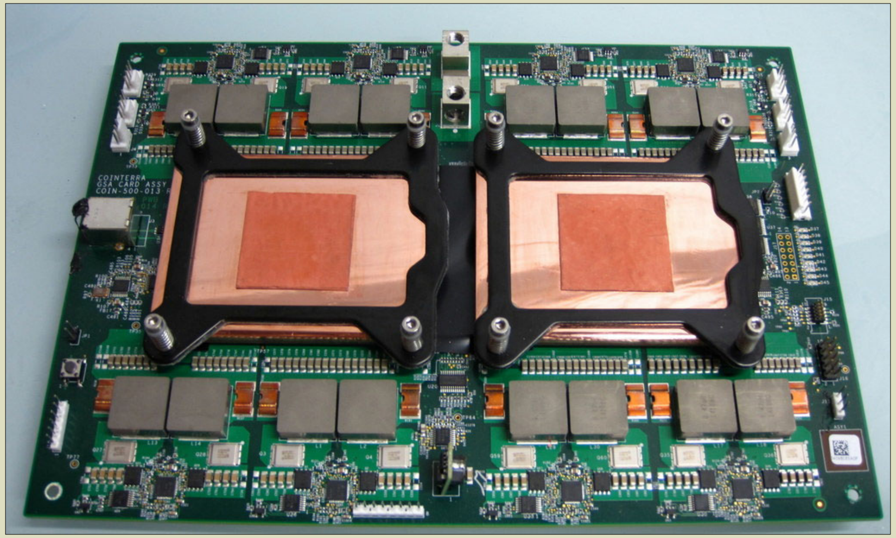
*Note: * Eliminated in two-phase operation.*

Source: Panel Discussion, "One Year of Two Phase (2P) Immersion Cooling in the Cloud: Lessons Learned", Raniwala, A. (moderator); Alissa, H., Manousakis, I., Shaw, M., Microsoft Corporation; Tuma, P., 3M Company; Chen, S., Wiwynn. OCP Global Summit, November 9-10, 2021.

Liquid Immersion Systems: Two-Phase Boiling Enhancement

Two-phase liquid immersion performance is significantly enhanced with use of larger boiling surfaces for bubble nucleation:

- Die surface areas are not typically large enough as boiling initiation surfaces;
- Adding a boiling enhancement plate increases available surface area for bubble formation;
  - Boiling enhancement plates are copper plates with a surface enhancement applied;
  - Variety of boiling enhancement plates are available from commercial vendors;
  - Boiling enhancement place must be attached with mechanical fasteners applying known force



Note: Photograph illustrates commercial BEC applied to all-copper boiling enhancement plate.
Source, Photograph: 3M Company, Specialty Liquids

Liquid Immersion Systems: 1P/2P Fluid Contamination

Liquid Immersion Cooling Systems – Potential Contamination Sources						
Material Source of Contaminant	**Rectifier**	**Server**	**Cabling**	**Tank**	**Example of Component Containing Contaminant**	**Mitigation/Comment**
PVC insulation	•	•	•		Wiring: Communication and power cables, etc.	Use cleaner alternative
Silicone RTV	•				Transistor potting, vibration dampening capacitors	
Hot-melt adhesives	•				Wire retention	
TIM - Thermal grease		•			Transistor and diode heat sinks	*
TIM - Thermal grease		•			Heat sink attach to processors	OK to use but alternatives exist
TIM – Gap-fillers	•	•			Attach heat sinks for voltage regulators, diodes, etc.	*

*Note: * Eliminated in two-phase operation.*
Source: Panel Discussion, "One Year of Two Phase (2P) Immersion Cooling in the Cloud: Lessons Learned", Raniwala, A. (moderator); Alissa, H., Manousakis, I., Shaw, M., Microsoft Corporation; Tuma, P., 3M Company; Chen, S., Wiwynn. OCP Global Summit, November 9-10, 2021.

Liquid Immersion Systems: Challenges for TIM0/1/2 in 1/P, 2/P

Liquid Immersion Cooling Systems – TIM Challenges

IC or Power Component Type	Processor	AI/GPU	ASIC	RDIMM	VRM	Power Device	Material	Challenge
TIM1	•	•	•				Polymeric TIM, gel, thermal grease	Potential for cavitation, extraction, or solvating of hydrocarbon-based substances such as silicone oil carrier in silicone thermal grease, gels, gap-fillers *(See new information in subsequent slides on 2P boiling erosion of polymeric and silicone-containing TIMs)*
TIM1	•	•	•				Hybrid/liquid metallic TIM	
TIM0	•	•	•	•			Polymeric TIM, thermal grease	
TIM2	•	•	•	•	•		Polymeric TIM, gel, thermal grease	
Gap-fillers				•	•	•	Silicone/siloxanes and polymeric	
Lid seal adhesives	•	•	•				Epoxy, one-part silicones, other	

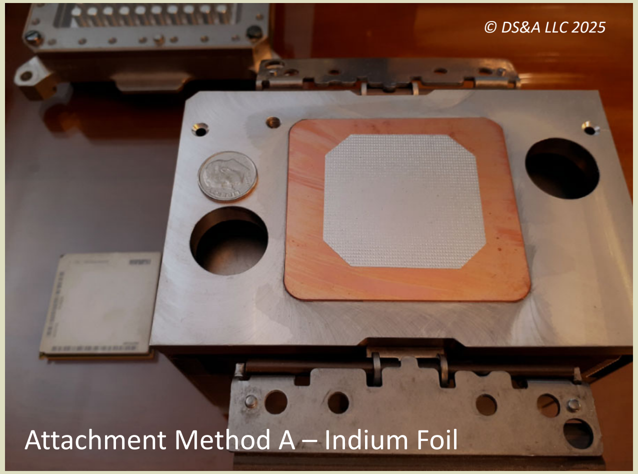
Liquid immersion (1P/2P) requires evaluation of many materials within a server:

- Potential for extraction of constituents from each material type by the fluid;
- *Potential for fouling of the immersion fluid* by extracted hydrocarbons, constituents, other particulates;
- *Potential for fouling of filters* and other system components with extracted and redeposited constituents.

*Note: * Eliminated in two-phase operation.*

Source: Panel Discussion, "One Year of Two Phase (2P) Immersion Cooling in the Cloud: Lessons Learned", Raniwala, A. (moderator); Alissa, H., Manousakis, I., Shaw, M., Microsoft Corporation; Tuma, P., 3M Company; Chen, S., Wiwynn. OCP Global Summit, November 9-10, 2021.

Liquid Immersion Systems: Challenges for TIM0/1/2 in 1/P, 2/P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Attachment Method A – Indium Foil

Simple immersion fluid contamination test:
Fluid: PAO6 (agitation 30 seconds):

- Polymeric phase-change compound
- Silicone oil carrier thermal grease
- Indium metal

Indium foil pre-attachment mechanisms:
A: Pressure attachment, Indium Heat-Spring® TIM2 (without adhesive)
B: Indium Corporation NC-702 tacking agent (pending liquid immersion fluid contamination testing)

Source: A. Test and photograph - A. Mackie, Indium Corporation, February 2023. Used with permission. Similar testing undertaken at 3M Company, Specialty Liquids.
B. Source: T. Jensen, Indium Corporation, USA. Photograph: DS&A LLC. IBM Power 9 Monza heat pipe/heat sink assembly with Indium Heat-Spring® pre-attached TIM2 by heat sink vendor.

Liquid Immersion Systems: Challenges for TIM0/1/2 in 1/P, 2/P

TIMs for Liquid Immersion		
TIM Type	**Potential for Contamination**	**Mitigation/Comment**
Silicone Thermal Grease (<4% silicone)	Minimal	Currently in use
Silicone Thermal Grease (4-16% silicone)	Significant	Select better formulation w/reduced silicone oil content
Gap-fillers	Significant	Concern for silicone content. Eliminated in 2/P operation.
Graphite film/sheet	None	Concern for potential fretting, electrically conductive (not yet tested) Evaluation needed: Potential for air entrapment in interface[2] (Heat spreaders w/poor through-plane effective conductivity)
Indium foil **Patterned indium foils[2]**	None	Currently in use
Hybrid/liquid metals; solid/liquid hybrids	Unknown	Evaluation needed
Soldered joint	None	Residual flux will redeposit on contacts for power components, causing shorting (Two-phase systems)
Sintered foil/sintered joint	None	No compatibility testing identified to date*

Notes: 1. Indium Corporation Heat-Spring® and similar.

▨ Joining materials, not TIMs. Included for completeness.

2. See investigation: Coles, H., Herrlin, M., "Immersion Cooling of Electronics in DoD Installations," DOD ESTCP Project EW-201347, Lawrence Berkeley National Laboratory Report (May 2016).

** Suggested for academic investigation.*

Liquid Immersion Systems: Two-Phase Immersion TIM Challenges

TIMs for Liquid Immersion		
TIM Type	**Potential for Contamination**	**Boiling Erosion Potential**
Silicone Thermal Grease (<4% silicone)	Minimal	**Significant**
Silicone Thermal Grease (4-16% silicone)	Significant	**Significant**
Gap-fillers	Significant	**Significant**
Graphite film/sheet	None	**None identified to date**
Indium foil **Patterned indium foils**[2]	None	**None**
Hybrid/liquid metals; solid/liquid hybrids	Unknown	**Evaluation needed**
Soldered joint	None	Residual flux will redeposit on contacts for power components, causing shorting (Two-phase systems)
Sintered foil/sintered joint	None	No compatibility testing identified to date*

Notes: 1. Indium Corporation Heat-Spring® and similar.

▨ *Joining materials, not TIMs. Included for completeness.*

2. See investigation: Coles, H., Herrlin, M., "Immersion Cooling of Electronics in DoD Installations," DOD ESTCP Project EW-201347, Lawrence Berkeley National Laboratory Report (May 2016).

** Suggested for academic investigation.*

Summary

TIMs are critical to efficient heat transfer from a semiconductor source.

- Understanding TIM types, testing methods is critical to proper evaluation.
- Specialized TIM types are required for challenging requirements for test.
- Selection of a TIM is not based only on maximum bulk thermal conductivity.
- Few TIM manufacturers focus on semiconductor test TIM requirements.
- *Semiconductor test has highly specialized and unusual requirements* not found in other industry segments -- *challenging for polymeric TIMs*.
- A range of metallic, carbon fiber, other TIM types have been developed and described, for specialized applications and reliability in semiconductor test.
- TIM types in development such as graphene-enhanced graphite and certain new forms of metal TIMs may be applicable to semiconductor test.

Notes

- ASTM D 5470-12, issued by ASTM International, is available for purchase and download at www.astm.org.
- Heat-Spring® is a Registered Mark of Indium Corporation, Clinton NY USA.
- Kapton® is a Registered Mark of DuPont de Nemours, Wilmington DE USA.
- Other trademarks and Registered Marks are the property of their respective owners.

Selected References

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Product development strategy and market analysis for electronics thermal management: *Advanced thermal materials, components, and systems.*

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