The Challenge of Lead-free Electronics for Aerospace Electronic Systems

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Problem: Electronic Waste contains hazardous materials

<u>Lead</u>, Barium, Beryllium, Mercury, Cadmium, Arsenic ...

Pb (Lead) **Hazard known since Roman times** (Pb=Plumbium)

Mentioned in Old Testament - *Jeremiah, 6:29* **-** *get the lead out*

Goal: reduce hazard risk to humans & environment

Electronic Waste Problem is Growing

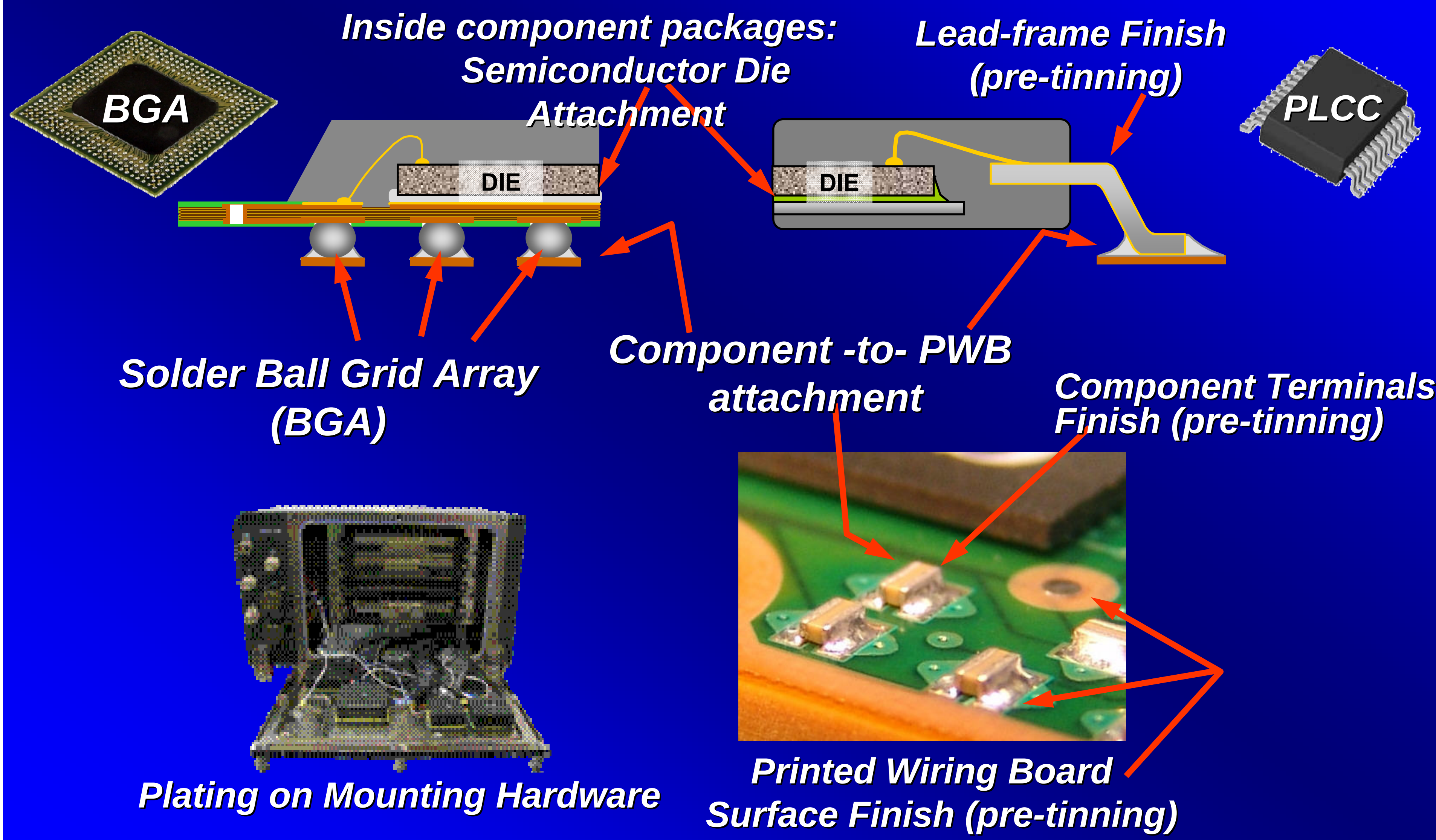
Table 1- Municipal Solid Waste (Volume in thousand tons)[8]

	2000	2005	Growth Rate
Durable Goods	36,980	40,280	8.9%
Misc. Durables	14,670	17,130	16.8%
Consumer Electronics	2,160	2,630	21.8%
Other Misc.	12,510	14,500	15.9%
Other Durables	22,310	23,150	3.8%
Non-Durables	64,120	63,720	-0.6%
Containers & Packaging	76,020	76,670	0.9%
Other Wastes	60,510	64,990	7.4%
Total	**237,630**	**245,660**	**3.4%**

So Pb contamination must be growing too

Source: US Environmental Protection Agency: *Municipal Solid Waste in the United States 2005 Facts and Figures.* P. 68-72

Where Is Pb Used in Electronics?



Legislation: Restrict Hazardous Waste

RoHS & WEEE directives

- **Reduction of Hazardous Substances**
- **Waste Electrical and Electronic Equipment**
- **Applies only to electronics**
  - **Cell phones, iPods, light bulbs, appliances, personal computers, tools, toys, sports equipment**
- **Applies to products sold in Europe**
  - Some similar movement in China, Korea, . .
- **Targets six hazardous materials only:**
  - **Lead, Mercury, Cadmium, Hex Chromium, PBB, PBDE**
- **Directive is in effect since 01-July-2006**

All European consumer electronics are Pb-Free

Limitations of RoHS & WEEE

- Directives do not restrict the <u>overall bulk quantity</u> of electronic waste
- No recycling / reuse requirement
- Directives *do not apply* to Medical, Industrial, Telecom, Aerospace, Defense, Automotive products *{Exemptions for High-Reliability Equipment}*
- Directives don't yet address Pb-acid battery waste

Lead-acid batteries are the biggest use of Pb in electronics

- Driving toward Pb-free electronic circuits

Pb-Free Electronics – New Failure Modes

- **"Tin Whiskers"**
  - Electrically conductive shorts
  - Metal shards, contamination
  - Arc flash leaves metal vapor
- **Environmental Effects**
  - **Fractures** in high shock & vibration environments
  - Higher **melting** temps
  - **Incompatibilities** with SnPb Solder
  - **Less-repairable** assemblies
- **Configuration control problems**
  - Mixed Pb and Pb-free **inventory**
  - Unidentified components

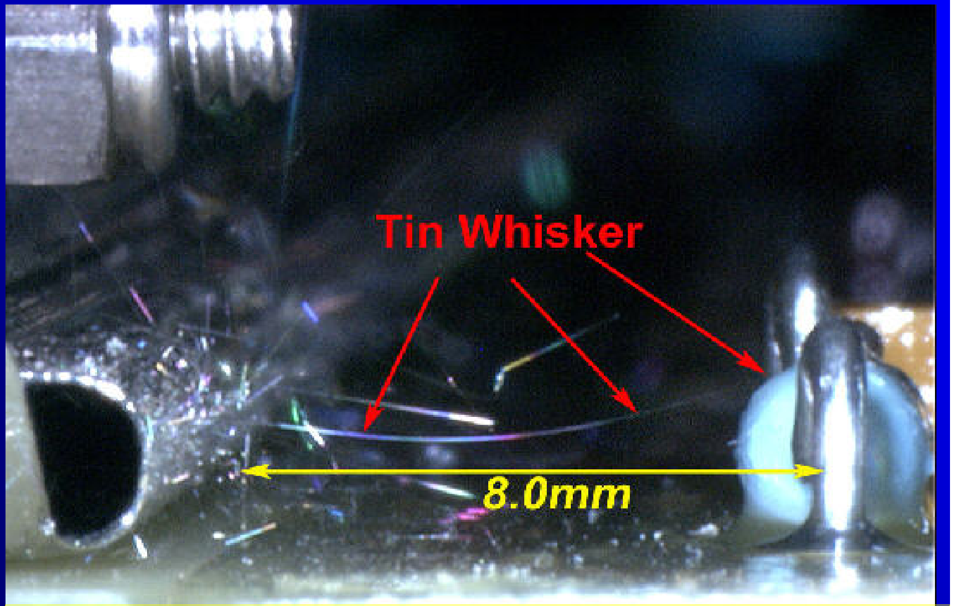
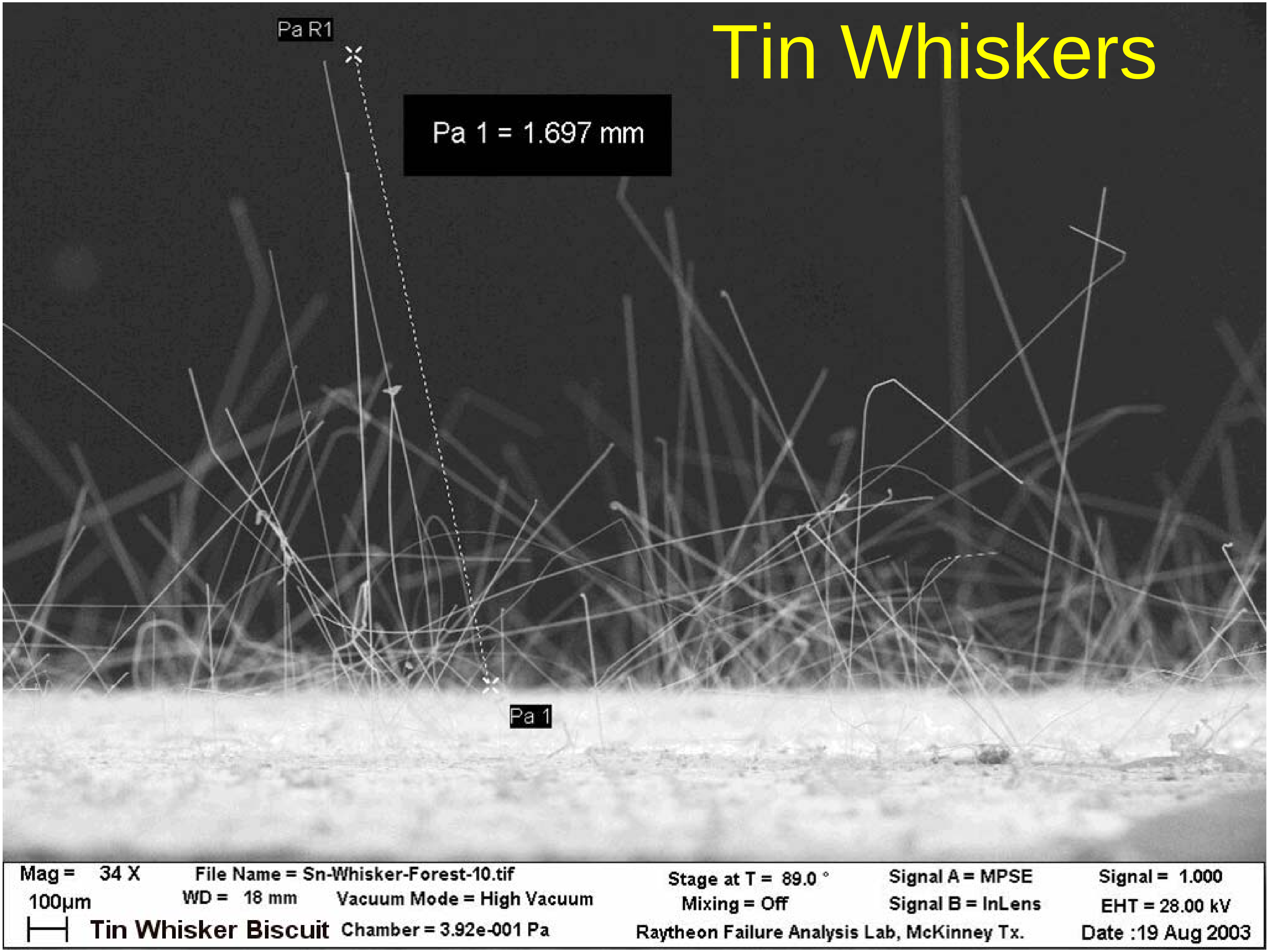


Photo Source: NASA Space Shuttle Program

Electromagnetic Relay Short Circuit

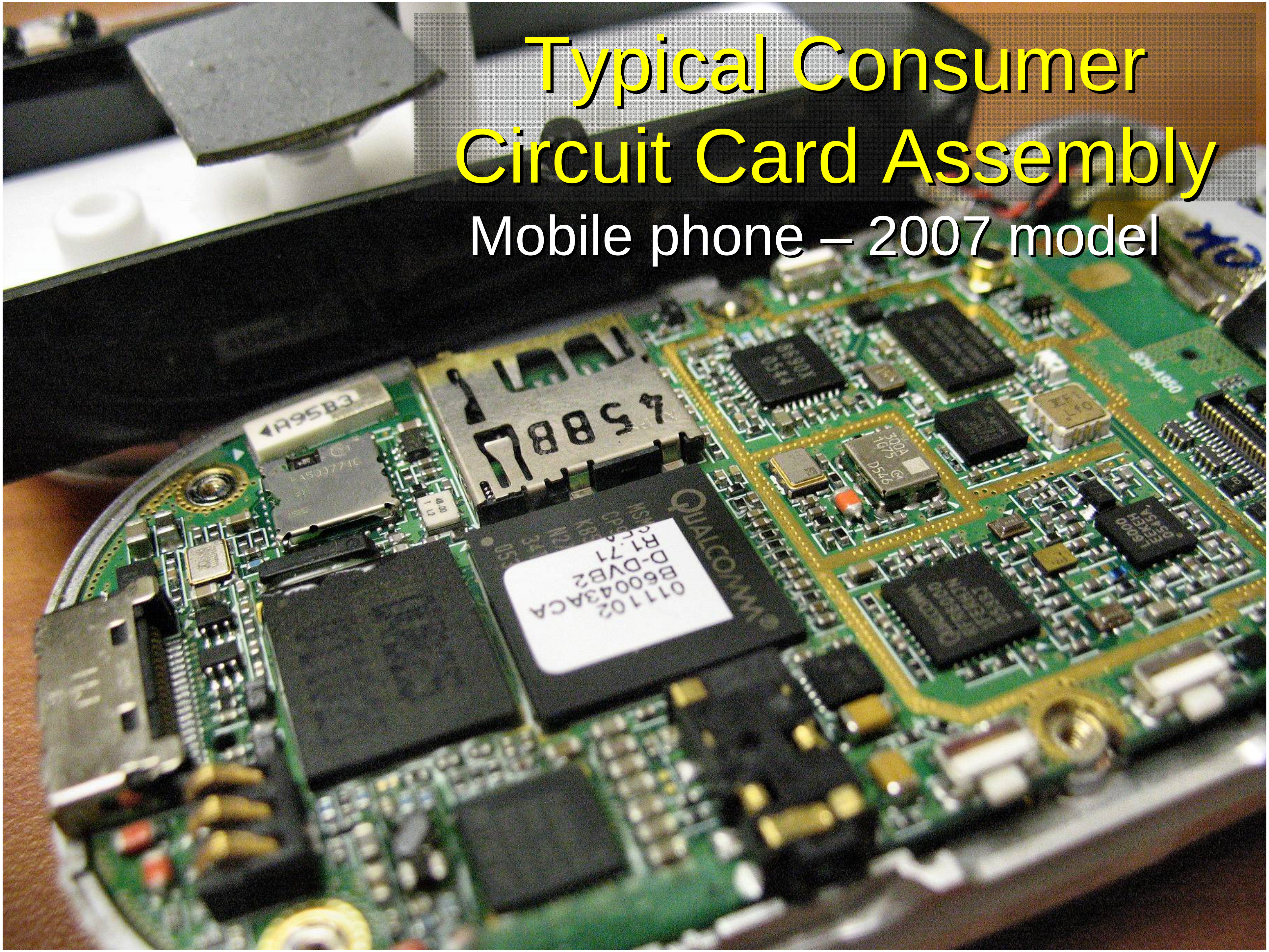
Cracked Solder Joint Open Circuit

Tin Whiskers



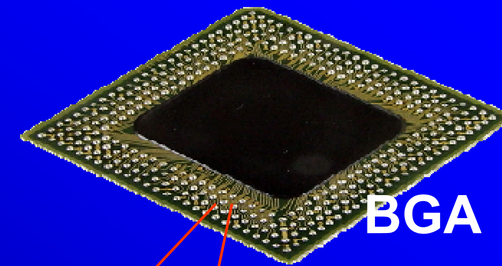
Typical Consumer Circuit Card Assembly

Mobile phone – 2007 model

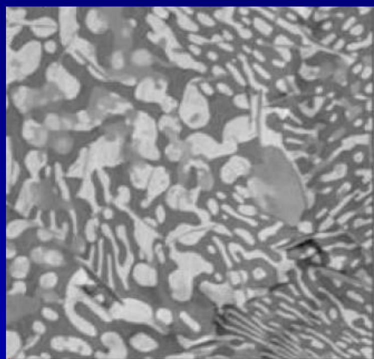


Pb-free Structures are Brittle

Open-circuit Failure Modes

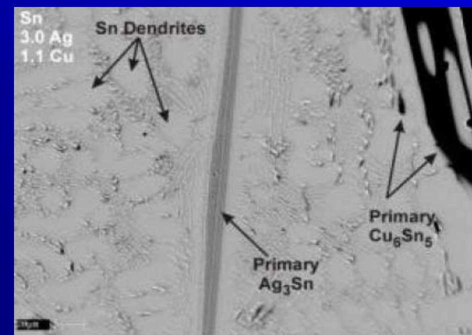


BGA



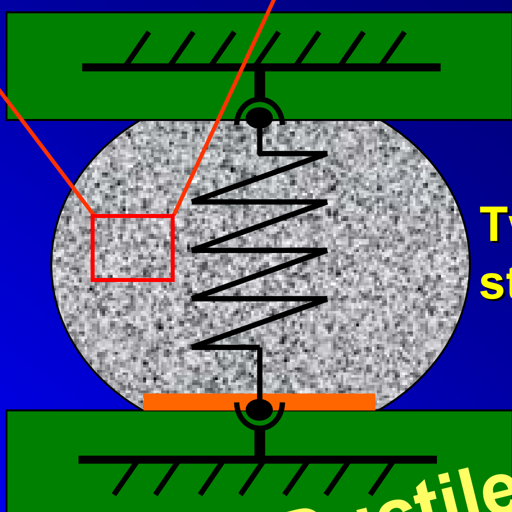
Tin-Lead (SnPb)

Eutectic



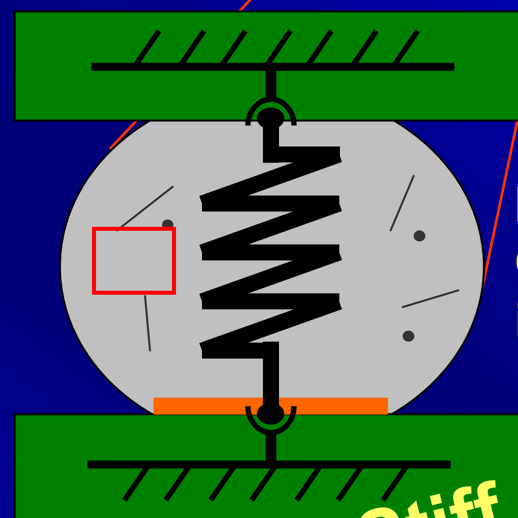
Pb-Free SnAgCu

Lead-Free



Two-phase structure

Ductile, flexible



Inter-Metallic Compounds in Sn Matrix

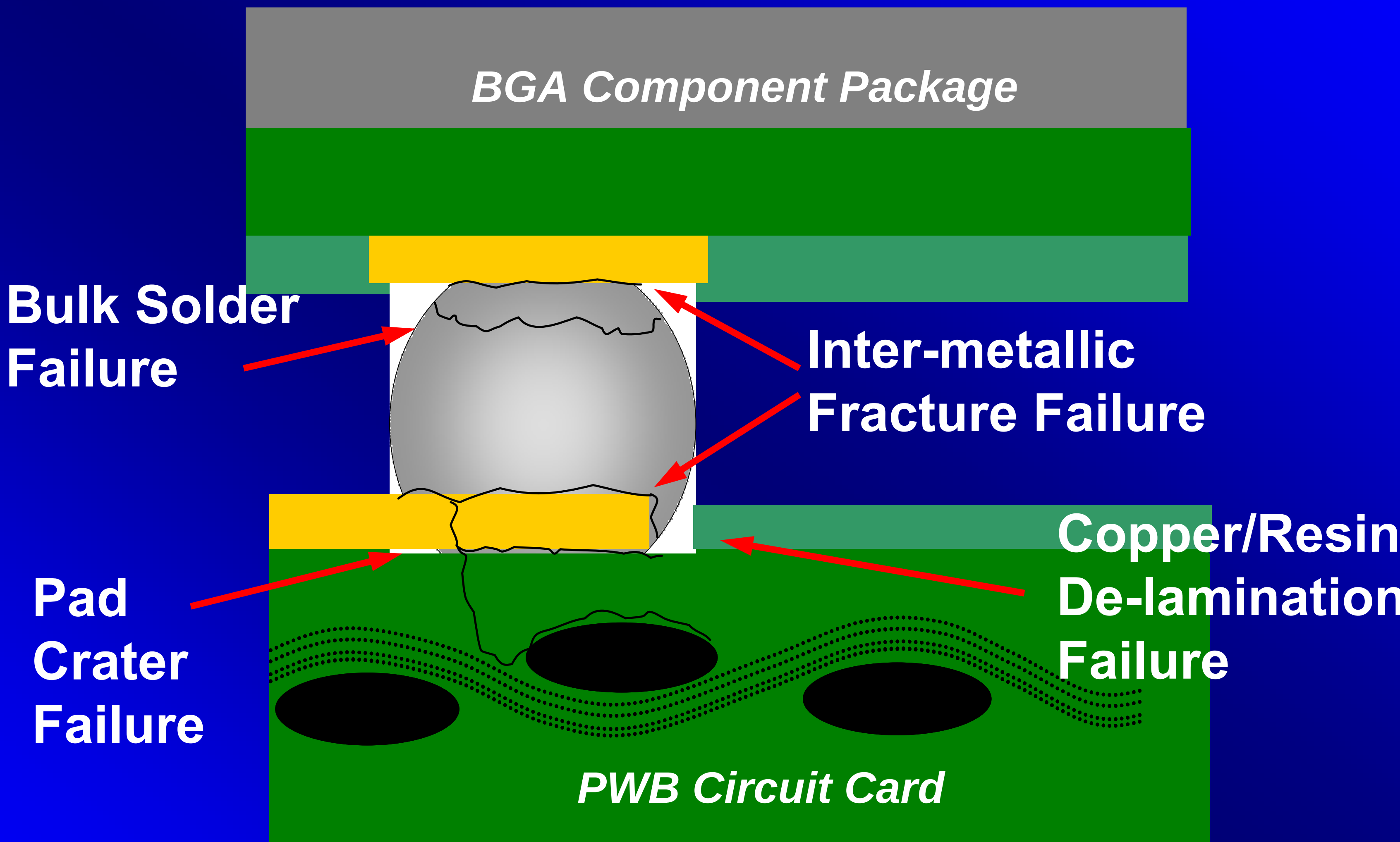
Stiff, brittle

Failure Modes:

Fractures, open circuit, intermittent contact, ball detachment

BGA failures are obscured, difficult to diagnose & repair

Pb-free Solder Joint Failure Modes

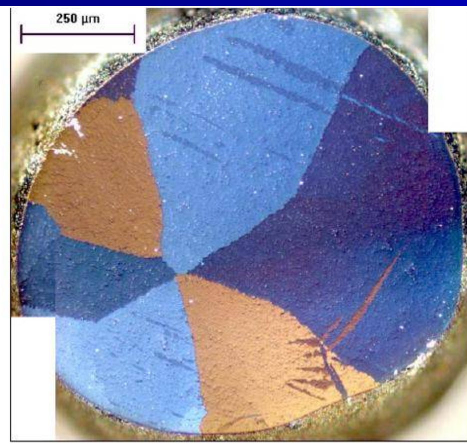


Symptom: "Intermittent open circuit" hidden under a Ball Grid Array

Tin-Silver-Copper (SAC) Grain Structure is affected by alloy balance

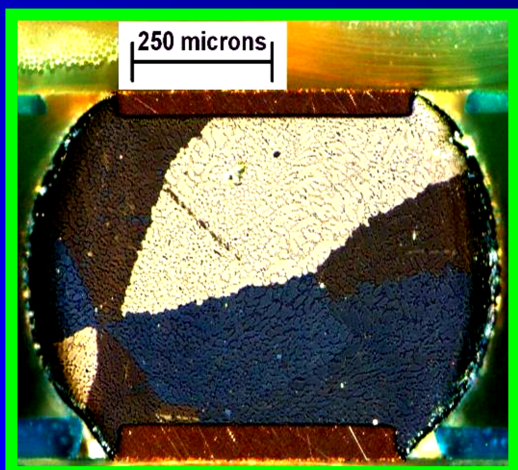
Polarized cross-sections show Tin grains structure

Tin -3.5% Silver

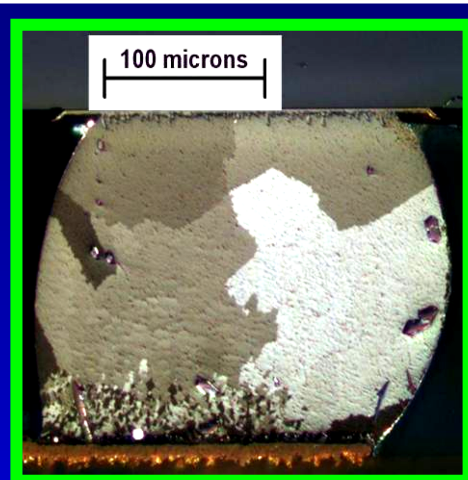


← Tin-3.5% Silver-0.6% Copper

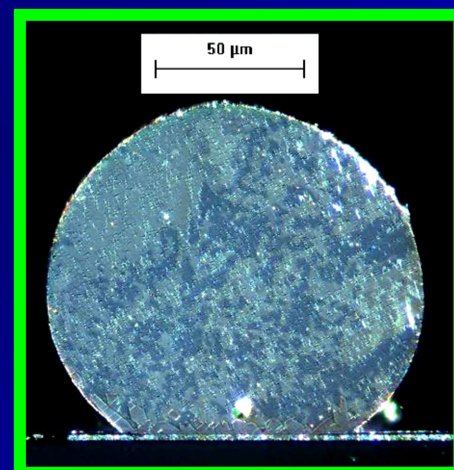
A small amount of copper radically alters the structure of the primary Tin grains.



BGA



Fine Pitch CSP



Flip Chip

Smaller balls contain fewer crystal grains

RoHS & WEEE Directly Impact Aerospace & Hi-Rel Industries

- Since RoHS & WEEE went into effect in 2006:
  - Lead, mercury, cadmium, hexavalent chromium, PBB, and PBDE are banned.
  - Lead (Pb) ban is the most immediate concern to aerospace industries
  - Aerospace, Medical, Automotive, Defense, Telecom are excluded as "out of scope" of RoHS & WEEE
- However, Pb-free components are slipping in, as the worldwide <u>consumer</u> electronics industry converts to Pb-free processes and materials.

Commercial-quality Pb-Free components are leaking into every supply chain

Why is Pb-free a problem for US Aerospace ?

- Aerospace & High-Reliability products are specifically exempt from RoHS & WEEE
- RoHS & WEEE are Europe-only, all products sold in US are exempt

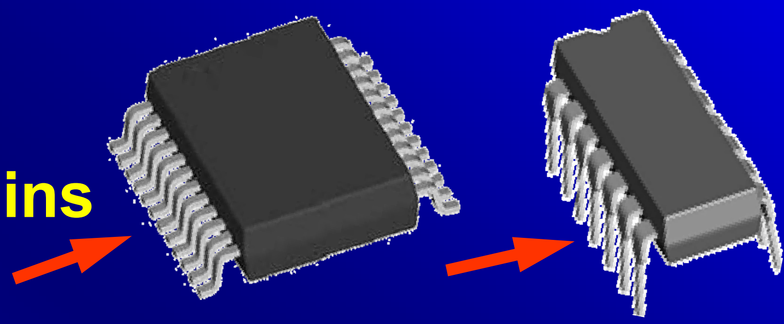
…so USA can use tried-and-true solder
Eutectic Tin-Lead [63% Sn, 37% Pb]

'Just Say No' to RoHS & WEEE

Aerospace can't "Just say No"

All mass-produced components are pre-plated with Pb-free solder

Pre-plated Pb-free pins

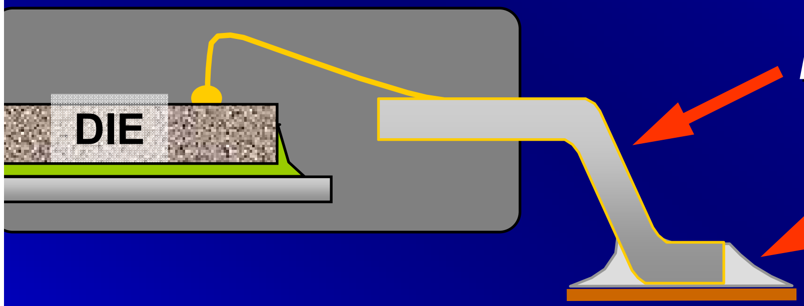


Semiconductor manufacturers must eliminate Pb from plate coating to comply with RoHS and WEEE

Problems:

- **Pb-free surfaces still grow whiskers**
- **Mixing Pb-free components with PbSn solder introduces new failure modes and metallic incompatibilities**
- **Cost benefits require cheap COTS components**

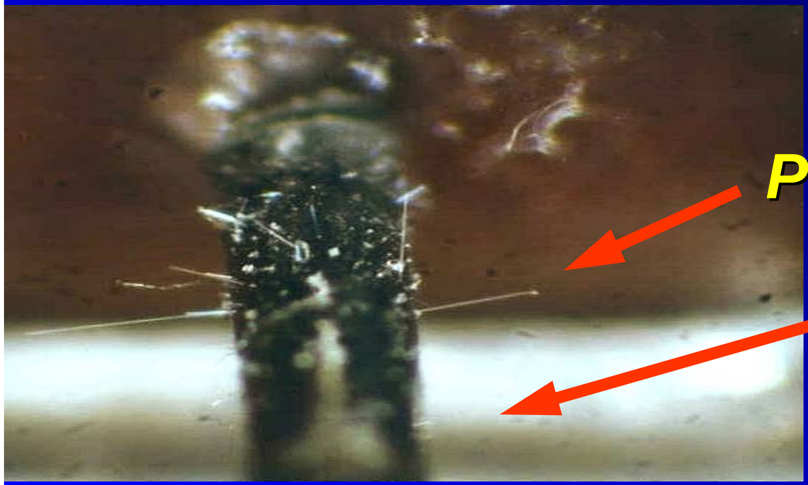
Pb-free packages don't meet aerospace requirements



Pre-plated Pb-Free area

Eutectic attachment solder

All Pb-free surfaces can still grow whiskers



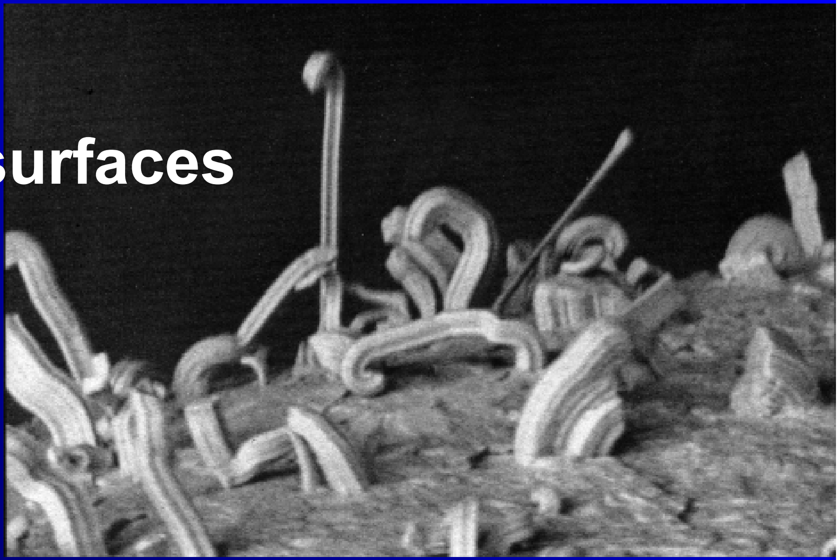
Pb-free plated area grows whiskers

Recoated eutectic area is clean and whisker-free

Whisker growth is more likely over time

How To Mitigate Tin Whiskers?

- **Design Practices**
  - Reduce exposed conductive surfaces
  - Conformal Coating
- **Material Selection**
  - Avoid Use of Tin Plating Greater than >97% Purity
- **Component & Assembly**
  - Re-flow of Pure Tin Plated Surfaces
  - Annealing
  - Solder Dip / Strip & Re-plate Terminations
- **Handling Practices**
  - Provide Stable Storage Environment
  - Temperature/Humidity
  - Provide Protection From Mechanical Damage
- **Prevent supply chain pollution**
- **Mitigation ≠ Elimination**



Curly Tin Whiskers Growing on Capacitor

Failure Effects
Pb-Free in Consumer Electronics

- Cell Phones, laptops, PCs
- Music Players, stereos, GPS
- Television sets, video games,
- Digital watches

Failure is treated as a nuisance.
Product is replaced, not repaired.

Consumer Response to Failure
"Throw it away, get a new one"

Aggravates the bulk waste problem for landfills

Trend toward shorter warranty periods

- **Small hard-disk drives**
- **Increases extended warranty sales**

Products are not designed to be repaired

Hi-Reliability Systems

- **Aerospace, Medical, Automotive, Hi-Rel:**
  - **Human life-critical. Cost of failure is high**
  - **Long service life (10…40+ years)**
  - **Extended temperatures & vibration range**
  - **Rigorous Configuration Control**
  - **Systems must be Repairable**
- **Commercial Pb-free components don't meet requirements for most military / aerospace applications**

But high-reliability systems are increasingly dependent on commercial electronic parts !

Pb-Free has a Long History of Failures

Military	F-15 Radar	Tin whisker shorted inside hybrid microcircuit, growing from tin-plated component lids.
	U.S. Missile Program	Tin whisker on plated relay caused short-circuit
	U.S. Missile Program	Tin whisker from tin-plated TO-3 can. Short sent a false command to turn ON an electrical unit.
	Phoenix Air-to-Air Missile	Tin whisker shorts inside hybrid microcircuit. Whisker grew from a pure tin-plated hybrid microcircuit lid.
	Patriot II	Tin whiskers from pure tin plated terminals
Aero-Space	GALAXY IV satellite	Complete loss of satellite operation. Tin whisker short (metal vapor arc in vacuum) from pure tin plated relays.
	GALAXY VII satellite	Complete loss of satellite operation. Tin whisker short (metal vapor arc in vacuum) from pure tin plated relays
	Solidaridad I satellite	Complete loss of satellite operation. Tin whisker short (metal vapor arc in vacuum) from pure tin plated relays.
	Additional Satellites	Three additional satellites of the same general design as above lost first of two redundant satellite control processors, due to tin whisker shorts.
Energy	Nuclear Power Plant	Tin whiskers from pure tin plated relays shut down nuclear reactor power plant. Dominion Nuclear Connecticut, 2005
Medical	Heart Pacemaker	Class I Product Recall: Tin whisker short caused complete loss of pacemaker output.
	Apnea Monitor	Sleep monitoring alarm used for infants (SIDS) and adults post- anesthesia. Multiple lawsuits filed. Whisker short-circuits on control panel switches. 1994

Source: NASA http://nepp.nasa.gov/WHISKER/failures/index.htm

Tin Whisker Failures well-documented since 1940s

Failures during product life: <u>Reliability</u>

In short-life products, early failures are no problem

- **Cell phones, music players, "fashion" products, dynamic product function & style, disposable**
- **Consumers are conditioned to <u>expect</u> short product life**
- **Planned Obsolescence enforcement**

In long-life products, failures are costly

- **Aviation, Space, Medical, Automotive, Industrial, Military have "Hi-Reliability" requirements**
- **Human life support (pacemakers, breathing gear..)**
- **High capital systems, remote locations**
- **Costly downtime – industrial plant**
- **System Repairability is a requirement**

Measured as MTBF (Mean Time Between Failure)

Common Failure Modes & Effects

1. Fails to actuate
   – Won’t power up, won’t connect to net
   – Weak or noisy performance
   – Battery drains too rapidly
2. Improper Actuation
   – Turns on or triggers unexpectedly
   – “Software crash”, erratic behavior
   – Won’t turn off, blaringly loud or bright
   – Over-temperature, exothermic, smells bad
3. Creates a safety hazard
   – Battery leakage, chemical or fire hazard
   – Catches fire spontaneously or explosively

Example: Combat Vehicle Electronics

Failure Modes & Effects in Aerospace & Hi-Rel Products

Environmental stresses are more extreme

- Outdoor operation: day/night thermal cycles
- Direct sunlight, rain, salt water, space
- Shock and vibration

Multiple mission-critical systems on board make a single-point failure more likely

Product life is long

- Design life of 25 years is common, actual use past 75 years..

System must survive repairs

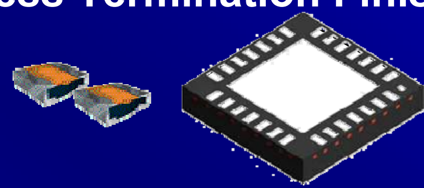
User must survive failure events.

Equipment must survive repair events.

Pb-free Process Effects: Yield

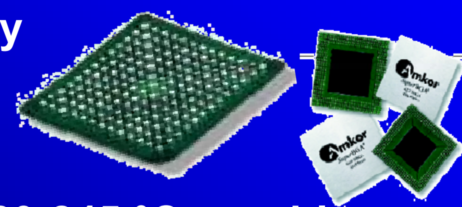
Lead-frame Finish

Leadless Termination Finish



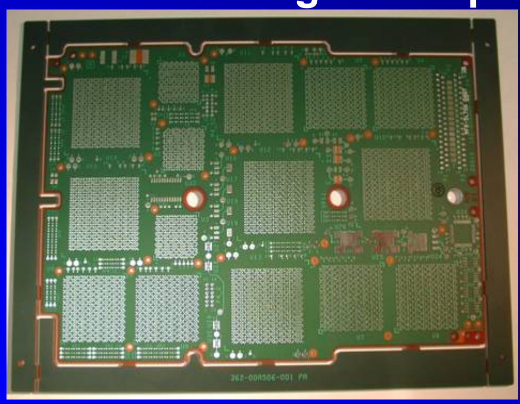
Common lead-free finishes on current products: matte tin, NiPdAu, SnAgCu

Ball Grid Array Solder Balls



Tin-Lead: 220-245 °C capable
Lead-Free: 245-260 °C capable

Printed Wiring Board prep



Heritage: Sn-Pb finish, 140 °C Laminate
Lead-free: Sn, Nickel/Gold, or Silver, 170°C Laminate

Wave Solder

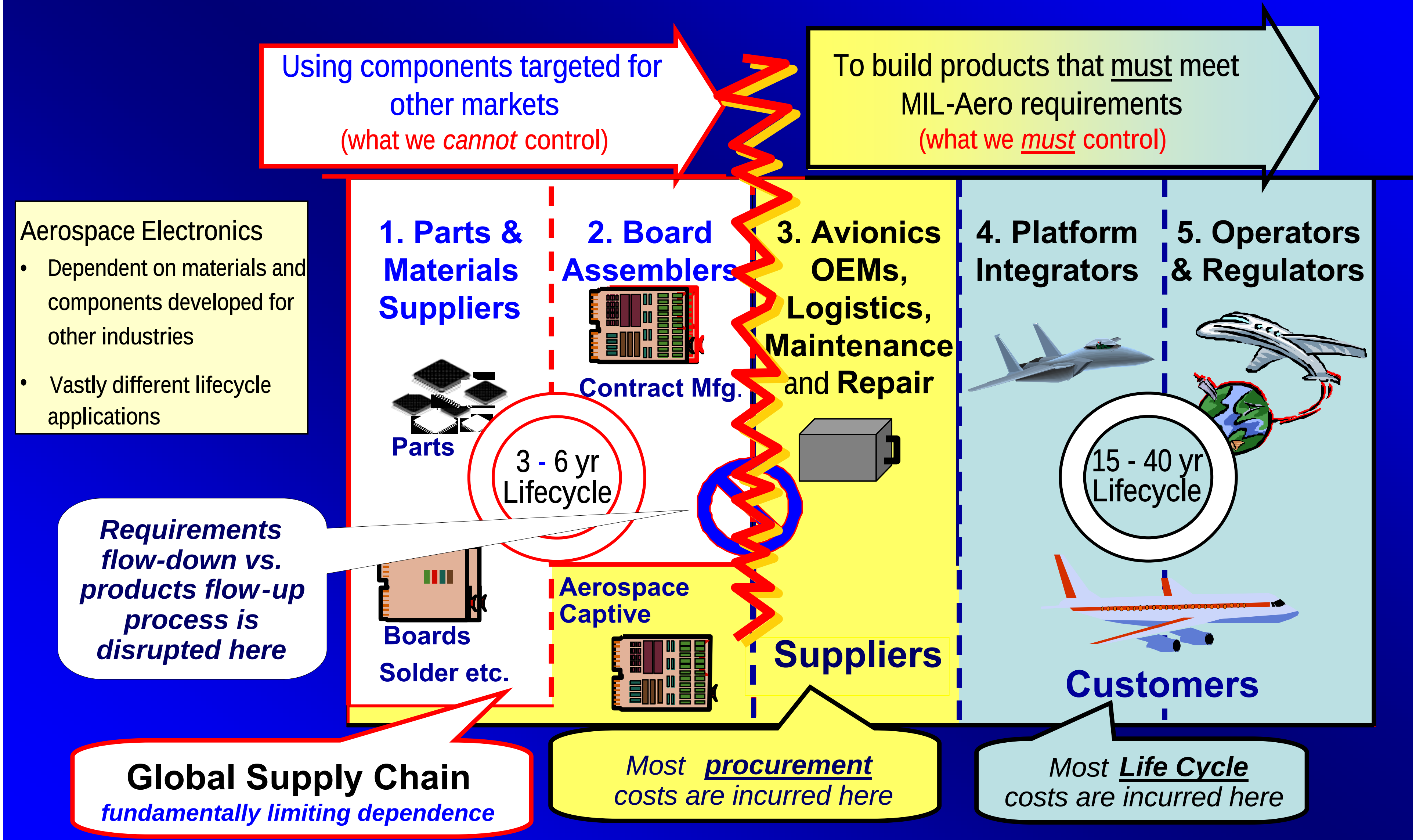
Solder Paste

Wire Solder

Heritage: Tin-Lead solder 220 °C
Lead-free: Sn-Cu: 260°C,
Tin-Silver-Cu solder: 245 °C

Packages & die must survive manufacturing

Break in Aerospace Supply Chain

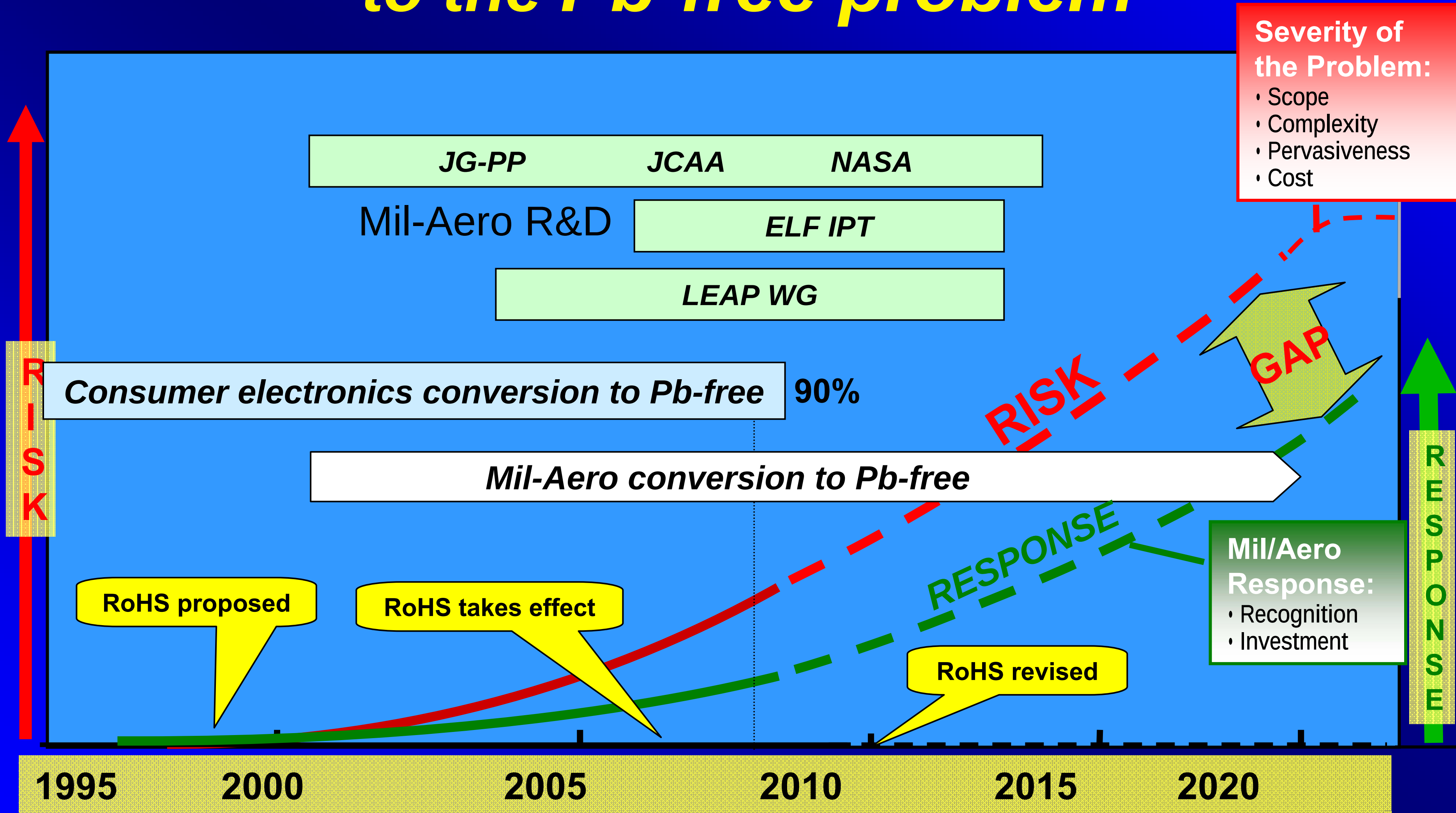


Total Cost of Ownership Increases

Customers see increased operating costs

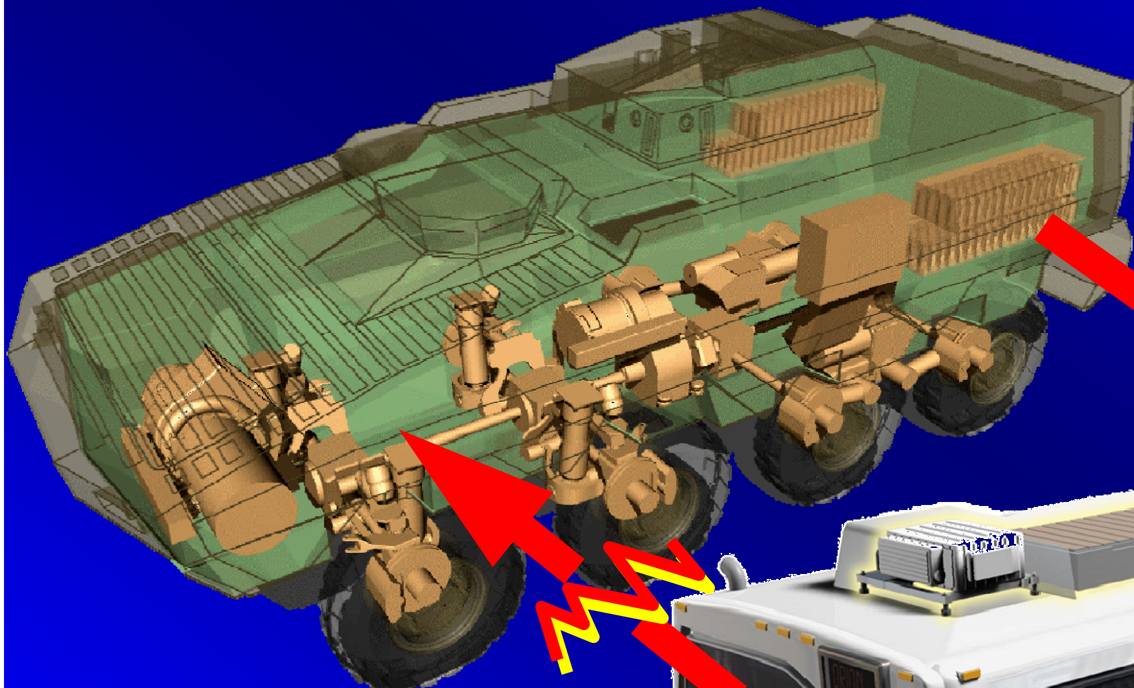
- **<u>Component Obsolescence</u>: Difficult and costly to maintain today's systems as suppliers convert to lead-free**
- **Configuration Management Issues:**
  - **Many vendors don't create new part numbers for lead-free parts. This creates a logistics quagmire and future sustainment problem**
  - **There is no easy technical solution. <u>No</u> drop-in replacement for today's eutectic SnPb solder. Multiple solutions are being touted as "the" technical solution**
- **Manufacturing Cost Increase: There is an increased cost of implementing new lead-free manufacturing, rework and repair processes**
- **Cost differential drives piracy, "counterfeit parts" market**
- **Repair, Rework and Sustainment: Increased cost of maintaining dual inventories and manufacturing lines**

Aerospace Industry Response to the Pb-free problem



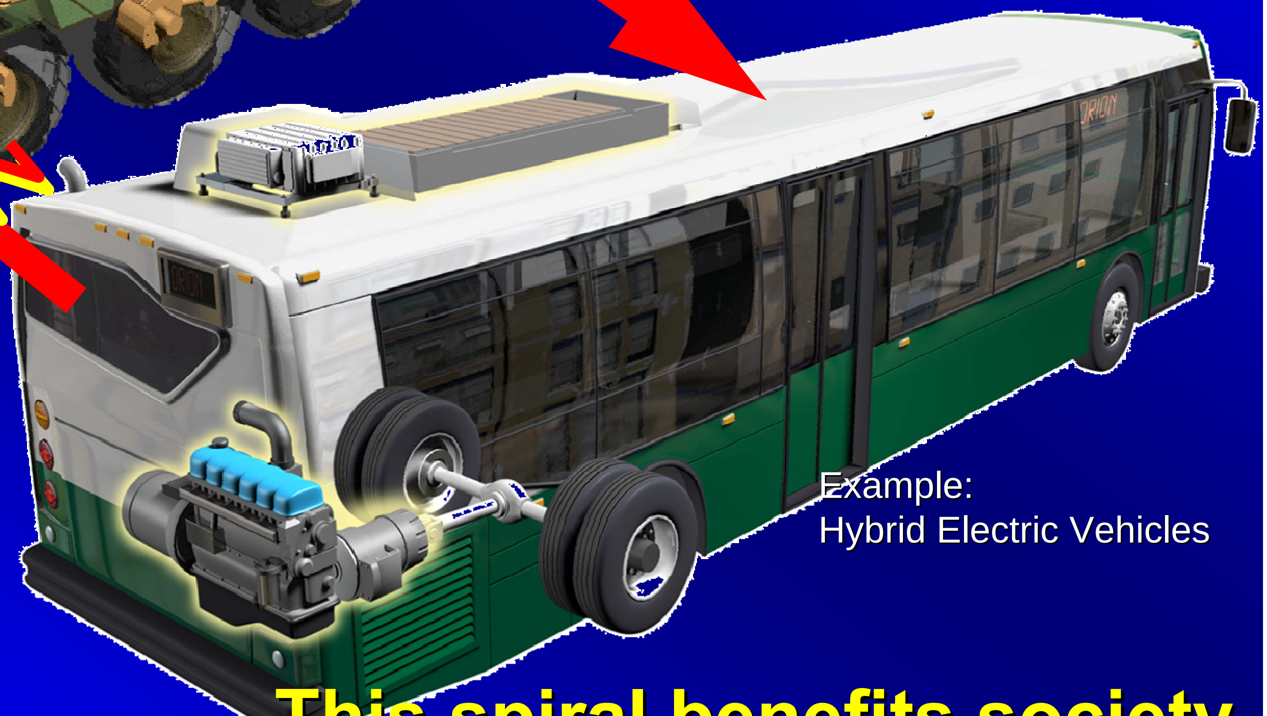
Doing Nothing Maximizes Risk

Synergy between government & commercial electronics industry threatened



Government:

Sustained R&D Funding
Entirely new functions
Working prototypes, systems
Risk reduction
Specialized, trained workforce



Commerce & Industry:

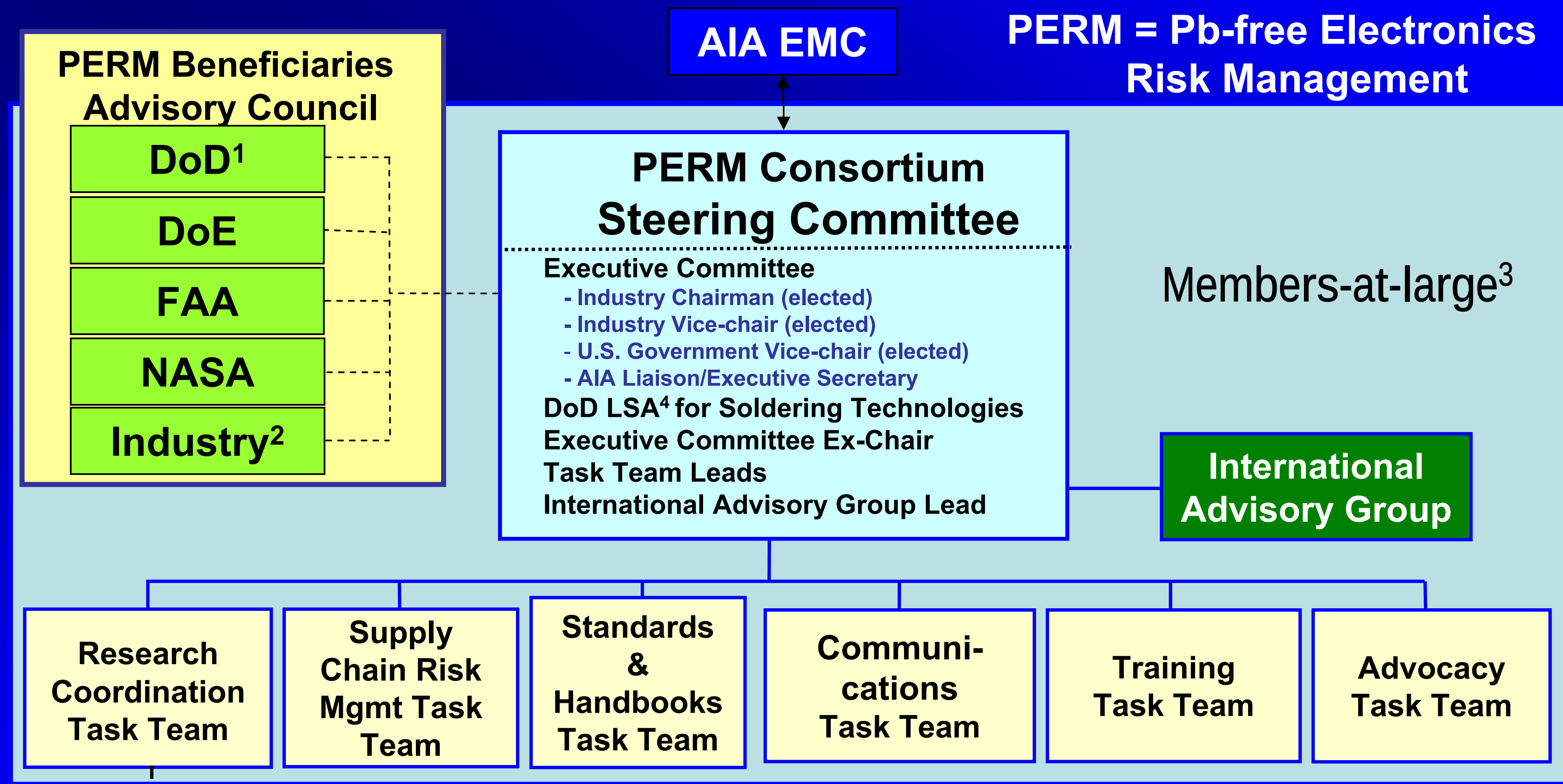
Standardization
Cost reduction
Mass production
Improved Reliability
Broad application
Capital infrastructure

This spiral benefits society

What Industry Is Doing About It

- **Lead-free Electronics in Aerospace Project Working Group (LEAP WG) AIA-AMC-GEIA**
  - **Includes all aerospace industry stakeholders**
  - **> 150 aerospace organizations represented**
  - **20 meetings (attendance ~90 in US, 50 in Europe)**
  - **6 published industry documents, 1 more in work**
  - **Addresses issues unique to aerospace, and within our control**
- **Executive Lead-free Integrated Process Team**
  - **Includes all US stakeholders (government and industry)**
  - **Recommended Government Policy, SOW, deliverables**
  - **Pb-free training through Defense Acquisition University**
- **Research**
  - **Joint Group on Pollution Prevention**
  - **NASA & DoD Research**
  - **CALCE -Center for Advanced Life Cycle Engineering (Univ of MD)**
  - **Additional needs identified by AIA Technical Operations Council**
- **PERM (Pb-free Electronics Risk Management)**

PERM Consortium Functional Framework



Lead-free Electronics Research Manhattan Project (Gov't Contract)

1. Membership of Senior Stakeholders determined by OSD & DoD
2. Including representatives of Industry Associations such as AIA, TechAmerica, AMC, IPC, etc.
3. Any individual participant (Government, industry and academia) in PERM meetings and consensus process; Integrated Membership from prior LEAP WG and ELF IPT
4. LSA = Lead Standardization Activity

Beneficiaries
Sponsor
Working Teams
International

LEAP Working Group - New Standards

GEIA-STD-0005-1, Performance Standard for Aerospace and High Performance Electronic Systems Containing Lead-free Solder

Used by aerospace electronic system "customers" to communicate requirements to aerospace electronic system "suppliers"

GEIA-STD-0005-2, Standard for Mitigating the Effects of Tin Whiskers in Aerospace In High Performance Electronic Systems

GEIA-STD-0005-3, Performance Testing for Aerospace and High Performance Electronic Interconnects Containing Lead-Free Solder and Finishes

Used by aerospace electronic system "suppliers" to develop reliability test methods and interpret results for input to analyses

GEIA-HB-0005-1, Program Management / Systems Engineering Guidelines For Managing The Transition To Lead-Free Electronics

Used by program managers to address all issues related to lead-free electronics, e.g., logistics, warranty, design, production, contracts, procurement, etc.

GEIA-HB-0005-2, Technical Guidelines for Aerospace and High Performance Electronic Systems Containing Lead-Free Solder and Finishes

Used by aerospace electronic system "suppliers" to select and use lead-free solder alloys, other materials, and processes. It may include specific solutions, lessons learned, test results and data, etc.

GEIA-HB-0005-3, Rework and Repair Handbook for Aerospace and High Performance Electronic Systems Containing Heritage SnPb and Lead-Free Solder and Finishes

GEIA-HB-0005-4, Impact of Lead Free Solder on Aerospace Electronic System Reliability and Safety Analysis

Used to determine, quantitatively if possible, impact of lead-free electronics on system safety and certification analyses, using results from tests performed per GEIA-STD-0005-3

Published

In Work

What Product Designers & EEs Can Do: Pb-free Problem Mitigations

STRATEGY	APPLICATION	LIMITATIONS
Avoid use of pure tin finished components	Design, component selection	Increasingly difficult as component suppliers transition to pure tin
Re-coat pure tin with tin-lead { Re-dip }	Component reprocess, circuit card assembly	Adds cost, reduces yield, and may not be possible with some parts
Increase gap size between tin and adjacent conductors	Design, component selection	Limited by space constraints and component geometry
Use nickel under-plating	Design, component selection	Many components are not available with this feature
Use post-plate bake out	Component selection	Costly - not all component suppliers will perform this
Reflow plating	Component selection, circuit card assembly	Not always achievable during circuit card assembly, rarely available from component suppliers
Use conformal coating	Circuit card assembly	Increased cost, complicates repair
Embed components in potting compound	Higher level assembly	Increased cost, complicates repair

Program Concerns

Program Issues
- Regulatory Compliance
- Contract Compliance
- Program Cost
- Warranties
- Product Quality
- Product Liability
- Risk Assessment

Design and Manufacturing Issues

Product Design

Assembly Materials and Processes

Fluxes and Cleaning Materials

Repair and Rework

Inspection and Acceptance Processes and Criteria

Product Performance Issues
- Tin whiskers
- Reliability

Product Support Issues
- Configuration control
- Supply chain control

Summary Observations

- **Aerospace engineers "battle fatigued" by Pb-Free issues**
- **Cultural issues regarding Pb-free electronics are as complex as the technical issues**
  - **"I have more important and immediate problems than Pb-free."**
  - **"I cannot get funding for a project for which there is <u>no clear solution</u>, <u>no definitive schedule</u>, and <u>no estimate of the total budget required</u>."**
  - **"Show me the recent evidence that this is a problem that merits my attention."**
  - **"This is everyone's problem, therefore it's <u>no one's</u> problem."**
  - **"We cannot share this with anyone."**
  - **"The problem is too big for us. Let someone else solve it."**

But hi-rel systems can not afford failures

Has the original problem been solved?

Goal: reduce hazard to humans & environment

US$~34 Billion has been spent on Pb-free transition so far.

What are the results? RoHS & WEEE enforced since 2006

EPA says: switch to Pb-free electronics is <u>not</u> beneficial

US Environmental Protection Agency study (2005):

"Solders in Electronics: A Life-Cycle Assessment"

Compared 5 solder alloys: tin/lead, tin/copper, tin/silver/copper, bismuth/tin/silver, tin/silver/bismuth/copper

Measured impacts on:

- Human toxicity & ecological toxicity
- Landfills
- Air and water resources consumed
- Materials consumed
- Energy consumed

Conclusion: switch to Pb-free solder is <u>NOT beneficial</u>

Reference: www.epa.gov/dfe/pubs/solder/lca/

Pb in Lead-Acid Batteries

- Recycling programs are effective
  - At Reducing Waste
  - Avoid landfill
  - Recover materials, minimize Pb mining
- Recycling driven by recovery fees, not by manufacturers.

Consumers respect dead batteries - unlike cell phones

Research questions

- How to measure Pb hazard?
- How to measure total hazard from electronics?
  – Hazmats: **Pb, Ba, Be, Hg, Ca, As, Hex Chrome, PBB, PBDE**
  - How much Non-Pb Hazmat comes from electronics ?
- Impact of Pb from non-electronics sources?

Total amount of electronics Pb (solder) is small compared to lead-acid batteries.

Is Pb actually causing damage? How much Pb is actually getting into ground water and humans ?

Electronics may be minor source of total environmental Pb.

How to measure solder Pb versus non-electronics Pb?

How to measure the benefits derived from RoHS program?

How to measure the costs of RoHS compliance?

Is legislation reducing total hazard? (Pb & non-Pb)

Research questions

Short-life products increase waste

- **Throw-away products create waste**
- **Hazardous materials thrown away increase health risk**
- **Landfills are undesirable**
- **Throw-away products decrease repair business (local), but increase new manufacturing (global)**

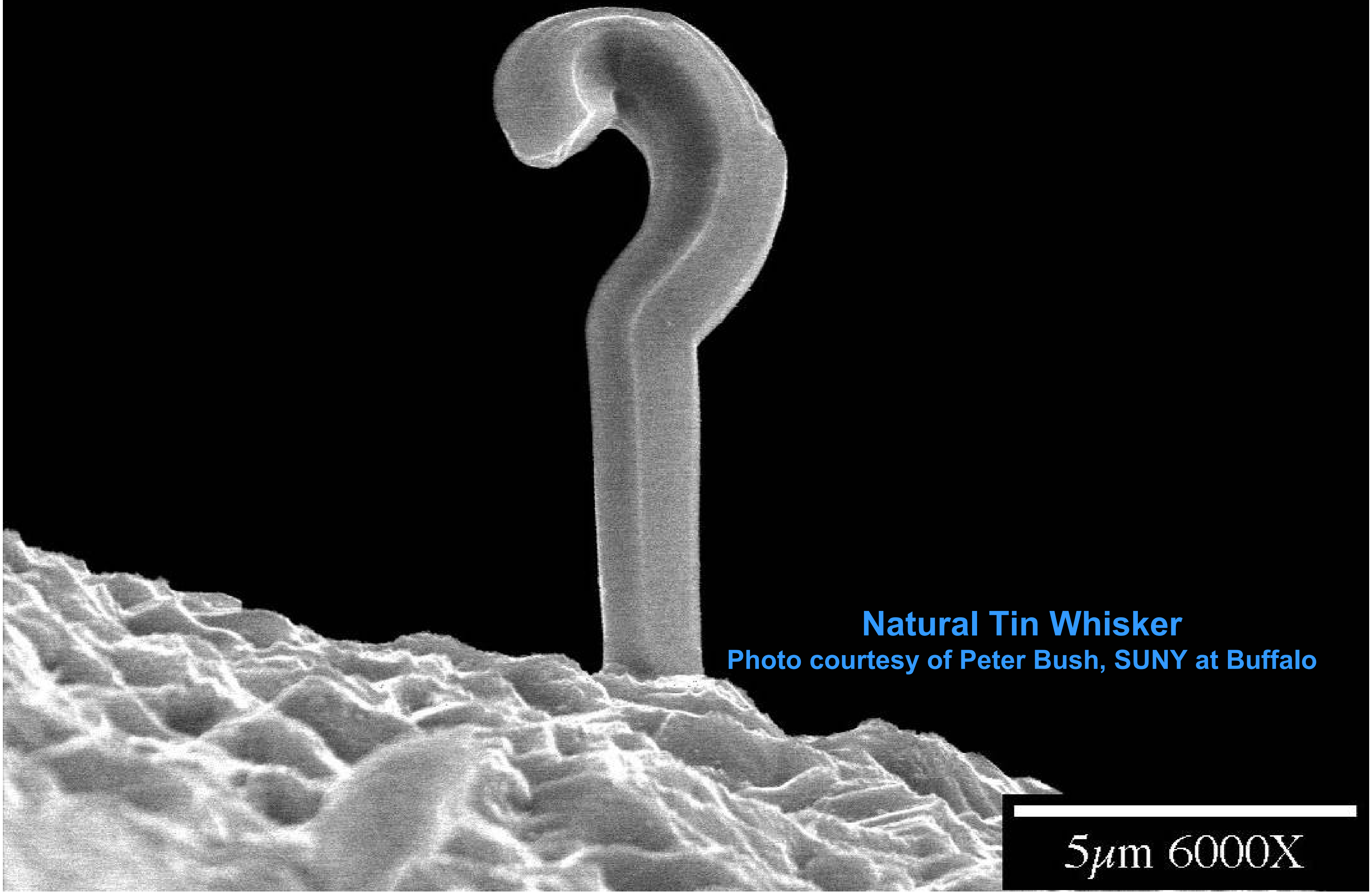
How to encourage longer-life & repairable products?

Cost-effectiveness of Pb-free electronics legislation?

- **$34 Billion is ~5X greater than the budget of the World Health Organization !**
- **Is this expenditure effective? Best use of funds?**

<ap.pennnet.com/display_article/329119/36/ARTCL/none/INDUS/1/The-Riley-Report/>

Questions / Suggestions?

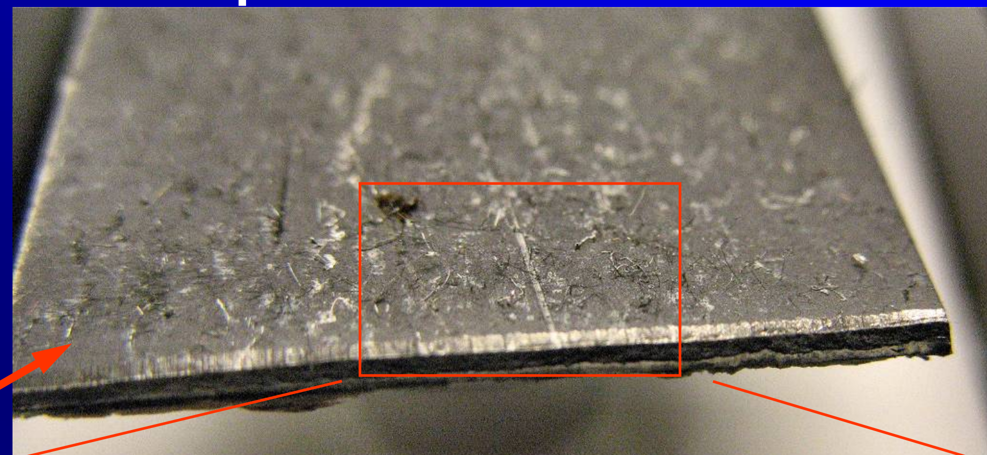


Natural Tin Whisker

Photo courtesy of Peter Bush, SUNY at Buffalo

Natural Whisker Growth

Clean Room Floor Specimen



Typical Consumer Circuit Card Assembly

Mobile phone – 2007 model