THERMAL APPLICATIONS
OF
OPEN CELL METAL FOAMS

by

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November 15, 2001
ASME
2001 International Mechanical Engineering
Congress& Exposition

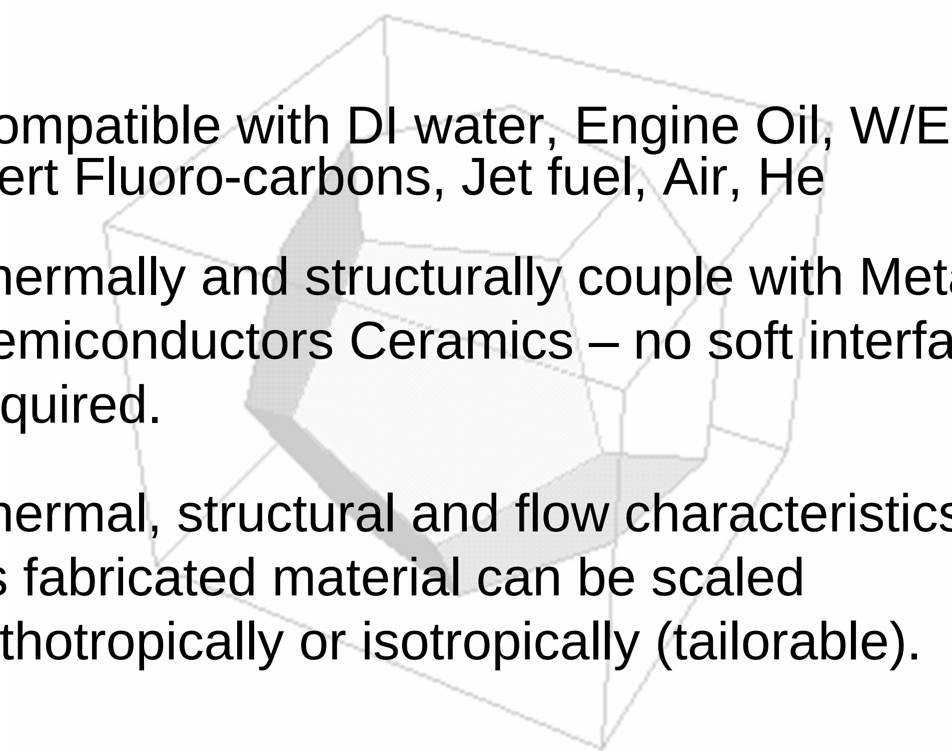
AGENDA

- Advantages and applications
- Structural Characterization
- Thermal characteristics
- Integration of foam heat exchangers
- Characterizing thermal performance
- Modeling and testing
- System level requirements

FOAM MATERIALS:

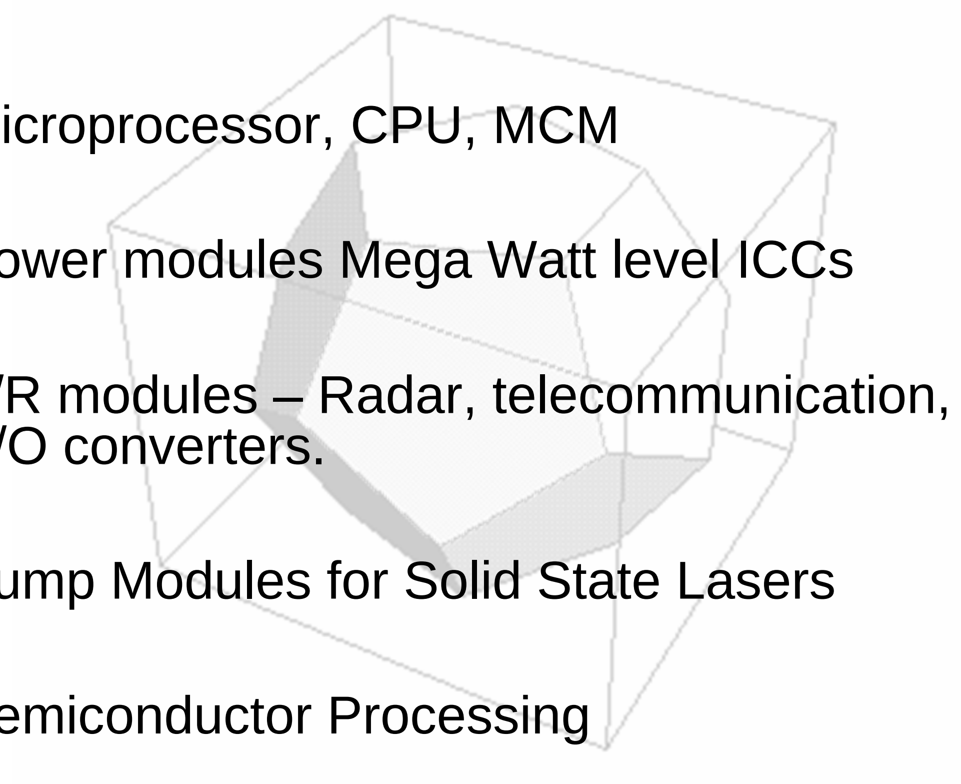
	Bulk Commercial	*Custom*	*Demonstrated*
Metals	Al, Cu	Ni, Ag, Zn	SS, Au,Sn,Pb Be,Inconel
Carbon	Vitreous Carbon		
Ceramics		SiC,SiN	Boron Carbide Hafnium Carbide Alumina
Semiconductors			Si

Advantages and Applications



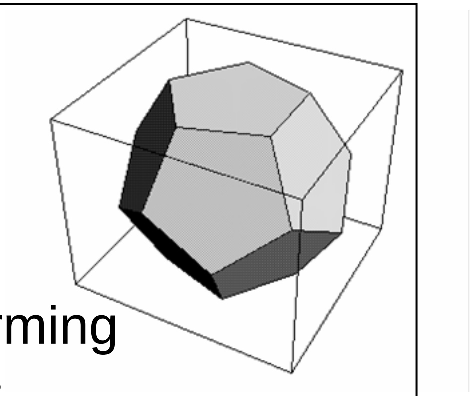
- Compatible with DI water, Engine Oil, W/EG Inert Fluoro-carbons, Jet fuel, Air, He
- Thermally and structurally couple with Metals, Semiconductors Ceramics – no soft interfaces required.
- Thermal, structural and flow characteristics of as fabricated material can be scaled orthotropically or isotropically (tailorable).
- System weight, volume, performance and the life cycle cost can be significantly improved.

Advantages and Applications

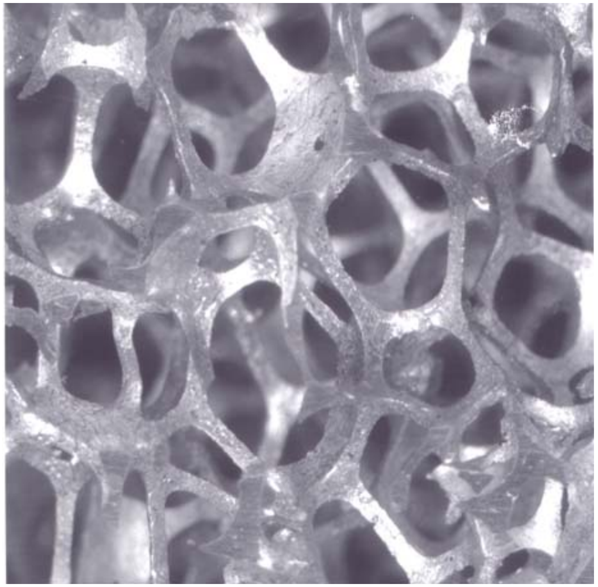


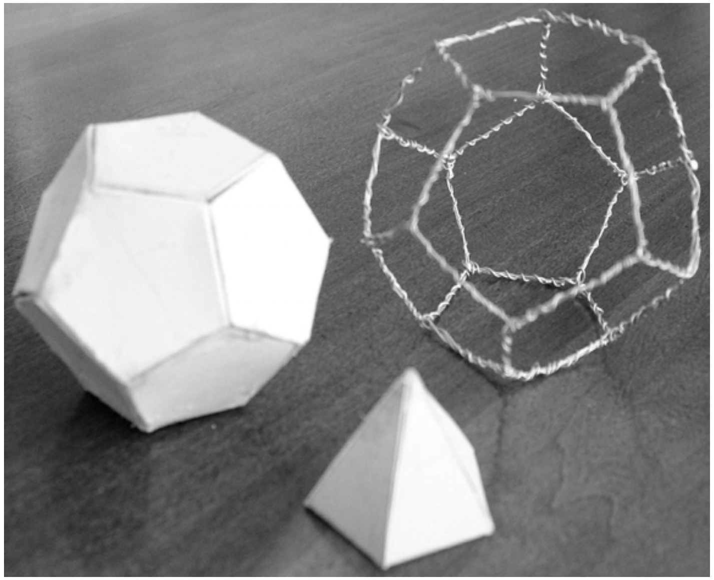
- Microprocessor, CPU, MCM
- Power modules Mega Watt level ICCs
- T/R modules – Radar, telecommunication, E/O converters.
- Pump Modules for Solid State Lasers
- Semiconductor Processing

Structure of RMF

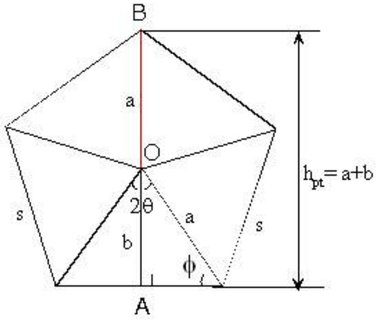


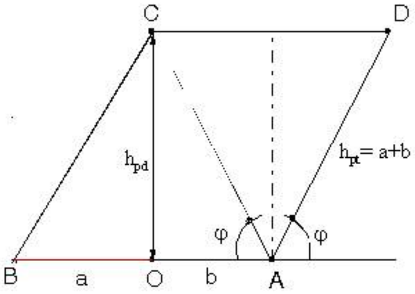
- Continious, interconnected ligaments forming a 3-D stacking of 12-14 sided polygones





Measures of Dodecahedron





- Cell edge: S
- Ligament size: d
- Diagonal of the base: $\grave{h}_p = 1.54\,s$
- Average diagonal: $\dfrac{1}{\alpha} \approx h_{d,avg} \approx 2.5\,s$
- Cross section of a ligament: $A_l \approx \dfrac{d^2}{\sqrt{3}}$
- Volume: $V_d \approx 7.66\,s^3 = \beta\,s^3$

THERMAL CHARACTERISTICS of RMF

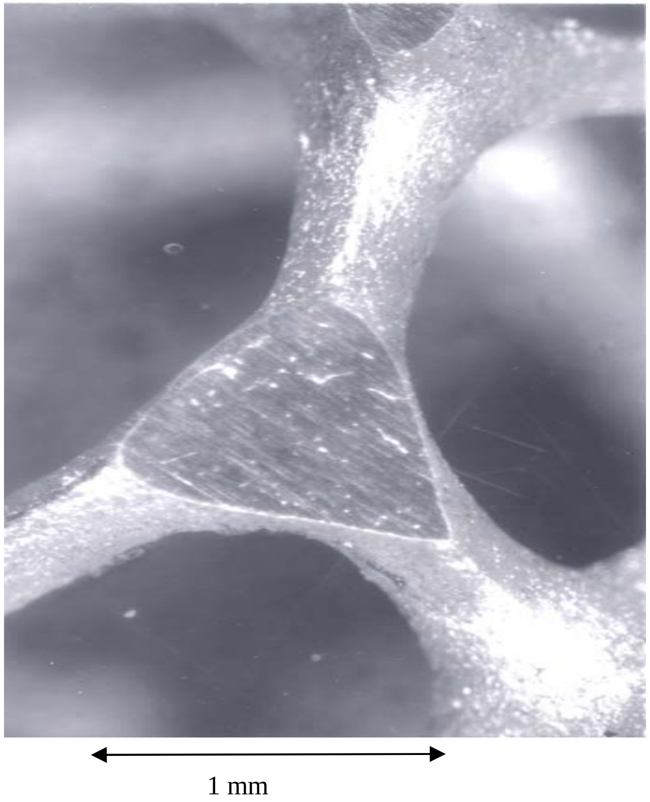
Ligament thickness d

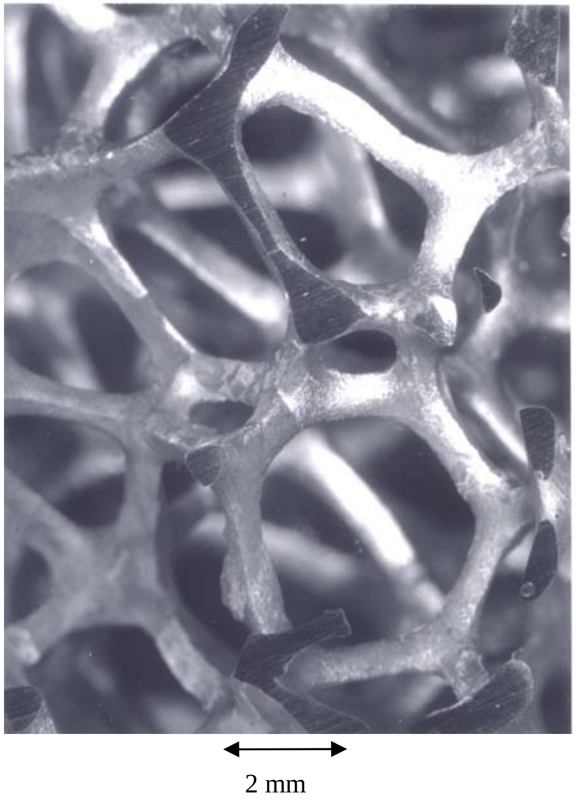
Relative density (%): ρ

Pore density (ppi): α

$$A_l.(s-\lambda_1.d).\frac{\mu_e}{3}+\lambda_2\frac{\mu_c}{3}d^3=\rho.V_d$$

10 ppi and 8% dense Al foam





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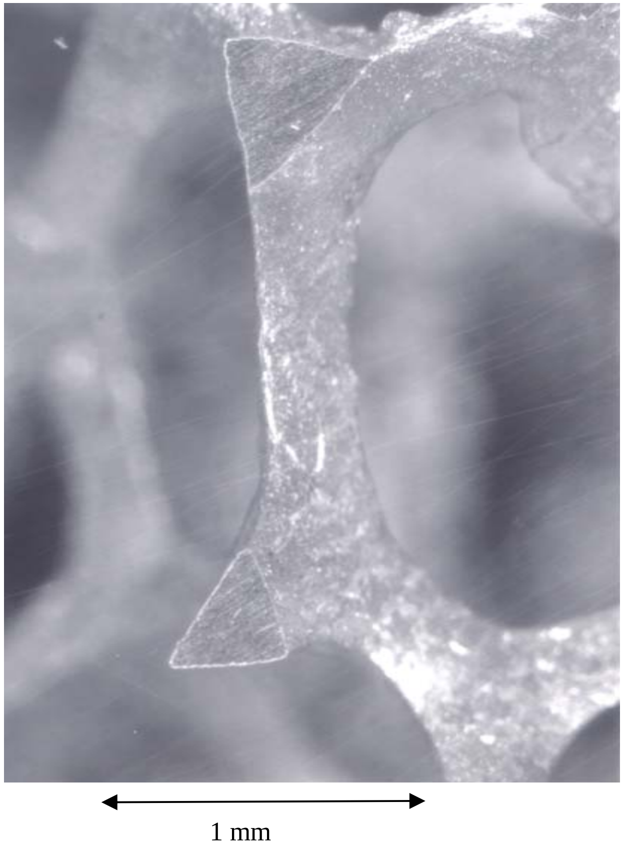
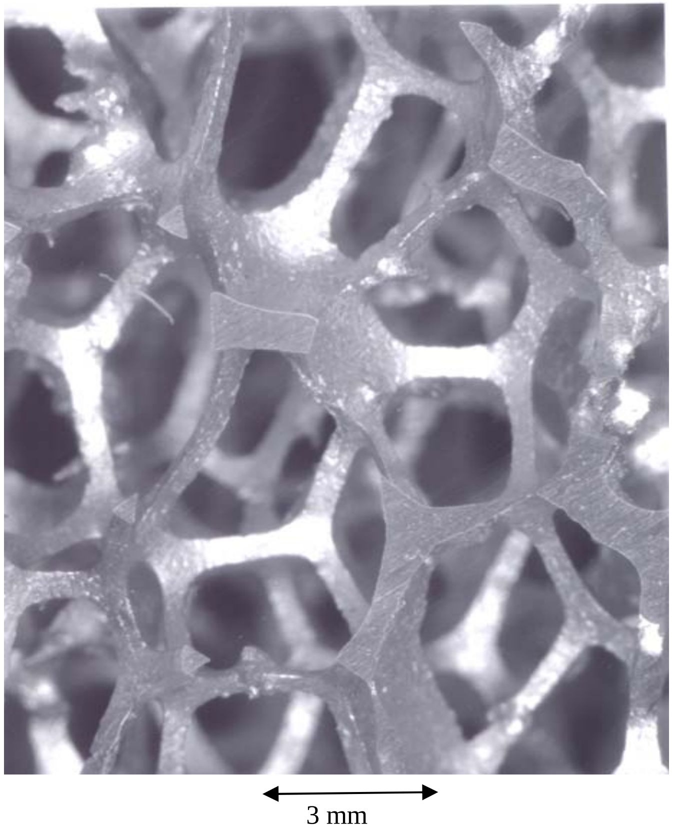
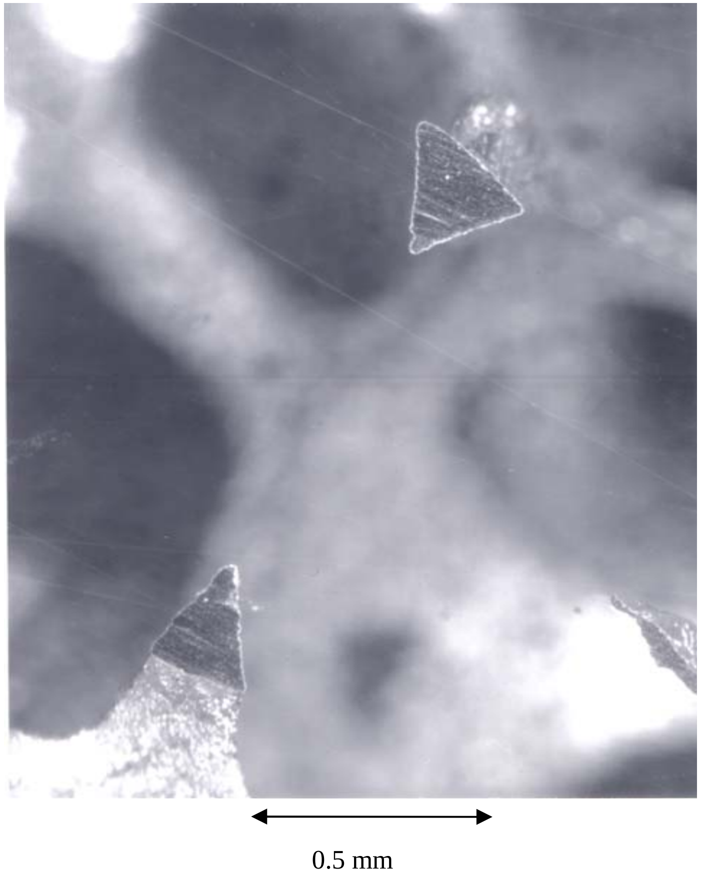
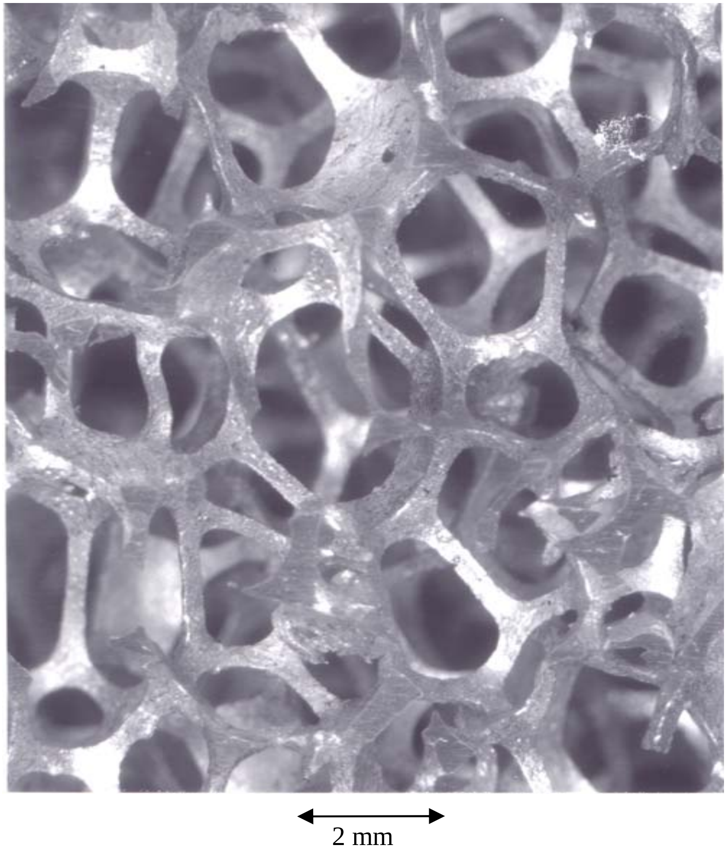




30 ppi and 8% dense Al foam





Ligament Thickness

Cell edge "s " (Inch)	Pore density "α" (ppi)	Foam density "ρ"	Ligament size "d" calculated (Inch)	Ligament size "d" measured (Inch)
0.020	30	0.08	0.0089	0.009
0.027	20	0.08	0.012	0.012
0.040	10	0.08	0.018	0.019

Specific Surface Area

RMF	Density (%)	Ligament (Inch)	Measured ($in^2/in^3/\%$)	Calculated ($in^2/in^3/\%$)
10 ppi	8.1	0.040	2.8	2.6
20 ppi	6.1	0.027	5.5	5.1
30 ppi	5.4	0.020	6.9	7.5

$$s_o = \frac{d.(a-\lambda_{s1}.d)\mu_e + \lambda_{s2}.d^2.\frac{\mu_c}{3}}{100.\rho.V_d}$$

Thin fin [0.030"/0.060”] $\approx$ 30 (in^2/in^3)

Square pin grid array [0.06”x0.06”/0.120”] $\approx$ 15 (in^2/in^3),

30 ppi RMF $\approx$ 60 (8%), 350 (45%)

Thermal Conductivity

Electrons and phonons

Metallic Glass

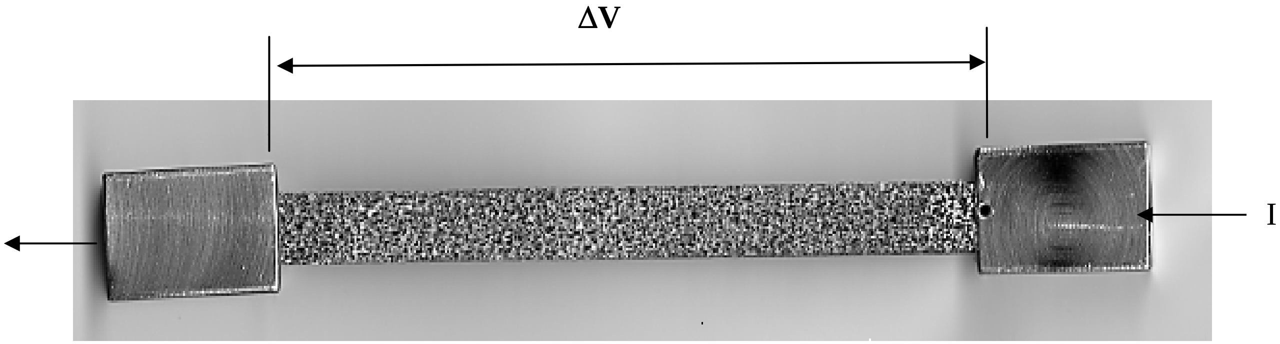
β sodumene ($Li_2O.Al_2O_3.4SiO_2$) the same E, ρ and d_g as Al
$k_\beta = 2 \sim 0.01.k_{Al}$ (W/m-°K)

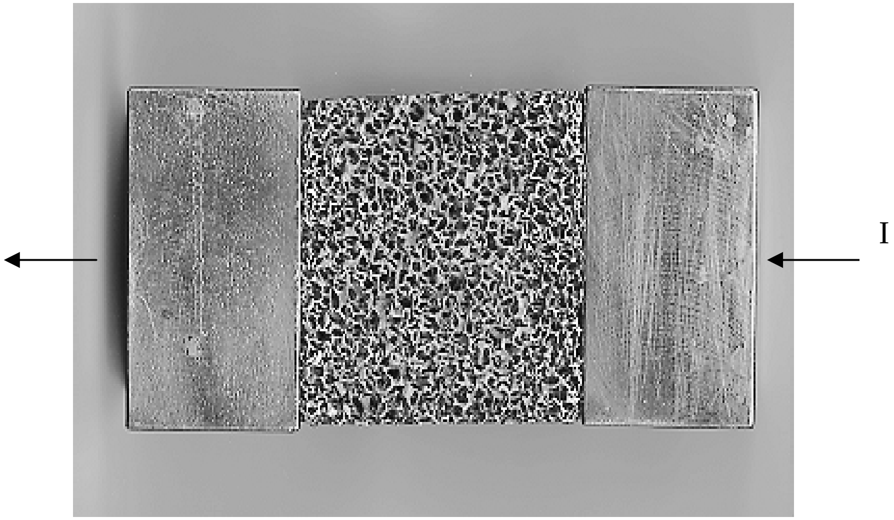
$$K_{th} = L.K_{el}.T$$

$$k_e = \lambda.k_{Cu}.\rho$$

$$\omega_e = \lambda.\omega_{Cu}.\rho$$

THERMAL APPLICATIONS OF OPEN CELL METAL FOAMS





THERMAL APPLICATIONS OF OPEN CELL METAL FOAMS

α ppi	L (In)	Area (Inch^2)	ρ	$\Delta L/L$	ΔV (mV)	(λ)	K_{eff} (W/m-^{o}K)
1-30	5.0	0.75x0.75	0.088	0	5.8	0.3575	12.2 - x,y,z
2-30	5.0	0.775x0.42	0.151	Y -0.436	5.9	0.3420	20.6 - x,z 7.2 - y
3-30	5.0	0.43x0.42	0.272	X -0.457	5.9	0.3457	37.4 - z 11.2 - x 13.2 - y
4-30	3.5	0.44x0.42	0.173	Z -0.300	6.7	0.3475	23.8 - z 16.1 - x 17.2 - y
1-10	4.7	2.0x2.0	0.083	0	0.81	0.3571	11.6 - x,y,z
2-10	2.67	2.06x2.06	0.136	Z -0.432	0.75	0.3420	6.8 - z 18.6 - x,y

$$k_e = k_s.\lambda.\rho.(1+\varepsilon_p)^n \qquad n = 1, -1$$

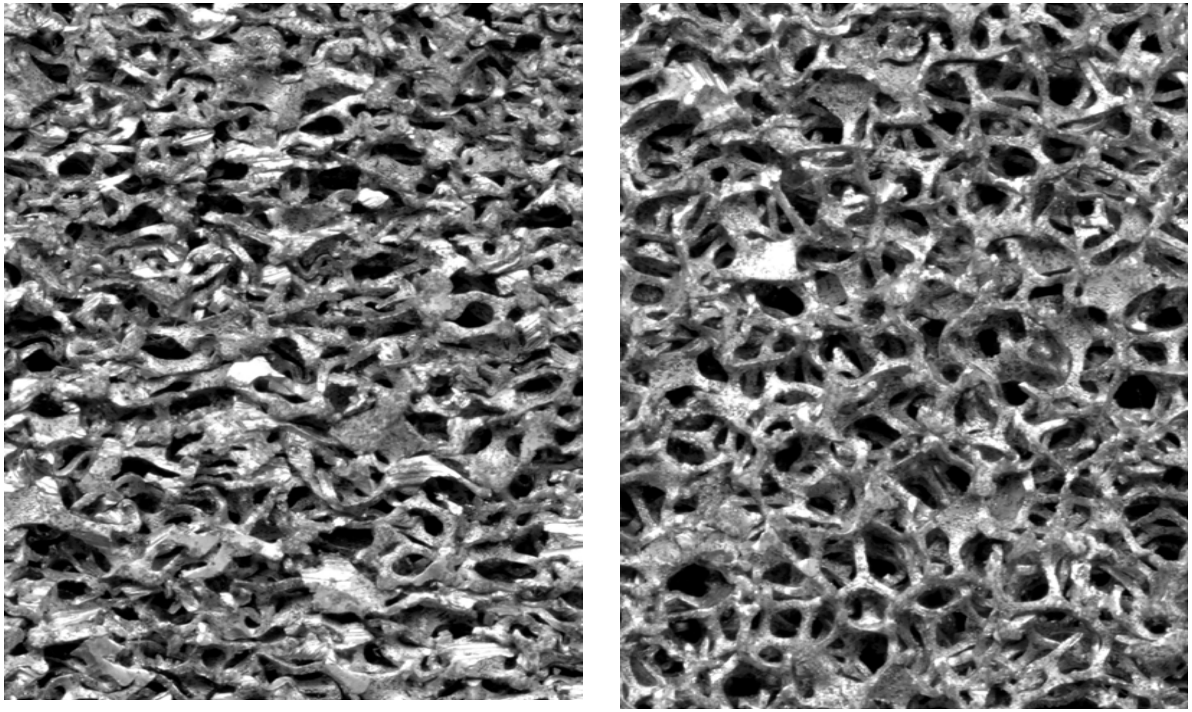
Convective energy transfer

Cell size $l \approx \left(\frac{\rho}{\eta}\right)^{-p} . \frac{1}{\alpha} - d$

Hydraulic Diameter $D_h \approx 2 . \frac{l_1 . l}{l_1 + l}$

Flow area(%) $\omega_1 \approx l_1 . l . \alpha_1 . \alpha$

THERMAL APPLICATIONS OF OPEN CELL METAL FOAMS

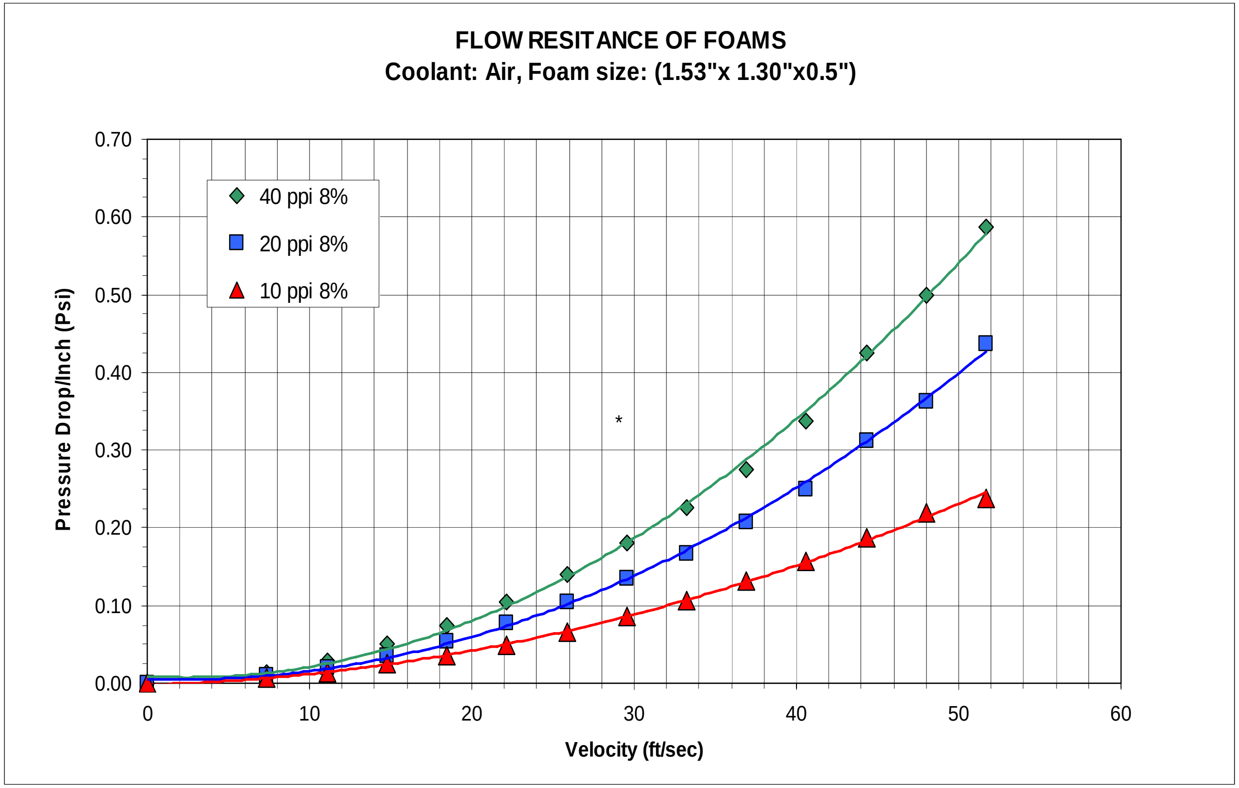


30 ppi foam uniaxially compressed to 20 % density in plane (left) and out off plane (right).

$$D_{he} = (c_1 . D_o + c_o D_1)$$

$$\omega_{he} = (c_1 . \omega_o + c_o \omega_1)$$

Characterizing thermal performance :



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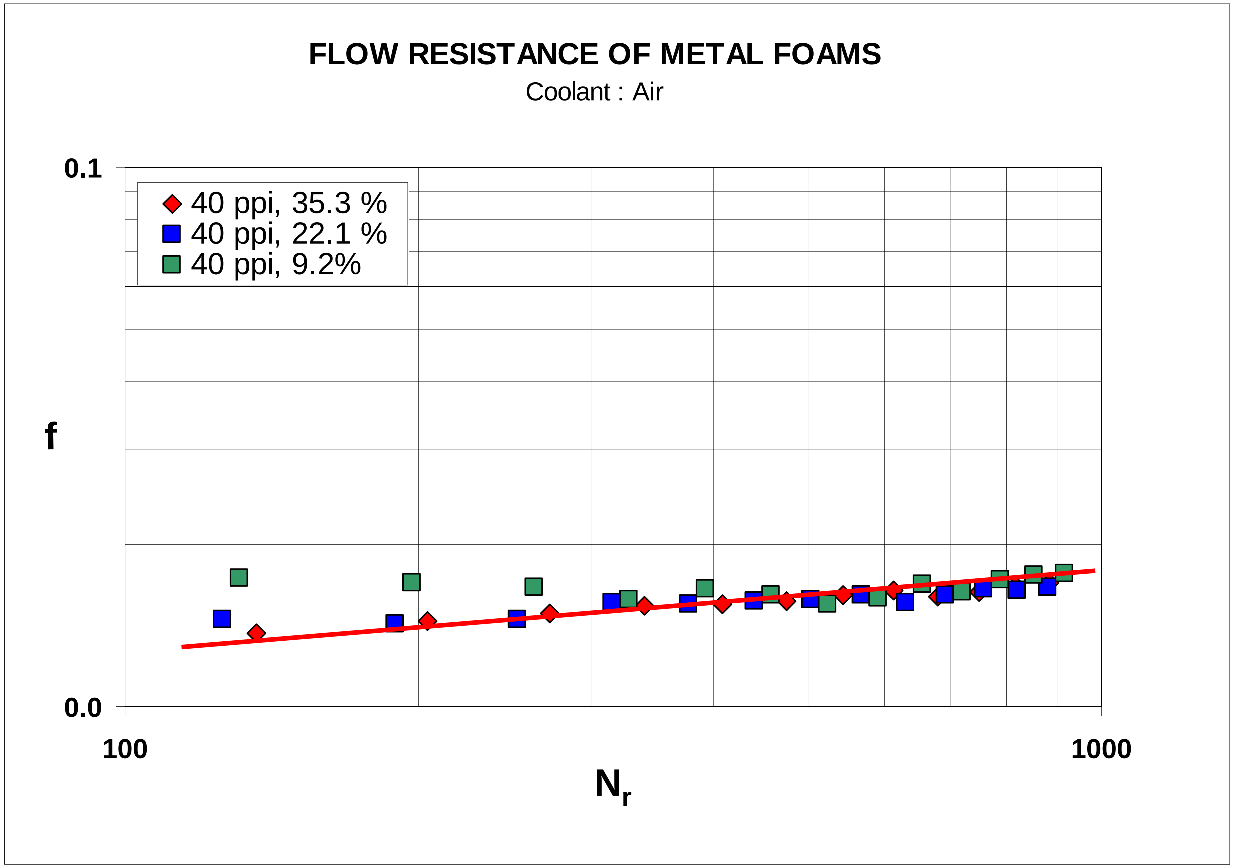

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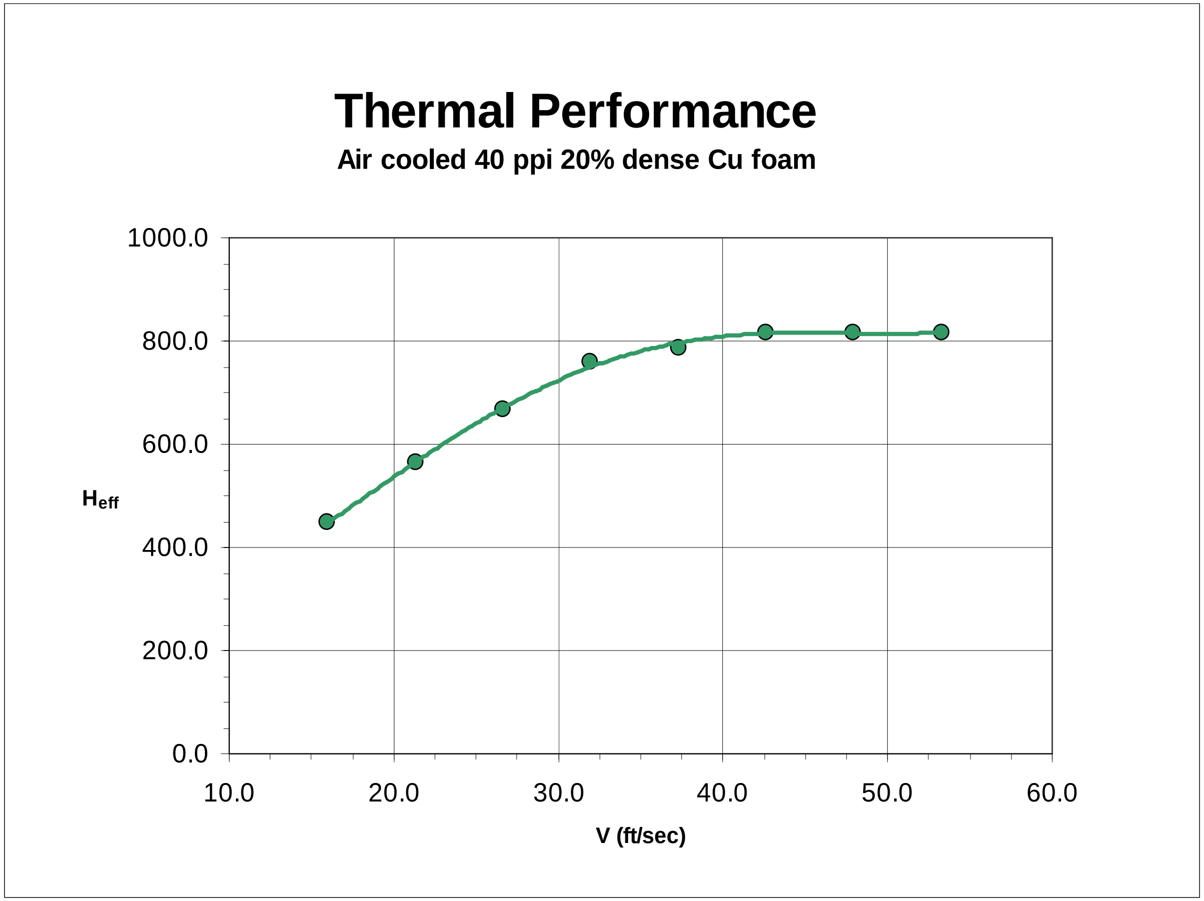

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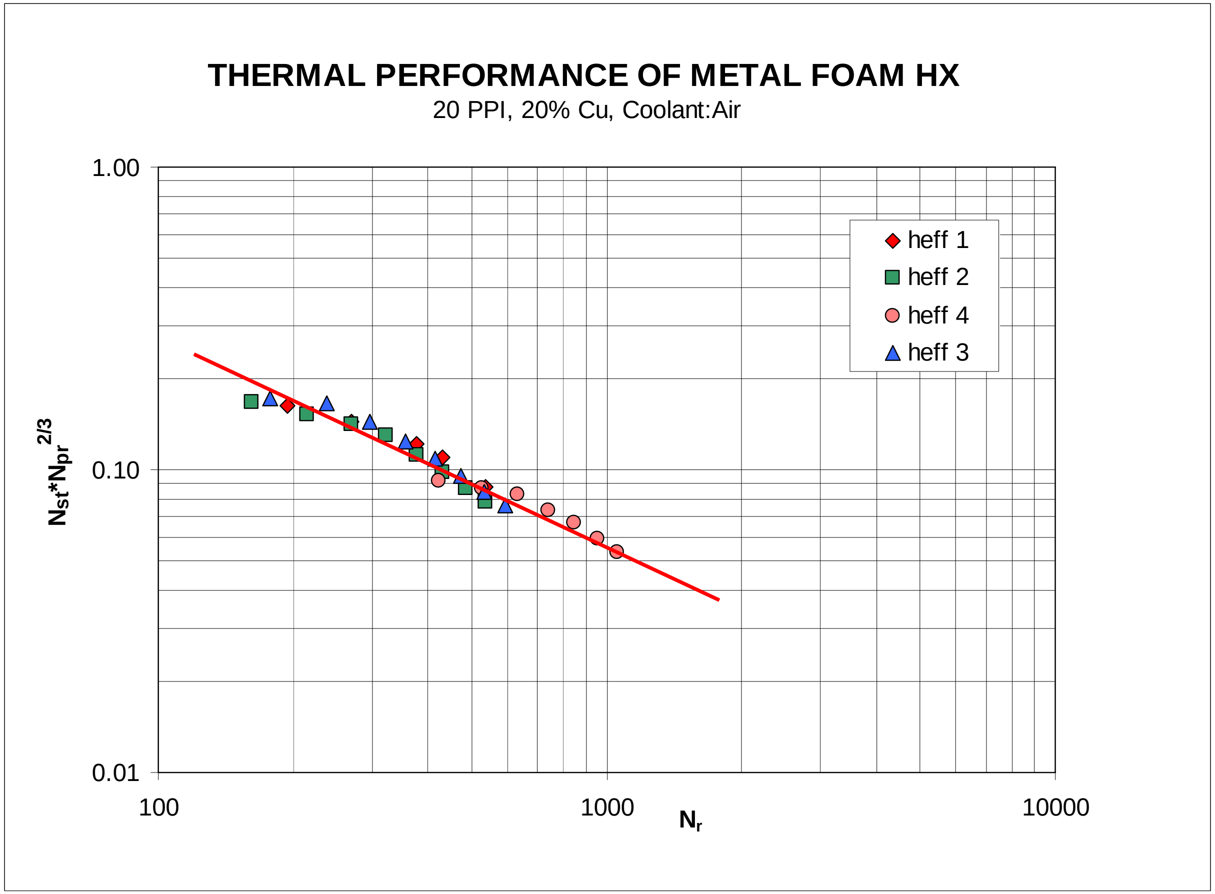
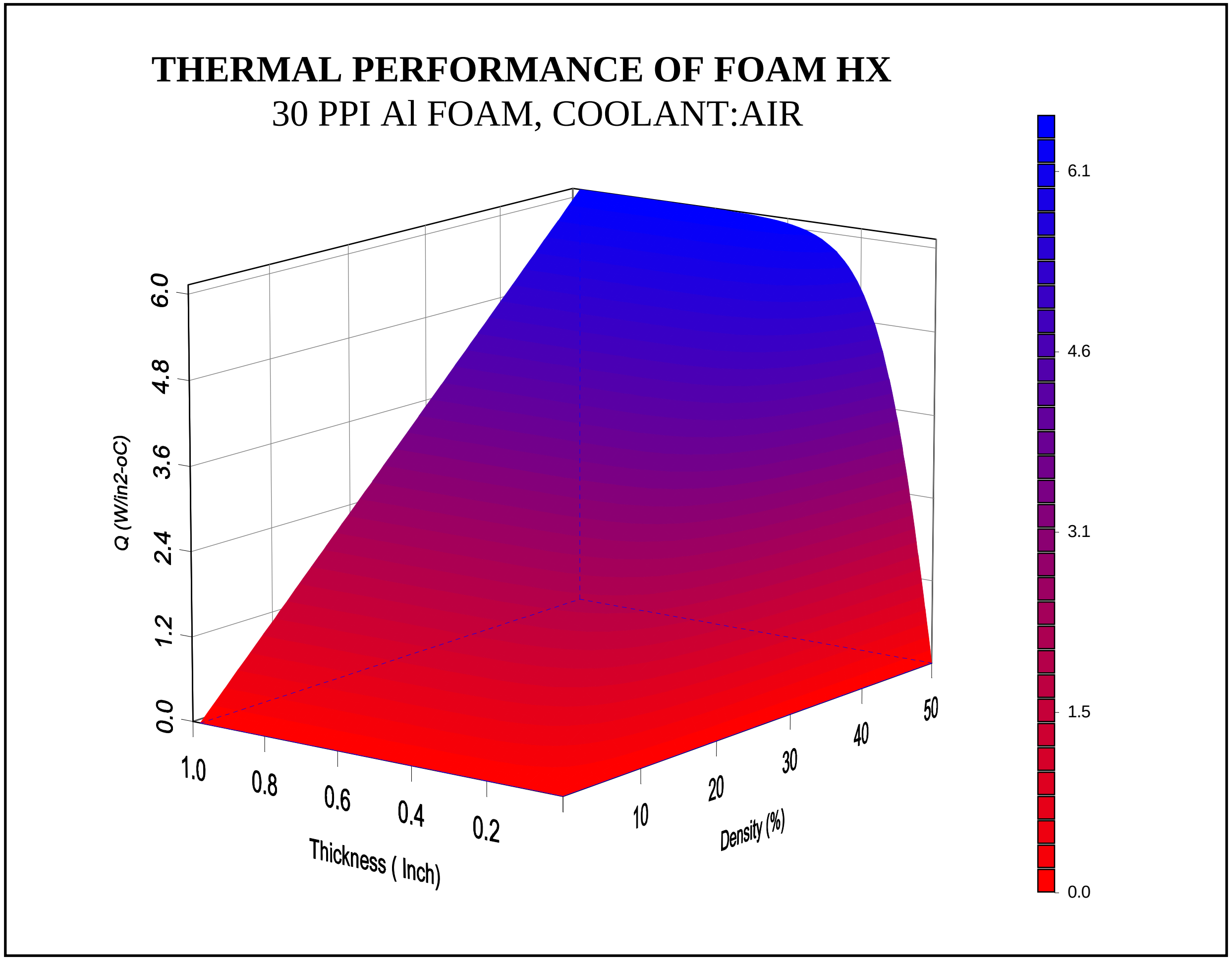


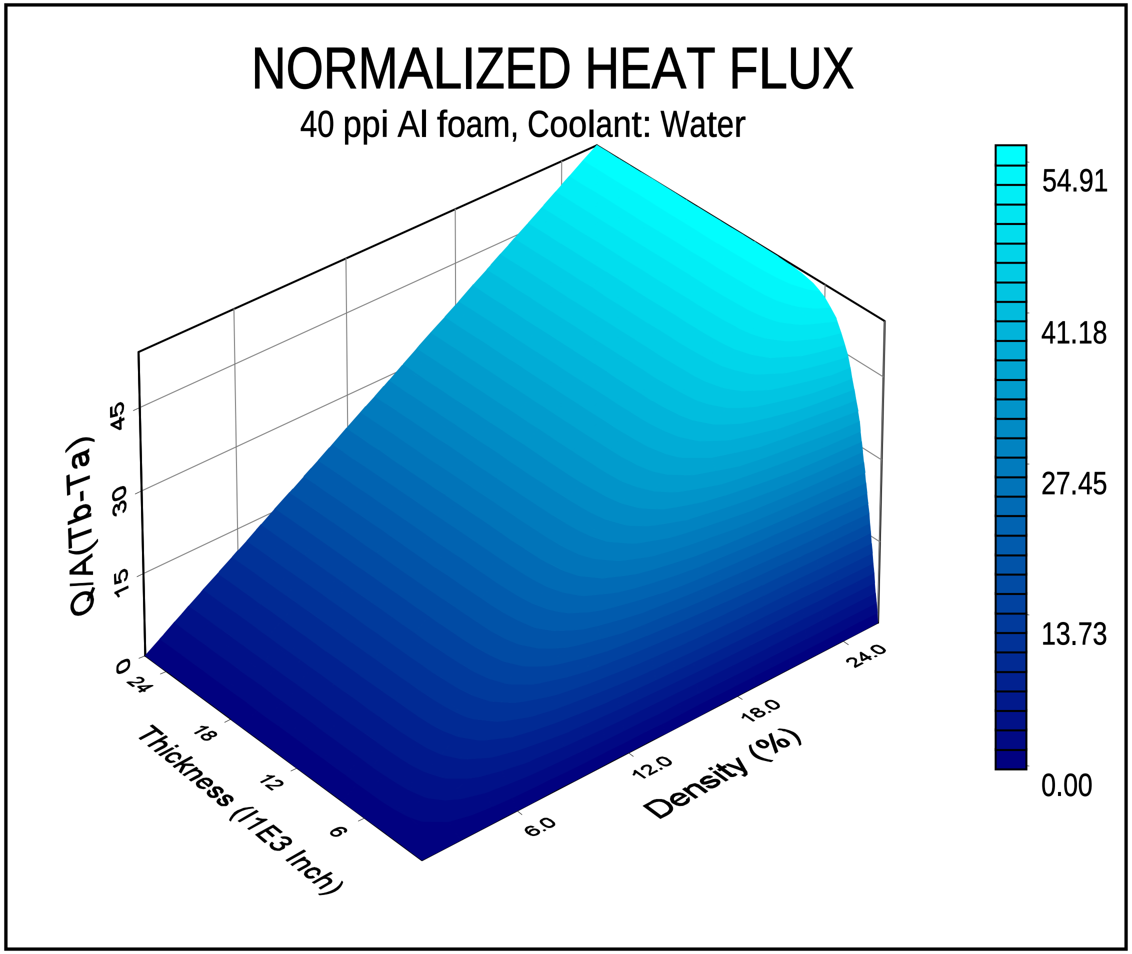
Thermal Performance Limits for RMFs



THERMAL PERFORMANCE OF FOAM HX

30 PPI Al FOAM, COOLANT:AIR

Thermal Performance Limits for RMFs



Thermal Performance Limits for RMFs

FOAM MATERIAL	**PORE DENSITY (PPI)**	**CRITICAL THICKNESS (Inch)**	**COOLANT**	**Q_{max} /ΔT-A ($W/^oC/In^2$)**	**R_{th} ($^oC/W$)**
Cu	10	0.090	WATER	30.0	0.033
Cu	20	0.060	WATER	45.0	0.022
Cu	30	0.045	WATER	65.0	0.015
Cu	10	0.850	AIR	2.8	0.357
Cu	20	0.520	AIR	5.0	0.200
Cu	30	0.400	AIR	7.0	0.143
Al	10	0.070	WATER	23.0	0.043
Al	20	0.050	WATER	33.0	0.030
Al	30	0.030	WATER	50.0	0.020
Al	10	0.750	AIR	2.0	0.500
Al	20	0.400	AIR	3.5	0.286
Al	30	0.380	AIR	5.0	0.200

Specific Thermal Resistance ($^{o}C/W/in^2/in^3$)

Air cooled Server Application - 50 scfm/processor (7x)

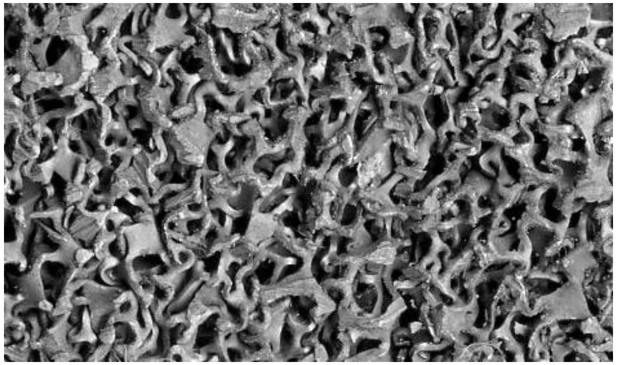
20% Orthotropic Cu foam	$R_s \sim 0.6$
Folded and brazed thin fin	$R_s \sim 4.2$

Thin fin [0.020"/0.060”] $\approx$ 20 (in^2/in^3)

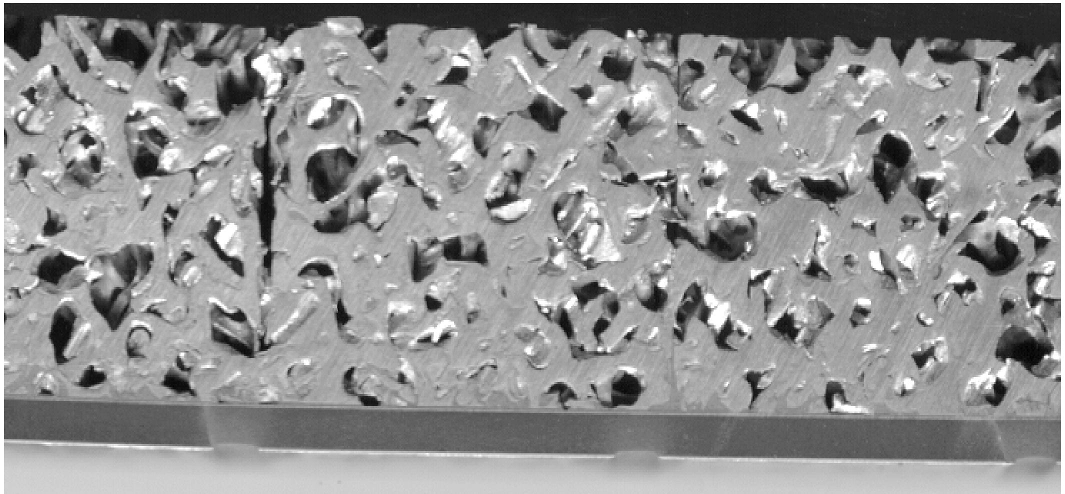
Water cooled Power Module Application 2KW-2GPM (5x)

Integral foam	$R_s \sim 0.005$
External, High performance CP	$R_s \sim 0.025$

An experimental study of RMF based HX

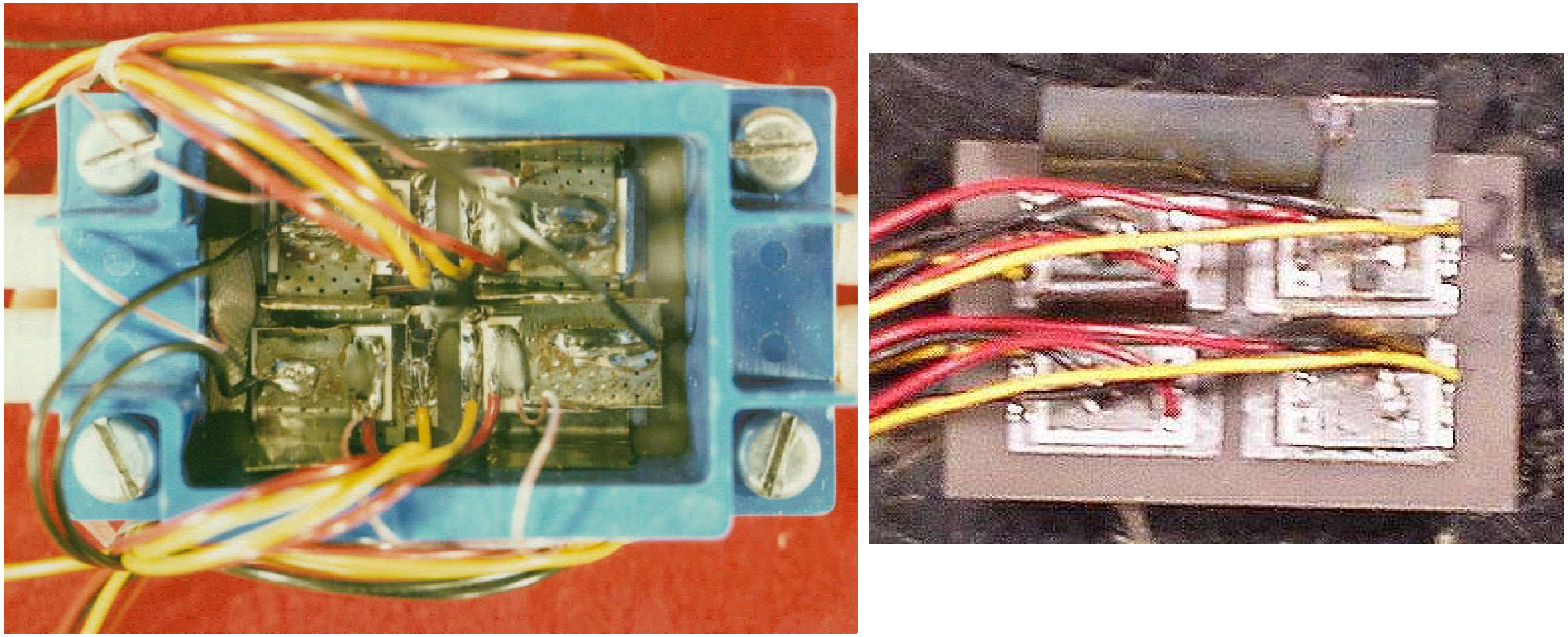


A 30 ppi, 8% dense Cu foam was biaxially compressed to 35% density.



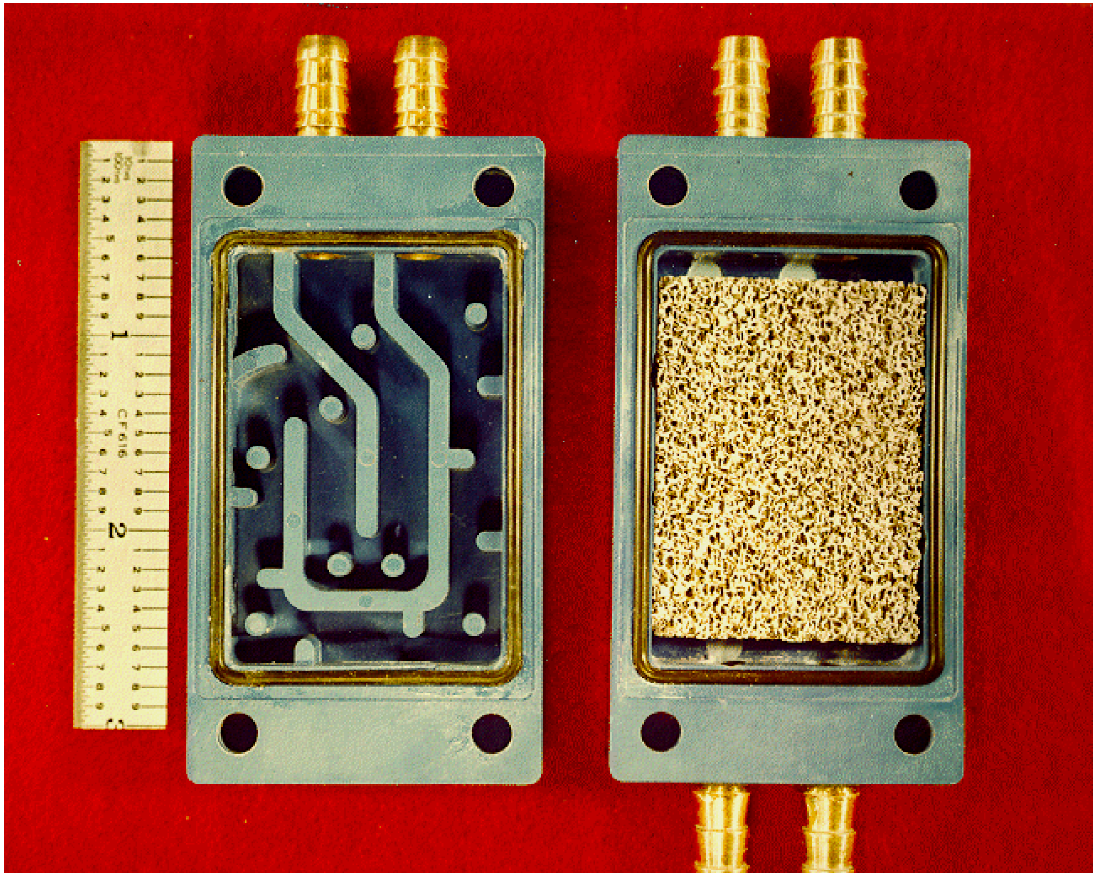
A Cu foam based integral heat exchanger

An experimental study of RMF based HX



THERMAL TEST MODULE

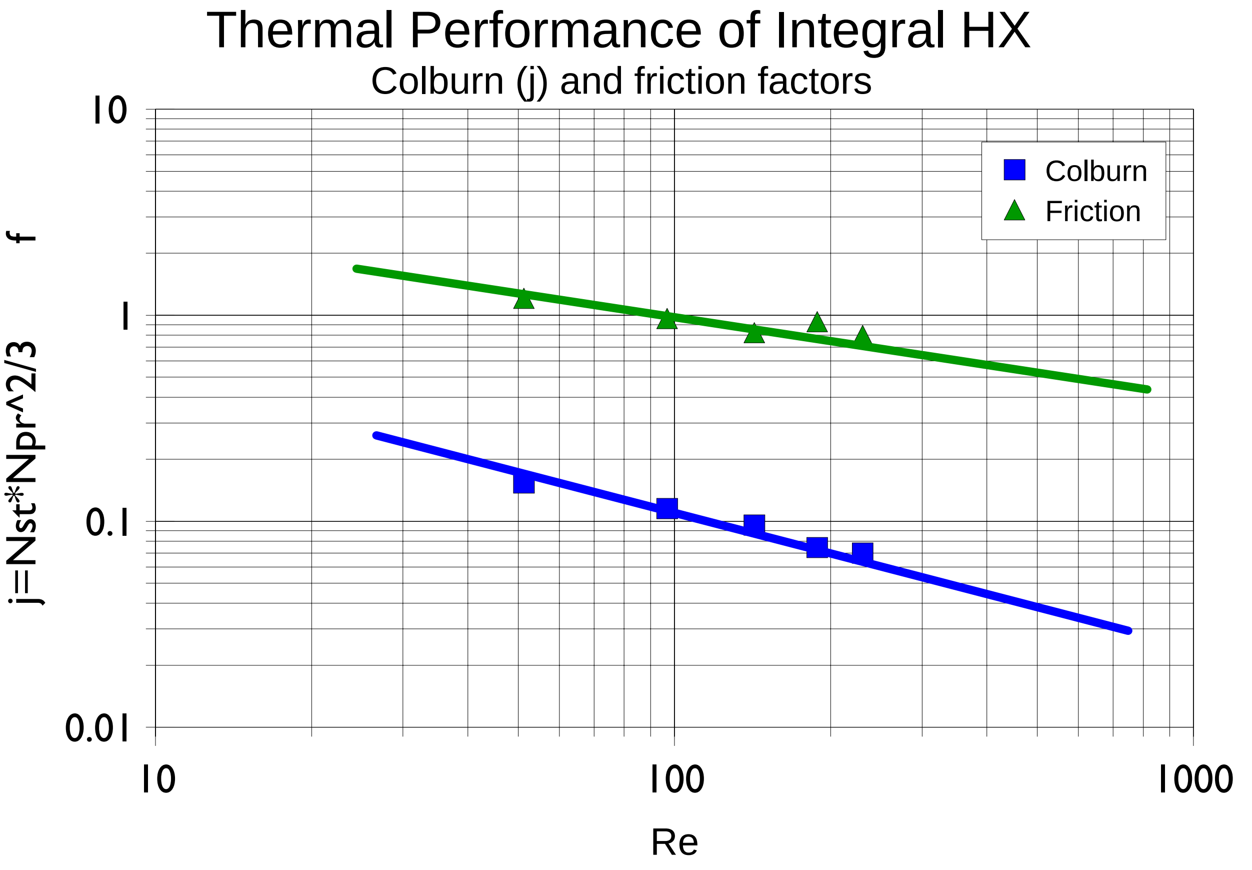
Characterizing thermal performance :



The baffled heat sink consists of an external cavity with baffled flow passages (left).

An Al `foam based HX retrofitted into the same size cavity.

An experimental study of RMF based HX



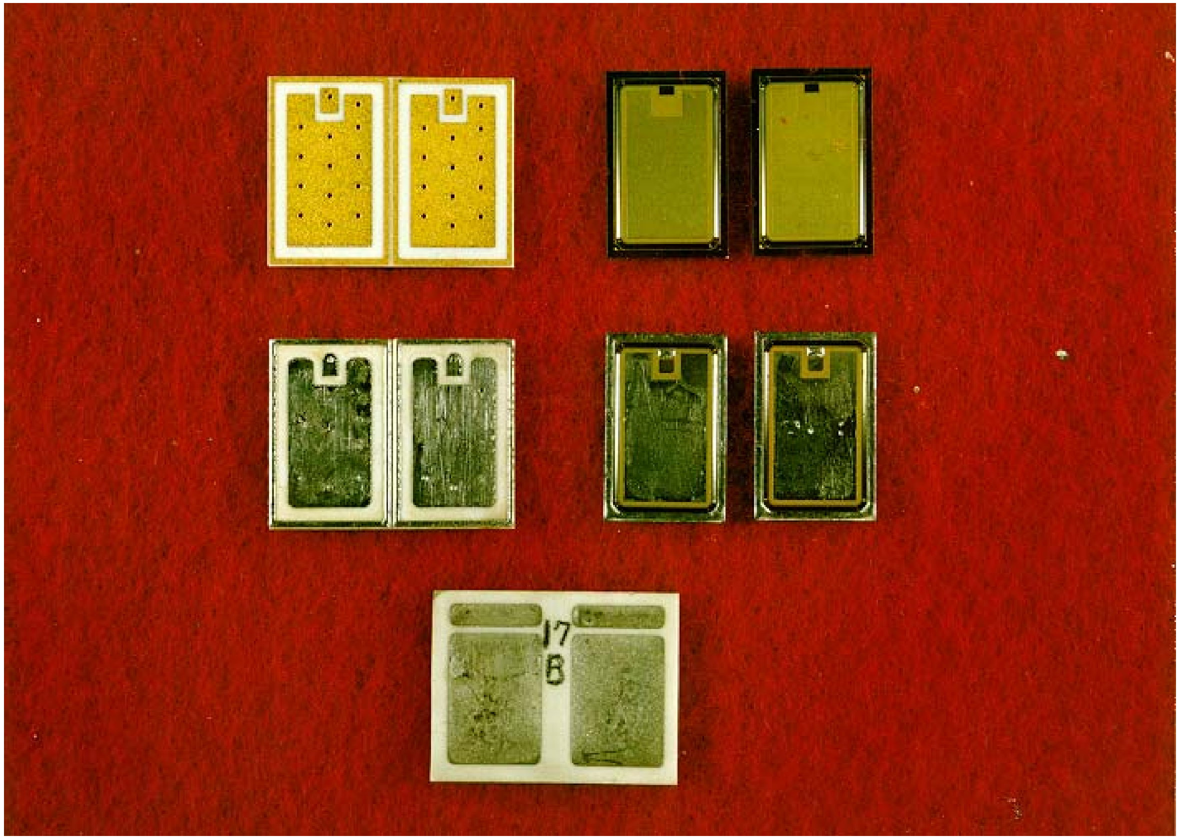
An experimental study of RMF based HX

	Heat Sink	**ΔT_{ja}, (^{o}C)**	**R $_{ja}$ (^{o}C/W)**	**P max. @ ΔT_{ja} 60 ^{o}C**
1-FEM	INTEGRAL-30 ppi Cu-36 %	60 ^{o}C	0.043	1,400
2	BAFFLED CAVITY	75 ^{o}C @ 800W	0.095	640
3	EXTERNAL Cold Plate	95 ^{o}C @ 800W	0.120	505
4	INTEGRAL-30 ppi Al-10%	86 ^{o}C @ 800W	0.108	560
5	INTEGRAL-30 ppi Al-20%	69 ^{o}C @ 850W	0.080	740
6	INTEGRAL-30 ppi Al-36%	47 ^{o}C @ 850W	0.059	1020
7	INTEGRAL-30 ppi Cu-36 %	38 ^{o}C @ 800W	0.047	1310
8	INTEGRAL-30ppi Cu-36 %	63 ^{o}C @ 1000W$^{E/G}$	0.063	950
9	INTEGRAL-30ppi Cu-36 %	35 ^{o}C @ 500W^{EO}	0.070	860

EG/W : 50% Water-Ethylene Glycol mixture
EO : Engine Oil, Castrol 399.

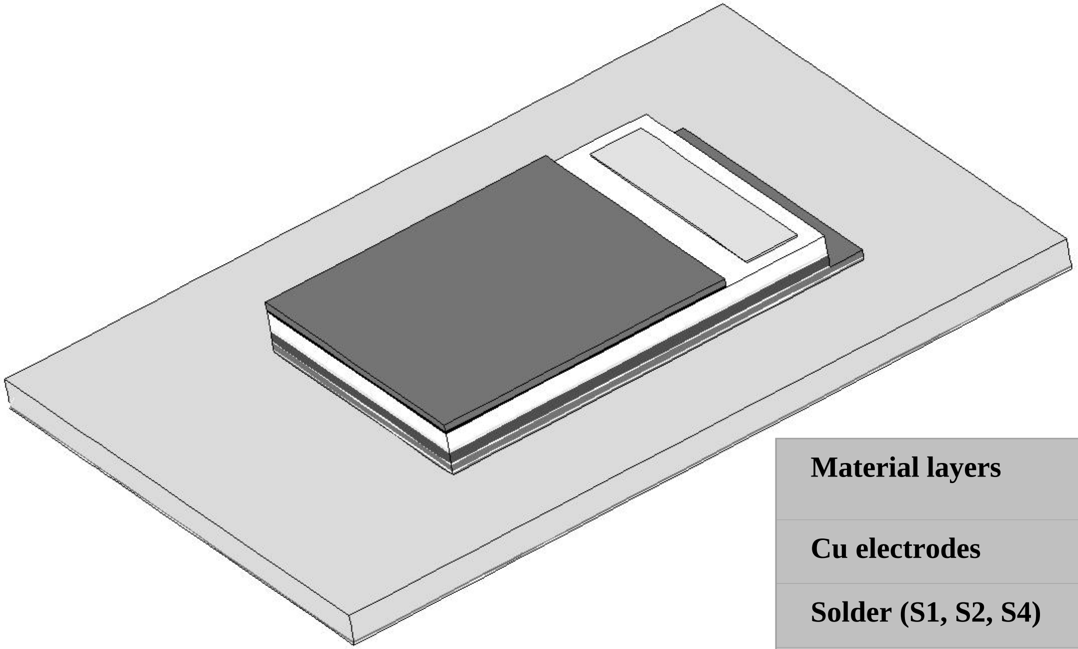
Results of the FEA and the second set of tests

An experimental study of RMF based HX



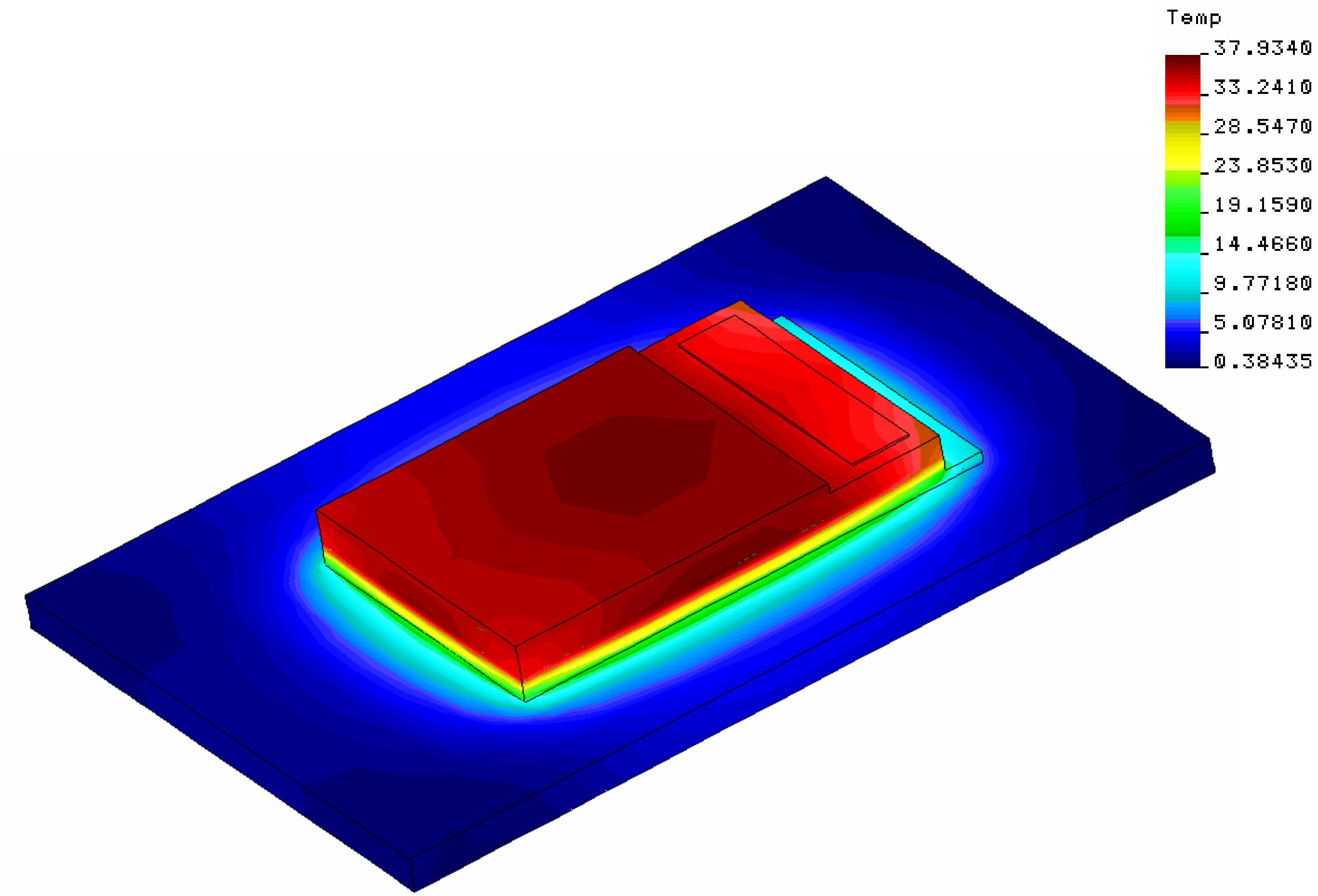
THERMAL RESISTOR ASSEMBLY PROCESS FLOW

An experimental study of RMF based HX



Material layers	t (inch)	K_{th} (W/cm-°C)
Cu electrodes	0.010	3.900
Solder (S1, S2, S4)	0.002	0.400
Solder (S3)	0.002	0.300
Lid metalization (Al)	0.002	1.800
Lid (Al_2O_3)	0.025	0.300
Silicon	0.016	0.800
Thermal base (AlN)	0.040	2.700

An experimental study of RMF based HX



System Level Requirements:

Water base coolant

Demineralized water
Closed loop system
Expansion-de-aeration chamber
Positive displacement pump (~ 100 psig)
(Commercial recirculating chillers- up to 25KW-$10K)

Air cooled electronics

Pressure drop - fans < 2" water
Low resistance manifold
Redundant air supply (fans)
Central compressed air supply ~ 80 psig
Noise levels < 50 dB

SUMMARY:

- Potential benefits of Metal Foam based Heat Exchangers include

  Lower Cost/Performance

  Increase in market share

  Upgrade electronics (performance)

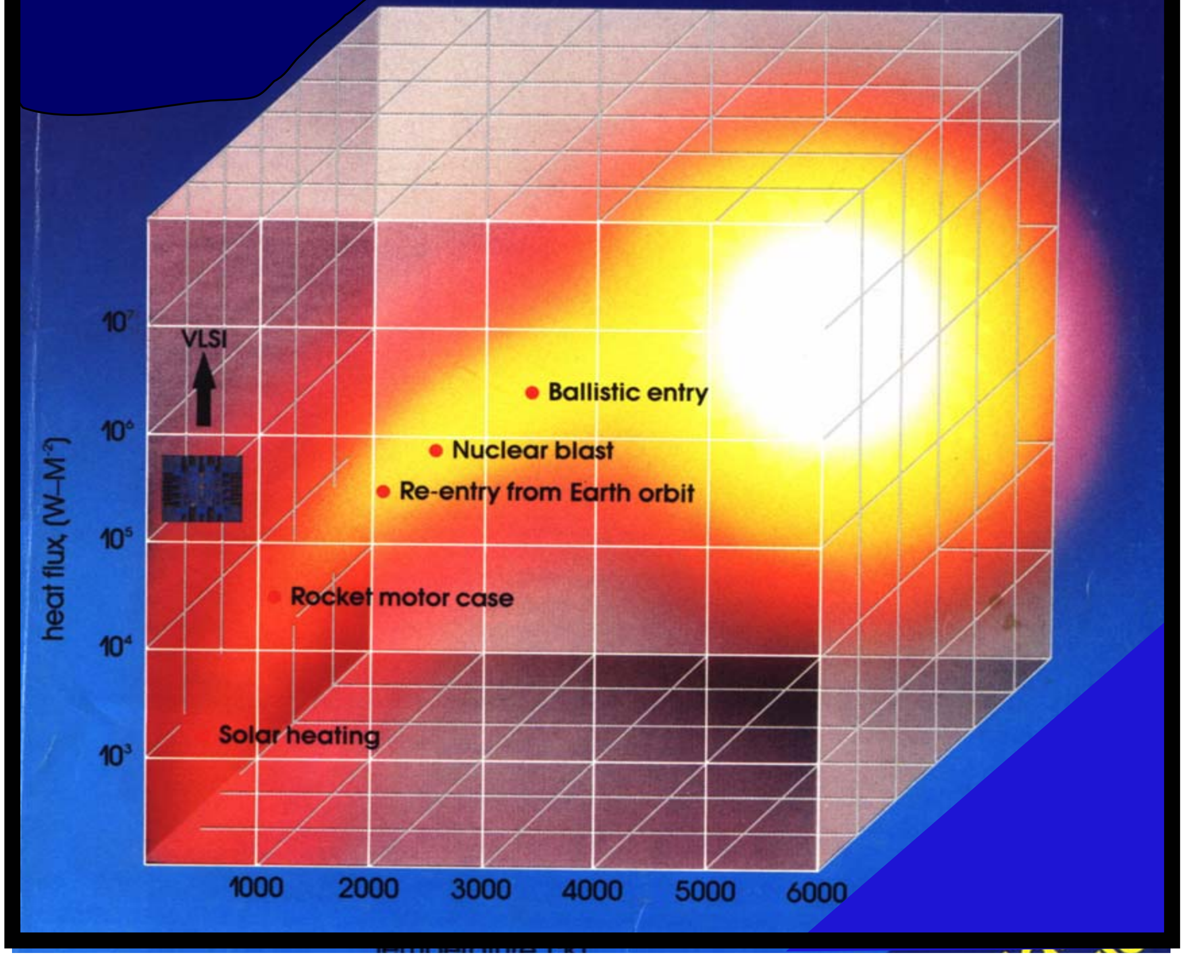
  Increased Reliability

- ERG offers modeling, design, test and fabrication capabilities for foam based Heat Exchangers

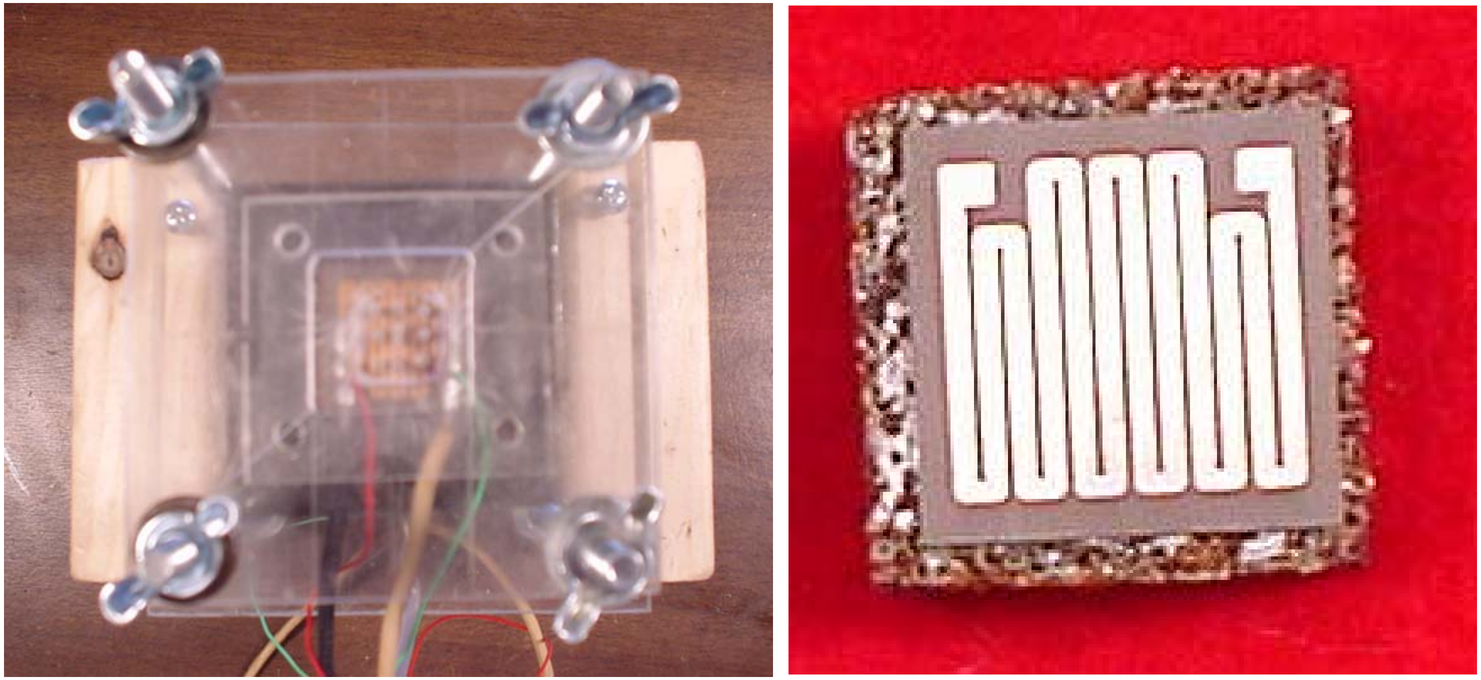
In house capabilities:

- Inert atmosphere high temperature soldering;
- Fluid flow, pressure, temperature testing
- Large scale computerized data acquisition and processing;
- Finite Element Analysis (Structural and Thermal), CAD
- Metallurgical sample preparation, optical microscopy
- Model shop to fabricate prototypes fixtures and articles (milling, drilling, cutting).

Challenges in Cooling Computers and Power Modules



Characterizing thermal performance :



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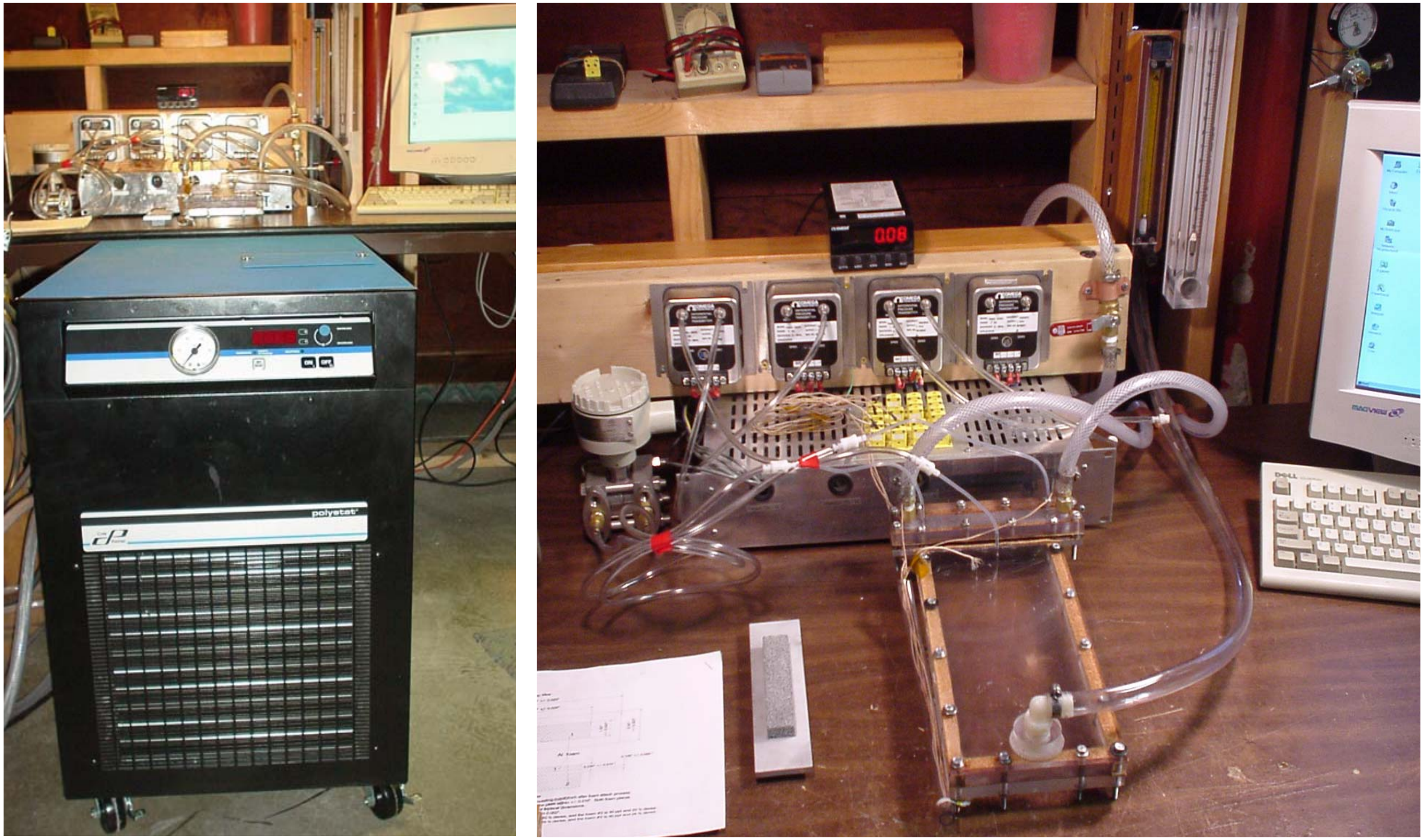
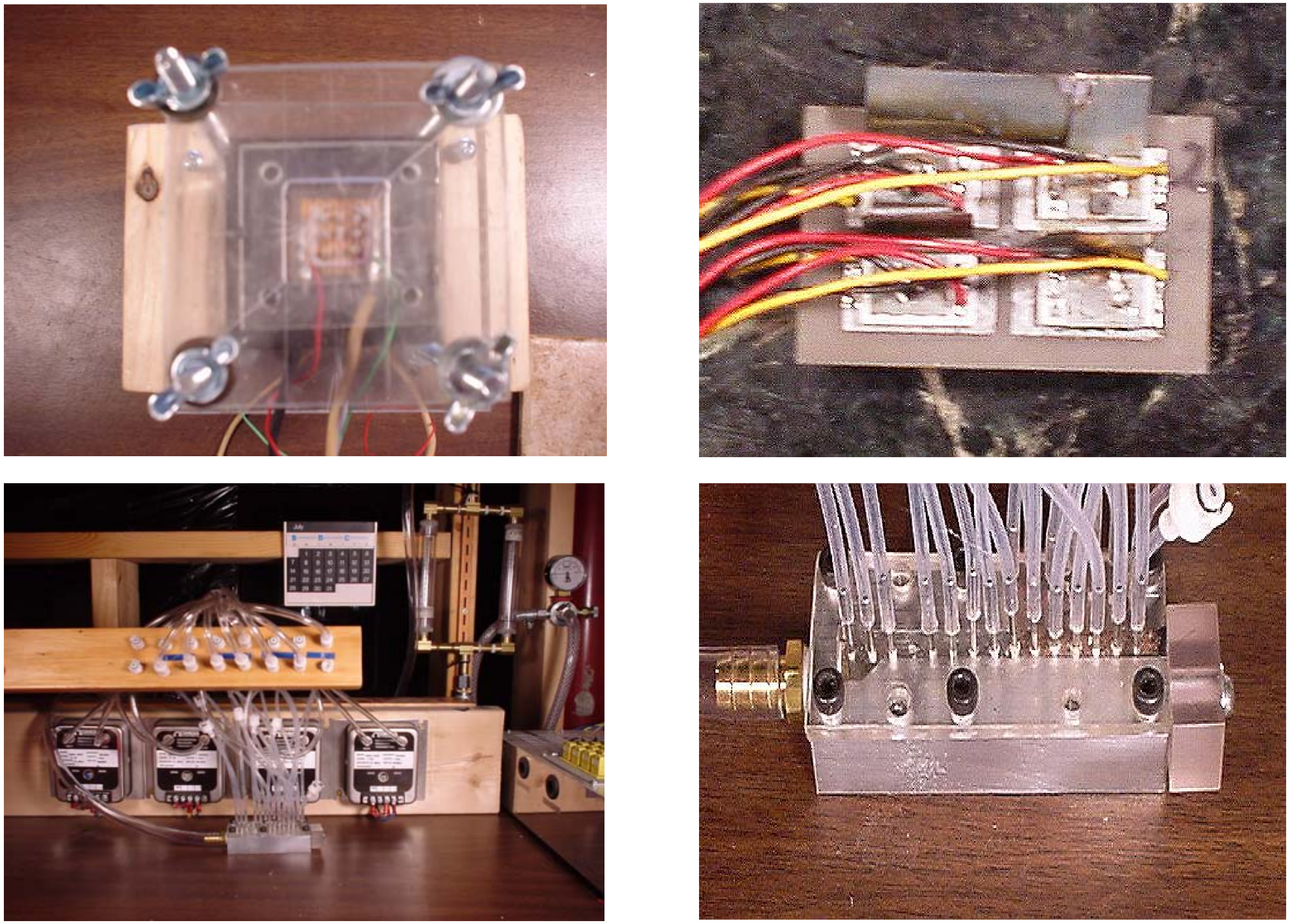


CROSS/COUNTER FLOW HX UNIT UNDER TEST

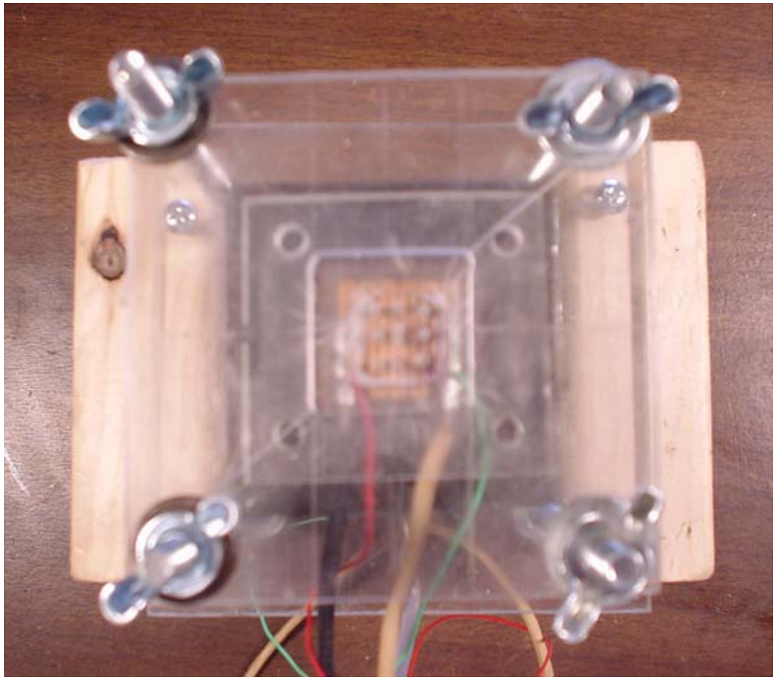
RMF Based 1KW Air to Liquid HX, 0.3 lb, 5.3 in^3 (0.003 ft^3)

COUNTER FLOW HX UNIT UNDER TEST



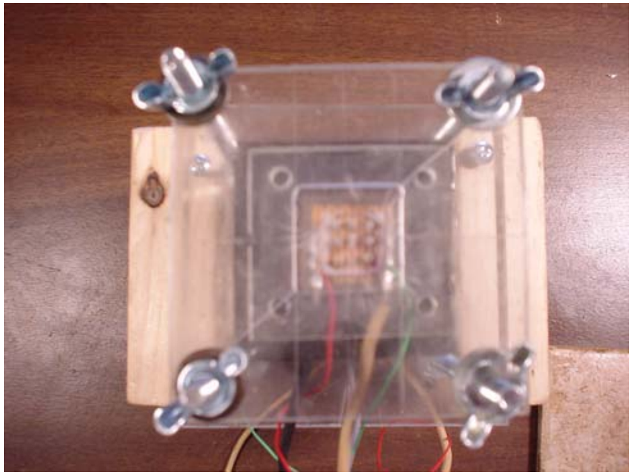
Thermal performance characterization- Power Electronics and Server applications

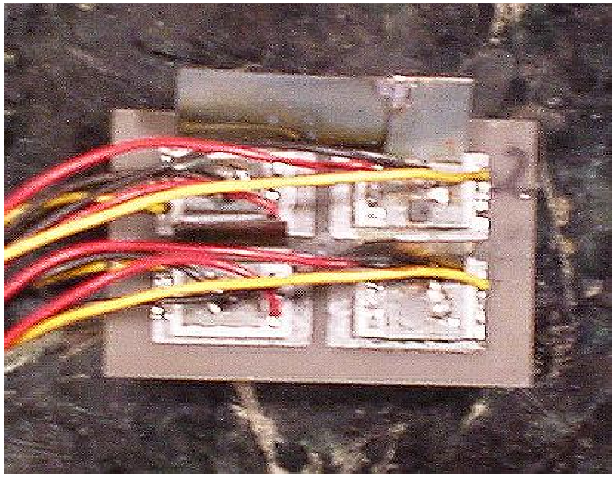
THERMAL APPLICATIONS OF OPEN CELL METAL FOAMS

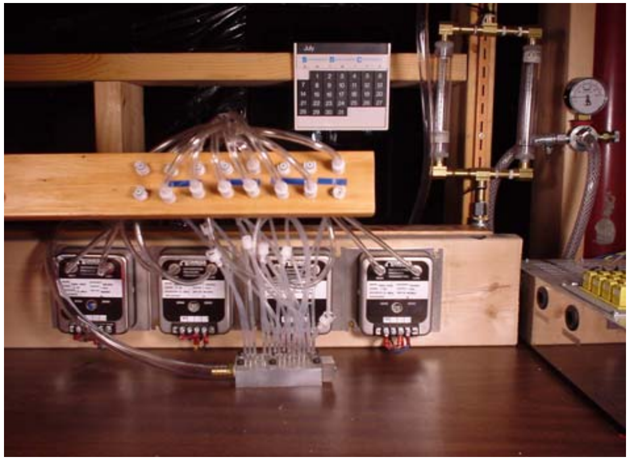


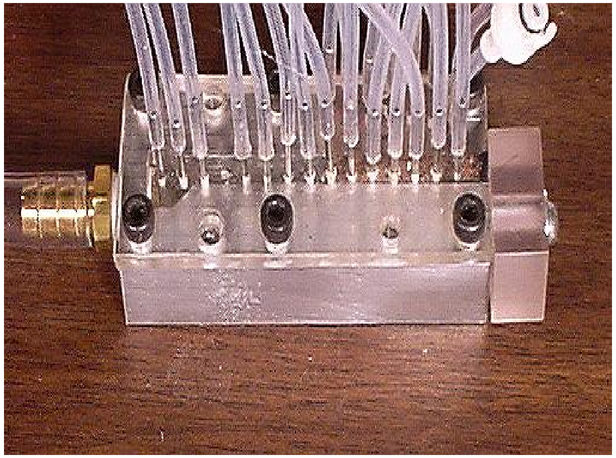
Cu foam HX for a 8 CPU server application under test
Metalized AlN resistor simulates Thermal load

Characterizing thermal performance :









THERMAL APPLICATIONS OF OPEN CELL METAL FOAMS

Final test Results	*8/5/2003*	*8/14/2003*	*8/15/2003*	*8/8/2003*	*08/10/03*	*8/14/2003*	*8/06/2003*	*08/10/03*
Sample #	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Temperature data								
T liquid in (°C)	65.5	68.3	68.3	65.7	68.3	68.2	66.0	66.8
T liquid out (°C)	49.5	52.1	51.1	49.5	52.2	51.3	50.2	50.7
T air in (°C)	25.4	27.2	24.7	23.0	26.6	24.6	27.2	25.1
ΔT_{liq} (°C)	16.0	16.2	17.2	16.2	16.1	16.9	15.8	16.1
$T_{avg}=(T_{in}+T_{out})/2$	57.5	60.2	59.7	57.6	60.3	59.8	58.1	58.8
Mass flow rates								
Liquid (kg/sec)	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
C_p liquid (J/kg-°C)	3269.4	3287.7	3284	3270	3288	3285	3274	3278
Air (kg/sec)	0.015	65.500	0.015	0.015	0.015	0.015	0.015	0.015
C_p air (J/kg-°C)	1050.0	1050.0	1050.0	1050.0	1050.0	1050.0	1050.0	1050.0
Volume flow rates								
Liquid (ml/min)	570.0	570.0	570.0	570.0	570.0	570.0	570.0	570.0
Liquid (gpm)	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Liquid side V_∞ (ft/sec)	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011
Air side V_∞ (ft/sec)	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.7
Pressure Drop								
Liquid flow (psi)	5.00	3.75	4.70	7.20	7.30	6.10	5.40	7.50
Air flow (psi)	0.24	0.21	0.24	0.23	0.21	0.22	0.22	0.22
Thermal performance								
Measured (W)	534	533	565	530	528	555	511	521
Calculated (W)	543	557	591	561	565	591	526	562
Performance (%)	***-1.8***	***-4.6***	***-4.6***	***-5.9***	***-7.1***	***-6.5***	***-2.9***	***-7.9***
Effective h - expected								
h_{eff} -air side (W/in^2-°C)	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3
h_{eff} -liquid side (W/in^2-°C)	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0
Thermal operating point								
Liquid (gpm)	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Liquid (kg/sec)	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
C_p liquid (J/kg-°C)	3269.4	3246.8	3246.8	3246.8	3246.8	3246.8	3246.8	3246.8
Air (scfm)	27.4	27.4	27.4	27.4	27.4	27.4	27.4	0.0
Air (kg/sec)	1050	1050	1050	1050	1050	1050	1050	1050
C_p air (J/kg-°C)	1050.0	65.5	65.5	65.5	65.5	65.5	65.5	65.5
T liquid in (°C)	65.5	42.8	42.8	42.8	42.8	42.8	42.8	42.8
T air in (°C)	11.7	11.7	11.7	11.7	11.7	11.7	11.7	11.7
Calculated (W)	***730.6***	***730.6***	***730.6***	***730.6***	***730.6***	***730.6***	***730.6***	***730.6***
Expected (W)	***717.7***	***697.1***	***696.9***	***687.5***	***678.7***	***683.4***	***709.4***	***673.0***

Thermal and structural coupling of metal foam HX

Minimize the CTE mismatch related thermal stresses

$$E_f \approx E_s \, (\rho_f / \rho_s)^2$$

Foam elastic compliance=160 x of solid at 8% density

I- Pure or composite metal heat spreaders - package lids

- Cu-CuMo-CuW spreader to Cu foam
  - CuSil brazing at 800 °C
  - Solder attach 90Pb/10Sn at 350 °C, 60Pb/40Sn at 220 °C

- Al or AlSiC spreader to Al foam
  - Dip brazing or vacuum brazing at 590 °C
  - Solder attach 90Pb/10Sn at 350 °C, 60Pb/40Sn at 220 °C

Thermal and structural coupling of metal foam HX

II- Thermally conductive, metalized ceramics (AlN - BeO - SiN) Cu
metalized lands -active brazed or DBC (.010"Cu, .040" AlN)
IVD Al metalized lands (~0.002" IVD Al)

CuSil brazing at 800 ^{o}C

Dip brazing or vacuum brazing at 590 ^{o}C
Solder attach 90Pb/10Sn at 350 ^{o}C,
60Pb/40Sn at 220 ^{o}C

III- Thermally conductive bare ceramic spreaders (AlN - BeO)

Active brazed Cu foam at ~ ^{o}800 C

Applications:

- Power modules
- Microprocessors
- MCM
- Smart skins
- Secondary HX.

Advantages:

- Delaying transition to water cooling
- Improved size, performance, system reliability
- Ease of upgrading electronics on existing platforms
- Reduced system cost/performance

Advantages of Metal Foam HX $$$

- Reduced spacing between processors.
- Shorter bus lengths,
- Simpler design
- Lower loses
- Increased timing and noise margins
- Increased processor speed (duty factor)
- Increased performance
- Lower Cost/Performance indice
- Lower chasis volume, weight and cost
- More added value and higher profit margin (DB Slots)
- Higher system reliability

Advantages of Metal Foam HX $$$

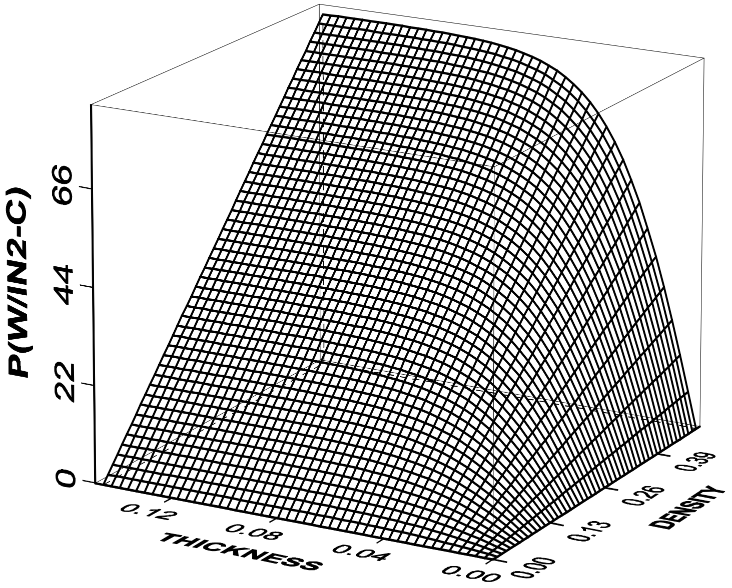
- Thermal performance of Power Modules ↑ by ≈ 2.5X
  Lower T_j ⇒Improves reliability,
  Device ratings increase , ⇒ less Silicon, lower cost
  Package power devices more closely ⇒
    Smaller module size/performance
    Lower weight/performance ,
    Lower material cost

- Ldi/dt is reduced ⇒(lower V_b rating)
  Higher device efficiency & lower device cost
  Faster switching ⇒ smaller filter C and L ($,Lb)

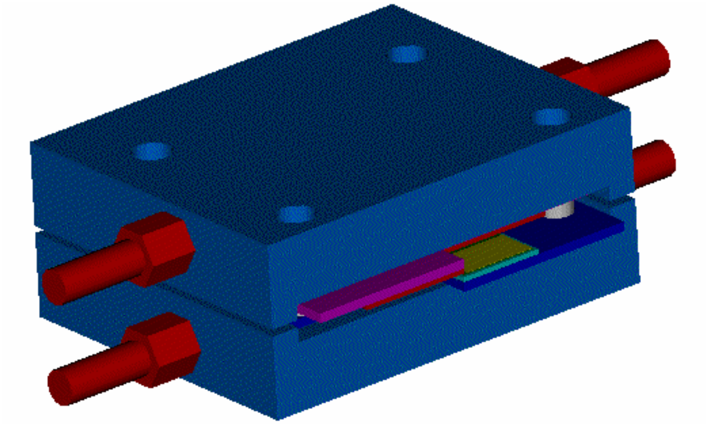
Characterizing thermal performance :

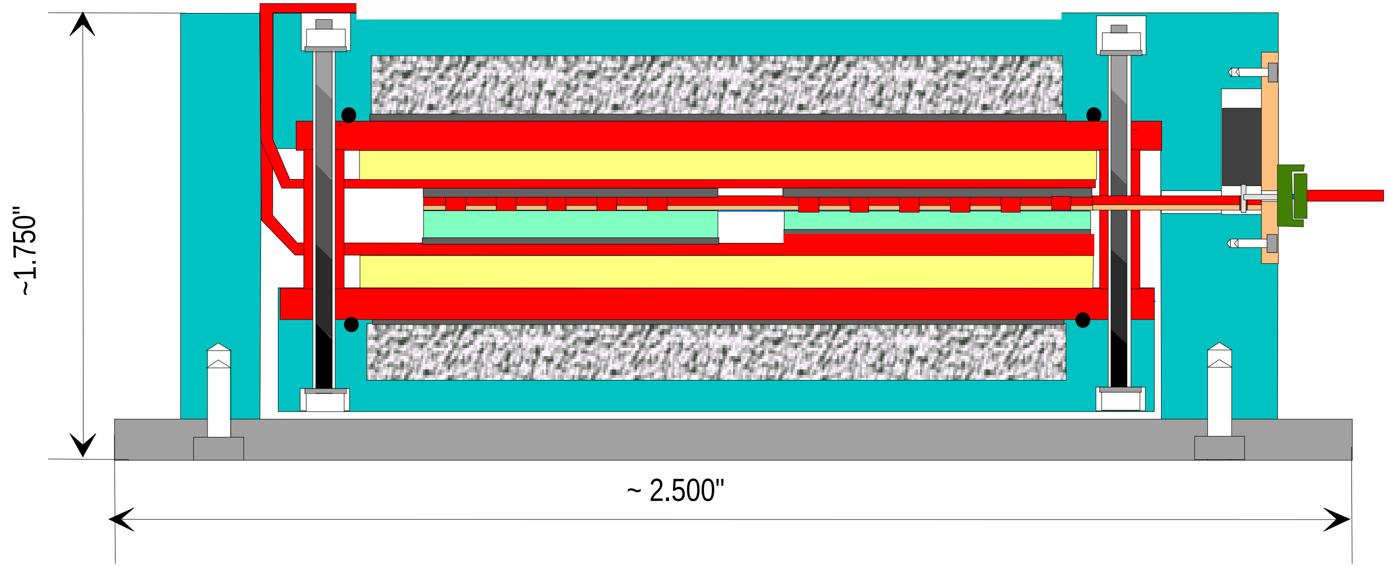
NORMALIZED HEAT FLUX FROM THERMAL BASE

40PPI Cu FOAM, COOLANT: WATER

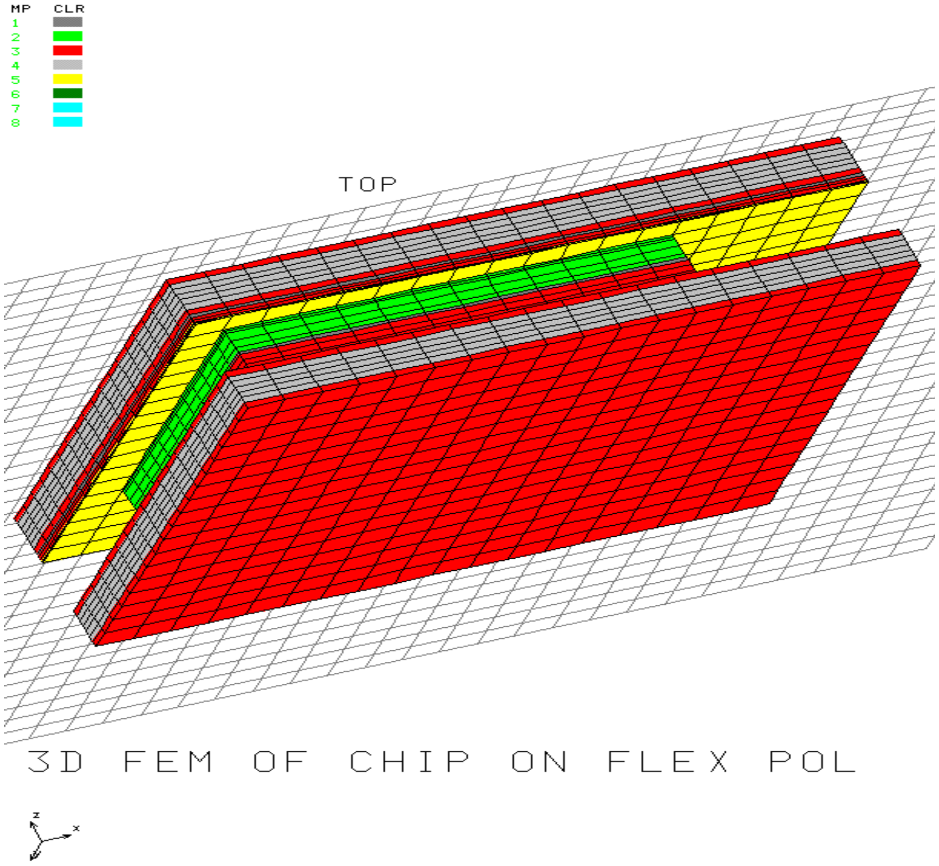


Characterizing thermal performance :



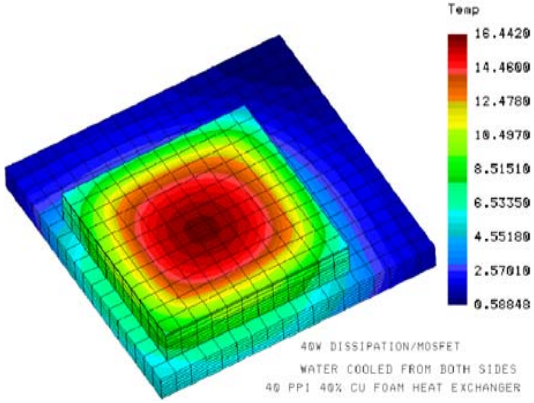


Characterizing thermal performance :

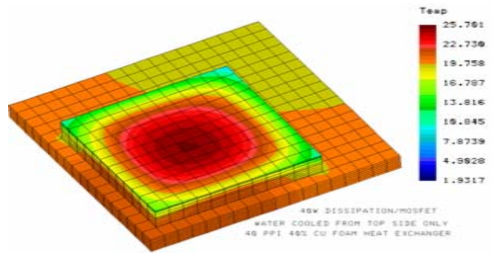


A cross section of the 3D FEM of POL (b) a 4 fold symmetry based FEM of the CPOL structure showing the Mosfet and PI-Via layer

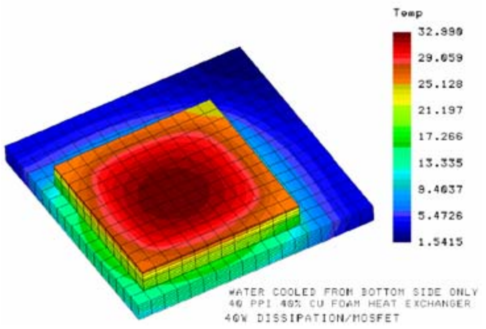
Characterizing thermal performance :



a)



b)

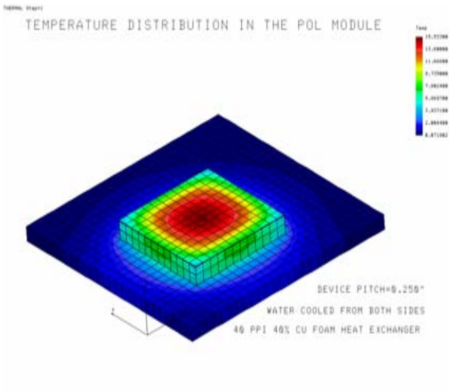


c)

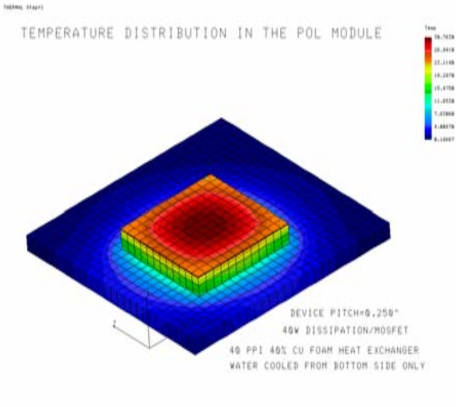
Temperature distribution in the POL module.
Device pitch is 0.050” inch.
Water cooled by a foam based integral heat exchanger
From both sides (a), from top side only(b)
and from bottom side only (c)

Characterizing thermal performance :

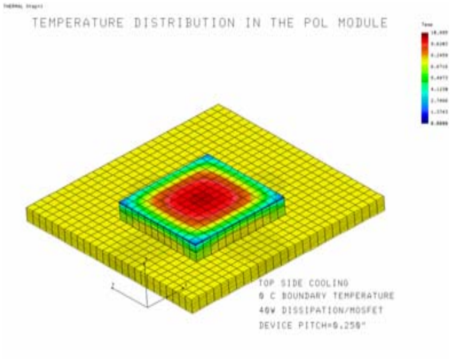
(a)



(c)



(b)



Temperature distribution in the POL module.
Device pitch is 0.250” inch.
Water cooled by a foam based integral heat exchanger
From both sides (a), from top side only(b)
and from bottom side only (c)

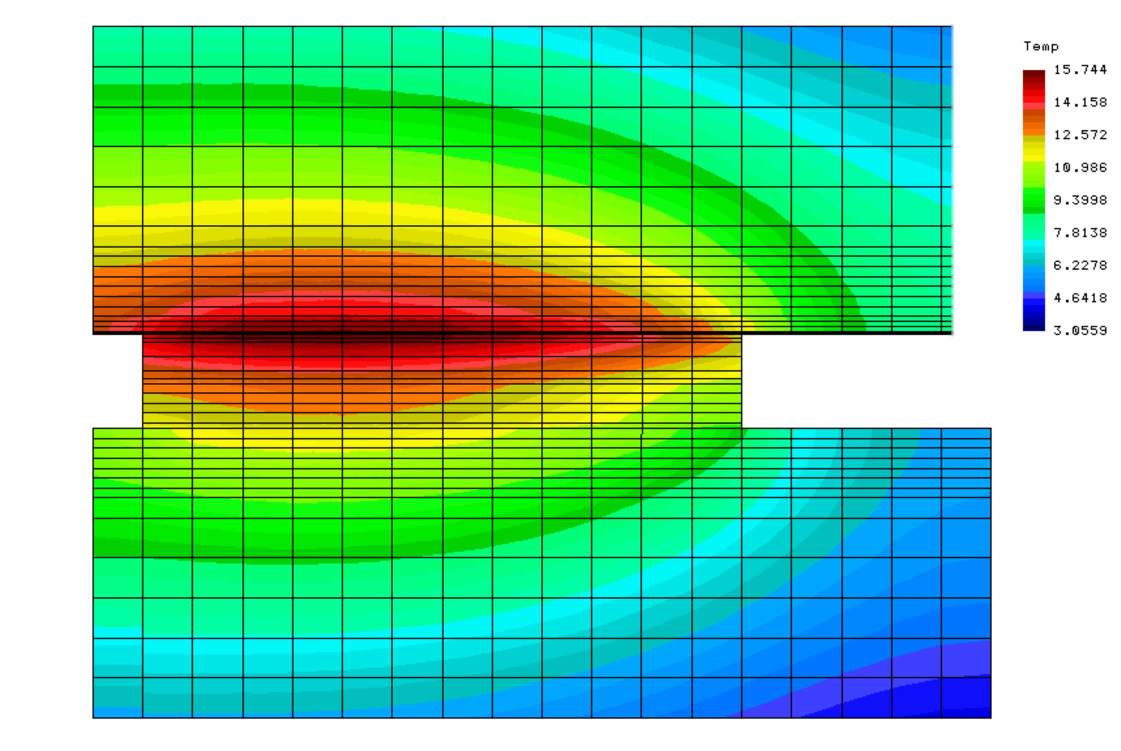
Characterizing thermal performance :

Summary of 3D thermal FEA results

Average coolant temperature R_{ja} ($^oC/W$)		
	Pitch=0.050”	Pitch=0.250”
Double	R_{ja}= 0.40	R_{ja}= 0.38
Top side	R_{ja}= 0.62	R_{ja}= 0.58
Bottom side	R_{ja}= 0.80	R_{ja}= 0.78

Characterizing thermal performance :

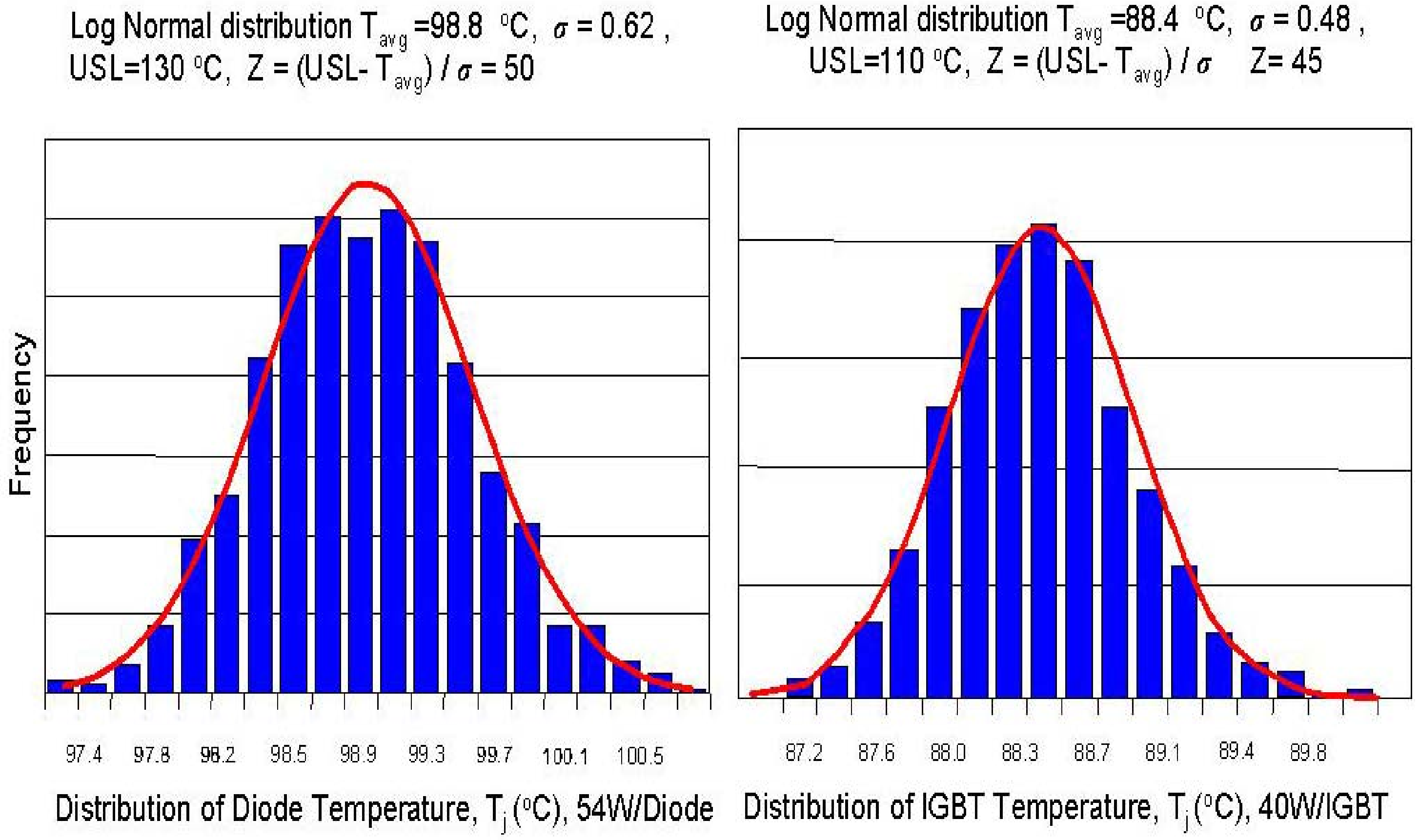
Temperature distribution in the double sided cooled ICC Module



Dissipation:58 W, Diode dimension 0.300”x0.300”. Heat Exchanger: Integral reticulated, 40 ppi and 36% dense Cu foam. Coolant:PAO at 75 ^{0}C. R_{th}= 0.27 ^{0}C/W

Characterizing thermal performance :

Estimated variation in the thermal resistance of power modules.



Log Normal distribution T_{avg} =98.8 °C, σ = 0.62 , USL=130 °C, $Z = (USL - T_{avg}) / \sigma = 50$

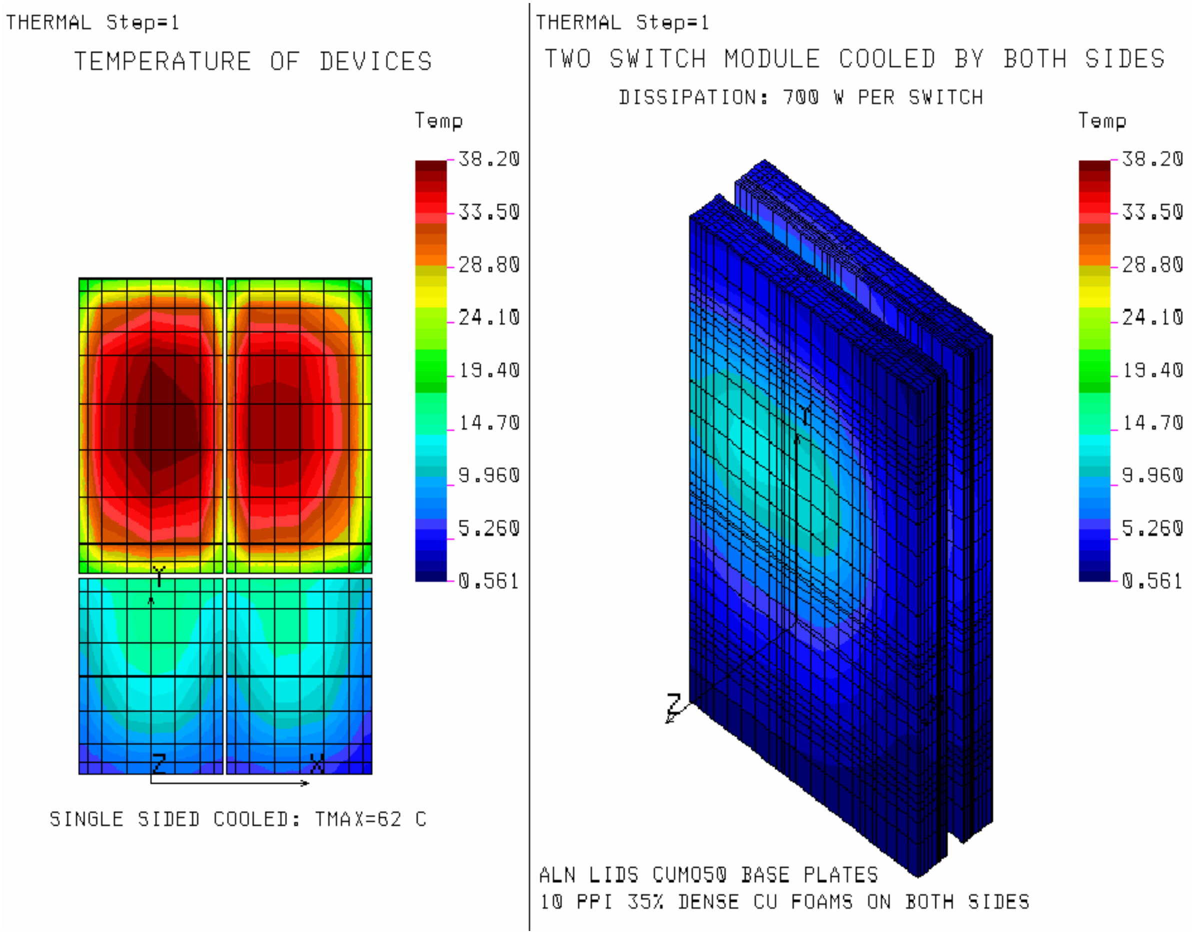
Log Normal distribution T_{avg} =88.4 °C, σ = 0.48 , USL=110 °C, $Z = (USL - T_{avg}) / \sigma$ Z= 45

Distribution of Diode Temperature, T_j (°C), 54W/Diode

Distribution of IGBT Temperature, T_j (°C), 40W/IGBT

Characterizing thermal performance :

DOUBLE SIDED COOLED POWER MODULE



Characterizing thermal performance :

Results of the experiments and 3D FEAs of various power module configurations

		AREA (In^2)	HEAT SPREADER	HEAT SINK	ΔT_{max} (°C)	R ja (°C/W)	P max. $\Delta T=60\ ^oC$
1	**C**	10.2	AlSiC - 0.100"	EXTERNAL	178	0.127	470
2	**C**	10.2	AlSiC - 0.200"	EXTERNAL	163	0.116	515
3	**C**	10.2	AlSiC - 0.200"	EXTERNAL	150^s	0.107	560
4	**C**	10.2	CuMo - 0.200"	EXTERNAL	147	0.105	571
5	**C**	10.2	CuMo - 0.200"	EXTERNAL	129^s	0.092	651
6	**C**	10.2	CuMo - 0.100"	EXTERNAL	164	0.117	512
7	**C**	10.2	CuMo - 0.100"	BAFFLED CAVITY	121	0.086	694
8	**C**	10.2	CuMo - 0.100"	INTEGRAL	70	0.050	1,200
9	**C**	10.2	Cu - 0.150"	EXTERNAL	137	0.980	613
10	**C**	3.2	NONE	EXTERNAL	264	0.189	318
11	**C**	3.2	NONE	BAFFLED CAVITY	162	0.116	519
12	**C**	3.2	NONE	INTEGRAL	60	0.043	1,400
13	**E**	3.2	NONE	BAFFLED CAVITY	75 °C @ 800W	0.095	640
14	**E**	3.2	NONE	EXTERNAL	95 °C @ 800W	0.120	505
15	**E**	3.2	NONE	INTEGRAL-40ppiAl-10%	86 °C @ 800W	0.108	560
16	**E**	3.2	NONE	INTEGRAL-40ppiAl-20%	69 °C @ 850W	0.080	740
17	**E**	3.2	NONE	INTEGRAL-40ppiAl-36%	47 °C @ 850W	0.059	1020
18	**E**	3.2	NONE	INTEGRAL-40ppiCu-40%	38 °C @ 800W	0.047	1265
19	**E**	3.2	NONE	INTEGRAL-40ppiCu-40%	63 °C @ $1000W^{E/G}$	0.063	950
20	**E**	3.2	NONE	INTEGRAL-40ppiCu-40%	35 °C @ $500W^{EO}$	0.070	860

E :Experimental, C:Calculated,
E/G: 50% Water-Ethylene Glycol mixture , EO : Motor Oil, Castrol 399

Characteristics of the brushless DC FlatPak Impeller/Blower RG160 by EBM.

Part #	CFM @ 0”	DC V	Watt	dBA	Max T (^{o}C)	Weight (Oz)	Type	Wiring
RG160	123	24/12	20	66	70	50	Ball bearing	Leads