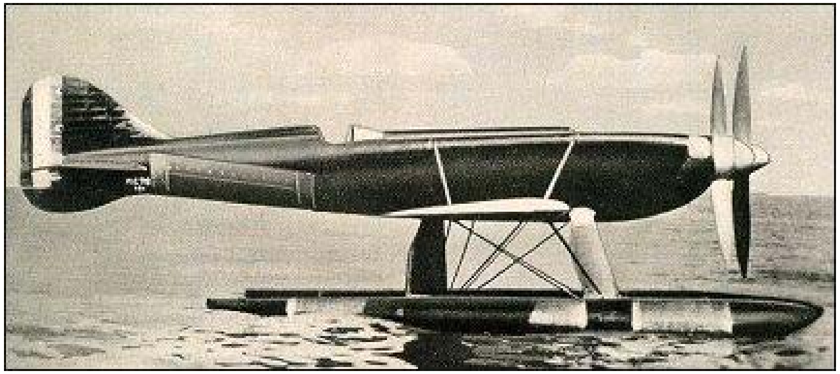

# Electromigration Study of Pure Sn Conductors

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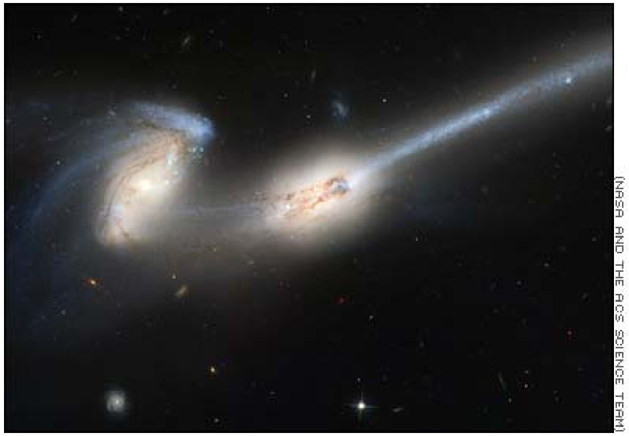
# Purpose/Charter

- **“Green” Computer**
  - Pb may (will) be banned from use in the next decade in electronic components
    - Unfortunately it is a wonderful material for solder joining, there ain’t nothin’ better
  - Sn is a **“green”** metal
    - Not as well characterized as Pb
      - Strange stuff
    - Has significant problems that Pb does not
      - Sn “Pest”
      - Extreme fast diffusion of Noble and transition metals
    - Anisotropy
      - Mechanical and electrical

# Interesting Initial Results

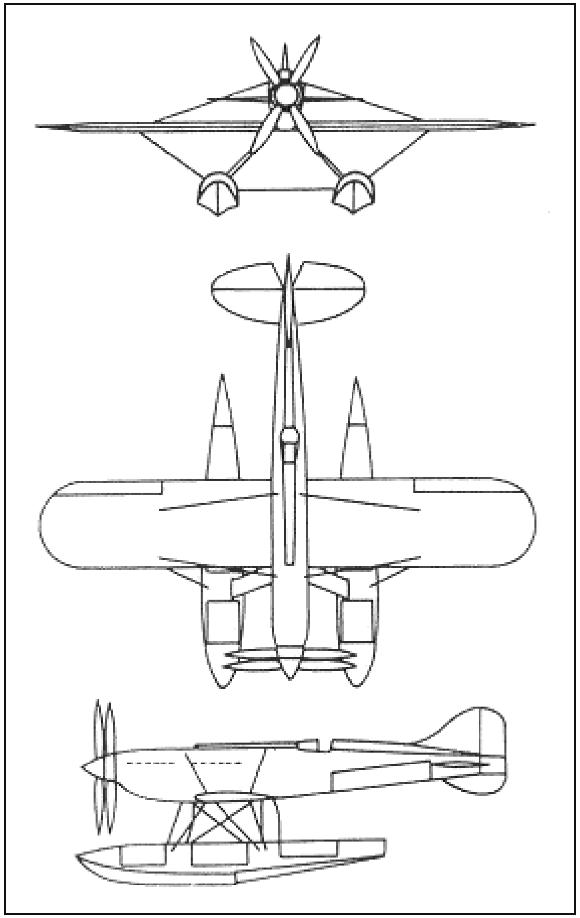
- Engineering
  - j x l Determination
    - Immortality
  - Activation Energy
- Science
  - Resistance Decay


U.S. Air Force Photo


(NASA AND THE ACS SCIENCE TEAM)

# Sn Characterization

- Blech Length effect
  - Literature is very inconsistent
    - Wide variation in jxl product
- Effect of contacted metals
  - Cr
    - No solid solubility (<.0001%)
    - No IMC formation
  - Ni
    - No solid solubility (<.005%)
    - IMC formation
  - Oxide



# Failure Physics

## (Metallization Driving Forces)

$$F = \left( \sum_i F_i \right) = F_{em} + F_{tm} + F_\sigma + F_S$$

$$\vec{F}_{em} = Z^* e \rho \vec{j}$$

$$F_{tm} = \frac{Q^*}{T} \frac{dT}{dx}$$

$$F_\sigma = \Omega \frac{d\sigma}{dx}$$

$$F_S = \frac{kT}{C} \frac{dC}{dx}$$

# Mass Transport Equation

$$J = \frac{DC}{kT}\left( Z^* e\rho\, j - \Omega \frac{d\sigma}{dx} \right)$$

Due to electromigration and stress gradient

Stress gradient builds to oppose electromigration.

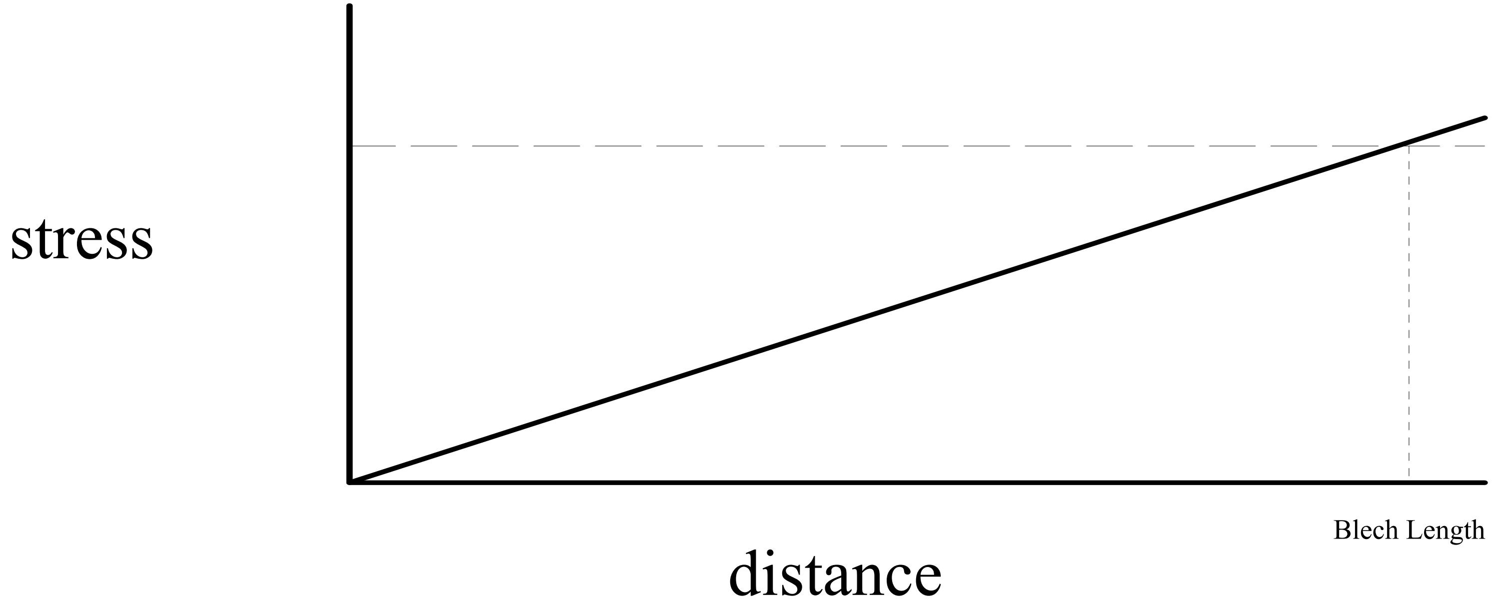
# Blech Condition

$$J = \frac{DC}{kT}\left( Z^{*} e\rho j - \Omega \frac{d\sigma}{dx} \right) = 0$$

***If there is a blocking boundary condition, electromigration stops completely at steady state***

# Blech Length

$$j \times l_{Blech} \leq A_{Blech}$$



A Blech Length will be defined for any current density.

# Consequences for C4 Electromigration Testing

- “Black’s Law” isn’t
  - Only valid for nucleation dominated failure far from the steady state
- The static steady state condition is very near the use condition in solder ball technology
  - More important to go to lower than higher current density

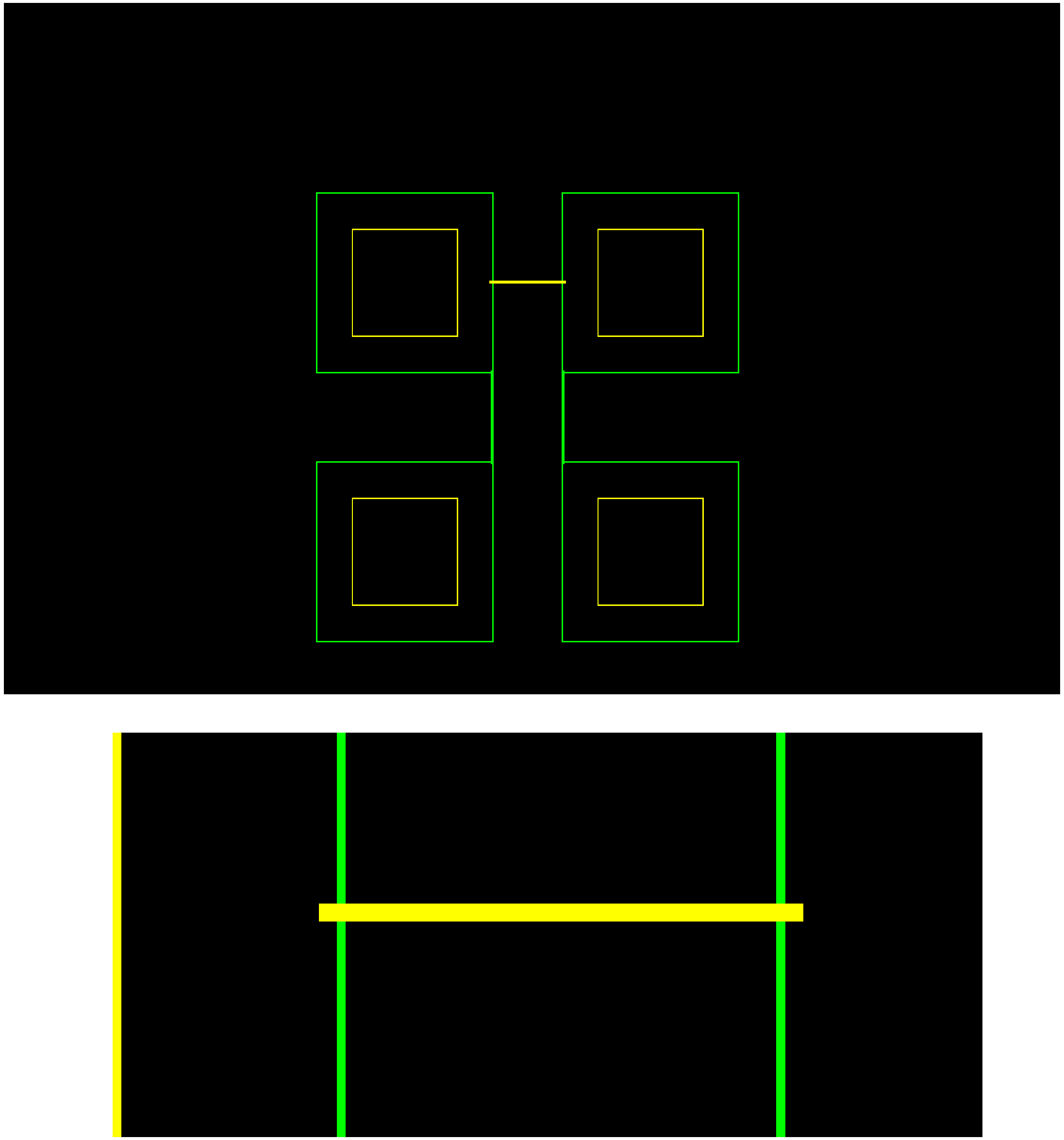
**We may luck out and have solder ball Immortality**

# Blech Product Determination

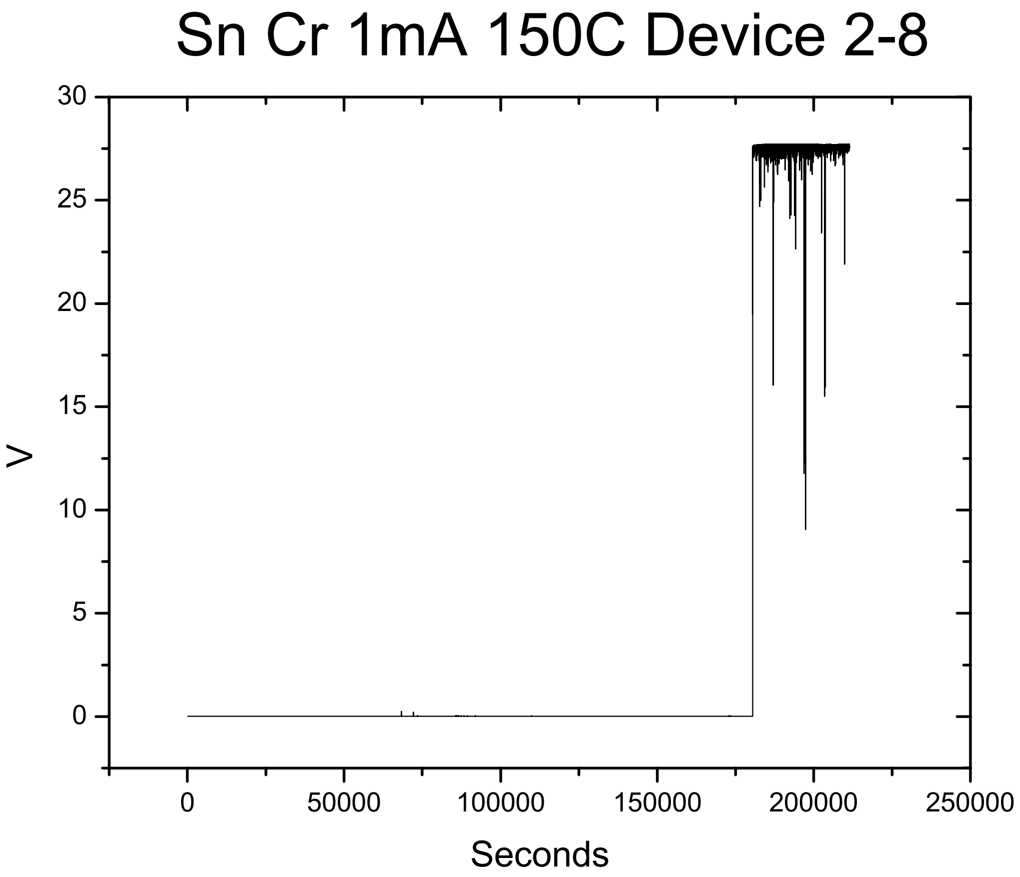
- First Experiments with Sn/Cr
  - Successively lower j to find when Blech Condition is satisfied
  - Initial thoughts were that Blech Product for Sn would be substantially less than for Al or Cu
    - lower yield strength
    - Higher z*

***If Blech Product is on the order of 100 we may be able to design immortality***

# Test Structure

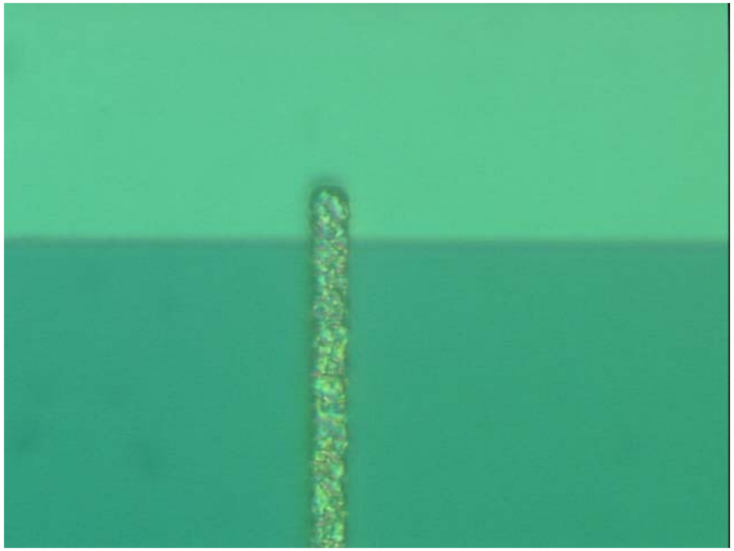


# Resistance vs Time

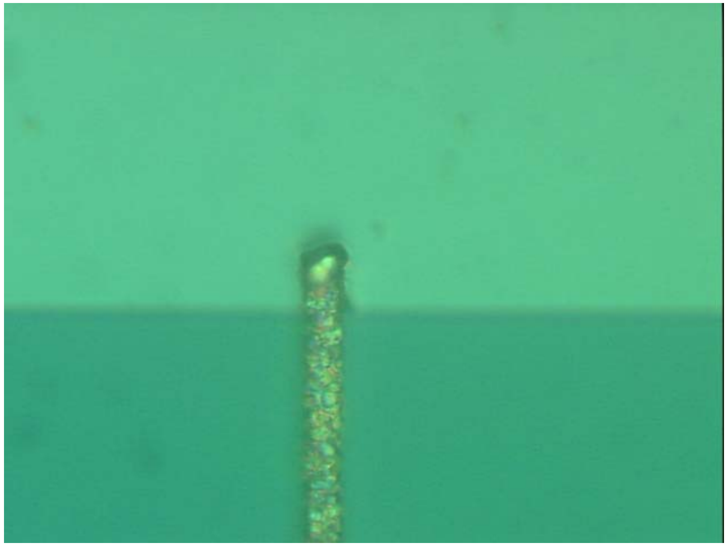


Therefore the Blech Product is less than 250

# Extrusion



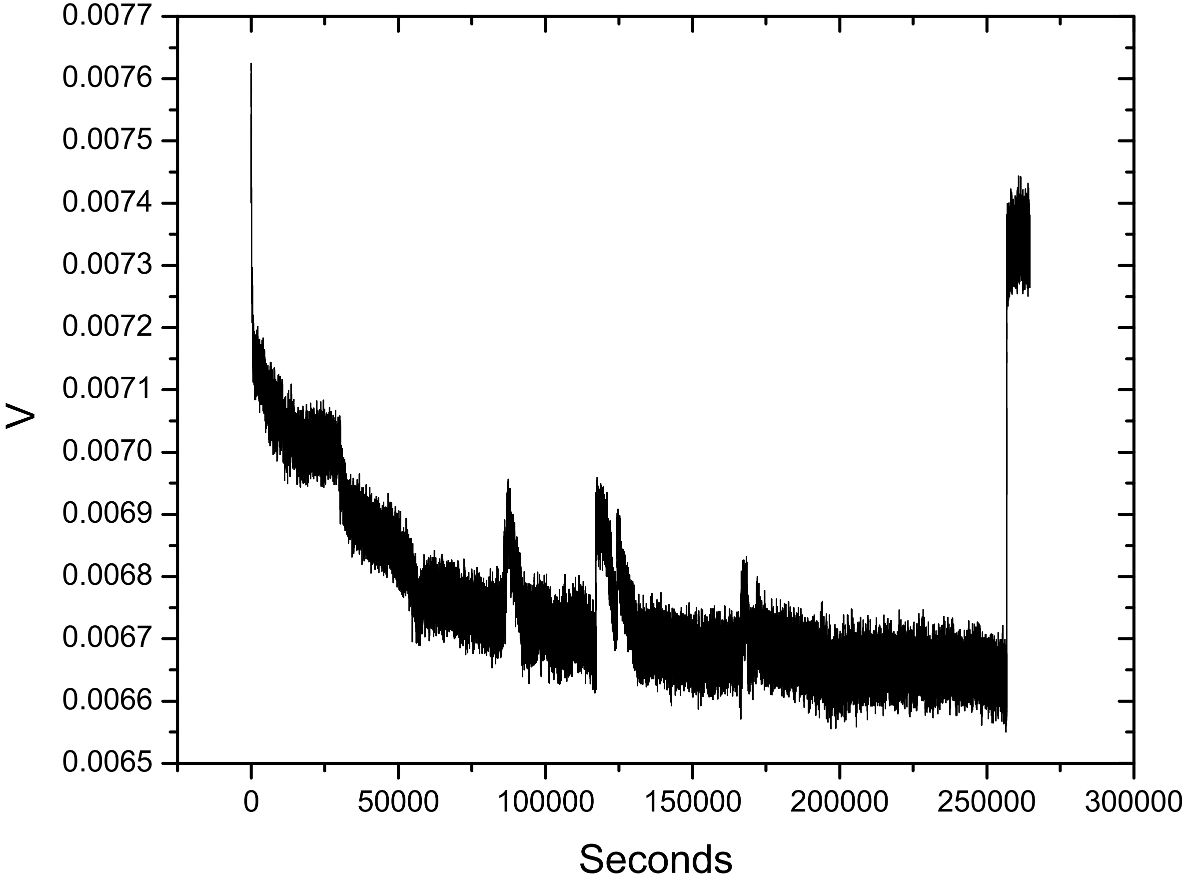
Before



After ~20 hours at 5 mA

Therefore Blech Product is less than 1250

# Sn Cr 0.5 mA 150C then 170C



Therefore the Blech Product is > 100

# Length Effect?

- Failures can occur at 1 mA @ 150C
  - Sample dimensions
    - 2 X 4 X 200 μm
    - $j = 1.25 \times 10^4$ A/cm$^2$
  - $jl < 250$ A/cm
- Failures do **NOT** occur at 500 μA
  - $jl > 125$ A/cm
  - For 125 μm solder ball , $j_{crit} = \sim 10{,}000$ A/cm$^2$
    - ***Immortality below 1.2 A***
  - For 75 μm solder ball, $j_{crit} = \sim 15{,}000$ A/cm$^2$
    - ***Immortality below 650 mA***

# Back Flow

- Merely exceeding the Blech Length of a value of j is not sufficient
  - If the length of the sample is twice $l_B$, the driving force for failure is reduced by half near end of life and failure times are increased proportionally
- Apparent current density exponent ($j^{-n}$) will be incorrect
  - Extrapolations to use condition unrealistic

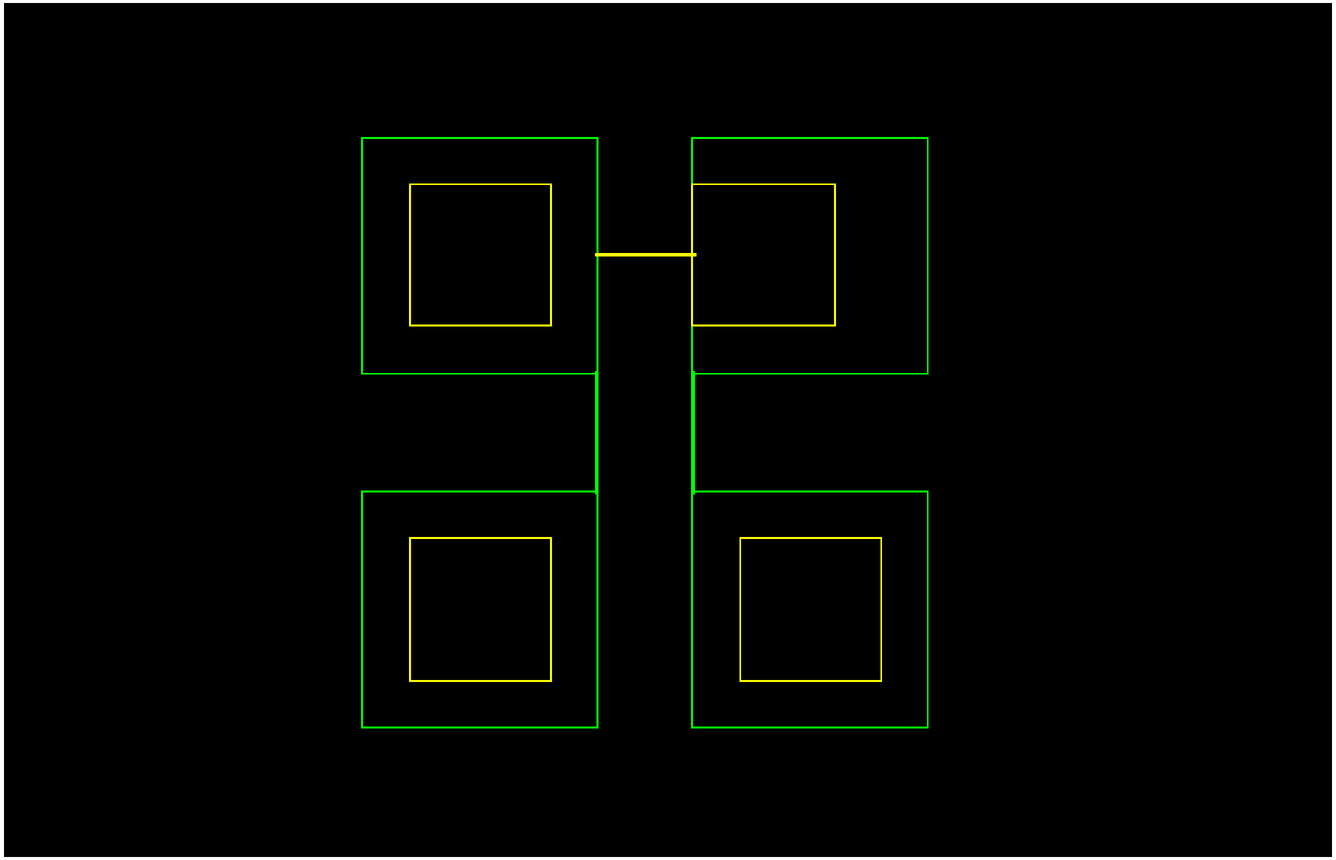
# Back Flow

- Experiments at higher current density may be irrelevant
  - Failure by Sn electromigration may not be possible at use conditions
  - For jl = 12.5 ma/μm the Blech current density for a 125 μm C4 is ~ 0.1 ma/μm² (10⁴ A/cm²)

Actually

$$\int_0^l j(x)dx \leq 12.5\,\frac{mA}{\mu m}$$

# Test Structure II

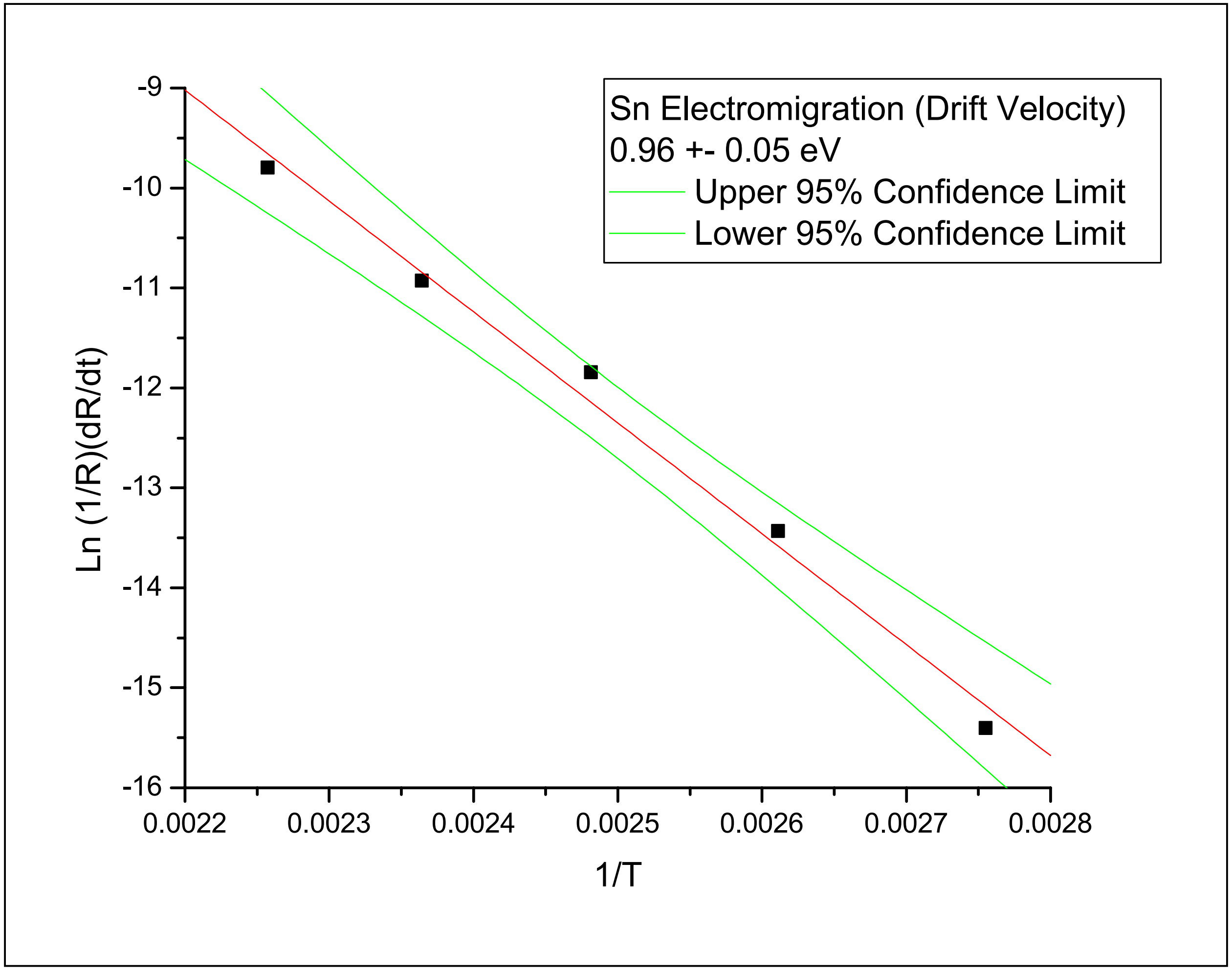


Like TS I but with different boundary conditions
“Reservoir Effect” on RHS

# Activation Energy

- From Drift Velocity
  - 5 temperatures
    - 90C, 110C, 130C, 150C, 170C
    - Wide temperature range
    - Down to operational use condition
  - 10 mA
    - Order of magnitude higher than Blech Current for this structure
    - No contribution from back stress gradient
  - Samples allowed to relax fully before measurement

# Activation Energy



# Activation Energy

$\Delta H = 0.96 \pm 0.05$ eV

- No Evidence of Grain Boundary Contribution
- Literature
  - Lattice 0.99 and 1.1 eV
  - Grain Boundary 0.41 to 0.51 eV

# Other Configurations

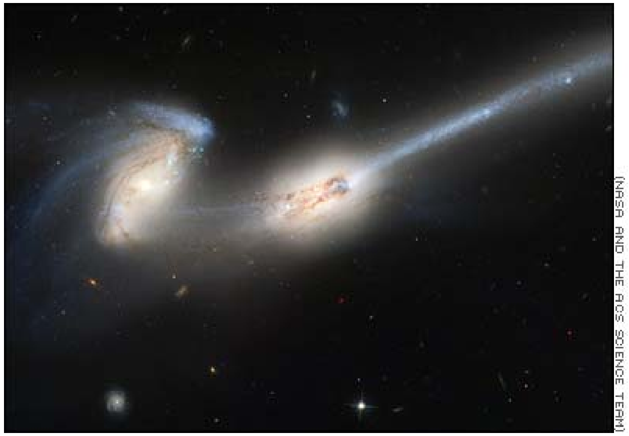
- Similar Behavior wrt Blech Product
  - Sn on Ni
  - Sn on Oxide
  - Sn – 0.7 % Cu alloy

# Interesting Initial Results

- Engineering
  - – j x l Determination
    - Immortality
  - – Activation Energy

U.S. Air Force Photo

- Science
  - – Resistance Decay



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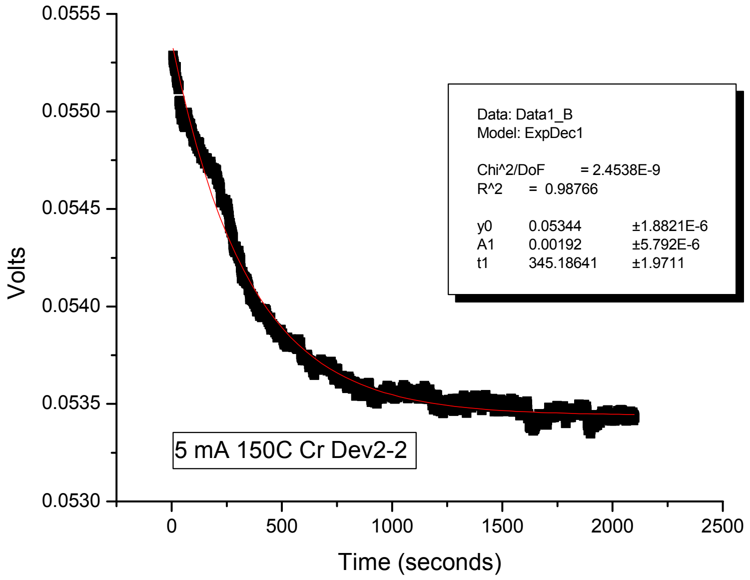
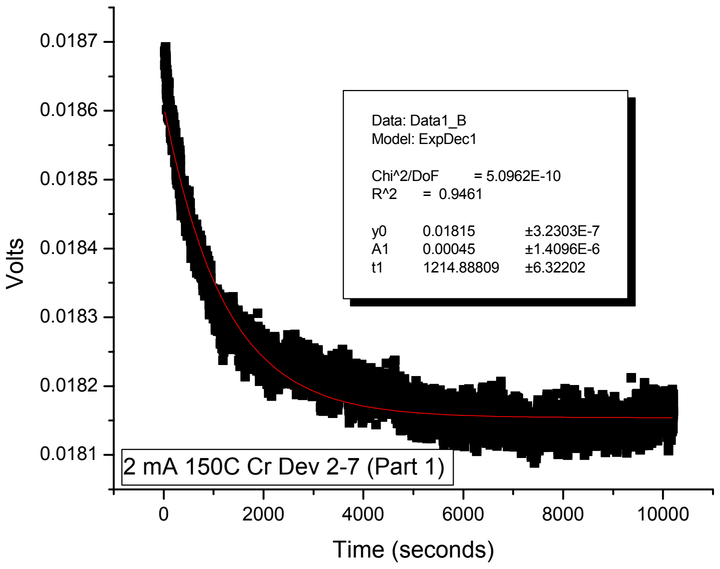
# Resistance Decay



Data: Data1_B
Model: ExpDec1

Chi^2/DoF = 2.4538E-9
R^2 = 0.98766

| | | |
|---|---|---|
| y0 | 0.05344 | ±1.8821E-6 |
| A1 | 0.00192 | ±5.792E-6 |
| t1 | 345.18641 | ±1.9711 |



Data: Data1_B
Model: ExpDec1

Chi^2/DoF = 5.0962E-10
R^2 = 0.9461

| | | |
|---|---|---|
| y0 | 0.01815 | ±3.2303E-7 |
| A1 | 0.00045 | ±1.4096E-6 |
| t1 | 1214.88809 | ±6.32202 |

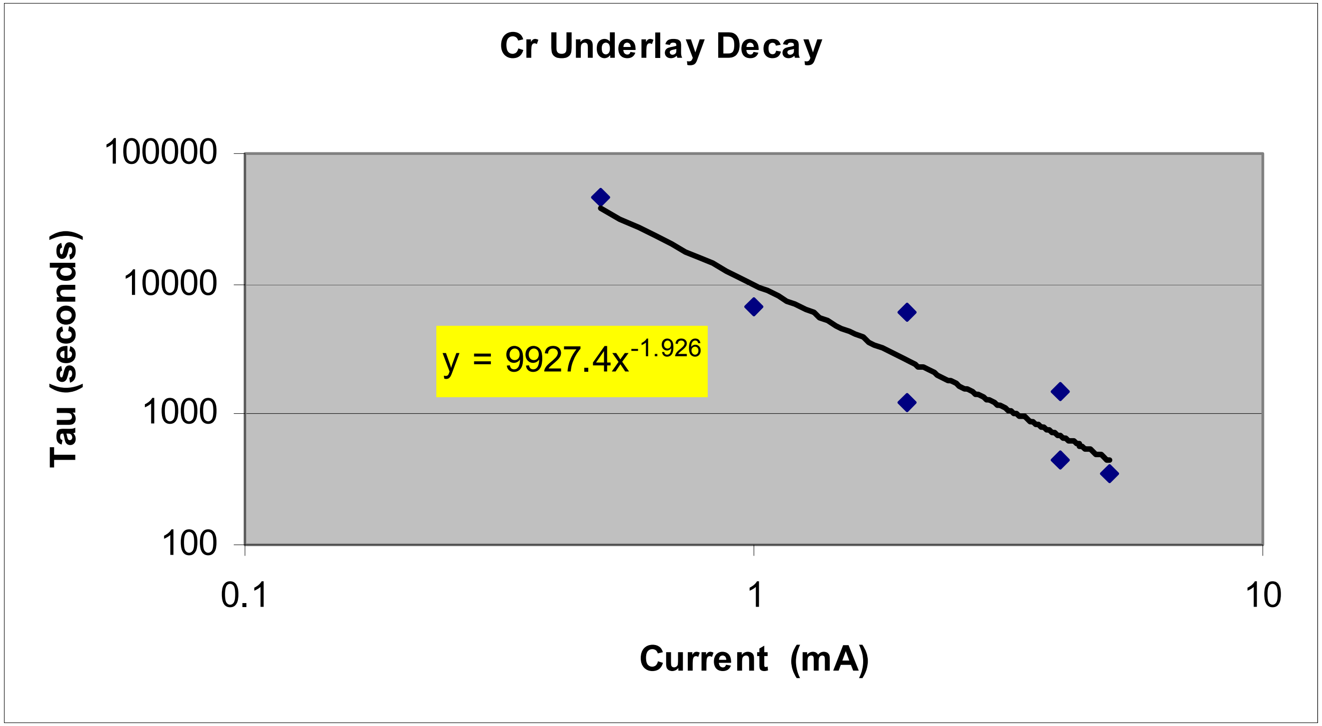
Decay time is a function of the current
Resistance later rises due to damage/edge motion

# Decay

| | I | tau | A | | Vo | Ro | V inf | R inf | DV/Vo % | Delta |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | |
| 2-9 Cr | 0.5 | 47172 | 5.00E-07 | | 0.00716 | 14.32 | 0.00667 | 13.34 | 6.843575 | 0.98 |
| 2-8 Cr | 1 | 6581 | 8.10E-04 | | 0.0149 | 14.9 | 0.0142 | 14.2 | 4.697987 | 0.7 |
| 2-7 Cr | 2 | 1214 | 4.50E-04 | | 0.0187 | 9.35 | 0.0182 | 9.1 | 2.673797 | 0.25 |
| 2-5 Cr | 2 | 6018 | 3.10E-03 | | 0.025 | 12.5 | 0.0218 | 10.9 | 12.8 | 1.6 |
| 2-3 Cr | 4 | 453 | 4.00E-03 | | 0.0416 | 10.4 | 0.0376 | 9.4 | 9.615385 | 1 |
| 2-4 Cr | 4 | 1525 | 9.50E-04 | | 0.0347 | 8.675 | 0.0338 | 8.45 | 2.59366 | 0.225 |

Substantial uncorrelated variation in initial resistance and in delta R

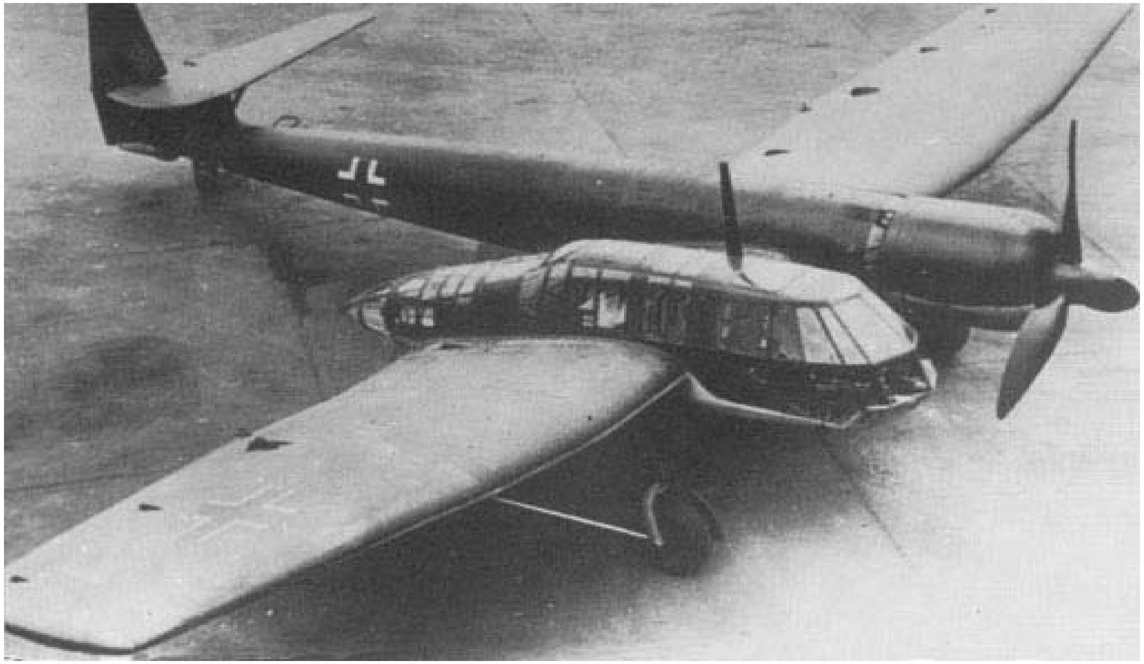
# $1/j^2$ Dependence



# Other Results

- Not due to temperature alone
  - Samples sitting at 150 C for up to 2 months before application of DC
    - Joule heating is too small
  - AC tests show only minimal changes (<0.5%)
    - Frequency dependent
      - 1 KHz a small possible effect
        - » (probably due to temperature)
      - 10 KHz, 100 KHz no effect

# Why?



- Sn is anisotropic
  - 40% difference in resistivity
    - (14.3 to 9.9 μΩ–cm)
  - 20% difference in elastic modulus
    - $C_{11} = 7.23$ and $C_{33} = 8.84 \times 10^{11}$ dyne/cm$^2$

# Why?

- Electromigration induced stress gradient produces driving force inducing re-orientation of Sn structure to minimize strain energy.
- Final orientation is lower resistance

# Effect of Structure

- Effect prominent on Sn/Cr and Sn/Ni
- Much less on Sn/$SiO_2$
- Texture (Ken Rodbell) is very different in as deposited condition
  - Sn/$SiO_2$ already aligned with lower resistivity orientation
- Before and after Sn/Ni showed change in $\rho$ and change in preferred orientation

# What?

- How does this come about?
  - Decay τ suggests grain boundary processes
    - Consistent with ~0.4 eV
  - Grain boundary diffusion?
- More work needs to be done

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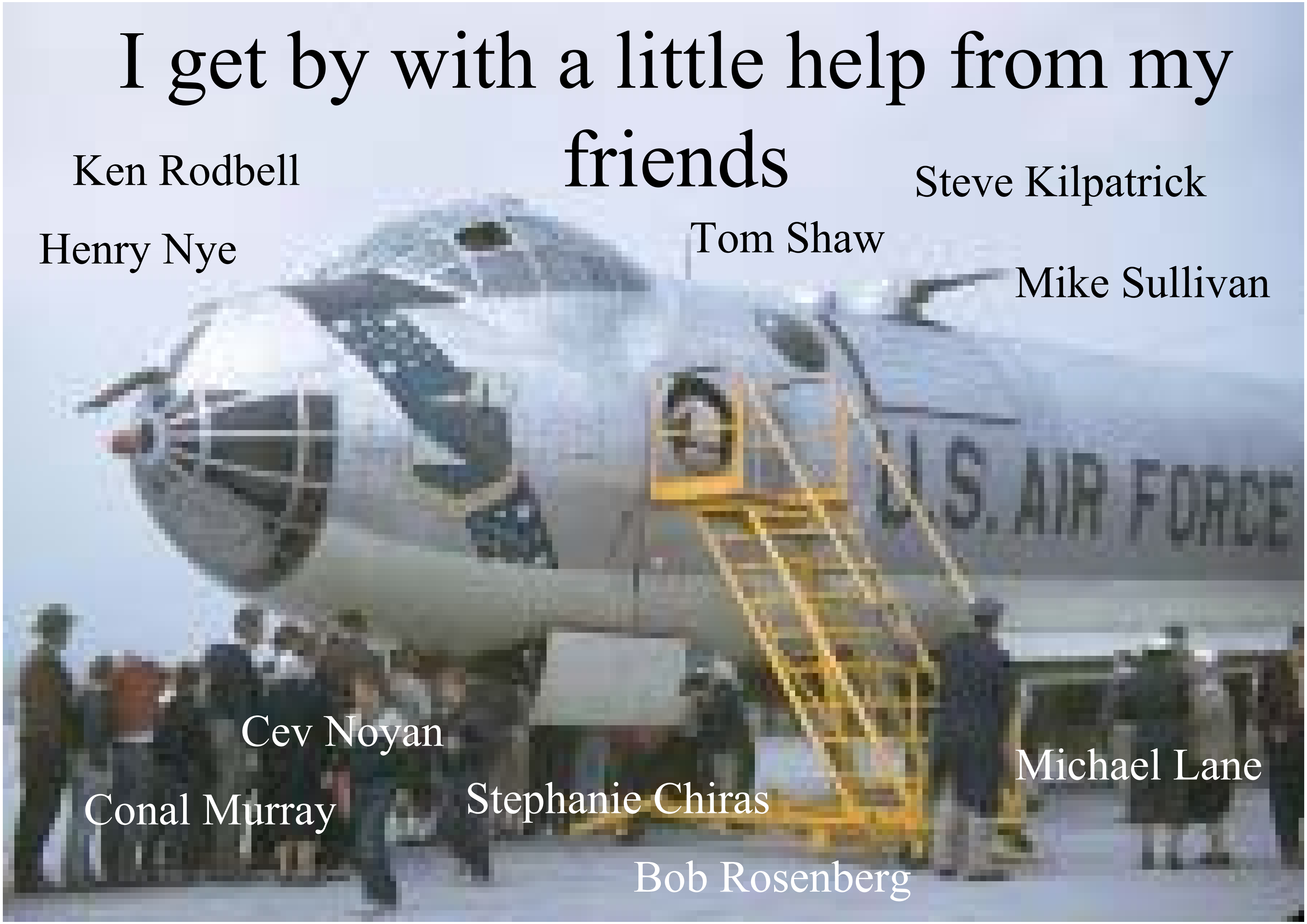
# Comment:
# Mass Transport with Soret Effect

$$J = \frac{DC}{kT}\left( Z^{*} e\rho\, j + \frac{Q^{*}}{T}\frac{dT}{dx} - \Omega\frac{d\sigma}{dx} \right)$$

# Mass Transport with Soret Effect

- Soret diffusion can have a profound effect on the behavior
  - Comparable to the electromigration driving force in Sn
  - Bizarre current density effects can be expected
- Any projection of reliability must be made in terms of the temperature gradients
  - Must be restricted/eliminated/specified in design rules

# I get by with a little help from my friends



Ken Rodbell

Steve Kilpatrick

Henry Nye

Tom Shaw

Mike Sullivan

Cev Noyan

Michael Lane

Conal Murray

Stephanie Chiras

Bob Rosenberg