High Performance Packaging of Power Electronics:

Role of Thermally Engineered Materials

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14. ABSTRACT
? Advantages of new approaches must be demonstrated at the system, e.g., motor drive, level. Device Power Density (A/cm2 or W/cm2) System Power Density (W/m3) Lifetime Assurance of Entire System System Cost Analysis Ultimately Required

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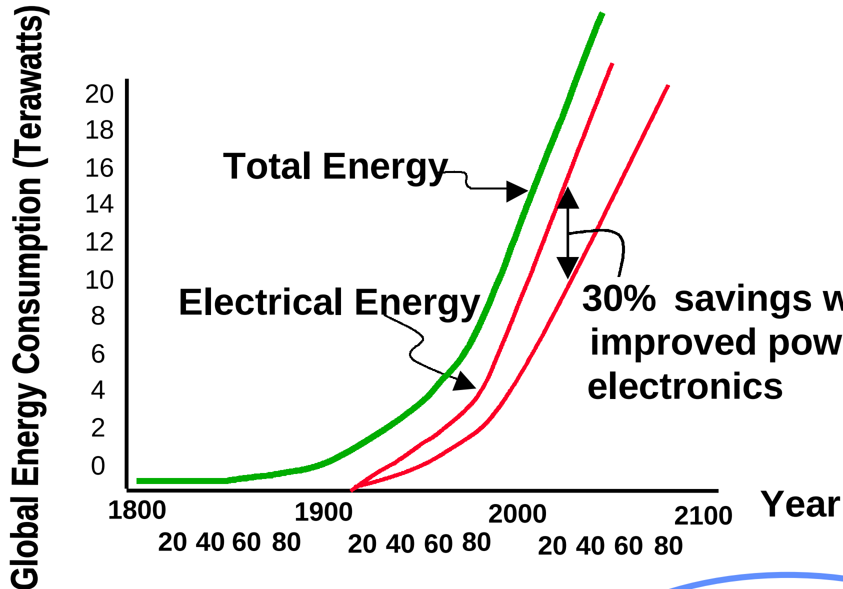
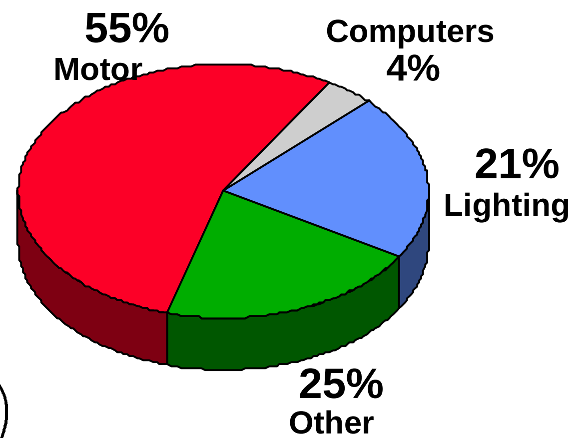
Global Energy Consumption and Power Electronics

(Source: NSF Center for Power Electronic Systems: http://www.cpes.vt.edu/]***)***



US Electrical Energy Consumption



*** Output of 840 power plants**

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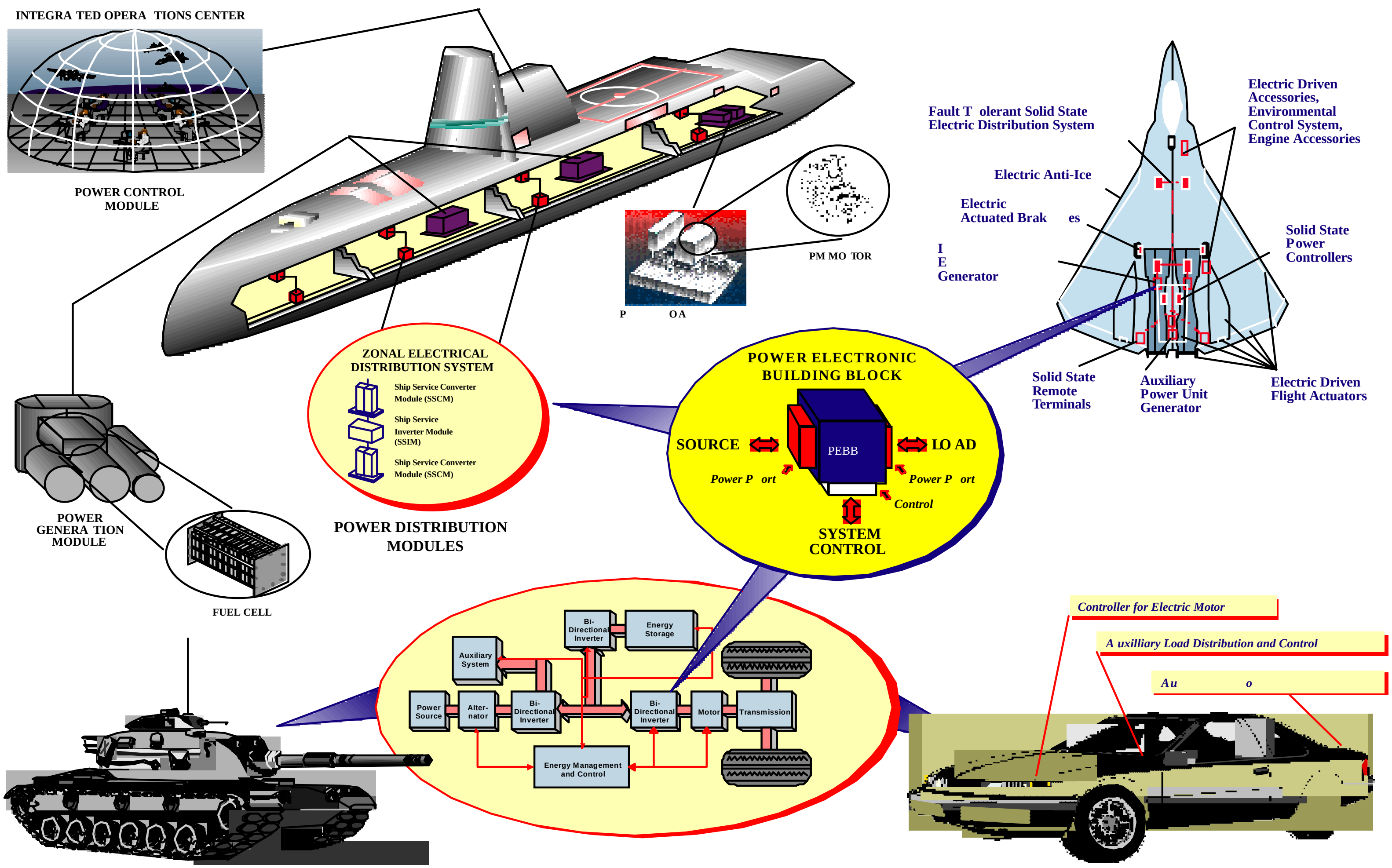
* EPRI

Defense Power Electronics Requirements Example: PEBBs

Courtesy of G. Campisi, Office of Naval Research



Power Electronic Systems

- **Motor Drives**

Today's Topic

- **Radar / Microwave Communications**
- **dc to dc Converters**
- **Power Supplies**
- **Electric Vehicle Drives**
- **Weapons Systems**

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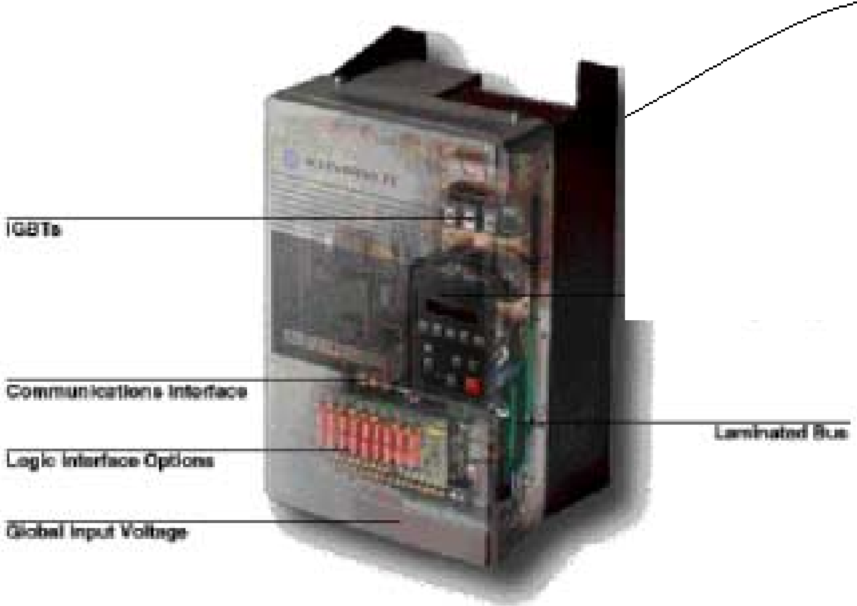
Drive & Motor *Automation System*

Rockwell Automation - Allen Bradley 1336 Force Drive



Performance Metrics:
- ***Power Density***
- ***Cost***
- ***Reliability***

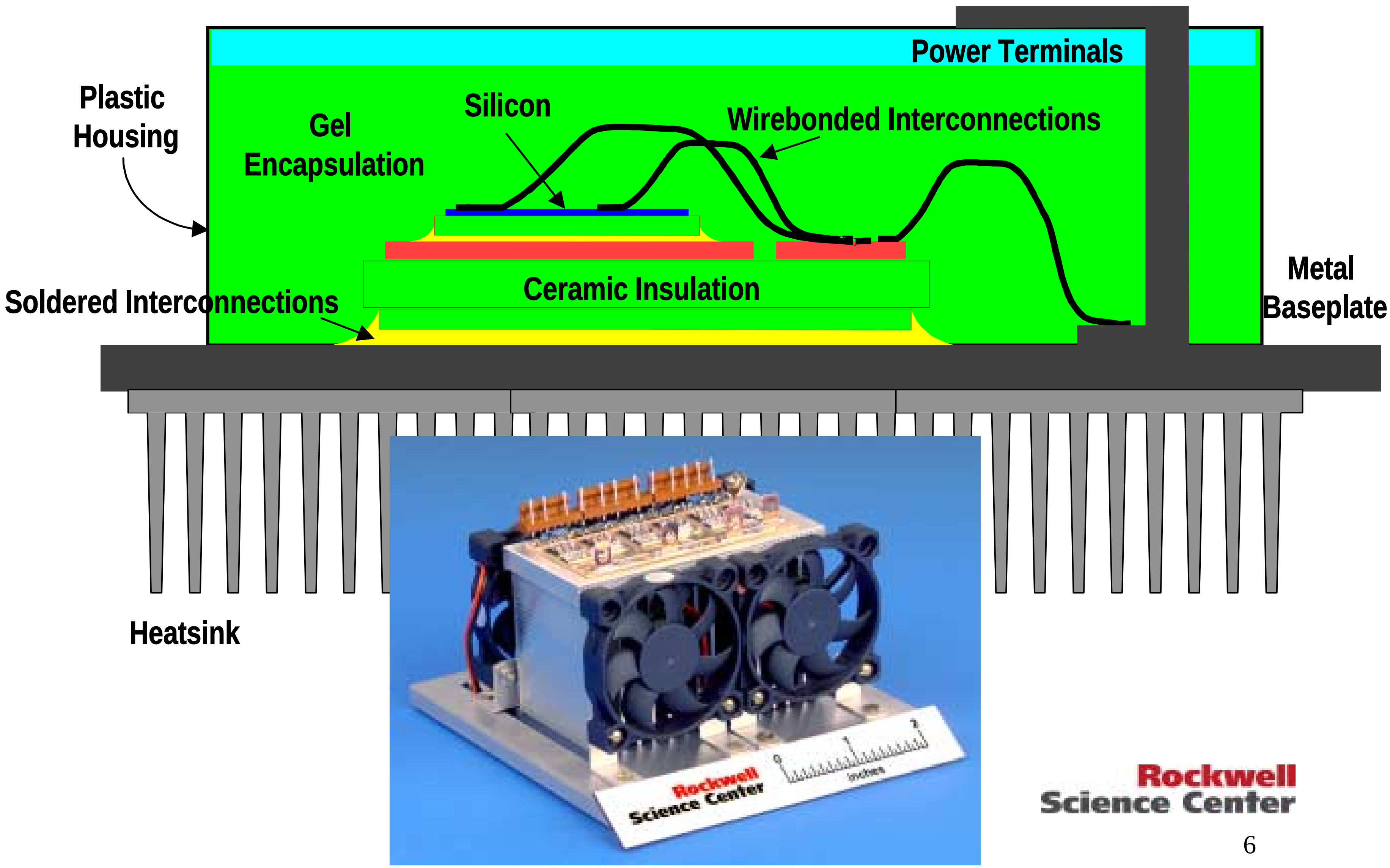
Rockwell Automation
Reliance Electric AC Motor

Converts AC power (<u>fixed</u> frequency, voltage) to
AC Power (<u>variable</u> frequency, current, and voltage)

Enables exact control of speed (RPM) and torque of *motors*

Motors *become controlled electromechanical energy converters*.

Basic Power Packaging Elements



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Generic Electronic Packaging Technology Hurdles

Controlled Power Density (W / m^3)

- High Power Requirements from Devices
- High Packaging Densities
- Weight Requirements

Cost ($ / Function)

Reliability (MTBF)

High-Temperature Packaging of SiC Electronics

M.C. Shaw, J.R. Waldrop, F. Zok,[1]

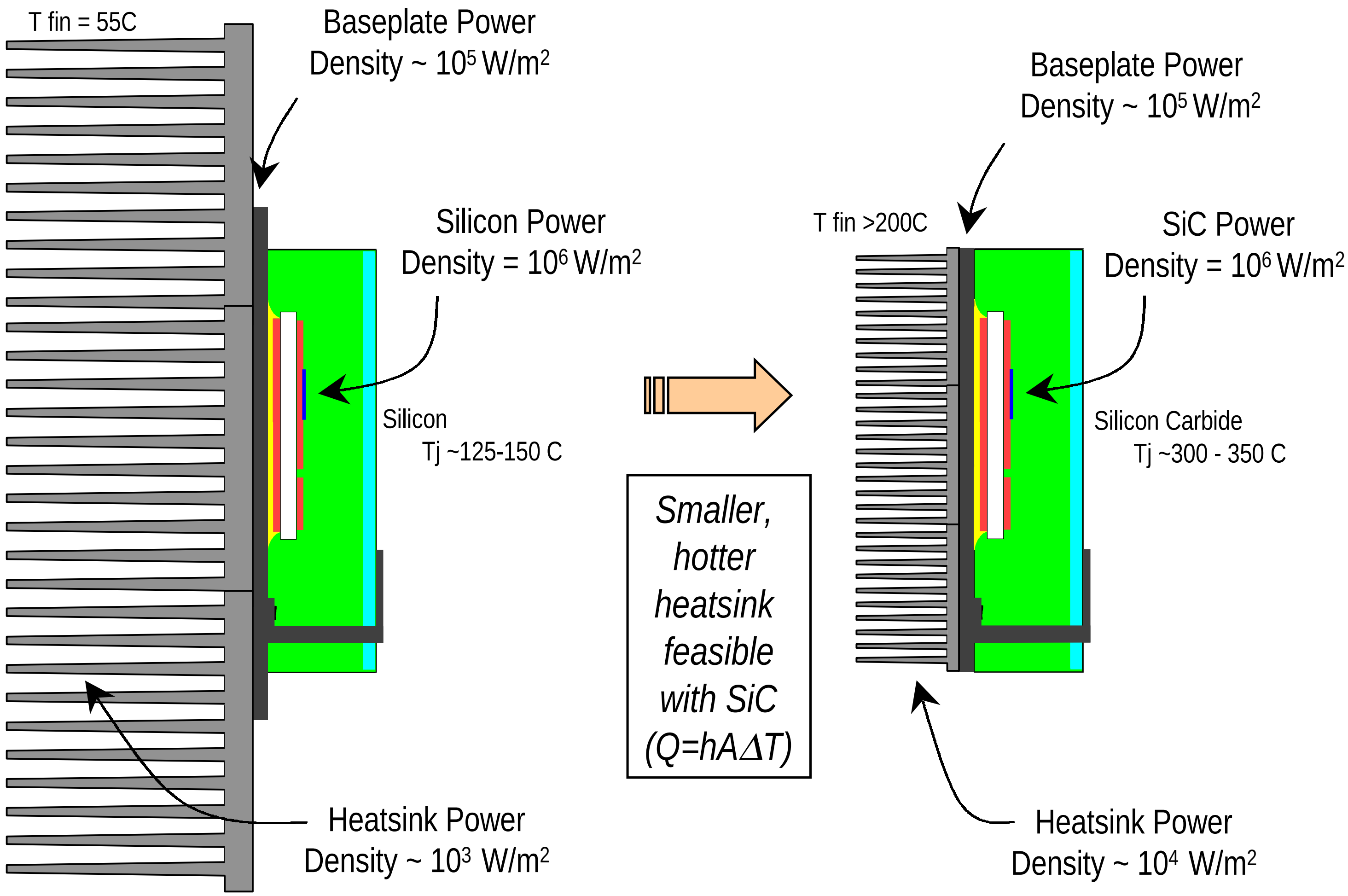
Rockwell Science Center, Thousand Oaks, CA

[1]*University of California, Santa Barbara CA*

30 May, 2001

Contract Number MDA97298C0002

Decrease in System Volume Through Utilization Of *Silicon Carbide (SiC) Electronics*



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Thermomechatronics

M.C. Shaw and E.R. Brown,[1]

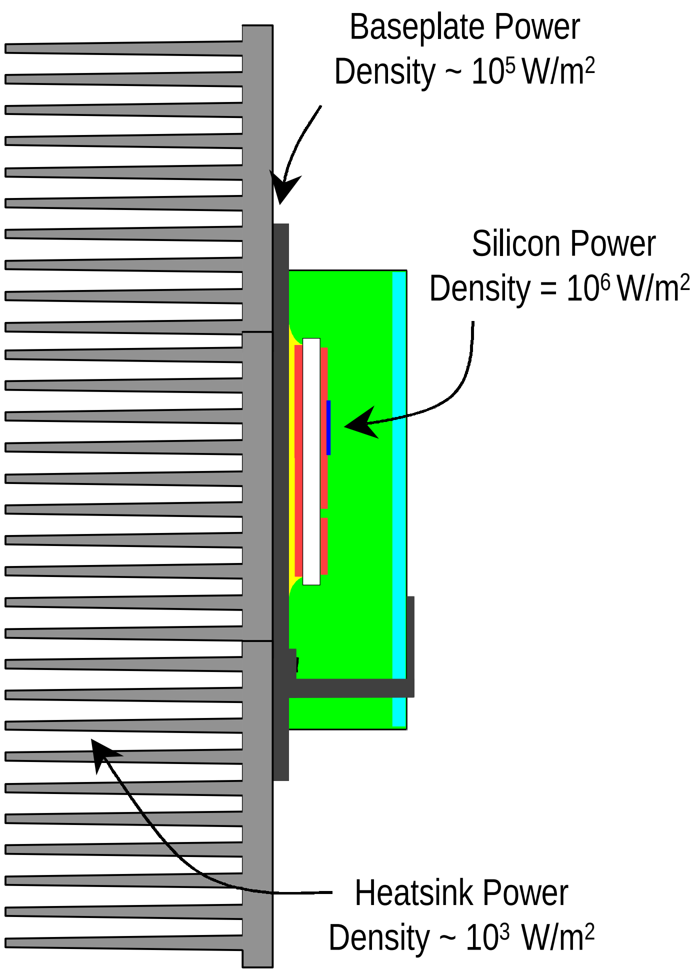
Rockwell Science Center, Thousand Oaks, CA

[1]University of California, Los Angeles CA

30 May, 2001

Contract Number MDA97298C0002

Thermal Management of Power Electronics: Spread Power Density from Device to Heatsink



5 hp Motor Drive Example

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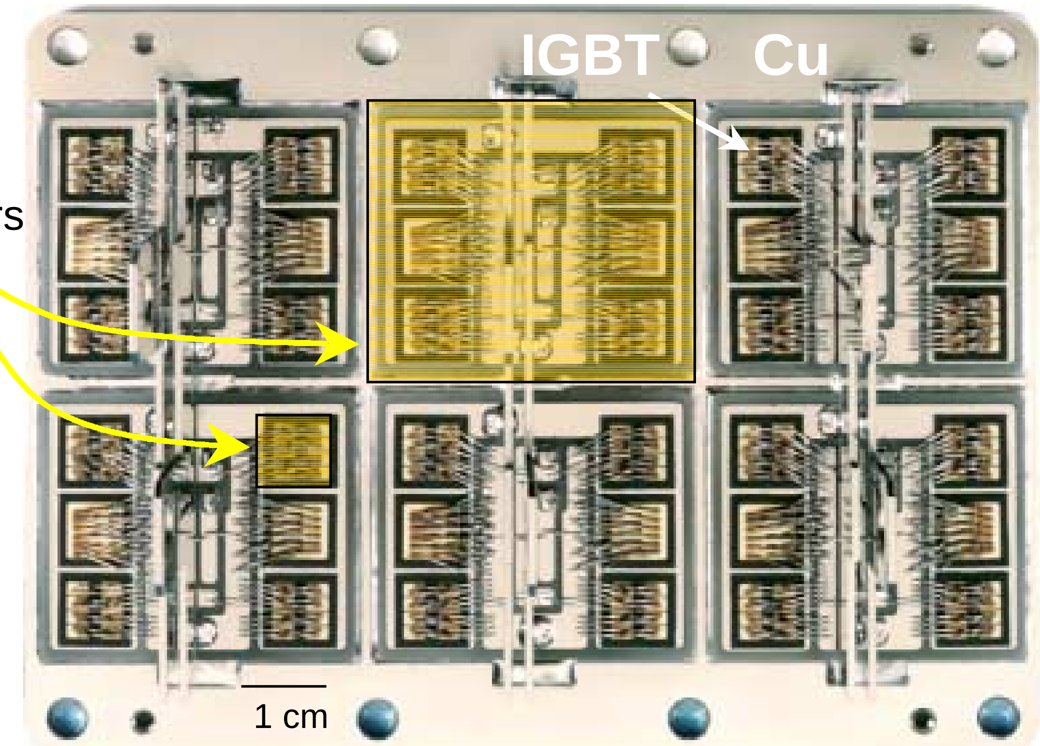
Large Area Solder Joint Reliability in Power Assemblies

Examples of Buried Continuous Solder Layers



Internal view of a 1200A, 3300V IGBT module (courtesy: Eupec GmbH+ Co.)

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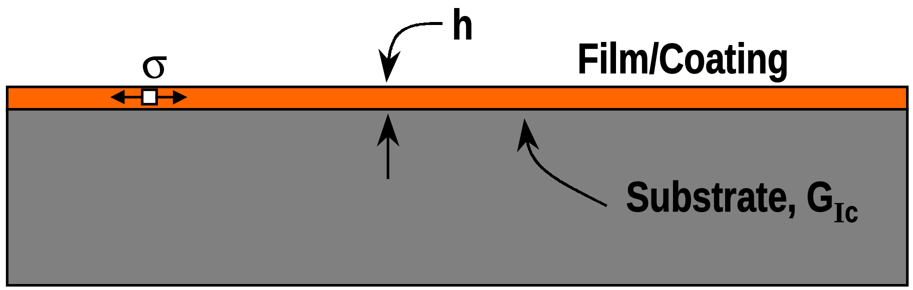
Elastic Fracture Mechanics Energy Balance in Layered Systems

σ = Stress in coating
h = Coating thickness
E, v = Elastic properties
Z ~ 0.3



$$\frac{Z\sigma^2 h\left(1-\upsilon^2\right)}{E} \gtrless G_{Ic}$$

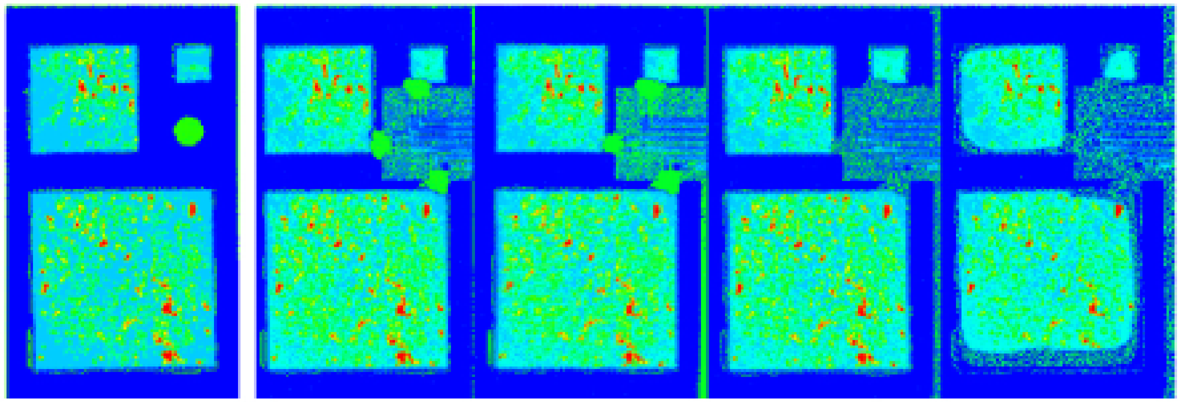
Driving Force for Crack Growth or Material or Interfacial Crack Growth Resistance

Cracking depends on which is larger:

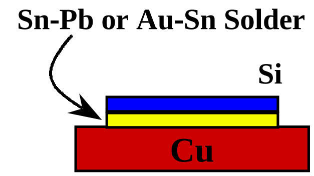
Thermal Cycling of Sn - Pb (Elastic/Plastic) vs Au-Sn (Elastic) Joints

0.6”

80Au20Sn on Copper

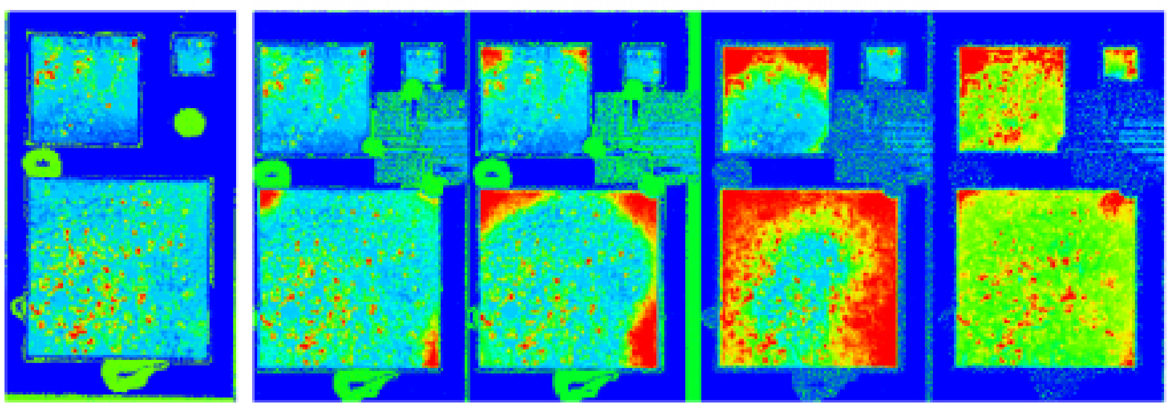


$\Delta\alpha$ = 14.1 ppm; Elastic Solder

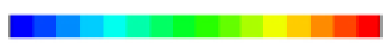


As Soldered | **1 cycle** | **10 cycles** | **100 cycles** | **1000 cycles**

63Sn37Pb on Copper



$\Delta\alpha$ = 14.1 ppm, Elastic / Plastic Solder



Ultrasonic Reflection Microscopy

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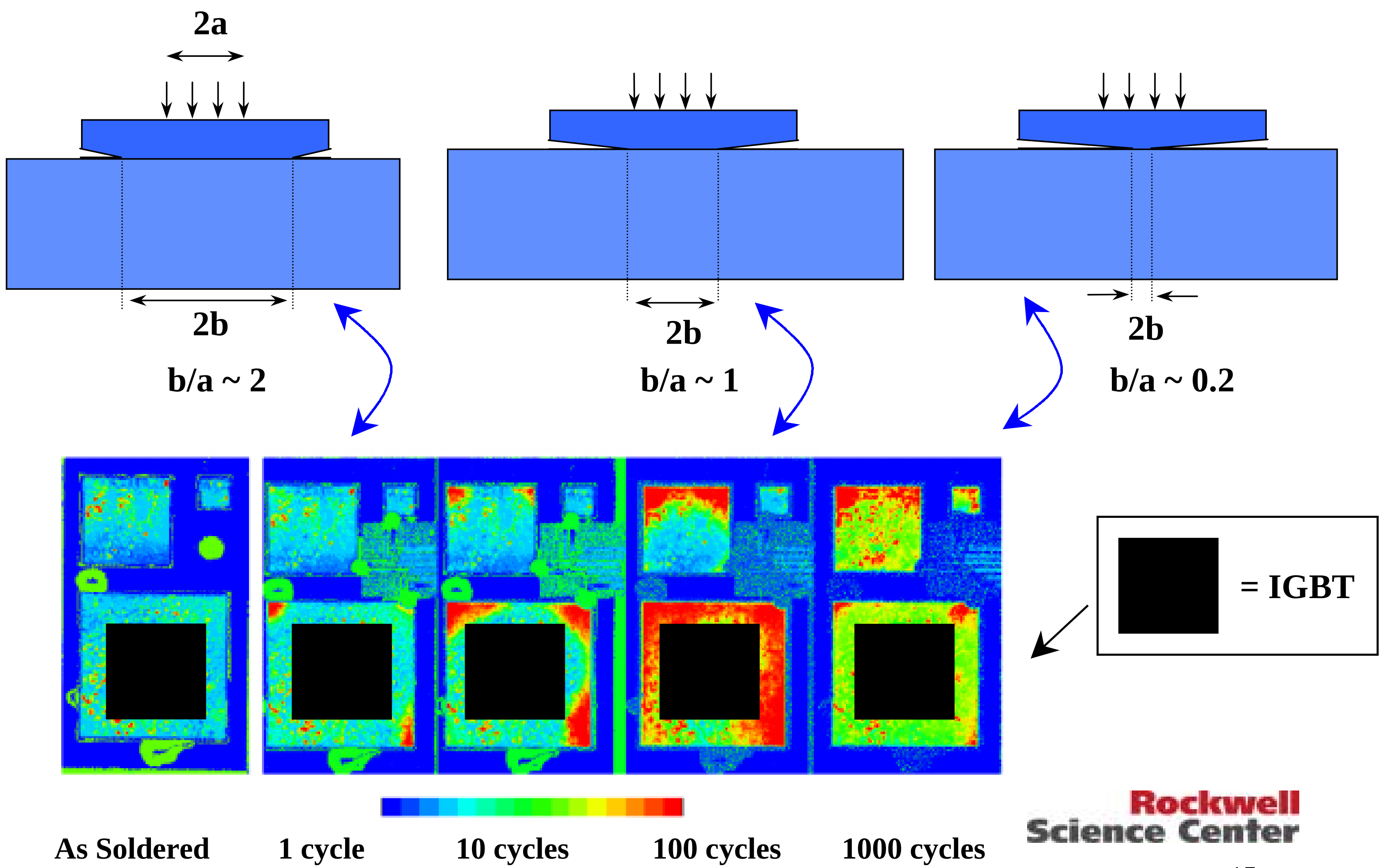
Model of progressive crack growth in DBC/baseplate solder joint



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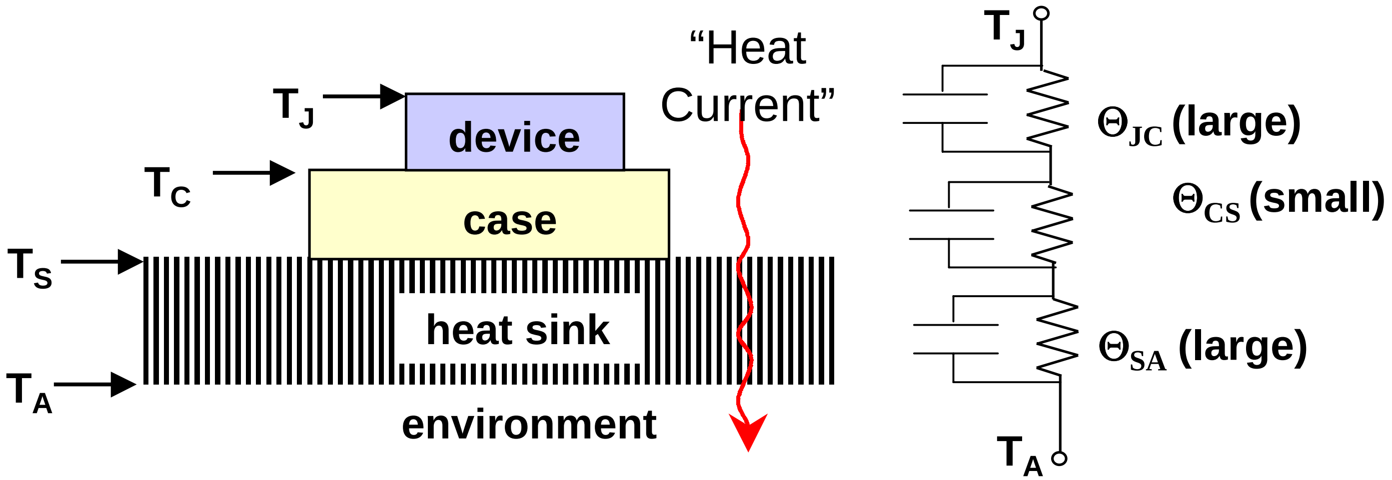
Thermal Equivalent Circuit



$$\Theta_{JC} + \Theta_{CS} + \Theta_{SA} = \Theta_{JA} = (T_J - T_A)/P_0$$

Thermal Resistance	Analytic Form	Typical Values
θ_{JC}	~ $\rho t/A_s$ ρ -> thermal resistivity, t -> thickness	1.4°C/W
θ_{CS}	~ $\rho t/A_s$	~ 0.1-1 °C/W
θ_{SA}	~ $1/hA_s$ h -> heat transfer coefficient	10-33°C/W (natural convection); 1-10°C/W (forced air)

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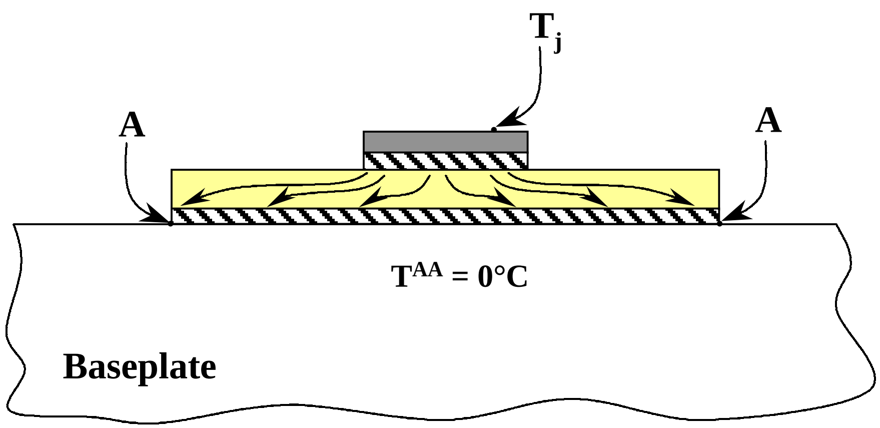
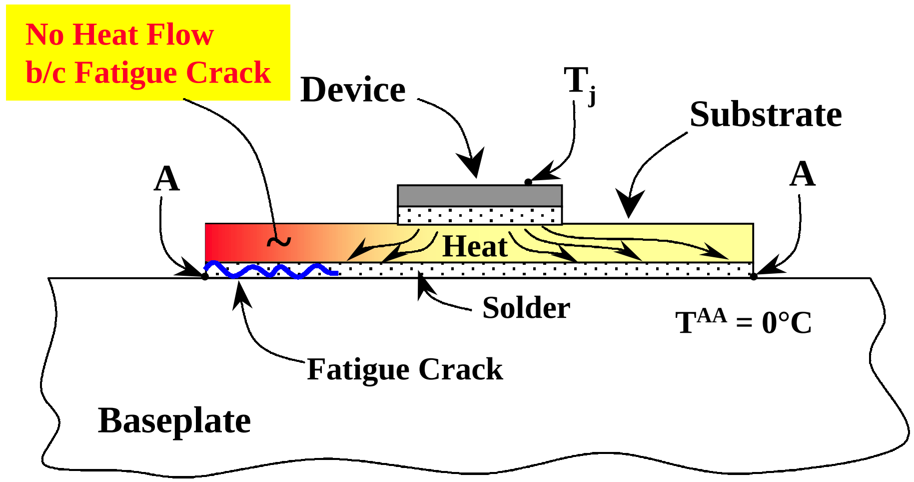
Solder Joint Fatigue Raises Package Thermal Resistance



Pristine condition - lowest thermal resistance



Thermally cycled condition - higher thermal resistance

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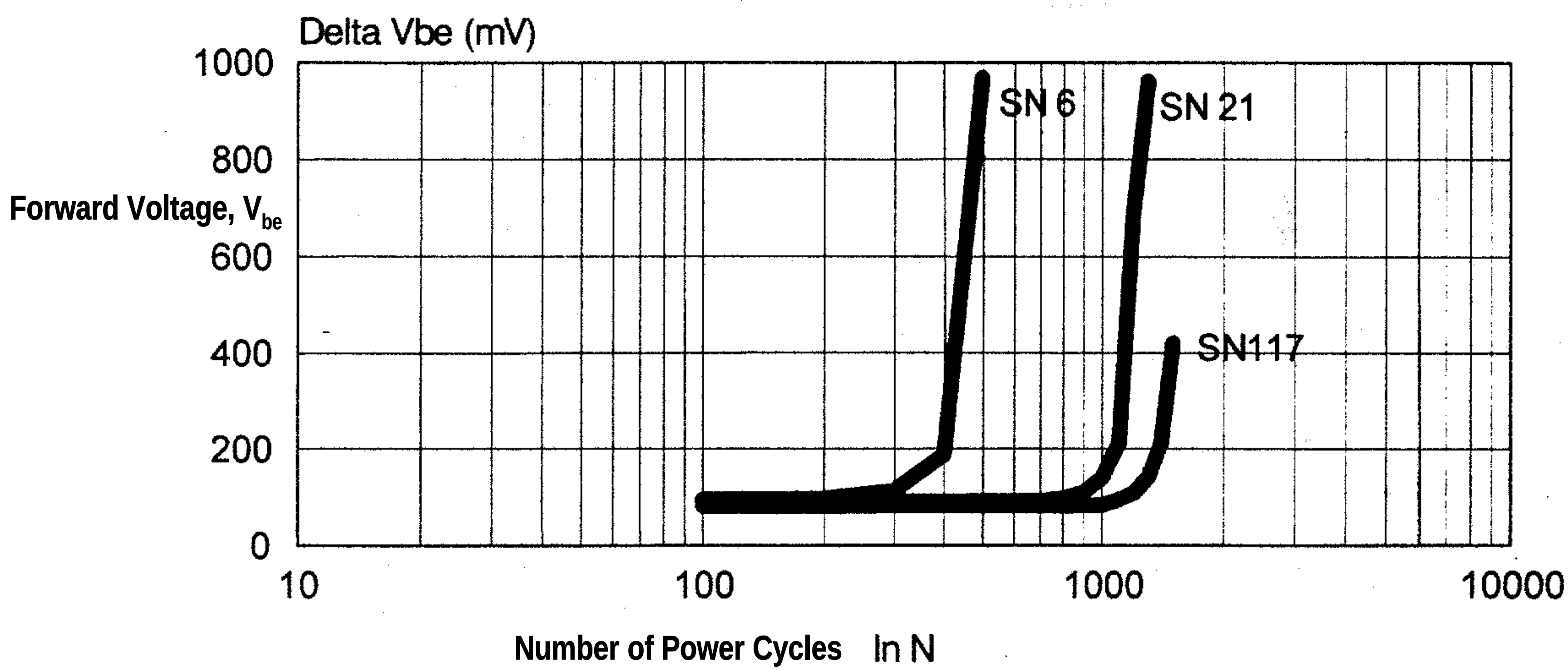
Bipolar Transistor Performance Degradation with Repeated Power Cycling (Ref: Evans and Evans)

(Evans and Evans, IEEE Trans. Comp. Pack., Mfg. Tech., Part A, v. 21 no. 3 pp. 459 - 468, 1998)



Experimental Results Showing Large Increase in Forward Voltage Drop, ΔV_{be}, with Repeated Power Cycling, N

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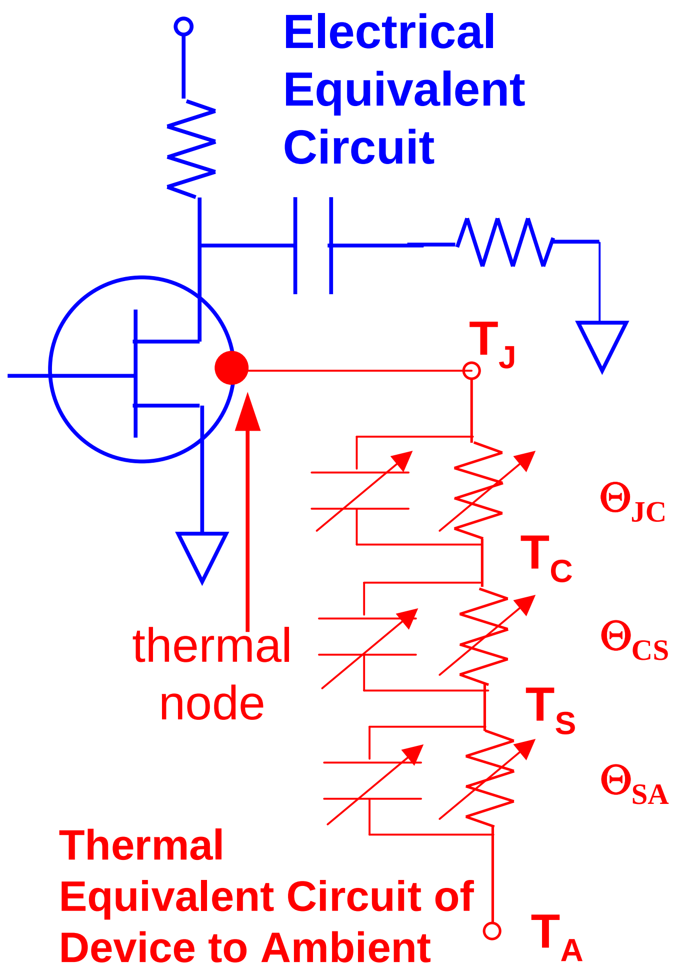
Coupled Electro-Thermal Simulation



Modeling Features:

- **Nonlinear thermal circuit models**
- **Connect electrical to thermal circuits through unique "thermal node" (after A. Hefner of NIST)**
- **SPICE-like environment**

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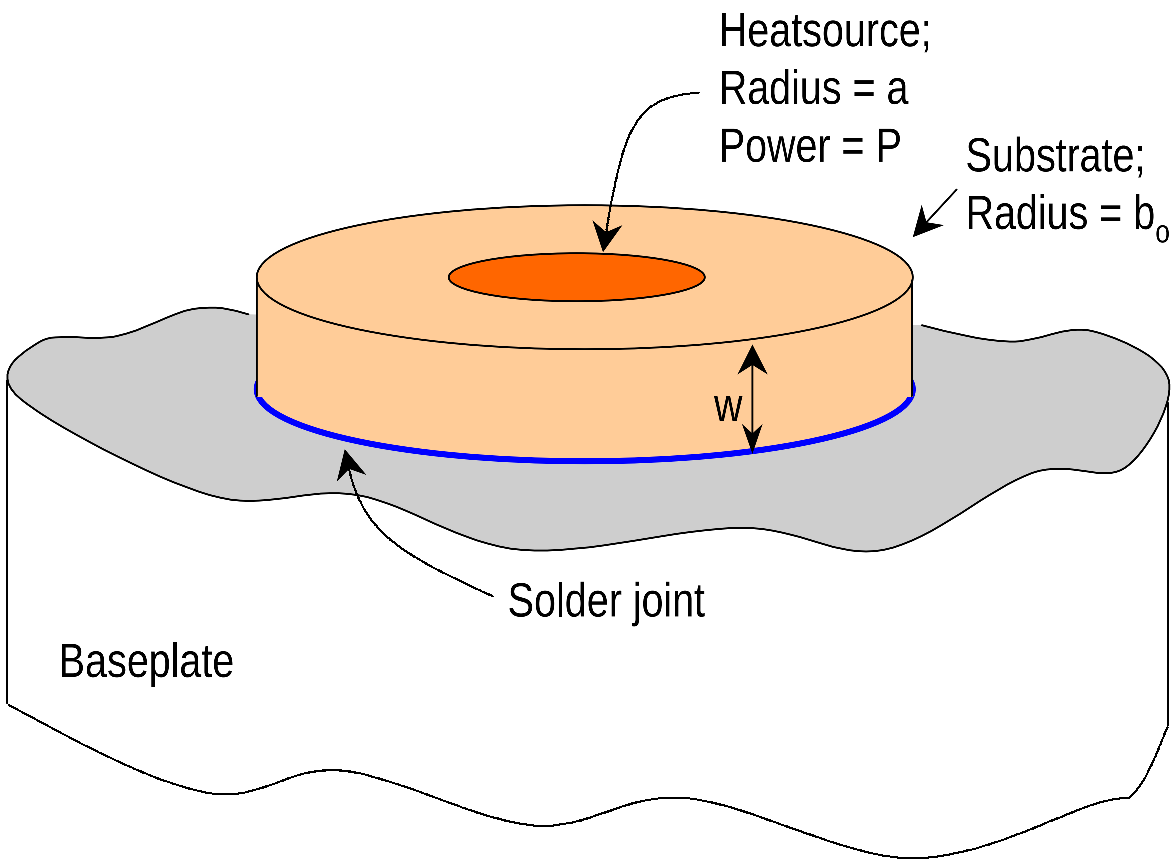
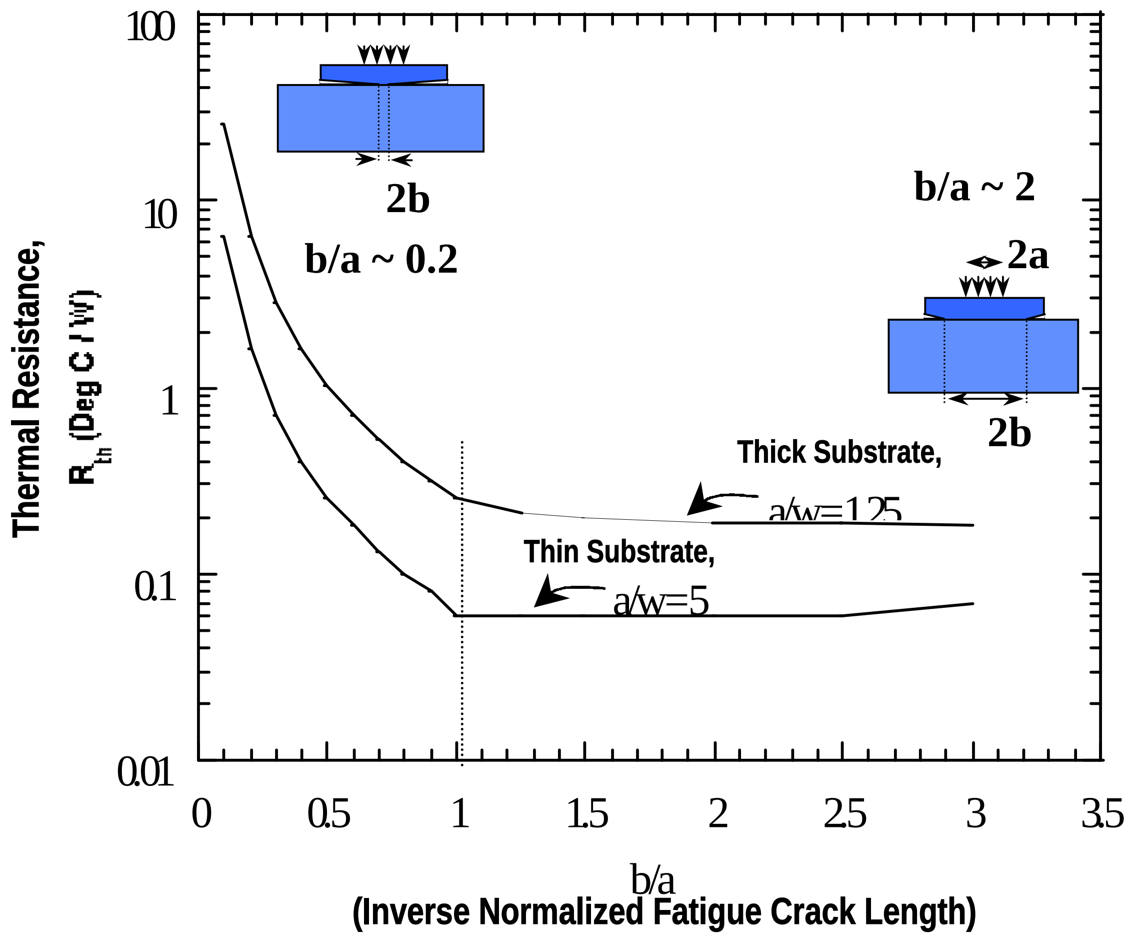
Schematic of Model Package Geometry



Calculated Thermal Resistance, R_{th}, vs. Inverse Normalized Fatigue Crack Length, b/a.

Note the rapid increase in R_{th} with penetration of the fatigue crack into the region below the device (b/a~1)



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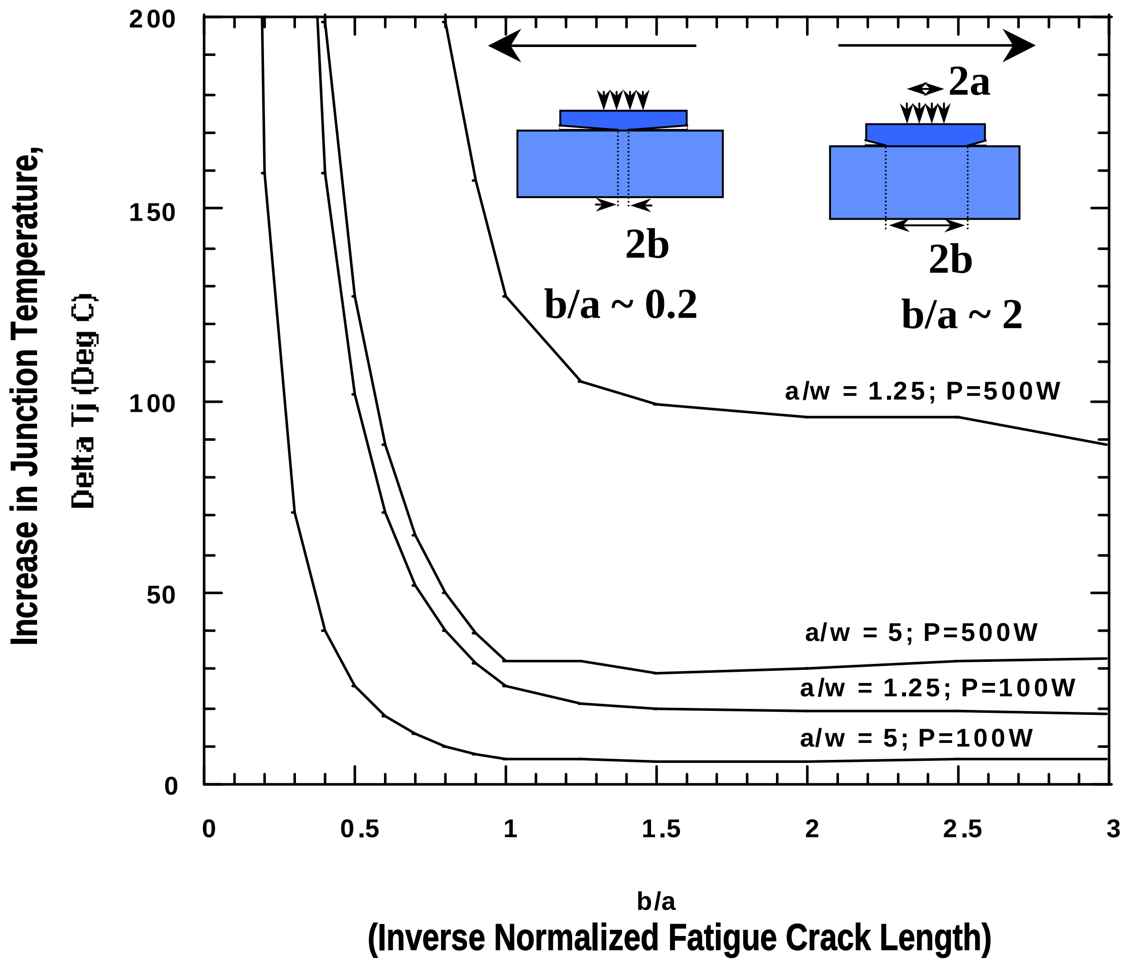
Dependence of Junction Temperature Increase, ΔT_j, on Inverse Normalized Fatigue Crack Length, b/a



Two different power levels and substrate thicknesses.

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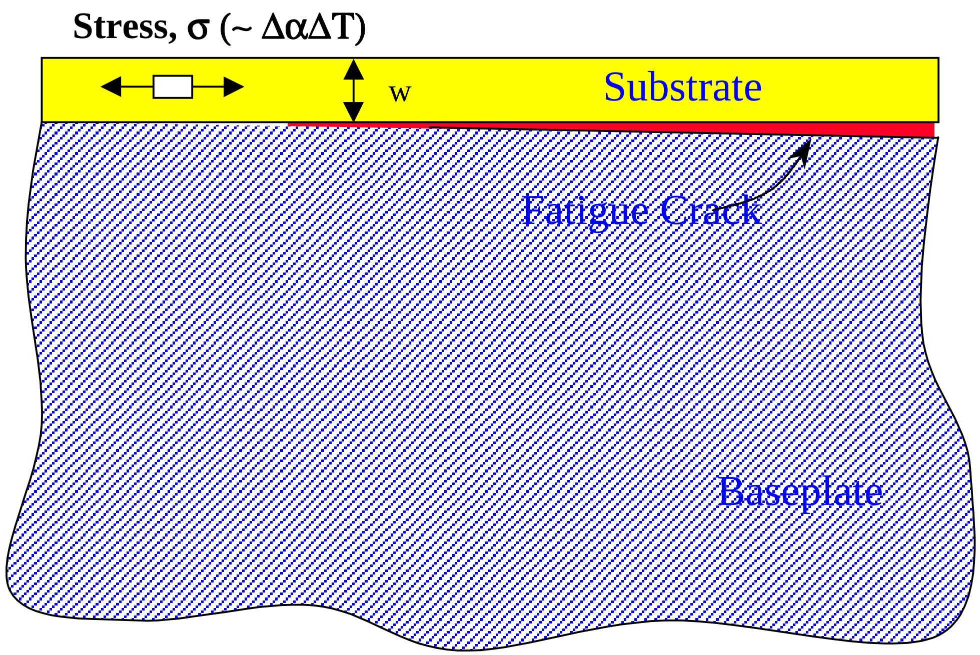
Strain Energy Release Rate, G_{Ic}, Depends on ΔT_j

$$\frac{Z\sigma^2 h\left(1-\upsilon^2\right)}{E} = G_{Ic}$$



Strain energy release rate is the driving force for fatigue crack growth

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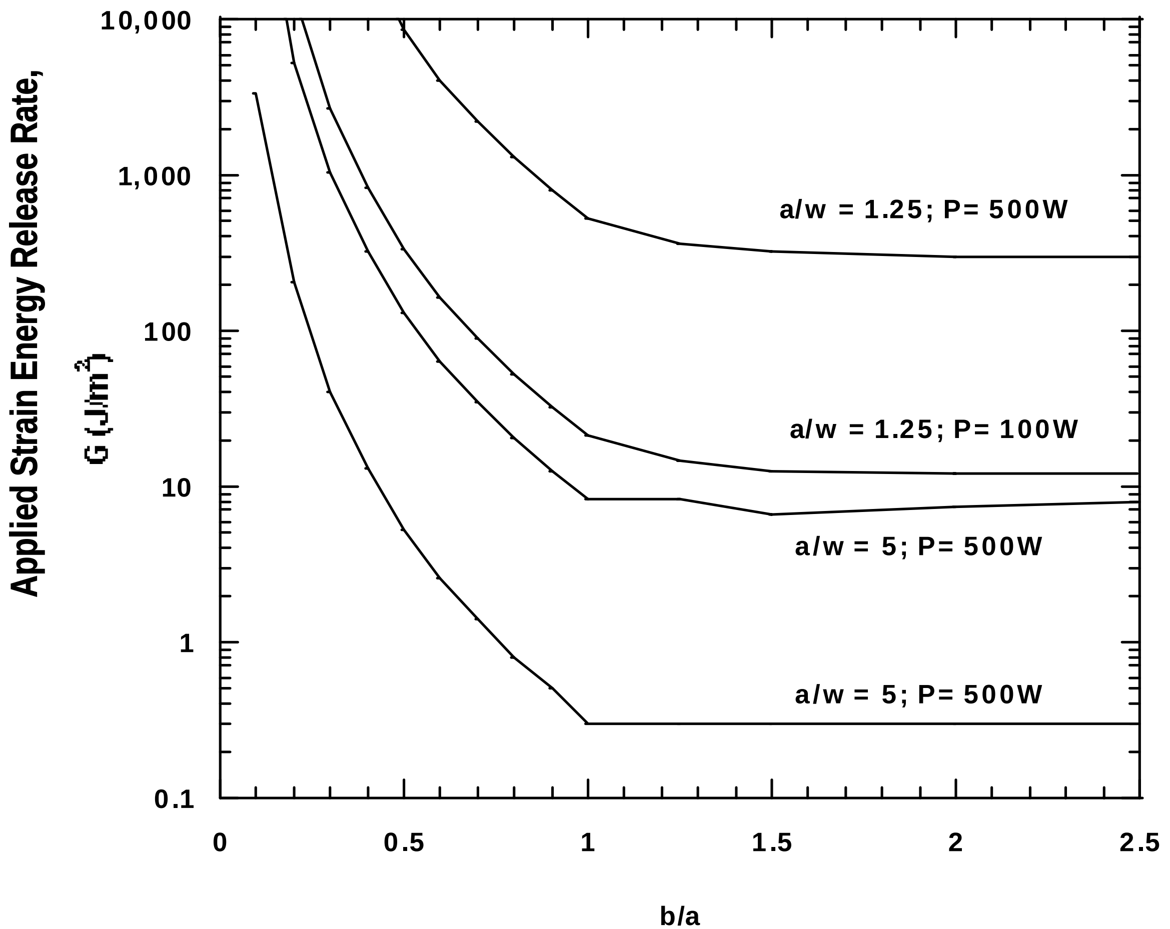
Applied Strain Energy Release Rate, G, at Fixed Device Power Dissipation vs. b/a.



(Inverse Normalized Fatigue Crack Length)

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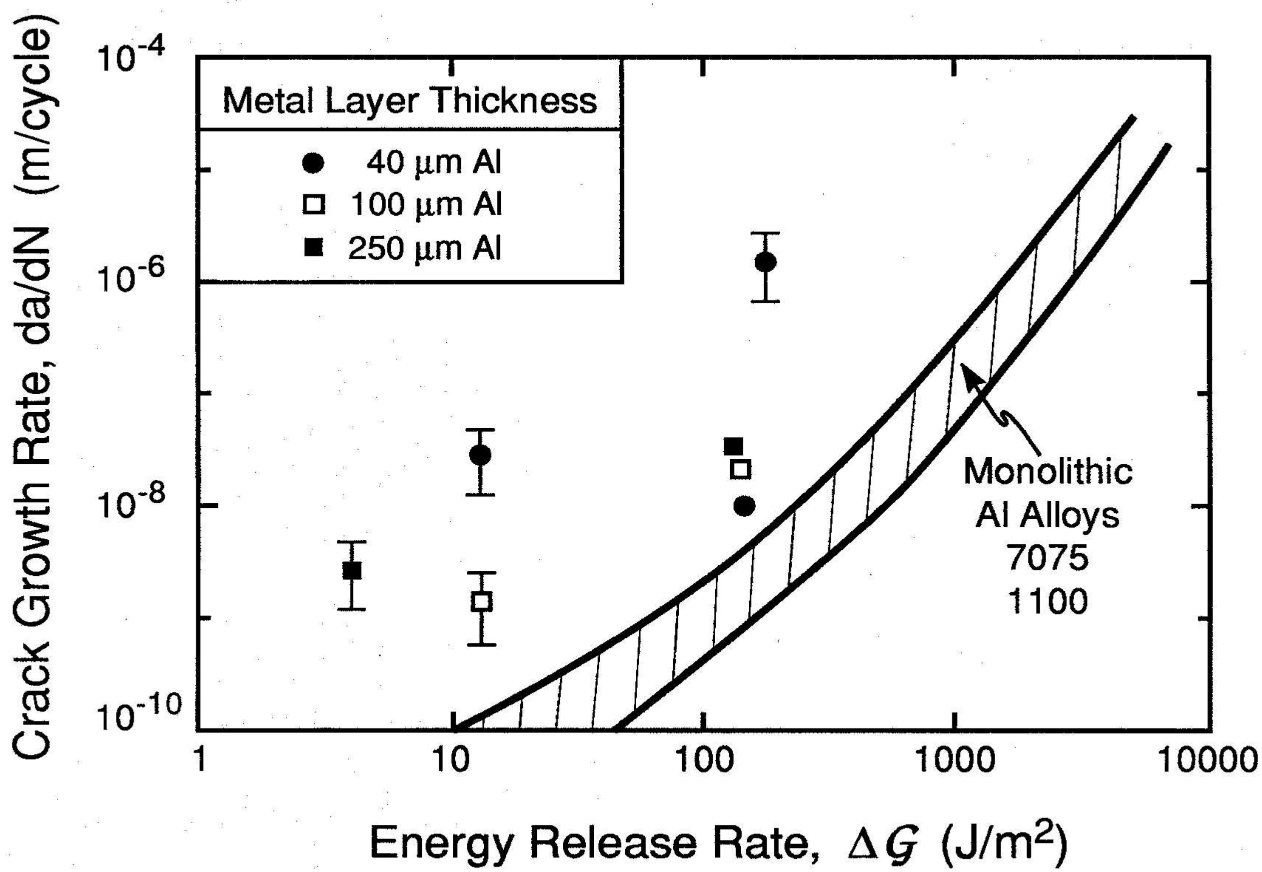
Experimental crack growth *rate* data, da/dN, vs. cyclic *strain energy release rate range* ΔG for the Al-Al_2O_3 and Al-Al systems.



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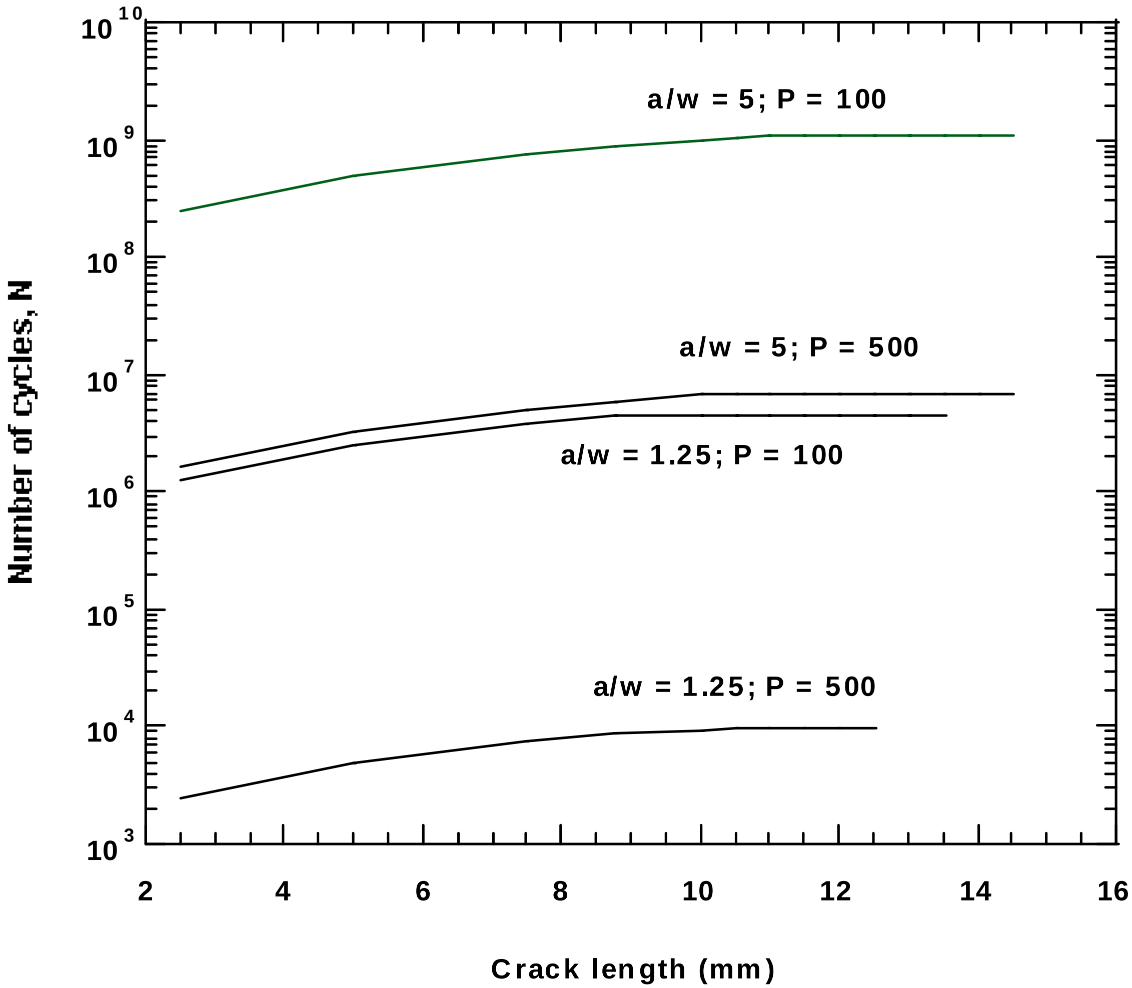
Relationship between the number of power cycles, N, and the crack length, l for two different power levels and substrate thicknesses.



Note the highly nonlinear relationship between the crack lengths and number of power cycles.

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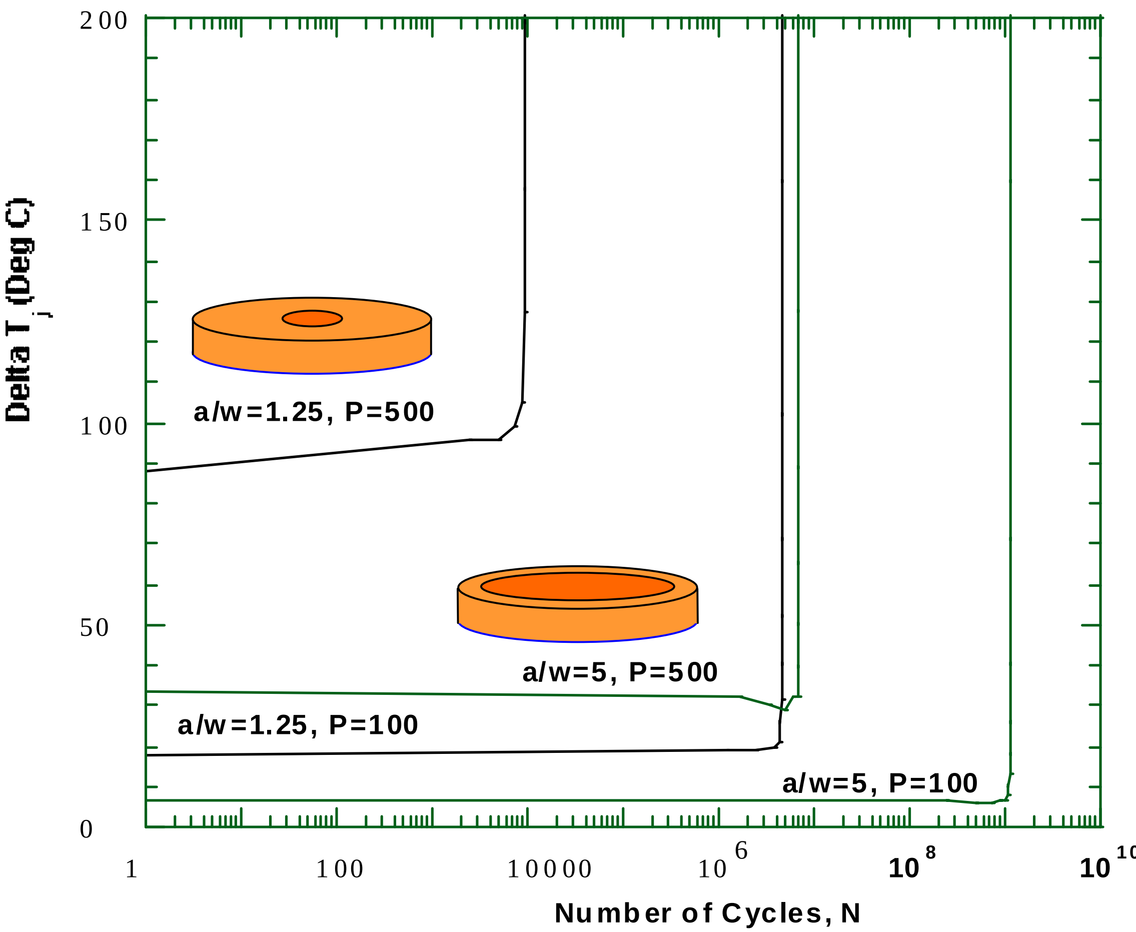
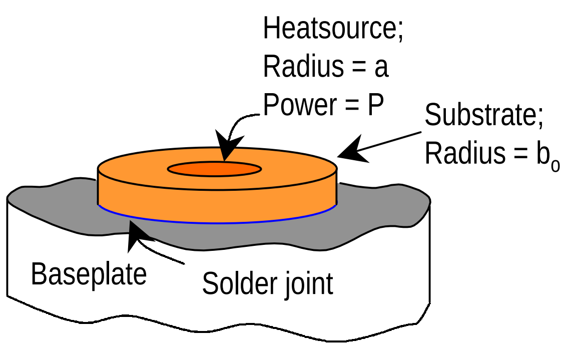
Predicted Junction Temperature Increase, ΔT_j, vs. Power Cycles, N





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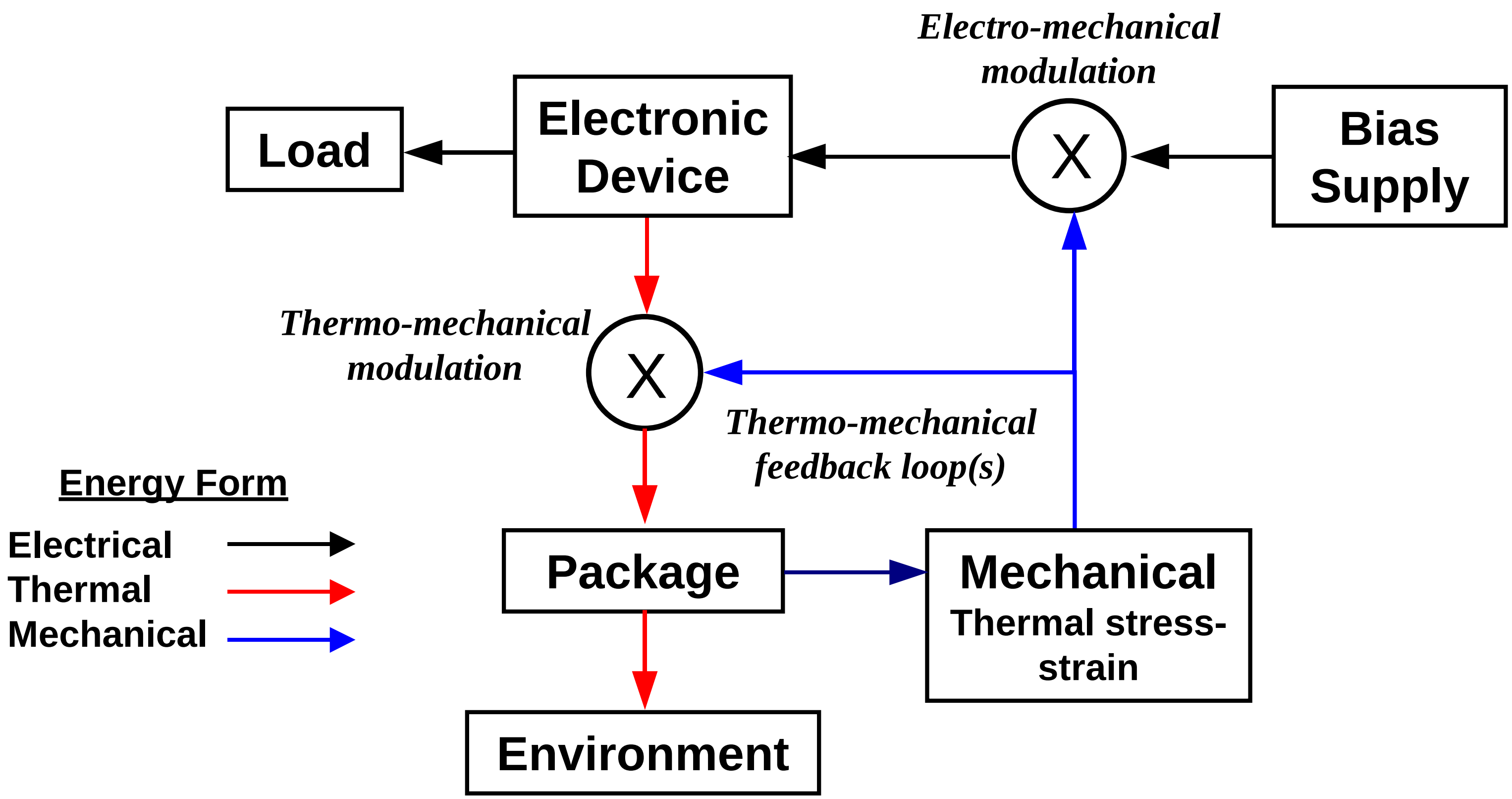
Thermomechatronic Analysis of coupled flow of electrical, thermal and mechanical energy



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Conclusions

• Advantages of new approaches <u>must be demonstrated at the system, e.g., motor drive, level</u>.

Device Power Density (A/cm^2 or W/cm^2)
System Power Density (W/m^3)
Lifetime Assurance of Entire System
System Cost Analysis Ultimately Required

•Research Needs:

<u>1) Materials</u>

- Controllable and High Thermal Conductivity
- Functional Integration of Electrical, Thermal, Mechanical Features
- High Temperature Capability
- Lightweight
- Compatible with Solid-State Devices
- Easily Processed

<u>2) Efficient, System-Based Design Methodologies</u>

- Mechanical, Thermal, Coupling
- Lifetime Prediction / Reliability
- Design Optimization / Tradeoff Capability

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