Power Electronics Cooling for Automotive Applications

Progress Report

Desikan Bharathan

Outline

- Objectives
- Methods
  - Indirect and direct jet cooling
  - Direct spray cooling
  - Spreaders
- Development of models & example results
- Next steps
- Conclusions

The Need

Cooling needs for automotive applications consist of:

a) predominantly engine cooling

b) cabin a/c systems

c) other auxiliary systems

With the advent of electric hybrids, we add:

d) power electronics

The Sink

Ultimate sink for the heat is the ambient air!

Heat is rejected via sensible heat.

(is latent heat an option? – perhaps not)

Performance is tied to ambient temperature.

System must accommodate hottest climates.

The Load

Typical load consists of dominantly:

Engine (120kW) ➔ 120 kW (cooling)

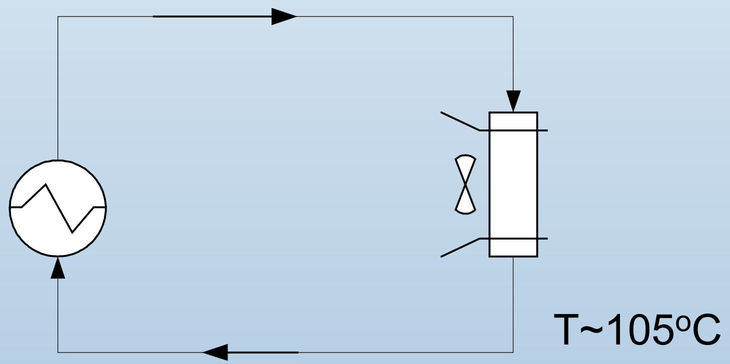
Other Minor Loads

A/C (3kW; COP 1.5) ➔ ~5 kW

Power Electronics ➔ ~2-5 kW

The Cooling Circuit

Most vehicles are “water-cooled.” A coolant (EG 50% in water) carries heat from the engine block to a radiator.



Cooling Power Electronics - Characteristics

- Cooling needs are small
- Heat is generated in localized
- Heat generation is highly transient
- Spots with low thermal capacities show large local temperature swings

Power Electronics Cooling

- Independent loop:
  - May be cooled using an independent loop (because of small loads), however, this approach requires more components
- Using engine coolant:
  - This approach forces the incoming coolant temperature to 105^{o}C, thus making the cooling system design difficult

Objective

Explore the use of jet and spray cooling techniques through simulation and experiments toward achieving the programmatic goals

Program Goals

- To achieve a heat flux of 250 W/cm^2, at a coolant temperature of 105^oC
- To maintain chip source temperature of less than 125^oC
- To meet other requirements on reliability, safety and cost

These requirements translate to an overall heat-transfer coefficient of 125,000 W/m^2K.

FY04 completed activities

- Literature review performed
- Modeling capabilities evaluated
- Numerical models developed for jet and sprays
- Validated some models under specific conditions
- Commercial CFD code modified for specific needs

Technical Approaches

- Direct Cooling
  - Cooling fluid is directly in contact with the heat source
  - Fluid must be electrically non-conducting, e.g.. Air, CO_2, He, or Fluorinert (FC-72)
- Indirect Cooling
  - A cooling plate acts as a barrier between the heat source and the coolant, coolant can be glycol mixture or any other fluid

Direct Cooling

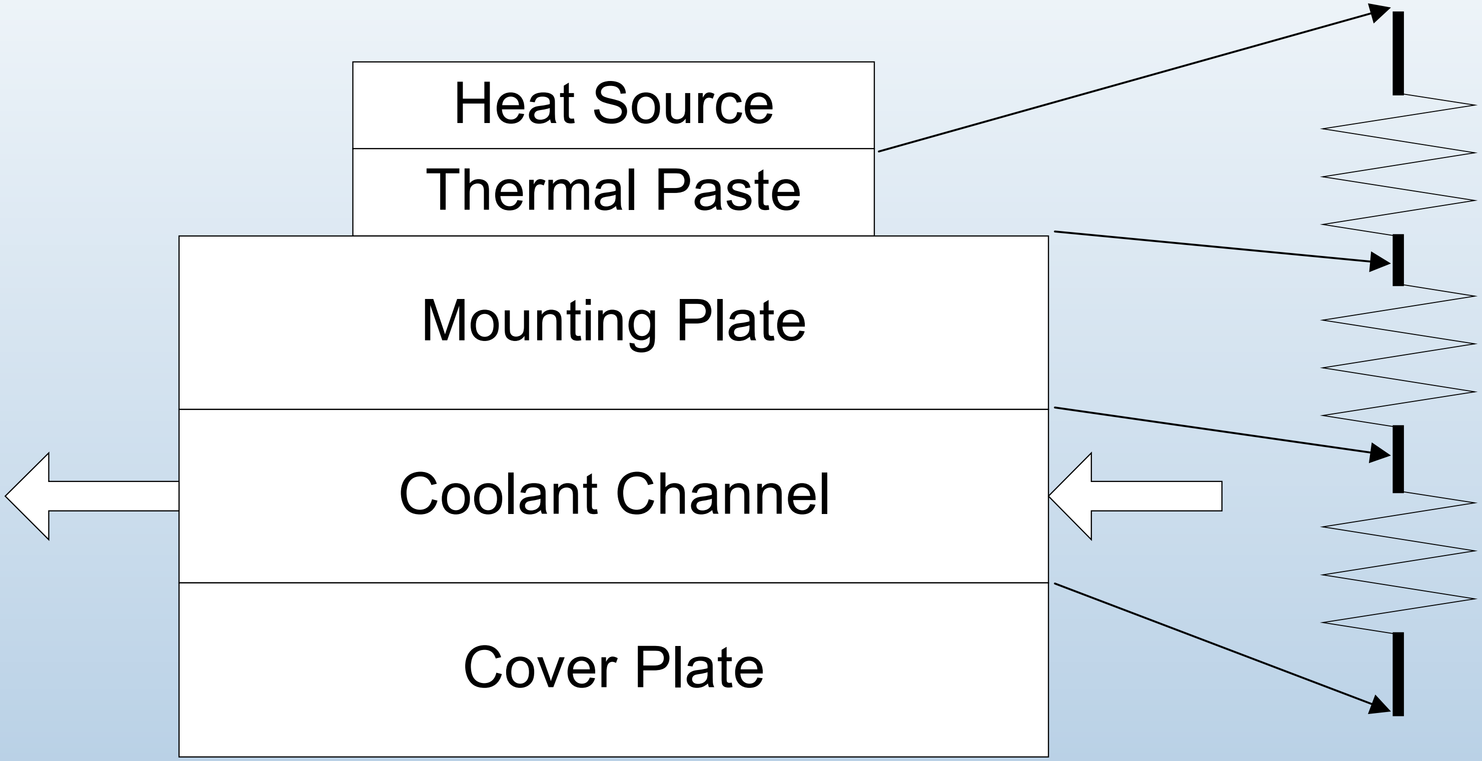
Examples:

Fluid	Potential HTC (W/m^2K)
Air (Nat. Conv)	20 - 40
Air (Forced)	40 - 80
Refrigerated Compressed Air	80 -120
Fluorinert (FC-72)*	1000 - 2000

---

*Its low thermal conductivity and heat of vaporization limits HTC;

Indirect Cooling



In this approach, we introduce more resistances in series.

Indirect Cooling

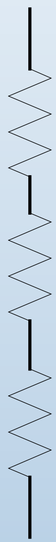
Potential Performance (SOA)

Component	Conductivity (W/mK)	Thickness (μm)	HTC (W/m^2K)
Thermal Interface Material	2	20	100,000
Plate (Al)*	165	6350	25,000
Coolant (EG mixture)	0.342	1 mm jet; sprays	100,000

*Spreading will increase its effective conductivity

Indirect Cooling

SOA



R_{TIM} = 0.1

R_{Plate} = 0.4

$R_{Coolant}$ = 0.1

We are at least a factor of six below the programmatic goal;

Bottleneck being the mounting plate (the thickness is perhaps governed by structural reasons)

Overall U = 16,700 W/m^{2}K

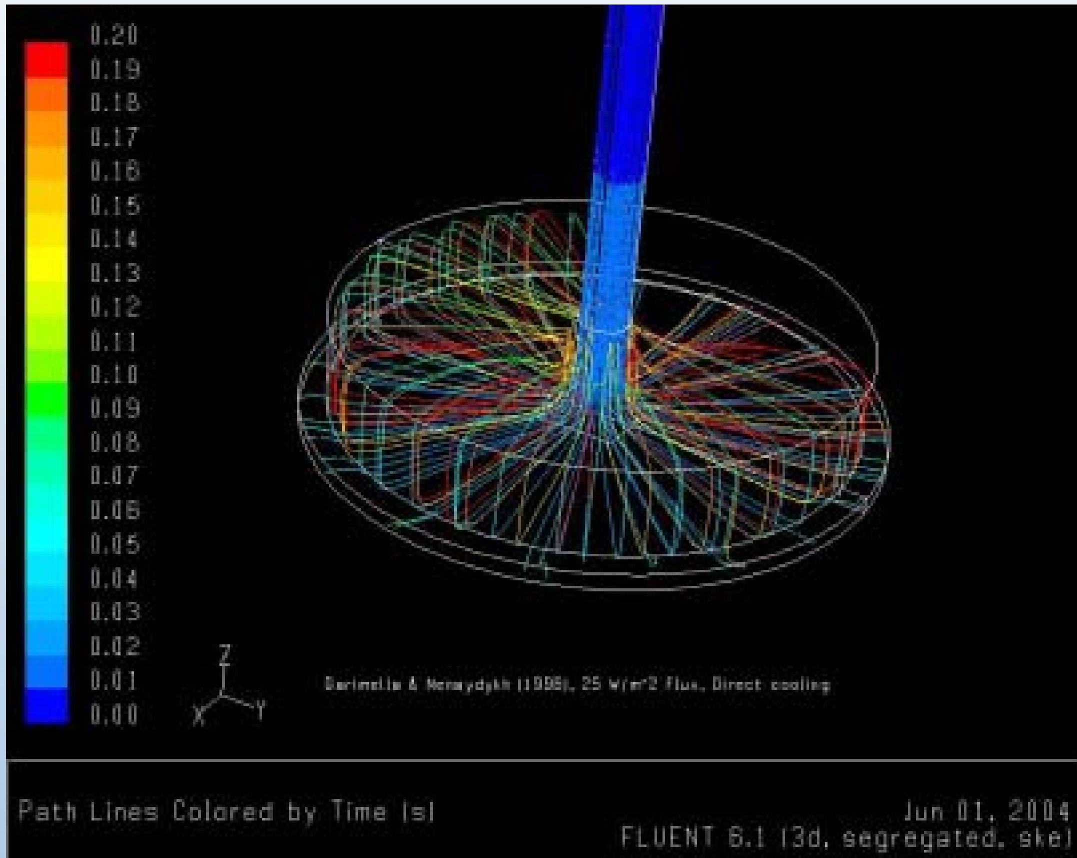
NREL Research Efforts

- Direct cooling using FC-72
  - Jet impingement
  - Spray cooling
- Indirect cooling (with antifreeze mix)
  - Jet impingement
    - Spent liquid removal

Background - Jets

- Substantial number of works are reported on jet impingement, micro channel, and heat transfer
- Key correlations are provided by Garimella (1996)
- Optimization methods are summarized by Lin and Vafai (1999)
- Key findings are that :
  - submerged jets perform better than free-surface jets
  - effective removal of spent liquid is essential

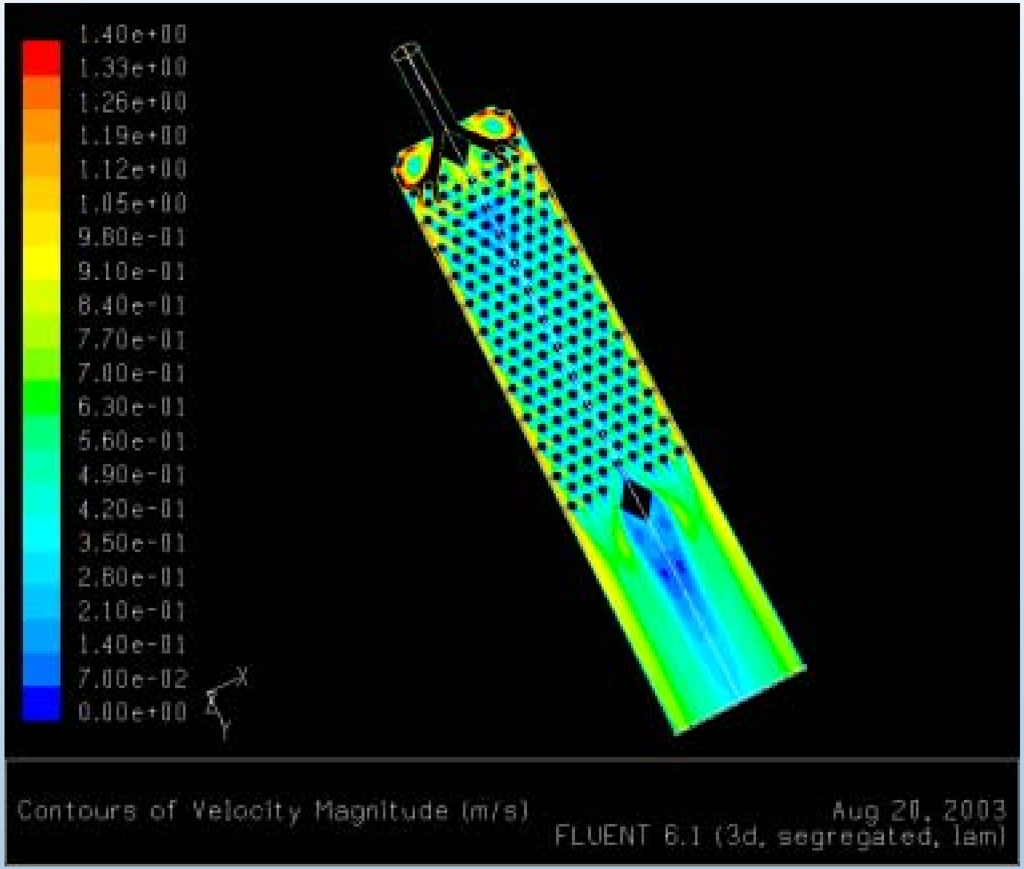
Direct jet impingement



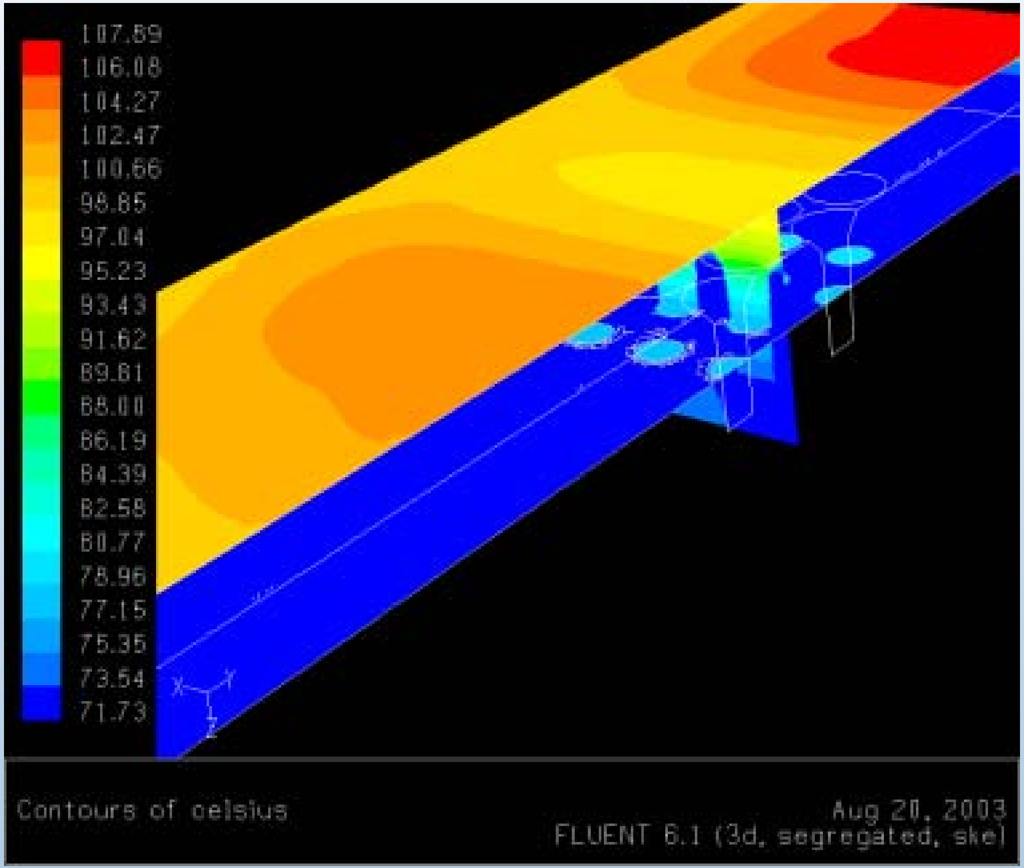
- Minimum residence time is ~0.01s;
- Maximum is well over 20 times the minimum, showing large recirculation zones
- Spent liquid removal is key to maintain high heat transfer coefficients

*FC-72 jet, Garimella, et. al, 1996

Indirect cooling
Semikron's baseline cold plate



Cold plate temperatures

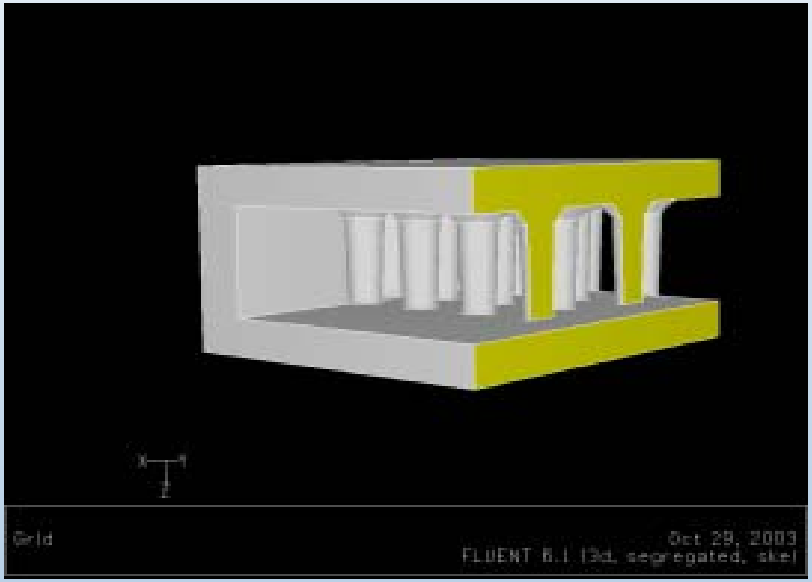


$q' = 40\ W/cm^2$;

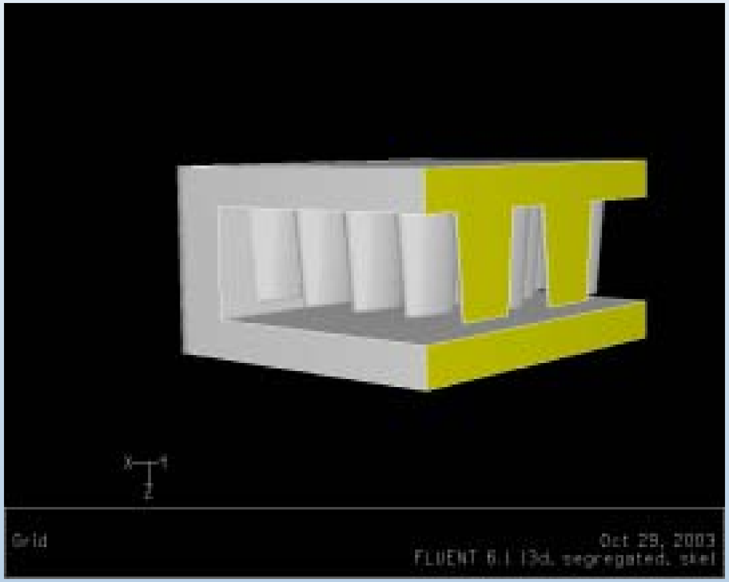
$T_{coolant} = 70\ ^oC$;

Improved pin-fin design – rev. 1

Baseline

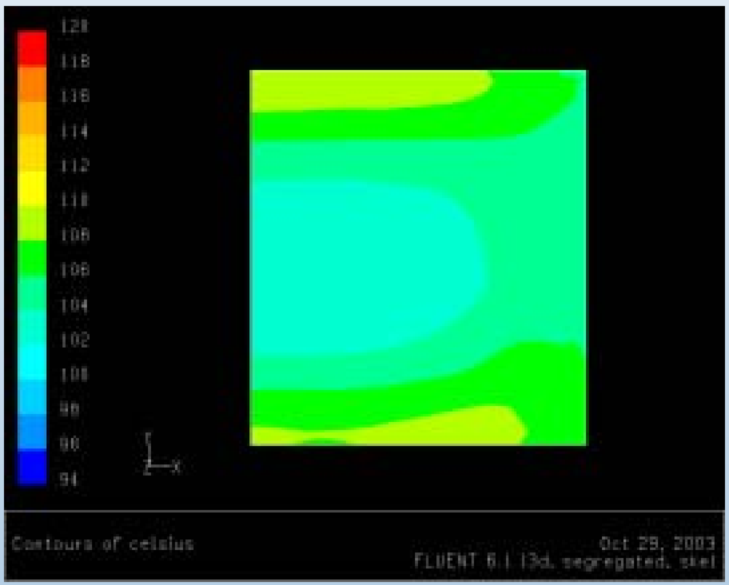


Recommended

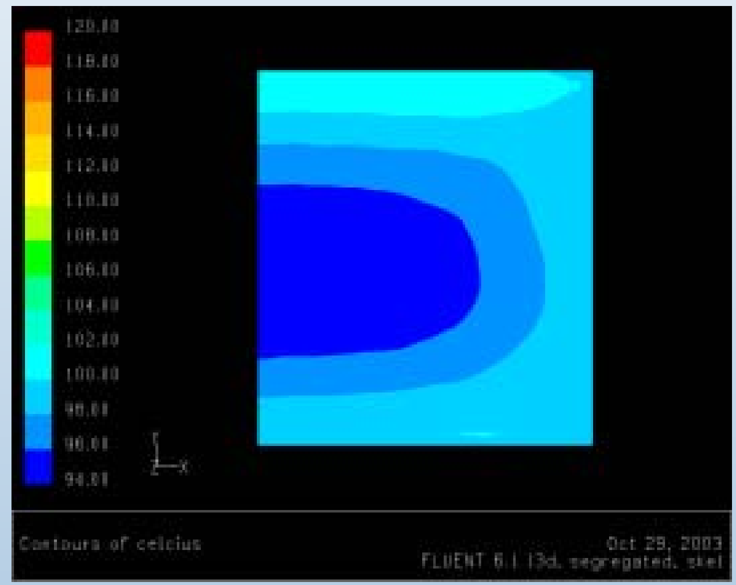


Cold plate temperatures

Baseline

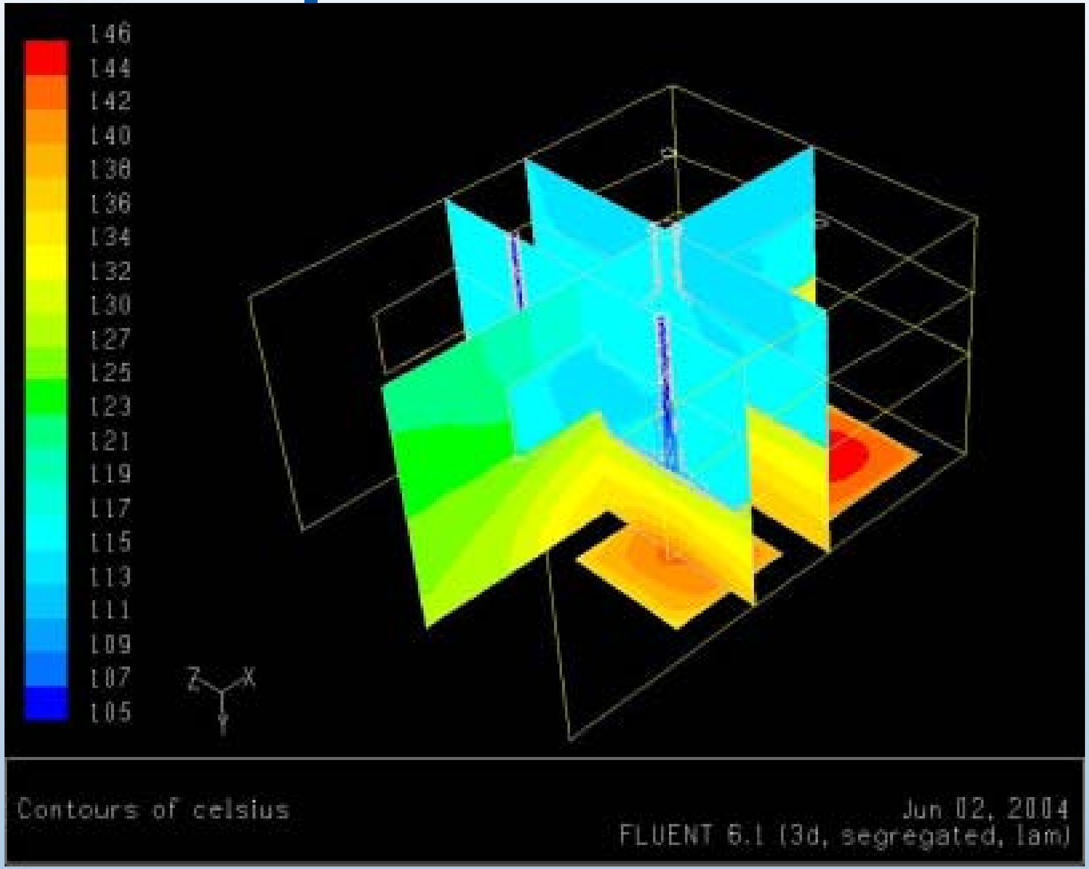


Recommended



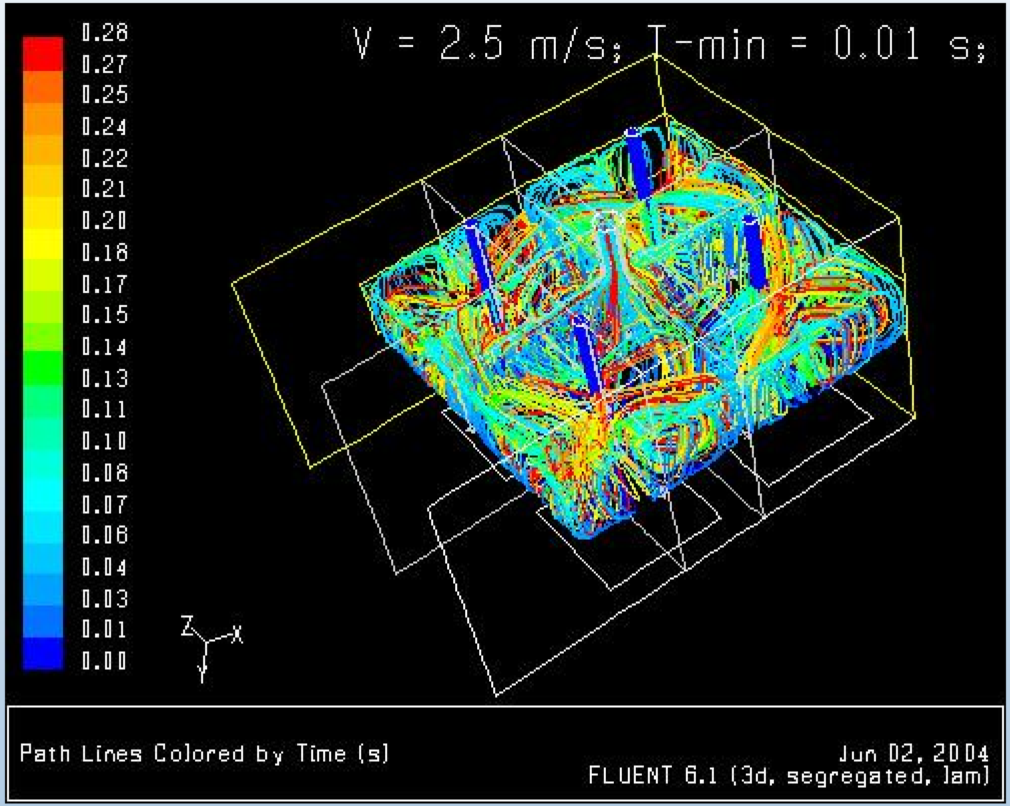
An 8°C improvement

Indirect jet cooling; temperatures – rev 2

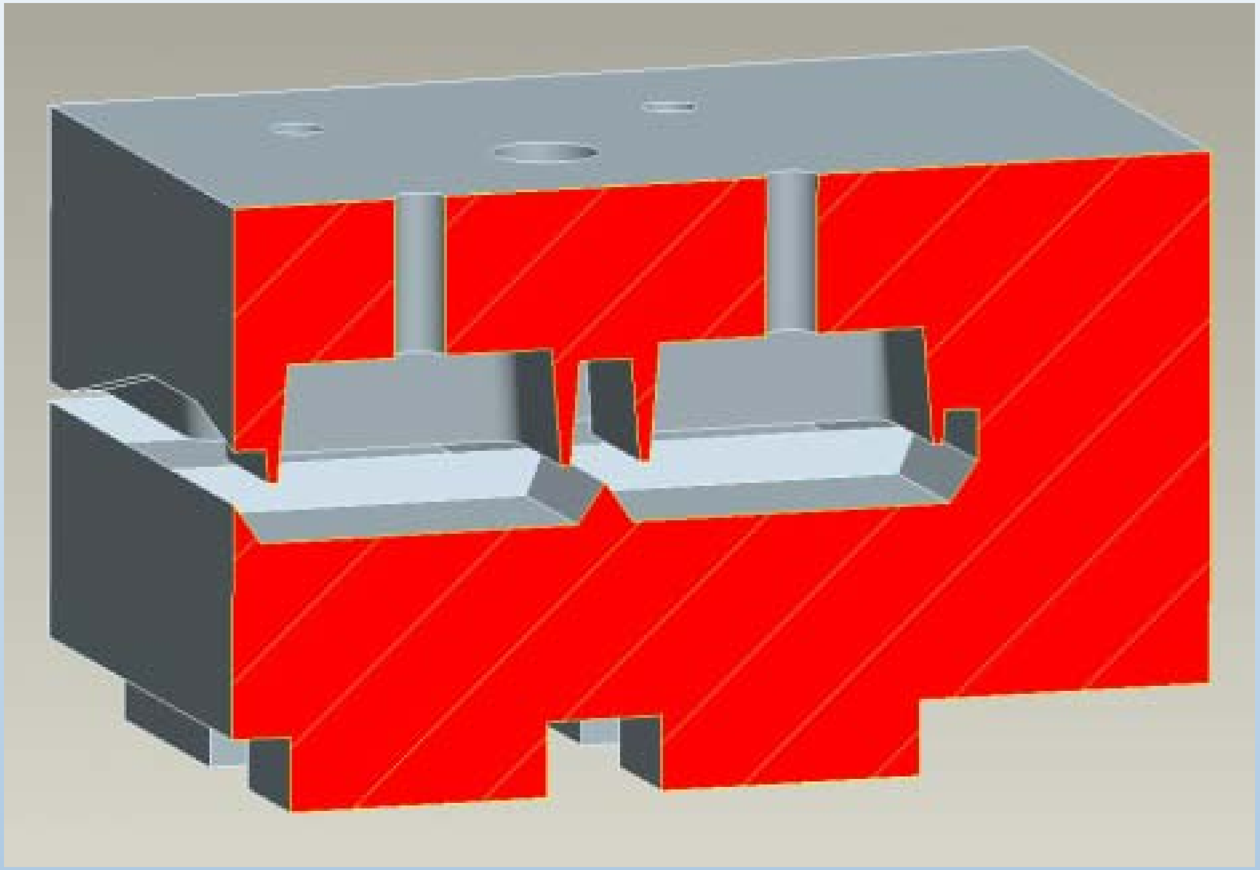


Each jet is directed at each hot spot; Spent liquid is removed via a central outlet.

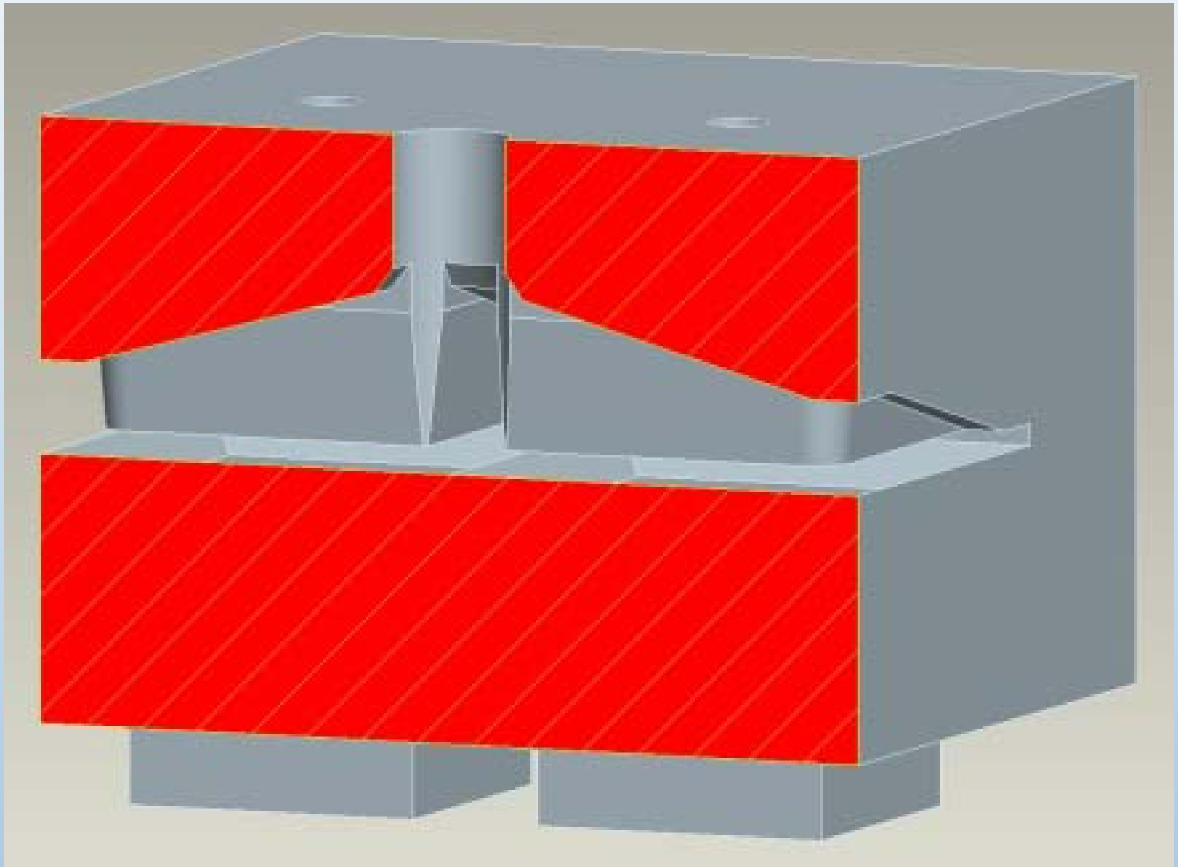
Spent liquid recirculates!



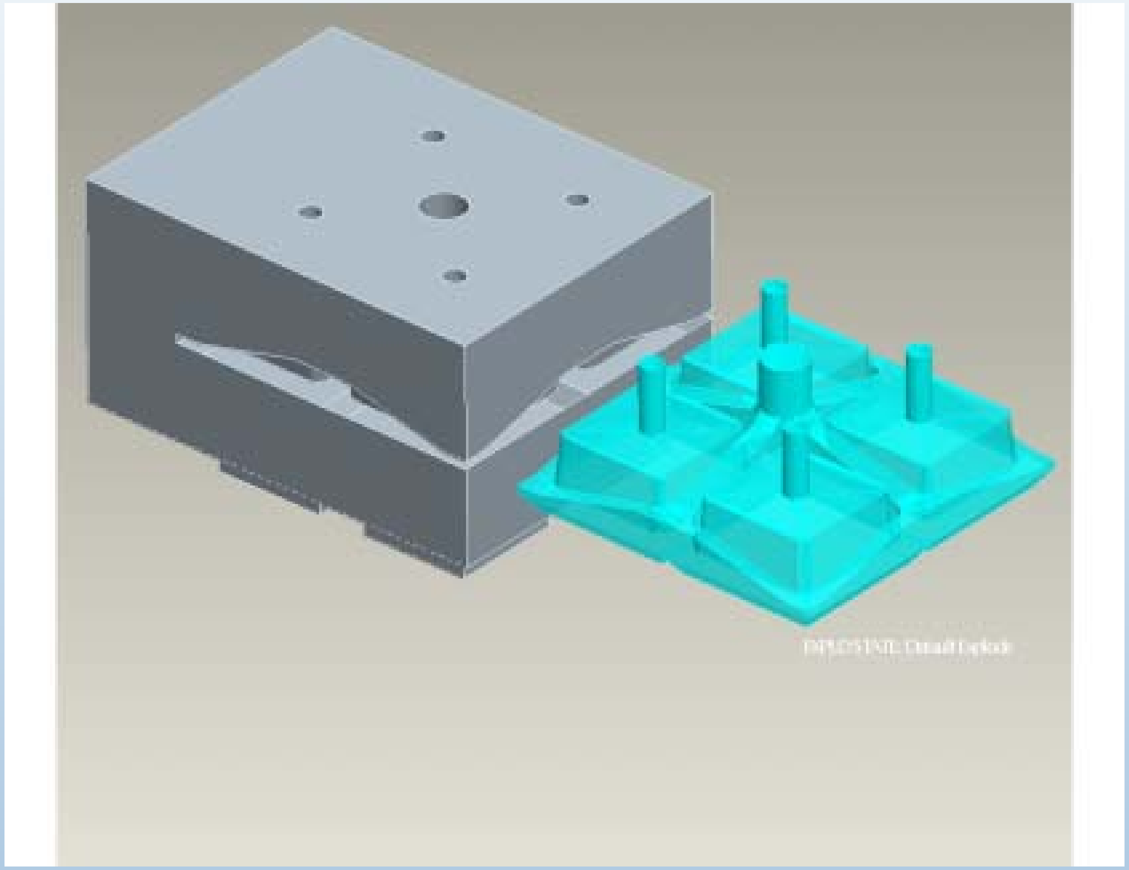
Indirect jet cooling – rev 3



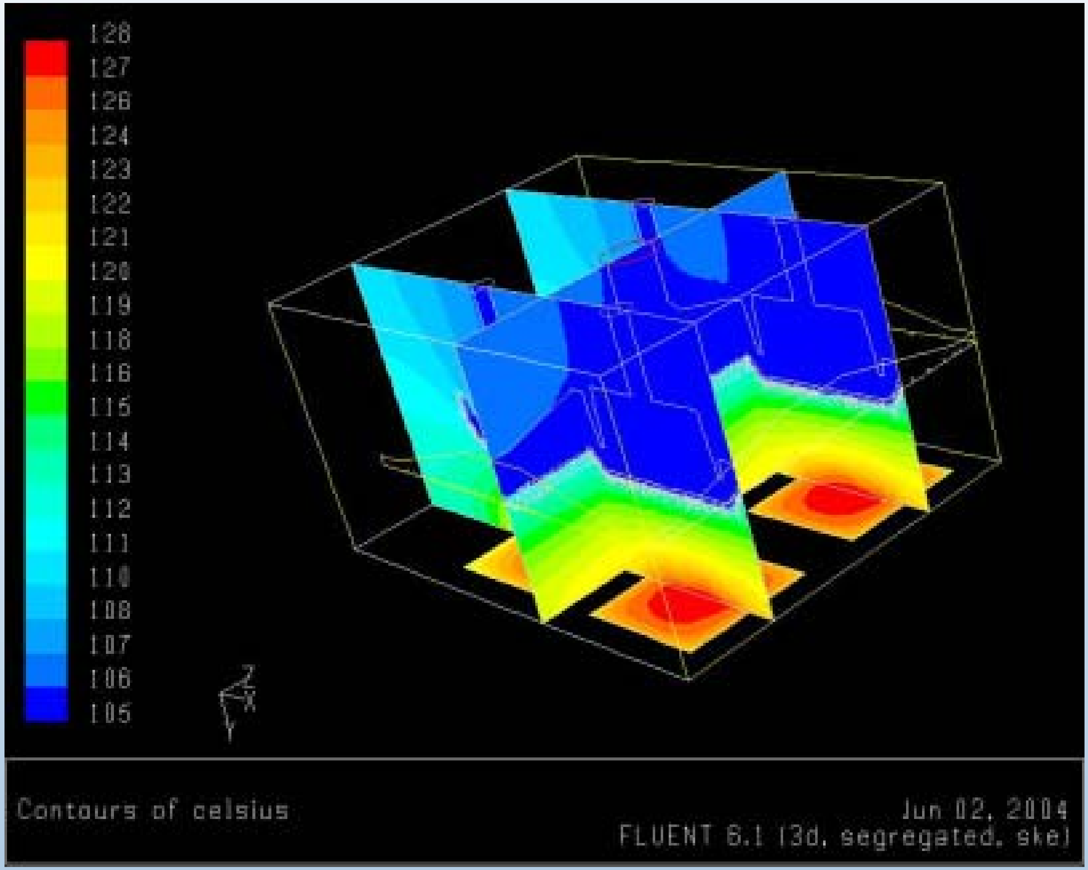
Section via plane through outlet



Exploded view of the cavities



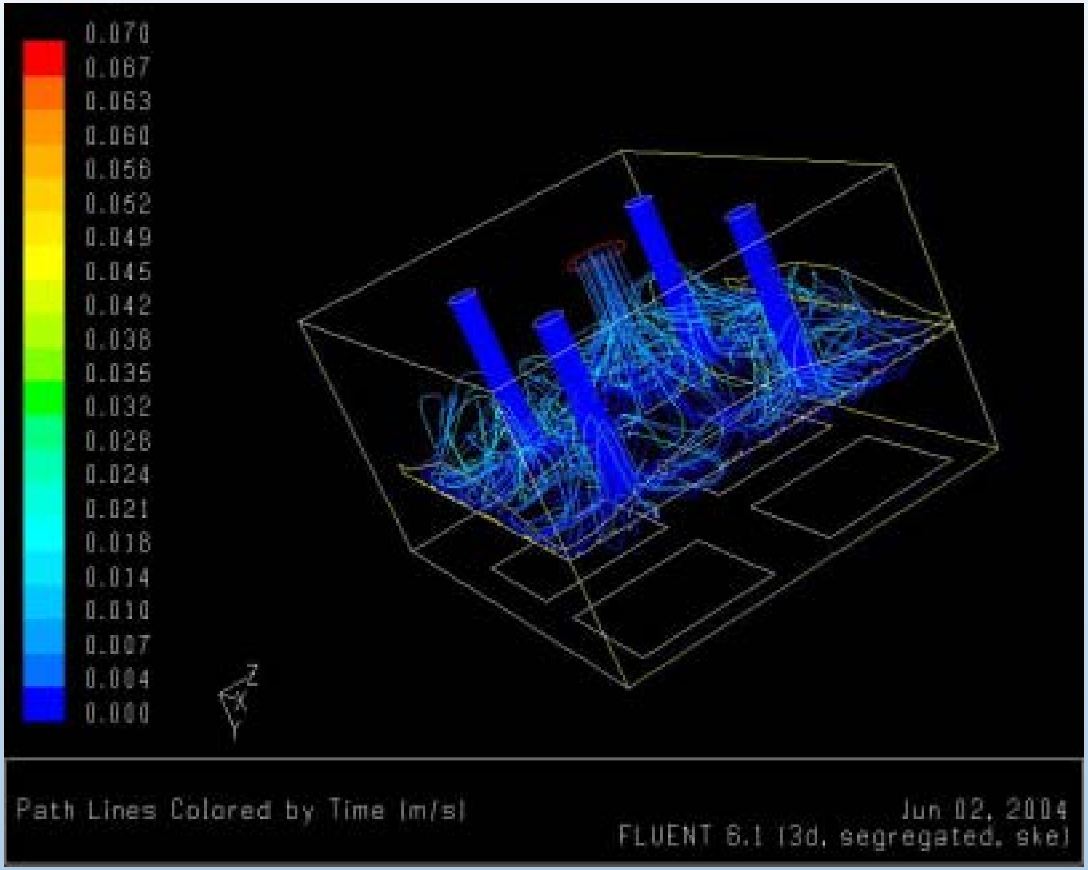
Temperature distributions



q'=84 W/cm$^{2;}$

$T_{coolant}$=105 ^{o}C;

Flow paths and residence times



V=10 m/s;
T_{min}=1.8 ms;

Spent liquid removal is more effective;

Spray cooling

Keith Gawlik

Why consider direct spray cooling?

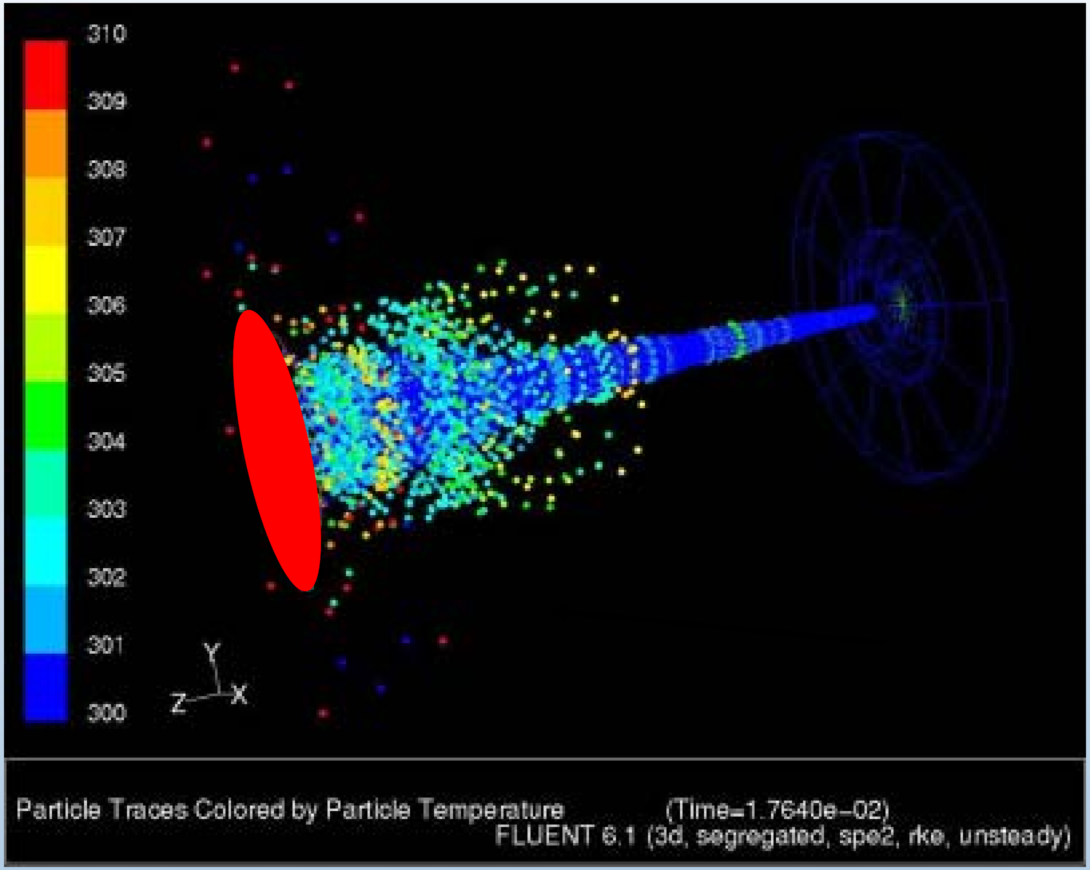
- Eliminates all interface material between source and sink
- Makes a variety of fluids available for use
- Makes heat flux potentially more uniform than with jets
- Supports the program goal to improve heat transfer and reduce cost and complexity

- However, the physics of sprays are very difficult to capture in numerical and analytical models

First model development

- Geometry and operating conditions based on published experimental work (Purdue)
- Estes & Mudawar, “Comparison of Two-Phase Electronic Cooling Using Free Jets and Sprays,” 1995.
- 11 W/cm^2 at 10^o DT, 0.76 lpm, FC-72
- Our first simulation used current CFD capabilities

Spray model - Temperatures

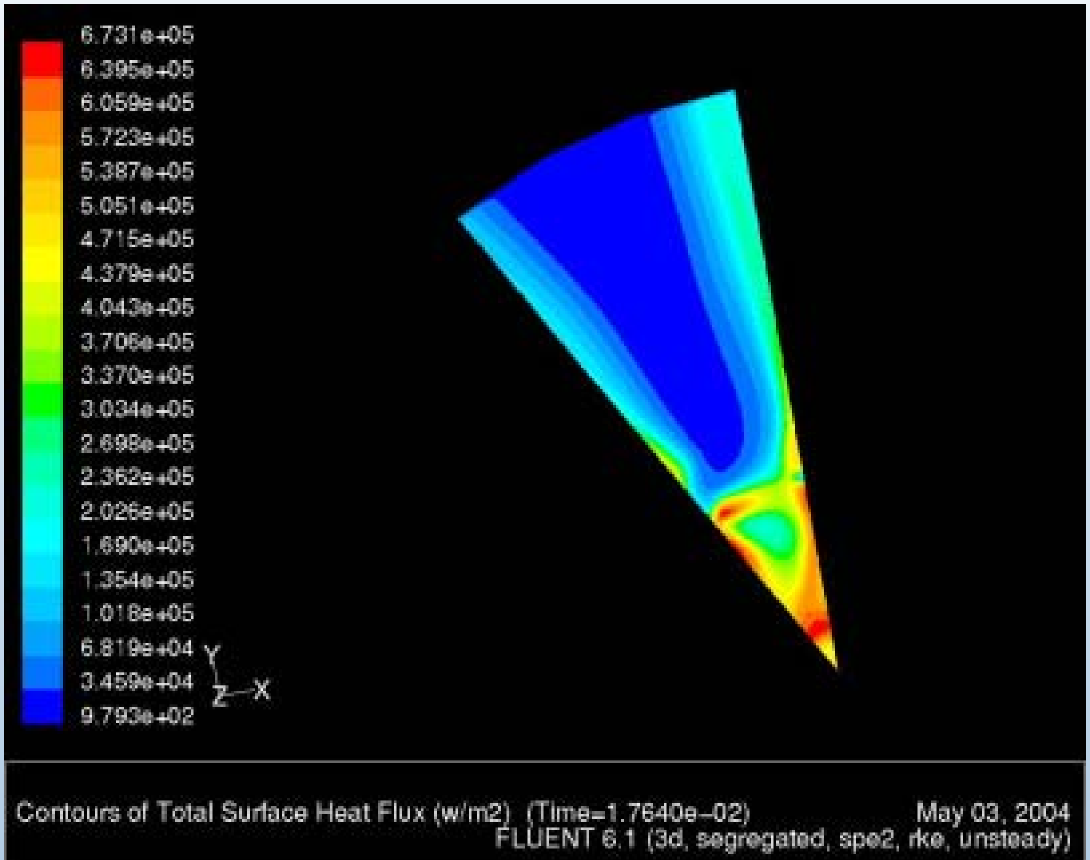


FC-72 spray

q''_{avg} = 12.4 W/cm^2

at 10^o DT

Heat flux variation across surface of 30^o segment



Region of low droplet density

Region of high droplet concentration

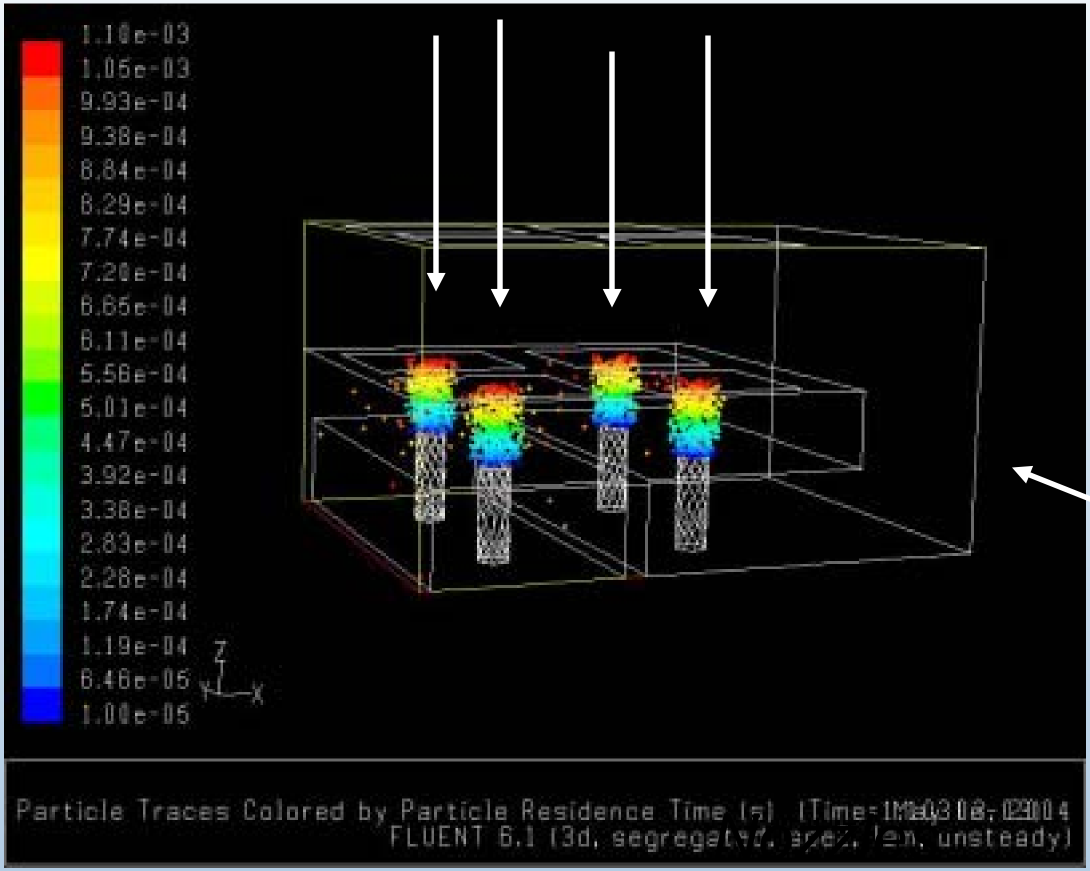
CFD spray modeling capabilities

- Different modes of interactions between particles and surfaces are possible:
  - wall jets and films: either single phase heat transfer or limited phase change allowed
  - particle trapping: complete evaporation
- Particle trapping mode is considered similar to physical behavior at high heat fluxes

Multiple sprays

- Simulates specific hardware
- Components mounted inside housing with four nozzles, and two outlets
- Each nozzle cools a single hot spot
- Heat flux from chips 83.4 W/cm^2
- Modified CFD code used

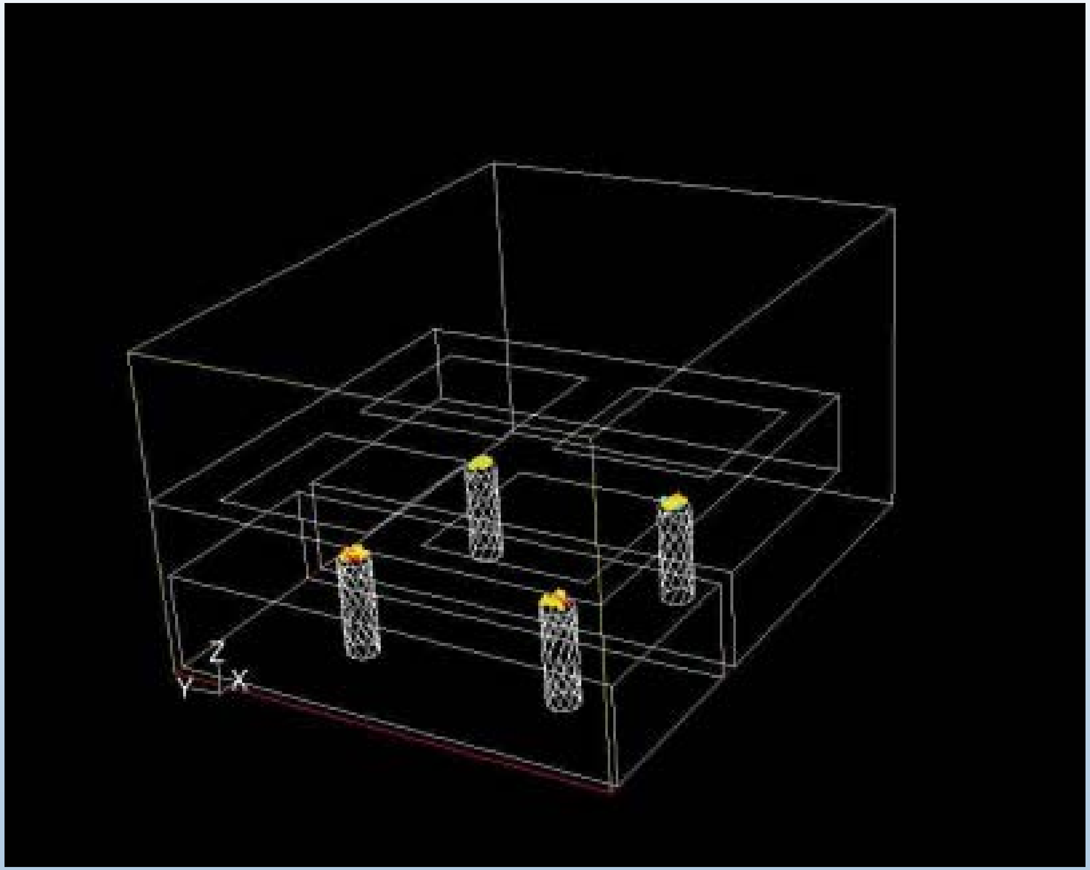
Spray flow geometry



Chips mounted inside housing opposite nozzles

Housing

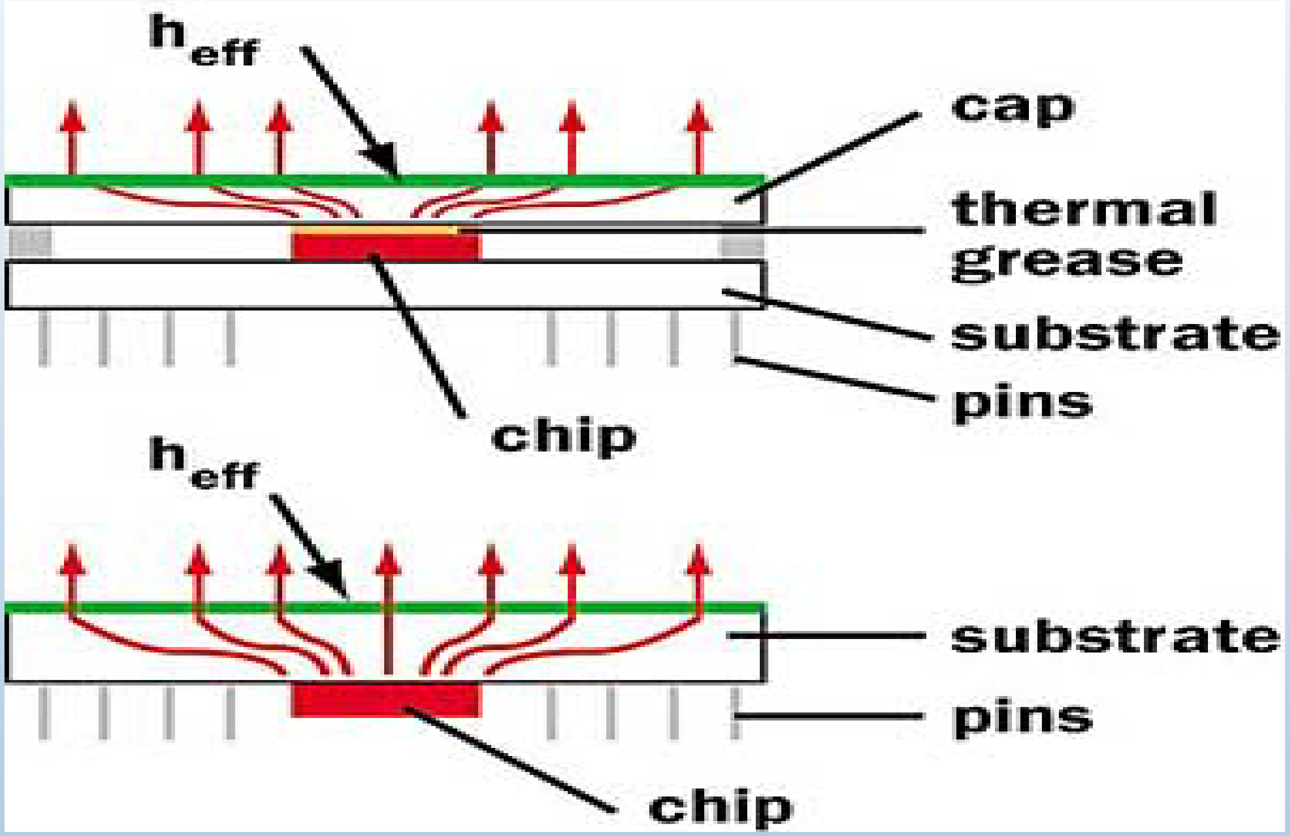
Animated Spray



Enabling Technologies

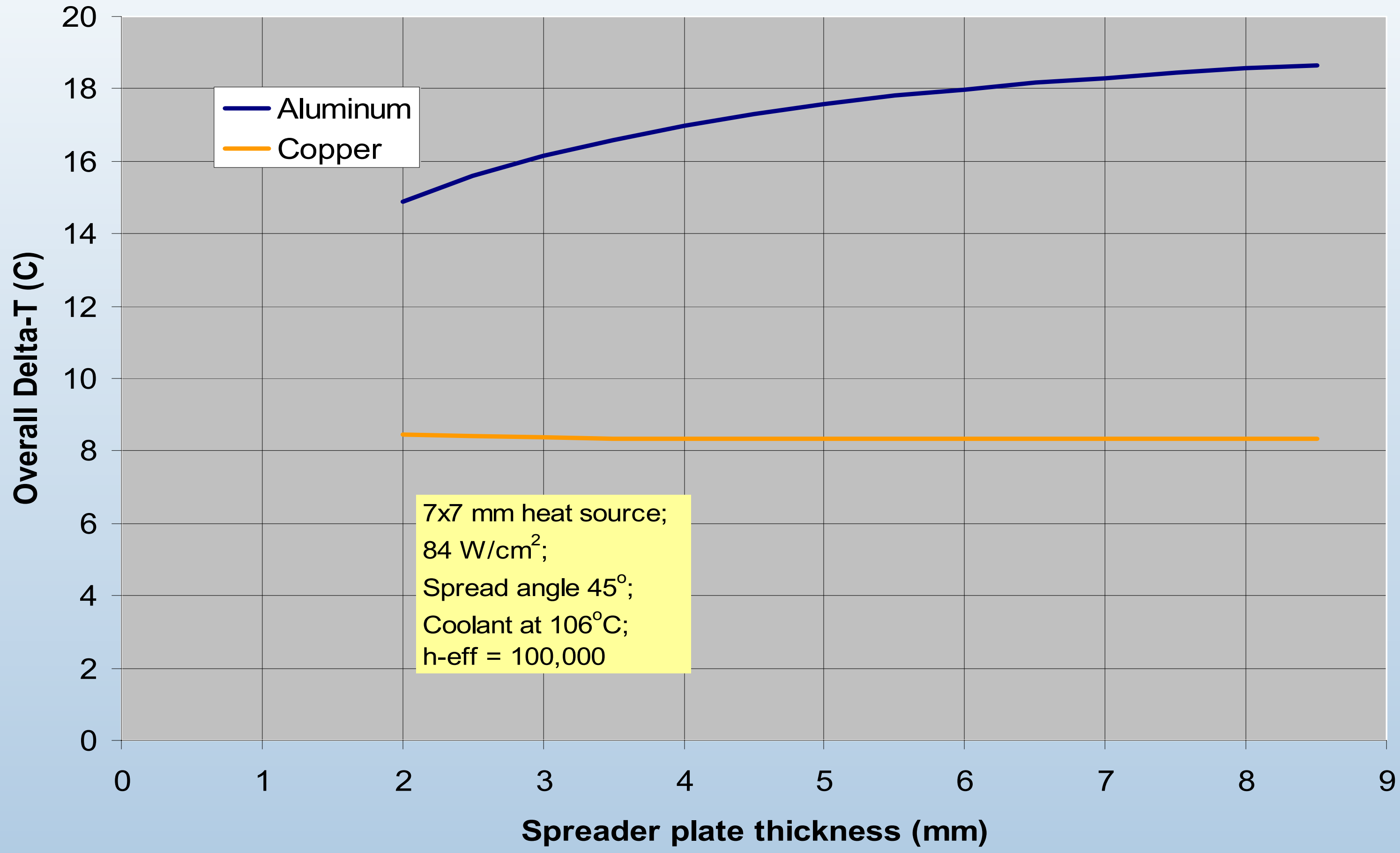
- Heat spreaders, including heat pipes
- Improved thermal interface materials
- Surface enhancements
- Heat pumping
  - using waste heat
  - using auxiliary refrigeration system
  - using thermoelectrics

Heat Spreaders*



*Simons, R.E., Electronics Cooling, 2004

Influence of Spreader Conductivity



Summary of current technologies

Approach	Advantages	Disadvantage	Technology	Advantages	Disadvantages	Remarks
Direct cooling	Eliminates many intermediaries between source and sink	Non-conducting liquids are necessary; Coatings are possible; pulsed jets possible;	Jets	Very high heat transfer coefficients are possible	Potential for erosion exists	Submerged jets are preferred
			Sprays	Offers gentle contact with the heat source	Modeling difficulty is severe; requires testing and verifications; requires filtering	Modeling difficulty is severe
Indirect Cooling	Use of conventional coolants is possible	Additional barriers such as spreader plate and TIM are introduced	Jets	Very high heat transfer coefficients are possible; submerged jets are preferred; Can handle impurities;	Potential for erosion exists	Can benefit from improved heat spreader, TIM, surface enhancement and other technologies
			Sprays	Offers gentle contact with the heat source	Modeling difficulty is severe; requires testing and verifications; requires filtering	
			Microchannels	Requires only small volumes; is readily modeled.	Requires effective filtering	

Next steps

- Continue improving simulation approaches for jets and sprays
- Investigate the use of micro-channels
- Model heat transfer cases for actual hardware
- Compare and validate model with experimental data
- Investigate other enabling technologies

System level approaches may yield larger benefits

- System studies to assess cost benefit of independent loop
- Cost tradeoffs on miniaturization of chips
- Use of PCM or other means to increase local thermal capacity to reduce transient temperature swings

Conclusions

- Jet and spray models offer means to improve hardware designs
- Spray models require substantial empirical data on interactions
- Experimental verification of models for specific hardware are needed in collaboration with industry