Thermal Challenges of Complex FPGA/3D ICs for Space Applications

by

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SEMI-THERM, March 18, 2013

Outline

- Package/Thermal
  - Package trend
  - Power density trend
- Thermal Challenges
  - General
  - Space
  - TM (Thermal Management) approaches
- Thermal Management
  - Low/high I/O CGAs
  - 3D ICs
- Summary

MPF to Curiosity (1996-2012)

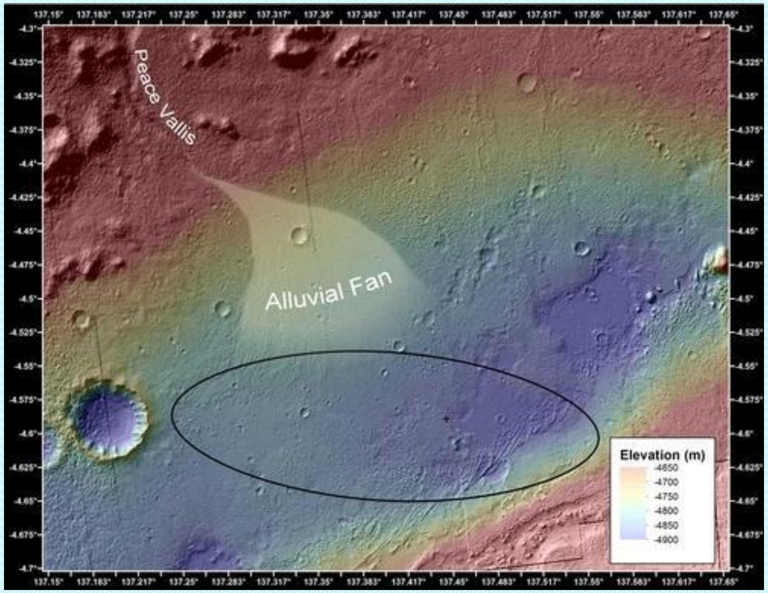
Curiosity Rover

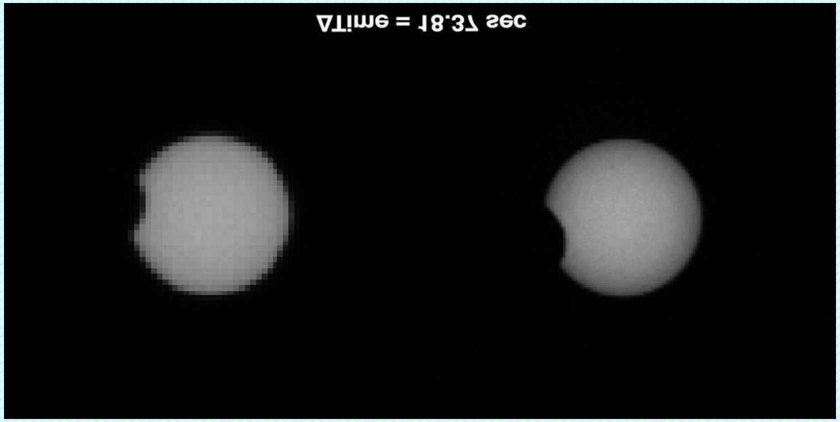
Curiosity is Getting Ready for Mars

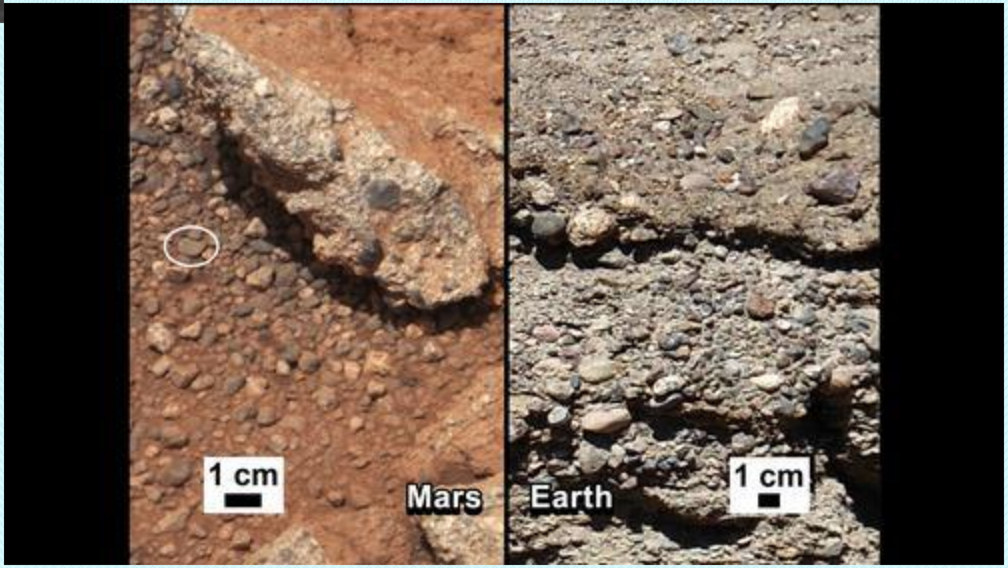
http://spacespin.org/article.php/101043-watch-construction-curiosity-live

Continuous live video of rover construction is available at: http://www.ustream.tv/channel/nasajpl

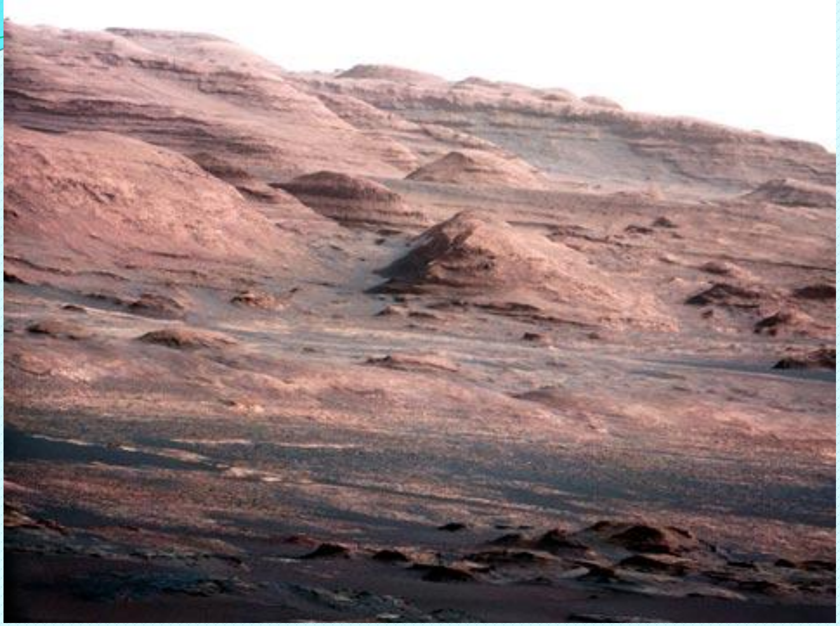
Safe Arrival & Images of Mars







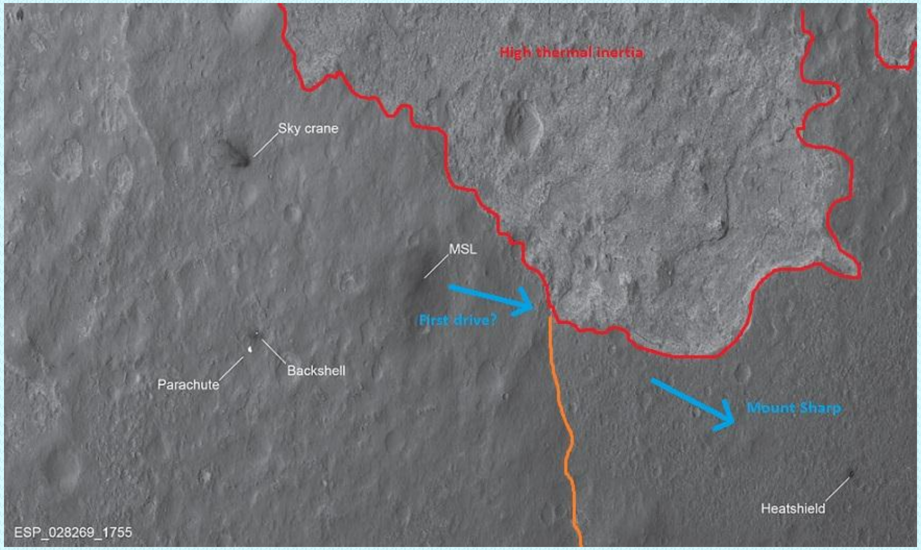
Images & 1st Time Drill on Mars/Planet

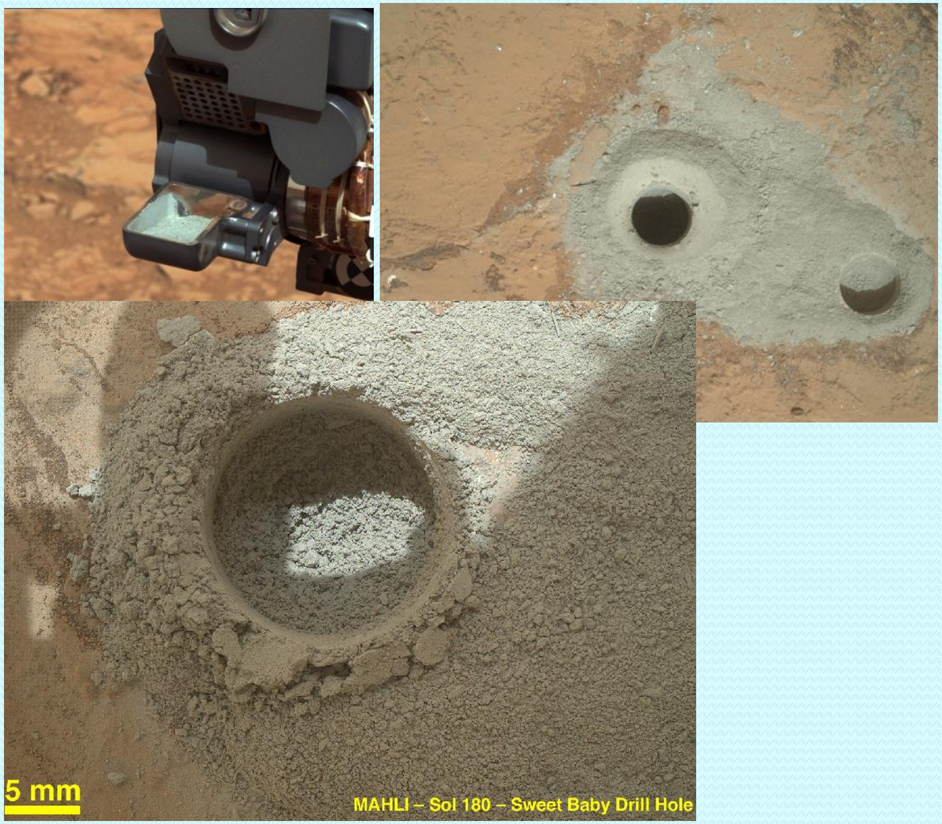


Detected Chloro-methane which could be resulted from organic-decomposition

Such benign, could drink water

NASA Briefing- Mar 12, 2013





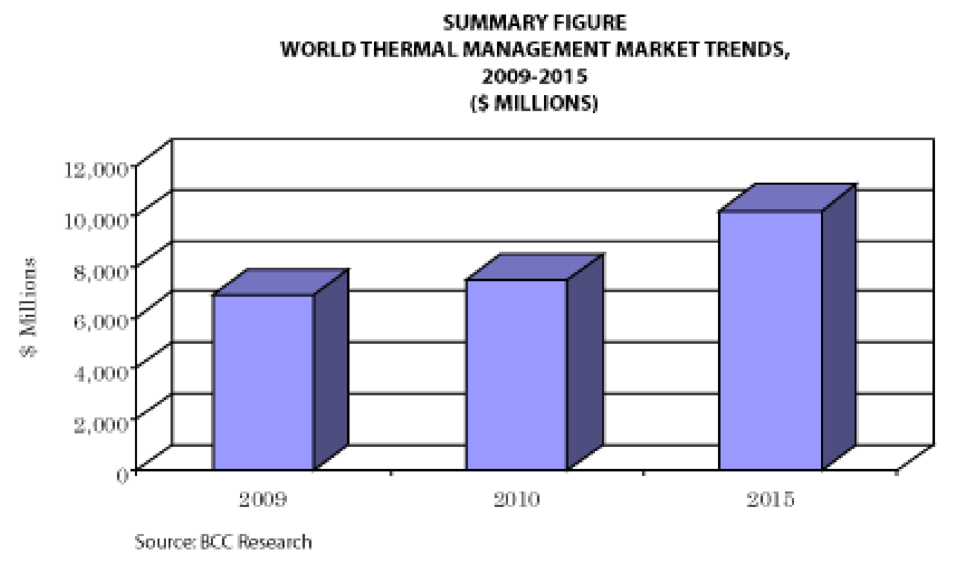
Curiosity Finds Habitable Env.

Opportunity- Sulfate rich sand stone
In presence of water
Not Habitable

Curiosity- Neutral pH
Habitable Env.
If microbes ever present

Why TM
Growth Market- $10.2B in 2015

The **North American** market will maintain its number one position throughout the period, with a market share of about **37%**, followed by **Asia-Pacific** with around **23% to 24%**

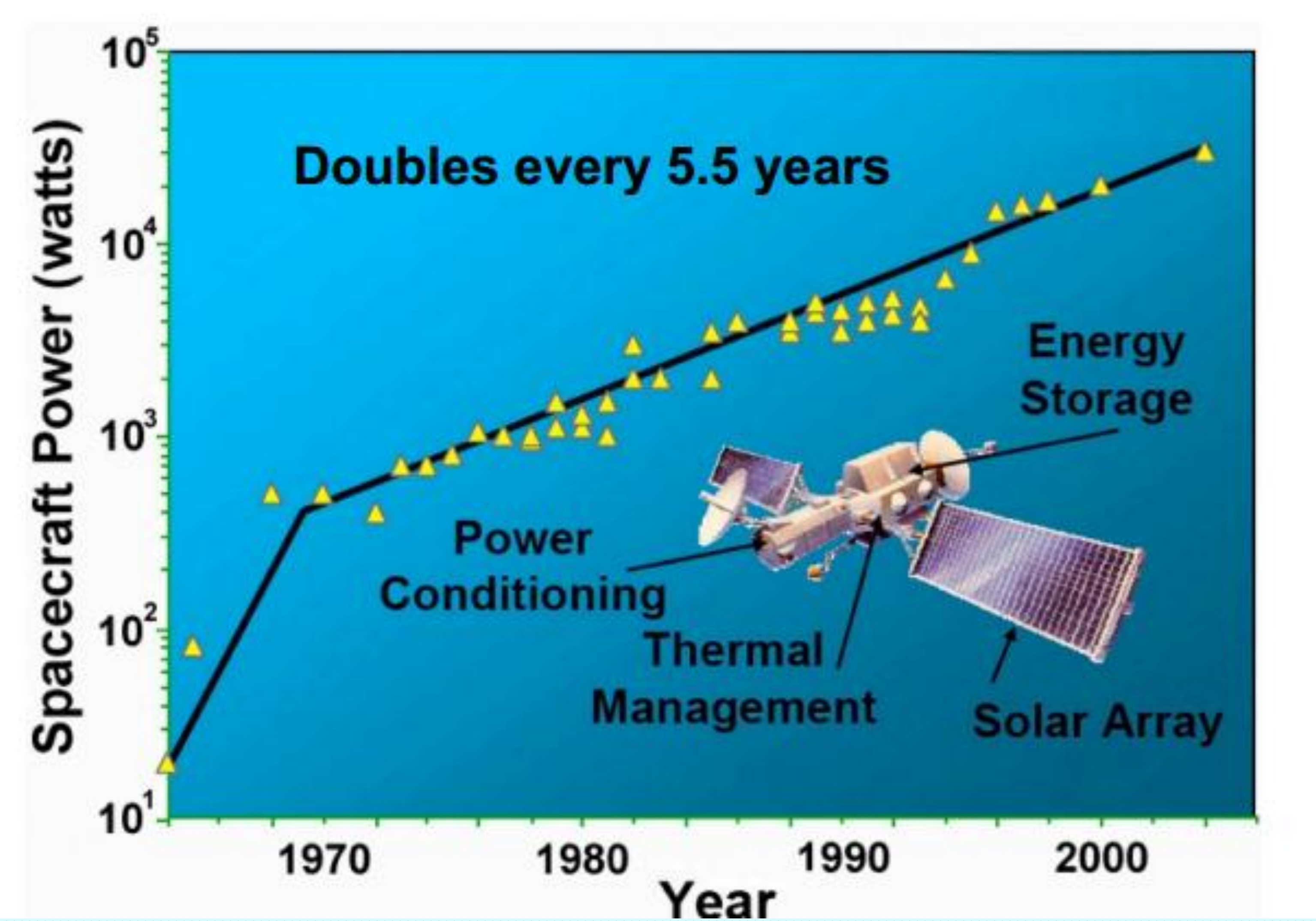


Source: BCC Research

- The world market for TM products to $10.2 billion by 2015, a compound annual growth rate (CAGR) of 6.4% between 2010 and 2015.
- Asia-Pacific is projected to be the fastest-growing region, with a CAGR of 7.3% between 2010 and 2015. This region is valued at $1.7 billion in 2010 and should reach $2.5 billion by 2015.
- The market in the Americas is projected to grow from $2.9 billion in revenues in 2010 to $4 billion in 2015, a CAGR of 6.7%.

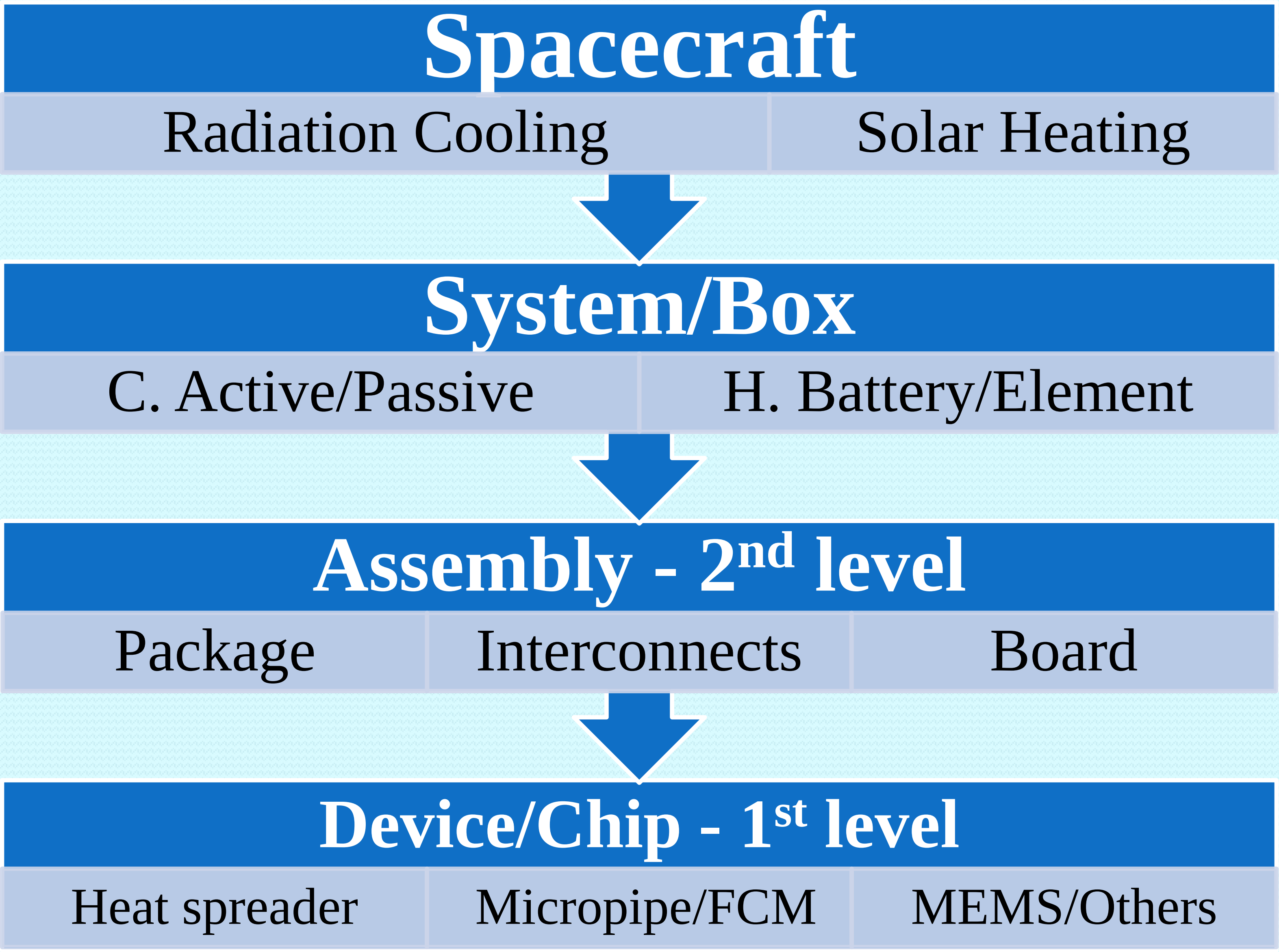
http://www.bccresearch.com/report/thermal-management-technology-smc024f.html

TM Must for Rising Power



http://sdsi.asu.edu/wp-content/uploads/2012/01/Dahm-Dayton-Thermal.pdf

TM from System to Device



Spacecraft

Radiation Cooling | Solar Heating

System/Box

C. Active/Passive | H. Battery/Element

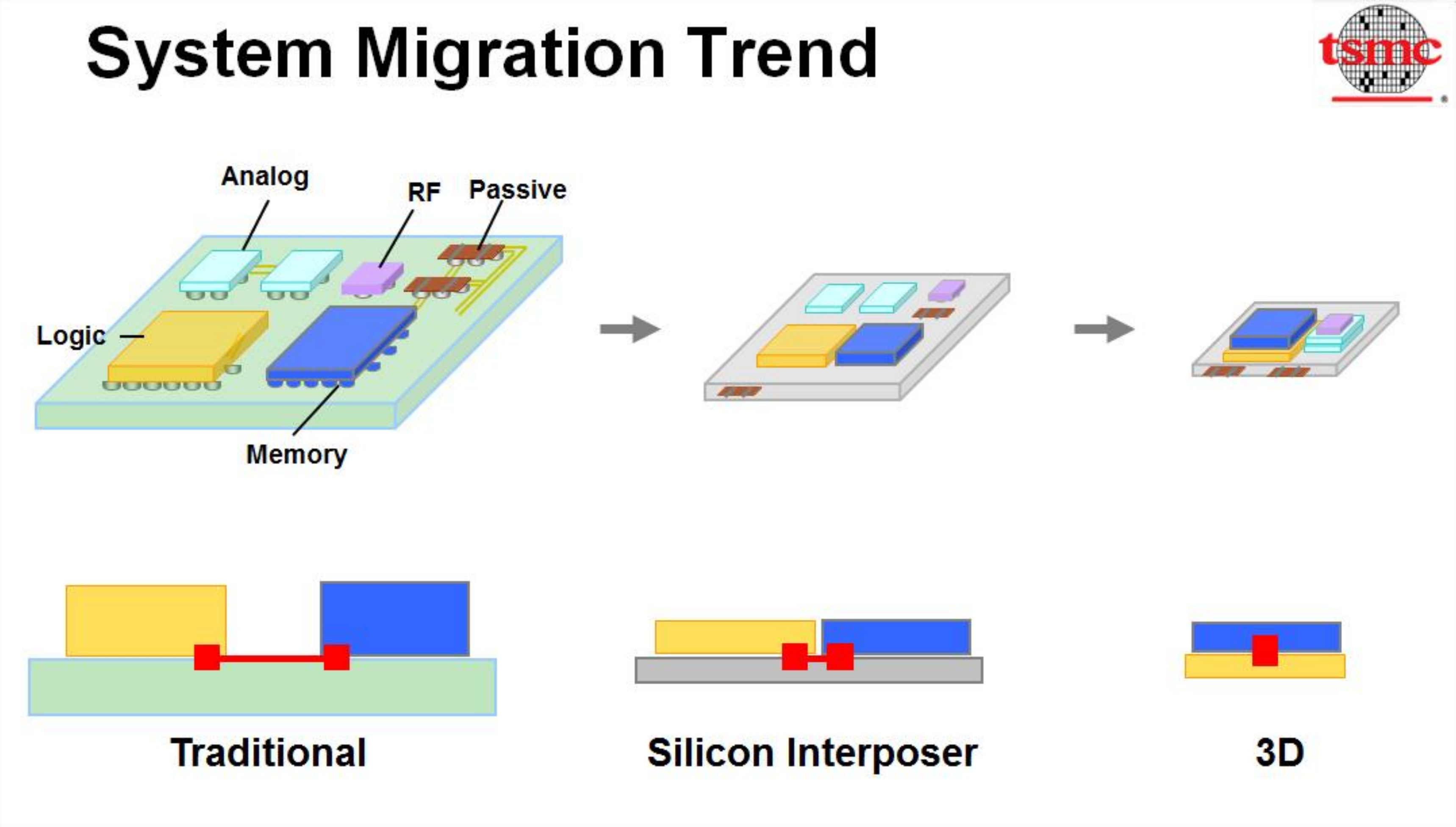
Assembly - 2nd level

Package | Interconnects | Board

Device/Chip - 1st level

Heat spreader | Micropipe/FCM | MEMS/Others

Density Increase Approaches

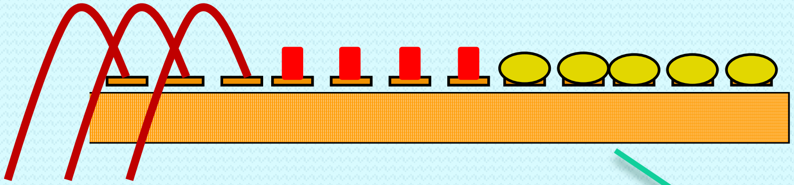


System Migration Trend

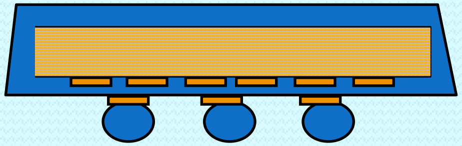
http://www.i-micronews.com/news/Xilinx-brings-3D-TSV-interconnects-commercialization-phase,5693.html

Advanced Package Concepts

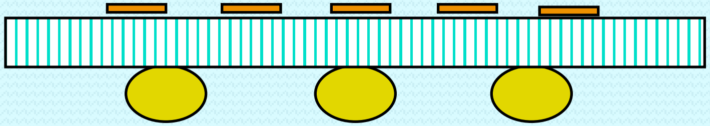
- **Die Tight Pitch**
- **Al Pad- Non Reflow**

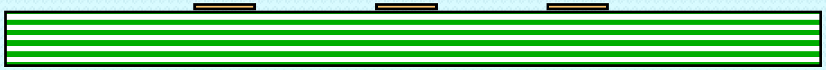


- **Wafer**
  - **Pitch limitation**



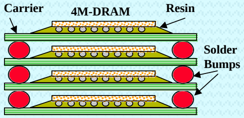
- **Interposer**
  - **Polymer, Ceramic, Flex**
  - **Cu:Ni:Au Pad**

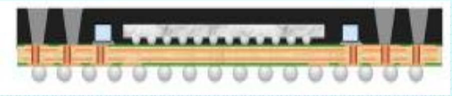




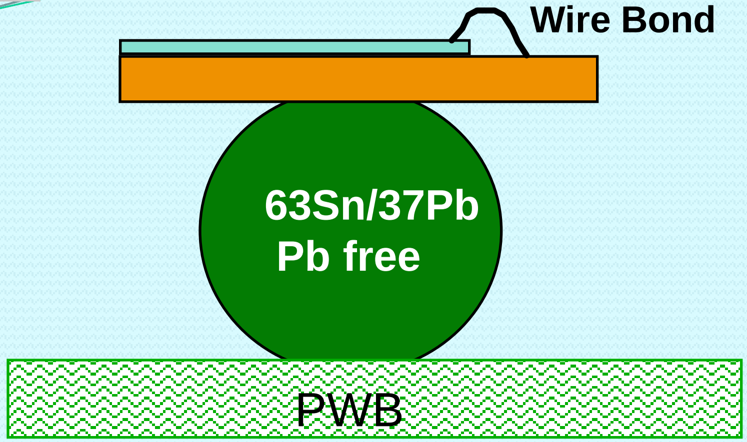
- **Norm Pitch for PWB**
  - **0.3-1.27 mm**

- **Stack**
  - **die/wafer/package**

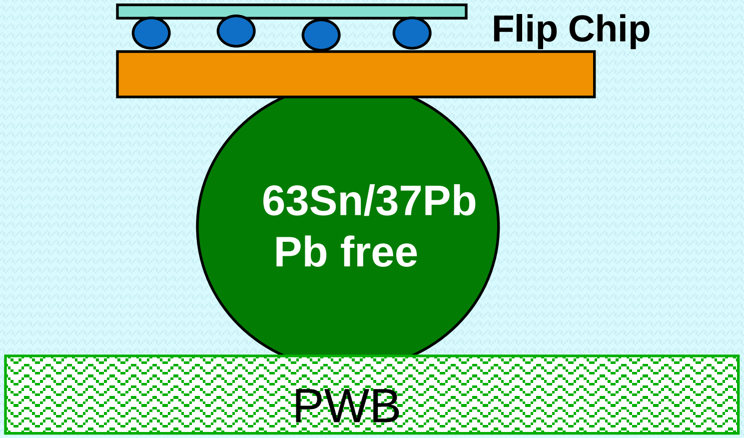




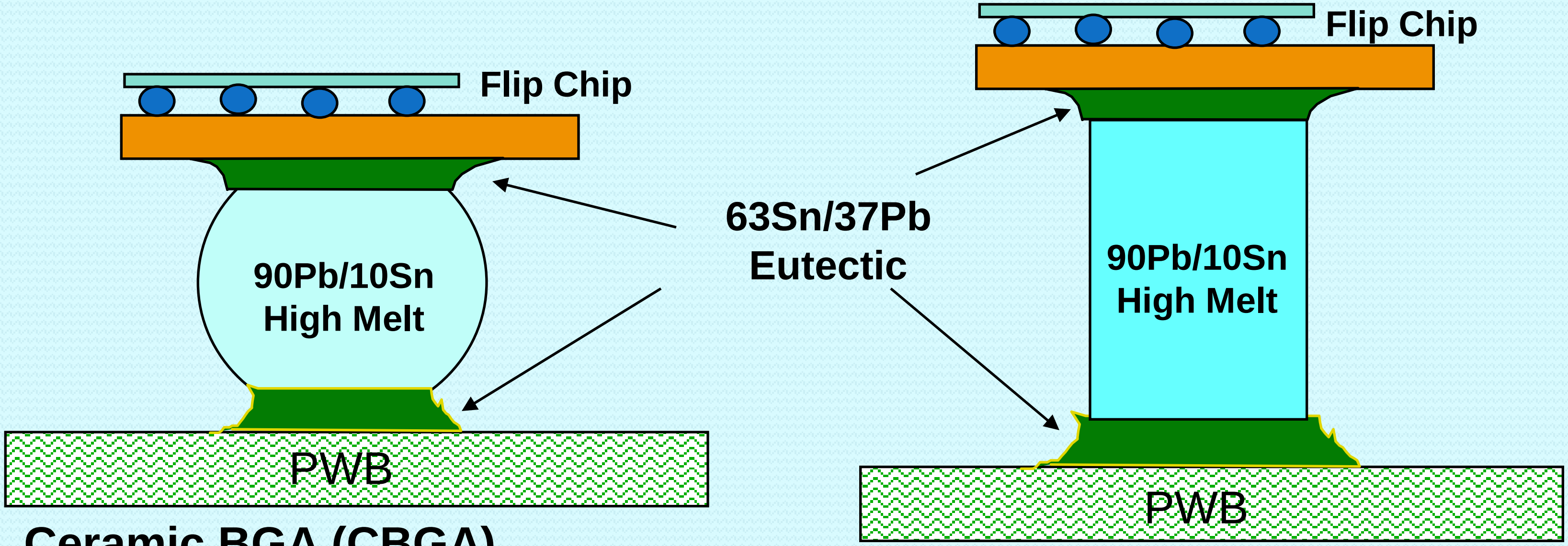
FCBGA and CGA



Plastic BGA (PBGA)



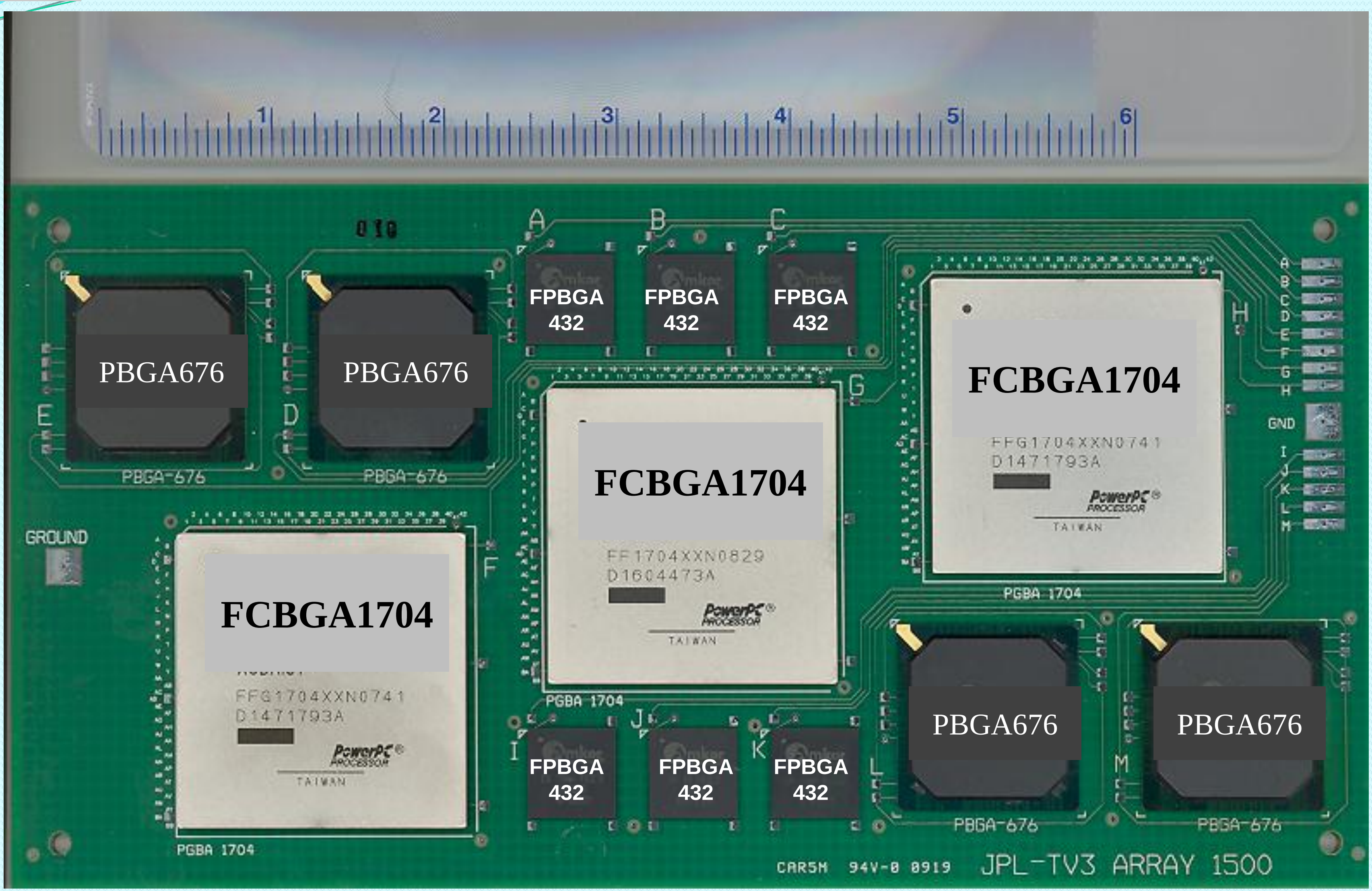
Flip Chip BGA (FCBGA)



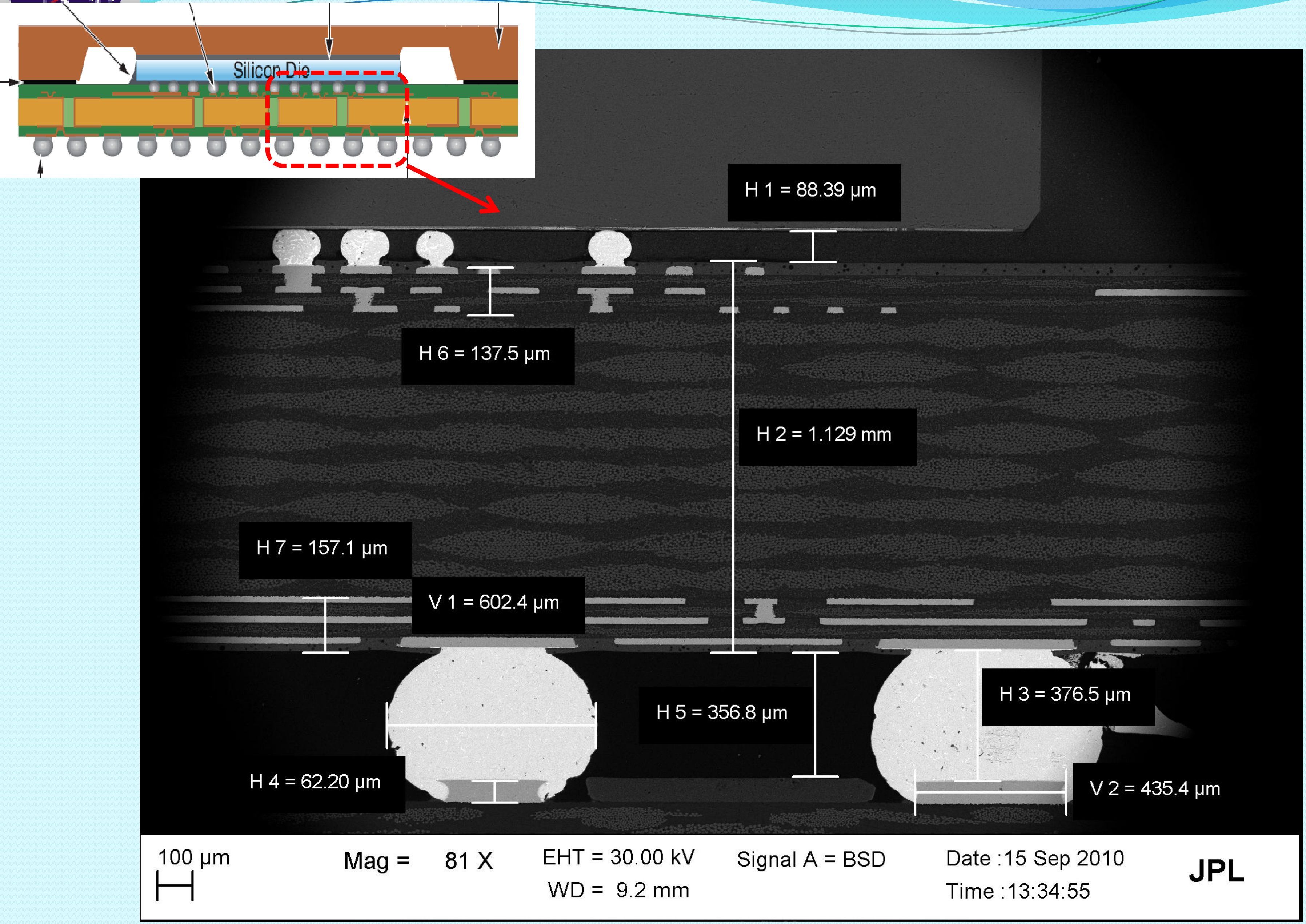
Ceramic BGA (CBGA)

Column CGA (CCGA)

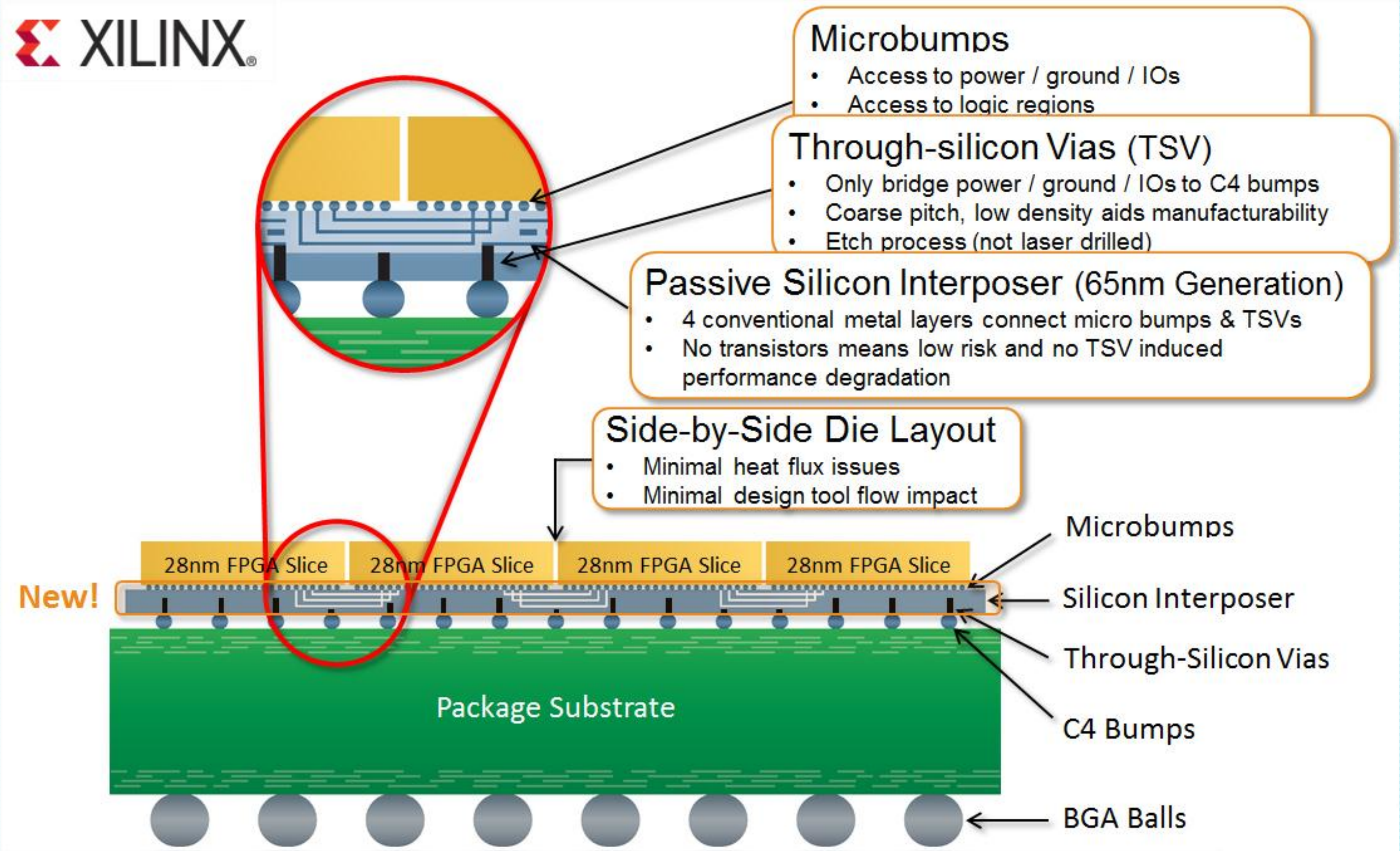
FCBGA , PBGA, FPBGA



FCBGA Heat Sink & Build



Interposer/TSV & Dies



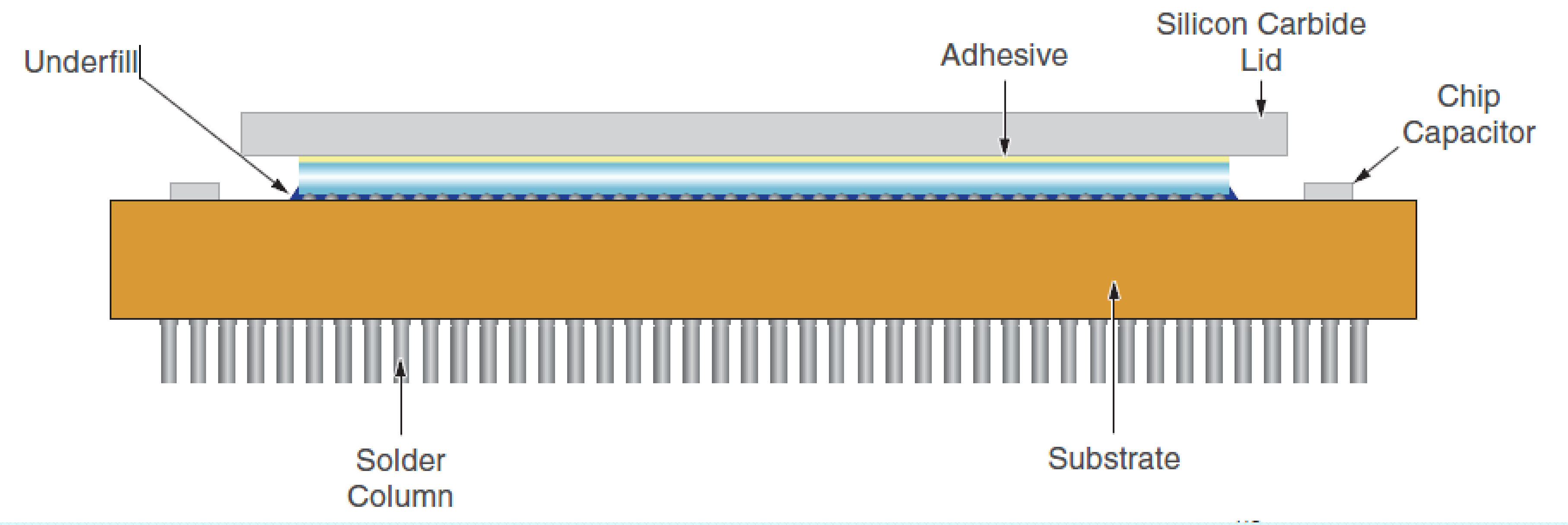
Microbumps
- Access to power / ground / IOs
- Access to logic regions

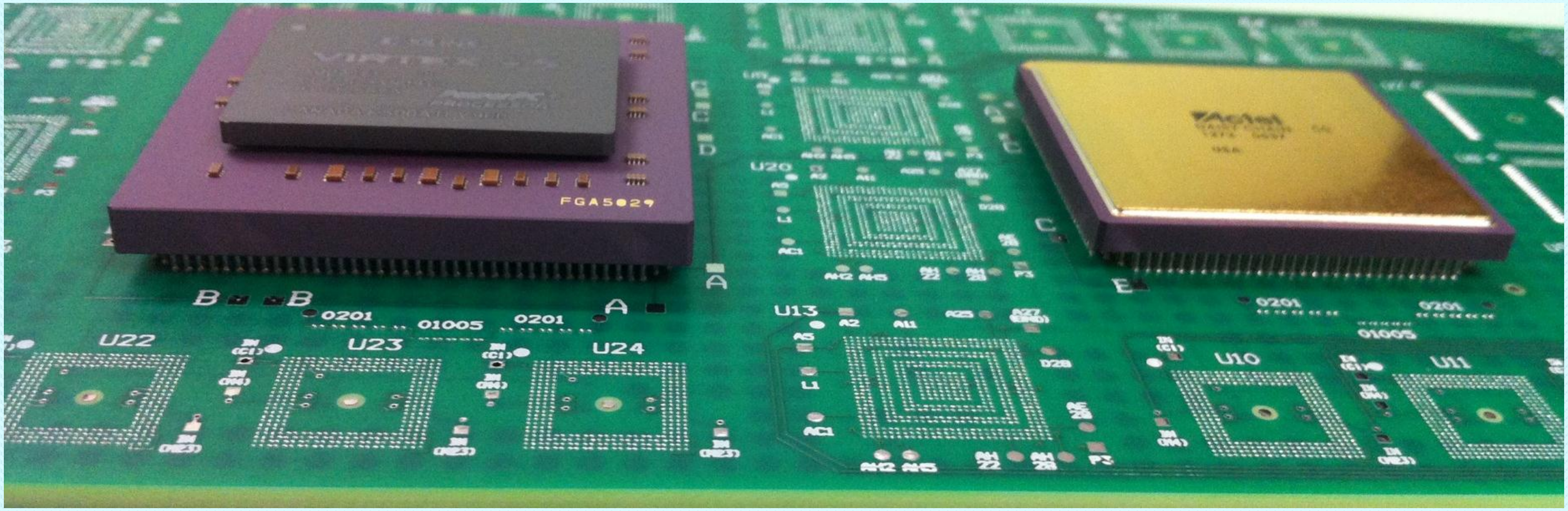
Through-silicon Vias (TSV)
- Only bridge power / ground / IOs to C4 bumps
- Coarse pitch, low density aids manufacturability
- Etch process (not laser drilled)

Passive Silicon Interposer (65nm Generation)
- 4 conventional metal layers connect micro bumps & TSVs
- No transistors means low risk and no TSV induced performance degradation

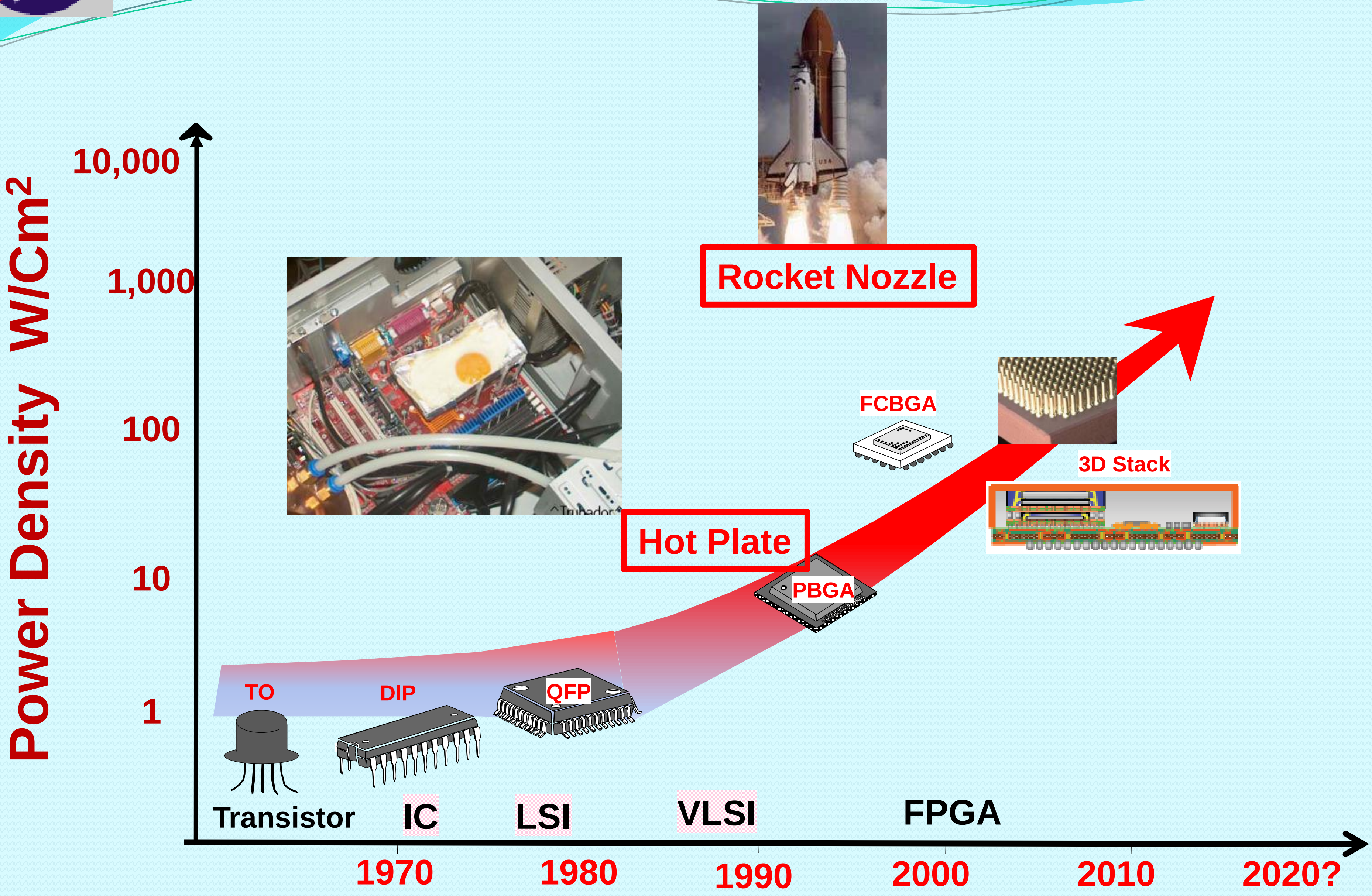
Side-by-Side Die Layout
- Minimal heat flux issues
- Minimal design tool flow impact

High I/O CGAs


Underfill
Adhesive
Silicon Carbide
Lid
Chip
Capacitor
Solder
Column
Substrate

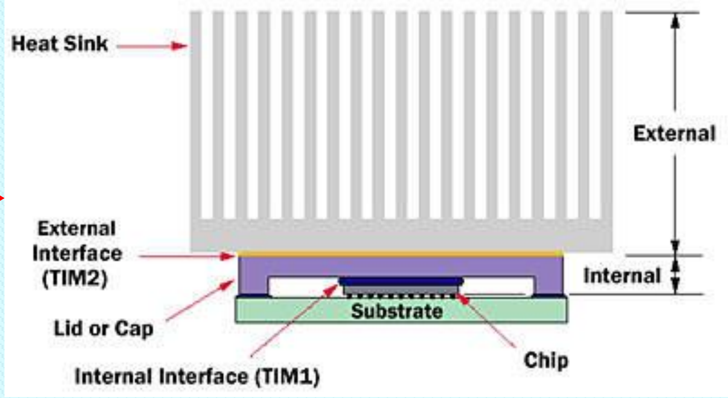


Power Density Explosion



Cooling of Electronics

- Heat Spreading
- Air Cooling
  - Piezo fans
  - Synthetic jet cooling
- Liquid Cooling
  - Heat pipes
  - Cold plates
  - Micro-channels
- Liquid Metal/Immersion
- Solid State/Spray Cooling
- More …



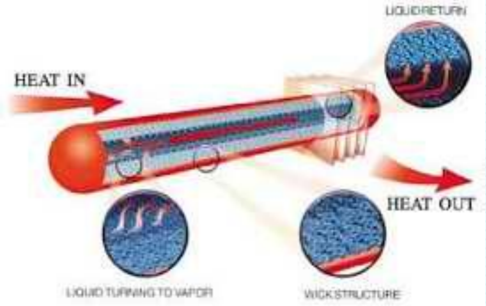
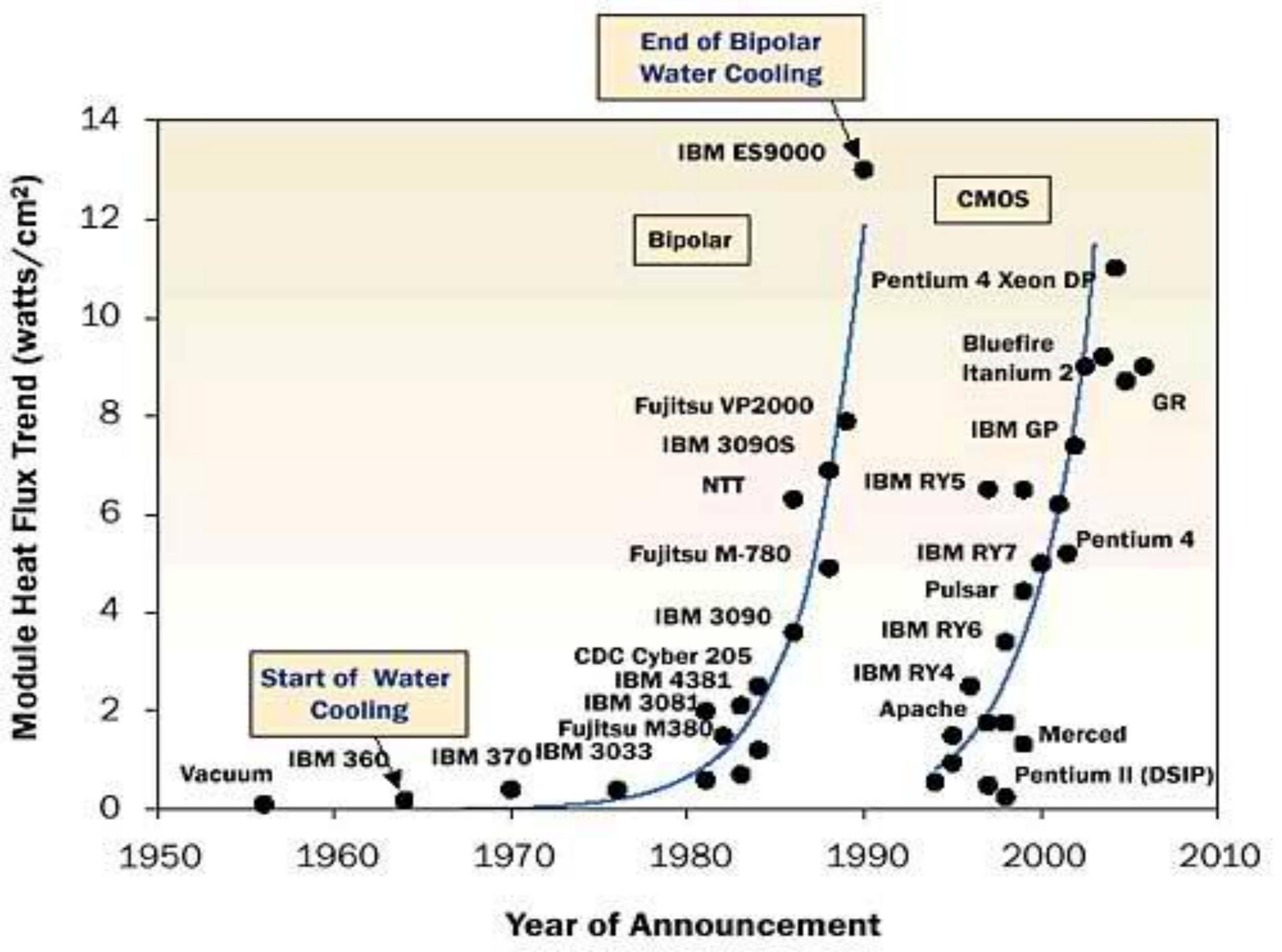


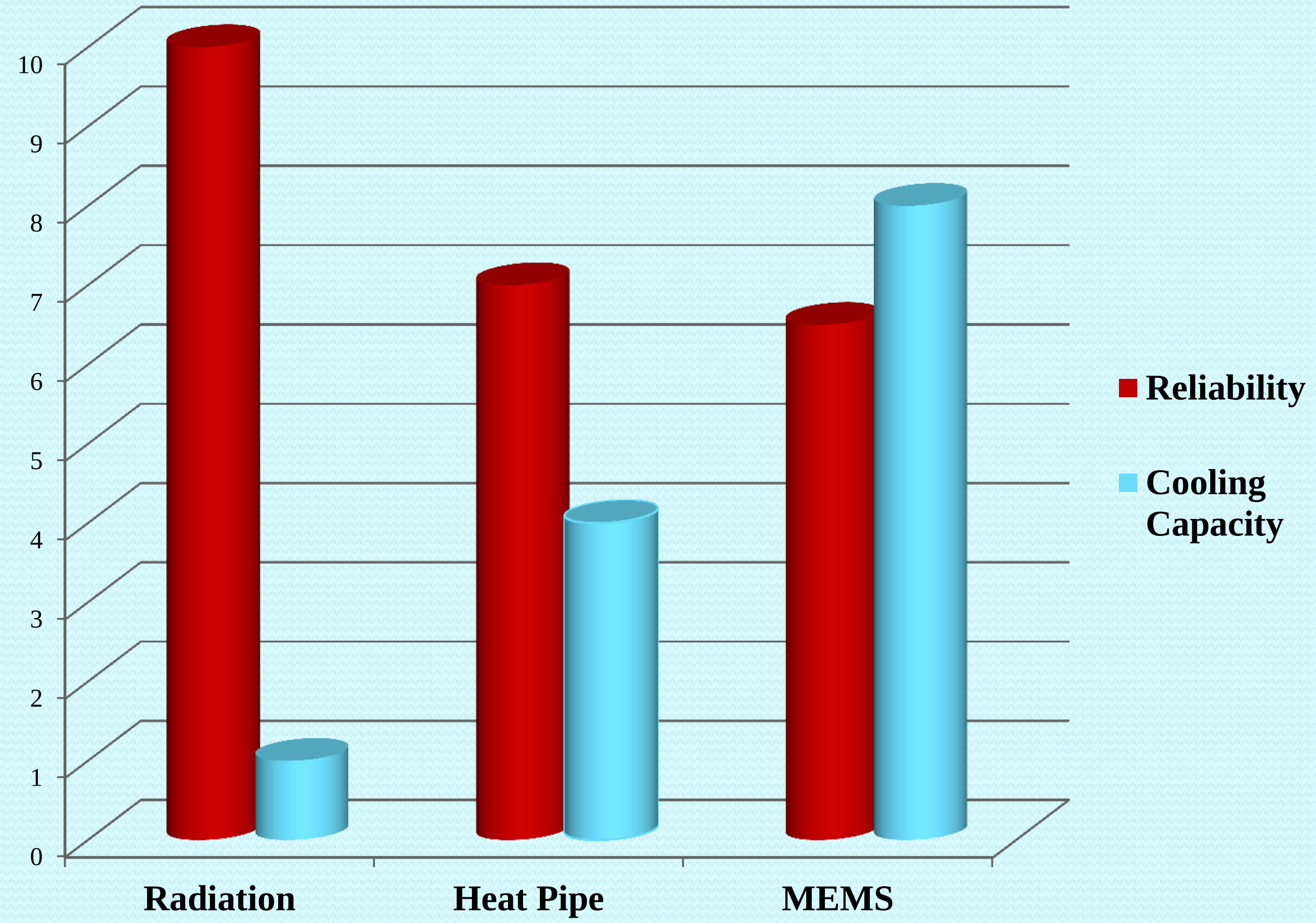
Illustration of a Capillary Two-Phase Heat Transfer Device-a Heat Pipe

Power & Encore of Water Cooling



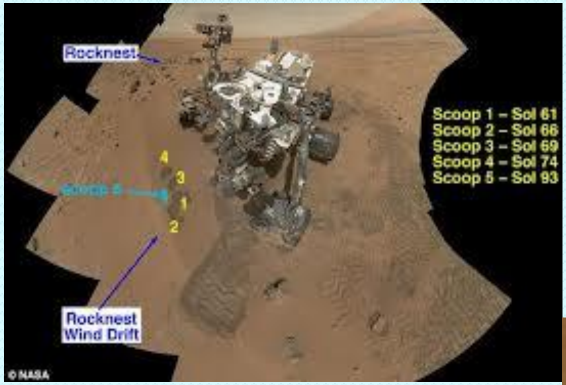
http://www.electronics-cooling.com/2005/08/liquid-cooling-is-back/

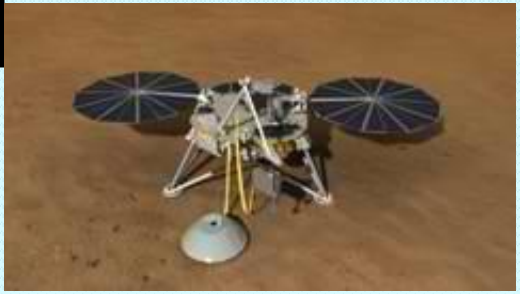
TM Techniques & Reliability



TM Earth vs. Space

- Air of Earth
  - Radiation
  - Convection
  - Conduction

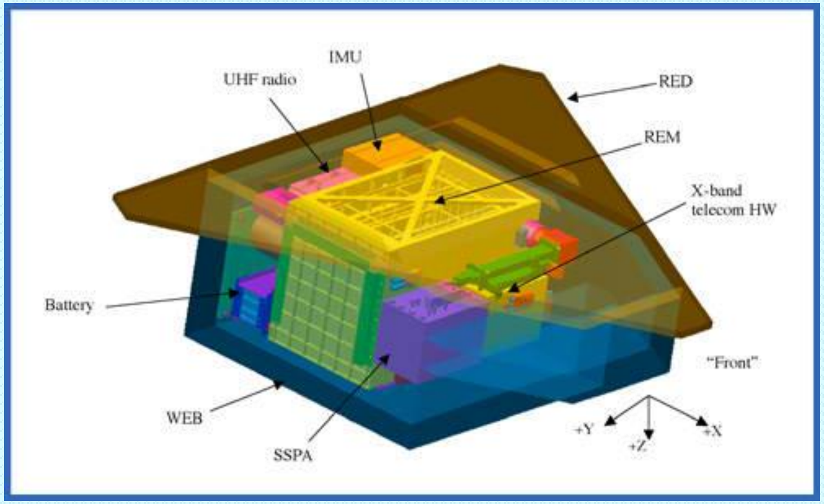




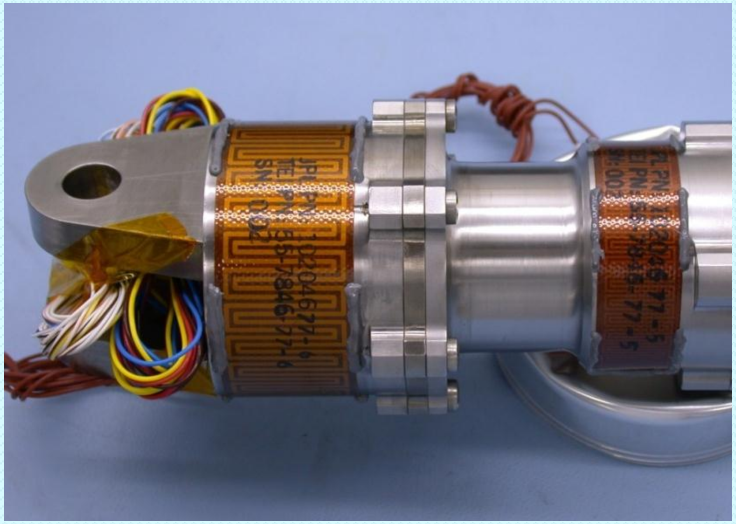
- Vacuum of Space
  - Radiation to space
  - Controls (passive/active), coating/MLI/Louver
- Why TM
  - Control Min/Max Temp. range for electronics use
  - Control Temp. range for electronics/materials stability
    - Use solar/RTG (Radio-isotope Thermoelectric Generator)/battery
    - Mars Rovers, e.g., W/WO env. Controls WEB/camera

Heater to Keep Electronics Warm

- Control hardware/electronics Temp.
  - Global control, Warm Electronic Box (WEB)



- Local heaters ($P = I^2R$)
  - Kapton film heaters
  - Wire wound resistors
  - Cartridge heaters
  - Radioactive heating units
  - Others

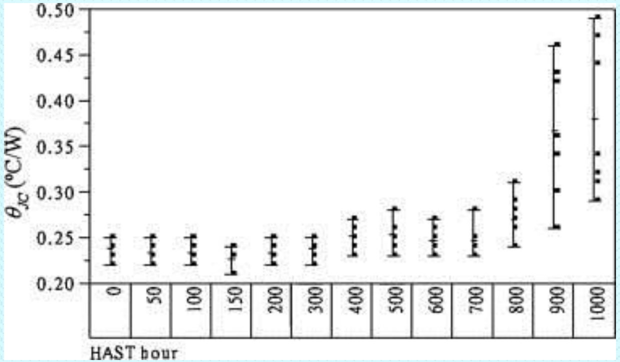


Space Cooling Technologies

- Passive cooling
  - Rolling it, sun side cools off
  - Coating (white/gold)/MLI/shield
  - Radiator, Louver shutter, heat pipe
  - **Simple/reliable/low cost, but cooling limited**
- Active cooling
  - Mechanically pumped loops
  - Recuperative cryocooler, Optical cryocooler, etc.
  - **Complex/less reliable/hi cost, cools to lower T**
- Stored cryogen
  - Superfluid helium, solid nitrogen,

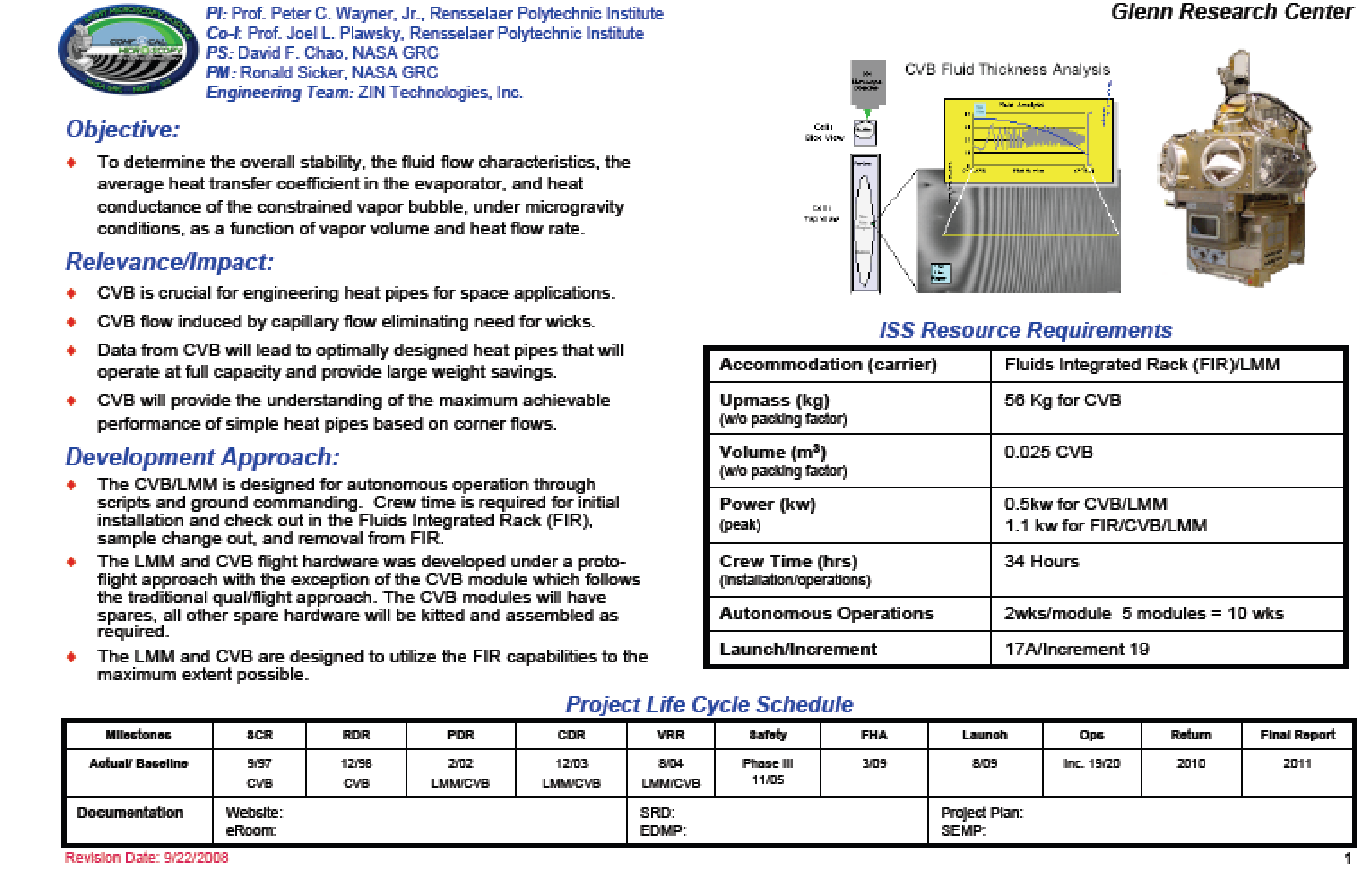
TM Device/Board

- Device Level- heat spreaders
  - High performance thermal interfacial materials thermal grease, thermal paste and PCM
  - Low CTE, high thermal conductivity pkg. materials
  - **Heat pipe/pump loop**
  - Embedded micro-heat pipes
  - Micro- or mini-channel heat sink



- Board Level
  - Single phase micro-mini channel cooling
  - Phase change cooling, ultra thin-film evaporator cooling
- Software/Hardware
  - Static, offline at design level
  - Dynamic, online during execution level

Constrained Vapor Bubble (CVB)



PI: Prof. Peter C. Wayner, Jr., Rensselaer Polytechnic Institute
Co-I: Prof. Joel L. Plawsky, Rensselaer Polytechnic Institute
PS: David F. Chao, NASA GRC
PM: Ronald Sicker, NASA GRC
Engineering Team: ZIN Technologies, Inc.

Glenn Research Center

Objective:

- To determine the overall stability, the fluid flow characteristics, the average heat transfer coefficient in the evaporator, and heat conductance of the constrained vapor bubble, under microgravity conditions, as a function of vapor volume and heat flow rate.

Relevance/Impact:

- CVB is crucial for engineering heat pipes for space applications.
- CVB flow induced by capillary flow eliminating need for wicks.
- Data from CVB will lead to optimally designed heat pipes that will operate at full capacity and provide large weight savings.
- CVB will provide the understanding of the maximum achievable performance of simple heat pipes based on corner flows.

Development Approach:

- The CVB/LMM is designed for autonomous operation through scripts and ground commanding. Crew time is required for initial installation and check out in the Fluids Integrated Rack (FIR), sample change out, and removal from FIR.
- The LMM and CVB flight hardware was developed under a proto-flight approach with the exception of the CVB module which follows the traditional qual/flight approach. The CVB modules will have spares, all other spare hardware will be kitted and assembled as required.
- The LMM and CVB are designed to utilize the FIR capabilities to the maximum extent possible.

ISS Resource Requirements

Accommodation (carrier)	Fluids Integrated Rack (FIR)/LMM
Upmass (kg) (w/o packing factor)	56 Kg for CVB
Volume (m³) (w/o packing factor)	0.025 CVB
Power (kw) (peak)	0.5kw for CVB/LMM 1.1 kw for FIR/CVB/LMM
Crew Time (hrs) (installation/operations)	34 Hours
Autonomous Operations	2wks/module 5 modules = 10 wks
Launch/Increment	17A/Increment 19

Project Life Cycle Schedule

Milestones	**SCR**	**RDR**	**PDR**	**CDR**	**VRR**	**Safety**	**FHA**	**Launch**	**Ops**	**Return**	**Final Report**
Actual/ Baseline	9/97 CVB	12/98 CVB	2/02 LMM/CVB	12/03 LMM/CVB	8/04 LMM/CVB	Phase III 11/05	3/09	8/09	Inc. 19/20	2010	2011
Documentation	Website: eRoom:				SRD: EDMP:			Project Plan: SEMP:			

Revision Date: 9/22/2008

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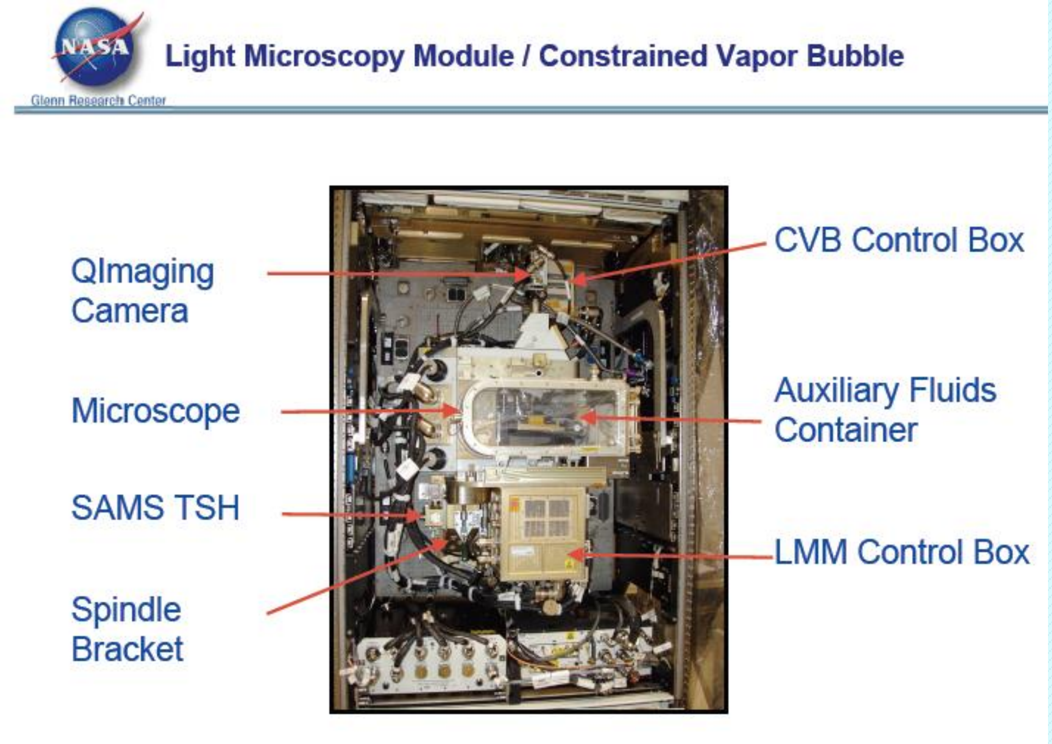
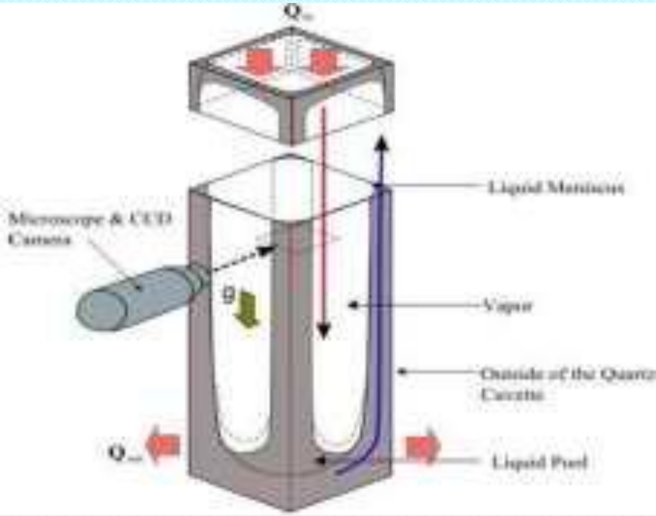
Heat Pipe Study on Space Station



- Cuvette heat pipe: Rectangular-shaped glass tube of quartz
- Observation of fluid flow
- Accurate temp. measurement
- Operate on earth, then at microgravity ISS (higher T/P)
- No convection to cool pipe surface, only radiation in Space
- Understand basic principles, heat transfer with no moving part



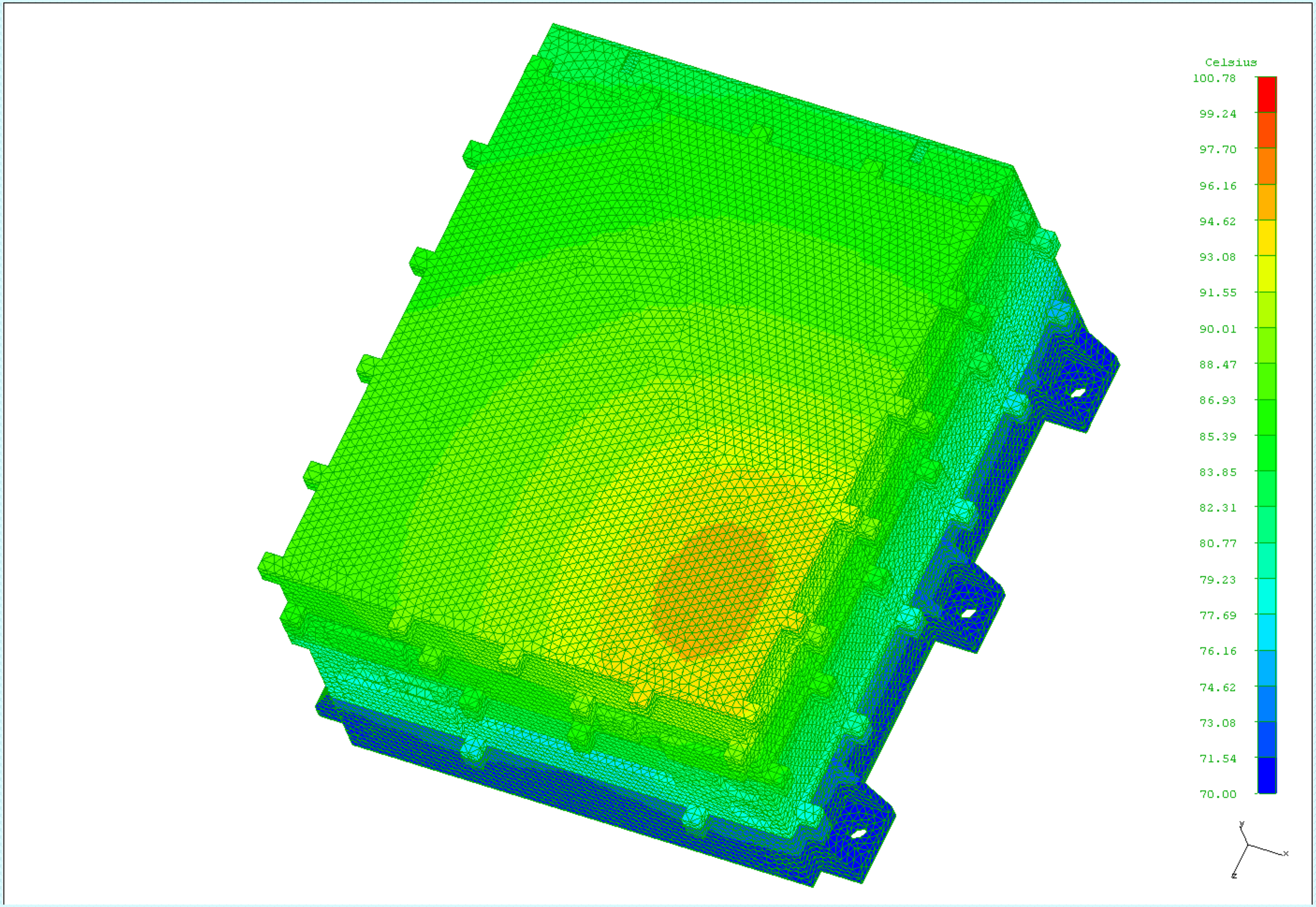
http://www.nasa.gov/mission_pages/station/research/news/heat_pipes.html

Heat-Pipe for Commercial Use

NASA heat pipe technology used in spacecraft to keep hardware and critical electronics cool has found its way into notebook computers. Tiny heat pipes are in wide use to cool the main central processor chip.

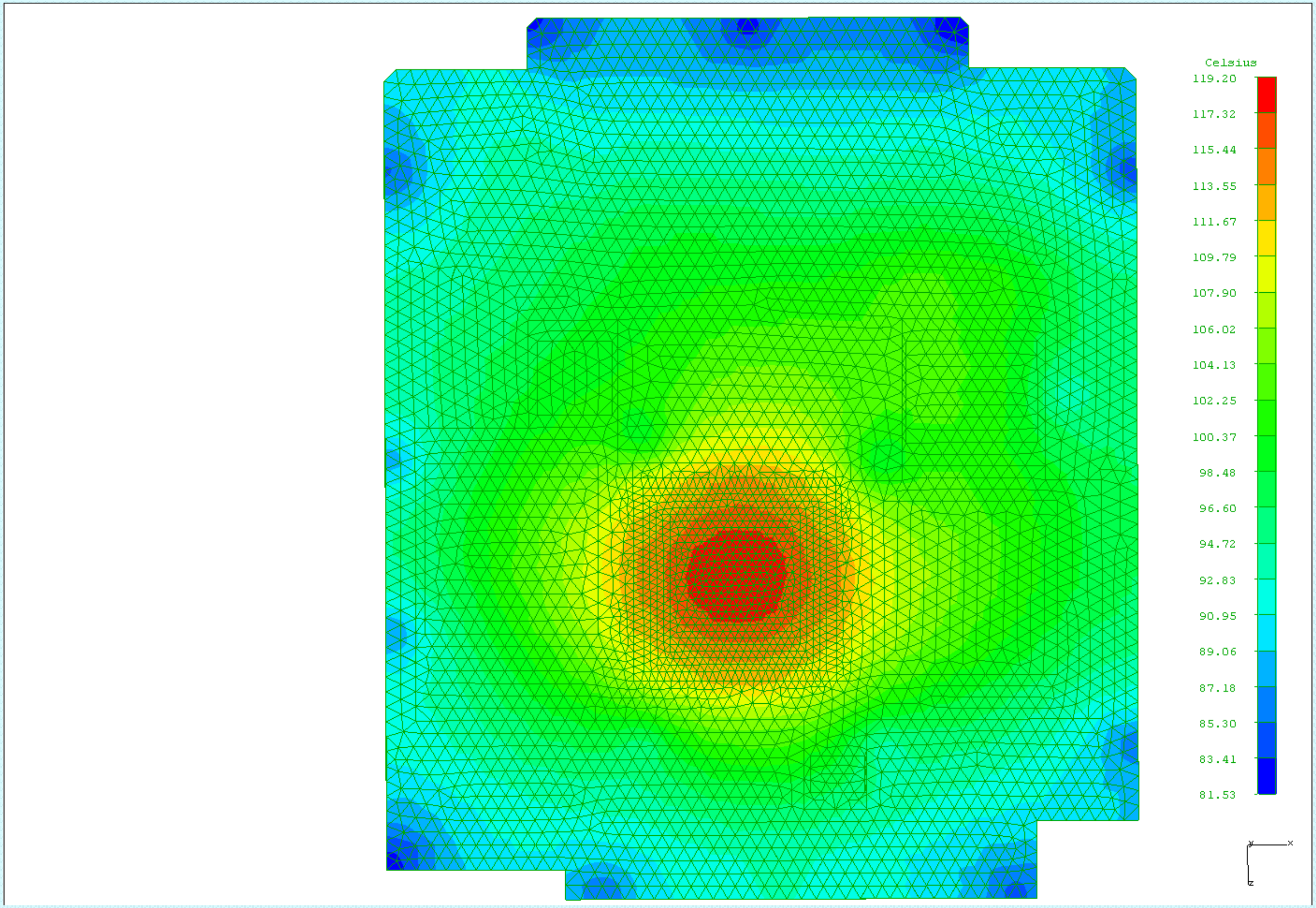
http://spinoff.nasa.gov/spinoff1997/ct4.html

Box Temp Rise



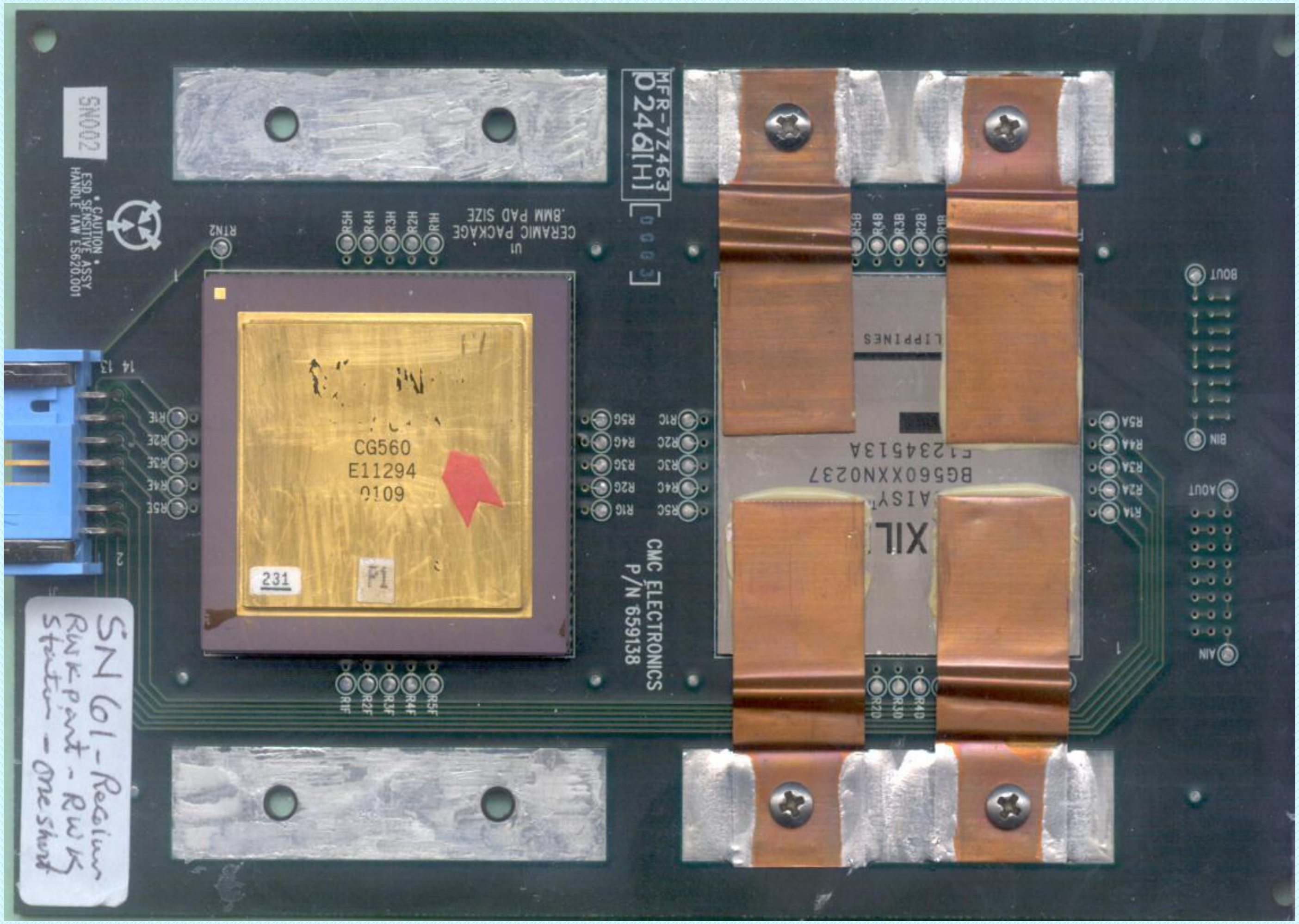
Temperature Contour Plot – Low Power

FPGA Temp Rise – High Power

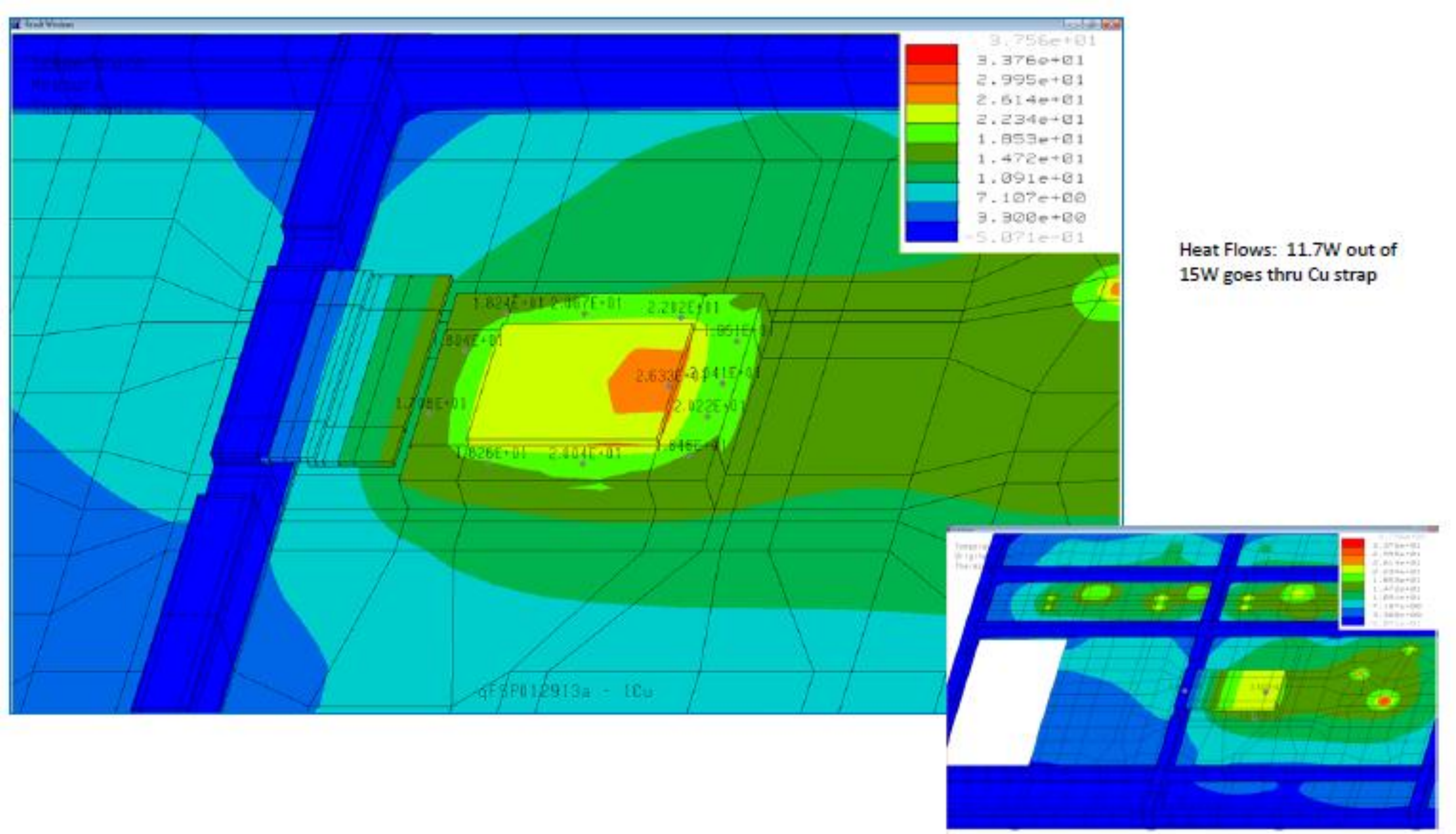


Total rise 49.2 °C from baseplate temp (70°C B/P)

Integrity of Heat Sink for SBGA560



High I/O CGA Temp- WO/W Heat Sink



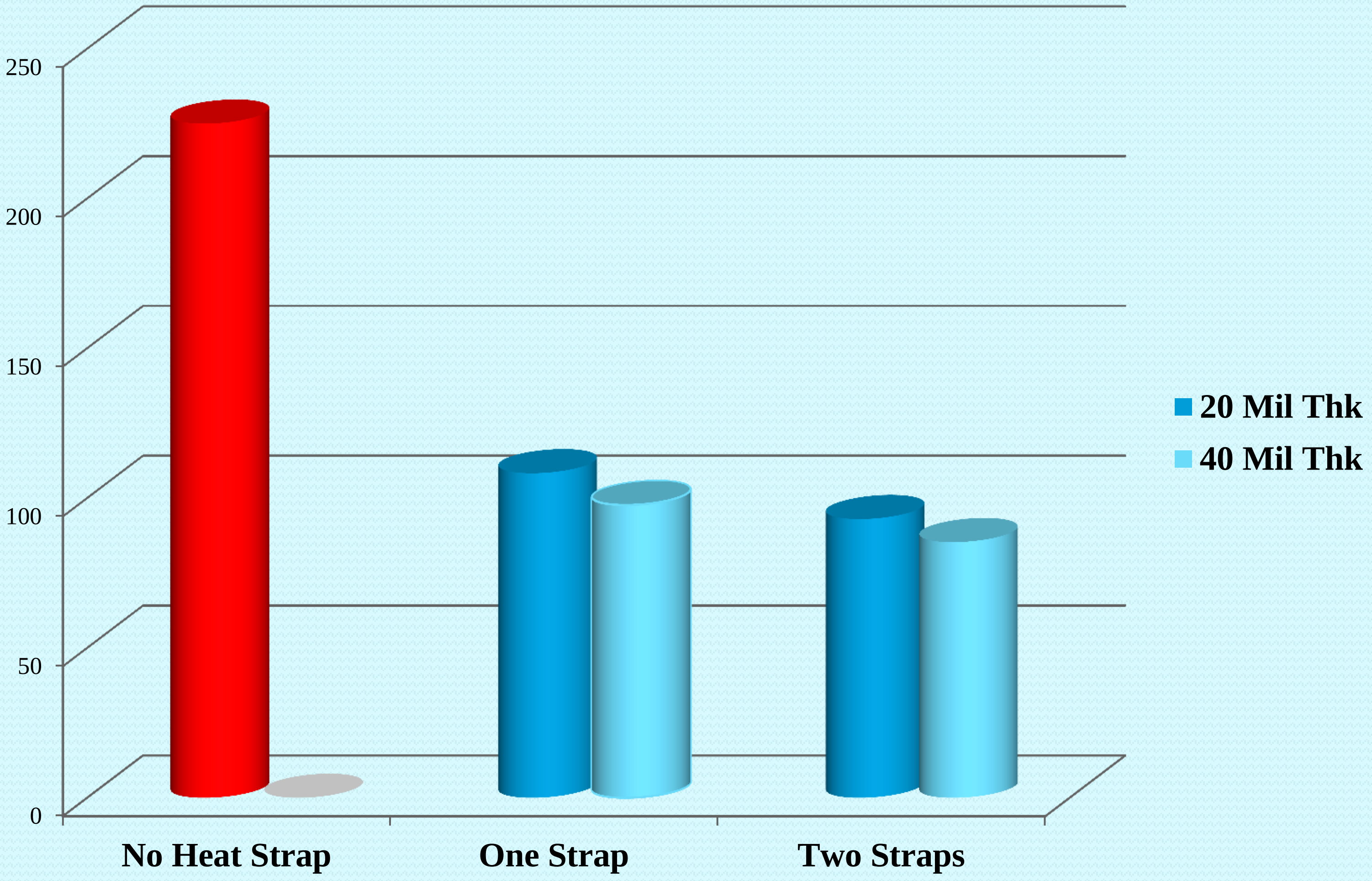
Heat Flows: 11.7W out of 15W goes thru Cu strap

No Heat Sink-Max Temp 225 °C (70°C B/P)

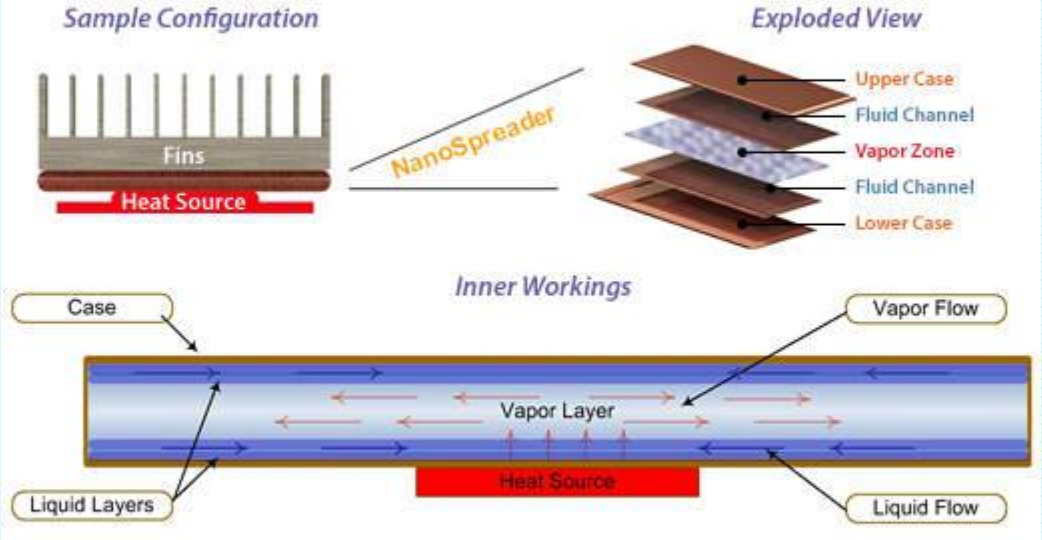
With Heat Sink- Max Temp 98°C (70°C B/P)

Ref: S. Tseng JPL, 2013

Temp Rise WO/W Heat Sink
15 Watts/Close to Radiator



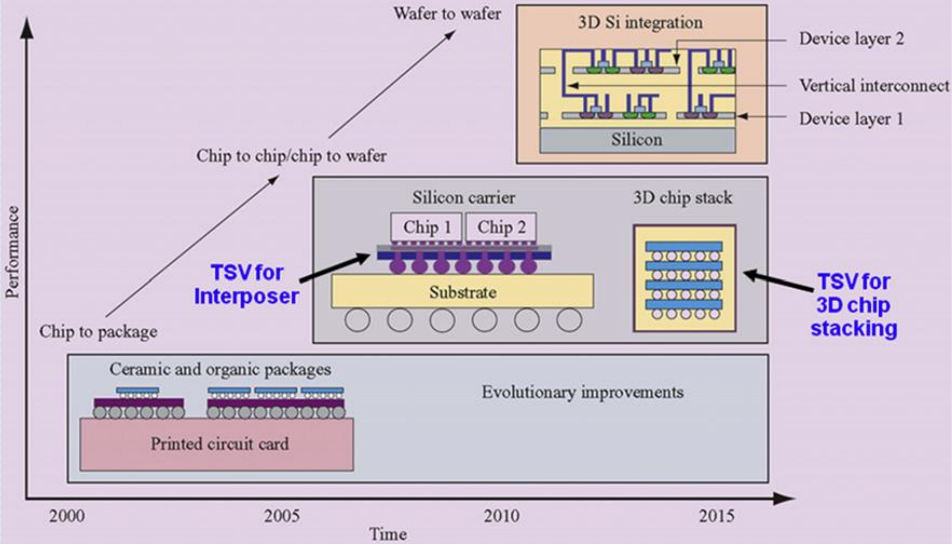
Heat Pipe/NanoSpreader



http://www.celsiatechnologies.com/nanospreader_technology.asp

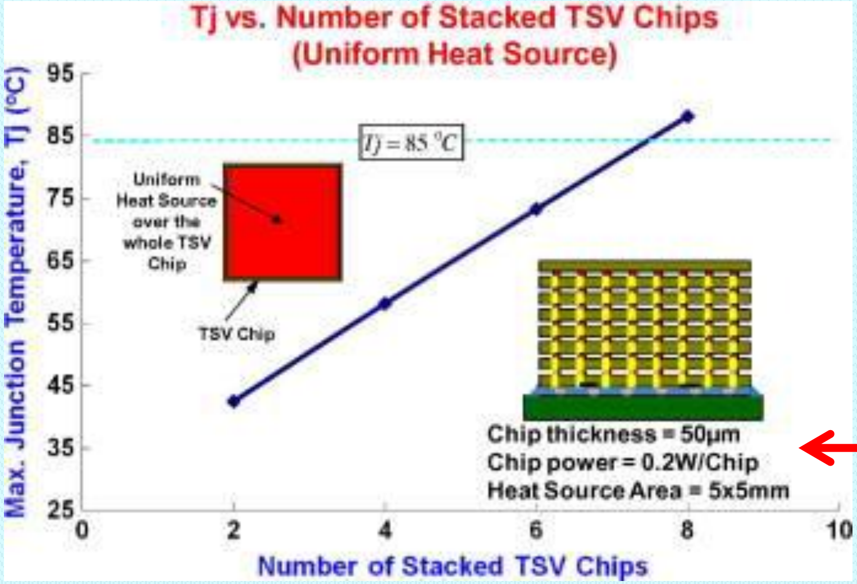
TM for 3D ICs

- Increase in power density
  - Heat of various stacks adds up
  - Cooling of inter-stacks is difficult
  - Heat flux different for each stack
- Local chip overheating
  - Inter-stack spacing is decreasing
  - Thinner die, hot spot
  - Partial remedy by TSV
- 3D stack hotter with
  - Higher stacks
  - Thinner die
  - Coarser TSV pitch, higher aspect ratio (t/d)
  - Thinner interposer, lower via conductivity
  - Smaller die

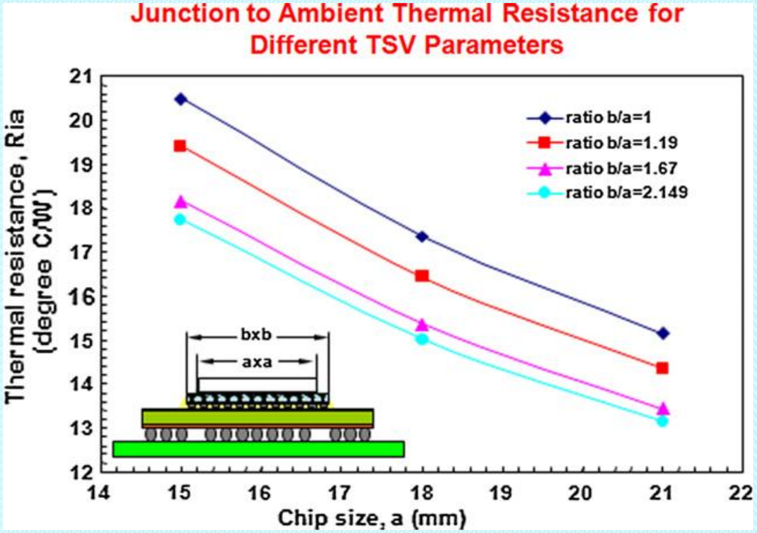


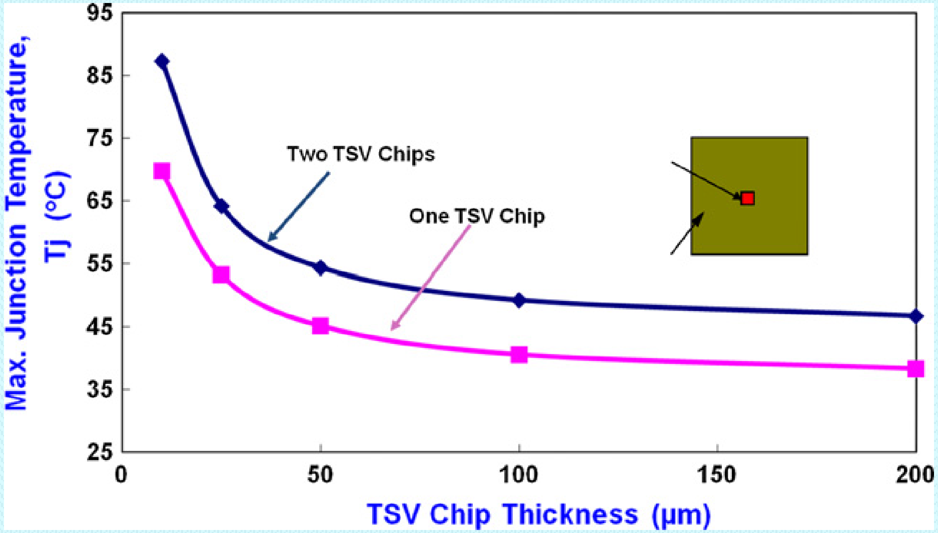
DRAM/ 0.4 W
5x5 mm/10 μm
Hot Spot
138°C>> 85 °C

3D IC &TSV/Die Effects on TM



Chip Power
0.2 W/Chip
5x5 mm
50 micron





http://www.sciencedirect.com/science/article/pii/S0026271412001199

Summary

TM Needs and Growth

- Market
  - Market projects study growth
  - High I/O FPGA/3D ICs continue to grow
  - Technology needs
- Space Applications
  - Limited on use of advanced technologies
  - Reliability and efficiency are critical
  - Processing power grows; therefore TM needs
- Approaches
  - Heat sink
  - Heat pipe
  - New tech. must addresses reliability /efficiency/reworkability
  - System approaches: hardware/software

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