Thermal Management Technologies (TMT)

Avram Bar-Cohen
DARPA/MTO

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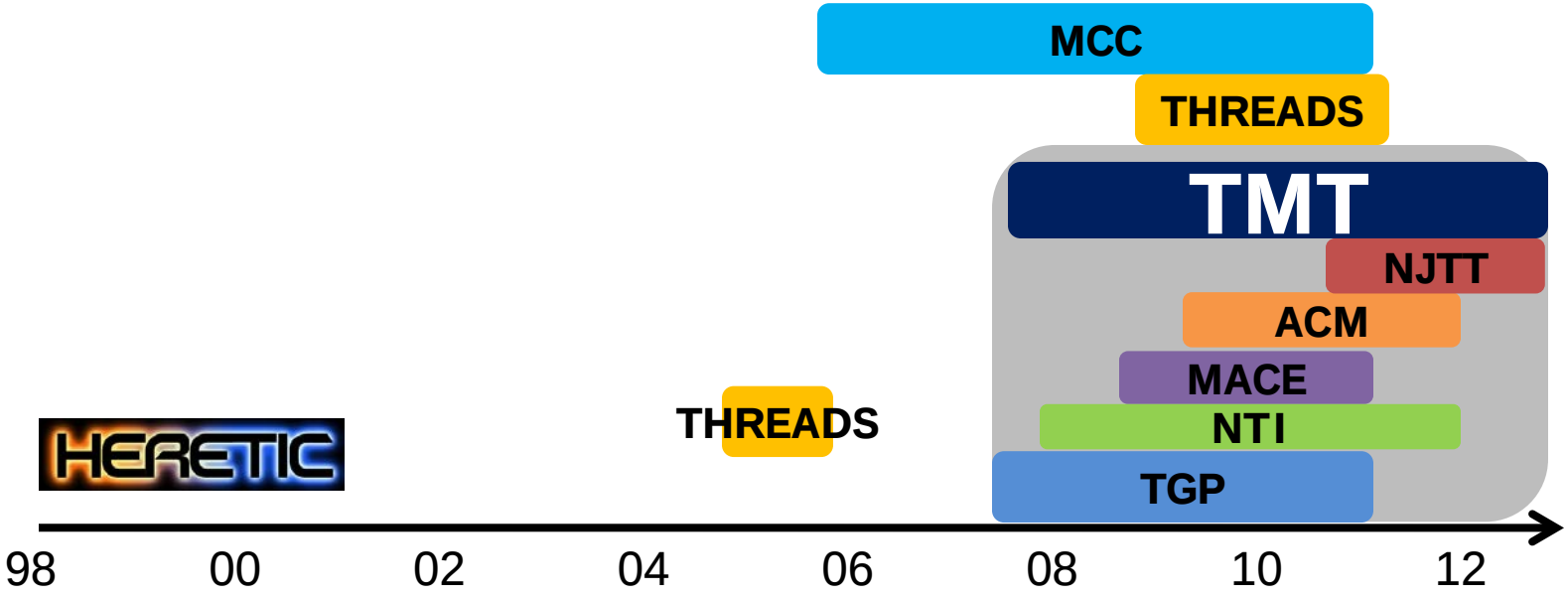
DARPA Thermal Management Programs Timeline



Heat Removal by Thermo-Integrated Circuits (HERETIC)

1998: DARPA PM Towe
2001: DARPA PM Radack
2002: HERETIC ends

Micro Cryo Coolers (MCC)

2006-2011: DARPA PM Dennis Polla

Thermal Management Technologies (TMT)

- 2007-2010: DARPA PM Kenny
- 2010-present: DARPA PM Bar-Cohen

Technologies for Heat Removal in Electronics at the Device Scale (THREADS)

- 2005-2006: DARPA PM Rosker
- 2009-present: DARPA PM Albrecht

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DARPA Thermal Management Thrust

Focused on Transformative Technologies

- Core mission: prevent/create technological strategic surprise for the US
- Serve as DoD's primary innovation engine
- Create ***lasting*** revolutionary change

Agency Leadership Committed to Rapid Technology Transition

- Research, development and demonstration of high-risk, high-payoff projects for the *current* and future combat force
- Insertions in "high value" fielded systems primary vehicle for transformative change

TMT Insertion Philosophy

- Laboratory "insertion" prototype and modeling tools primary project deliverable
- Prototype should utilize unique feature of TMT technology
- Prototype performance should materially exceed SoA in key parameter(s)
- Experimental/modeling results serve to articulate "value proposition"

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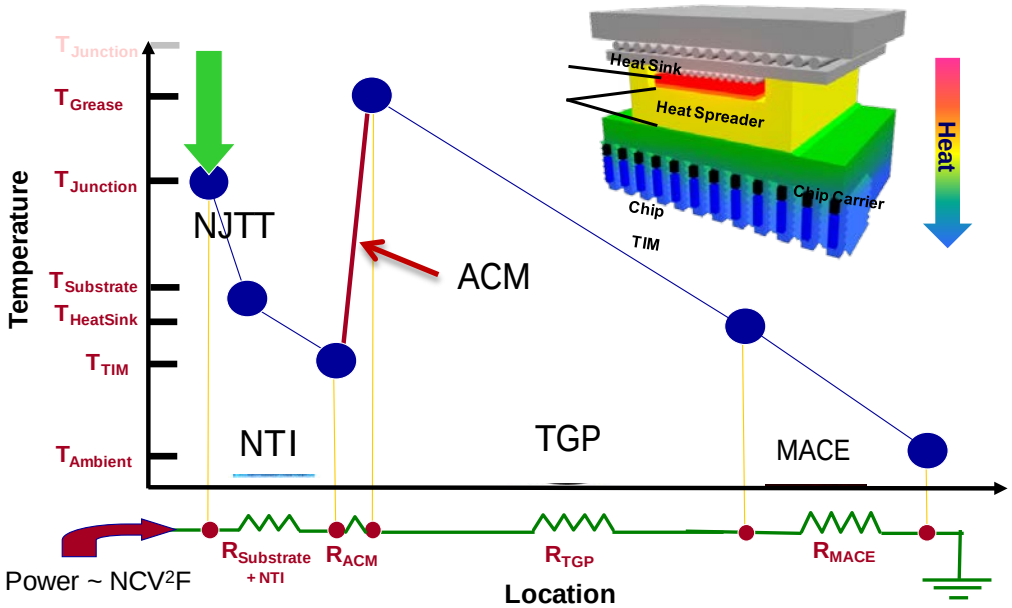
Thermal Management Technologies (TMT) Program Goals 2008-2013

- Leverage significant recent advances in nanostructured materials, active structures and integrated manufacturing
- Enhance performance of DoD systems through manipulation, transport and rejection of waste heat



Task Areas :

Thermal Ground Plane (TGP): Nanostructured wicks and cases for 2-phase vapor chambers
Microtechnologies for Air-Cooled Exchangers (MACE): Active surfaces and jets for enhanced heat sinks
Nano-Thermal Interfaces (NTI): Engineered, reworkable nanostructures for low resistivity TIMs
Active Cooling Modules (ACM): High COP cooler using novel TE materials and refrigeration concepts
Near-Junction Thermal Transport (NJTT): Active and passive technologies for cooling PA junction

Goal: To deliver transformative thermal management technology that will reduce or remove thermal limitations on DoD platforms

Thermal Management Technologies (TMT) Overview

2008	2009	2010	2011	2012	2013

Thermal Ground Plane (TGP)

- Thermal Conductivity >20,000 W/mK
- Operational at >10g

Microtechnologies for Air-Cooled Exchangers (MACE)

- >4x improvement in thermal resistance
- >3x improvement in energy efficiency

NanoThermal Interfaces (NTI)

- >8x improvement in thermal resistance
- Reworkable at T<170C

Active Cooling Modules (ACM)

- 7X better energy efficiency
- 100W device

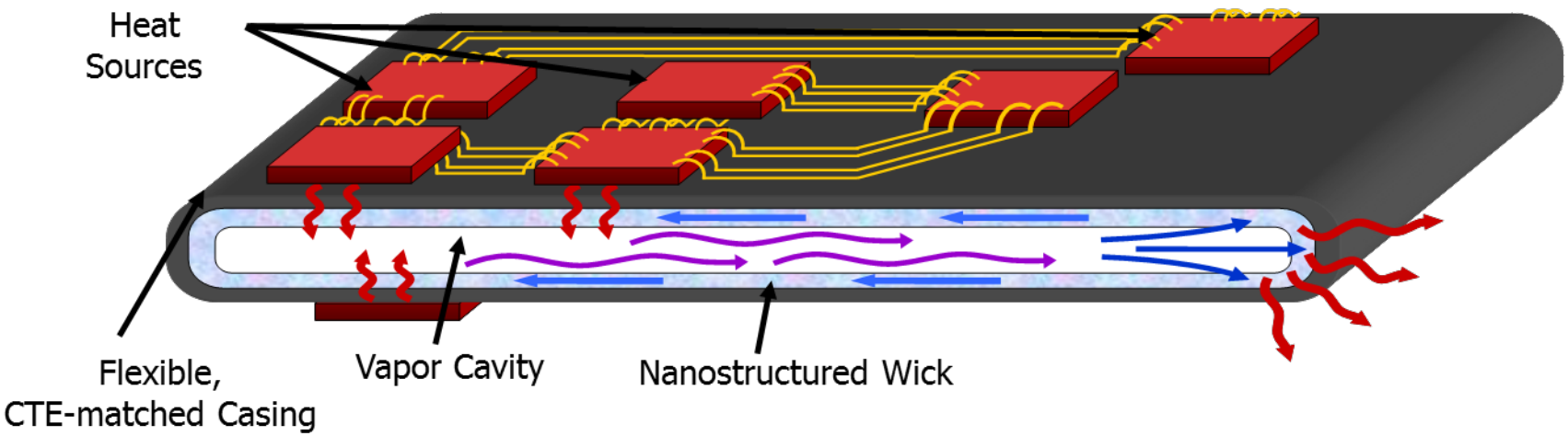
TMT Aggregation October 2009

Near Junction Thermal Transport (NJTT)

- 3x improvement in RF output power
- < 100 microns from junction

Thermal Management Technologies (TMT)
Thermal Ground Plane (TGP)

Vision : A new 2-D, thin, lightweight MCM substrate incorporating modern and nanostructured materials to achieve vastly superior thermal conduction & possessing all mechanical properties necessary for hard-mounting ICs.



TGP Goals

- Extreme lateral thermal conduction, 10kW/mK-20kW/mK
- Large 2-D area, <1 mm thick, Operation at 10g-20g
- Nanostructured wick for enhanced heat transfer and fluid transport
- Structural, flexible, thin, & light-weight materials that match the CTE of Si, GaAs, or GaN
- 2-phase heat transfer to eliminate load-driven thermal non-uniformity across substrate

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Thermal Management Technologies (TMT)
TGP Overview

2008	2009	2010	2011	2012	2013

Thermal Ground Plane (TGP)

- **Thermal Conductivity >20,000 W/mK**
- **Operational at >10g**

Wick \ Case	SiC	Liquid Crystal Polymer (LCP) /Flex	Metal Matrix Composite	AlN	Si	Titanium
Etched Graphene 2-path Geometry	✓					
Cu Nanorod + Nanomesh, ALD		✓				
Metallic Powder + Post Biporous			✓			✓
Patterned CNTs on Cu			✓			
Nano-Super phobic/philic				✓		
CNT/Si Structures with Adaptive Coatings					✓	
CPSi, Nucleating Evaporator					✓	

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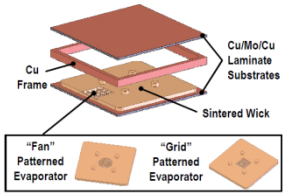
Thermal Management Technologies (TMT)
TGP – Revised Metrics

Metric	*Unit*	*Phase I*	*Phase II*	*Phase III**
Hermeticity	% fluid loss/yr @ 100°C	10	1	0.1-1
Wicking	g (inertial force)	2	10	1-13.5
Thermal Expansion Mismatch	%	10		
Wick Thermal Conductivity	W/m·K	100	-	-
TGP Thermal Conductivity	W/m·K	--	500	1,000-20,000
TGP Thickness	mm	2	3	1-4
Area	cm^2	--	9	4.5-75
Weight	gm	--	20	5-400
Duration	hours	--	100	1,000-infinite

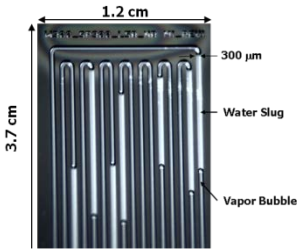
Stage 1: Materials Selection/Preliminary Testing – **completed**
Stage 2: Integrated TGP Construction/Testing – **completed**
Stage 3: Targeted Design and Insertion – **underway**

*Performers determine Application-Specific Metrics

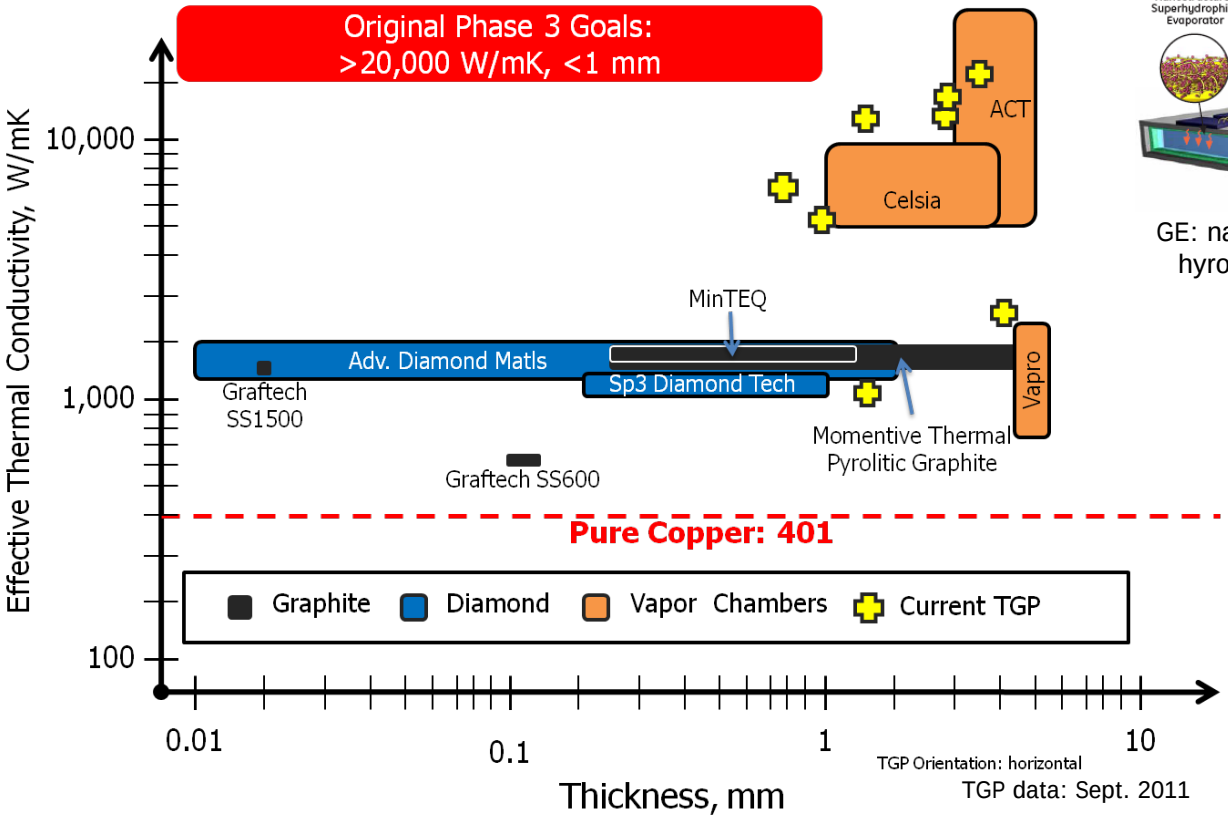
Thermal Management Technologies (TMT)
Thermal Ground Plane (TGP) Performance

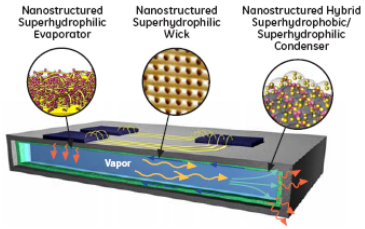


Raytheon: Patterned CNTs on Cu wick

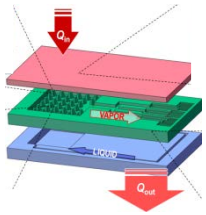


Northrop Grumman: SiC oscillating heat pipe

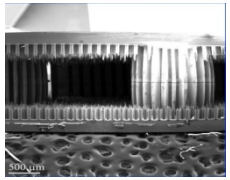




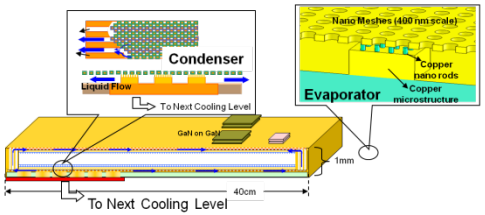
GE: nanostructured super hyrophobic/philic wick



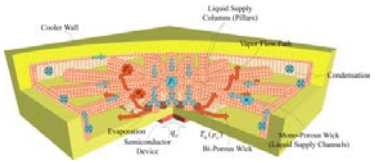
UC Berkeley: two phase flow with coherent porous silicon wick



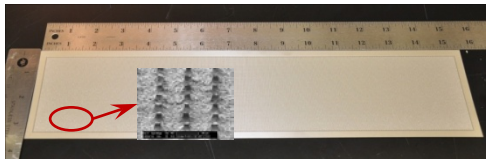
Teledyne: CNT/Si wick structures



U Colorado: flexible/conformal case with Cu nanomesh wick



UCLA: metallic powder + post biporous wick



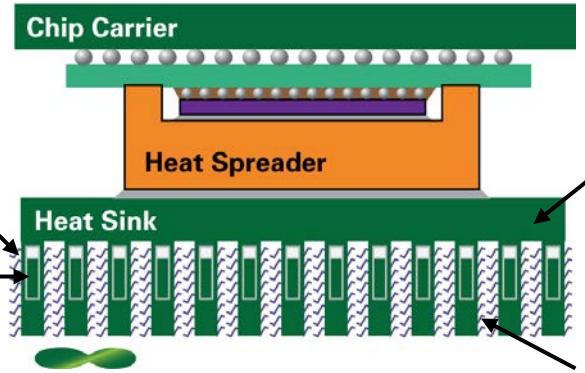
UC Santa Barbara: large scale titanium TGP

Thermal Management Technologies (TMT)
Microtechnologies for Air Cooled Exchangers (MACE)

Vision : Develop new technologies to enhance the performance of heat sinks by reducing thermal resistance and airflow resistance. MACE will enable lighter, more compact systems with better thermal performance.

Nano-textured fins to enhance convection surface area & turbulence.

Micro-pump integrated micro-channel heat sink.



High conductivity, low density material (graphene /Cu, graphite /Al, etc). TGP could go here.

MEMS flaps, jets, other ideas to enhance airflow throughout heat sink

MACE Goals:

- Reduction in Heat Sink Thermal Resistance to 5 cm^2K/W
- Reduction in Airflow Resistance through Heat Sink
- Use of Direct Air Cooling in Dense High-Power Systems
- Reduced Power Consumption in Cooling Systems, COP~30

Thermal Management Technologies (TMT)
MACE Overview

2008	2009	2010	2011	2012	2013
	Microtechnologies for Air-Cooled Exchangers (MACE)				

- >4x improvement in thermal resistance
- >3x improvement in energy efficiency

Convective / Conductive	Synthetic Jets	Fin Convection Optimization	Compressed Air	Fan/Fin Integration	Vibrating Elements
Micro/Macro Fin	✓				
Synthetic Air/Solid Fin		✓			
Copper/Aluminum			✓		
3D Vapor Chamber				✓	✓

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Thermal Management Technologies (TMT)
MACE Revised Program Metrics

Metric	*Unit*	*Phase I*	*Phase II**
MACE Thermal Resistance	C/W	0.05	0.05
MACE Size	cm^3	"Single fin"	10-262
System Coefficient of Performance	W_{heat}/W_{input}	30	20-23
Electronic Device Power Dissipation	W	1000	750-835

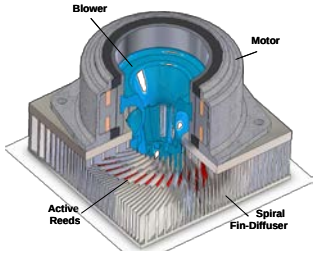
Stage 1: Materials Preliminary Technology Development and Demonstration **– completed**.

Stage 2: Full System Demonstration and Application-Specific Effort – **underway**

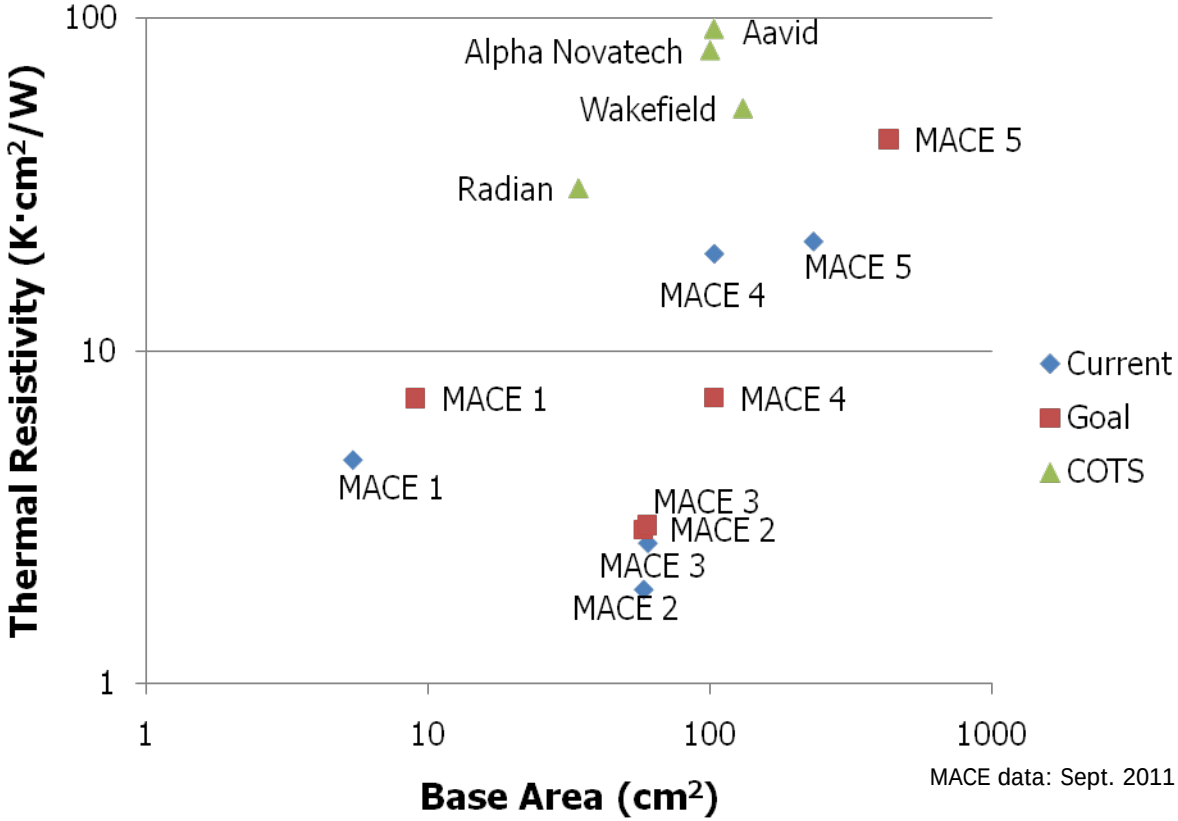
*Performers determine Application-Specific Metrics

Thermal Management Technologies (TMT)

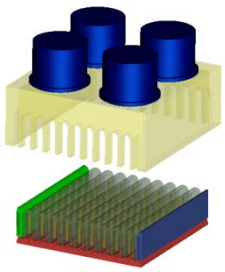
Microtechnologies for Air-Cooled Exchangers (MACE) Performance



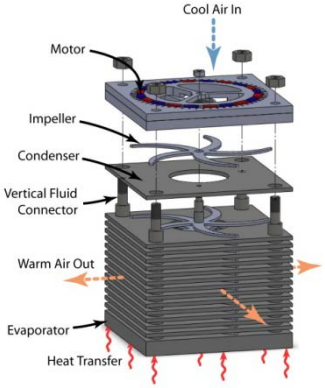
United Technologies Research Center: integrated blower/heat sink with optimized fin geometry



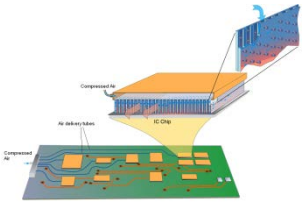
MACE data: Sept. 2011



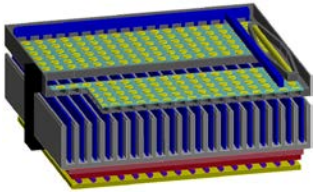
Raytheon: Micro/Macro Fin; Synthetic jets



MIT: 3D vapor chamber; fan/fin integration



Honeywell: jet-driven entrainment



Thermacore: 3D vapor chamber, vibrating elements

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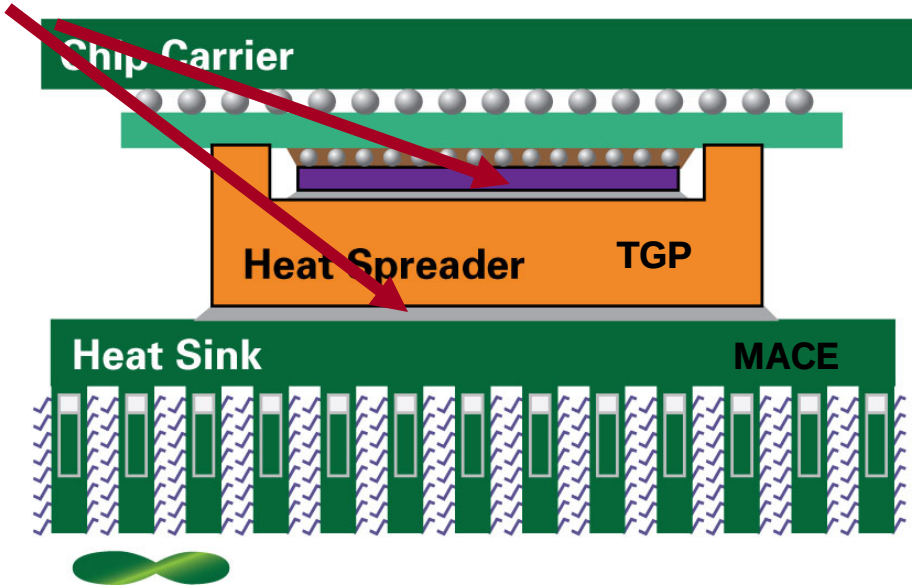
Thermal Management Technologies (TMT)
NanoThermal Interfaces (NTI)

Thermal Interface Material (TIM)

- TIM Resistance: thermal bottleneck in DoD systems
- TMT Success requires x10 reduction in TIM Resistance
- Success in TGP and MACE will shift focus to this layer.
- Existing solutions (epoxy, grease, In, Solder) Not Doing the Job!



NTI Goals:

- Lower Thermal Resistance (10x reduction to 0.01 cm^2K/W)
- Easily Installed and Reworkable (5x rework with other specs in NTI)
- Accommodate Lateral Shear
- Long-Term Reliability and Consistency from Chip to Chip (1000 temp cycles)

Thermal Management Technologies (TMT)
NTI Overview

2008	2009	2010	2011	2012	2013
	NanoThermal Interfaces (NTI)				

- >8x improvement in thermal resistance
- Reworkable at T<170C

Interface / Conduction	Ti / Pd	Bismuth Solder	Molecular Coupling Layer	Indium Solder
Double-sided CNT foil	✓			
Diamond / Graphite		✓		
Open-Ended MWCNT			✓	
Metal Nanosprings / Nanowires				✓

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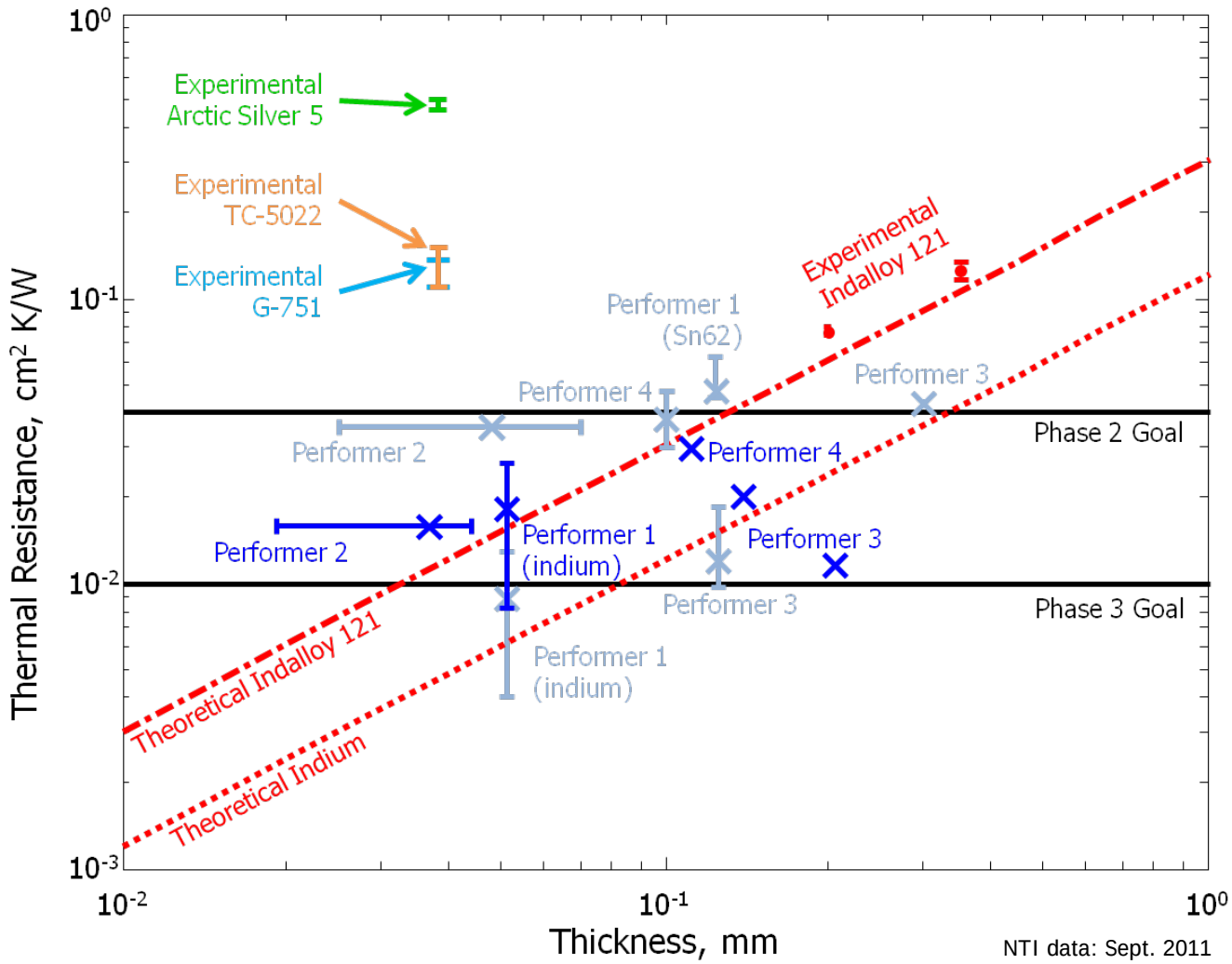
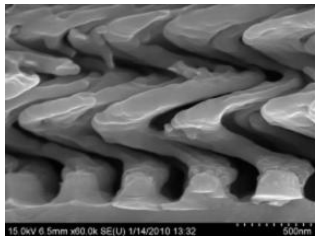
Thermal Management Technologies (TMT)
NTI Program Metrics

Metric	*Unit*	*Phase I*	*Phase II*	*Phase III*
Thermal Resistivity	cm^2 C/W	<0.07	<0.04	<0.01
Temperature Cycles	#, -40 to +150	>10 0 to 70C	>50 -40 to +80	>100 -40 to +125
Stability	Hours and % degradation	>100 <25%	>300 <10%	>1000 <5%
Rework	#	1	>3	>10
Application Time	Hours	10	5	2
Surface Roughness Tolerance	microns	5	10	10
Area	cm^2	0.25	>1	>1
Max Processing Temperature	C	240	240	240
Max Processing Pressure	kPa (psi)	<200 (30)	< 200 (30)	<200 (30)

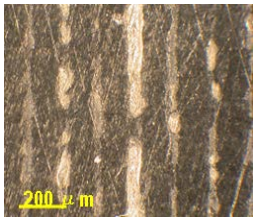
Stage 1: Models, Materials, Preliminary Measurements – **completed**
Stage 2: Working Samples and Reliability Testing – **in process**
Stage 3: High-Performance, High-Reliability, Reworkable TIM

NTI performance versus commercial TIMs

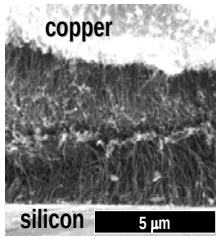




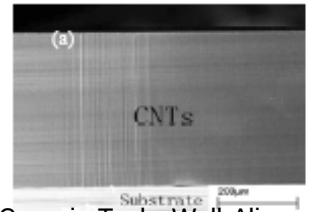
General Electric: Copper Nanosprings



Teledyne: Laminated Graphite and Solder



Raytheon: Double-sided Multi-walled Carbon Nanotubes



Georgia Tech: Well-Aligned Open-End Carbon Nanotubes

Commercial TIM data courtesy of D. Altman (Raytheon) and Y. Zhao (Teledyne)

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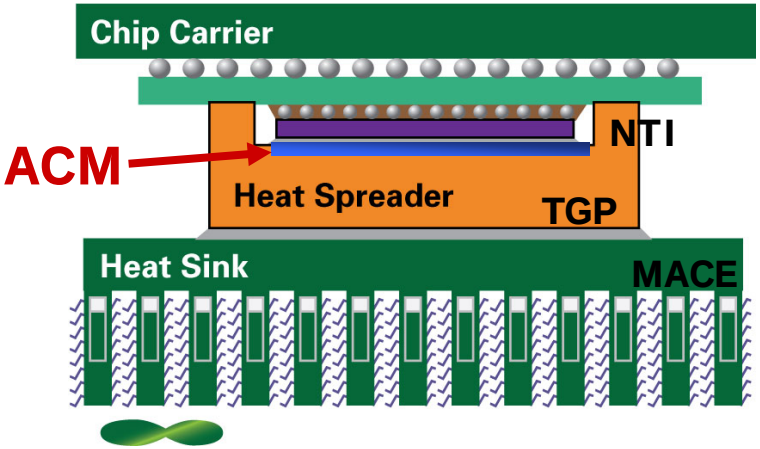
Thermal Management Technologies (TMT)
Active Cooling Modules (ACM)

Vision : Enable greater power utilization margins in electronic materials while also increasing device reliability. Enable lower-temperature operation of sensitive components, including operation below ambient temperature.



ACM Goals:

- Improved COP for high-flux applications; COP=2 for q”=25W/cm^2
- Build complete modules that demonstrate ACM benefits
- Reduce junction temperature rise for electronic devices
- Further increase electronic device power

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Thermal Management Technologies (TMT)
ACM Overview

2008	2009	2010	2011	2012	2013
TMT Aggregation October 2009		Active Cooling Modules (ACM)			

- **7X better energy efficiency**
- **100W device**

Approach \ Material	Sb_2Te_3	He	Bi_2Te_3	Bi_2Te_3 Alloy
Thin film TE Superlattice	✓			
Stirling Microcooler		✓		
Bulk Nanostructured TE Materials			✓	
TE Nanocrystals				✓

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Thermal Management Technologies (TMT)
Active Cooling Modules (ACM)

Metric	*Unit*	*Program*
Electronic Device Temperature	°C	25
Electronic Device Power	W	100
Thermoelectric Power Addition	W	<50
Temperature Cycles	-40 °C to +100 °C	200
COP	W/W	2 (ΔT=-15 °C)

- Construct first prototypes of operational cooling modules - **underway**
- End of program requires 2 x 2 x0.5 cm cooling modules meeting ACM metrics
- Perform specific tests required for a performer-identified transition opportunity

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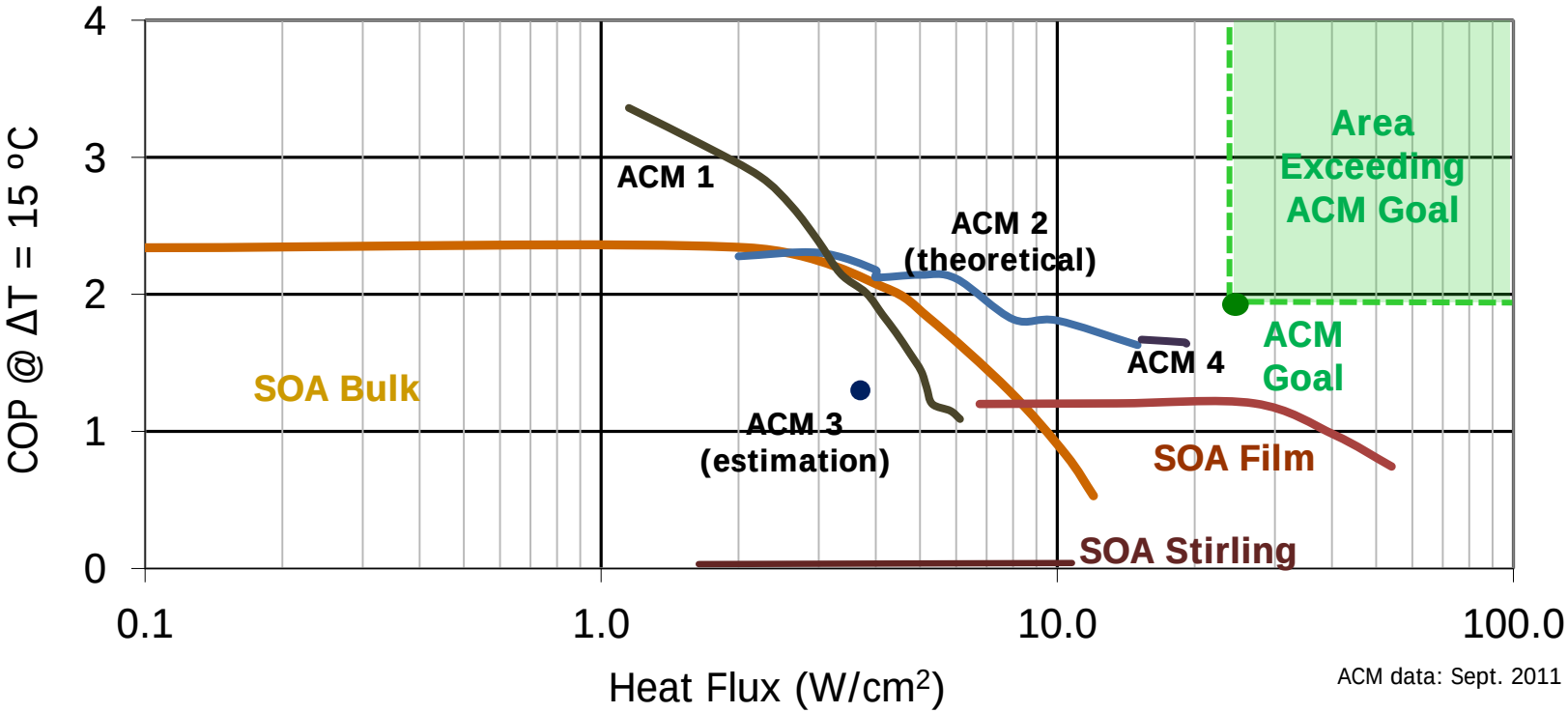
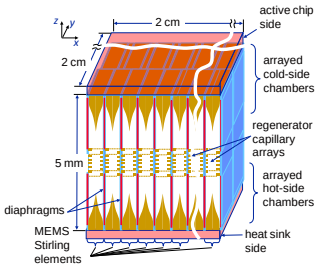
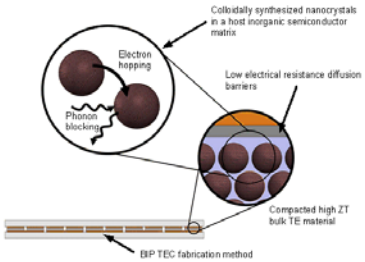
Thermal Management Technologies (TMT)
Active Cooling Modules (ACM) Performance



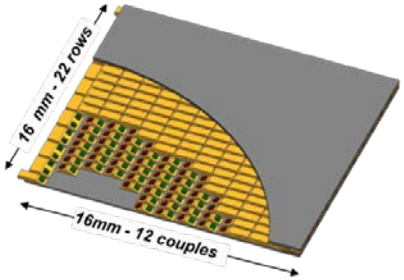
ACM data: Sept. 2011



Carnegie Mellon University: Stirling Microcooler



Marlow: Bulk TE device with novel nanocrystal materials

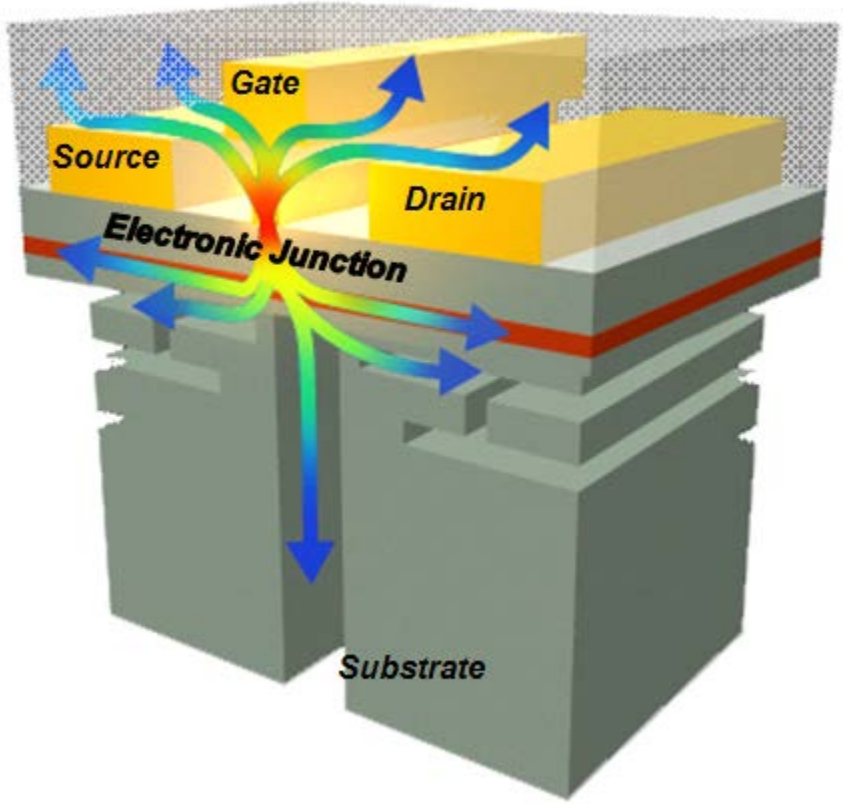


UTRC: Thicker thin-film-superlattice materials

GMZ Energy: Bulk nanostructured microsintered TE materials

Thermal Management Technologies (TMT)
Near-Junction Thermal Transport (NJTT)

Vision : Develop device compatible materials and structures to provide localized thermal management within the device substrate. Increase Output Power from WBG PA's by >3x



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