

**The NH Joint Engineering Societies 5th Annual
Joint Engineering Societies Conference
“Sustaining Our Future”**

**Designing Products to Last:
Is it Good for the Manufacturer,
the Environment, the Economy?**

**Presented by:
Bob Landman, LSM IEEE
President, H&L Instruments
Managing Partner, LDF Coatings, LLC**

Mark Twain said

“It aint what you don’t know that gets you into trouble. Its what you know for sure that just ain’t so”

Consumerism

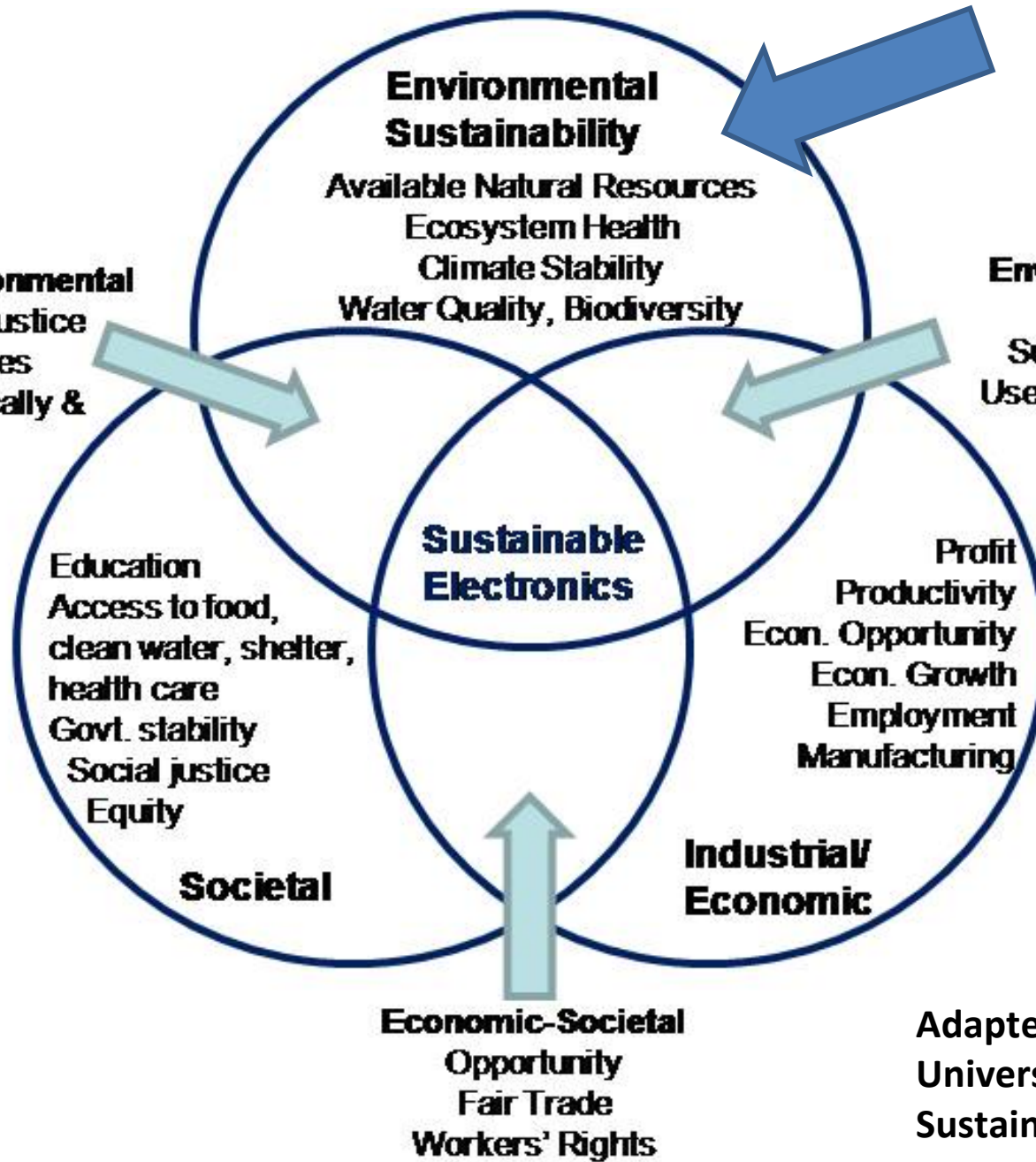
- The economy depends on people who
 - Don't reuse
 - Don't' recycle
 - Consume
- Durability of products isn't that important
- Newer is better
- Planned obsolescence is okay

Contributors to my talk

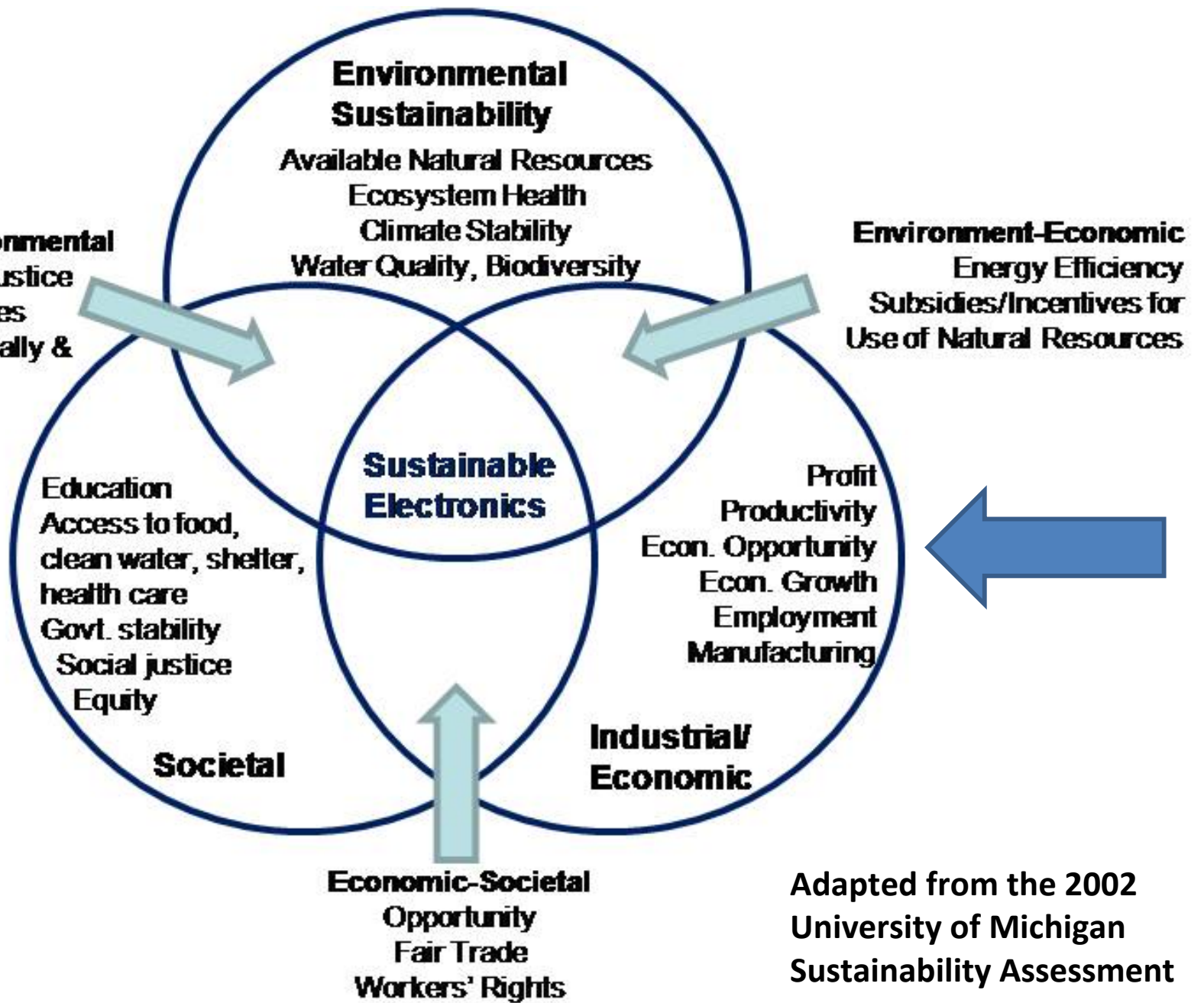
- Dr. Carol Handwerker, professor of materials engineering, environment and ecology at Purdue University
“Designing Electronics for Tomorrow; Manufacturing with Sustainability in Mind”.
- Joe Fjelstad, president, Verdant Electronics
“Reliability is Green”
- Dr. Andrew Kostic, Aerospace Corporation
“Lead-free Electronics Reliability”
- Dr. Henning Leidecker, NASA Goddard Space Flight Center
“Toyota Sudden Acceleration investigation”



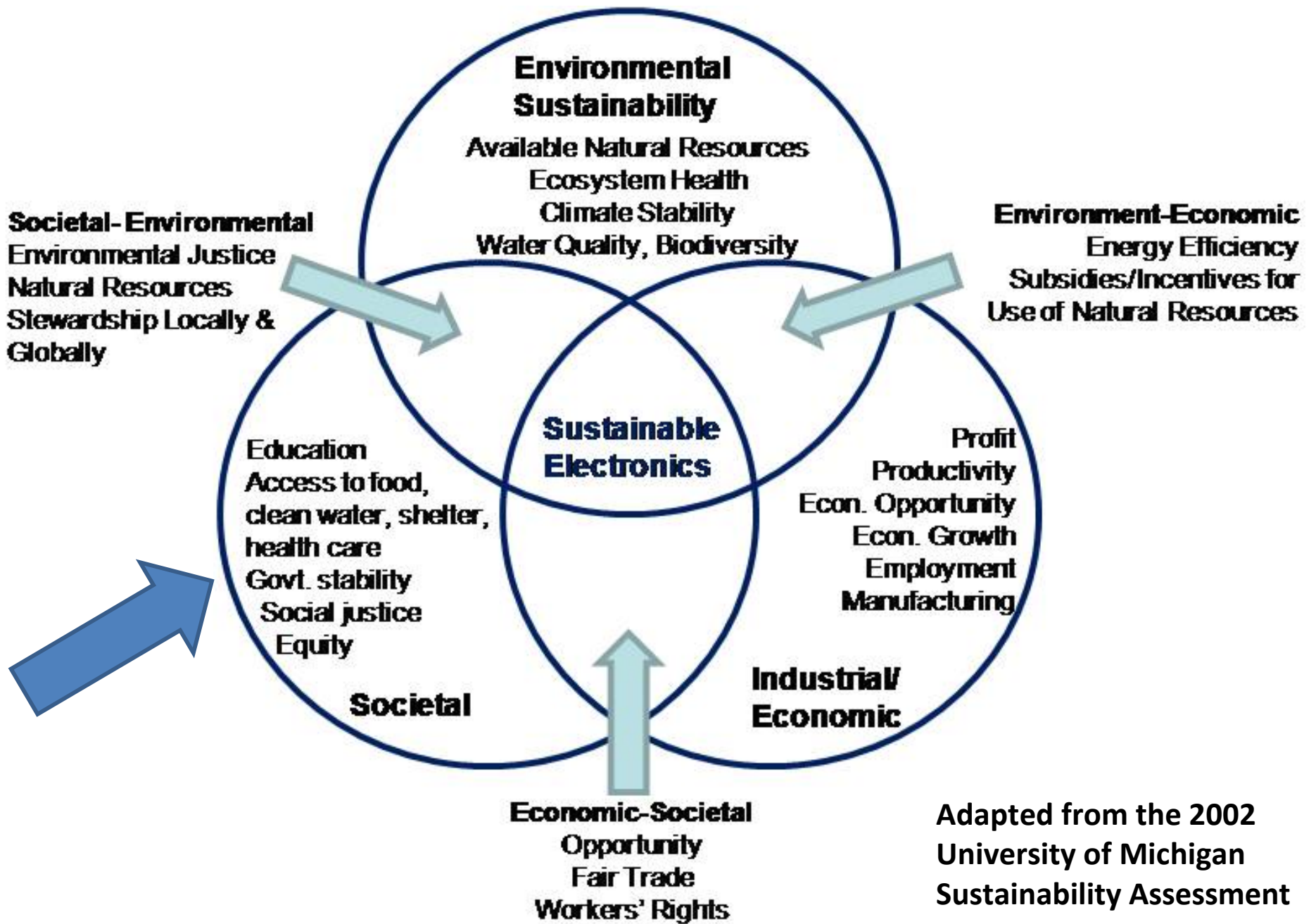
- Definition of sustainability
- Sustainability issues – not new
- Carrying capacity of the earth
- Role of electronics—
How do we measure what happens?
How do we frame the right questions?



Adapted from the 2002
 University of Michigan
 Sustainability Assessment



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 Sustainability Assessment

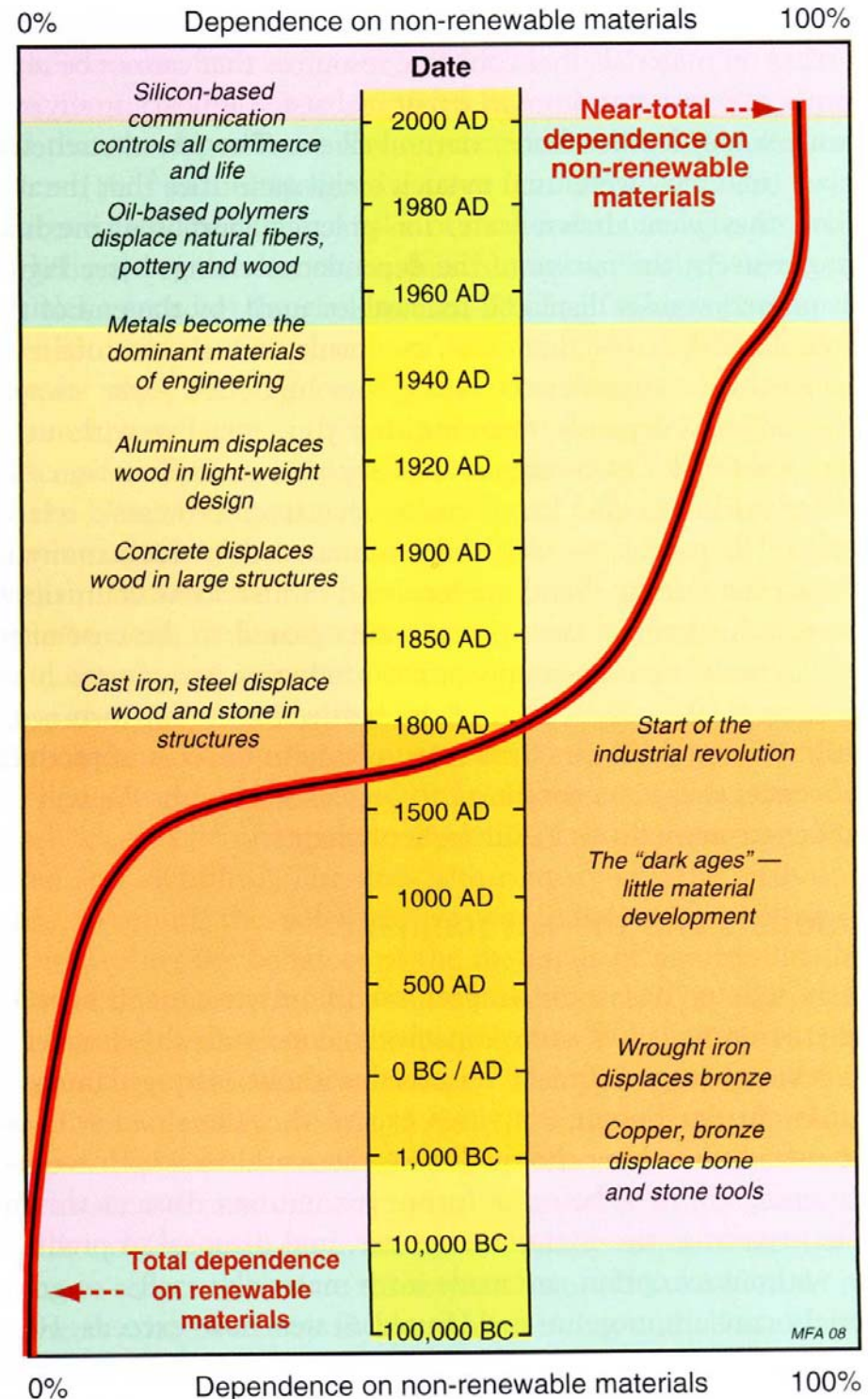


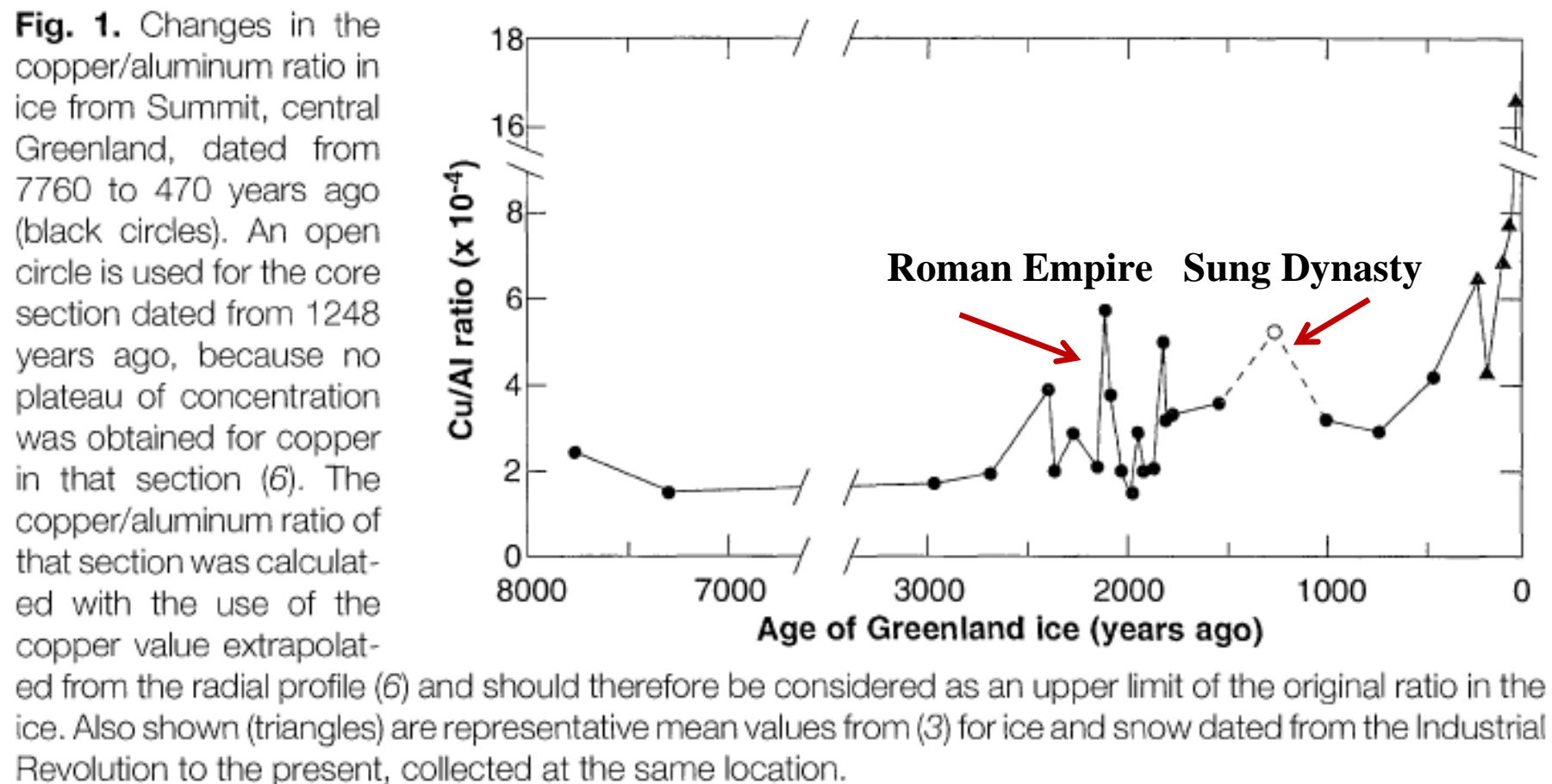
Adapted from the 2002
 University of Michigan
 Sustainability Assessment

Anthropology: Materials Development



Ashby, Shercliff, Cebon
*Materials – Engineering, Science,
Processing, and Design, 2010*





SCIENCE • VOL. 272 • 12 APRIL 1996

History of Ancient Copper Smelting Pollution During Roman and Medieval Times Recorded in Greenland Ice

Sungmin Hong, Jean-Pierre Candelone, Clair C. Patterson,*
Claude F. Boutron†



An Imperial Legacy? An Exploration of the Environmental Impact of Ancient Metal Mining and Smelting in Southern Jordan

F. B. Pyatt*

Extensive wastes from the copper mining and smelting activities of the Nabatean, Roman and Byzantine periods in the Wadi Faynan in the southern Jordanian desert continue to exert a profound influence upon the environment, mainly through processes of bioaccumulation. It is suggested that in antiquity both producers and consumers (plants and animals) would have similarly been subjected to enhanced bioaccumulation of potentially toxic heavy metals such as lead and copper, whose consequences are explored in this account.

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(Gilbertson *et al.*, 1997). Small wonder then that in Romano-Byzantine times the mines of Phaino were seen as a place to send recalcitrant criminals. Eusebius of Caesarea in his “Martyrs of Palestine” describes such a scene; “they demanded that he should be sent away to the mines, and not just any mines but to that of Phaino where even a condemned murderer is hardly able to live a few days”.

Environmental impact = population * (impact per person)

Impact to have needs met

Food

Shelter

Water

Safety

Community

...



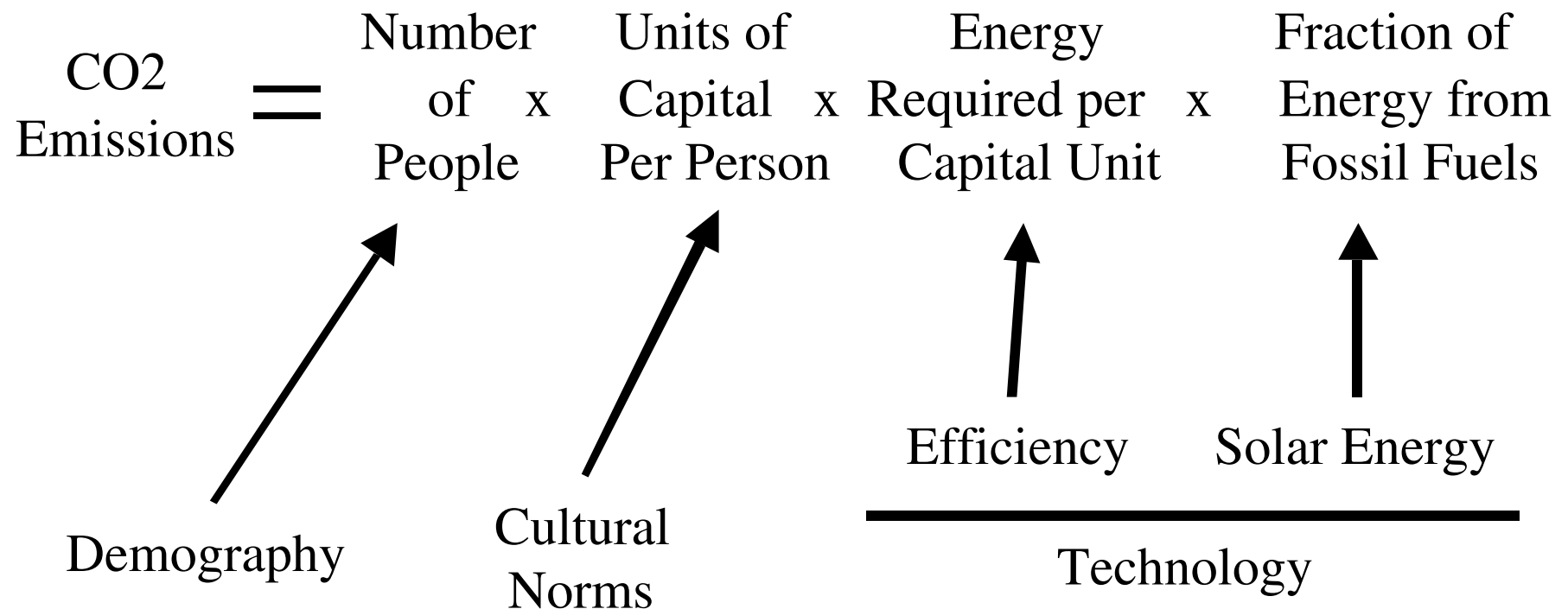


4.1B cell phone subscriptions worldwide in 2008



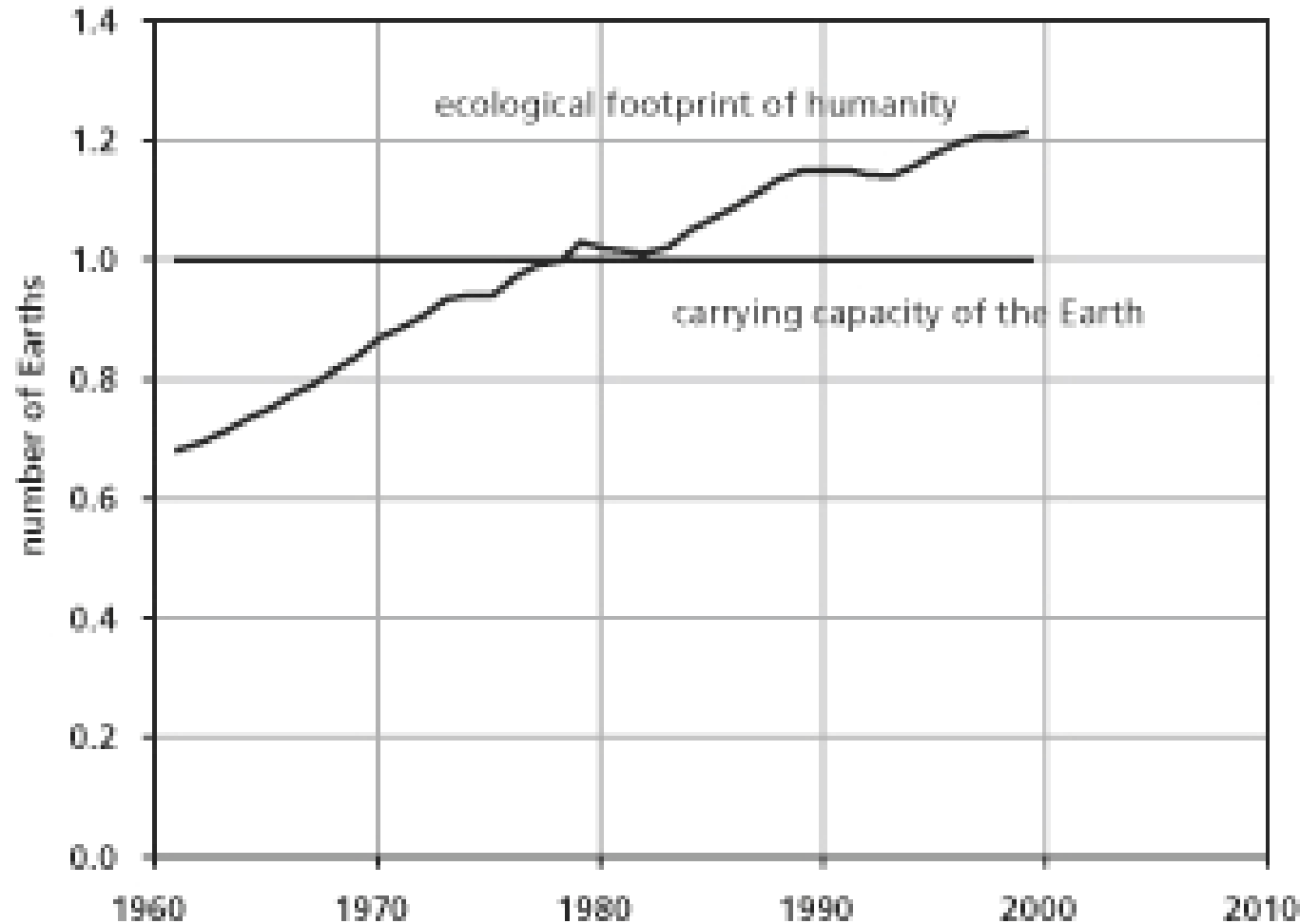
4.1B cell phone subscriptions worldwide in 2008
1.8B people on the internet
For a population of 6.9B

Four Factors Determine the Amount of CO₂ Emissions



© Dennis Meadows; 2007

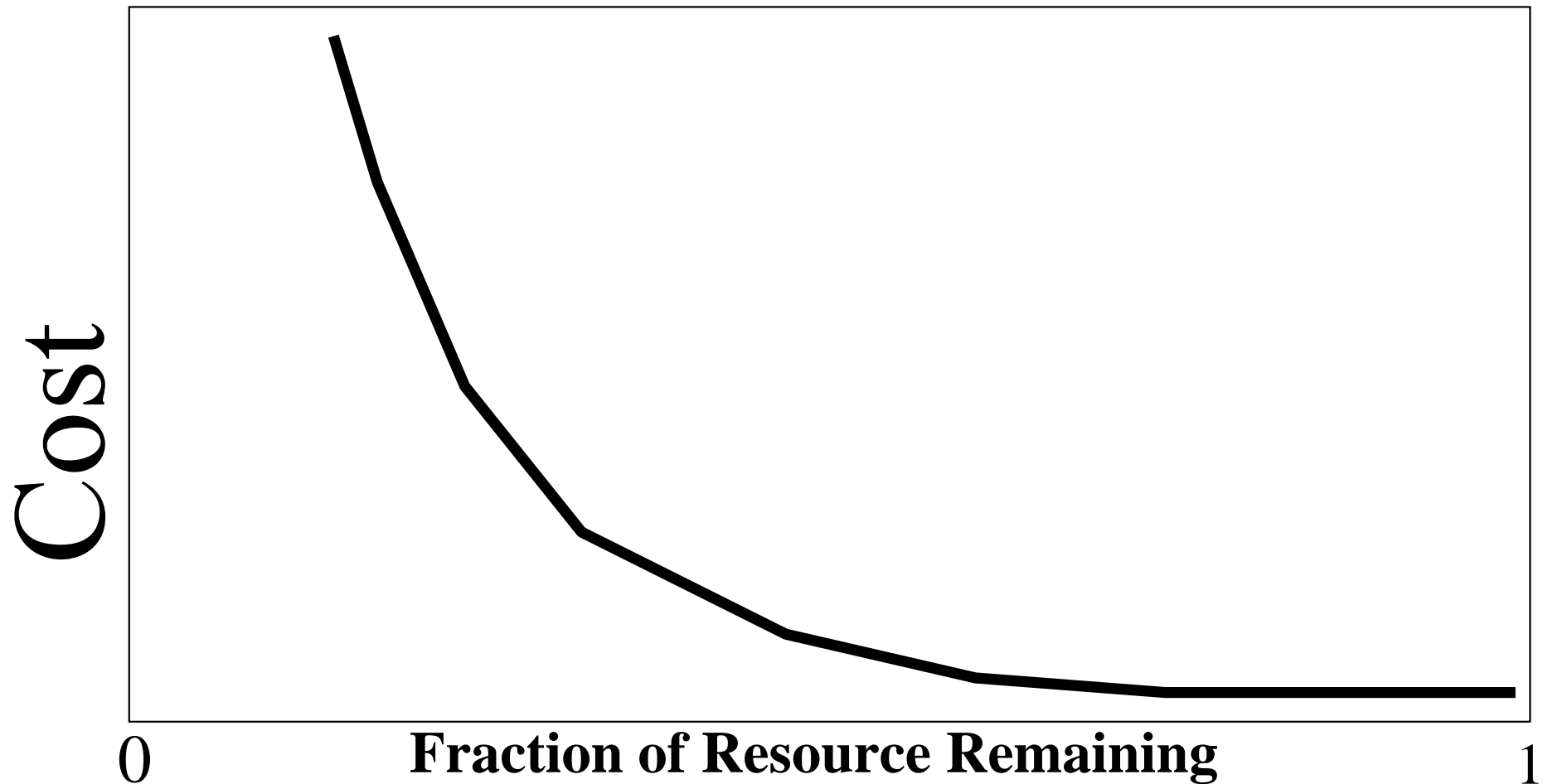
One Indicator of Overshoot



Economics and Limits to Growth: What's Sustainable?

Dennis Meadows
Washington, DC
October 6, 2009

Capital Cost of Discovery



**Economics and Limits to
Growth: What's Sustainable?**

Dennis Meadows

Washington, DC

October 6, 2009

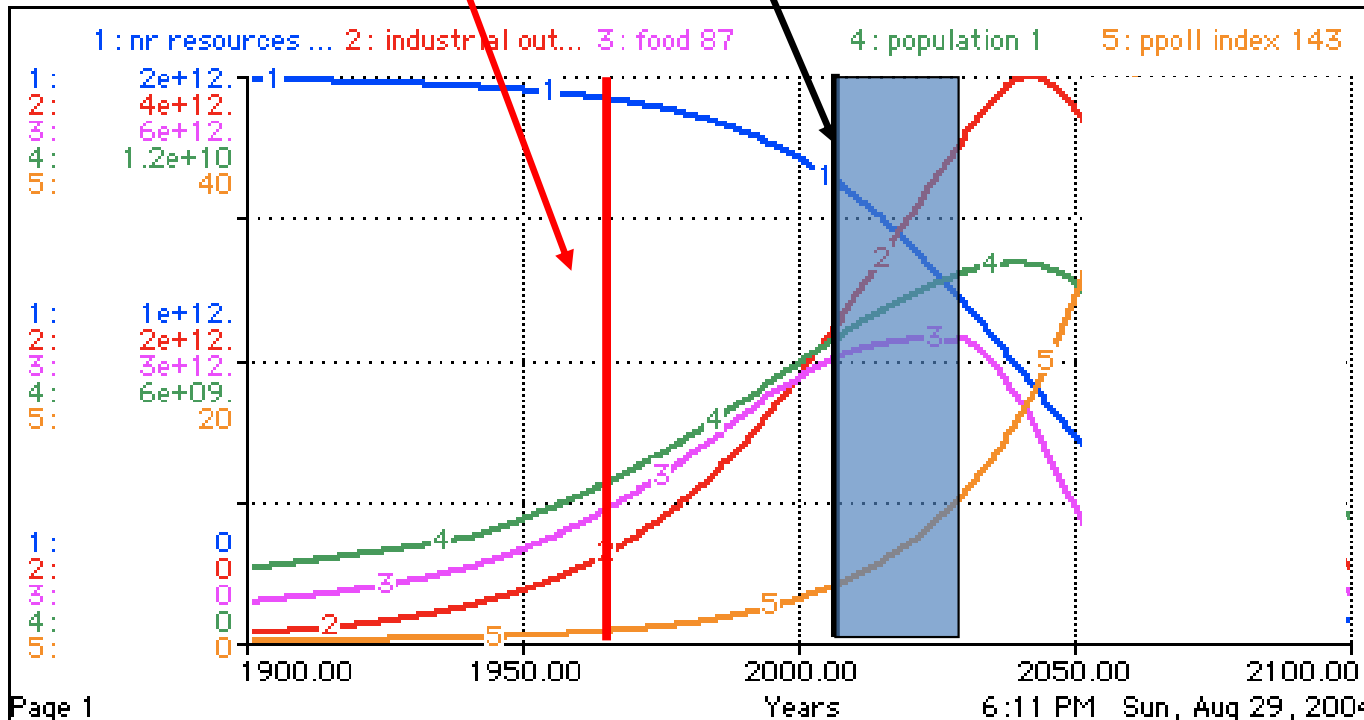
The Reference Scenario

Economics and Limits to Growth: What's Sustainable?

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Original Report

Today



Industrial Output

Population

Pollution

Resources

Food

Page 1



?

State of the World

Dennis Meadows:

Main Points of His Speech

- Growth has continued until we are now past sustainable levels.
- The global society will change more over the next 20 years than in the past 100. Design policies for what is coming, not what has been.
- The main forces for change will be climate change and resource scarcity - especially fossil fuels and water.
- The end of growth does not result from total depletion, but from rising capital costs.
- The most important scarcity is the absence of a longer-term perspective.

**Economics and Limits to
Growth: What's Sustainable?**

Dennis Meadows

Washington, DC

October 6, 2009

Dennis Meadows at Davos 2009

- Growth versus development
- The Link to the economy
- Development in societies
- The current state of our planet
- The danger of collapse
- Collapse is near
- The consequences
 - Shortages of oil, water and food

Richard Heinberg

Post Carbon Institute - September 2009

Antimony	China	Thermoelectric/paraelectric materials
Barium	China	Thermoelectric/paraelectric materials
Bismuth	China, Mexico	Thermoelectric/paraelectric materials
Cobalt	Kinshasa, Australia	Photovoltaics
Gallium	China	Photovoltaics
Germanium	Belgium, Canada	Photovoltaics
Indium	China, Canada	Photovoltaics, thermo/paraelectric mat'ls
Manganese	Gabon, S. Africa	Photovoltaics
Nickel	Canada	Fuel cells
Platinum	S. Africa	Fuel cells, thermoelectric materials
Rare Earths	China	Fuel cells, magnets, thermoelectric materials
Tellurium	Belgium, Germany	Solar cells, semiconductors
Titanium	Australia, S. Africa	Solar cells
Zinc	Canada, Mexico	Photovoltaics, fuel cells



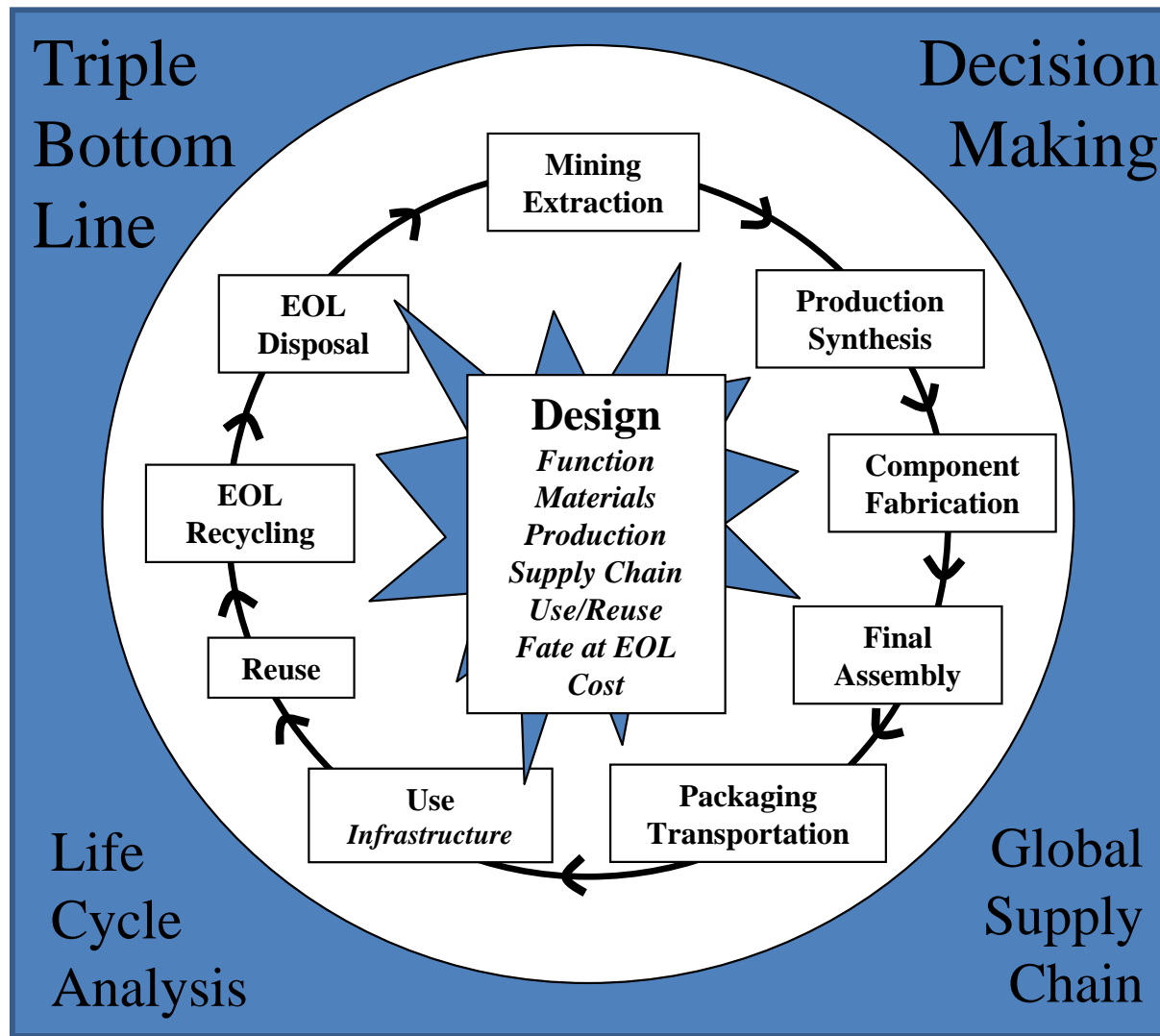
From cell phones to laptops, i-pods to digital cameras, we are buying - and throwing away - more electronic products than ever before. The cost is higher than the impact on your pocket book.

Electronic trash, or e-waste, contains toxic chemicals and heavy metals that cannot be disposed of or recycled safely. These pollutants end up in our water and the air we breathe. As consumers, we need your help to pull the plug on toxic technology. Urge leading electronic companies to clean up their act.

Every year, hundreds of thousands of old computers and cell phones are dumped in landfills or burned in smelters. Thousands more are exported, often illegally, to Asia, where workers at scrap yards, often children, are exposed to a cocktail of toxic chemicals and poisons.



- Definition of sustainability
- Sustainability issues – not new
- Carrying capacity of the earth
- Role of electronics–
How do we measure what happens?
How do we frame the right questions?



Each step creates its own or is affected by :

- energy flows • water flows • GHG emissions • materials flows • resource depletion
- cost competition • consumer behavior • legislation • national and regional competition • unintended consequences

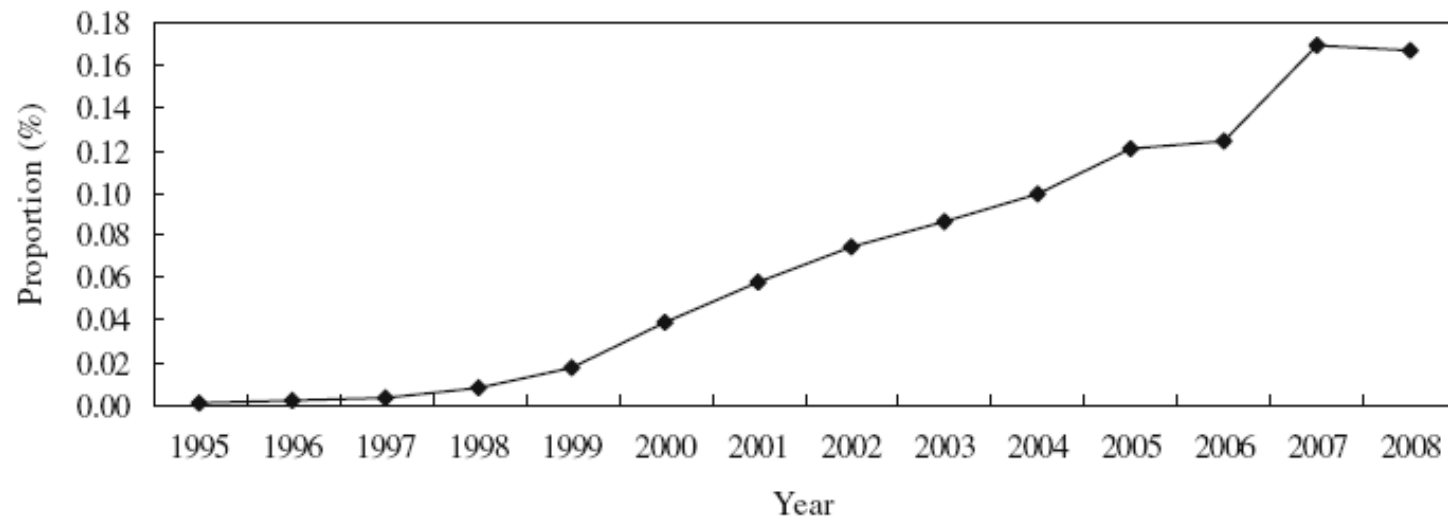


Fig. 5. Proportion of energy consumption of mobile phones to the over energy consumption in China.

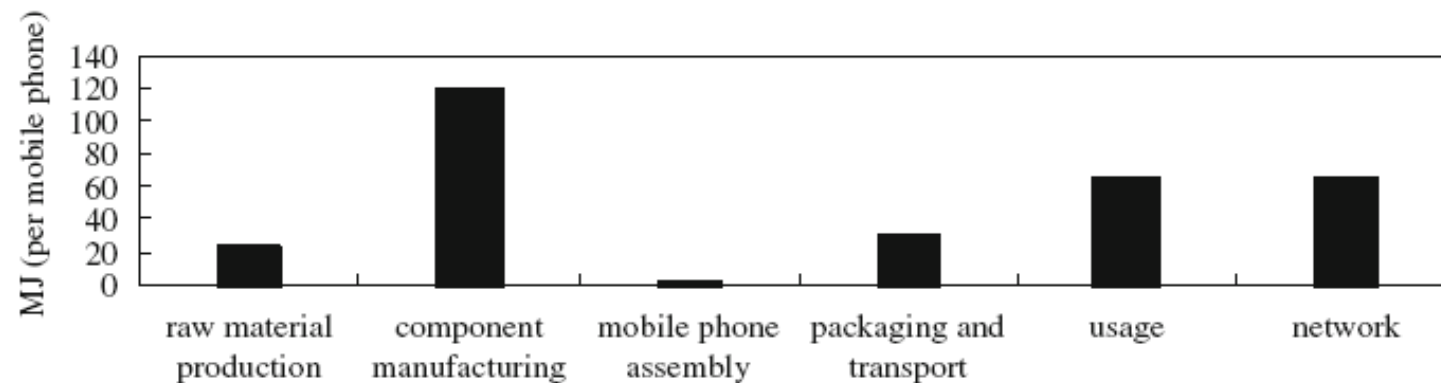


Fig. 6. Energy consumption of mobile phones during their life cycle.

Analysis of material and energy consumption of mobile phones in China

Jinglei Yu^a, Eric Williams^b, Meiting Ju^a,

Energy Policy 38 (2010) 4135–4141

TABLE II. WEIGHT VERSUS VALUE DISTRIBUTION

weight-%	Fe	Al	Cu	plastics	Ag [ppm]	Au [ppm]	Pd [ppm]
TV-board	28%	10%	10%	28%	280	20	10
PC-board	7%	5%	20%	24%	1000	250	110
mobile phone	5%	1%	13%	56%	1380	350	210
portable audio	23%	1%	21%	47%	150	10	4
DVD-player	62%	2%	5%	24%	115	15	4
calculator	4%	5%	3%	61%	160	50	5

value-share	Fe	Al	Cu	sum PM	Ag	Au	Pd
TV-board	4%	11%	42%	43%	8%	27%	8%
PC-board	0%	1%	14%	85%	5%	65%	15%
mobile phone	0%	0%	7%	93%	5%	67%	21%
portable audio	3%	1%	77%	20%	4%	13%	3%
DVD-player	13%	4%	36%	48%	5%	37%	5%
calculator	0%	5%	11%	84%	7%	73%	4%

Improving metal returns and eco-efficiency in electronics recycling

- a holistic approach for interface optimisation between pre-processing and integrated metals smelting and refining



Sum of Precious Metals

Christian Hageliken
 University of Applied Sciences, Datteln

This leads to the following observations and conclusions:

- Toxics or other harmful substances are usually concentrated in the circuit boards; the same applies for the material content values.
- Any major loss of precious metals decreases drastically the net recoverable value from electronic goods.
- Material composition can have a significant impact on recycling requirements and adequate technical processes, including emission control.
- Mixing different qualities in collection/pre-processing can negatively influence recycling returns (dilution, technical constraints).
- Legislation impacts the material composition (and hence the recycling requirements), e.g. the ban on lead from the EU ROHS-directive implies increased use of tin, copper, bismuth and silver in solders.
- Also miniaturization and technical progress impact the material composition. There is a tendency of decreasing absolute precious metals content in new models (miniaturization), but the relative content in ppm is more stable.

Improving metal returns and eco-efficiency in electronics recycling

- a holistic approach for interface optimisation between pre-processing and integrated metals smelting and refining

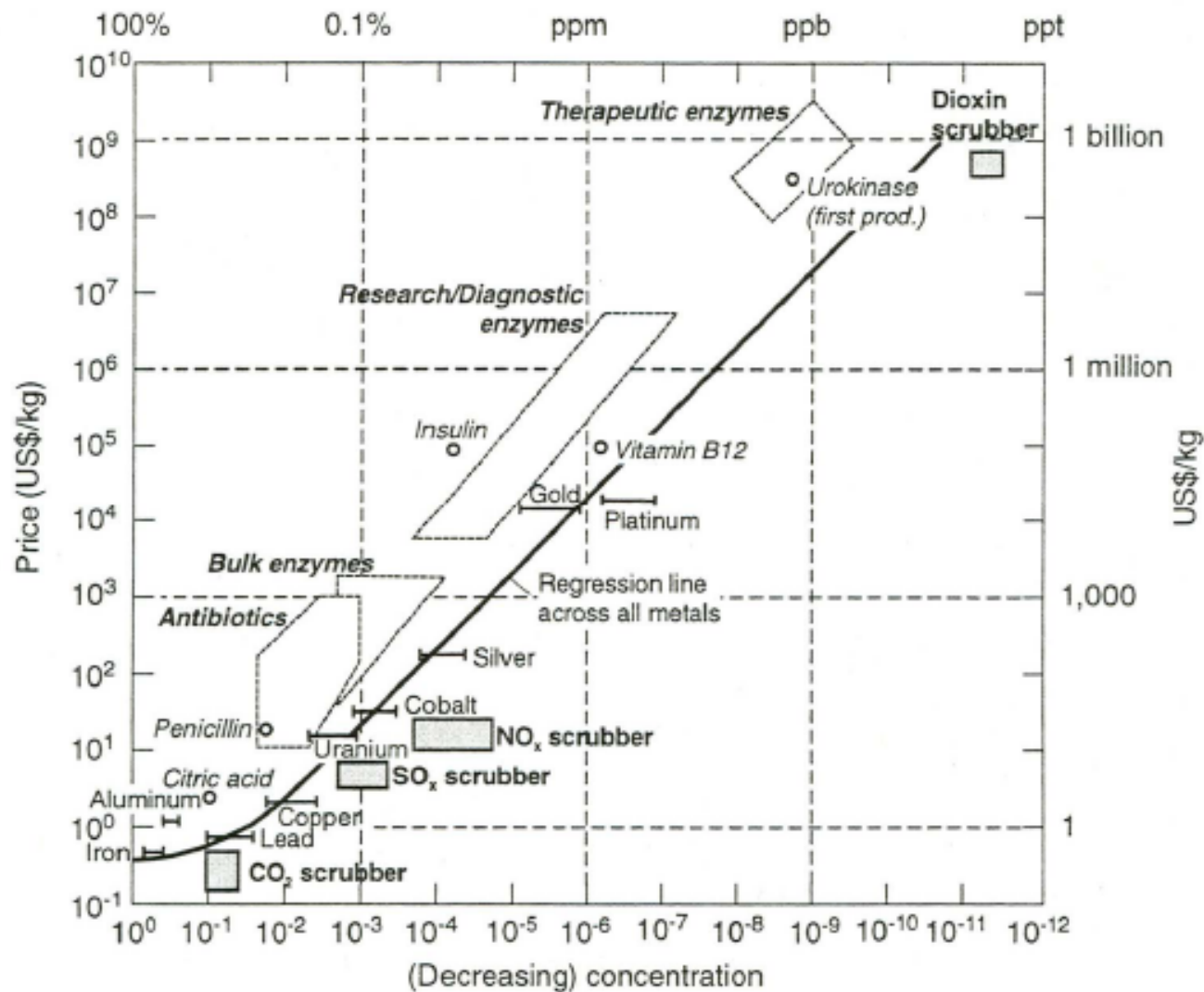


Figure 1. Sherwood plot showing the relationship between the concentration of a target material in a mixture of materials and the market value of the target material. Figure from Grüber [5].

[5] A. Grüber, Technology and Global Change. Cambridge, England: Cambridge University Press, 1998.

Material Recycling at Product End-of-Life

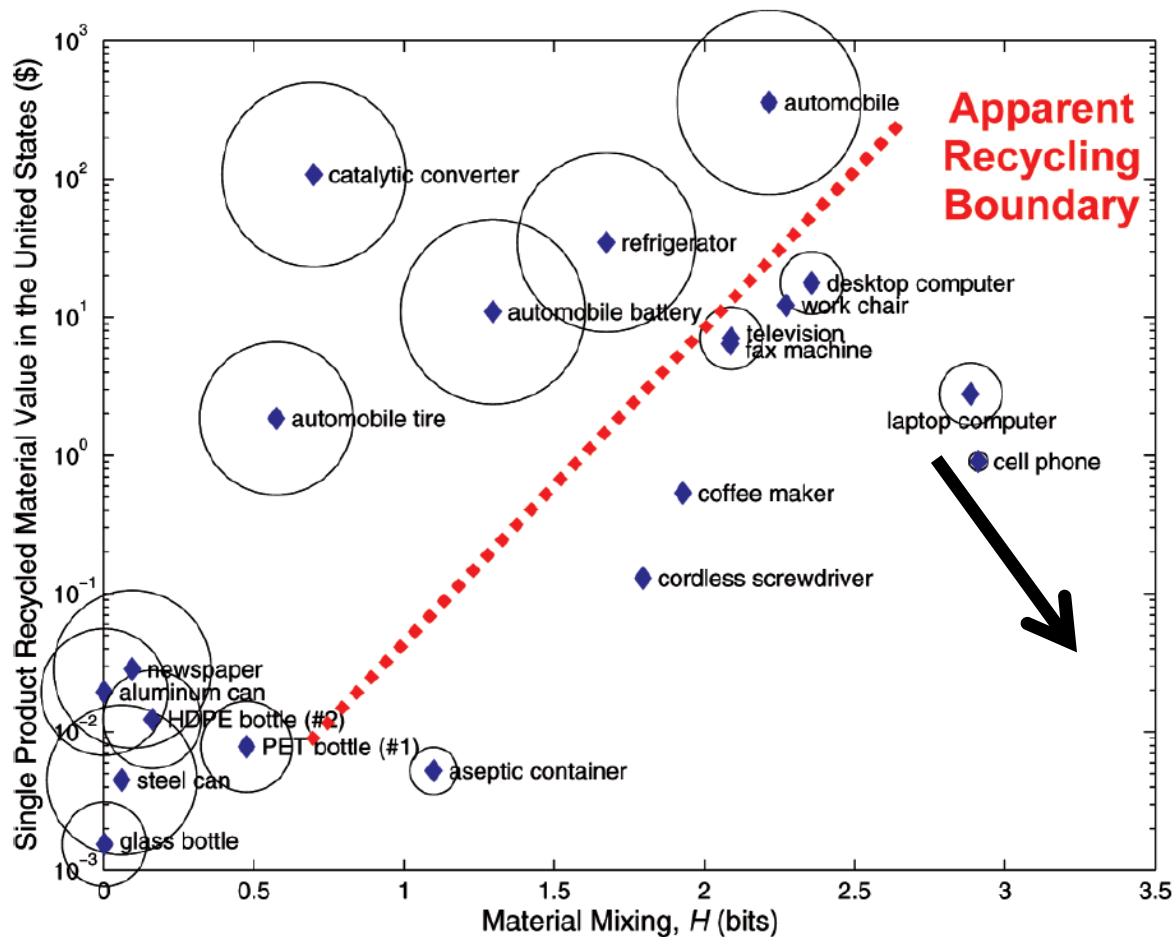


FIGURE 4. A plot of single product recycled material values ($\sum m_i k_i$), material mixing (H), and recycling rates (indicated by the area of the circles) for 20 products in the U.S. The "apparent recycling boundary" is shown.

“However, while recycling technologies may improve, design trends seem to be pushing products towards lower material value and greater material mixing. Designers are constantly motivated to reduce material costs in products, either by using less material or by using less expensive materials. At the same time, materials are being used in new and different applications, presenting designers with increasingly wider selections of potential materials.”

Material Recycling at Product End-of-Life

Jeffrey B. Dahmus and Timothy G. Gutowski

ENVIRONMENTAL SCIENCE & TECHNOLOGY / VOL. 41, NO. 21, 2007

September 2009

Mark Dempsey
European Waste Policy Advisor

The Problem...



- It will be impossible for Producers to achieve the 65% collection target as there are massive flows of WEEE outside the producer owned WEEE systems.

85%



- Producers would have to buy WEEE back from 'third party actors', which could lead to profiteering. The Commission's proposal could cost producers an extra €4.6 billion increasing the total costs of the WEEE Directive to €10.2 billion.



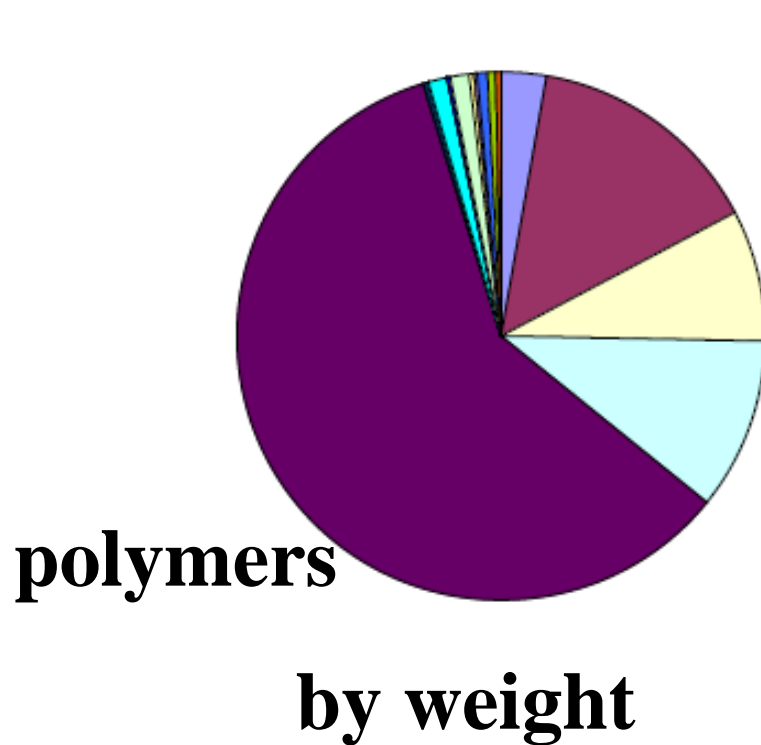
- For IT basing collection targets on previous year's sales means the target will be higher than the amount of IT in the waste stream.



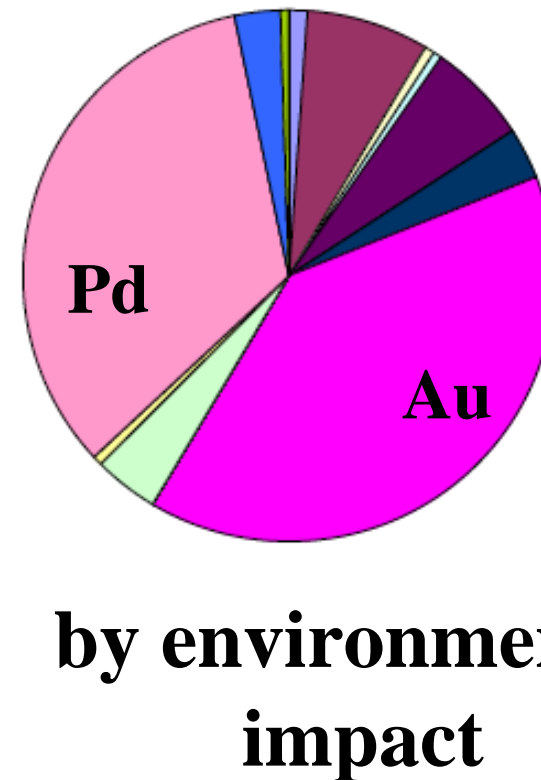
- The European Commission is concerned regarding the improper treatment and illegal export of WEEE. However scrap dealers and brokers are not covered by the WEEE legislation. The Commission Proposal will increase the gradient in favour of illegal export.

WEEE recast - Huisman and Magalini

NVMP – StEP Summerschool on WEEE
Philips HTC 2009-09-10



- Aluminium
- Copper
- Ferro
- Glass
- Plastics
- Silver
- Gold
- Bromine
- Nickel
- Lead
- Palladium
- Tin
- Zinc



ONE DECISION AN
ENGINEER
MAKES CAN HAVE MORE
IMPACT
ON THE ENVIRONMENT
THAN A LIFETIME
OF RECYCLING



ENVIRONMENTAL AND ECOLOGICAL ENGINEERING



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Reliability is Defined as:

... the measure of a product's ability to:

perform a specific function or service

in a specified use environment

for a specified amount of time without unscheduled interruption

Reliability is commonly reported in terms such as mean time to failure.

However it was suggested by one observer that reliability may perhaps be better measured not by the return of the product but by the return of the customer...

In this regard reliability is a matter of Trust

Changing Views on Reliability

- Reliability expectations vary for different types of products depending on application.
- However the importance of reliability has been fading, especially for consumer products due to faster products cycles
- The concept of application specific reliability should be a concern to manufacturer and consumer alike
- Electronic products are rapidly becoming much like seasonal fashion statements
- Are we headed down the right road and in the right direction?

Reliability and Economics

Planned Obsolescence

- Concept dated to 1932 with the publication of Bernard London's pamphlet titled *“Ending the Depression through Planned Obsolescence”*.
- The fundamental idea was to create products that became obsolete or ceased to function after a certain period of time or amount of use in a way that is planned or designed for by the manufacturer
- The concept holds sway still today but there have been subtle changes...
- Advertising influences emotions and confuses wants and needs

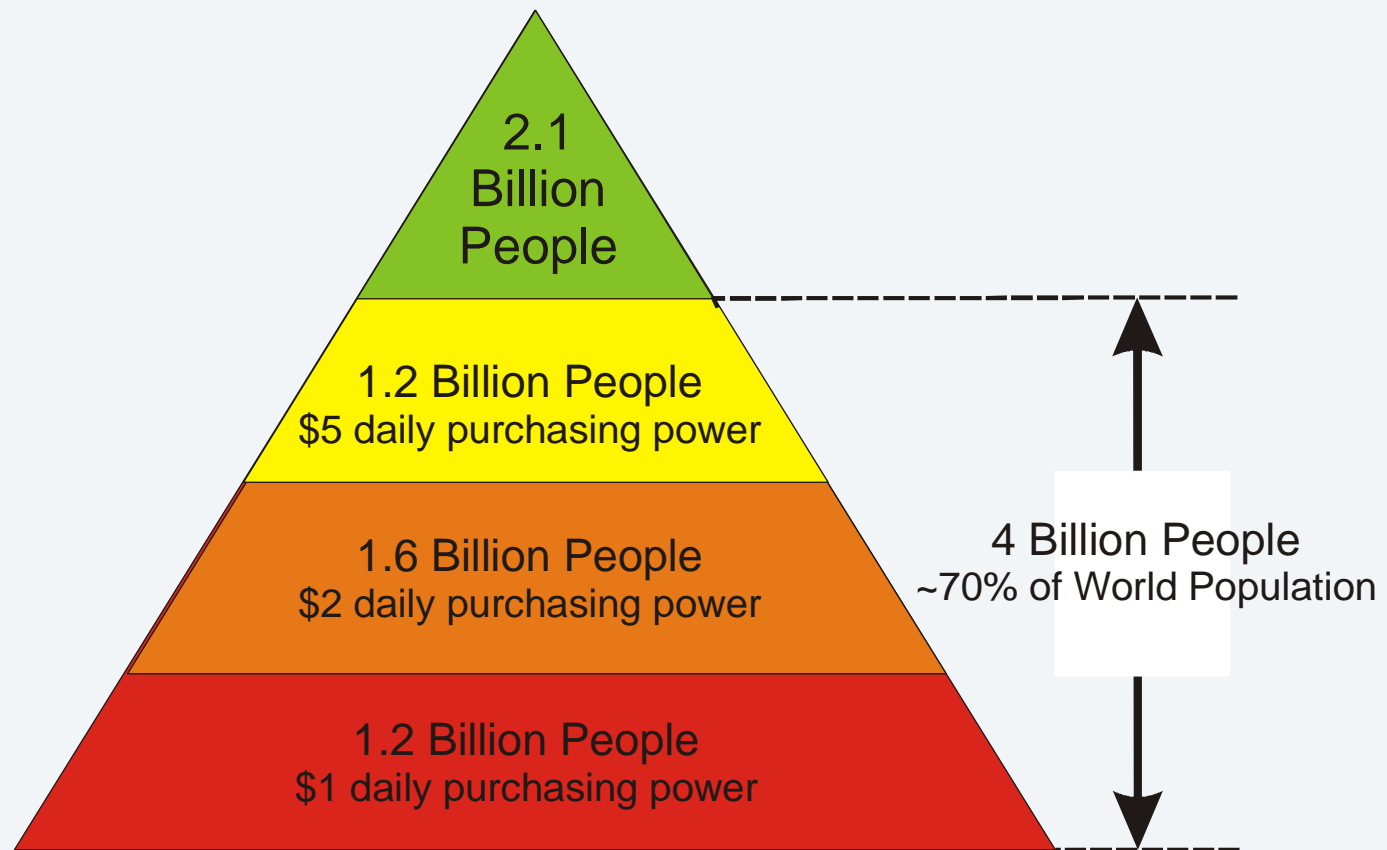
Planning for Failure

- For planned obsolescence to work, some self-destructive mechanisms must be integrated (implicitly if not explicitly) into the manufacturing systems. One is a reduced concern about reliability.
- "Brave New World" by Aldus Huxley - Here and Now
- There is a negative aspect to accelerating the rate of change in product cycles...

It is simply not sustainable if all of the world's peoples are to be served and benefit from electronic products

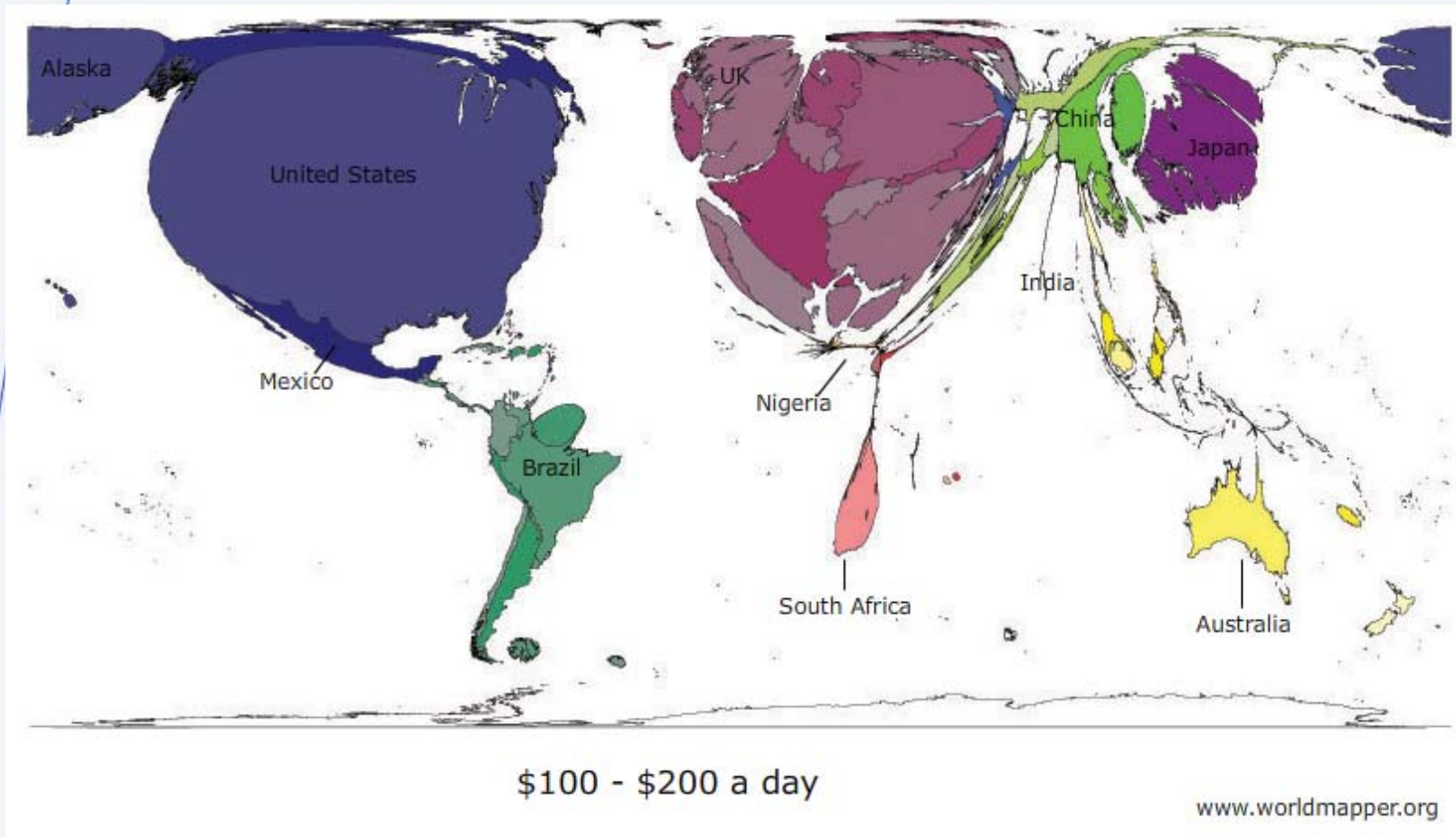
Moreover, it is not environmentally responsible

Reliable Products are Required to Meet the Needs of a Growing Population

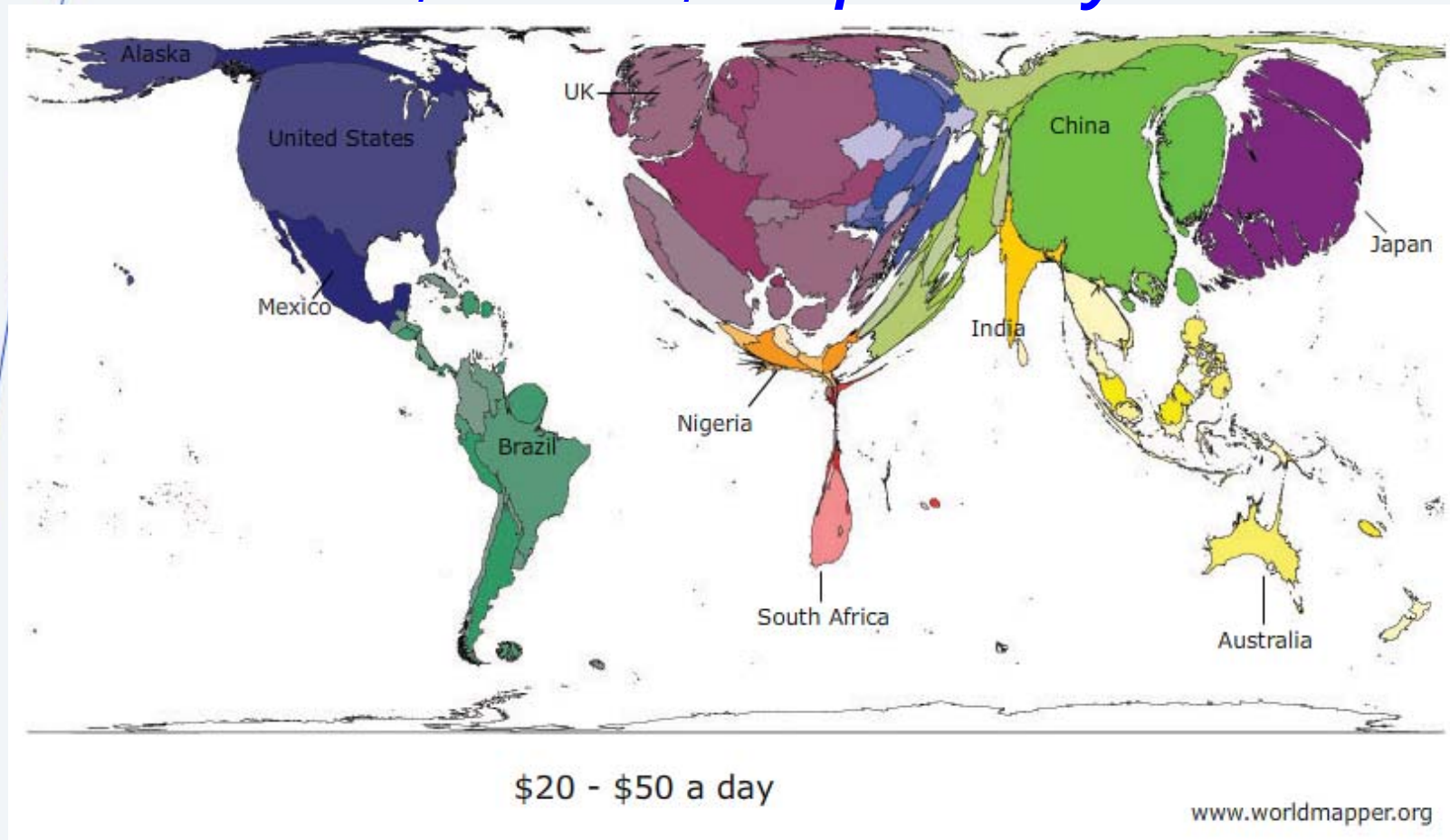


Low income = Lower education = Fewer opportunities

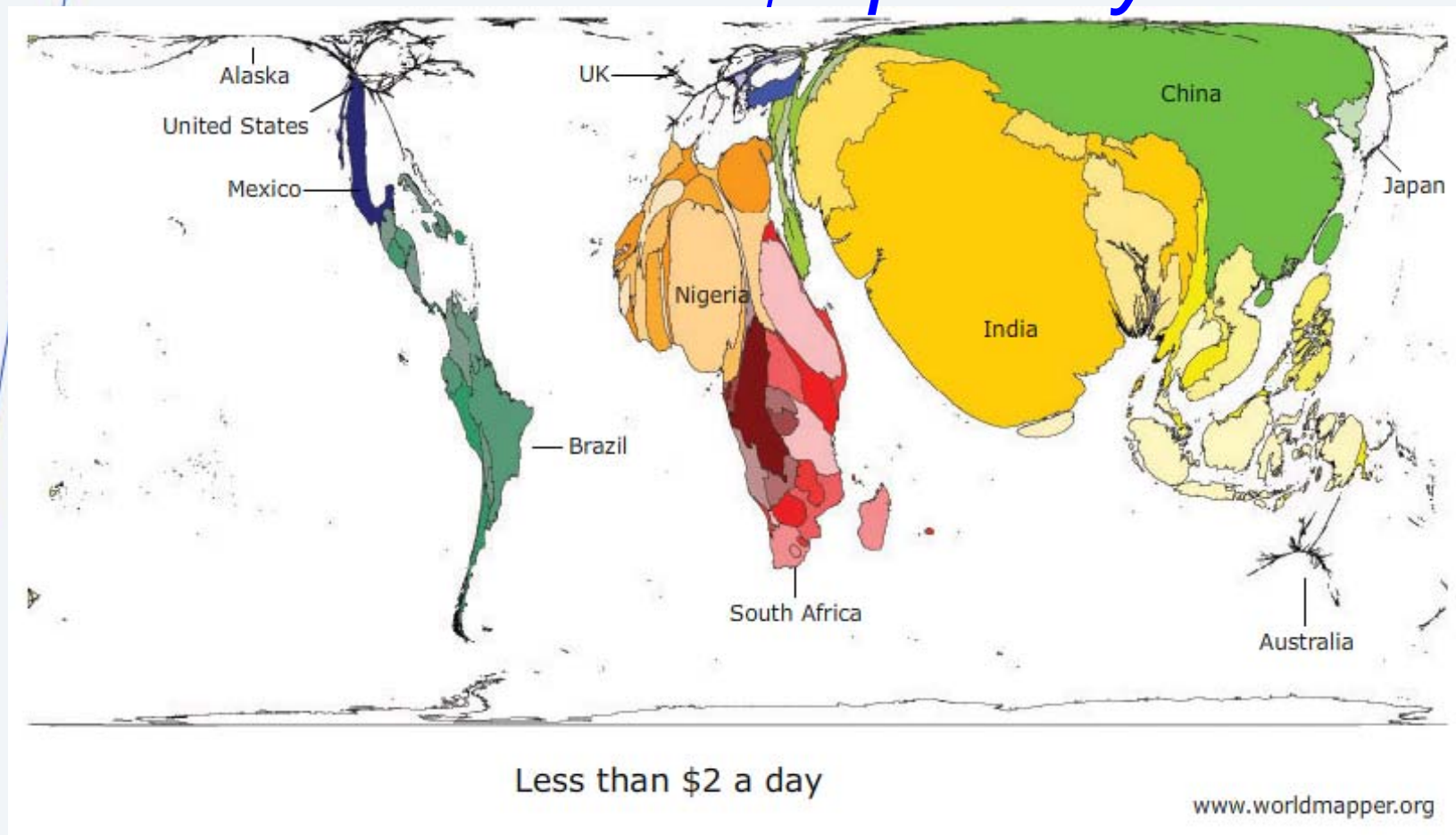
Individual Purchasing Power \$100 to \$200 per day



Individual Purchasing Power \$20 to \$50 per day



Individual Purchasing Power Less than \$2 per day



Electronics Slipping Reputation

- Warranty provider, Square Trade published a report last year titled: *"1 in 3 Laptops Fail Within 3 Years"*
- The report noted that a full two-thirds of these failures (20.4% of all product built) were the result of hardware malfunctions.
- The other third (10.6%) were from accidental damage
- The report also noted that the increasingly popular netbooks are projected to have a 20% higher failure rate from hardware malfunctions than more expensive laptop computers.
- This should be a wake up call to both electronic manufacturers and electronic consumers alike

Economics of Early Failure

- Early failures result in higher warranty costs to the manufacturer and the potential for product recalls, the cost of which can run into tens of millions of dollars
- Those millions in losses could potentially be multiplied many times over as every manufacturer faces the same risk when products do not perform to promised levels.
- In short, poor reliability is very costly to individual companies, the world's peoples & the environment

Reliability and The Environment

“Green” Legislation Impact

“The road to hell is paved with good intentions”
~ Proverb ~

- Lead free solder is impacting reliability
 - Moisture sensitivity increase
 - Thermal damage to components and boards
 - Shock and Vibration
 - Tin whiskers
- Net effect?
 - Reduced product reliability at increased cost
 - Net negative effect on the environment

Sustainability and Reliability

- To hold to the ideals of sustainable manufacturing, the electronics industry must make products that are be robust enough that they can be passed along to future users with no concern about longer term reliability.
- In Japan and elsewhere, the manufacturing community has rallied around the idea that there is need to build products tied to the goals the "Three Rs"... Reduce, (materials and energy), Reuse and Recycle.
- However, those three 'R's can be easily taken in and addressed by a single, bigger **R**, written in bold type, that **R** incorporaes all of the three smaller 'r's...
- That bigger **R** stands for reliability.

Reliability versus Technology Trends

Requirements for Pursuing Rapid Change

Rapid change require equally rapid cycles of learning.

When moving too fast some lessons do not get absorbed quick enough and problems ensue.

There is need to recall and address all of the factors that typically impact electronic product reliability in designing...

- Overall product design
- Manufacturing processes
- Device types used
- Temperature (in manufacture and use)
- Electrical load applied
- Shock and vibration
- Chemical/Environmental impacts
- Mechanical loading stresses

Some Known Weaknesses

Capacitors

Ceramic Capacitors (dielectric breakdown) are also fragile

Electrolytic Capacitors (electrolyte evap., dielectric dissolution)

Resistors

Must be properly de-rated for use in application to assure reliability

Integrated Circuits

Future generation designs with sub100nm features will be at risk

Relays (and other electromechanical components)

Limited ability to model wear out at present

Connectors

Must be properly matched to design, properly specified and placed

Solder Joints

Most electronic failures occur at interconnections

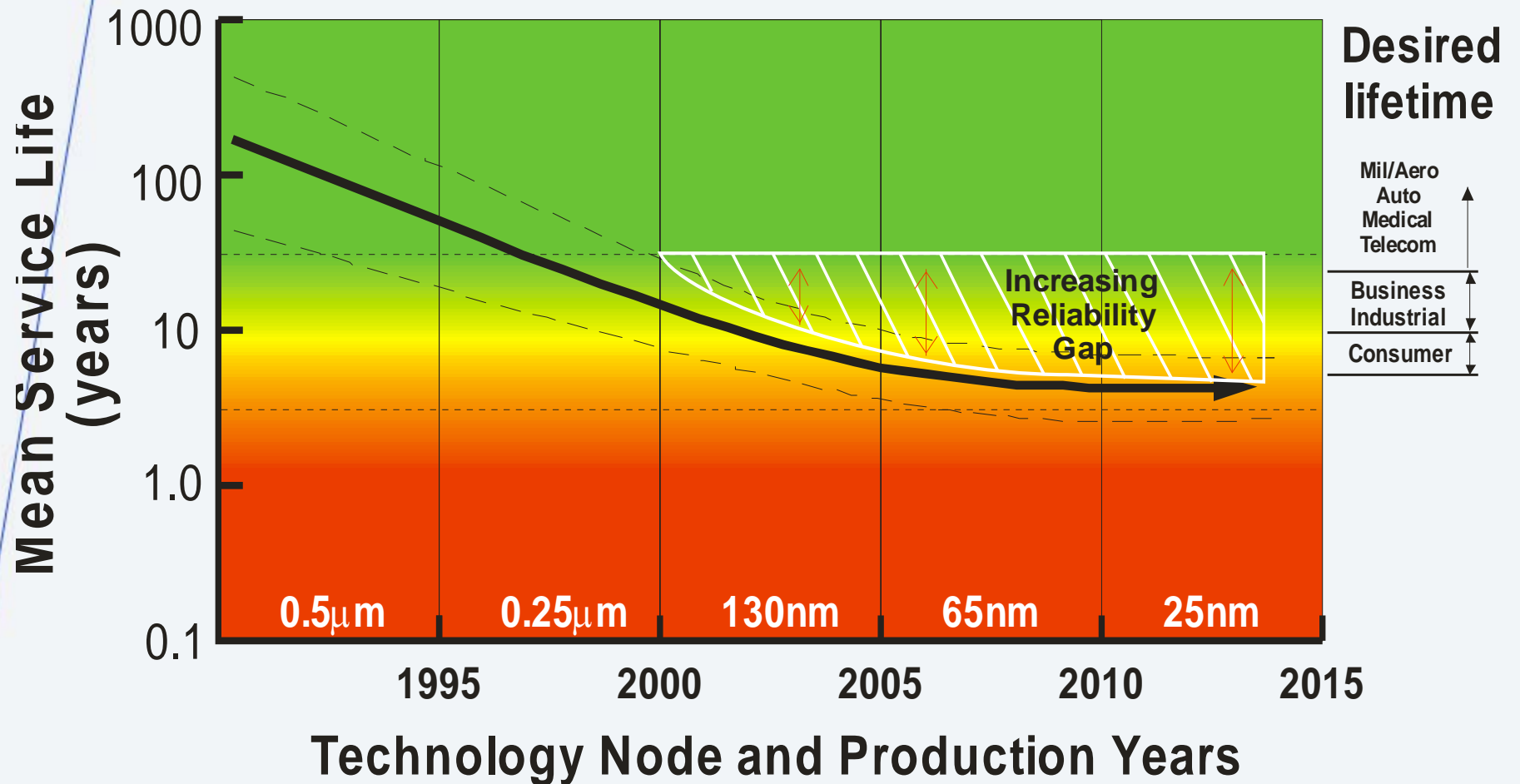
Solder creep, fatigue and shock resistance are concerns

Tin whiskers are a wild card

Looming Concerns About ICs

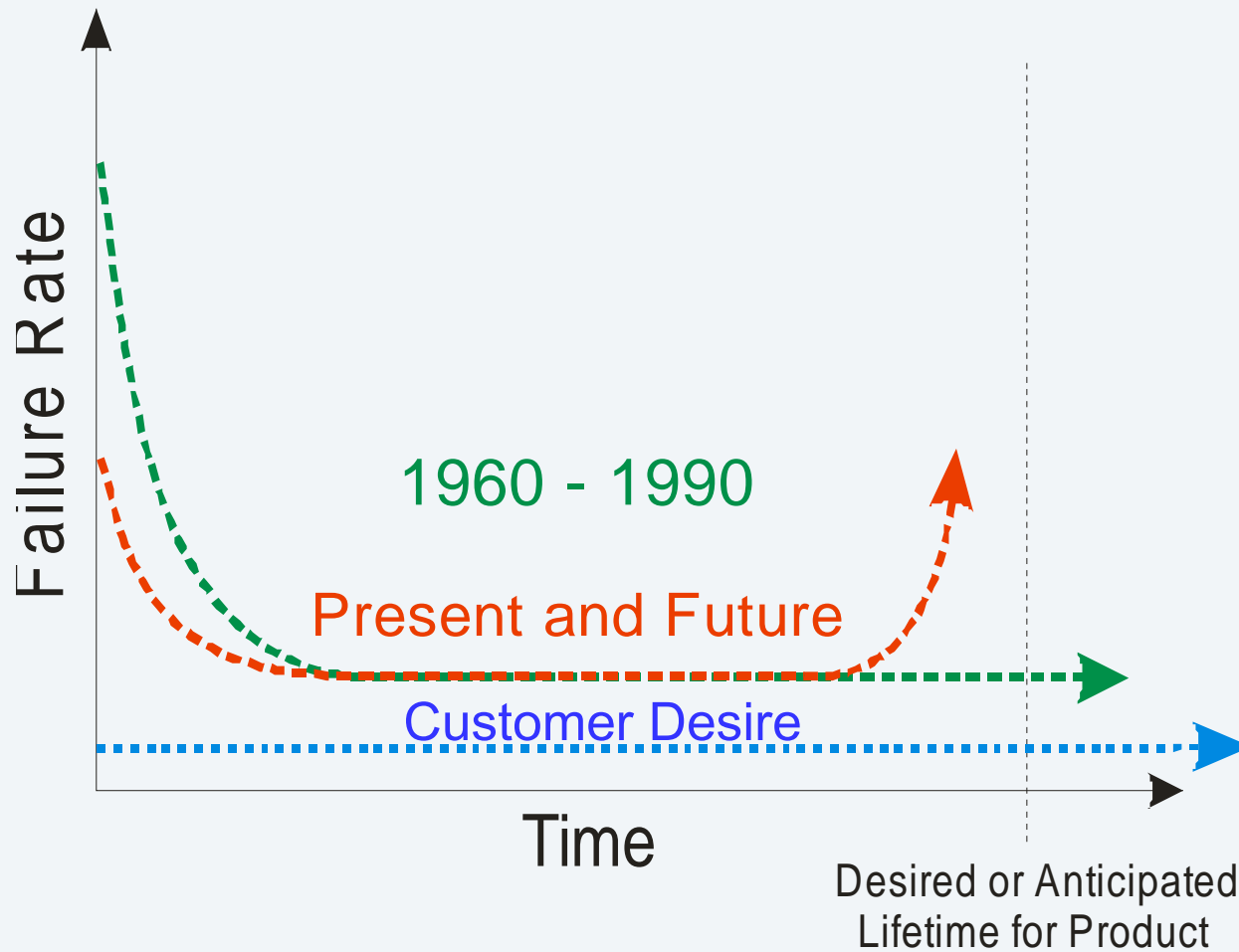
- Solder is not the only concern in the increase being seen in early electronic failures
- It has pointed out that the semiconductor industry, which is driven largely by Moore's Law, continues to pursue new ever finer feature nodes, seemingly oblivious to the impact of such efforts on long term reliability
- We are facing a growing gap between customer desires for long life and performance reality

The Growing Reliability Gap



Modified after C.Hillman

Meeting Customer Expectations



Reliability and Design

Most Reliability Problems Begin at Design

- **Some questions to ask:**
 - Does design match up with capabilities of the selected manufacturer?
 - Are trace and space within current standard manufacturing limits?
 - What laminate material will be used?
 - Is design symmetrical from side to side? How many layers?
 - What type of plated interconnections will be used?
 - How thick is board and what assembly methods are anticipated?
 - What assembly materials and equipment will be used?
 - What types of components will be used and what is their structure?
 - Is the component spacing appropriate?
 - What is the maximum size component?
 - Will stacking of components be employed?
 - Are components kept distant from prospective points of flexure?
 - What is/are the moisture sensitivity level (MSL) of the components?
 - Will second operation assembly be required?

Technical Challenges in DfR

- Electronic designs often incorporate a large number of simple components which are often very similar but which are of varying quality and reliability
- Identifying component defects or flaws that do not immediately affect performance during test is a difficult task.
- The designer has no control over device reliability but can and must attempt to make informed and hopefully better choices.
- While the designer does not control any aspect of manufacturing, his decisions will nevertheless impact the process and ultimate product reliability.
- Thus close attention must be given to the reliability of both the electronics parts and the interconnections that joint them.
- In short, the product design review must include a review by a reliability team familiar with total process

Summary

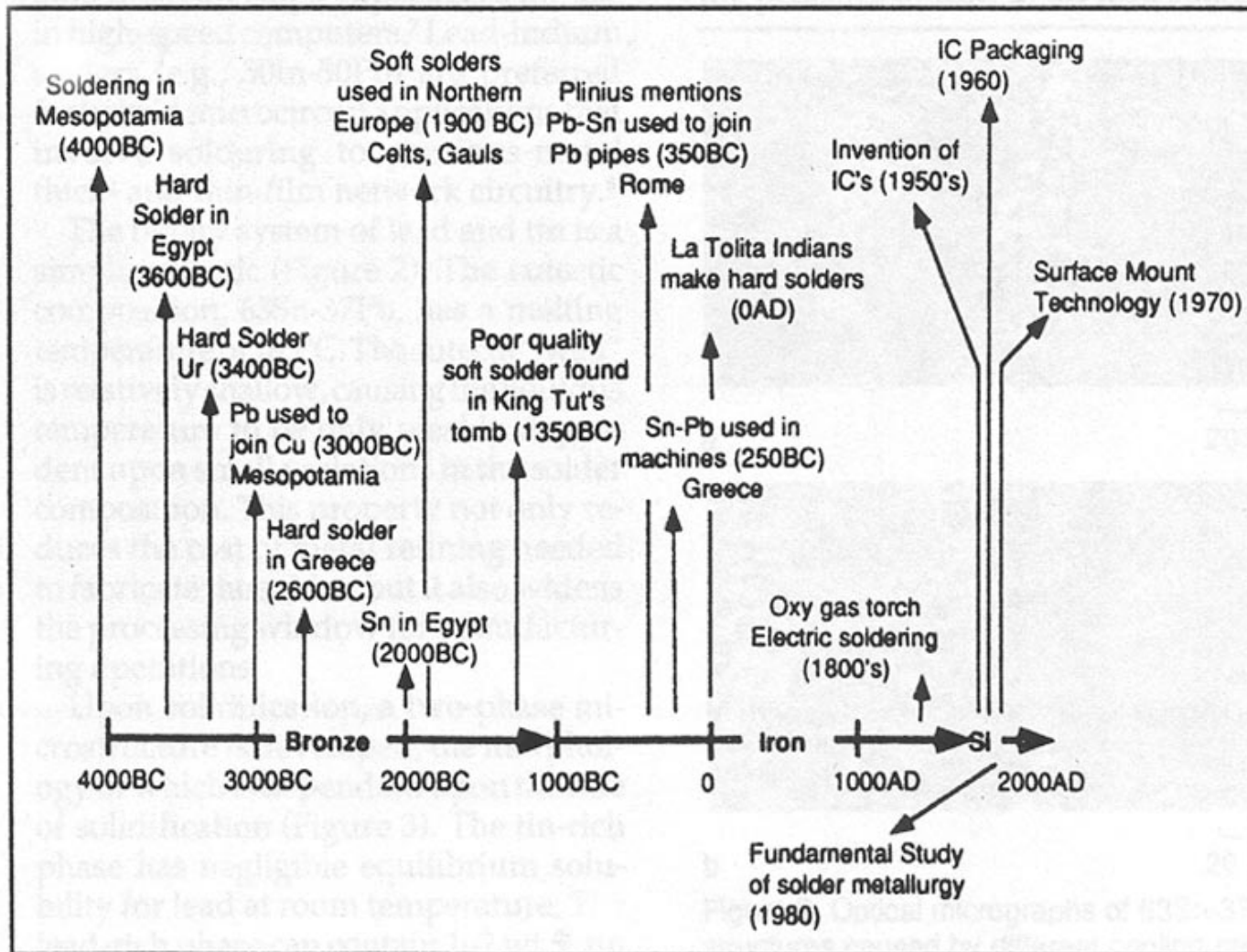
- Reliability is an important attribute for electronic products, notwithstanding the economic desire to make new products at an ever increasing rate
- Reliability has been the cornerstone of the electronics industry but it has been slipping from its position.
- Making more reliable products should result in significant cost and energy savings equally important, more sustainable and environmentally responsible products to help address the needs of the nearly five billion people at the bottom of the global economic pyramid.

Lead (Pb) – Some Background

- Lead (Pb) has been used by humans since at least 6500 BC
 - *Pb solder use dates back to 3800 BC when it was used to produce ornaments and jewelry*
- Harmful effects of excess Pb on the human body are well documented
 - *Pb gets into the body only through inhalation or ingestion*
 - *Acts as a neurotoxin, inhibits hemoglobin production, effects brain development*
 - *Children are more susceptible than adults*
- Dramatic reduction in blood Pb levels since 1975 due mainly use of Pb-free gasoline
 - *78% reduction documented in 1994 by EPA*
 - *Elimination of Pb from paints gave additional benefit*



Historical Timeline of Solder Usage



Lead Consumption

- World wide consumption of refined Pb decreased slightly to 8.63 metric tons in 2009 from 8.65 metric tons in 2008
 - *The first annual decline in global Pb consumption since 2001*
- The leading refined-Pb-consuming countries in 2009 were:
 - *China 45%*
 - *United States 16%*
 - *Germany 4%*
 - *Republic of Korea 3%.*
- Consumption of refined Pb in the U.S. decreased by about 11% in 2009

Application	2009 U.S. Consumption
Metal Products	5.8%
Electronic Solder	0.5%
Storage Batteries	88.3%

1) International Lead and Zinc Study Group (2010c, p. 8–9) (ILZSG),

2) Data from USGS statistics



Pb in the Electronics Industry

- Electronic component terminations have been electroplated and soldered to circuit boards with tin/lead (Sn/Pb) solder for many decades
- The entire electronics manufacturing process has been developed around the mechanical properties and soldering temperature of Sn/Pb
 - *Component packaging*
 - *PCB material*
 - *Design rules*
 - *Thermal management*



The Concern Regarding Pb in Electronics

- Apprehension about Pb from waste electronics entering the ecosystem
 - *Pb in solder and platings might leach away and get into ground water*
- “Green” movement in the European Union (EU) looked for ways to reduce Pb in landfills
- Consumer electronics account for 40% of Pb in landfills
- Recycling efficiency of Pb in consumer electronics is 5%



The Precautionary Principle

Ready, Fire, Aim!

- Precautionary Principle states:
 - *“When an activity raises threats of harm to human health or the environment, precautionary measures should be taken even if some cause-and-effect relationships are not fully established scientifically.”*
- Used as the basis for enacting environmental legislation in the EU and other countries around the world



What is RoHS?

- Fears over imagined harm from Pb used in consumer electronics resulted in legislative action in the Europe Union (EU)
- The EU issued the Restrictions on Hazardous Substances (RoHS) directive in 2003
 - *Prohibits certain substances in specific categories of electronic equipment sold in EU member nations*
 - *Prohibited materials are **lead**, mercury, cadmium, hexavalent chromium, polybrominated biphenyls (PBB) or polybrominated diphenyl ethers (PBDE)*
 - *Lead (Pb) not allowed in concentrations of greater than 0.1% by weight in component termination finishes and solder*
 - *Supporting laws took effect on July 1, 2006*
- RoHS fundamentally altered the electronics industry worldwide!

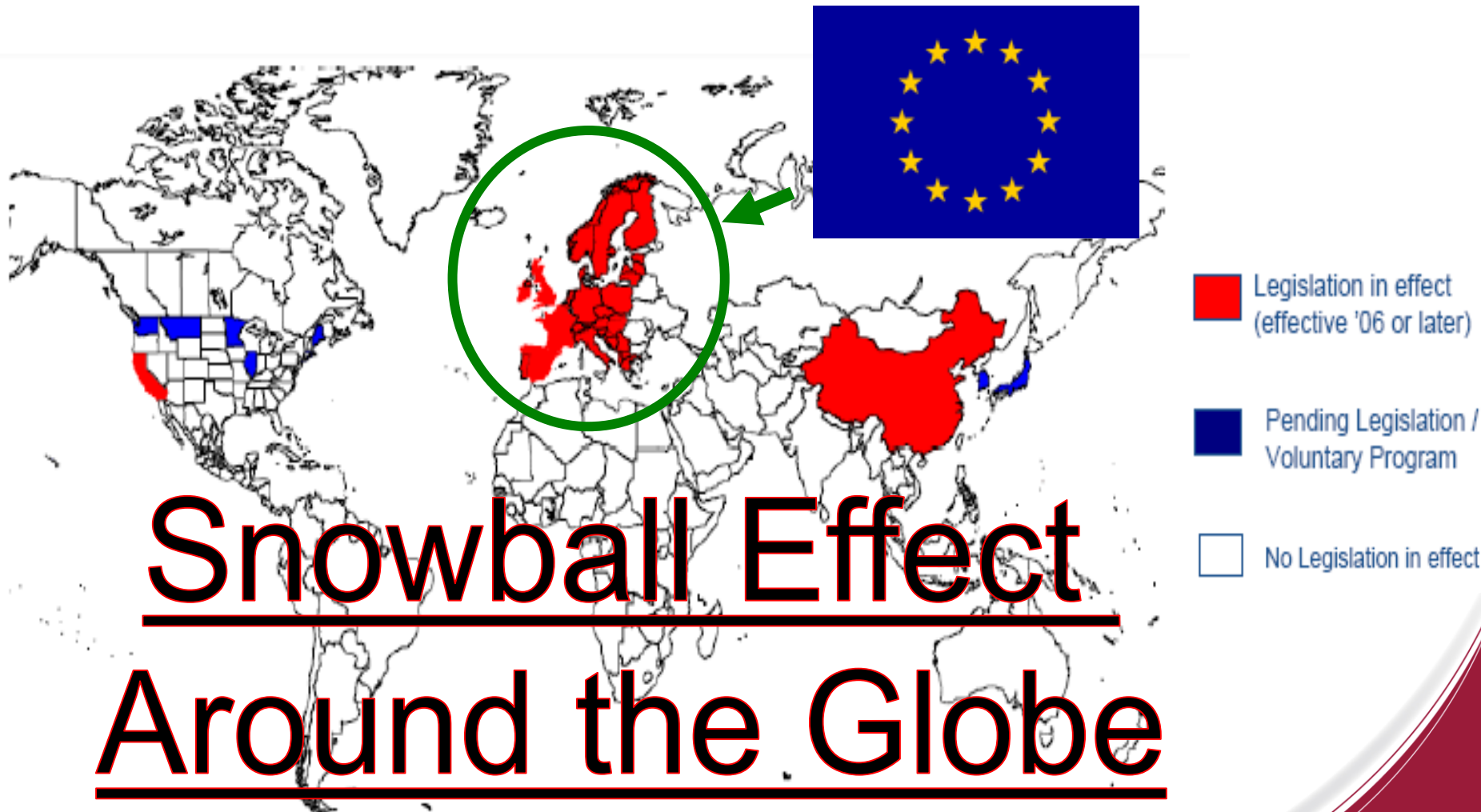


RoHS Exemptions

- RoHS exemptions are regularly reviewed and changed by the EU
 - *Fewer exemptions are being granted*
- Military and aeronautic/aerospace equipment are currently considered excluded/exempt/out of scope in guidance documents
- Automotive electronics must be RoHS compliant in the EU by 2016
- Medical electronics must be RoHS compliant in the EU by 2014
 - ~~*Defibrillators exempt until 2021*~~



Global Environmental Initiatives



Snowball Effect
Around the Globe



Transition Costs

- In 2005, Intel made the following statements
 - *“Intel's (\$34.2B annual revenue) efforts to remove lead from its chips have so far cost the company more than \$100 million and there is no clear end in sight to the project's mounting costs”*
 - *“the company hopes to be completely lead-free within five years”*
 - http://www.infoworld.com/article/05/03/16/HNleadfreemove_1.html
- In 2011, Intel is still not completely Pb-free although some of their product lines have achieved that status



Pb Reductions Achieved

- A huge (~ \$14B annual revenue) semiconductor manufacturer estimated the annual worldwide Pb reduction per 1,000,000,000 integrated circuits was only equivalent to ~100 automobile batteries
 - *This is less than 0.05% of car batteries that are not recycled yearly*



Pb Entering the Environment – Groundwater Pollution

- “In the environment, inorganic lead will mainly be particulate bound with relatively low mobility and bioavailability. Under most circumstances, humic substances will immobilize the lead. However, as the alkalinity and pH decreases the mobility of lead increases.”
 - *“Phasing out lead in solders” Ulrika Kindedjö, 2001*
- “Natural weathering processes usually turn metallic lead and its compounds into compounds which are relatively stable and insoluble.”
 - *“LEAD: the facts” is an independent report on lead and its industry prepared by Imperial College Consultants Ltd (London, UK) and was published in December 2001.*



Pb Entering the Environment – Groundwater Pollution

- “Lead does not break down in the environment. Once lead falls on to soil, it usually sticks to the soil particles.”
 - *Ohio Department of Health 08/10/09*
 - *“Lead – Answers to Frequently Asked Health Questions”*
- 148 year long continuing study in Brandy Station, Virginia by the author confirms Pb does not leach away
 - *Land has been farmed continuously*



.577 Caliber French Triangle Cavity Bullet
“Minie Ball”

Reprinted with permission of Andrew D. Kotic



Pb Entering the Environment – Recycling Impact

- Concern about recycling electronics in third world countries over open fires
 - *May create Pb vapor that would be inhaled causing Pb poisoning*
- Pb boils at 1,740 °C
- Typical open fire temperature is approximately 1,000 °C
 - *Vapor pressure of Pb is negligible at that temperature*
 - *Little/no possibility of Pb vapor inhalation*
 - *Same reason why Sn/Pb soldering personnel do not have elevated blood Pb levels*



Lead Poisoning from Electronics

- There is *no evidence* that Pb used in electronics manufacturing and products does any harm to humans or the environment
 - *Electronics industry consumes approximately 0.5% of world's Pb*
 - *No mechanism exists for transfer of Pb to blood through direct contact or proximity to Pb in electronics*
 - *No evidence of any elevated Pb levels in blood of soldering personnel*
- Lead-acid batteries account for over 80% of Pb consumed
 - **Batteries are exempt from all RoHS legislation**

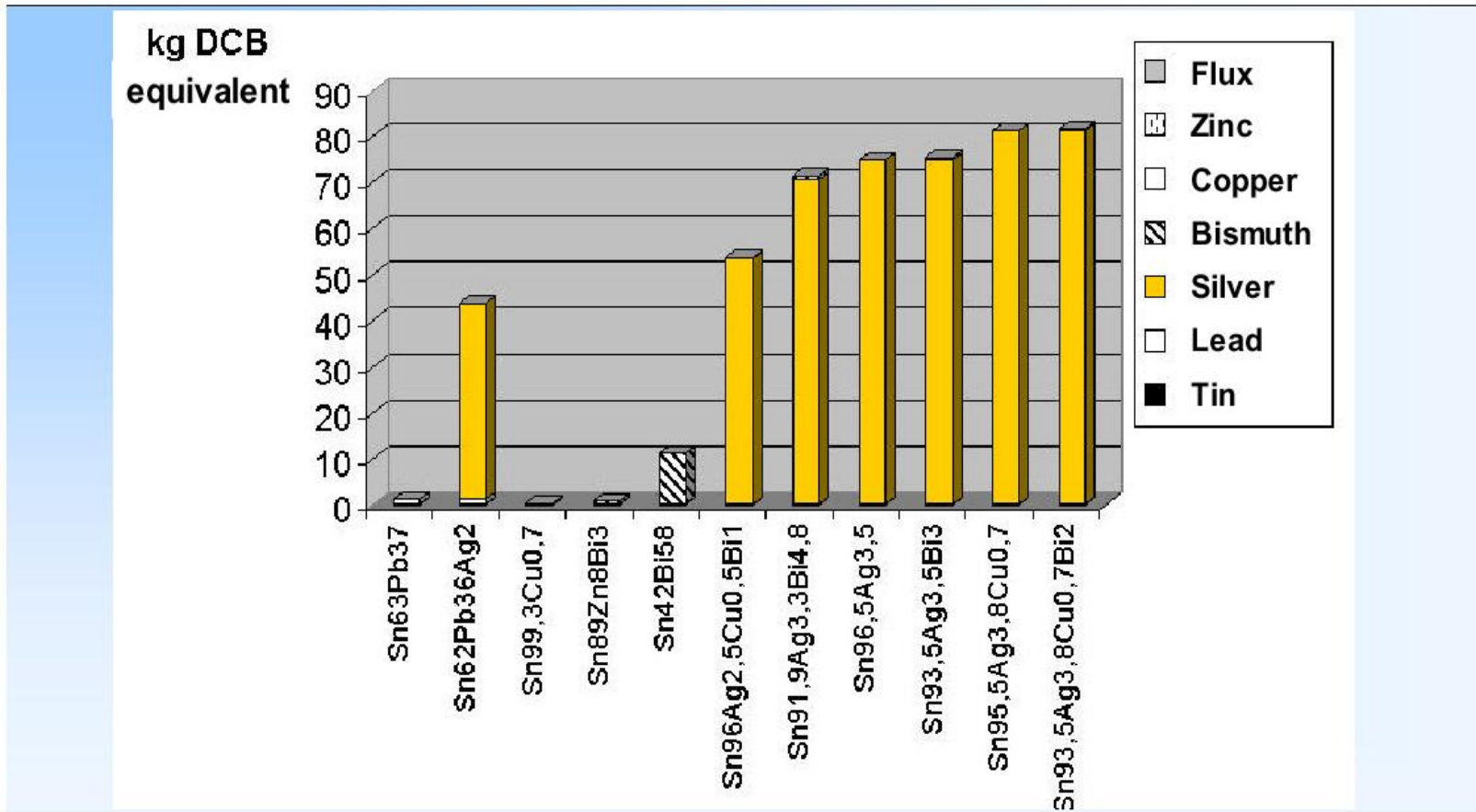


Environmental Impact of Pb-free Replacements

- Current alternatives are worse for the environment
- Study by IKP University of Stuttgart Department Life Cycle Engineering
 - http://leadfree.ipc.org/files/RoHS_15.pdf
- Boundary Conditions of the Study:
 - *The calculations are “cradle to gate” analysis, that means from extraction of the raw materials up to the finished product, including all pre-chains like energy supply or production of auxiliaries.*
 - *The life cycle phase “End of The Life”(recycling/deposition/incineration) is not considered, as there are no reliable data available today on the respective impacts (especially on landfills). In case considerable quantities of heavy metals are emitted from those landfills, this could have significant influence to the overall results.*



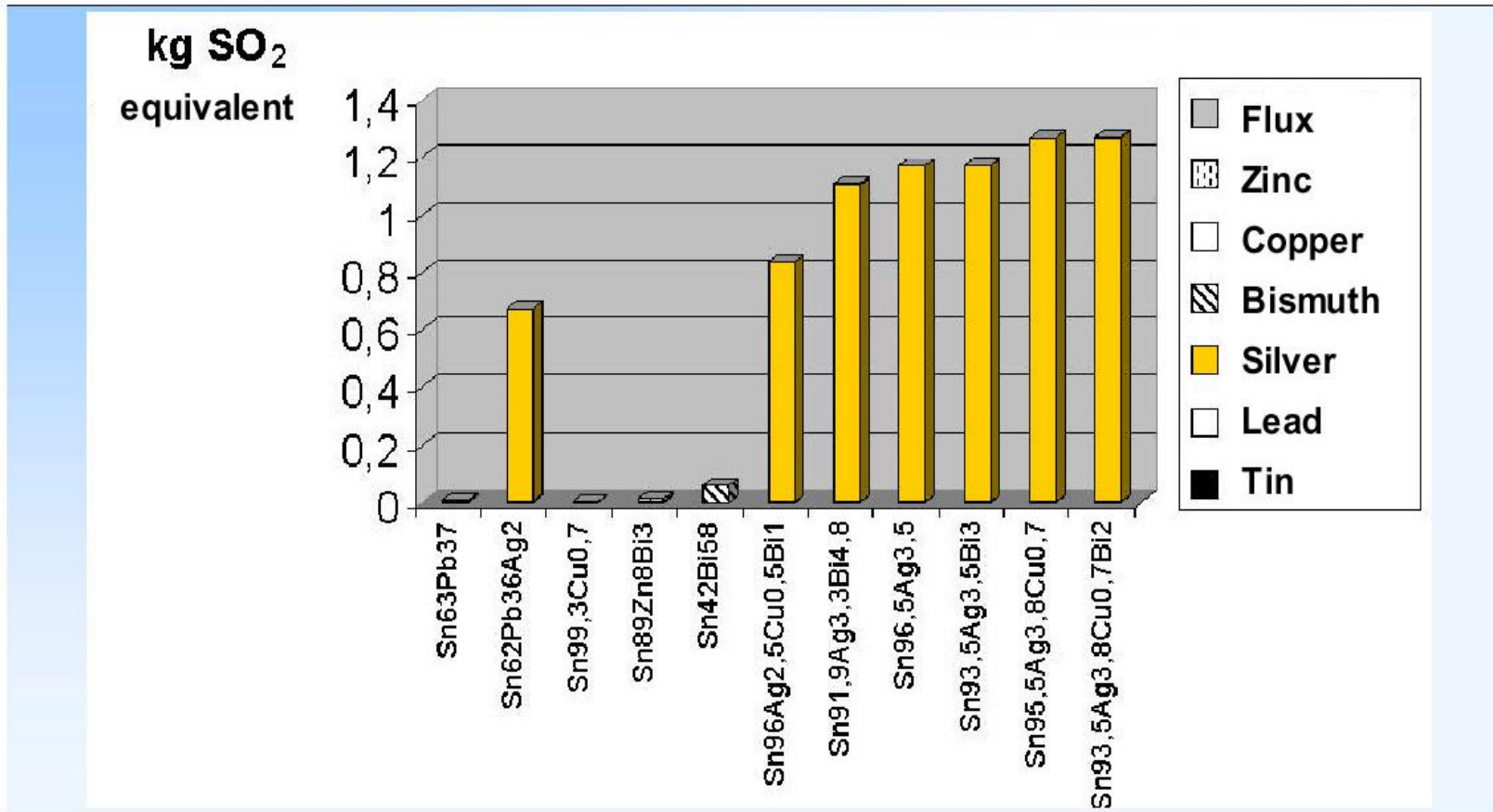
Comparison of Human Toxicity Potential (Extraction to Finished Product)



Source: Neil Warburg, IKP University of Stuttgart, Life-Cycle Study



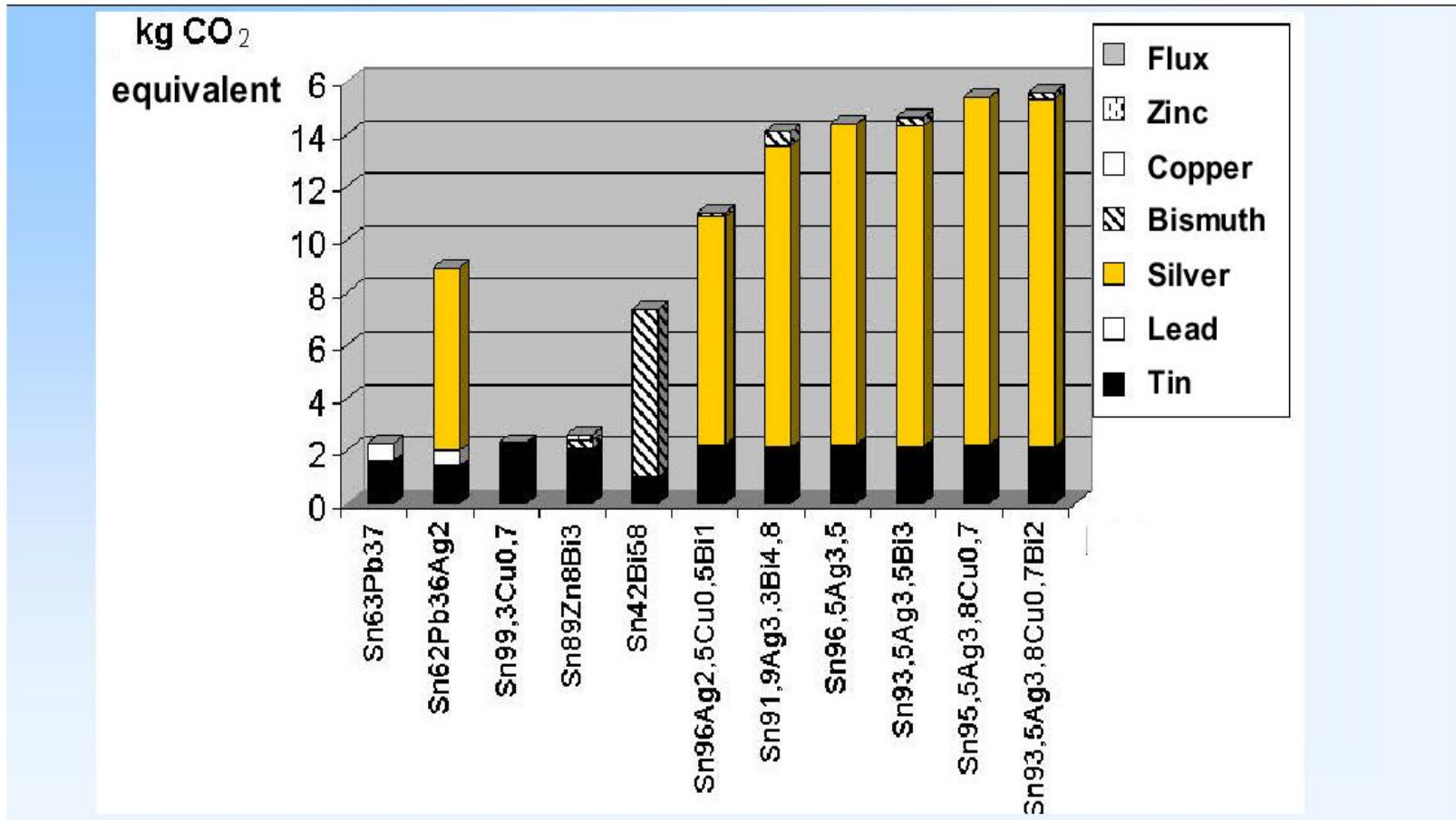
Comparison of Acidification Potential (Extraction to Finished Product)



Source: Neil Warburg, IKP University of Stuttgart, Life-Cycle Study



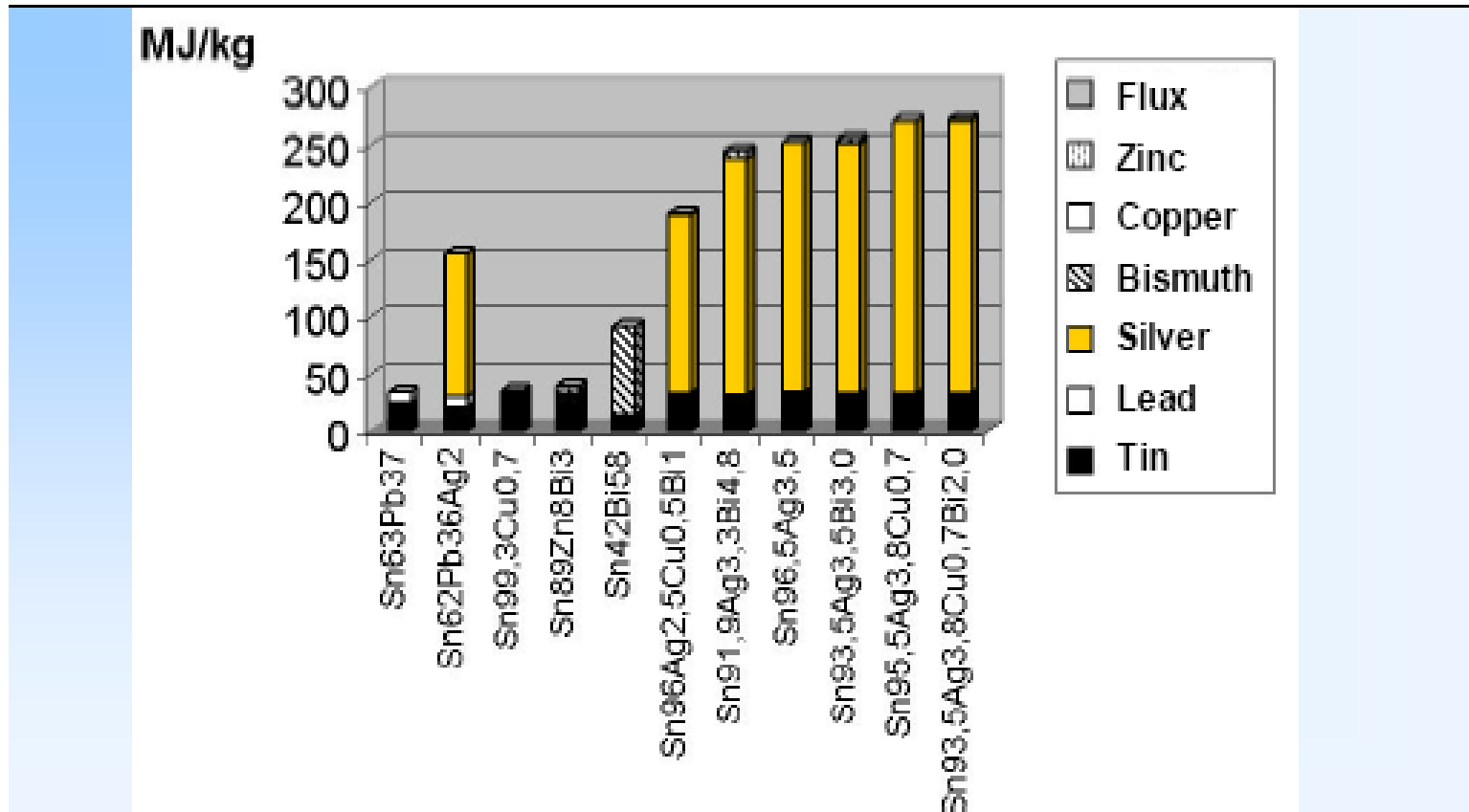
Comparison of Global Warming Potential (Extraction to Finished Product)



Source: Neil Warburg, IKP University of Stuttgart, Life-Cycle Study



Comparison of Primary Energy Use (Extraction to Finished Product)



Source: Neil Warburg, IKP University of Stuttgart, Life-Cycle Study



US Federal and State Legislation



- No Federal restriction on Pb in electronics...**yet**
- California State-level legislation
 - *Regulations effective January 1, 2007*
 - *Forbid sale of devices containing materials prohibited by EU RoHS but with narrow focus: CRTs, LCDs, Plasma Displays, etc (>4" screen)*
- Other states have “environmental” legislation similar to the EU including New Jersey



Lack of Technical Guidance

- DoD
 - *No position*
- Federal Aviation Agency (FAA)
 - *No official position*
- NASA
 - *Prohibits pure tin as a finish and often requires 3% lead*
- European Space Agency (ESA)
 - *Tin/lead required solder for assembly*



DON'T MOVE, or I'll fill you full of LEAD!!!

HAAA!! I happen to know that the lead in bullets is in the METALLIC form! This chemical form of lead has an intrinsically low bioavailability and toxicity!!

YES, but EARP et al (1886) have recently reported that the gunpowder-assisted acceleration of this form of lead to 1000 ft/sec substantially enhances its ability to penetrate biological membranes, effectively making it a whole lot MORE toxic!!!

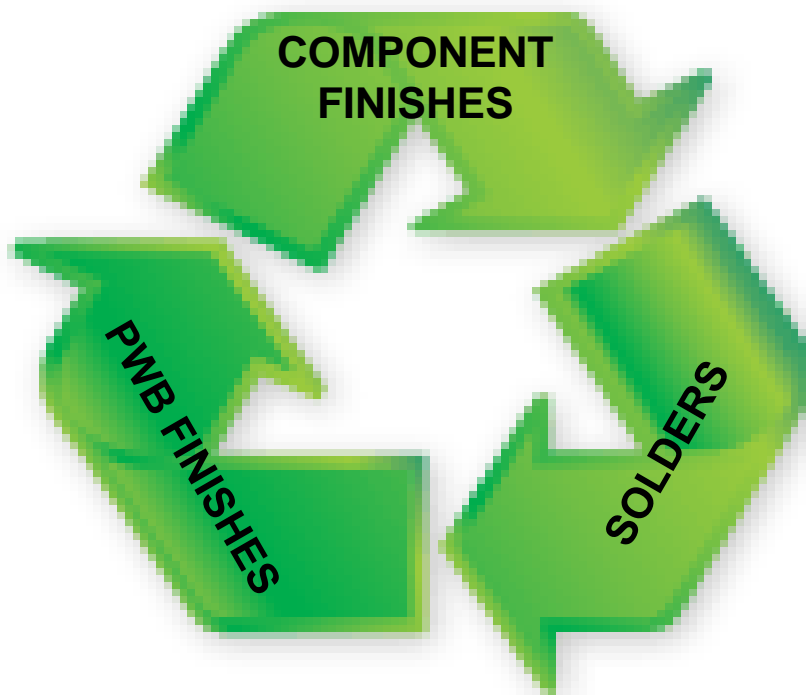
I don't believe I've read that paper...

ENVIRONMENTAL SCIENTISTS IN THE WILD WEST

Cartoon by Nick D Kim, strange-matter.net. Used by permission

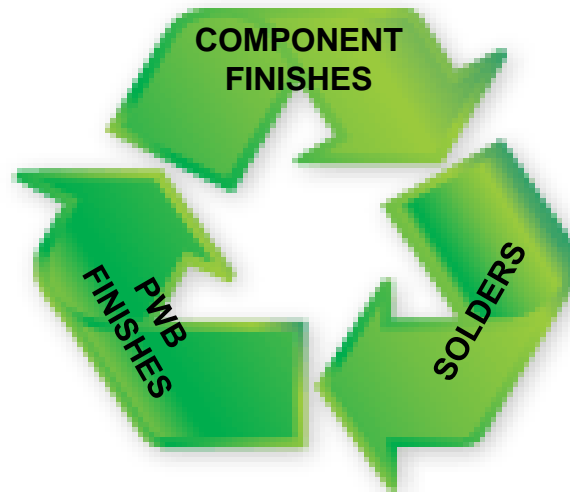
Suppliers Have Converted to Pb-free Products

- The suppliers are making the vast majority of their products for commercial applications
 - *Reaction to the RoHS restrictions*
 - *Marketing*



Suppliers Have Converted to Pb-free Products

- Most aerospace/military parts are “dual-use” (both commercial and mil/aero) so many parts are only available as Pb-free
 - *Not viable to keep a Sn/Pb manufacturing process for small market*
 - *Military/aerospace is less than 1% of the market*
- Many different aspects of products have changed
 - *Termination finishes*
 - *PWB finishes*
 - *Solder*
 - *Layout*
 - *Process flow*



Pb-free - Not “If” but “When”

Resistance is futile



Product Availability

- Some component suppliers continue to offer both RoHS-compliant versions *and* heritage Sn/Pb parts
 - *Number of suppliers offering Sn/Pb is decreasing*
- Contract assembly houses have also moved to Pb-free
 - *Some capacity remains for Sn/Pb assembly but is limited*
- Industry trends for heritage Sn/Pb parts
 - *Lack of availability (DMS)*
 - *Long lead times*
 - *Price increases*
 - *Increasing risk of counterfeit parts*



No Drop-in Replacement for Sn/Pb

- There are still **no “drop-in replacements”** for Sn/Pb solder or plating
- Industry **still has not standardized** on a replacement for Sn/Pb solder
 - *Mechanical characteristics of solders have wide variations*
 - *Different alloys have different reflow temperatures*
 - *Alloys may not interact well*
- Some alloys covered by patents or copyrights
 - *Finished solder joint compositions covered too!*



Component Termination Finishes

- Finishes containing Pb have basically been discontinued
 - *Well over 90% are Pb-free*
 - *Many suppliers consider Sn/Pb special orders*
- Pure Sn is the usual choice for termination finish
- Nickel/Palladium/Gold (Ni/Pd/Au) is a common Pb-free alternative to Sn
 - *Additional cost*



Impacts of Change to Pb-free Solders and Finishes

- Inability of users to know what material they are getting
- Identification methods varies
 - *New part numbers*
 - *Marking on packaging*
 - *Date of manufacture*
 - *Marked on part*
- Cannot visually differentiate between Sn/Pb and Pb-free Sn
 - *Lot sampling is mandatory*
 - *Energy dispersive x-ray analysis (EDX) and x-ray fluorescence (XRF) are common inspection tools*
 - *Typically +/- 1% absolute accuracy in measuring Pb in a Sn matrix*



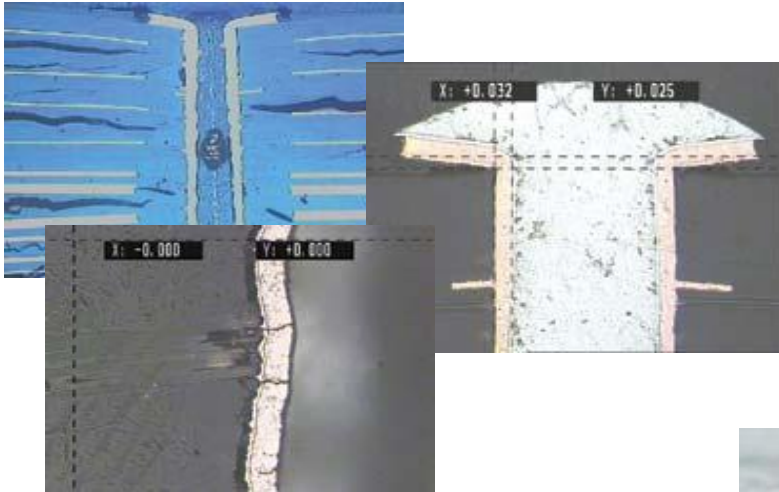
Impacts of Change to Pb-free Solders and Finishes

- Visual inspection criteria for solder joints are different
 - *Rejected Sn/Pb joint would typically be acceptable in a Pb-free solders*
 - *Significant operator retraining required*
- Mixing technologies during assembly, repair, or upgrade
 - *Difficulty in tracking parts with differing finishes*
 - *Different assembly techniques required*

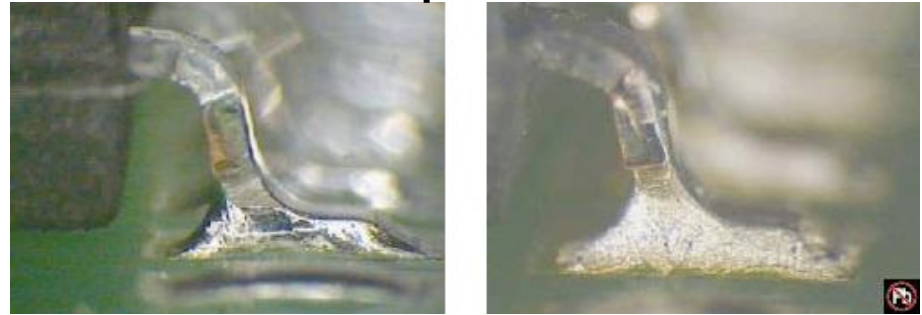


Pb-free Solder Assembly and Inspection Issues

PWB Laminate Stress



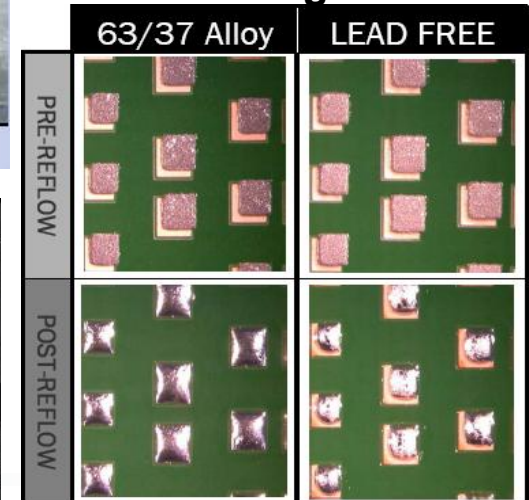
Inspection



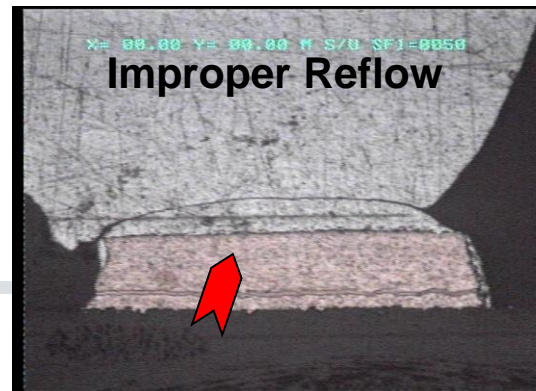
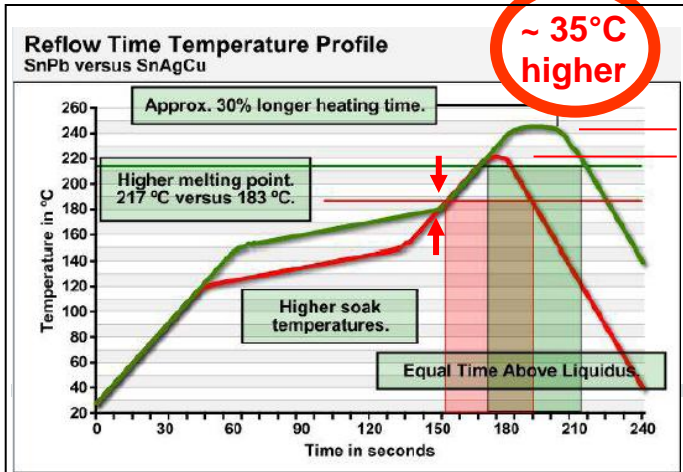
Components



Wetting and Storage Life



Higher Assembly Temperature



Impacts of Change to Pb-free Solders and Finishes

- Even materials that are not specifically called out in RoHS have changed in response to Pb-free soldering
 - *Laminates, fluxes ...*
- Use of no-clean fluxes results in greater likelihood of conductive flux residues on board after assembly
- Emergence of new/unfamiliar failure modes



Impacts of Change to Pb-free Solders and Finishes

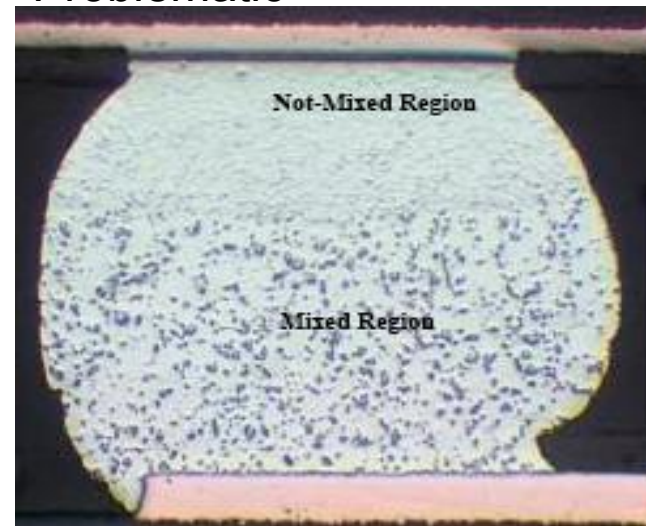
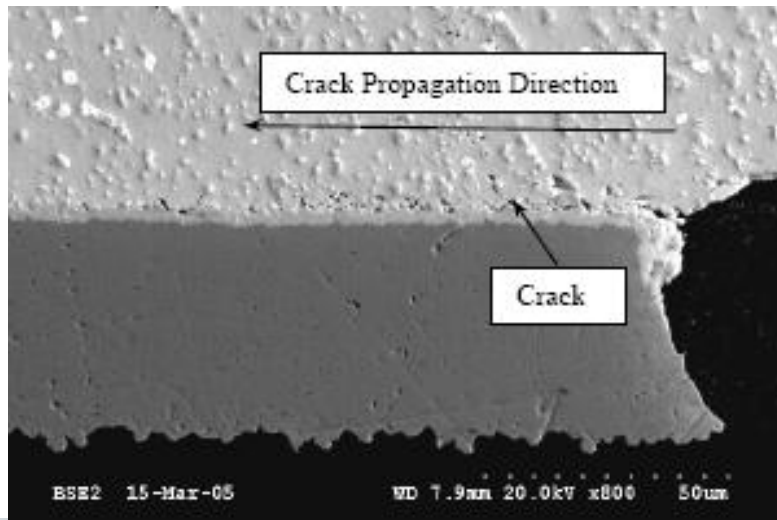
- Process and reliability improvements have been/are being developed for consumer electronics environments
 - *Not optimized for high reliability, severe stress, long life applications*
- Different solders may be needed for each different application depending on operating conditions and environment
 - *Temperature, thermal cycle, vibration, shock ...*



Rework and Repair Are Major Concerns

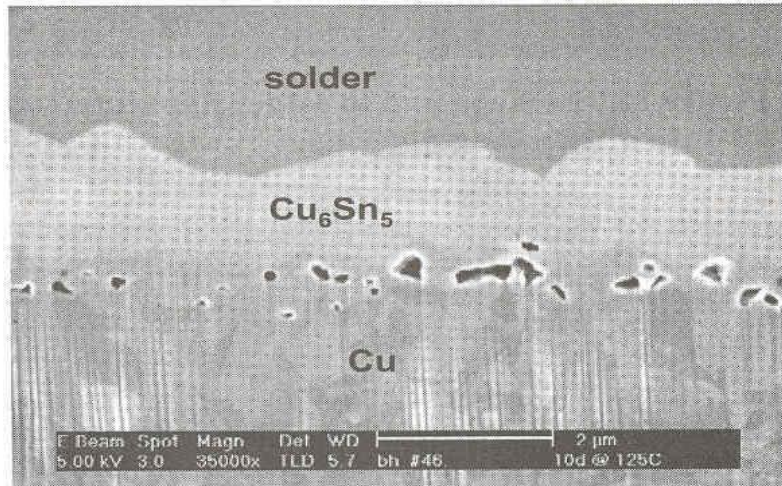
- Hardware will be received back for repair
 - *Only available replacement parts in many cases will be Pb-free*
 - *What records will identify termination finish or solder alloy used?*
- Cannot mix Sn/Pb and Pb-free solder on some components (e.g., BGAs) without risk to reliability
 - *Level of risk is still the subject of numerous studies*

“Backward Compatibility” Problematic

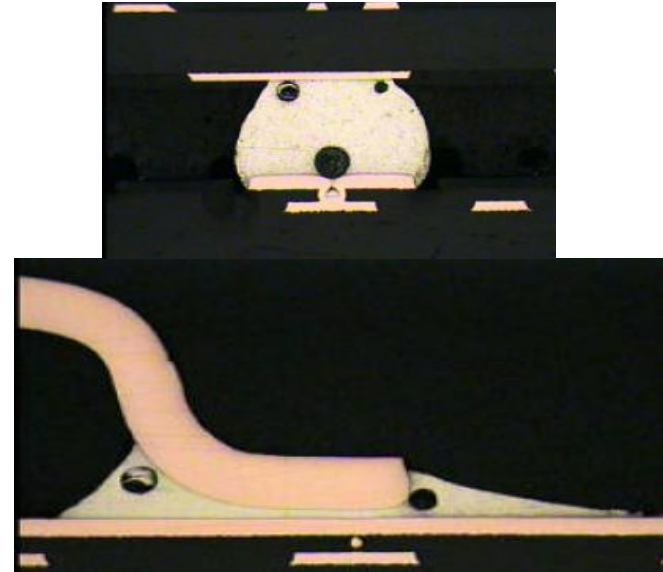


Pb-free Reliability Issues

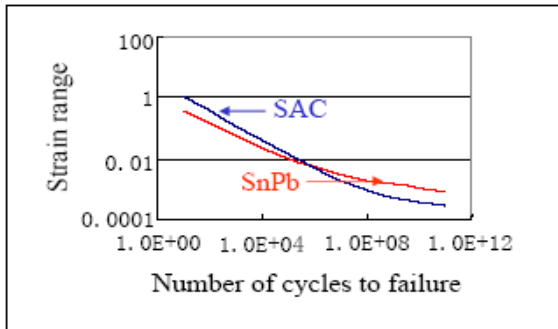
Microvoiding



Increased solder voiding

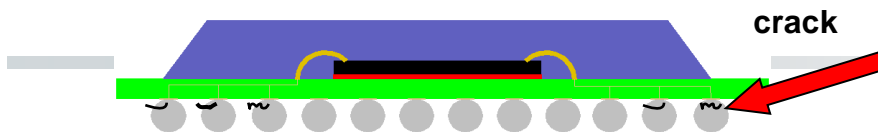


Less Reliability @ High Temps and Vibration



C05-02
Accelerated Qualification of SAC Assembly:
Combined Temperature Cycling & Vibration
CALCE Team: Y. Zhou, A. Dasgupta, M. Al-Basyouni

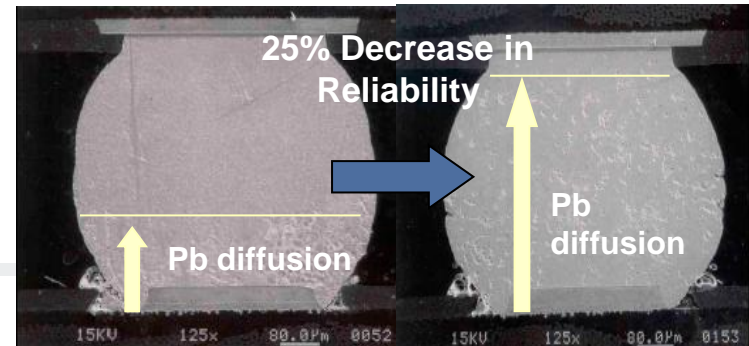
Sn / (3-4 wt%) Ag / (0.5-0.7 wt%) Cu



Mixed Technology

Sn/Pb paste/SAC ball
205°C peak reflow

Sn/Pb paste/SAC ball
214°C peak reflow



Solderability

- Lead free solders have decreased wetting ability
 - *Lead free surface finishes on components and boards will also decrease the amount of wetting*
 - *Longer exposure at increased temperatures will assist wetting at the risk of thermal damage*
- Lead-free component finishes and solders typically require higher soldering temperatures which will affect
 - *Cost*
 - *Reliability*
 - *Rework*
- Re-qualification required for components used in a lead-free assembly processes



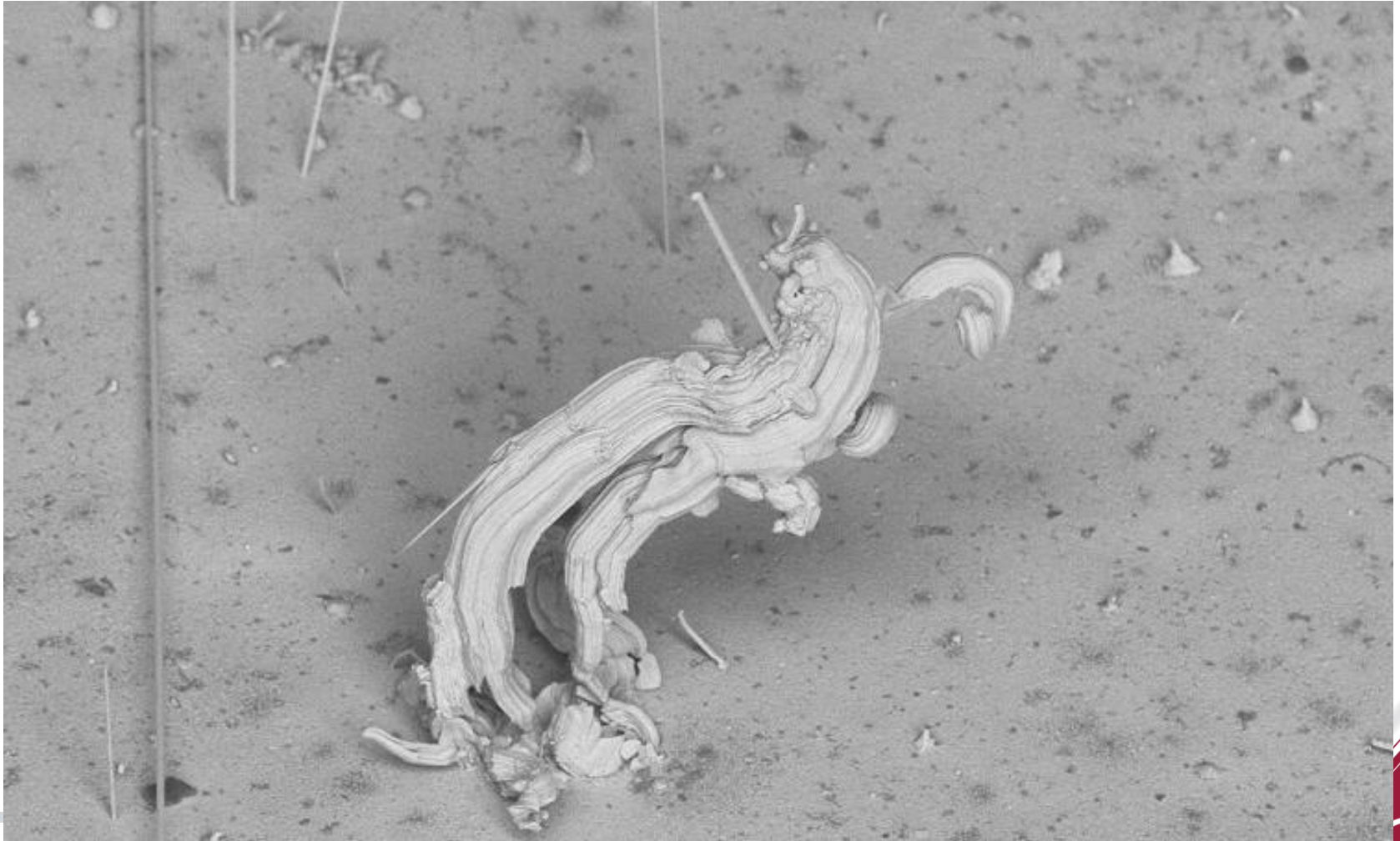
Pb-free Solder – Durability

- Field to lab correlation has not been established for Pb-free
 - *Especially in high stress long life applications*
- Pb-free (SAC) interconnects less reliable at
 - *Higher temperatures*
 - *Vibration*
 - *Shock*
- Not an issue for consumer products because of low stress levels
 - *Low stress: Pb-free is better*
 - *High stress: SnPb is better*



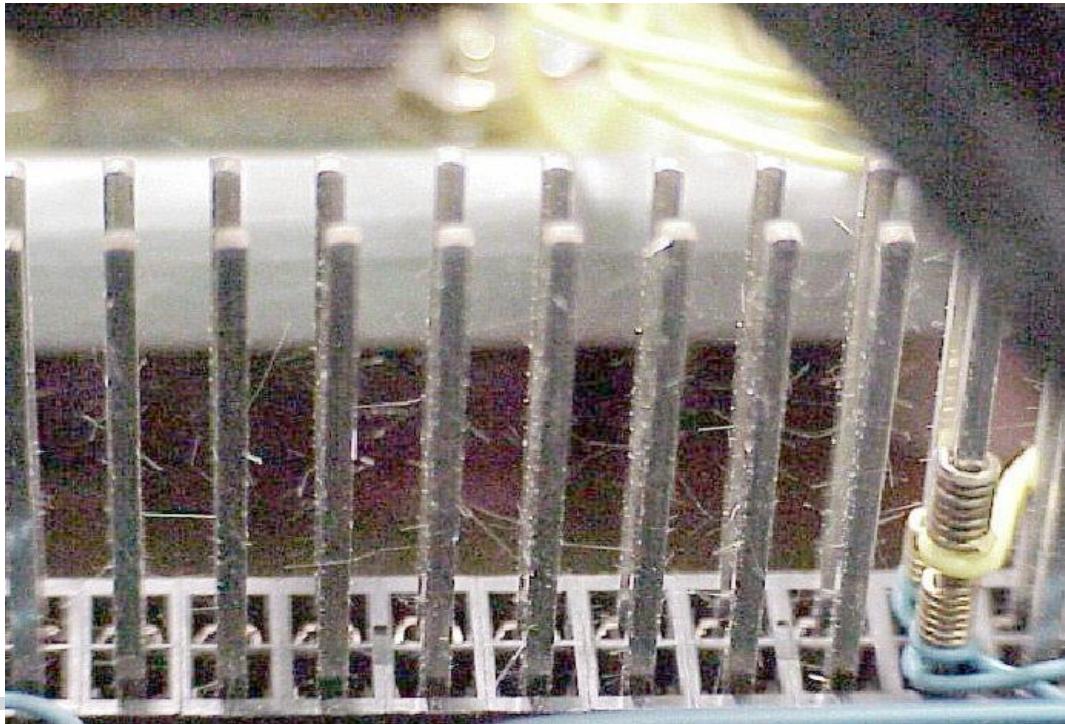
Pb-free Tin Reliability Issues

Tin Whiskers



What are Tin Whiskers?

- Tin whiskers are spontaneous hair-like growths from surfaces that use Pb-free tin (Sn) as a final finish
 - *Electrically conductive*
 - *May grow in hours, days, weeks, or years*
 - *Pb-free tin-plated electronic & mechanical parts can grow whiskers*
 - Nuts, Bolts ...



Courtesy: NASA Electronic Parts and Packaging (NEPP) Program



Tin Whisker Background

- Tin whiskers were first reported by Bell Labs around 1947
- Growth inception and rate varies widely
 - *Can start growing after years of dormancy or in a few hours*
 - *Whiskers can start growing, stop, and then resume growing*
- Whisker shapes and forms vary considerably
- Lengths range from few microns to over 20 millimeters
 - *23 millimeters is the current record holder*
- Up to 200 whiskers per square millimeter have been observed
- Whiskers can grow through thin conformal coatings

<http://www.calce.umd.edu/lead-free/>
<http://nepp.nasa.gov/whisker/>

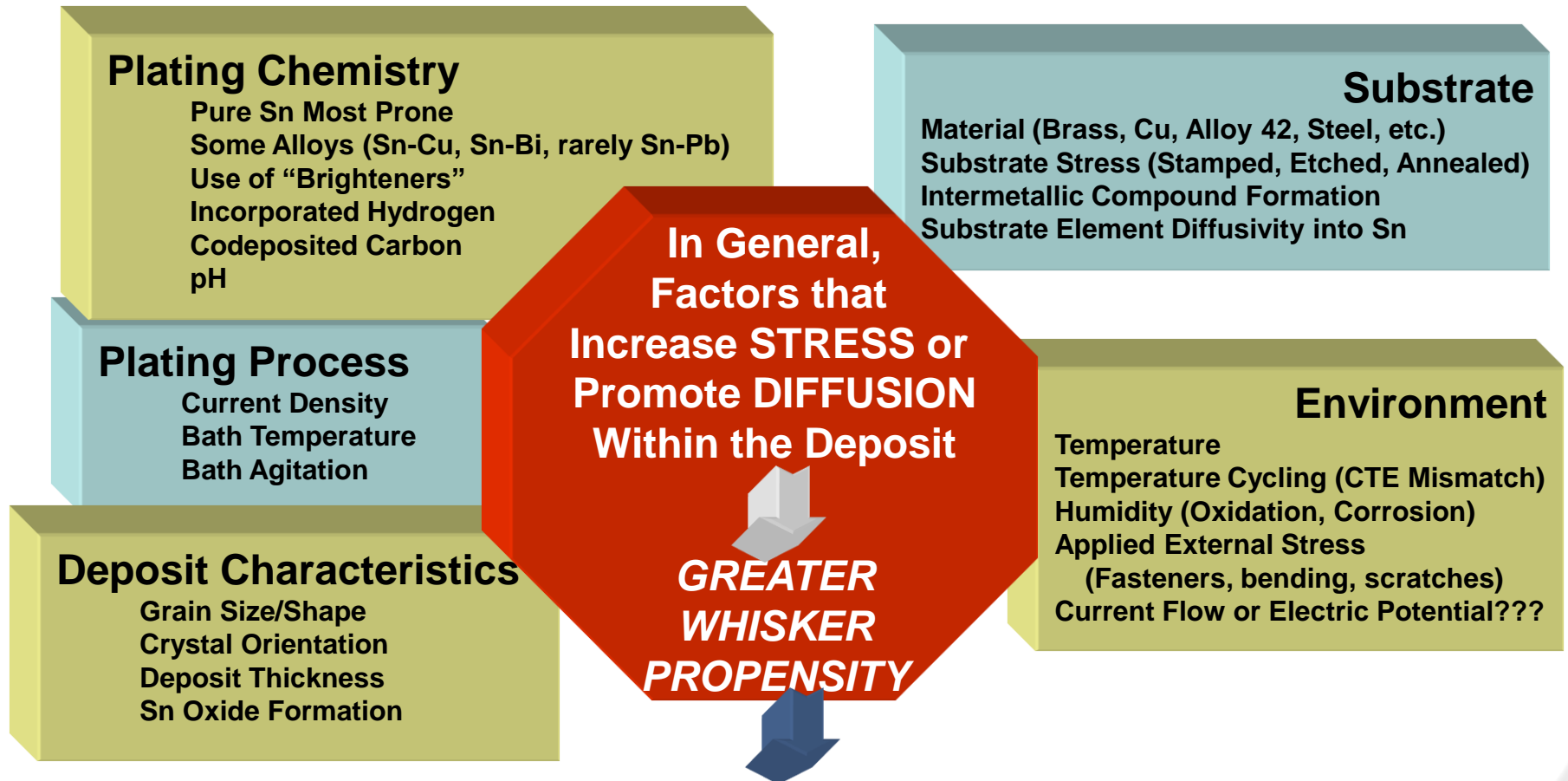


Tin Whisker Background

- Whisker growth mechanism(s) still not known after 60+ years of study
 - *Conflicting evidence*
- **No** effective tests to determine the whisker propensity of platings
- **No** single mitigation technique provides effective protection against whisker formation except the addition of 3% or more of Pb by weight
- **No** reliability models exist that can quantify impact of tin whiskers
- Whiskers are extremely difficult to detect
 - *Many “No Defect Found/Could Not Duplicate/No Trouble Found” faults may be due to tin whiskers*



What Causes Tin Whiskers?



HOWEVER....
Many Experiments Show Contradictory Results For These Factors

Courtesy: NASA Electronic Parts and Packaging (NEPP) Program



Why are Tin Whiskers a Major Concern?

- Small circuit geometries
 - *Whiskers can easily bridge between contacts*
 - *Adjacent whiskers can touch each other*
 - *Broken off whiskers can bridge board traces and foul optics or jam MEMS*
- Low voltages
 - *Whiskers can handle tens of milliamps without fusing*
- Manufacturers have moved to Pb-free tin platings
 - *Pb-free tin included*

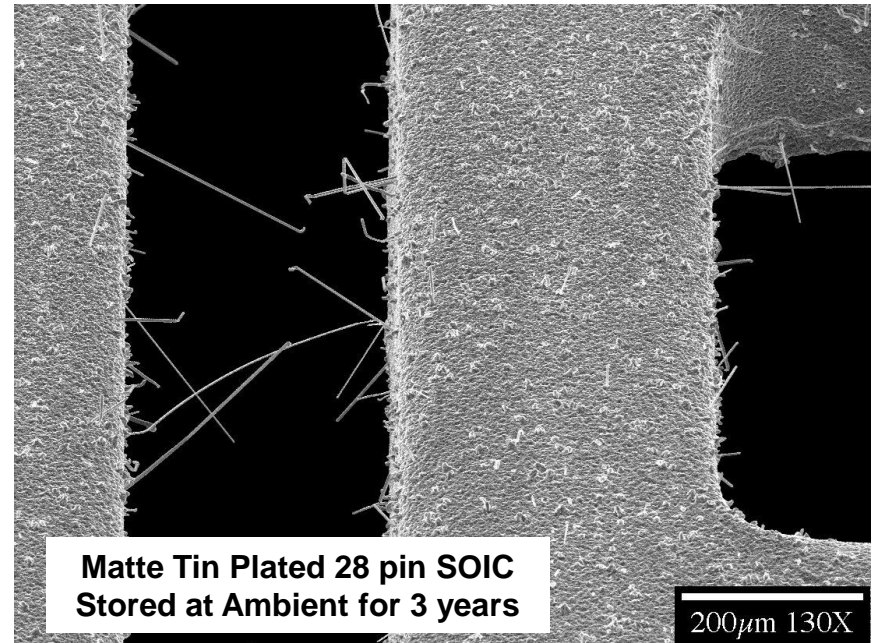
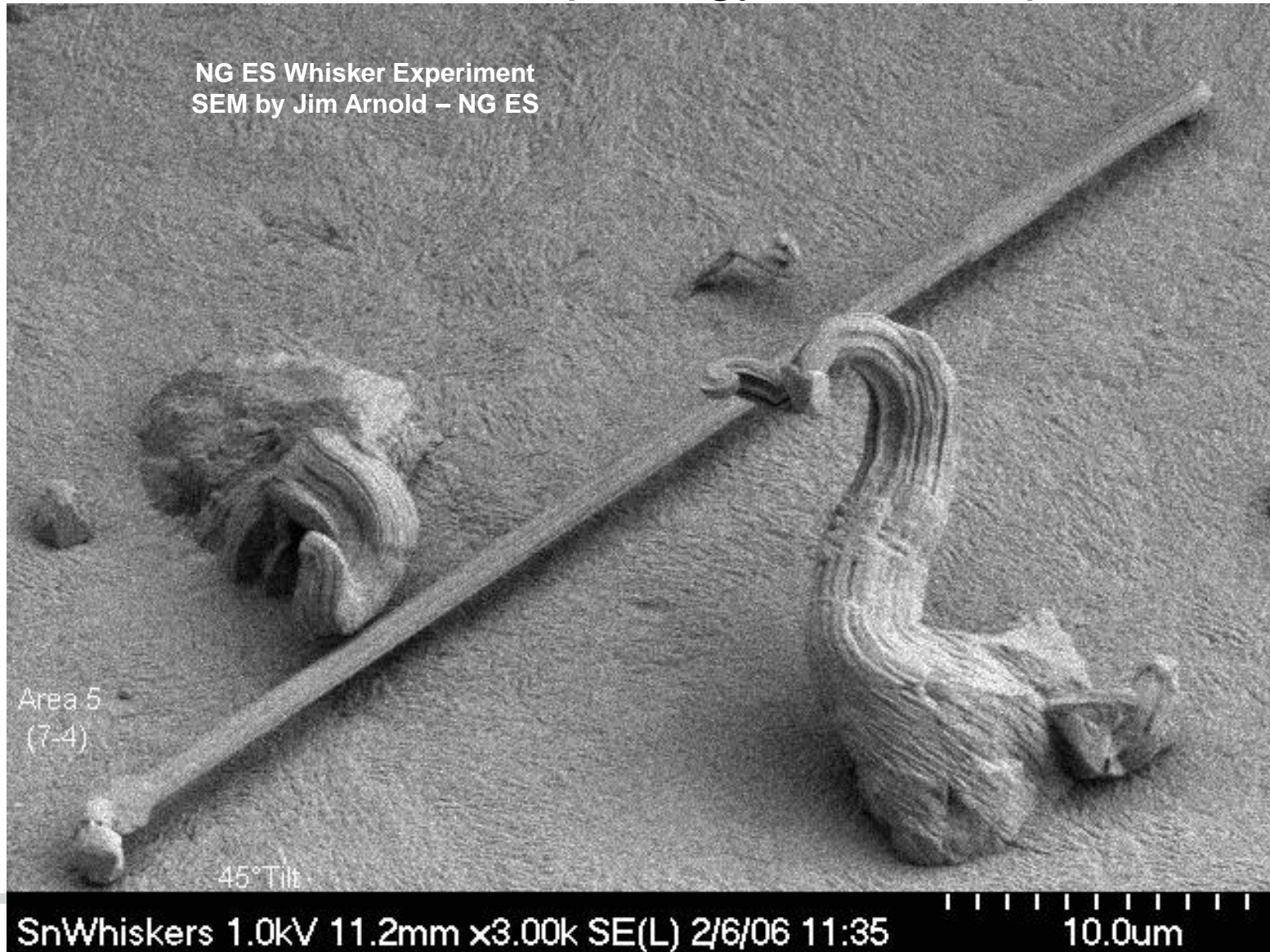


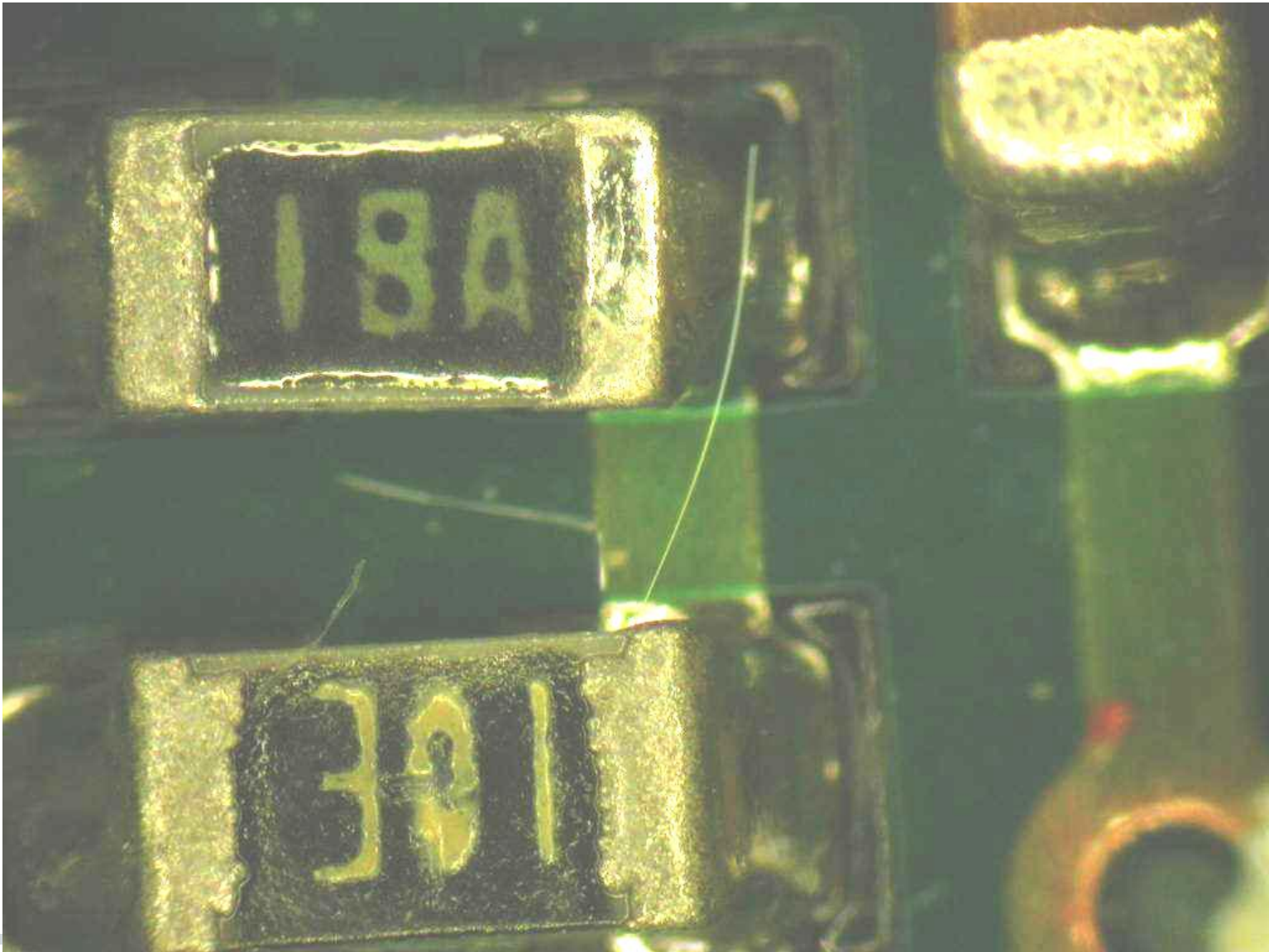
Photo Courtesy: Peter Bush, SUNY



Variation in Whisker Morphology on a Sample



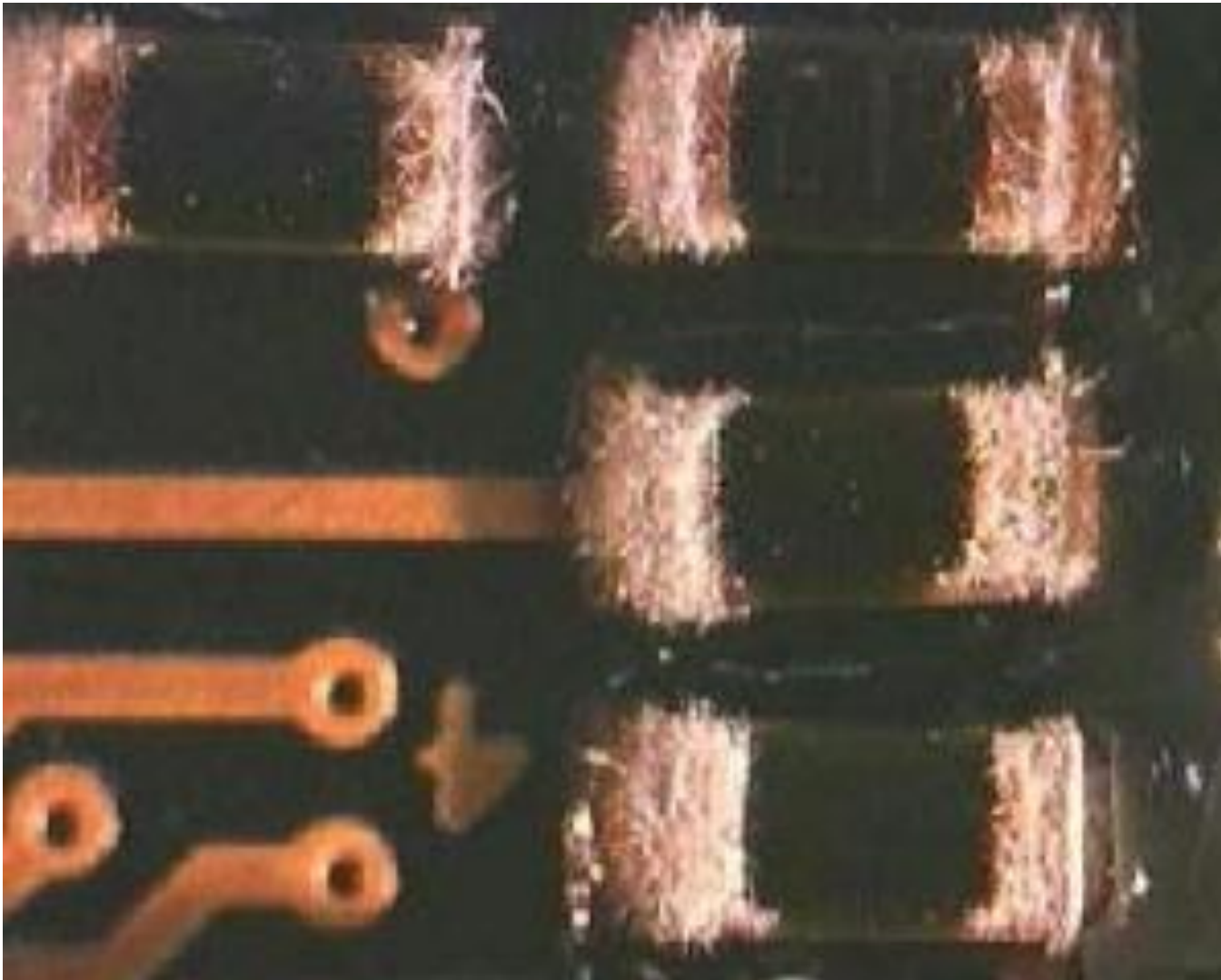
Tin Whisker Example



Courtesy: NASA Electronic Parts and Packaging (NEPP) Program



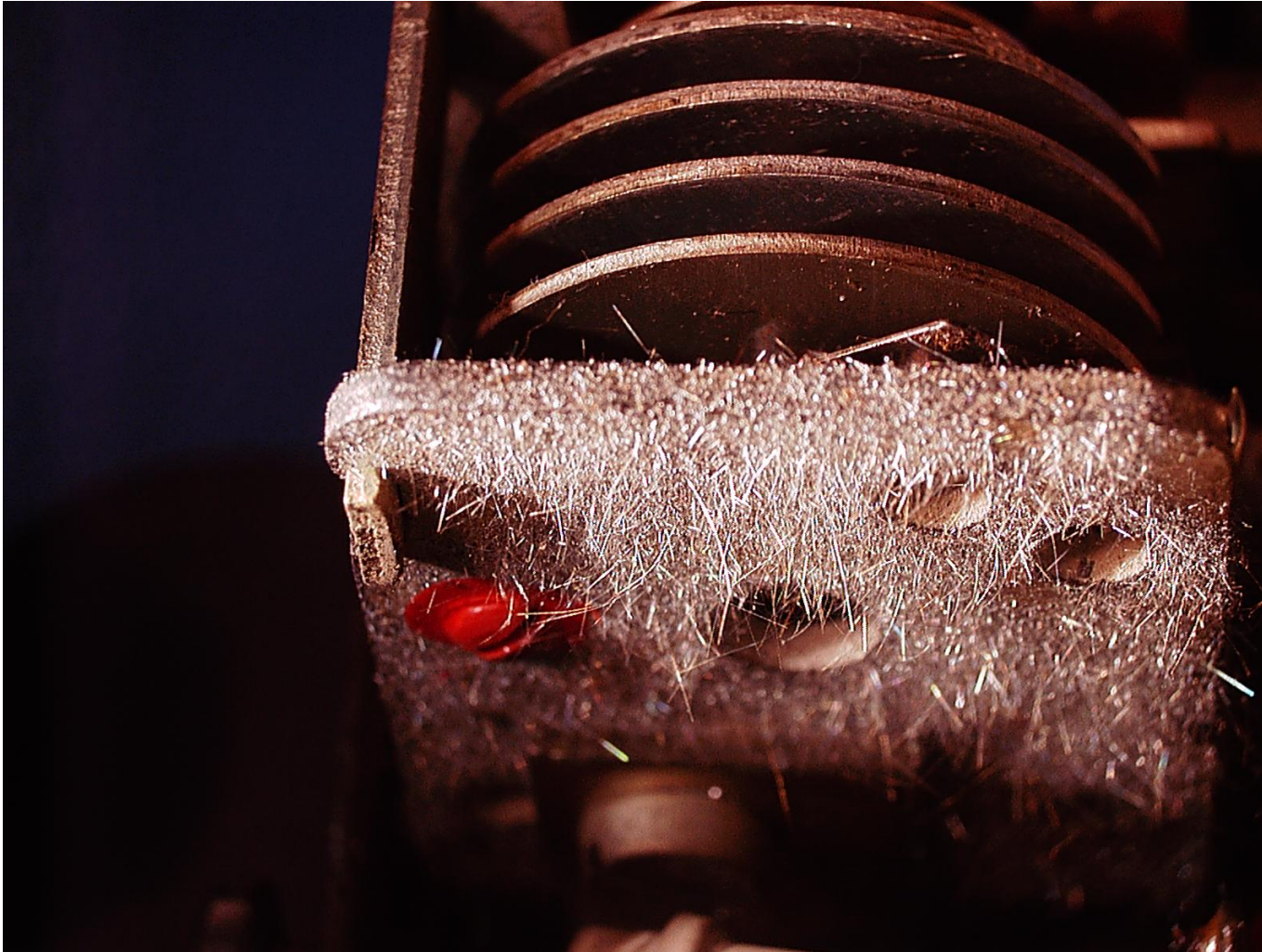
Tin Whisker Example



Courtesy: NASA Electronic Parts and Packaging (NEPP) Program



Tin Whisker Example



Courtesy: NASA Electronic Parts and Packaging (NEPP) Program



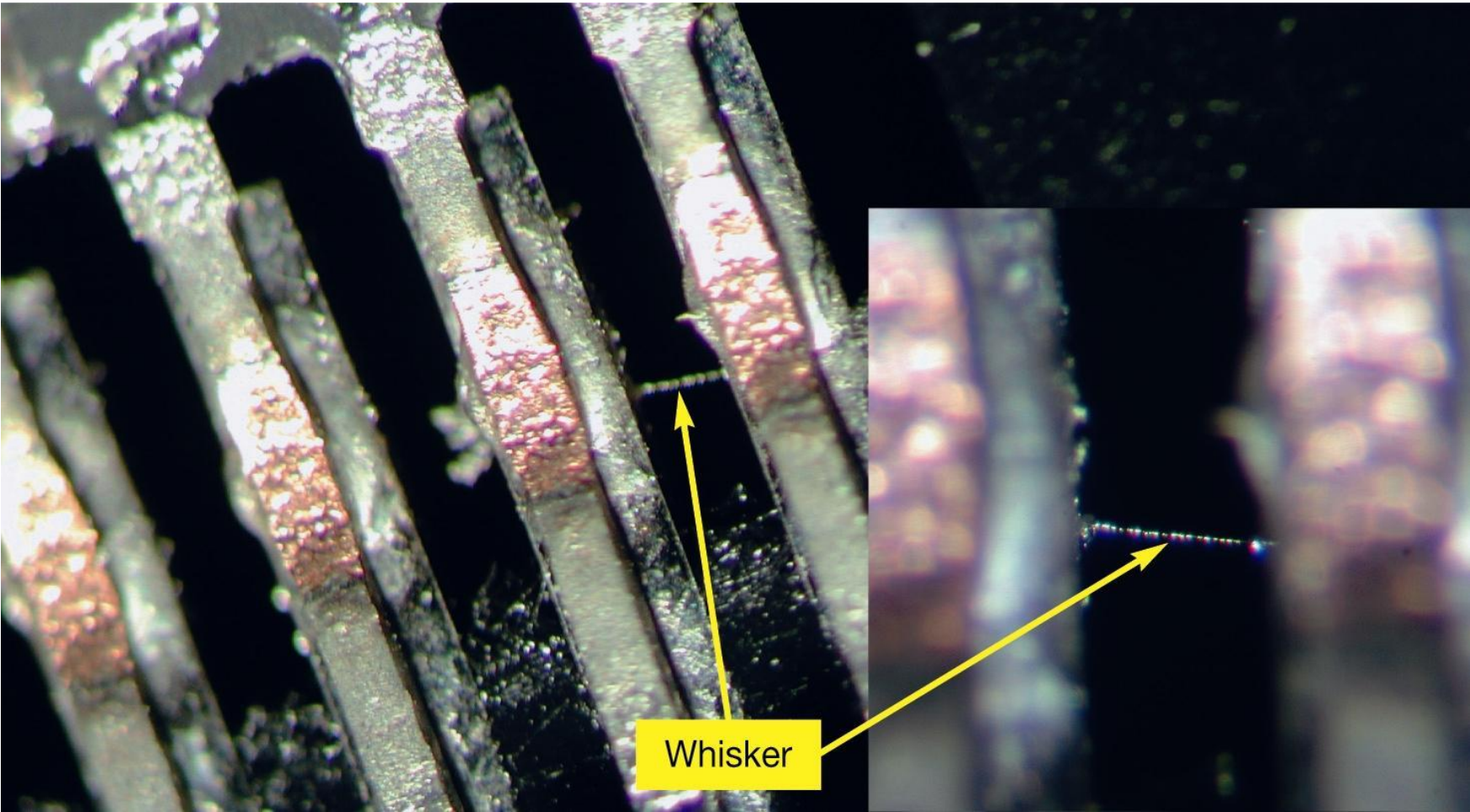
Tin Whisker Example



Courtesy: NASA Electronic Parts and Packaging (NEPP) Program



Tin Whisker Example



Courtesy: NASA Electronic Parts and Packaging (NEPP) Program

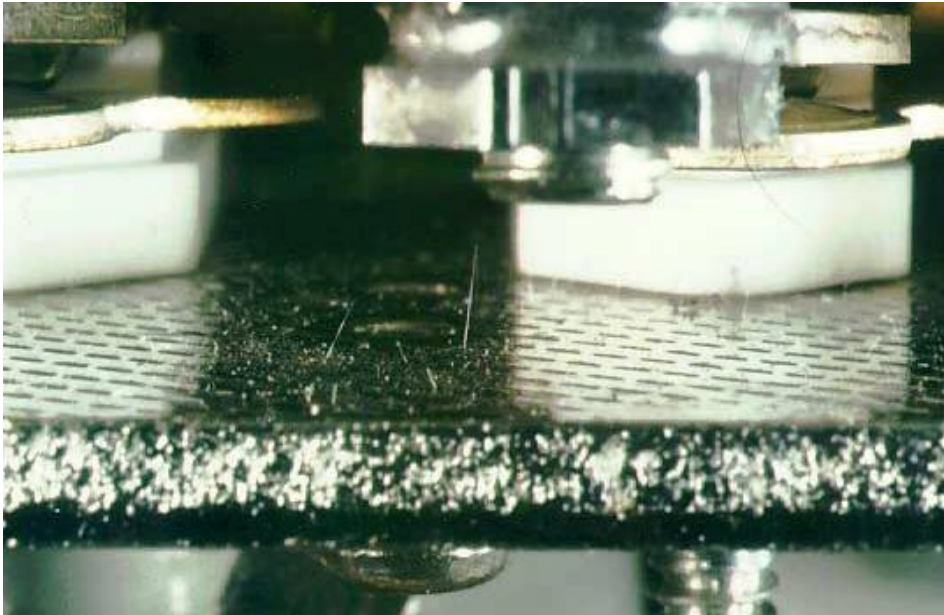


Tin Whisker Failure Mechanisms

- Stable short circuit in low voltage, high impedance circuits where current insufficient to fuse whisker open
- Transient short circuit until whisker fuses open
- Plasma arcing is the most destructive - whisker can fuse open but *the vaporized tin may initiate a plasma that can conduct over 200 amps!*
 - *Occurs in both vacuum and atmospheric conditions*
 - *Can occur with less than 5 V potential*
- Debris/Contamination: Whiskers or parts of whiskers can break loose and bridge isolated conductors or interfere with optical surfaces or microelectromechanical systems (MEMS)
- High frequency circuit performance degradation
 - *6 GHz RF and above*



Tin Whisker Failure – Plasma Arcing



**Tin whiskers on armature of relay.
Many whiskers longer than 0.1 inch (2.5 mm)**

Courtesy: Gordon Davy, Northrop Grumman Electronic Systems



**Relay failure due to whisker induced plasma arcing at
atmospheric conditions**

Courtesy: Gordon Davy, Northrop Grumman Electronic Systems



Tin Whiskers in Space Shuttle

- Conformal coatings on the boards prevented disaster

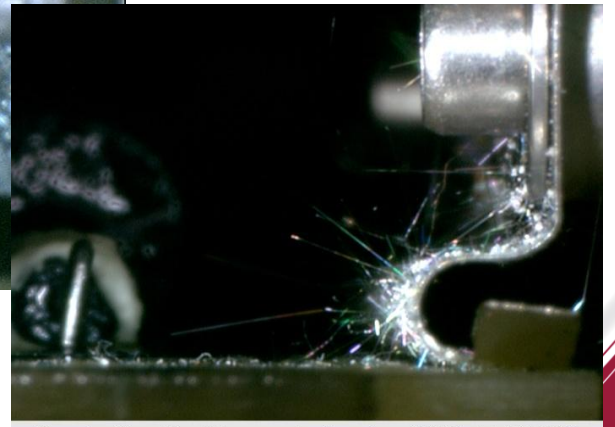
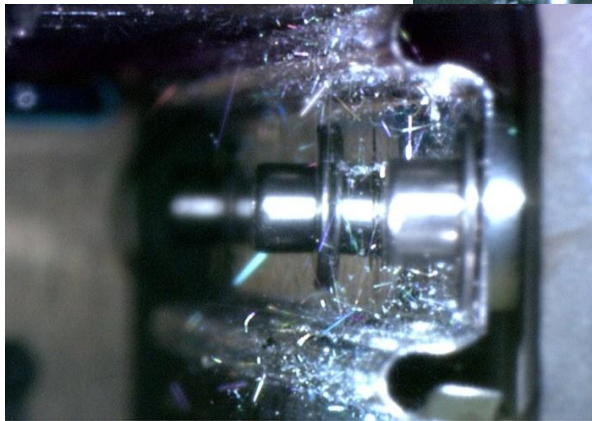
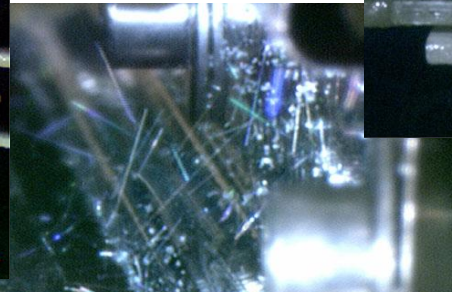
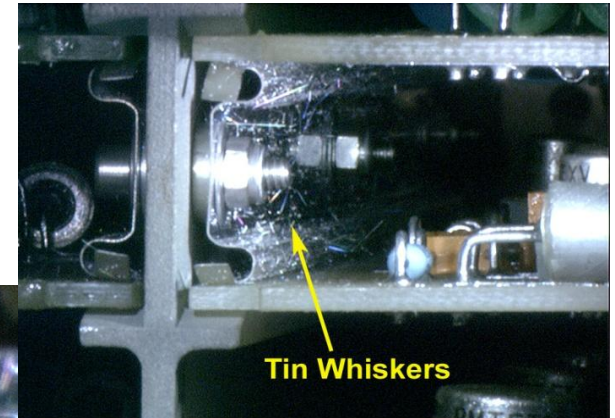
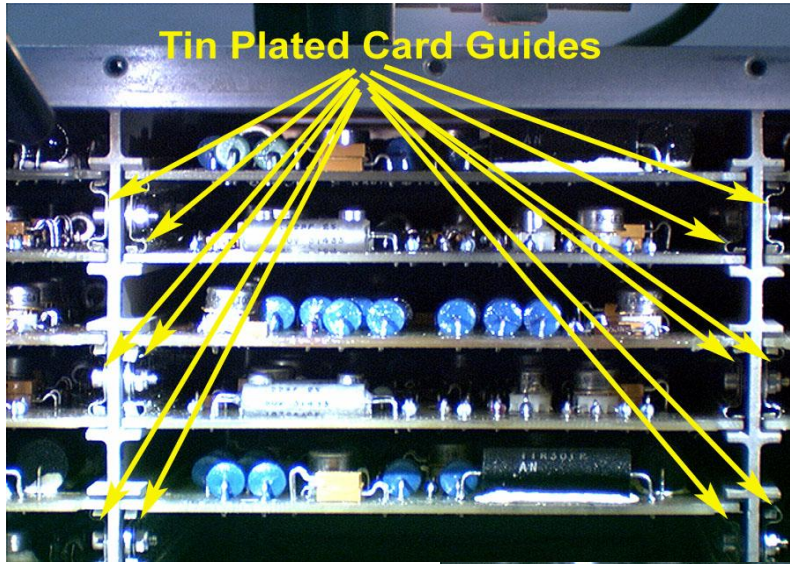


Figure 1. View of tin whiskers on card guide surface of ATV Control (S/N 0034). Many of these whiskers exceed 5 mm in length.

Courtesy: Peter Bush, SUNY



Tin Whiskers in Space Shuttle

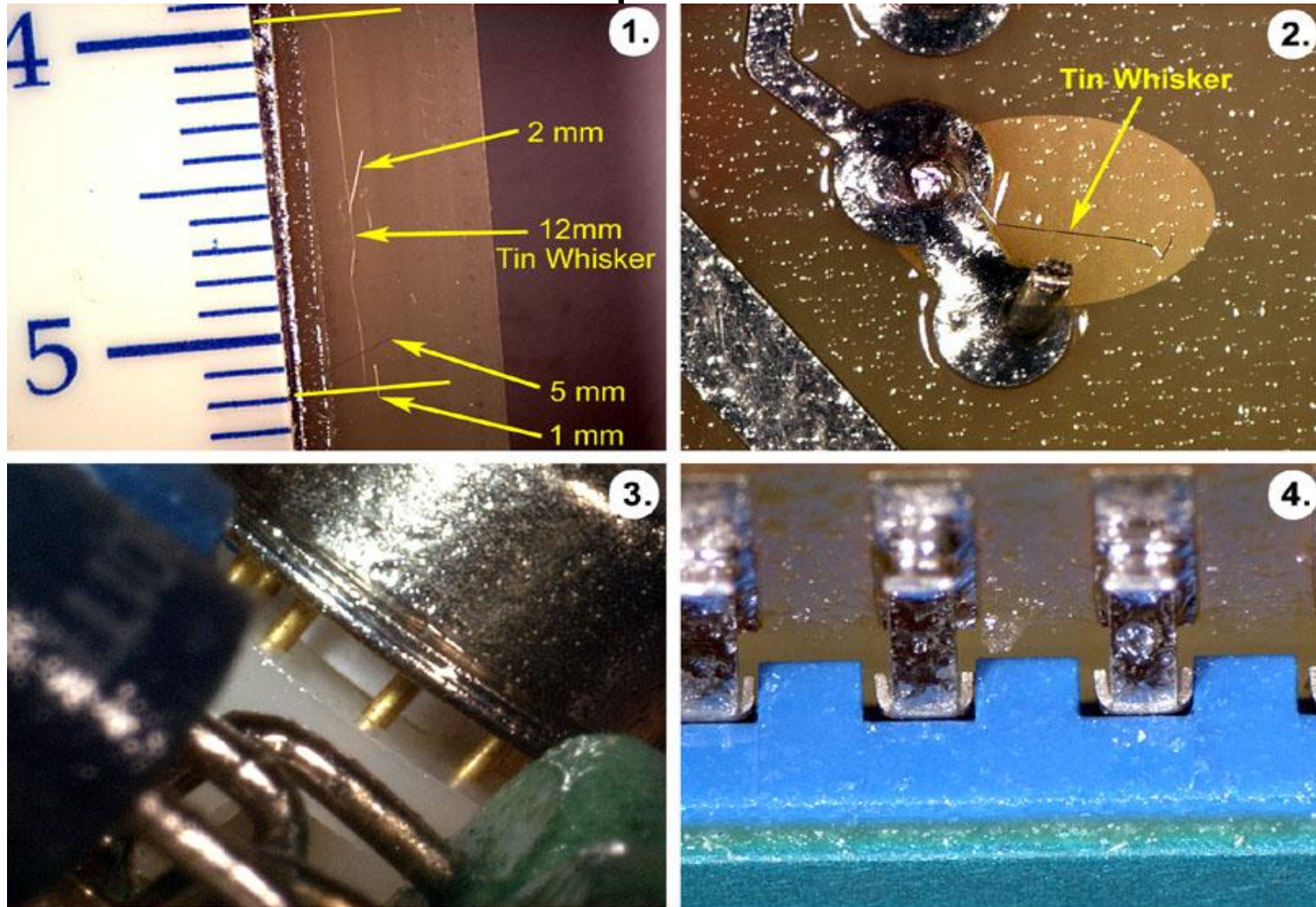


Figure 2. A18 circuit card from ATVC #34. Frame 1 shows several tin whiskers on the foil side, the longest of which is 12 mm. Frame 2 shows a whisker that has "stuck" to a component lead. Frame 3 shows an area of vulnerability for shorting by a whisker - some of these "op-amp" leads have no conformal coating on them. Frame 4 shows another area of vulnerability where the pin leads exit/enter the connector they are not conformally coated.

Courtesy: Peter Bush, SUNY



Tin Whisker Safety Issue

Toyota Sudden Unintended Acceleration

- “A 2005 Toyota Camry was located with a fault that had the potential to injure, maim, or kill”
- Detailed description obtained from the driver
- Pedal position assembly installed it into a Toyota-simulator and duplicated the fault
- The dual-potentiometer (the sensor used in the pedal position assembly) was disassembled
- 240 ohm leakage path between the two "taps" on the dual-pot was caused by a **tin whisker**

Reference: NESC Assessment #TI-10-00618



Tin Whisker Safety Issue

Toyota Sudden Unintended Acceleration

- 17 tin whiskers were found growing inside the dual potentiometer with lengths were greater than 0.05 mm
- Two whiskers were long enough to bridge and cause "shorts"
 - *One actually did*
- The density of whisker-infestation was approximately 0.2 whiskers per square millimeter
- Whisker densities up to 200 whiskers per square millimeter have been observed in other studies
 - *There could be much worse cases of whiskering amongst the hundreds of thousands of Toyota's using this style of sensor.*



Tin Whisker Safety Issue

Toyota Sudden Unintended Acceleration

- Investigators looking for plausible ways to get a dual-short
 - *This could precisely explain the "Gilbert" mechanism of violent uncontrolled acceleration.*
- 5 dual-pots were examined
 - *Whiskering found in 3 of the 5 units*



Heart Pacemaker Safety Recall for Tin Whiskers

- FDA March 1986
 - http://www.fda.gov/ora/inspect_ref/itg/itg42.html
- “Tin Whiskers Problems, Causes, and Solutions”
 - <http://www.fda.gov/ICECI/Inspections/InspectionGuides/InspectionTechnicalGuides/ucm072921.htm>
- “Recently, a little-known phenomenon called tin whiskering caused the recall of several models of a pacemaker. This incident revealed tin whiskers to be a general threat to all users and manufacturers of medical devices that incorporate electronic circuitry. “



Pb-free Tin Whisker Mitigation Techniques

- Matte tin (tin with a dull low gloss finish) may be more resistant to whiskering than bright tin
 - *Whiskers still grow as with bright tin*
 - *Matte tin has no common definition other than “not bright”*
- Annealing tin can reduce some of the stresses in plating that may contribute to whisker growth
 - *Whiskers still grow*
- Underplate with Nickel to reduce intermetallics which have been theorized to be important to whisker growth
 - *Whiskers still grow*
 - *Intermetallics do not appear to be critical for whisker growth*



Pb-free Tin Whisker Mitigation Techniques

- Reflow Pb-free tin finishes after plating
 - *Additional thermal exposure during assembly*
 - *Effectiveness unproven in general practice*
- Use of Ni/Pd/Au finish avoids the tin whisker issue
 - *Cost increases*
 - *Not available for all products*
- Soldering/solder dipping with Sn/Pb solder
 - *Unconverted areas can still grow whiskers*
 - *Whiskers can grow through thin Sn/Pb coating*
- Replating with Sn/Pb solder
 - *Not possible for all components*



Pb-free Tin Whisker Mitigation Techniques

- Reballing BGA/CGA
 - *Voids warranty*
 - *Additional handling causes damage*
 - *Fine pitch products are particularly difficult*
- Interposer layer for BGA/CGA
 - *Units attached to interposer using Pb-free process*
 - *Subassembly attached using standard Sn/Pb process*
 - *Need design for each package and pin-out pattern*



Pb-free Tin Whisker Mitigation Techniques

- Conformal coatings
 - *Can be an effective mitigant but whiskers will grow through thin coatings*
 - *Negatively effects performance of some circuits*
- Coatings are the focus of many research studies including
 - *Parylene*
 - *Whisker-Tough*
 - Conformal polymer
 - *Atomic Layer Deposition*
 - Ceramic coating
 - *Selective Metal Cap*

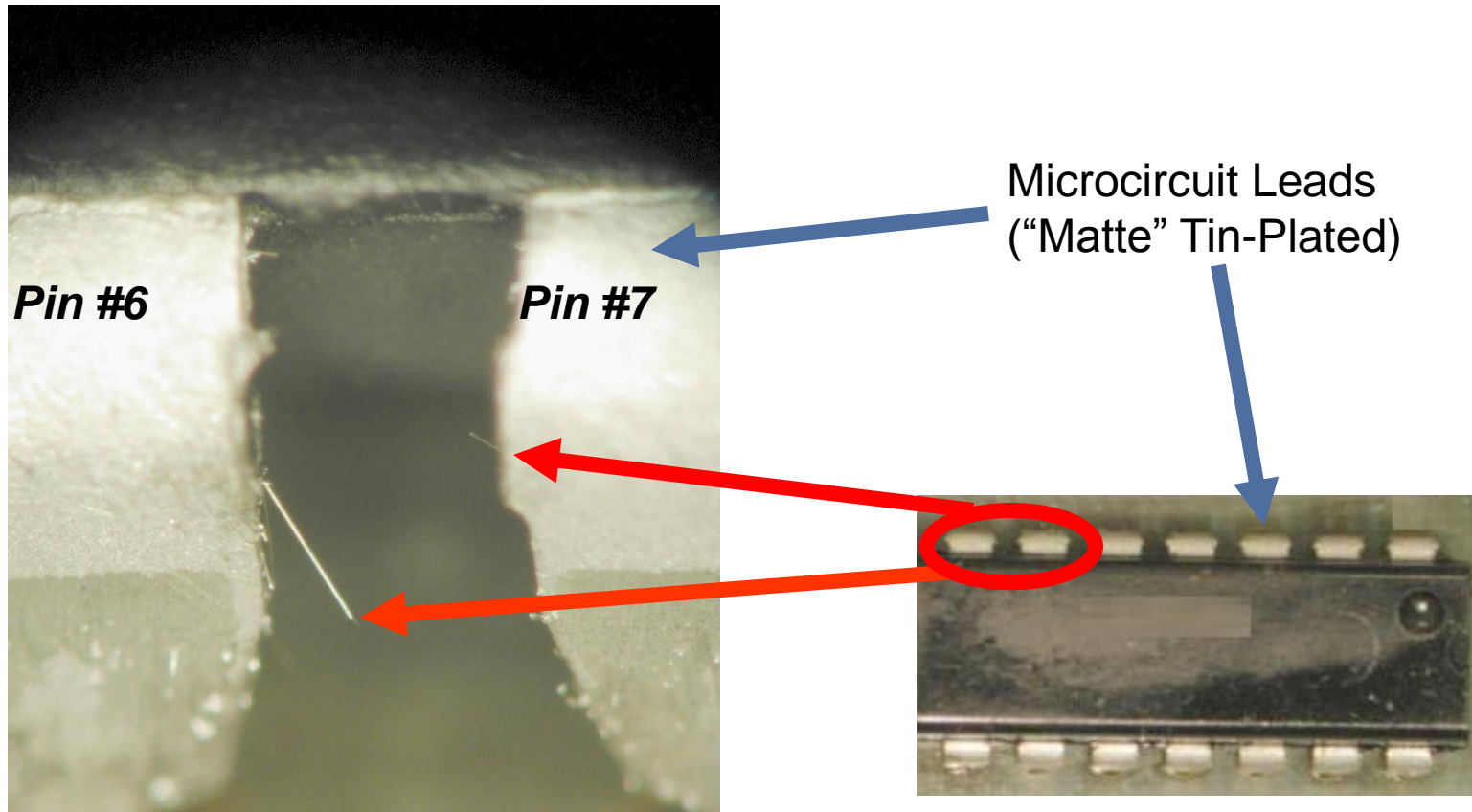


Whisker Risk Mitigation - Summary

- There are things that can be done to mitigate whisker risks that are inherent in Pb-free tin
 - *No single technique is 100% effective*
- Multiple mitigations are necessary until additional research has been completed
- Units that have been properly assembled with Sn/Pb solder and conformally coated provide reasonable protection with minimal cost and system impact



Tin Whisker Short on Matte Tin



Whiskers from this component caused a FAILURE in a nuclear power plant over 20 YEARS!!! after fielding the system

Courtesy: NASA Electronic Parts and Packaging (NEPP) Program



Tin Whisker Failure on Oscillator

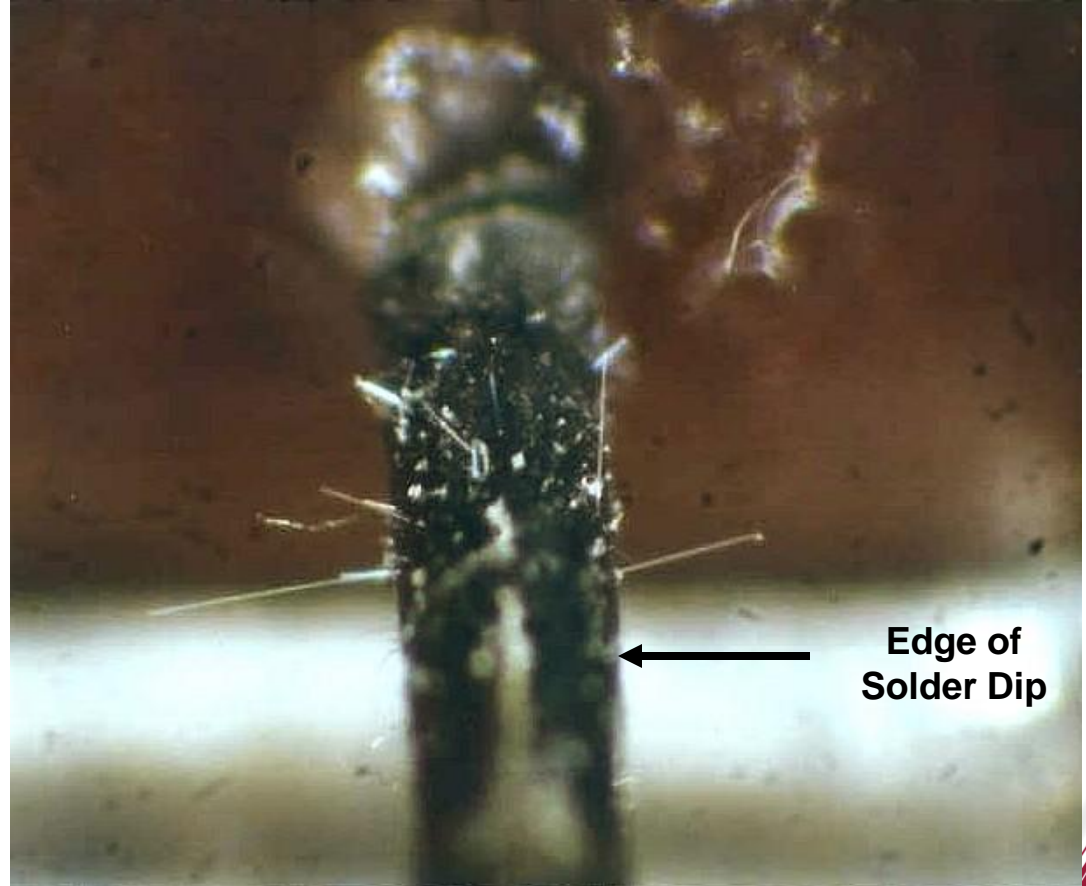


Thru hole oscillator.

Lead diameter 18 mils.

Bright tin finish leads and case.

Tin/lead solder dipped within 50 mils of glass seal and hand soldered to PWB.



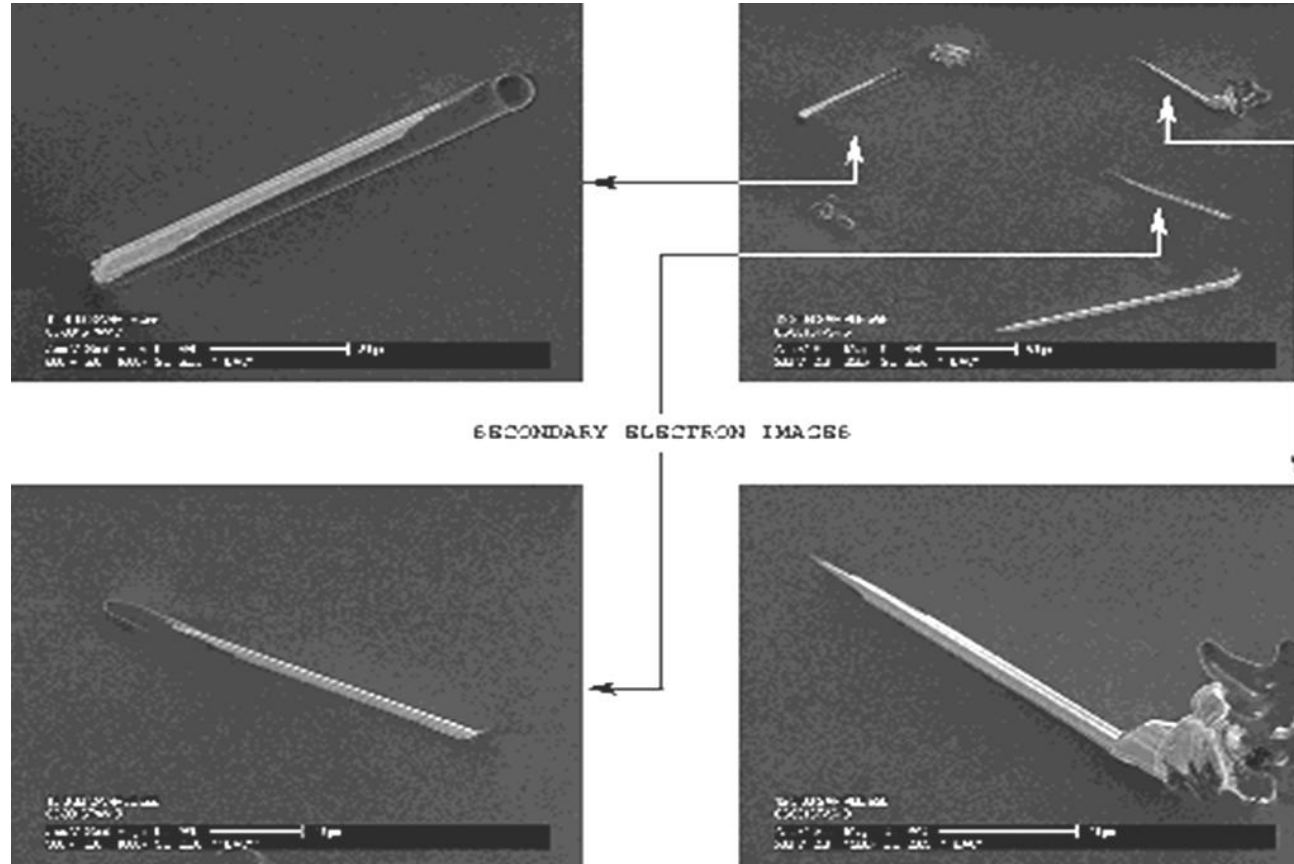
Tin whisker growth noted from seal to about 20 mils from edge of solder coat. Electrical failure was traced to a 60 mil whisker that shorted lead to case.

Courtesy: NASA Electronic Parts and Packaging (NEPP) Program

Photos by Ron Foor



Tin Whiskers Penetrate Some Conformal Coatings



- Whiskers penetrating acrylic conformal coating
– *Similar results with Parylene C and Silicone*

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How Widespread is the Tin Whisker Problem?

- At the June Pb-free Electronics Risk Management (PERM) meeting it was reported that 11% of all Pb-free assemblies examined had whiskers
 - *Neither length nor density was reported*
- For comparison
 - *11% of the world's population lives in Europe*
 - *11% of American homes are vacant*
 - *11% of Americans have a “great deal” or a “lot of confidence” in Congress*
 - *11% of bicycle accidents involve collisions with cars*
 - *11% of France's population was wounded during World War I*
 - *11% of Britons are bloggers*
 - *11% increase in CEO pay in 2010*



Summary

- Worldwide environmental legislation driving Pb-free electronics
 - *Continuing pressure from “environmentalists”*
 - *Tremendous costs associated with conversion to Pb-free products*
 - *There has never been any health risk from Pb in electronics*
 - *The overall environmental impact of changing to Pb-free is negative*
- Sn/Pb electronics are increasingly less available
 - *Higher costs*
 - *Longer lead-times*
- There are serious risks with the Pb-free products
 - *Manufacturing quality*
 - *Reliability*
 - *Tin Whiskers*
 - *Tin Plague*
 - *Inferior solder characteristics*



Summary - continued

- Numerous Pb-free solders and finishes have been/are being/ will be used
 - *Pb-free electronics manufacturing is fundamentally different*
 - Should be totally revised to optimize for Pb-free manufacturing
- There is limited field data for Pb-free products in high reliability, severe service, long life applications
- Commercial electronics are trying to develop Pb-free materials and processes that will provide highly reliable long-lived products
- No mitigation technique other than the addition of at least 3% Pb by weight to Sn has proven itself to be totally adequate in the field
 - *Multiple research efforts to develop effective mitigation for tin whiskers*
 - *The impact of tin plague is still unknown*



Summary - continued

- Estimation of failure rate change due to the use of Pb-free materials is impossible because the physics of the failure mechanisms are not known
- Test standards are incomplete and cannot accurately predict Pb-free materials field performance at this time
- High reliability, severe service, long life applications should not transition to new Pb-free materials

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