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Templated Micro-Channel Thermal Control System

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Agenda

- On-detector electronic cooling requirements
- Introduction to a new manufacturing process for producing thermal management units
- 5-Step manufacturing approach
- Representative devices produced via this method
- Thermal performance comparison to commercial devices
- Manufacturing cost assessment
- Summary

On-Detector Electronic Thermal Management Requirements

- A variety of physics based detection systems, both small and large need improved thermal management systems
- Representative needs for an on-detector cooling system for ALICE (A Large Ion Collider Experiment) at the Large Hadron Collider at CERN
  - Heat loads of 0.3 to 0.5 W/cm^2
  - Keep a working temperature of 30 °C
  - Working fluids of deionized water or perfluorohexane (C6F14)
  - Uniform temperatures in a flow channel 20 cm long x 1.6 cm wide to reduce stress caused by thermal gradients
  - Minimal HX mass to minimize radiation adsorption
- Interest in micro-channels on the order of 200 microns wide and tall
  - However, traditional thin walls (40 microns) limit the maximum pressure to 2.5 bar before deformation occurs

Micro-Channel Thermal Management Units

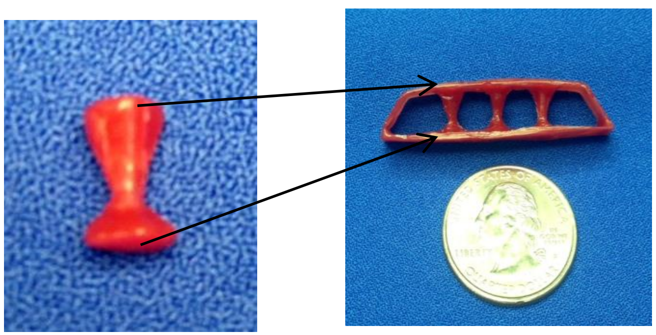
- Micro-channel heat exchangers have been demonstrated for applications including refrigeration, chemical processing, electronics, and automotive applications
- Early roots back in 1981 that developed micro-channel heat exchangers that could remove 1000 W/cm^2
  - However, the volumetric flow rate and pressure drop were too high for practical purposes
- Much current work focuses on MEMs systems where silicon is etched to form channels on the order of 50 microns wide
  - Produces systems with reasonable flow rates and pressure drops
- These and other micro-channel heat exchangers have resulted in significant reductions in the heat exchanger mass on the order of 25% with volumetric decreases of about 60%
- Improved thermal management for on-detector electronics possible using micro-channel systems

Template-Based Fabrication Approach

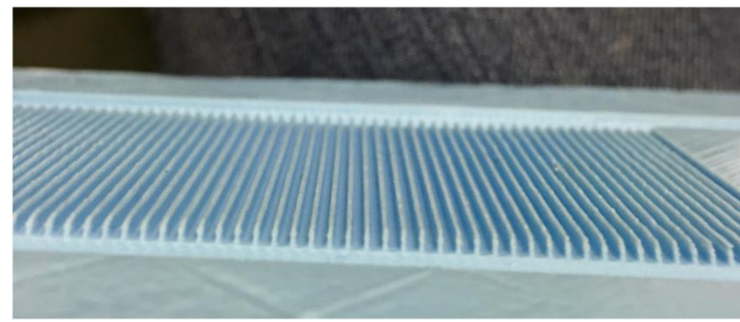
- 5 Step Manufacturing Process, Patent Pending 62/303,650
- Step 1
  - Produce dissolvable template structure that defines the fluid flow regime
- Step 2
  - Make the surface of this dissolvable template structure electrically conductive
- Step 3
  - Electroform a metallic coating over this template structure
- Step 4
  - Dissolve the internal template structure
- Step 5
  - Finish the device with fluid flow connections

Step 1: Produce Dissolvable Template Structure

- Dissolvable template materials
  - *e.g.*, dextrose that is dissolvable with water
  - *e.g*., wax that is dissolvable with hexane
- Use extrusion or casting methods to define the thermal management unit



Venturi nozzles in a two-phase unit

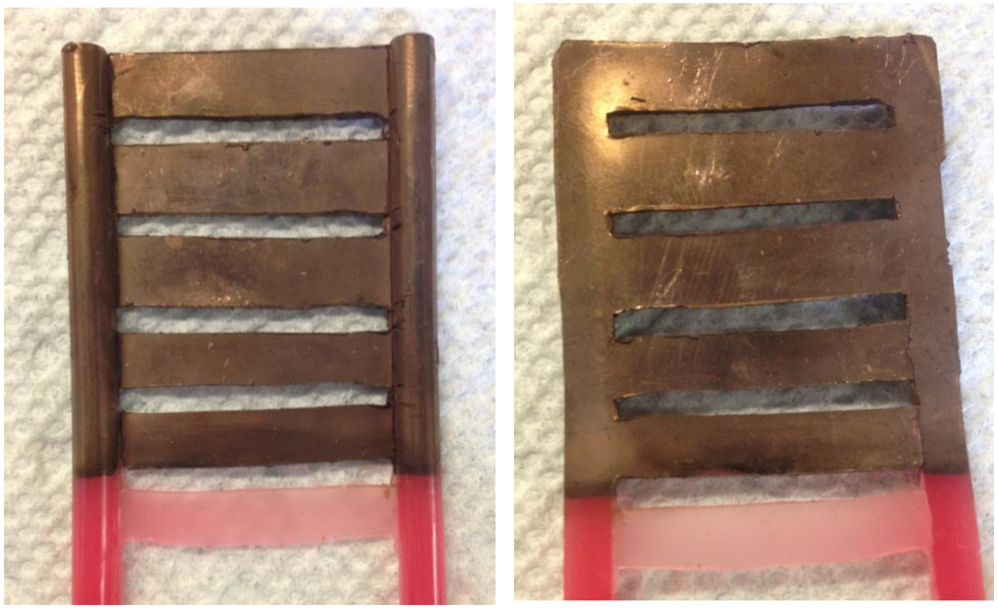


Mold for multi-channel liquid cooled units

Multi-channel liquid cooled unit

Step 2: Make the Dissolvable Template Structure Electrically Conductive

- To electrodeposit a metal over the template structure, the surface needs to be electrically conductive
- Methods can include
  - Carbon or metal powder coatings
  - Metallic inks or paints
  - Electroless copper or silver coatings

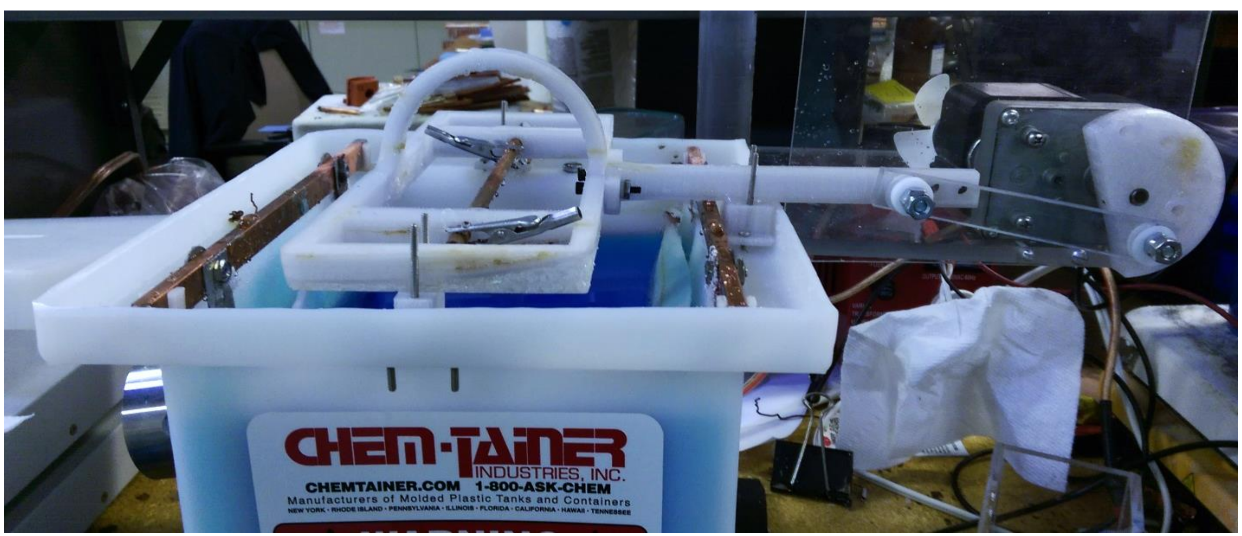


Electroless copper strike

Electroless silver strike

Step 3: Electroform a Metallic Coating

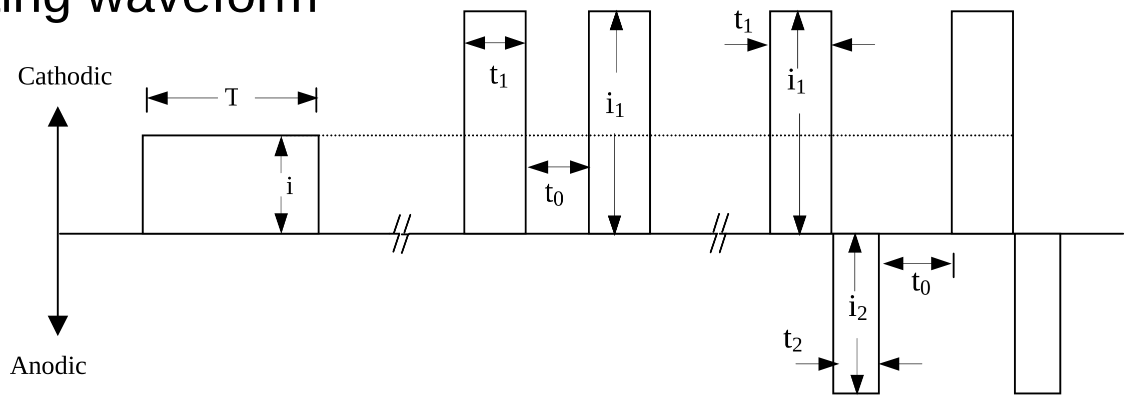
- Form a metallic deposit using electrodeposition methods
  - Previous step of applying a metallic strike enables the template to be electrified
- Aqueous or ionic liquid electrolytes containing the metal salt
  - Copper, aluminum, nickel, etc.
- Use direct current or periodic reverse current waveforms to control deposit morphology



Copper sulfate/sulfuric acid plating bath

Electroplating Waveform Affects Coating Morphology

- Deposit morphologies highly dependent on the electrolyte bath and plating waveform



<u>DC Process Variables</u>

- Peak current density
- Duty cycle

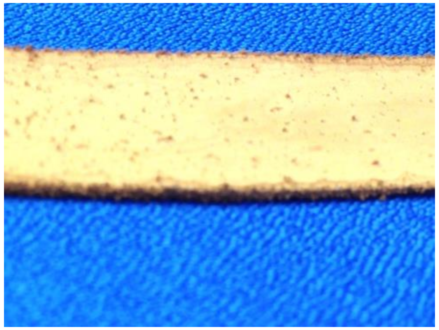
<u>PC Process Variables</u>

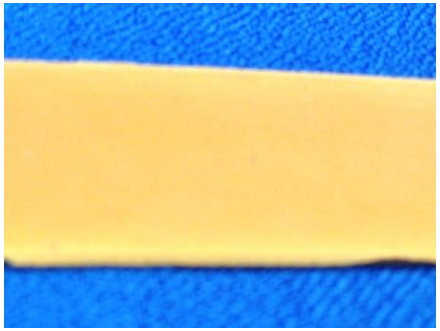
- Peak current density
- Duty cycle
- Frequency

<u>PRC Process Variables</u>

- Peak cathodic current density
- Peak anodic current density
- Cathodic duty cycle
- Anodic duty cycle
- Frequency

DC plated copper





PRC plated copper

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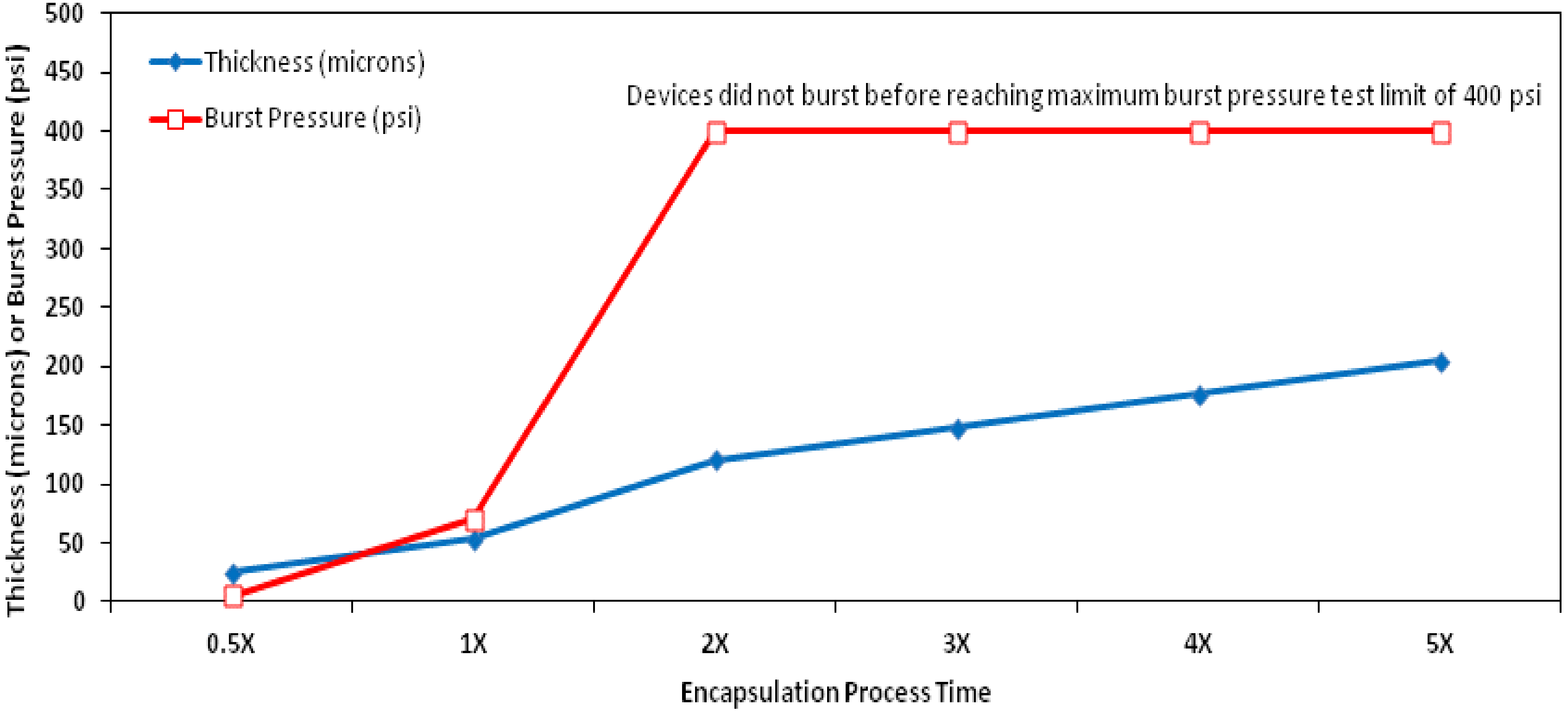
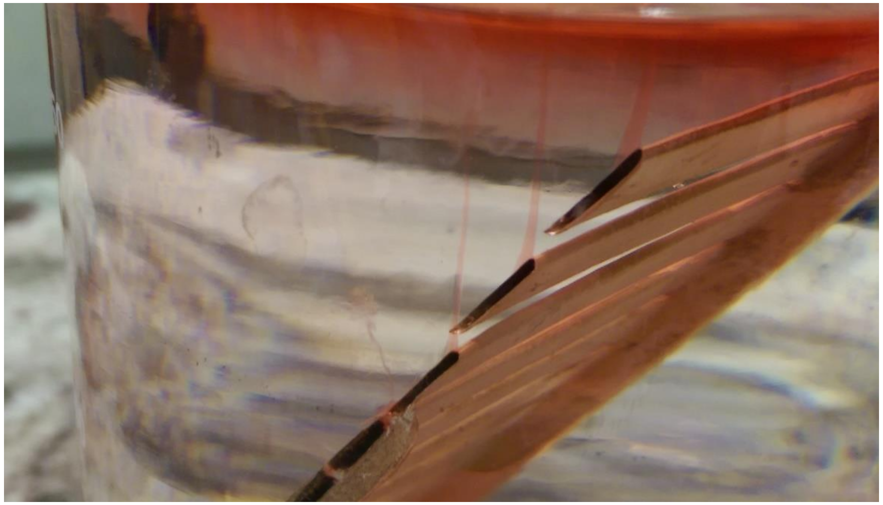
Electrodeposition Time Produces Thicker and Stronger Walls for Higher Pressure Operation



- 400 psi capable devices readily obtained at a wall thickness of 120 µm

Step 4: Dissolve Internal Template Structure

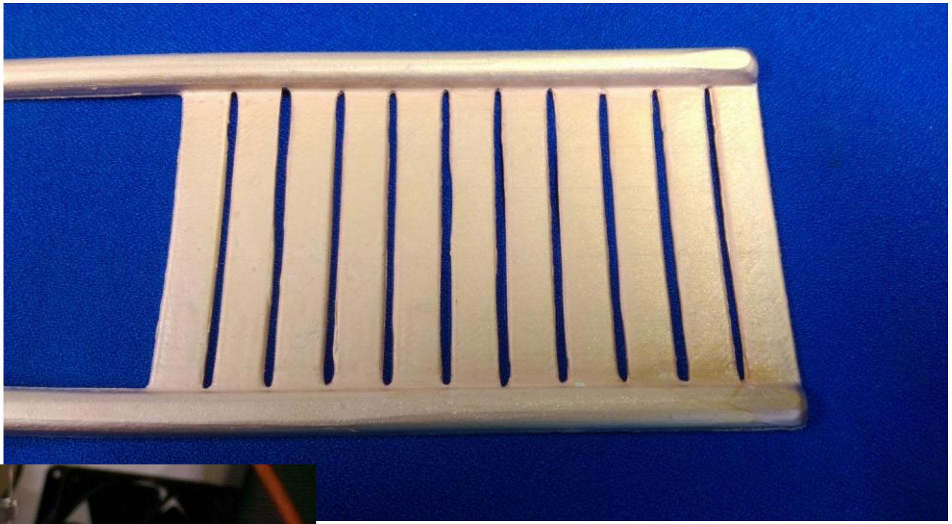
- Use solvents to dissolve internal template material
  - Water for dextrose, maltose based units
  - Hexane, trichloroethylene for wax
- Can also use heat to melt wax
- Small feature sizes approaching 1 micron successfully dissolved



Solvent dissolution of wax

Step 5: Finish Devices for Thermal Management Usage

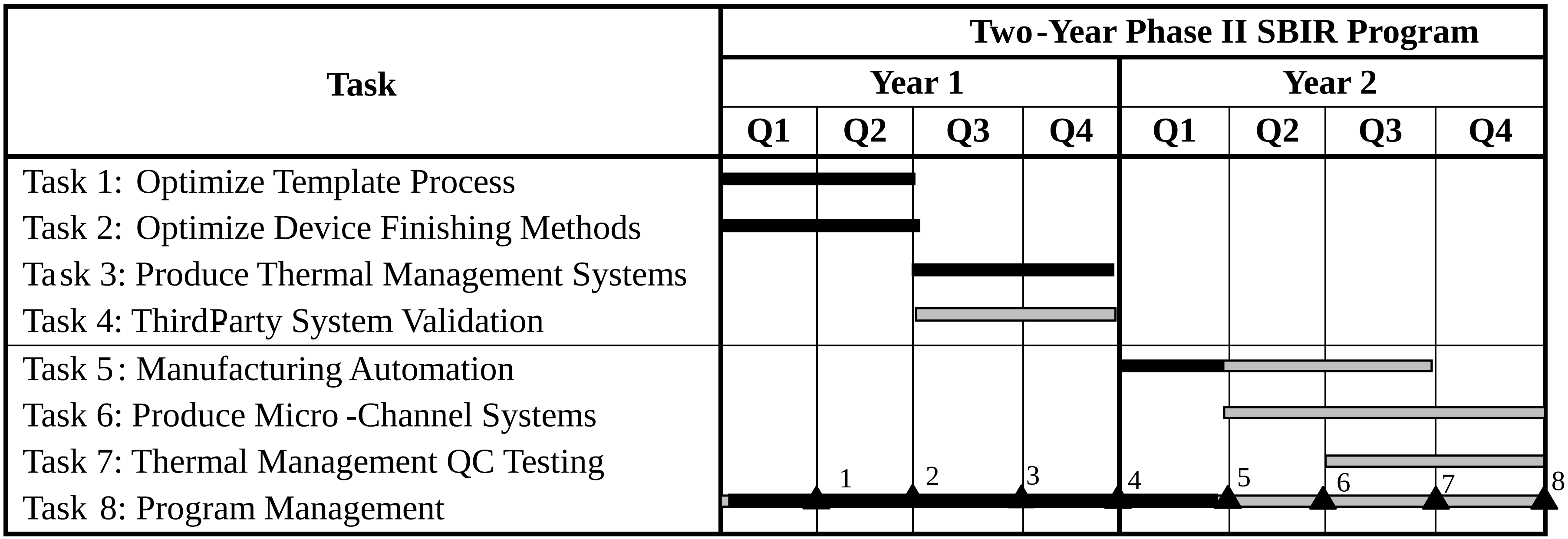
- Add fittings to fluid ports
- Attach mounting pads if not part of the unit
- Quality control testing for leaks



Phase II Program Objectives

- To develop a template-based manufacturing process to produce micro-channel thermal management systems for the marketplace
- Sub-objectives:
  1. Optimize the micro-channel materials and manufacturing methodology of each process step
  2. Automate the manufacturing process minimizing operator intervention to make reproducible hardware
  3. Show that Reactive's manufacturing technology can be used for rapid design variations and customization for a range of micro-channel thermal management systems
  4. Establish sales channels by developing a network of contacts and relationships with thermal management integrators and end-user customers

Program Schedule

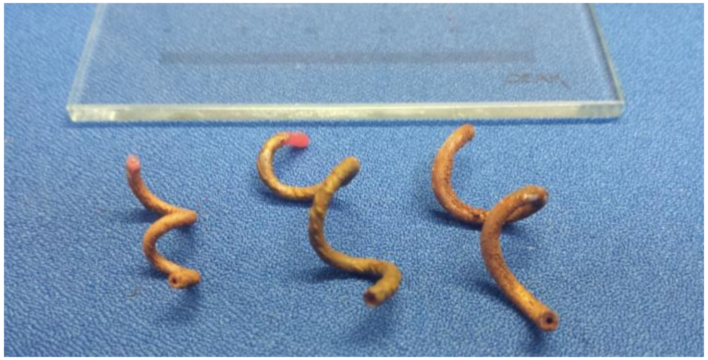


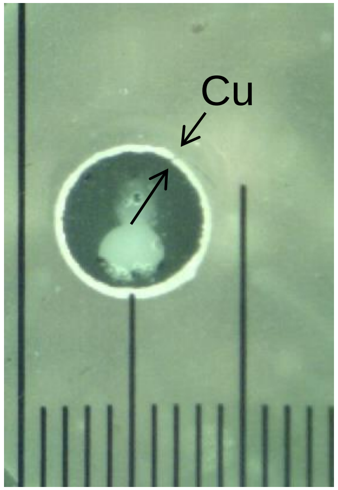
Major milestones include:

Milestone #1: Specifications Defined
Milestone #2: Optimized Fabrication Process
Milestone #3: Prototypes Completed
Milestone #4: Validation Completed

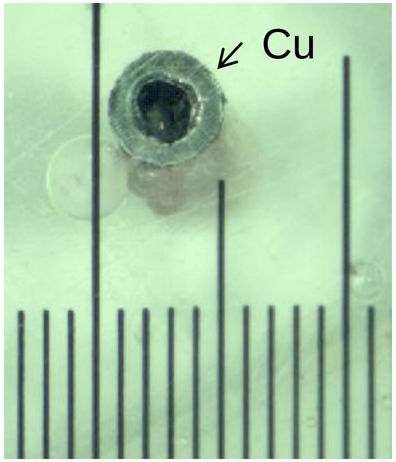
Milestone #5: Manufacturing Cost Assessment
Milestone #6: Process Automation Complete
Milestone #7: Quality Control Pass
Milestone #8: Thermal Management Production

Examples of Template-Based Fabricated Components

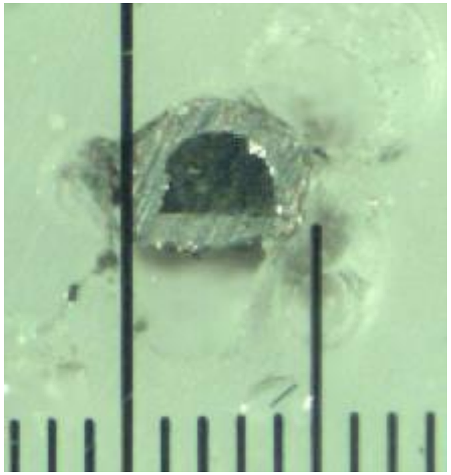




Cylindrical micro-channel with a 625 μm ID and a 25 μm wall thickness



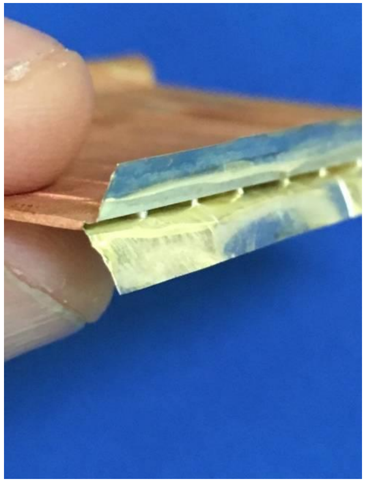
Cylindrical micro-channel with a 250 μm ID and an 88 μm wall thickness



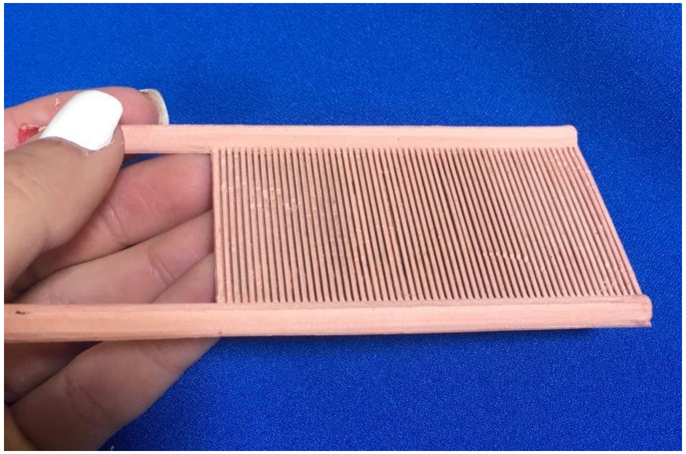
Semi-circular micro-channel structure with a 300 μm base by 212 μm high flow area

Multi-Channel Liquid Cooled Thermal Management Units

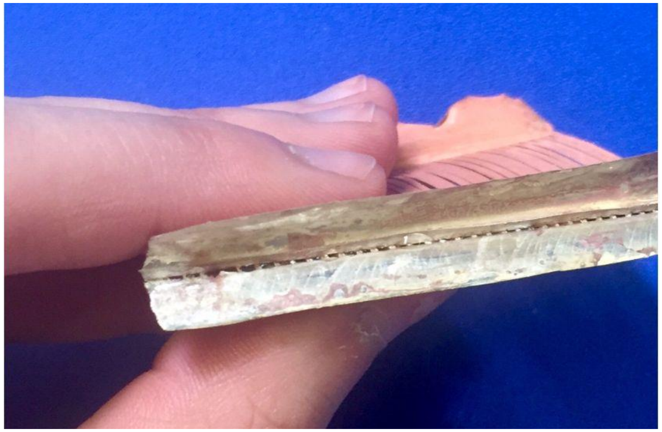
12-channel array measuring 5 cm x 7.6 cm and weighing 6 grams



Internal view of a 12-channel array structure



Micro-channel array measuring 5 cm x 7.6 cm and weighing 1.8 g



Micro-channel flow regions each measuring 127 μm by 838 μm

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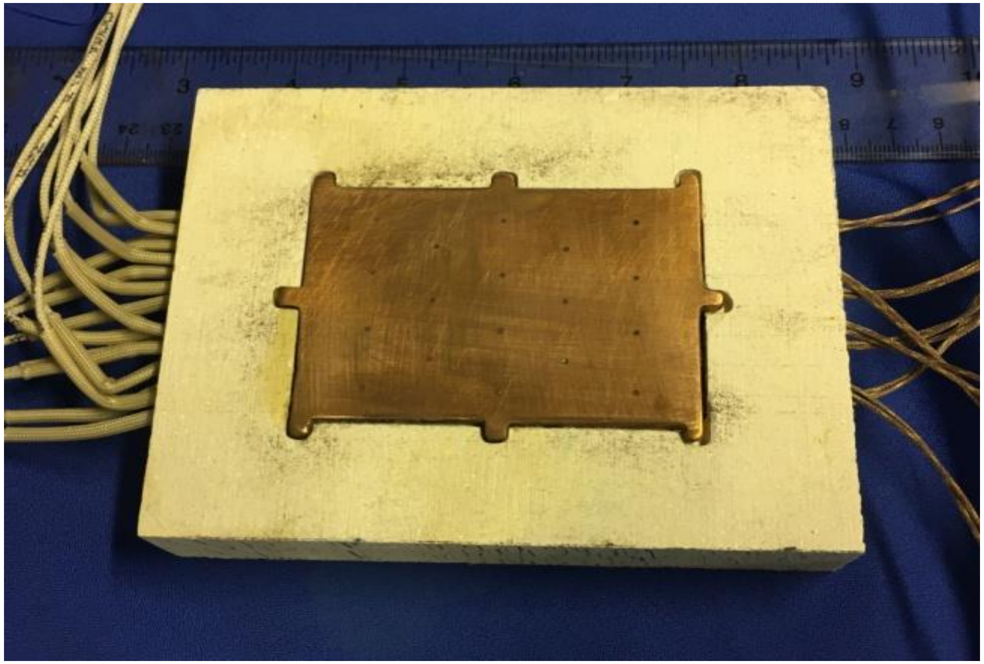
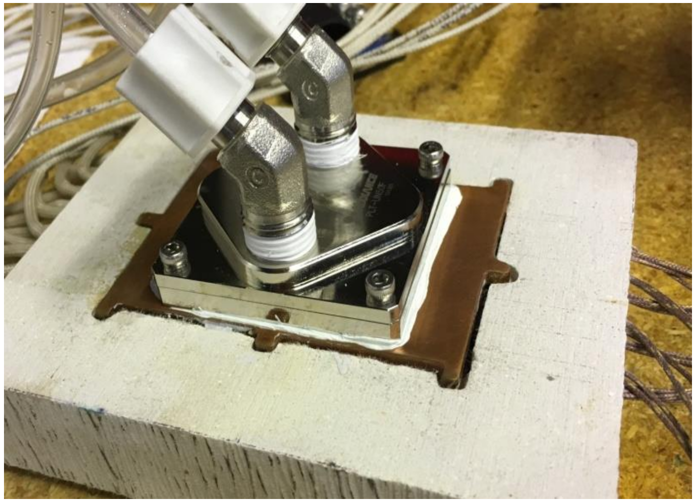
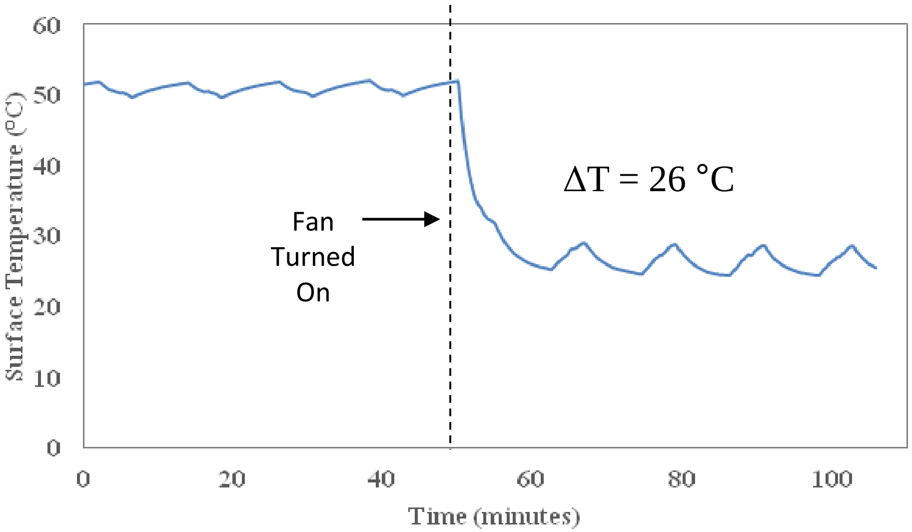
Thermal Test Platform

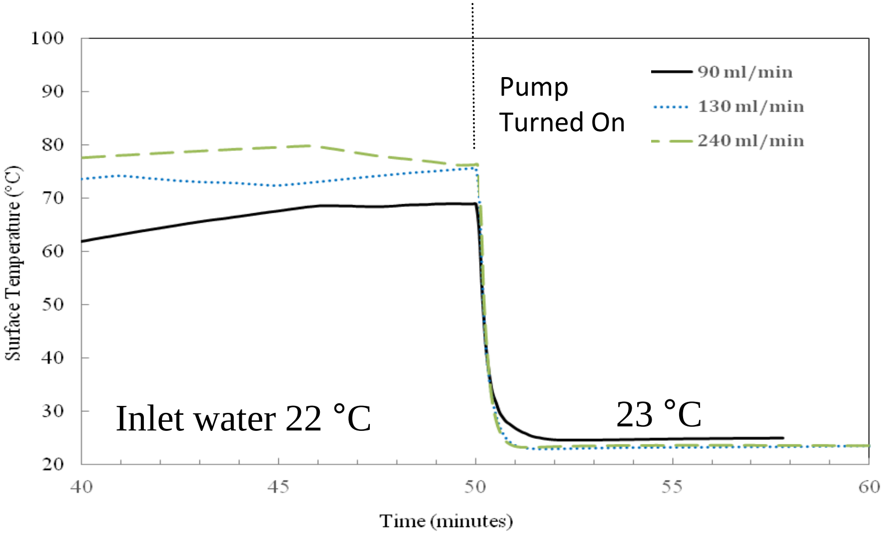
- Heated 5 cm x 7.6 cm copper plate
- Eight 300 watt heaters
  - Activated individually or collectively
  - Simulates uniform heat loads, gradient heat loads, or hot-spots
- 18 thermocouples located at the top copper surface
- Up to 100 W/cm^2 heat loads



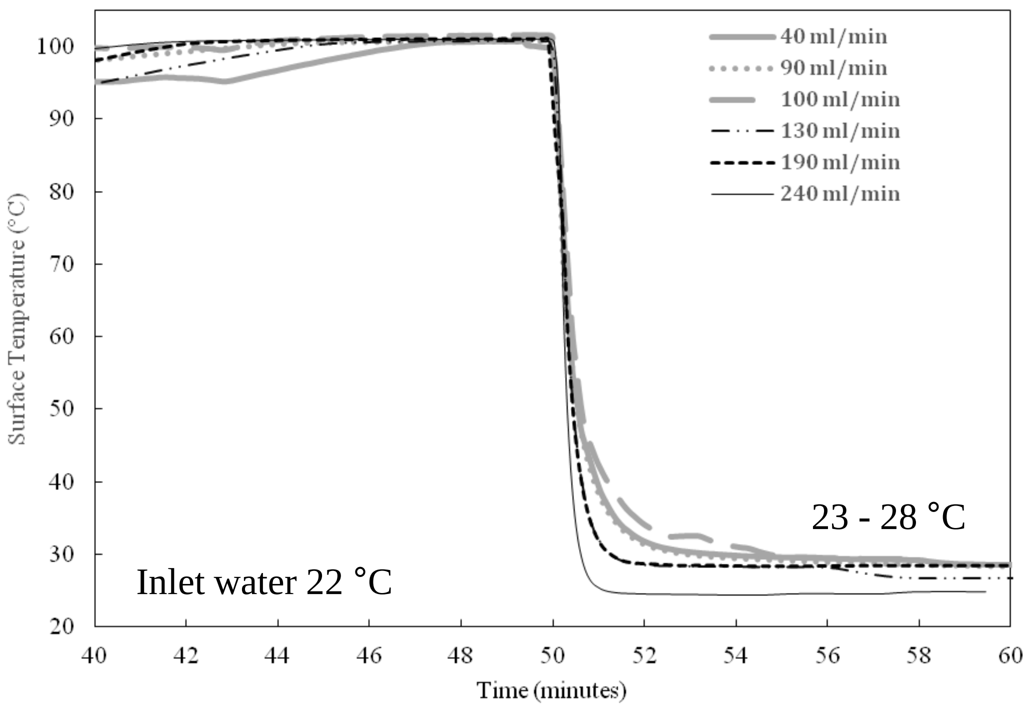
Baseline Test Cases for a Fin/Fan Unit and a Commercial Liquid Cooled Unit

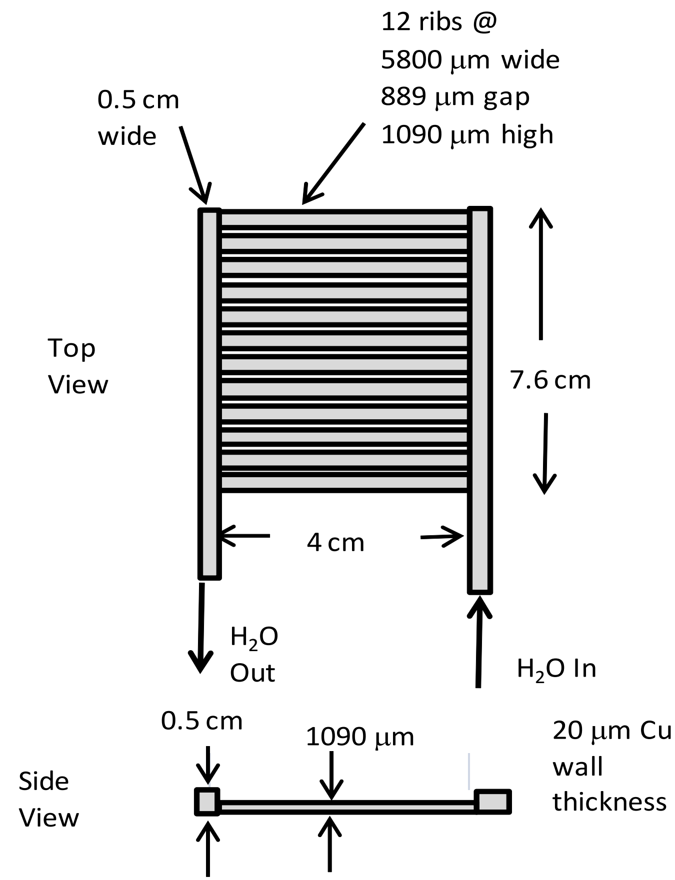






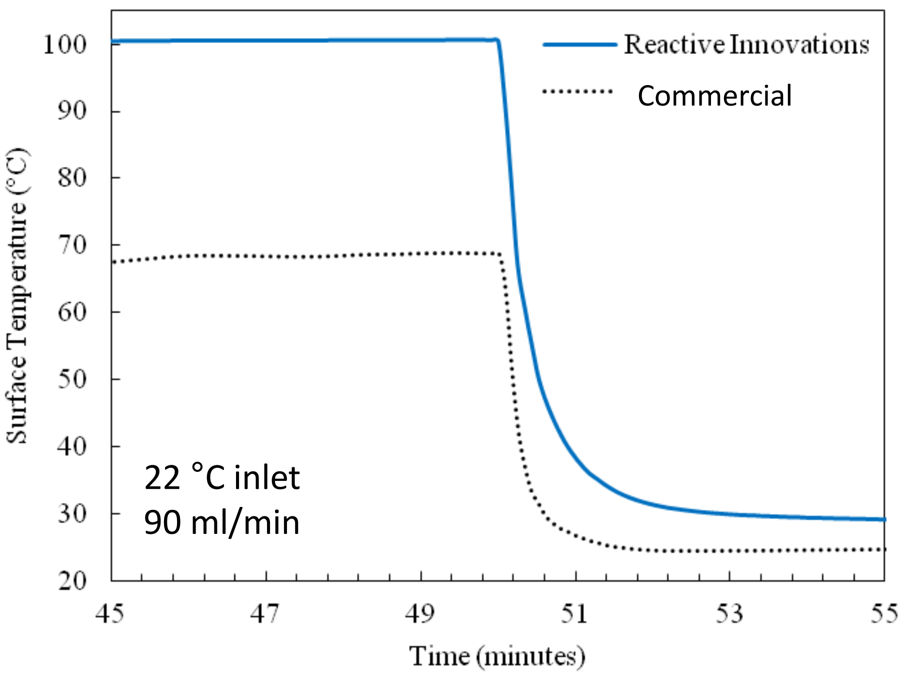
12-Channel Thermal Management Unit

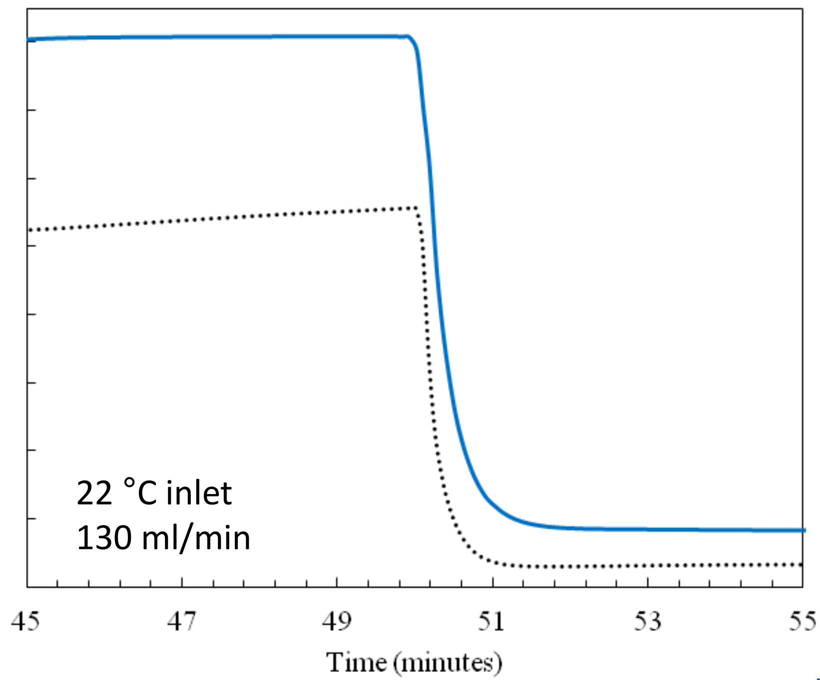




Thermal Performance Comparison at 90 and 130 ml/min Water Coolant Flows

- Reactive unit (Cu): 6 grams
- Commercial unit (Al): 181 grams
  - High free convection due to size and interfacial contact area
- Both devices show similar thermal response rates





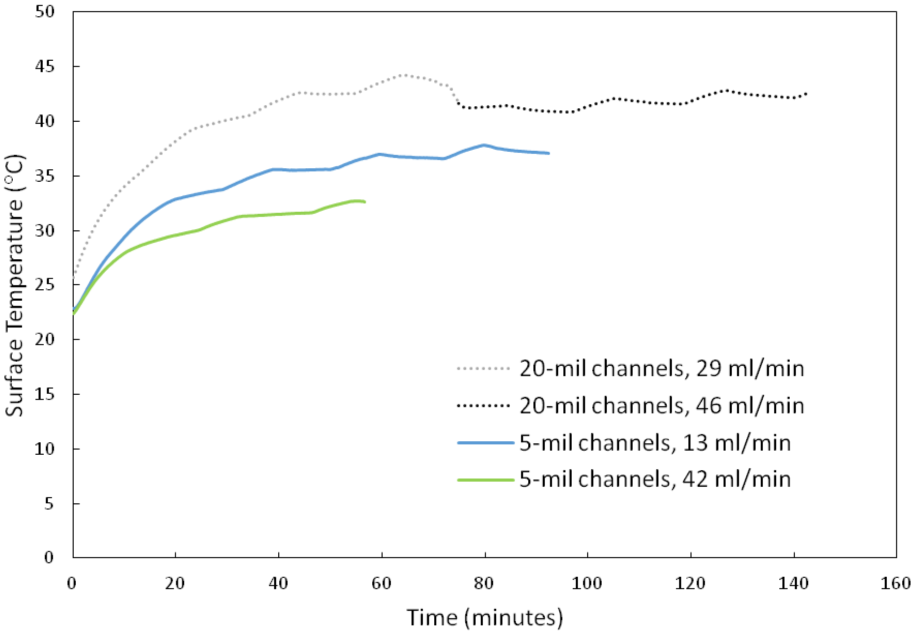
Thermal Resistance Comparison

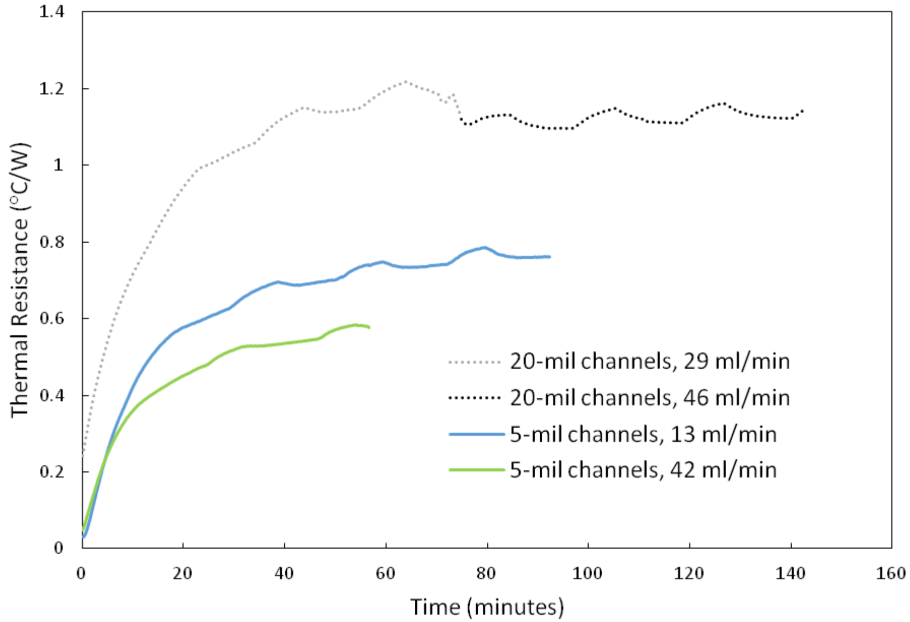
- 15.6 W heat input each case
- 22 °C inlet water temperature

Cooling Device	Coolant Flow Rate (ml/min)	Thermal Resistance (°C/W)	Device Footprint			
			Device Mass (g)	Mass-Thermal Resistance Value (g-°C/W)	Device Volume (cm^3)	Volume-Thermal Resistance Value (cm^3-°C/W)
Fins with Fan	-	0.26	217	56	152	39.5
Commercial Liquid-Cooled Unit	90	0.14	181	25	68	9.5
	130	0.11	181	20	68	7.5
	240	0.11	181	20	68	7.5
Reactive Innovations' 12-Channel Design	40	0.35	6	2.1	7.6	2.7
	90	0.38	6	2.3	7.6	2.9
	100	0.40	6	2.4	7.6	3.0
	130	0.23	6	1.4	7.6	1.7
	190	0.22	6	1.3	7.6	1.7
	240	0.20	6	1.2	7.6	1.5

- Considering mass and volume, additive-base thermal management units give minimal thermal resistance values

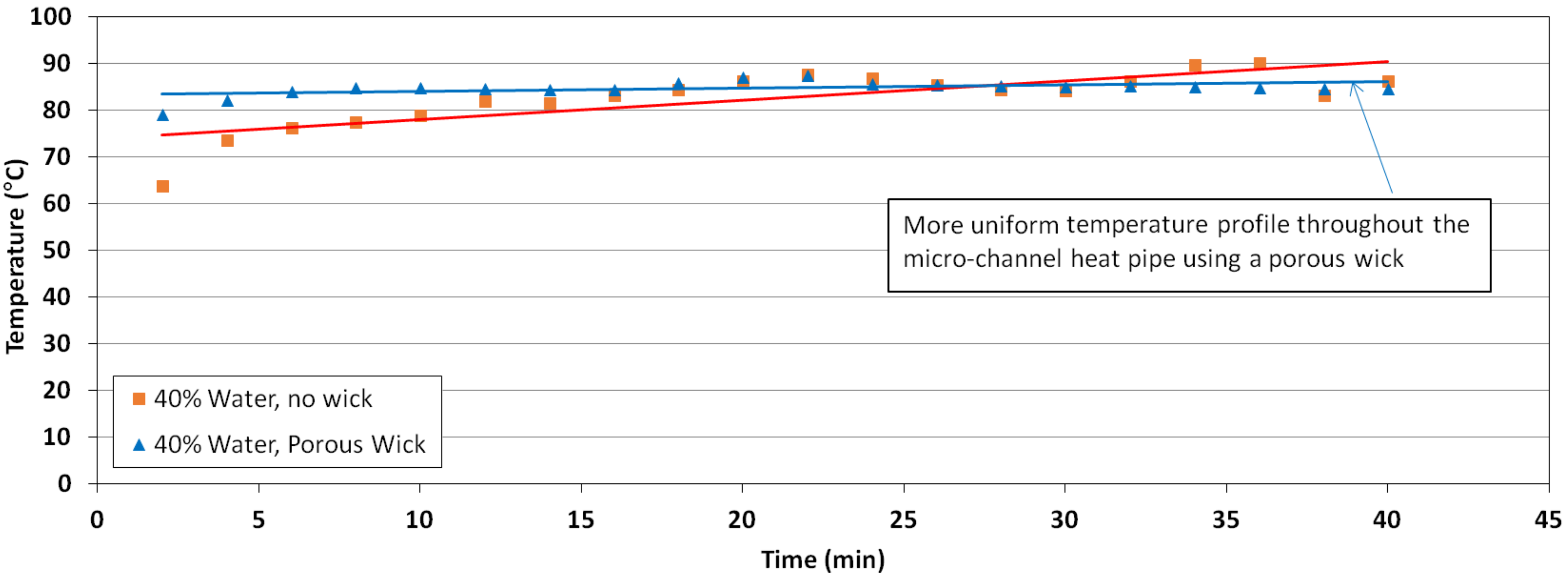
Small Micro-Channels Show Significant Improvement for Heat Removal





- Small, 5-mil high micro-channels cool the unit from 203 °C to 33 ° C

Templated Heat Pipes to Unify Thermal Profiles for On-Detector Electronics



Manufacturing Cost Assessment

- Reusable molds and extrusion nozzles for forming the dissolvable templates out of wax
- Industrial copper electroplating bath technology
  - Plating tanks, rectifiers, simple bath chemistry
  - Multiple units can be processed simultaneously
- Solvent recovery system
  - Enables wax and solvents to be reused
- Example cost for a single 2” x 4” multi-channel unit
  - Materials include the dissolvable wax template and electrolytic plating bath, 90% solvent recovery, and electrical cost
  - Labor applied over processing multiple units in racks
    - No machining, minimal assembly for fittings
  - Unit material cost is $5.70

Summary

- A new manufacturing method has been developed to produce thermal management systems
- Focus on lightweight, low cost devices with intricate flow features
  - Copper wall thicknesses ranging from 20 to 200 μm
  - Channel sizes as low as 127 μm
- Comparable thermal performance to existing commercial devices, yet significantly lighter
- Next steps
  - Focus on improving thermal management designs
  - Developing smaller channel sizes to increase heat transfer coefficients
  - Improving mounting methods for securing the devices
  - Extending designs to two-phase systems
    - Porous wicks for heat pipes
    - Looped heat pipe systems

Acknowledgment

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Contact Information

Discussions

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