Thermal Science and Engineering - From Macro to Nano in 200 Years

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University of Maryland, Distinguished Univ Prof
AIHTC, President

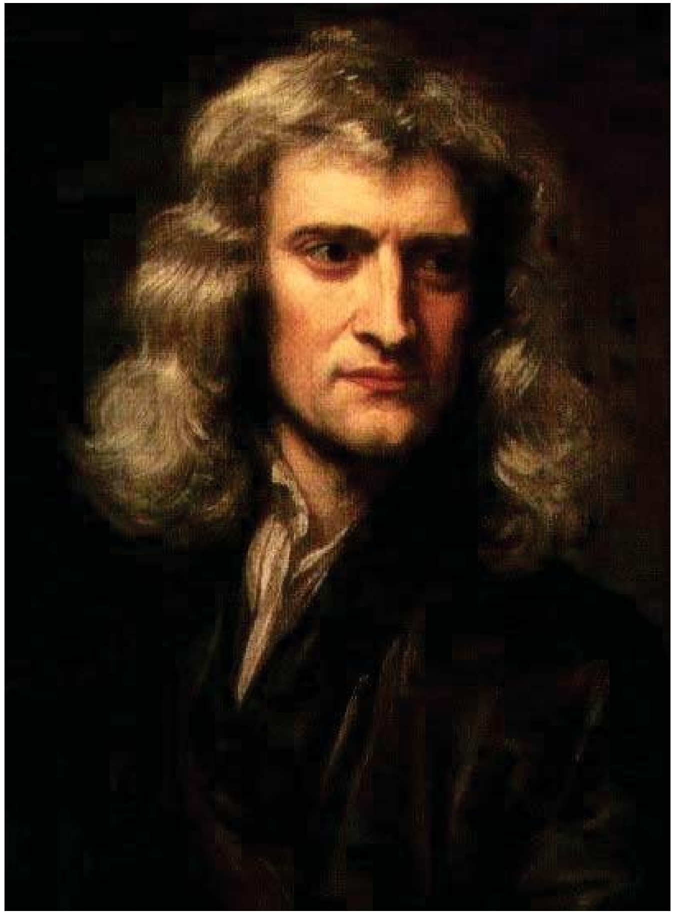
IHTC-15

15th International Heat Transfer Conference
August 10-15, 2014
Kyoto, Japan

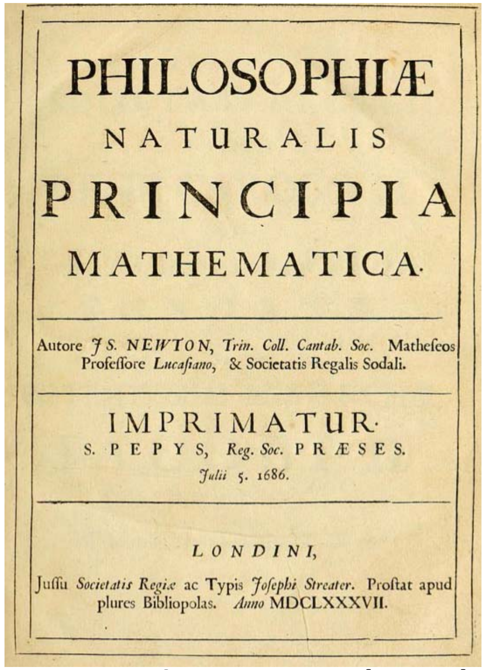
Fourier Lecture Roadmap

- Brief History of Heat Transfer
    - Genesis
    - Foundations of Conduction ***(Macro)***
    - Foundations of Convection ***(Macro)***
    - United States
    - Japan
- Assembly of International Heat Transfer Conferences
- Thermal Packaging of Electronics ***(Micro to Nano)***

Genesis of Heat Transfer



Isaac Newton (1642-1727)



PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

Autore J S. NEWTON, *Trin. Coll. Cantab. Soc.* Matheseos Professore *Lucasiano*, & Societatis Regalis Sodali.

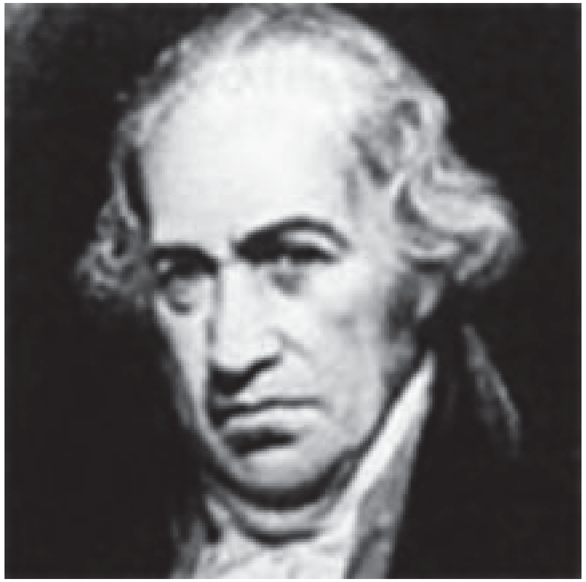
IMPRIMATUR.
S. PEPYS, *Reg. Soc.* PRÆSES.
Julii 5. 1686.

LONDINI,
Jussu *Societatis Regiæ* ac Typis *Josephi Streater*. Prostat apud plures Bibliopolas. *Anno* MDCLXXXVII.

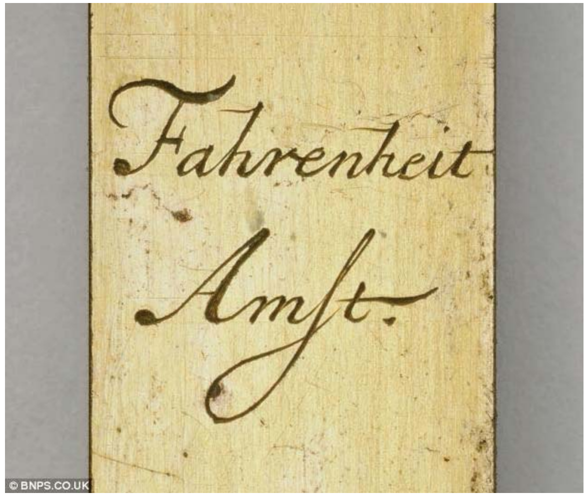
Newton's *Principia* (1687)

- Transient heat transfer experiments
- Devised linseed oil thermometer
- Rate of cooling proportional to temperature difference (1701) – Newton's Law of Cooling
- Distinction between natural and forced convection

Genesis of Heat Transfer



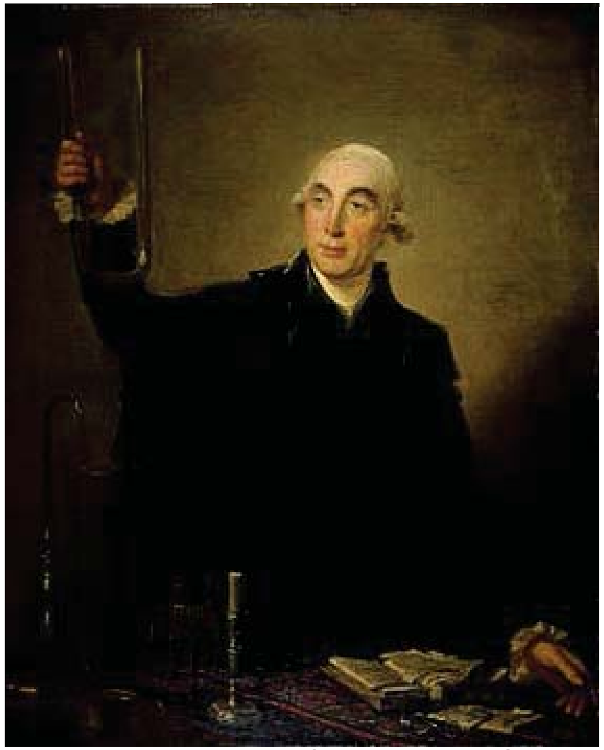
Daniel Fahrenheit (1686-1736)



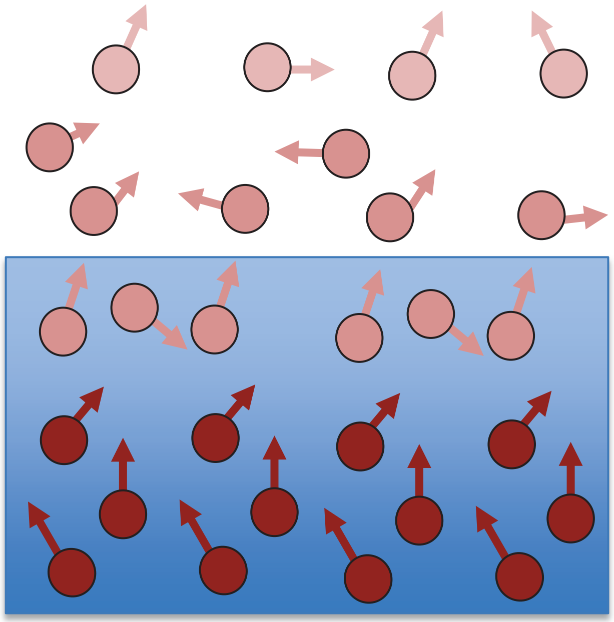
One of Fahrenheit's Thermometers

- Established thermometric standards for environmental measurements, 1714
- Fahrenheit's thermometer consisted of vertical glass tube, filled with mercury
- Temperature scaled to make environmental temperatures positive; divided water freezing point (32˚F) to boiling point (212˚F) into 180 segments

Genesis of Heat Transfer



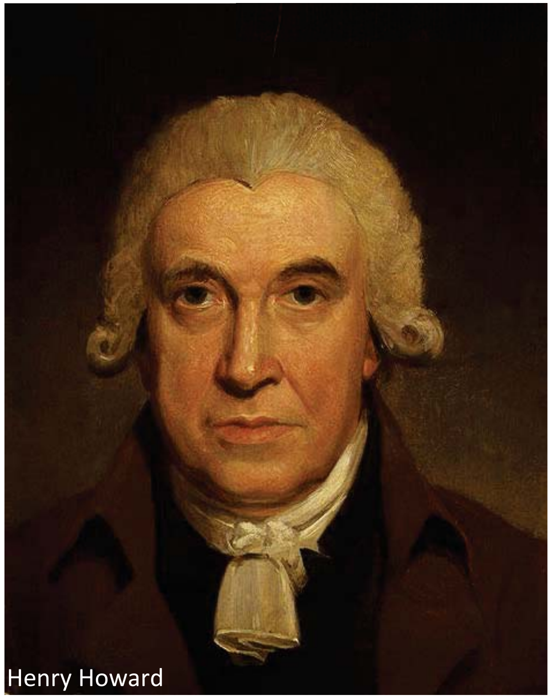
Joseph Black (1728-1799)



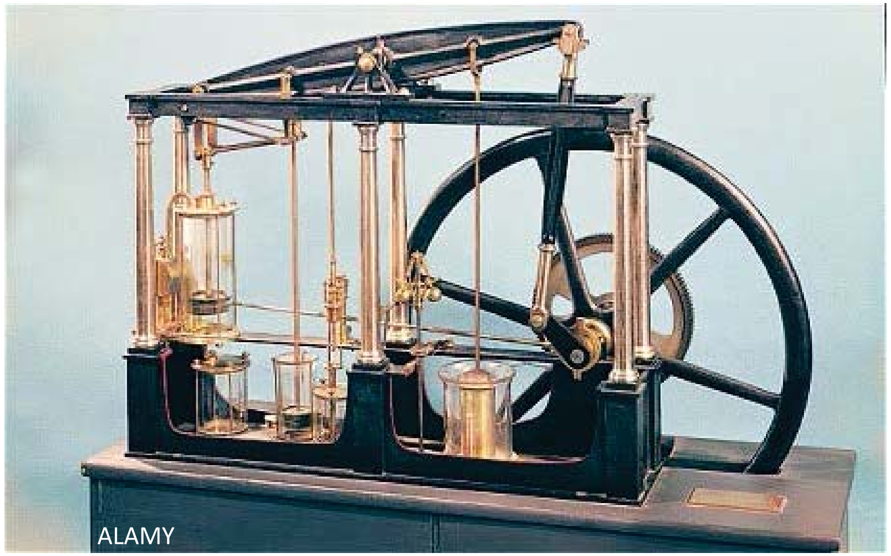
Evaporation

- Clear distinction between heat and temperature
- Observed that each material has it's own "capacity for heat"
- Empirically quantified "latent heat" of fusion, later latent heat of evaporation

Genesis of Heat Transfer



James Watt (1736-1819)

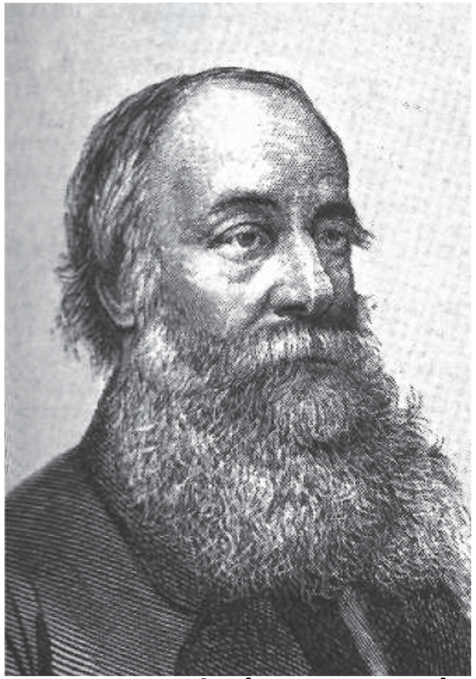


1781 Watt Steam Engine

Father of Thermal Engineering

- Applied Black's observations to create efficient & powerful steam engine
- Watt steam engine far more powerful than Newcomen steam engine
  - Separated condenser from body of engine
  - Ushered in the Industrial Age!

Genesis of Heat Transfer



James Joule (1818-1889)

Joule's paddlewheel and calorimeter, proved that heat and mechanical work are forms of energy

- Discovered relationship between mechanical work and heat
  - Officially refuted Caloric Theory with careful experiments
  - "Joule Equivalent" - mechanical equivalency of heat
  - "Joule heating" with electricity
- Experimentally confirmed 1st law of Thermodynamics (Energy Conservation)

ThermPES

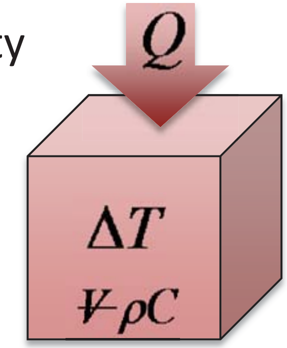
Foundations of Conductive Heat Transfer

Described three fundamental properties of heat flow:

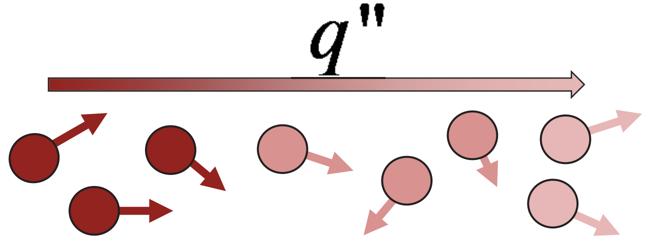
Joseph Fourier (1768-1830)

Father of Thermal Science

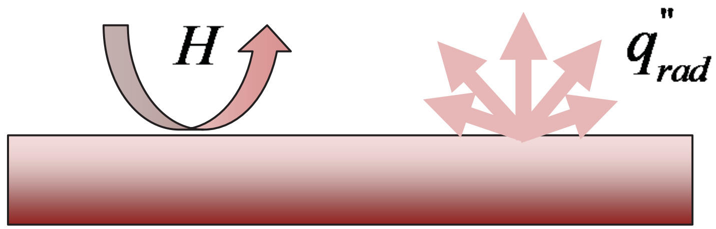
1. Heat Capacity



2. Interior Conductibility

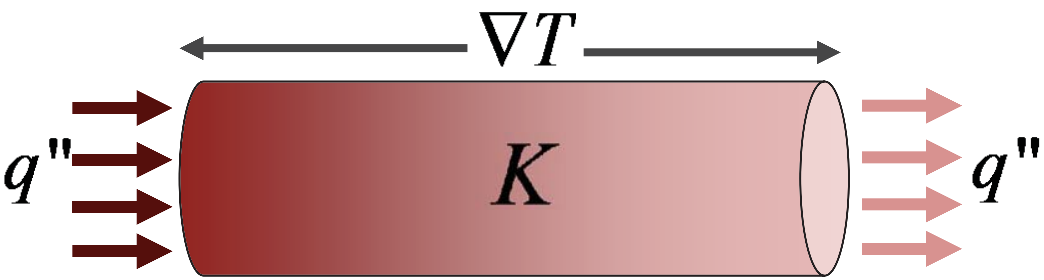


3. Exterior Conductibility (surface heat exchange)



Foundations of Conductive Heat Transfer

Joseph Fourier (1768-1830)



$$q'' = -K\nabla T$$

Fourier's Law

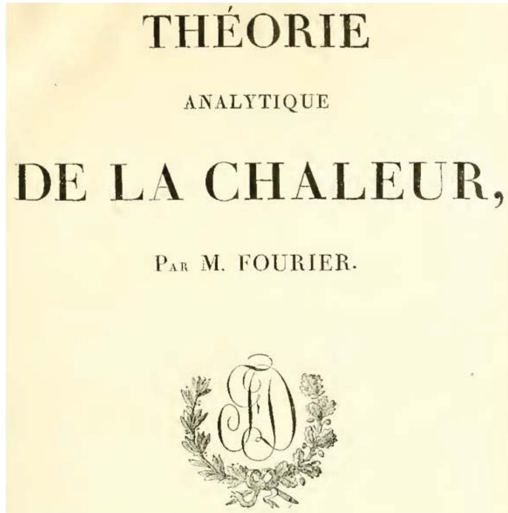
- Obsessively interested in heat transfer after joining Napoleon's army in Egypt (1798)
- Fourier's Law derived in *On the Propagation of Heat in Solid Bodies* (1807)
- Added heat transfer coefficient to Newton's Law of Cooling

Foundations of Conductive Heat Transfer

Joseph Fourier (1768-1830)

$$\rho C \frac{\partial T}{\partial t} = K \nabla^2 T$$

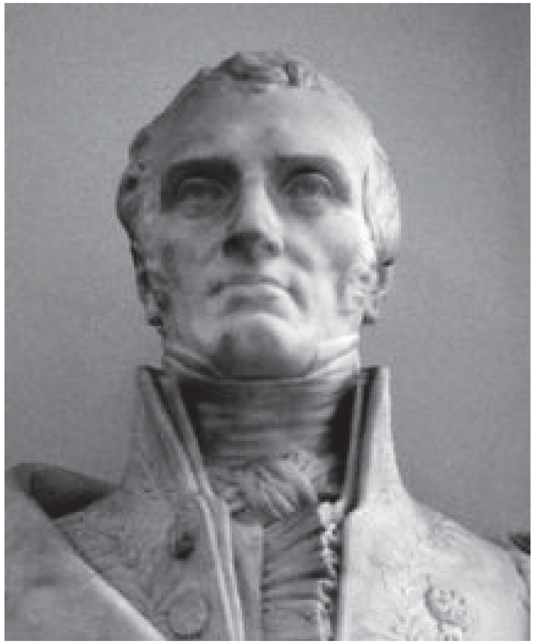
Heat Equation



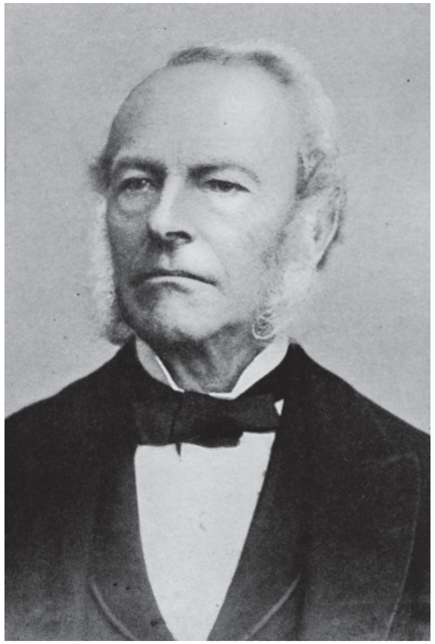
The Analytical Theory of Heat

- Fourier's memoir revised into "Prize Essay" and won the Grand Prize in Mathematics from the Institute de France in 1812
  - General form of interior conduction derived in "Prize Essay"
- Compilation of Fourier's work published in 1822, *The Analytical Theory of Heat*

Foundations of Convective Heat Transfer



C.L.M.H. Navier (1785-1836)



Stokes (1819-1903)

$$\rho \frac{Du_i}{Dt} = \rho F_i - \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left\{2\mu\left(e_{ij} - \frac{1}{3}\Delta\delta_{ij}\right)\right\}$$

Navier-Stokes Equation of Motion

$$T\frac{DS}{Dt} = c_p \frac{DT}{Dt} - \frac{\beta T}{\rho}\frac{Dp}{Dt} = \Phi + \frac{1}{\rho}\frac{\partial}{\partial x_i}\left(k\frac{\partial T}{\partial x_i}\right)$$

Energy Equation

- Navier-Stokes equation derived independently by Stokes (England) and Navier (France) in the early 1800's
- Energy equation was *arguably* derived with the 1833 Fourier-Poisson differential equation

Foundations of Convective Heat Transfer

1881: Lorenz

- Buoyancy-induced convective transport

1885: Graetz

- Thermal entrance region in pipe flow

1842: Reynolds

- Laminar & turbulent flow
- Turbulent heat transfer

1904: Prandtl

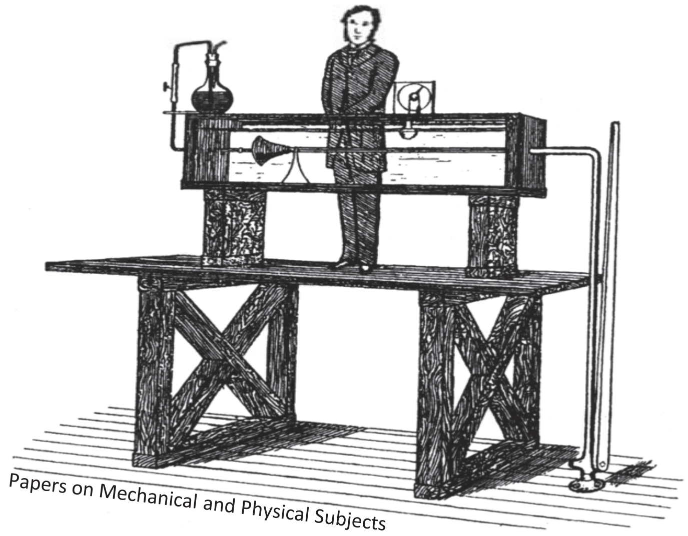
- Boundary layer concept
- Mixing length model

1915: Nusselt

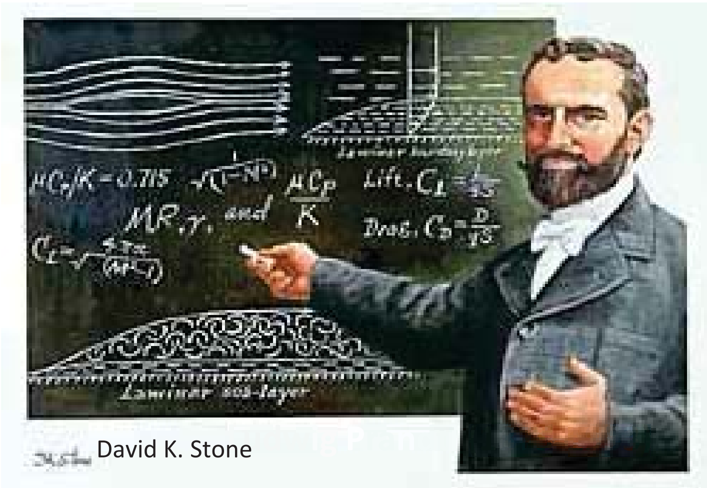
- Convective heat transfer
- Underlying dimensionless groups

1920's-30's: Max Jakob

- Steam thermal transport – boiling & condensation



Osborne Reynolds (1842- 1912)



Foundations of Convective Heat Transfer

Wilhelm Nusselt (1882-1957)

$$Nu = \frac{hL}{k} = \frac{\text{Convective}}{\text{Conductive}}$$

Dimensionless Nusselt Number

- In 1907, received doctorate in Mech. Eng. from Munich Technical University, Germany
- In 1915, published prominent paper: *The Basic Laws of Heat Transfer*
- Proposed dimensionless groups in convective HT using similarity theory
- Established a foundation for subsequent formidable advances in convective, radiative, and two-phase heat transfer across the world

IHTC Since 1951 Heat Transfer in the United States

Allan P. Colburn (1904-1955) [11]

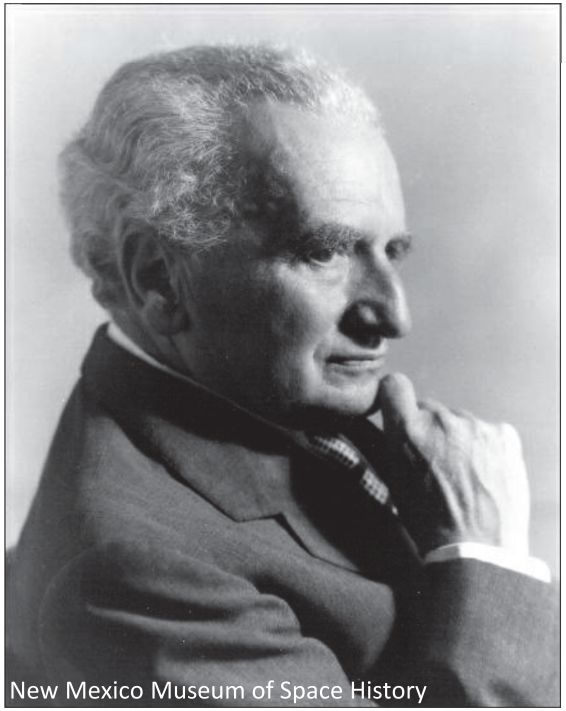
$$J_M = \frac{f}{2} = J_H = \frac{h}{c_p G}\mathrm{Pr}^{\frac{2}{3}} = J_D = \frac{k_c^{'}}{\bar{v}} \cdot Sc^{\frac{2}{3}}$$

J-Factor Analogy

- First US Heat and Mass Transfer Effort: University of Delaware's Chemical Engineering Department
- In 1936, Colburn published "Colburn Analogy" and heat transfer "J-Factor"
- Colburn's shell-and-tube HX research nurtured US HX industry

ThermPES

Heat Transfer in the United States



Theodore von Karman (1904-1955)

Jet Propulsion Laboratory

- von Karman escaped Germany when the Nazi regime started purging Jewish professionals in 1933
- Accepted Cal Tech's invitation to become head of Guggenheim Aeronautics Lab, later renamed JPL
  - Created foundation for American rocket and missile technology
  - Founded Aerojet Corporation, advised NASA

Heat Transfer in the United States

The Engines of Our Ingenuity

Max Jakob (1879-1955)

$$Ja = \frac{c_{p,f}\left(T_{sat} - T_w\right)}{h_{fg}}$$

Jakob Dimensionless Number

- In 1936, fled Nazi Germany to avoid persecution, after illustrious 25 year career
- Over 200 technical publications with profound heat transfer impact
- In 1938, became professor of Mech. Eng. at IIT and founded the Heat Transfer Lab
- Textbook and a two-volume treatise on heat transfer had a profound influence on heat transfer education and research in the United States

Heat Transfer in the United States

Stothe P. Kezios (1921-2005)

- "Mid-West" thermal engineering initially driven by Jakob at IIT
- 1937-1938 Heat Transfer lectures influenced several prominent academic leaders: Stoethe P. Kezioss (ITT), George Hawkins (Purdue), and Richard Jordan (Minnesota)
- Kezios became chair of Heat Transfer Division (1958-59), 1st editor of ASME Journal of Heat Transfer (1963), and ASME's 96th president (1977-78)

IHTC Since 1951 Heat Transfer in the United States

George A. Hawkins (1907-1978)

- Hawkins drove from Purdue to IIT to attend Jakob's 1937-1938 lectures
- Dean of Engineering at Purdue from 1953 to 1967
- Established world class heat transfer program at Purdue

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IHTC Since 1951 Heat Transfer in the United States

Richard Jordan (1909-2002)

Ernst Eckert (1904-2004)

- Jordan became head of Minnesota's Mechanical Engineering Department (1950)
- Persuaded Eckert to join department and establish the Thermodynamics and Heat Transfer Laboratory (THTL) at Minnesota in 1951
- THTL seminal contributions by E.M. Sparrow, Warren Ibele, Richard Goldstein, James Hartnett, Patankar, Simon, Bar-Cohen,…
- Mid-West key to formation of AIHTC and ICHMT

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IHTC Since 1951 Heat Transfer in the United States

William H. McAdams (1892-1975)

Warren M. Rohsenow (1921-2011)

- “East Coast” thermal engineering initially driven by McAdams at MIT
- Authored “Heat Transmission” in 1933 – primary teaching and reference book
- Warren Rohsenow joined MIT in 1946, established Heat Transfer Laboratory
    - Expanded research of boiling and condensation
    - Mentored numerous luminaries: Clark, Griffith, Mikic, Bergles, …….

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Heat Transfer in the United States

Llewellyn M. K. Boelter (1898-1966)

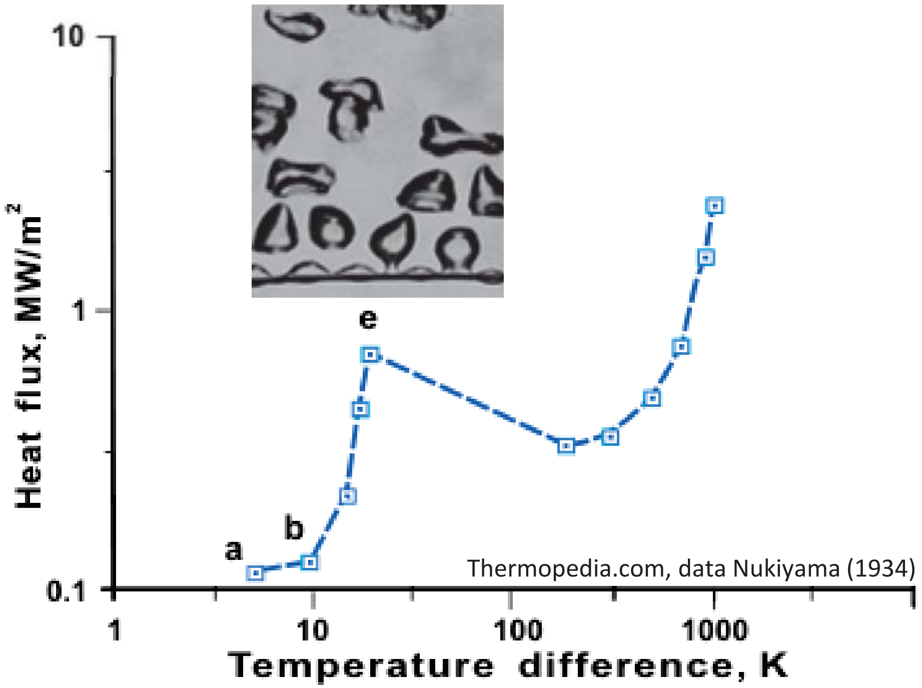
$$Nu_D = 0.023\,\mathrm{Re}_D^{4/5}\,\mathrm{Pr}^n$$

Dittus-Boelter Correlation
(Turbulent Pipe Flow)

- "West Coast" thermal engineering initially driven by Llewellyn Boelter at UC Berkeley
- Moved from EE to ME in 1923, formed heat transfer program with Floyd Cherry, Harold Johnson, and Robert Martinelli,
- Boelter produced analytic "Heat Transfer Notes" and Dittus-Boelter heat transfer coefficient correlation for Turbulent pipe flow

Heat Transfer in Japan

Shiro Nukiyama (1896-1983)



Nukiyama curve, 0.14nmm platinum wire, water

- Professor at Tohoku University from 1921 to 1956
- Pioneer in the understanding of boiling phenomena
- Established the Nukiyama boiling curve in the 1930's

Heat Transfer in Japan

Yasuo Mori (1923-2012)

- Professor of Tokyo Institute of Technology from 1961 to 1983
- Significant impact on heat transfer community with a wide range of subjects:
    - Convective heat transfer, magneto-hydrodynamic power generation, plasma, high-temp, condensation, geothermal, and ocean thermal energy
- Emphasized broad applications of thermal science and physics-based approach

IHTC Since 1951 Assembly of IHTC

Beginning of IHTC:

- "International Discussion on Heat Transfer"– London & Atlantic City, 1951

- "International Heat Transfer Conference" – Colorado, 1961
  - Companion meeting for USSR researchers in London, 1962

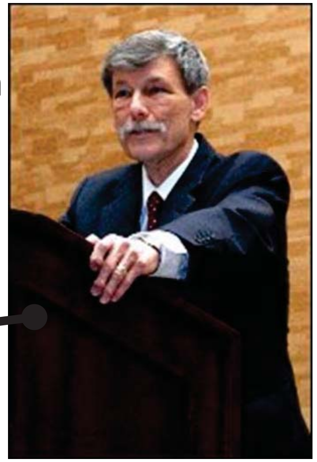
- 4-Year IHTC cycle began with 3rd conference – Chicago, 1966
  - Lead by Hartnett, Rohsenow, Eckert, Kezios, and Kutateladze
  - William Begell as publisher

History of IHTC's

IHTC Since 1951

AIHTC

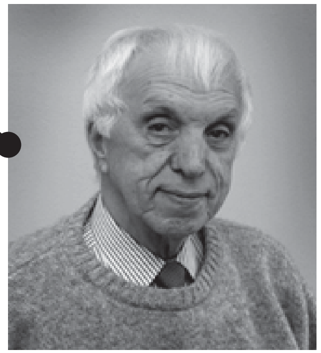
Kyoto, Japan (2014)	
Washington, DC, USA (2010)	
Sydney, Australia (2006)	
Grenoble, France (2002)	
Kyongju, Korea (1998)	
Brighton, UK (1994)	
Jerusalem, Israel (1990)	
San Francisco, USA (1986)	
Munich, Germany (1982)	
Toronto, Canada (1978)	
Tokyo, Japan (1974)	
Versailles, France (1970)	
Chicago, USA (1966)	



Avram Bar-Cohen
Conference Chair

Graham De Vahl Davis
Conference Chair

Geoffrey Hewitt
Program Chair



Richard Goldstein
Conference Chair

Sam Sideman
Conference Chair

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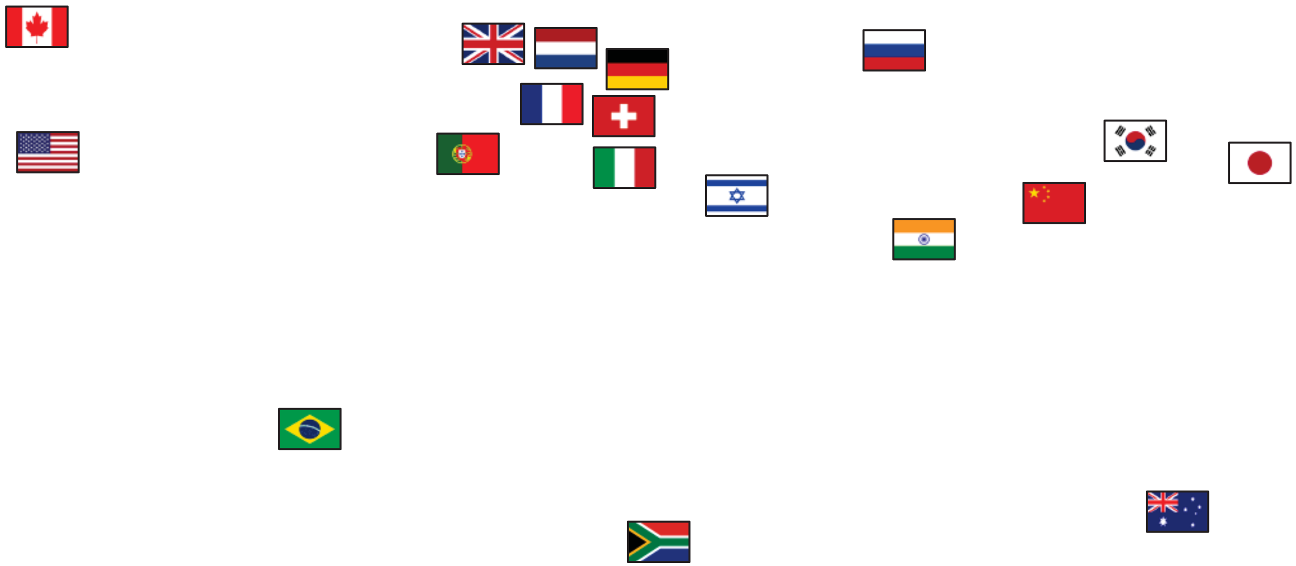
Members of AIHTC

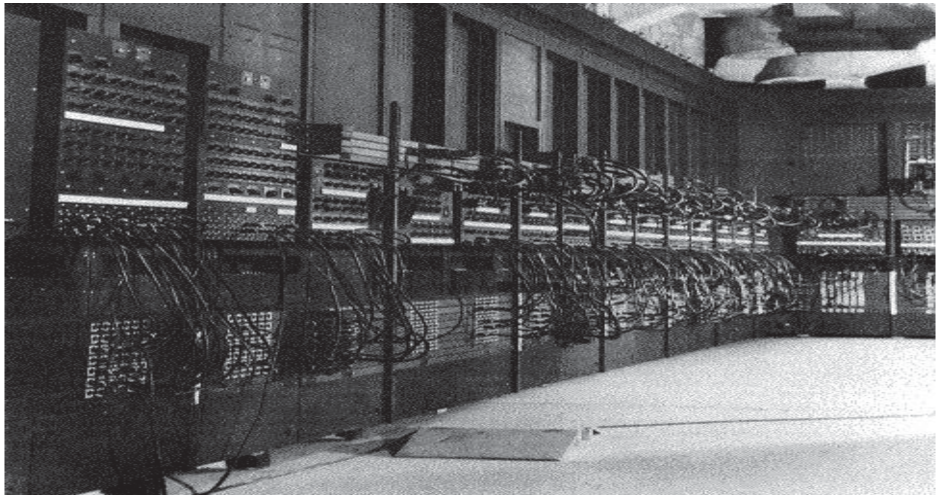


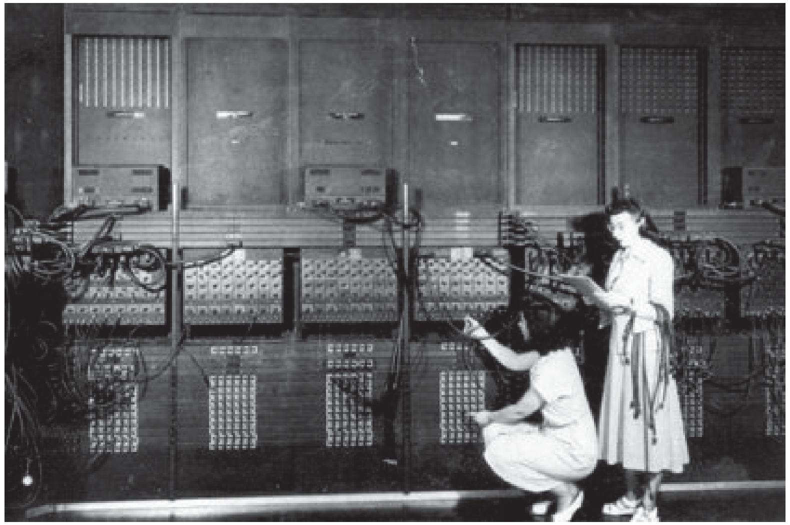
(18)

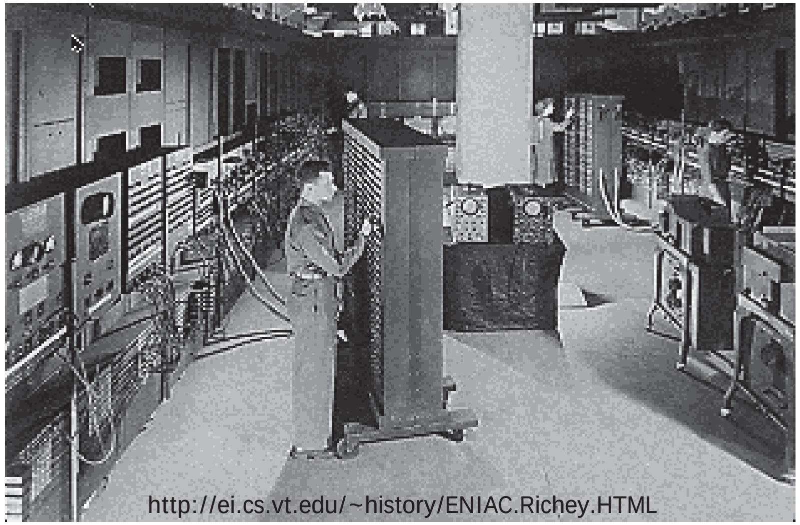
Birth of Thermal Packaging (1946)

Electronic Numerical Integrator and Computer (ENIAC)

- 5000 OPS
- 17,840 vacuum tubes
- 170kW
- 80’ x 8’, 28 tons
- $487,000







http://ei.cs.vt.edu/~history/ENIAC.Richey.HTML

Electronic Numerical Integrator and Computer (1946)

Thermal Packaging of Electronics

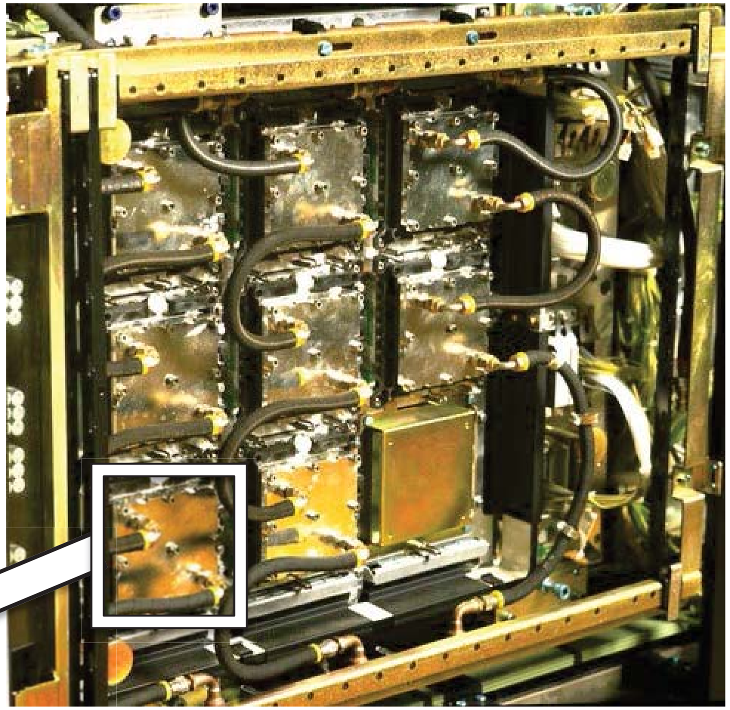
Generations of Thermal Packaging

Gen-2a: Attached Coolers, ’80-…

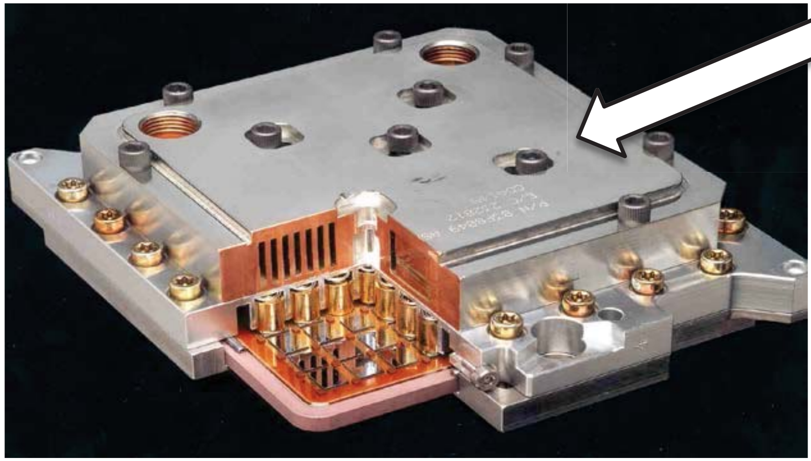
Liquid Coldplate Era ‘80-’90

- Maturation of bipolar devices: ~5W Chips, ~300W Multi Chip Modules
- Honeywell, IBM, CDC, Hitachi, NEC, Fujitsu, Cray,…

<u>GOAL:</u> Control temperature of “coldplate,” “coldbar,”…



IBM 3081 (1980)



IBM 3081 Water Coldplate

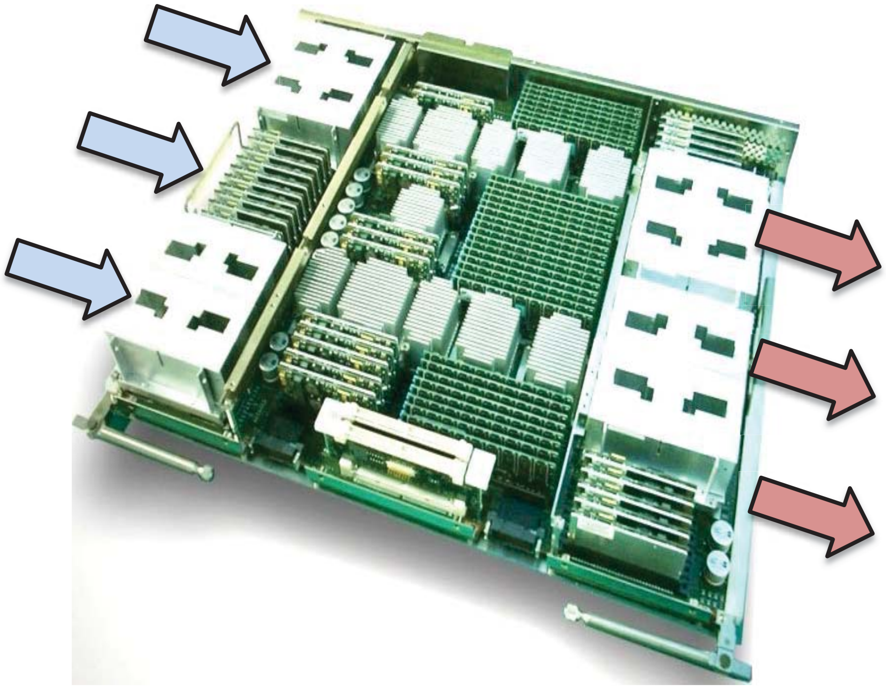
Generations of Thermal Packaging

Gen-2b: Attached Coolers, ’80-…

Heat Sink Era ’85-…

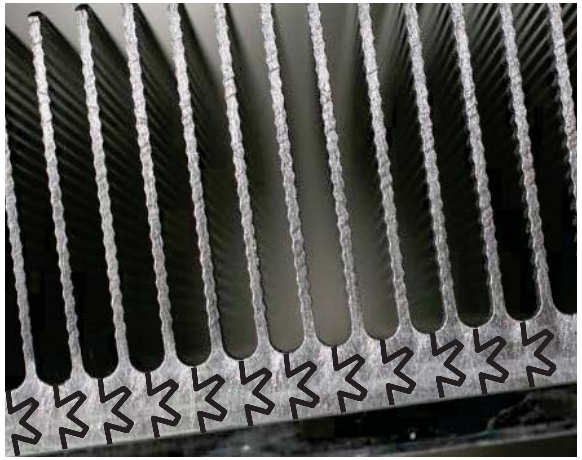
- Optimized heat sinks
- Improved TIM’s
- Air flow paths

GOAL: Reduce ϕ_{ca} “case-to-air” resistance

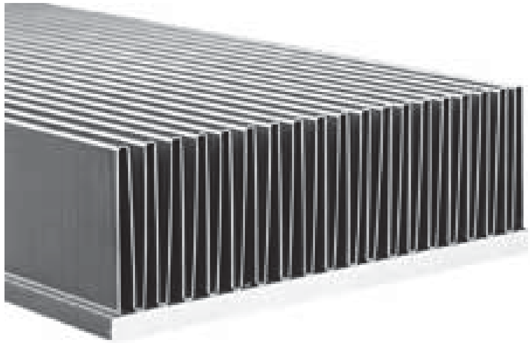


Fujitsu 8 CPU Air-Cooled Board (1985)

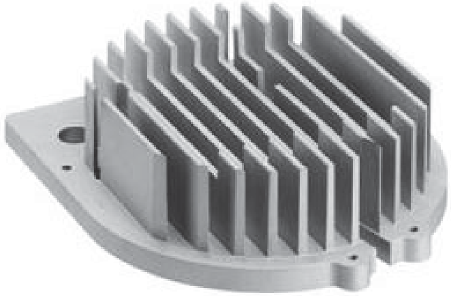
Air-Cooled Heat Sinks



(a) Bonding

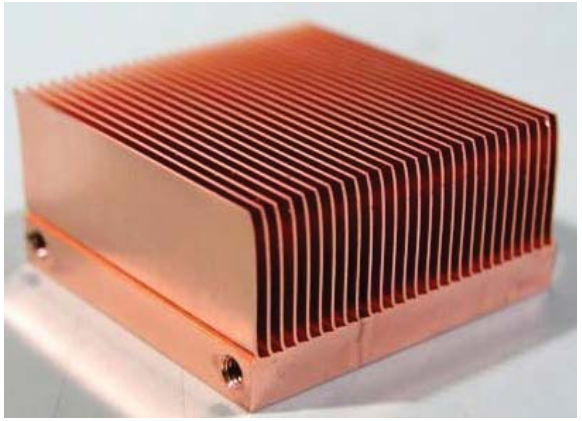


(b) Folding

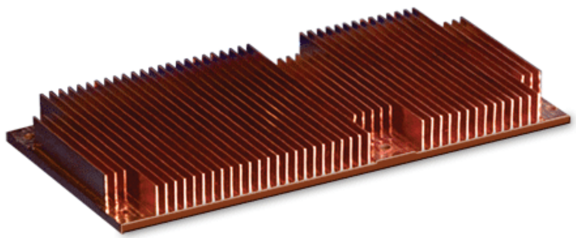


(c) Die-Casting

(d) Forging



(e) Skiving

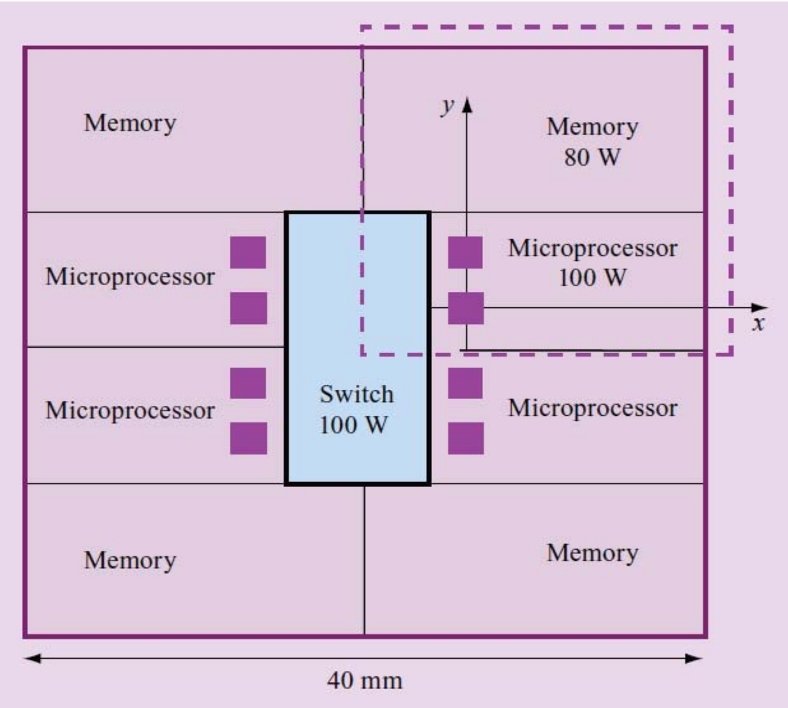


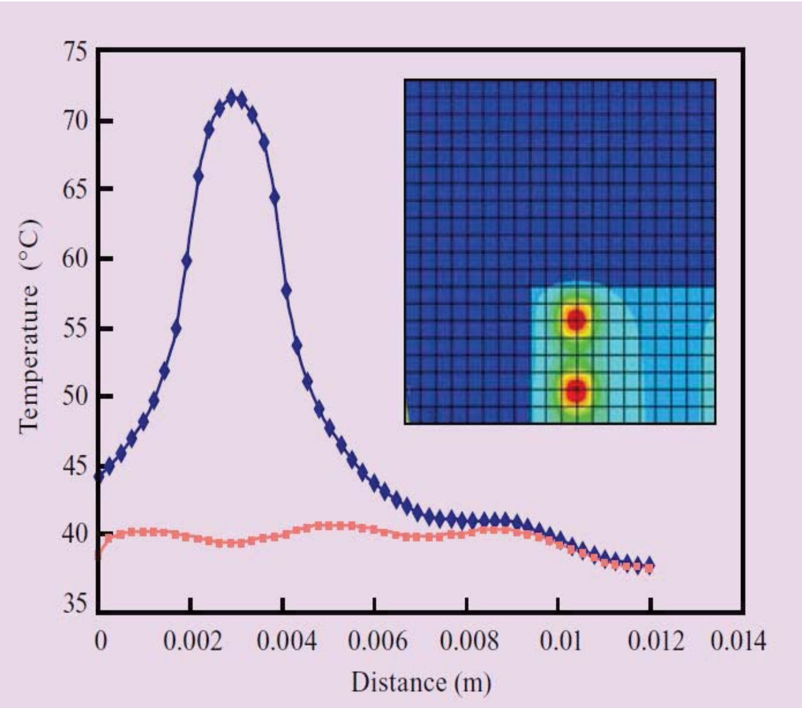
(f) Machining

Thermal Packaging of Electronics

Microprocessor Hot Spots

- $q''_{hot\ spot} = 500\ W/cm^2$ (2 x 2 mm)
- $q''_{avg.} = 50\ W/cm^2$ (40 x 40 mm)



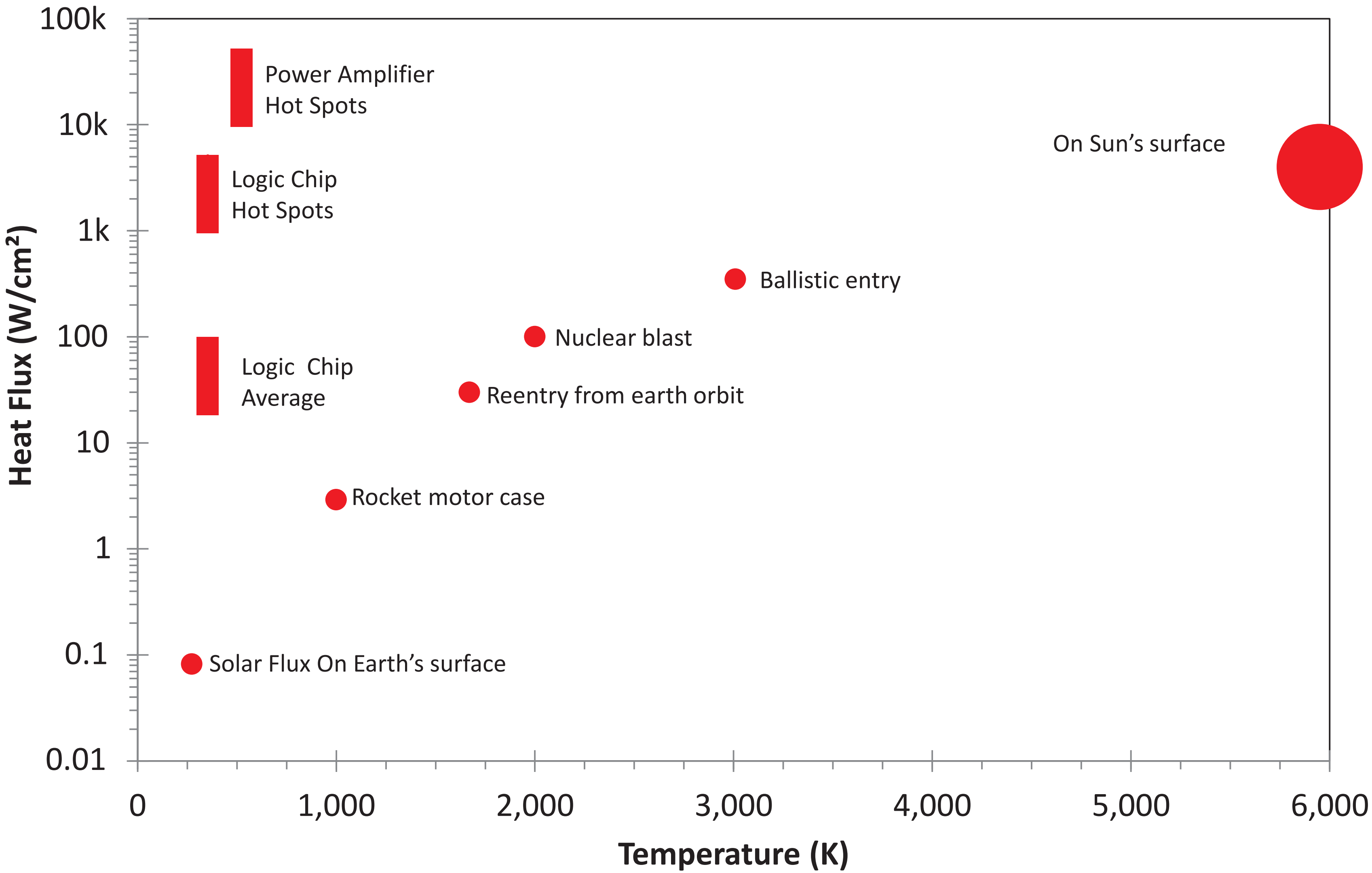


S.M. Sri-Jayantha, G. McVicker, K. Bernstein, J.U. Knickerbocker IBM Journal,Res & Dev, 2008, Vol 52, No 6

On-Chip Hot Spots in IBM 3D Chip Stack

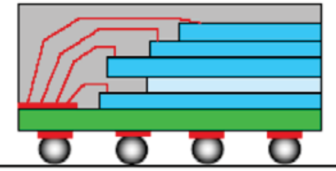
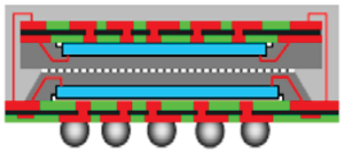
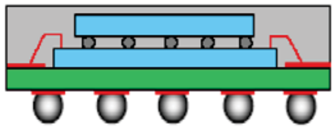
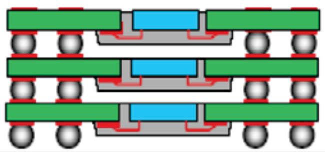
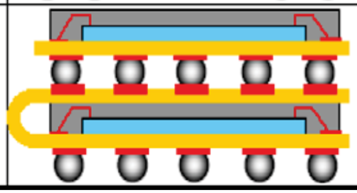
Thermal Packaging of Electronics

Chip Heat Flux Challenge

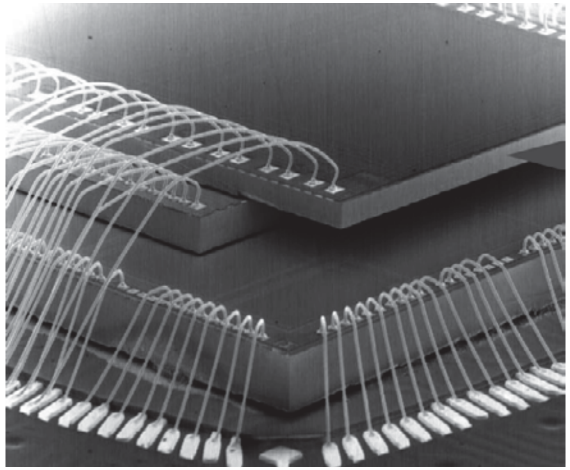


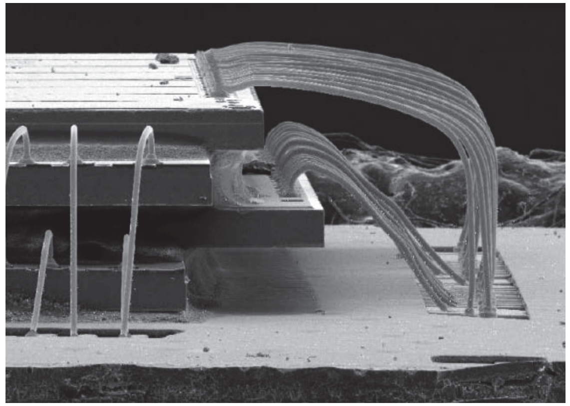
Heat Fluxes for Chips and Other Thermal Engineering Hardware

3D Chip Stacks

Technology & z-Interconnect	Module	Application
Die Stacking (ChipPAC) **Wire Bond**		▶Memory ▶ASIC + Memory
Package Stacking (ChipPAC) **Wire Bond**		▶Memory ▶ASIC + Memory
Die Stacking (ChipPAC) **Flip Chip**		▶ ASIC + other
Package Stacking (Amkor) **Solder Ball**		▶Memory
Folded Stacking (Tessera) **Substrate + Solder Ball**		▶Memory ▶ASIC + Memory

(Dereje Agonafer and Bahgat Sammakia, InterPACK'05)



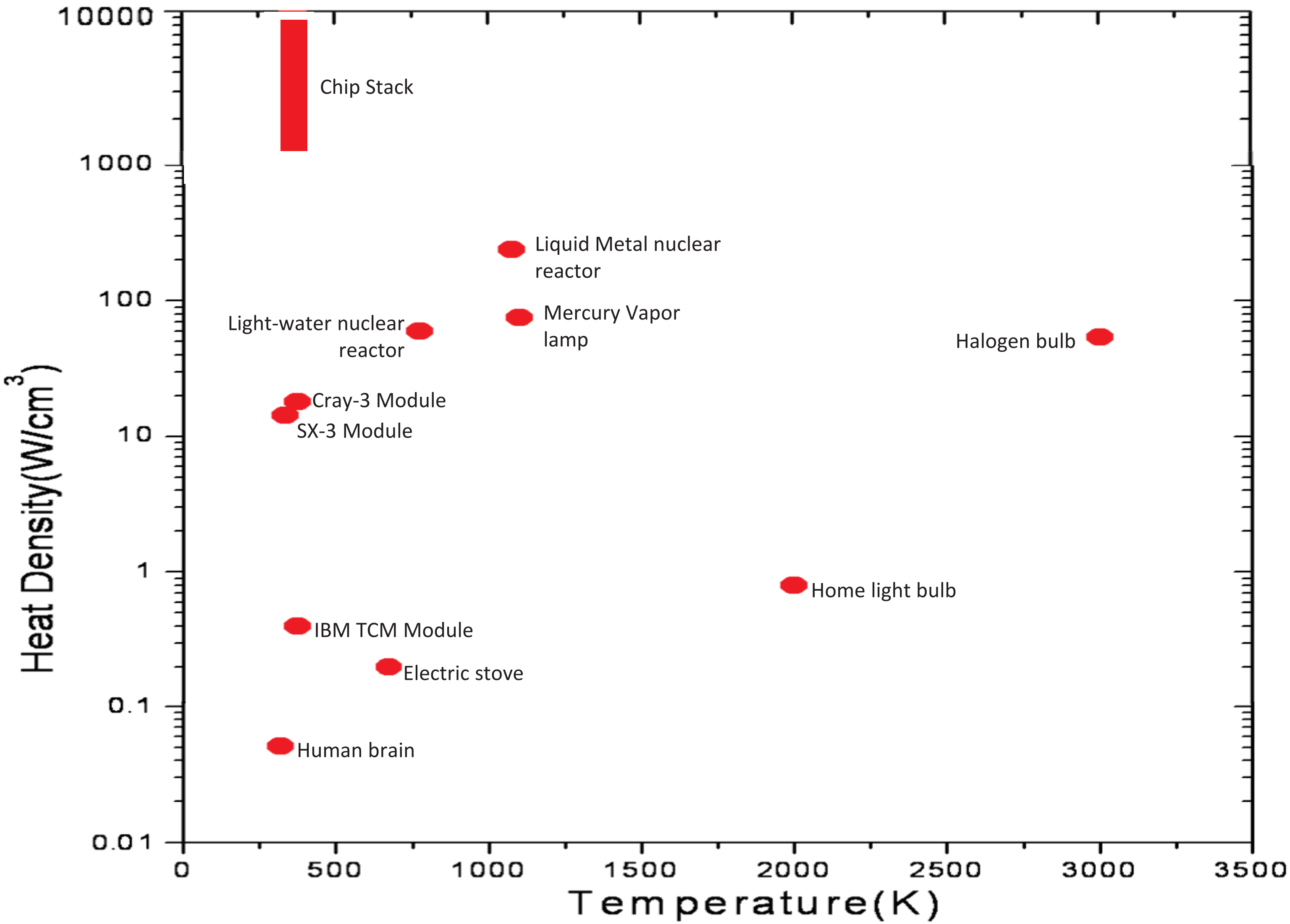


Typical 3D Chip Stacks (2005)

ThermPES

IHTC Since 1951 Thermal Packaging of Electronics

Chip Heat Density Challenge



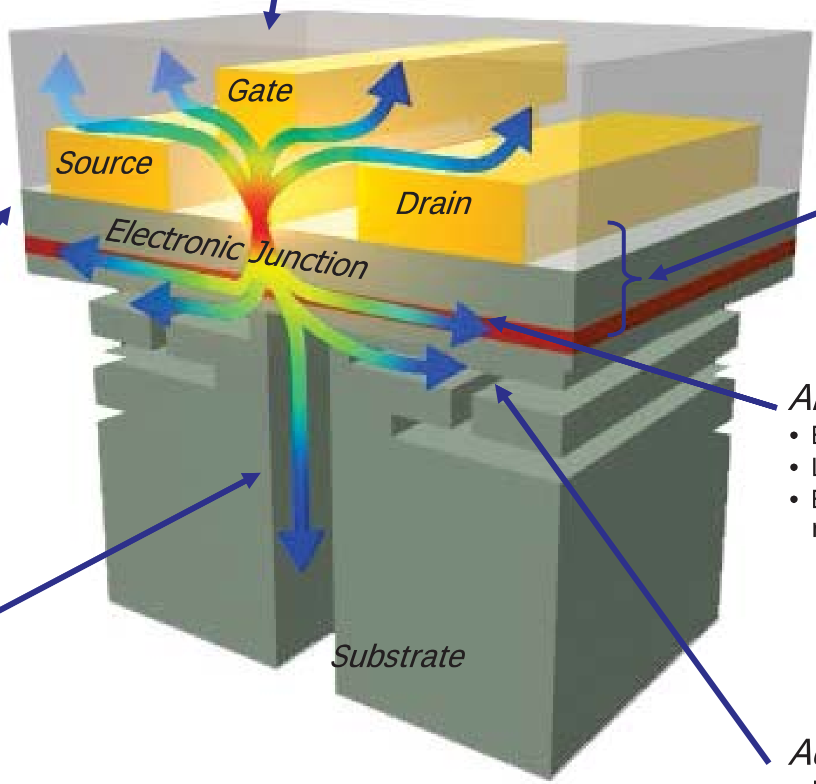
Heat Densities for Chip Stacks and Other Thermal Engineering Hardware

TherPES

Near-Junction Nano Thermal Transport (NJTT)

Vision: Provide localized thermal management within the device substrate to increase Power, Speed, Reliability

High Thermal Conductivity Over-layer for Heat Removal from Topside of Devices
- High thermal conductivity in deposited material
- Conformal coverage with no gaps



~ 1um thickness

High Thermal Conductivity Substrates
- Integrate lattice-mismatched heat spreaders
- Eliminate thermal interface resistance
- Match coefficient of thermal expansion of electronic material

Anisotropic Heat Transport
- Efficient nanoscale phonon channel
- Long LO phonon lifetime (3ps)
- Extremely low electrical contact resistance

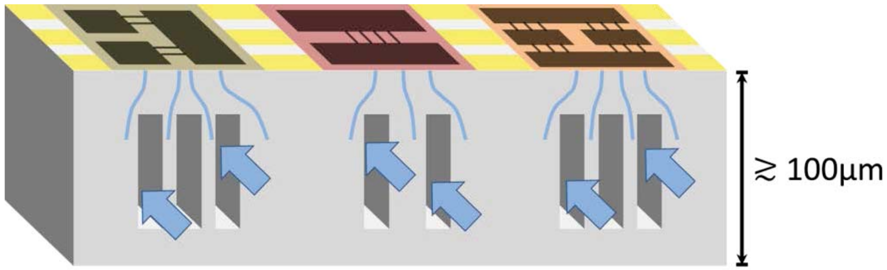
Embedded Thermal Vias
- Micro-machined vias within ~1 micron of junction
- High thermal conductivity conformal fill materials
- Low coupling resistance for junction-to-thermal via, thermal via-to-heat sink

Active Liquid Cooling
- Eliminate impact on device electrical properties due to time varying dielectric constant of liquid

DARPA ICECool Program

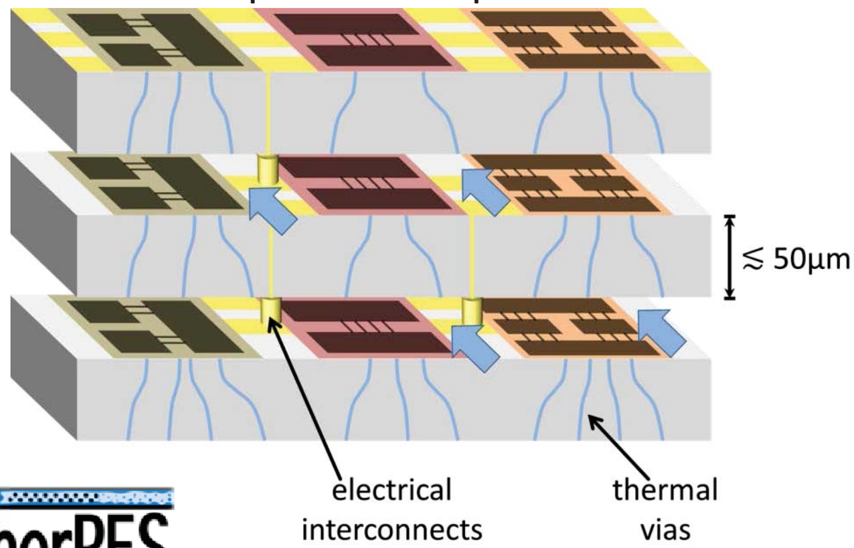
Intrachip:

- Cooling fluid flowing through microchannels fabricated directly into chip



Interchip:

- Cooling fluid flowing through the microgap between chips in 3D chip stacks



- Highly Efficient Cooling
- Chip Heat Flux > 1kW/cm2
- Chip Temperature Rise < 30K
- Hot Spot Heat Flux > 5kW/cm2
- Hot Spot Temperature Rise < 5K

Program Objective:

- Provide the fundamental thermofluid building blocks for the utilization of Intra and Interchip **evaporative** cooling in 3D DoD electronics

Towards an Embedded Cooling Paradigm

Challenges:

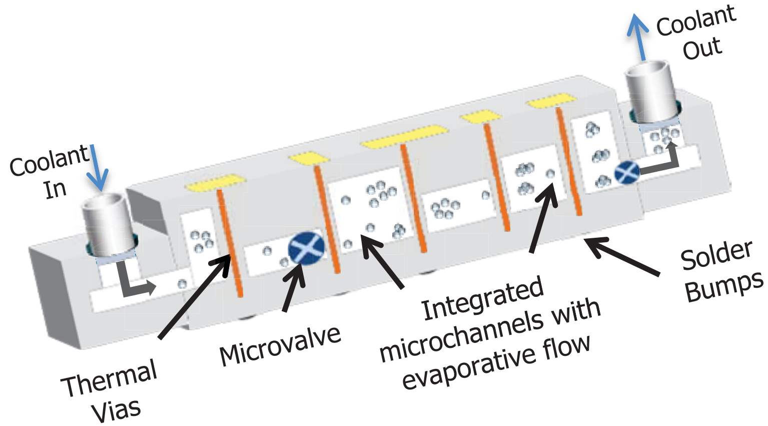
- Complete the Inward Migration of Thermal Packaging
- Extract heat directly from device, chip, and package
- Place thermal management on an equal footing with functional design and power delivery

Benefits:

- Allow electronic systems to reach material, electrical, optical limits
- Reduce SWaP-C for comparable performance
- Lead the way to integrated, intelligent system co-design

Enabling Technologies:

- Microfluidics – convective and evaporative
- Thermal interconnects – active/passive
- Microfabrication – channeling, hermeticity
- Thermal Co-Design



Concluding Remarks

- Long and illustrious history for international thermal science and engineering (TSE)
- AIHTC plays key role in nurturing community
- TSE efforts started in 1800's with Steam Engines, Furnaces, and moved to HVAC, Gas Turbines, and Satellites
- Microelectronics and microfabrication pushed TSE to micro-scale
- Embedded Cooling and nanofabrication necessitate TSE R&D and design at nano-scale.

Arthur E. Bergles, 1935-2014

- Born, NYC 1935
- SB, SM -1958, PhD 1962, MIT
- Married Priscilla, “Penny,” Maule 1960
- Ford Asst Prof, Mech Eng, MIT 1963
- Professor, Mech Eng, Ga Tech, 1969
- Chair, Mech Eng, Iowa State, 1972
- Professor, Mech Eng, RPI, 1986
- Dean, College of Eng, RPI, 1989-1992
- President, ASME, 1990-1991
- NAE member, 1992
- Published 400 papers, 26 books
- Graduated 82 PhD and MS students
- Survived by wife Penny, sons Eric and Dwight, and 5 grandchildren

AEB: “Two are better than one…”
Ecclesiastes, 4:9

Thank You !!

In Memory of:

Professor Yoram Zvirin (1942 – 2013)

Mechanical Engineering, Technion- Israel Institute of Technology

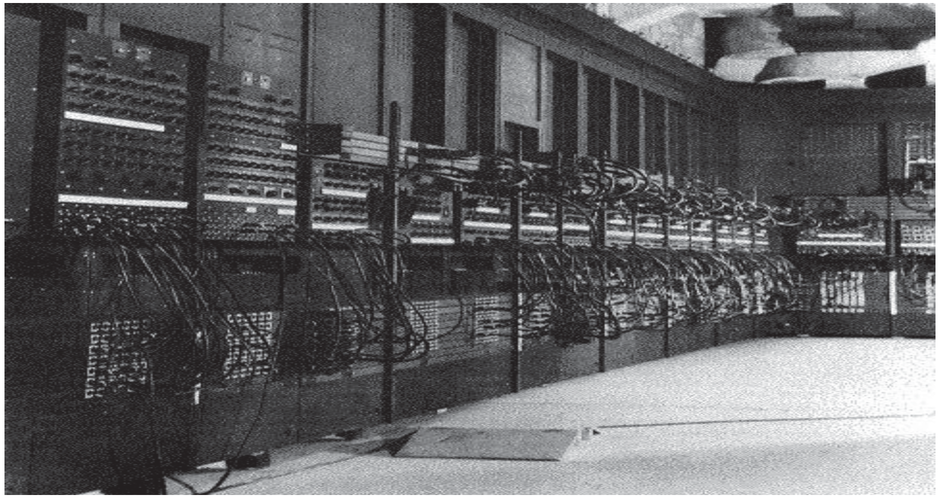
Academic and public service

Head, Technion Transportation Research Institute
Head, Internal combustion engines lab
Director, Israel National Museum of Science
Chairman, Solar World Congress 1999 (Jerusalem)
Secretary, Assembly of IHTC 9, Jerusalem, Israel 1990
ICHMT Scientific Council

Interest areas and contributions

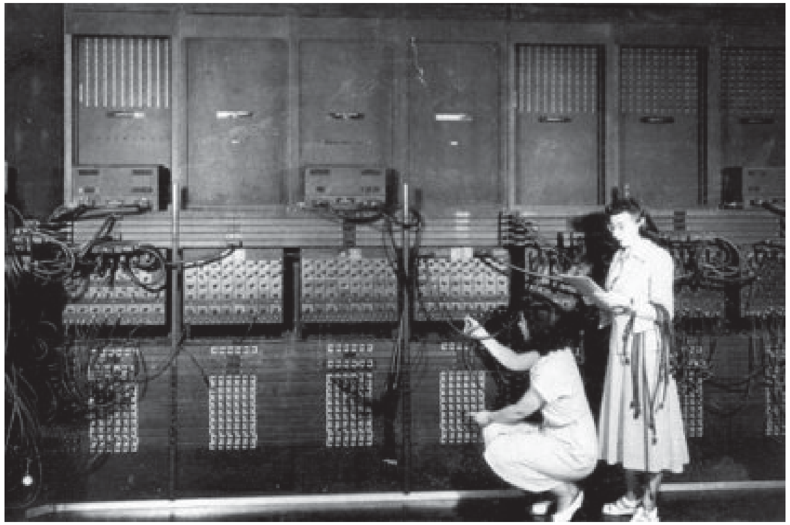
Combustion, fuel efficiency, alternative fuels, emissions
Transportation systems, autonomous vehicles, environmental impacts
Radiative heat transfer, conjugate heat transfer
Solar collectors, Natural convection in thermosyphons

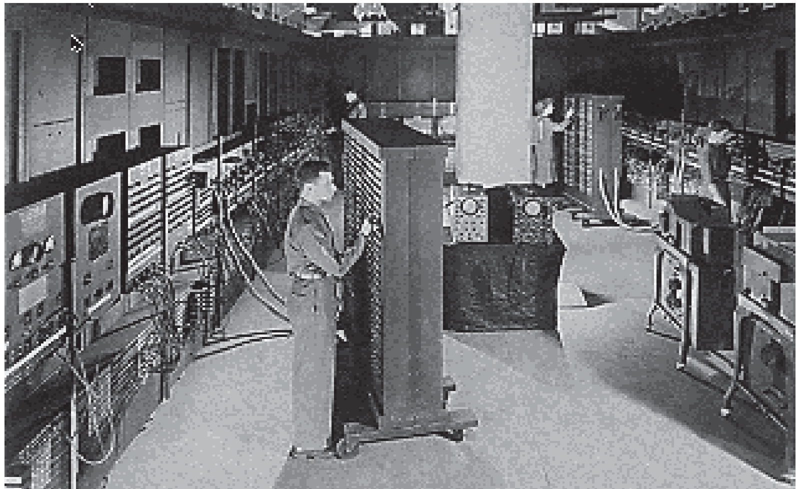
Birth of Thermal Packaging (1946)



Electronic Numerical Integrator and Computer (ENIAC)

- 5000 OPS
- 17,840 vacuum tubes
- 170kW
- 80’ x 8’, 28 tons
- $487,000



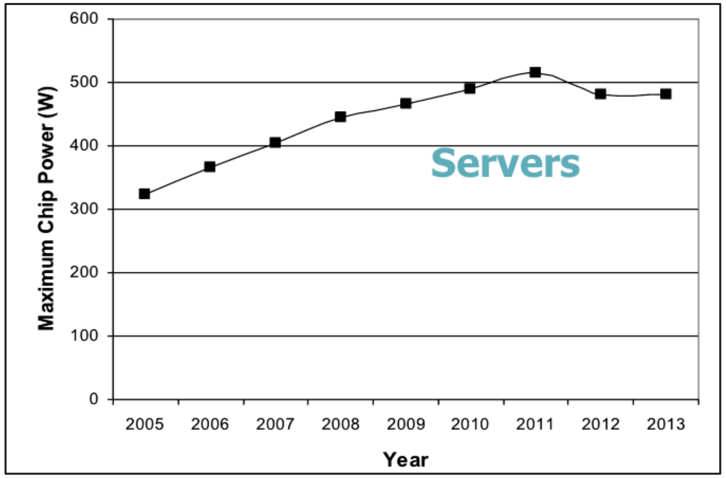


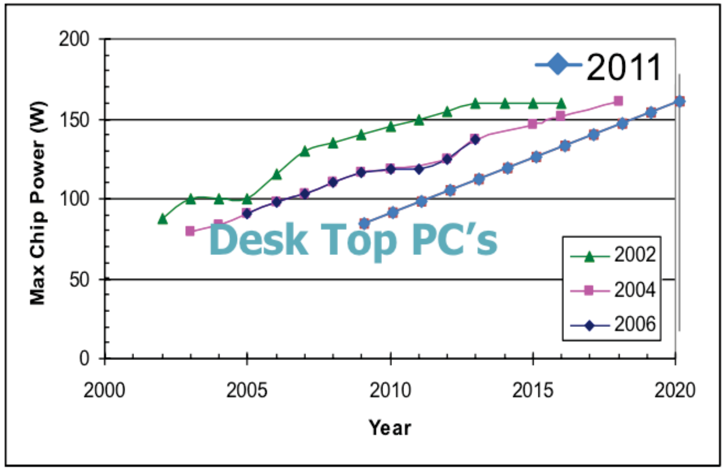
http://ei.cs.vt.edu/~history/ENIAC.Richey.HTML

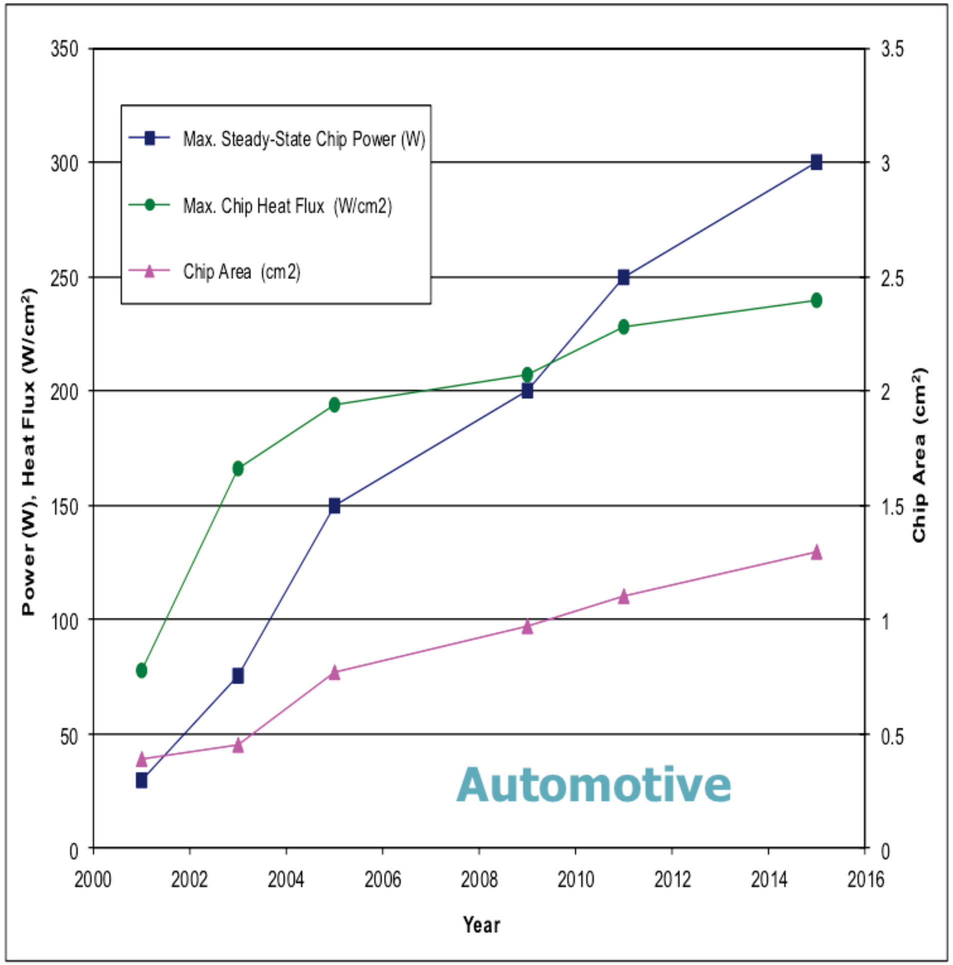
Electronic Numerical Integrator and Computer (1946)

IHTC Since 1951 Thermal Packaging of Electronics

Chip Power Dissipation





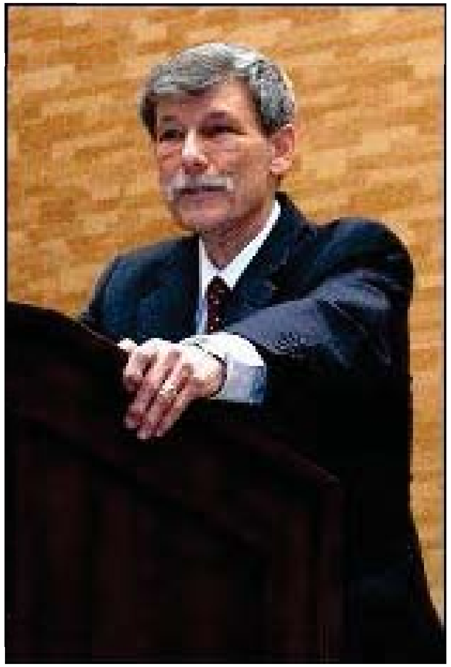


Chip Power Dissipation – iNEMI Roadmap

TherPES

IHTC Since 1951 Heat Transfer in the United States

Aurthur Bergles (1935-2014)



Avram Bar-Cohen

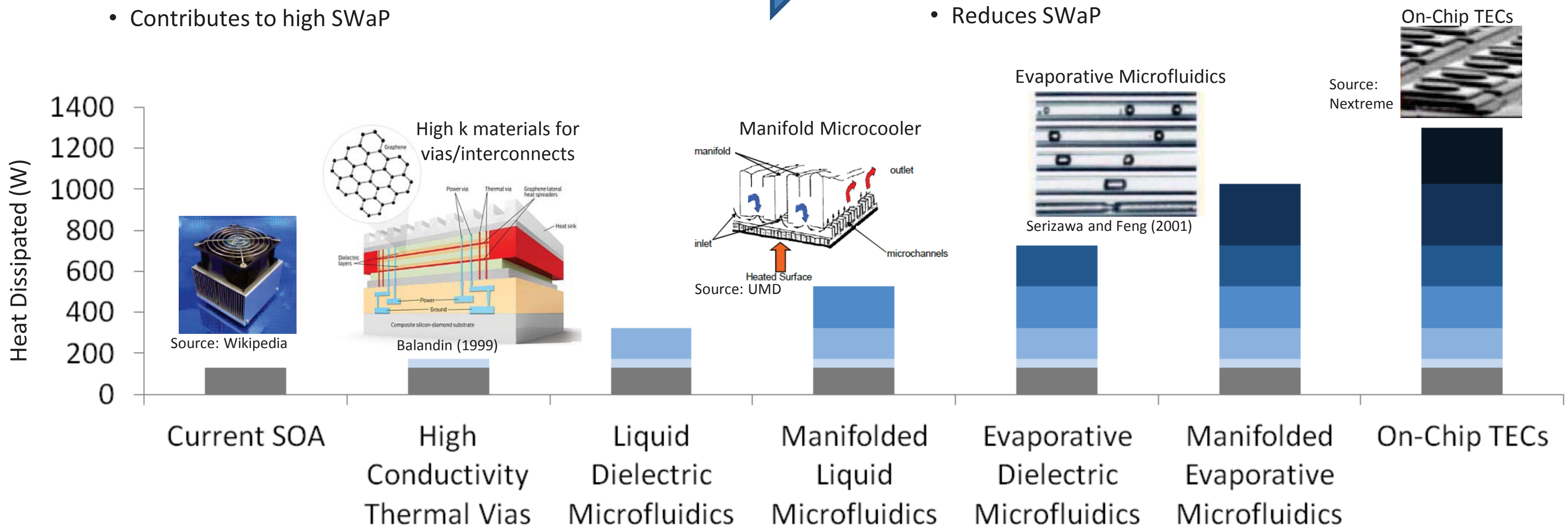
- HT at MIT progressed with: John A. Clark, Peter Griffith, Bora Mikic, and Arthur Bergles
- Avram Bar-Cohen – Distinguished UMD Professor – completed PhD with Art Bergles in 1971
- In 1992, John Lienhard V upgraded MIT's heat transfer laboratory
    - Renamed the Rohsenow Heat and Mass Transfer Laboratory

ThermPES

ICECool Technologies

SOA: Remote Cooling
- Heat removed far from chip
- Low ΔT for heat transfer to ambient
- Limits power dissipation
- Contributes to high SWaP

ICECool: Intrachip/Interchip Cooling
- Heat is removed at the chip
- High ΔT for heat transfer to ambient
- Overcome SOA component thermal limits
- Reduces SWaP



Areas of Focus
- Integrated Microfluidics
- Thermal Substrates and Interconnects
- Thermal Co-Design

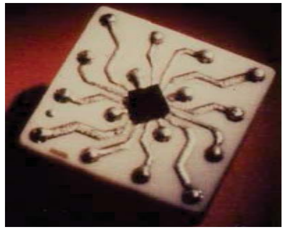
Technology Goals
- GaN MMIC PAs with 10x output power
- Microprocessors with up to 10x frequency

Generations of Thermal Packaging

Gen-1b: Rack Cooling ‘64-’85

- DIP’s and SMT’s on PCB’s
- PCB’s in Card Cages

GOAL: Control rack air temperature



IBM 360 (1982)

PCB “Card Cage”

Thermal Packaging of Electronics

“Triple Threat”

Nanoelectronics Era, 2000-…

- GHz-level CMOS with features below 100nm
- Power dissipation increasing, distinct on-chip “hot spots” on Si/compound semiconductors
- Emergence of homogeneous/heterogeneous “chip stacks” denying access to back of chip for “thermal solution”

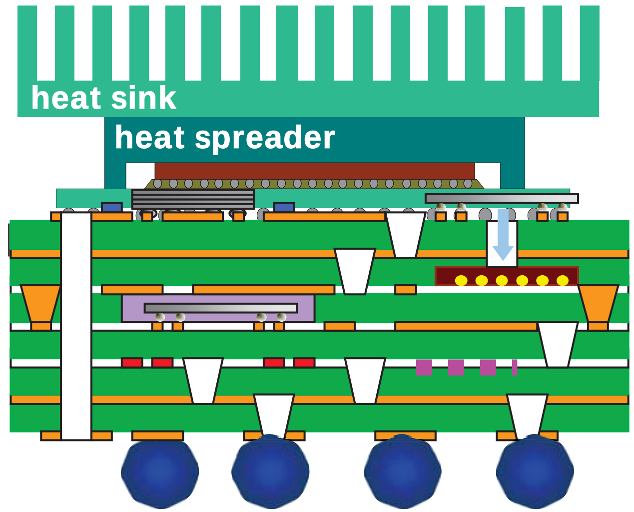
GOALS:

- **Remove large flux**
- **Reduce/eliminate on-chip “hot spots”**
- **Extract high heat density**

High Power

Hot Spots

3-Dimensional



Triple Threat