The Cassandra Project

Dealing with Uncertainty in an Evolving Stockpile

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UQWG Seminar

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LANL, NM

Introduction

- Sandia National Labs, Risk and Reliability Department (6413)
- Areas of uncertainty investigation
  - Application of uncertainty methods to stockpile aging
    - Fatigue
    - Corrosion
    - Stress-voiding
    - Tribology
  - Evaluation of existing methods
    - Analytical (MV, Hosofer-Lind, Rackwitz, Hoenbichler, etc.)
      - Survey paper available
    - Simulation
      - LHS, quasi-Monte Carlo
  - Development of new methods
    - Iterative qMC, field analysis
  - Non-stockpile issues (national power grid)
  - Development of uncertainty software
  - Bayesian methods
    - System analysis
    - Optimal test planning (optimization under uncertainty)

Outline

- Historical Background
- Cassandra Structure
- Processing Architectures
- Computational Platforms
- Imbedded Uncertainty Analysis Algorithms
- Current Applications

Historical Background

- Initial name in 1978: Icarus
- Developed originally as Monte Carlo analysis to support aging analysis for US Air Force
  - AGM 65A,B,C,D,E+
    - O-ring on hydraulic actuation system
    - Electronic packaging on guidance system
  - Low level laser guided bomb (LLLGB)
    - Operational fatigue of release mechanism
  - Minuteman ICBM
    - Evaluate replacement parts in support of MMII-III Hi-Rel program
- Extended to include MVFOSM (1981)
- Extended to include FORM (1986)

Historical Background

- Integral part of the design curriculum at AFIT
- Extended to include advanced analytical methods
  - Emphasis moved from storage reliability to design
    - » stochastically optimize
      - aircraft wing structures - weight vs reliability (manual perturbation)
      - WASP - flight stability, payload, fuel, pilot response, etc. in presence of uncertainty in operational conditions (Multi-objective RSM-based opt)
    - » risk analysis of RTG on Ulysses spacecraft (AMV)
    - » optimal composite lay-up - ABDR program (GA-based opt)
    - » structural integrity programs - ASIP, AVIP, ENSIP
- Sandia National Labs - 1996+
  - Thermo-mechanical fatigue of lead-free solders
  - Stress-voiding of IC interconnections

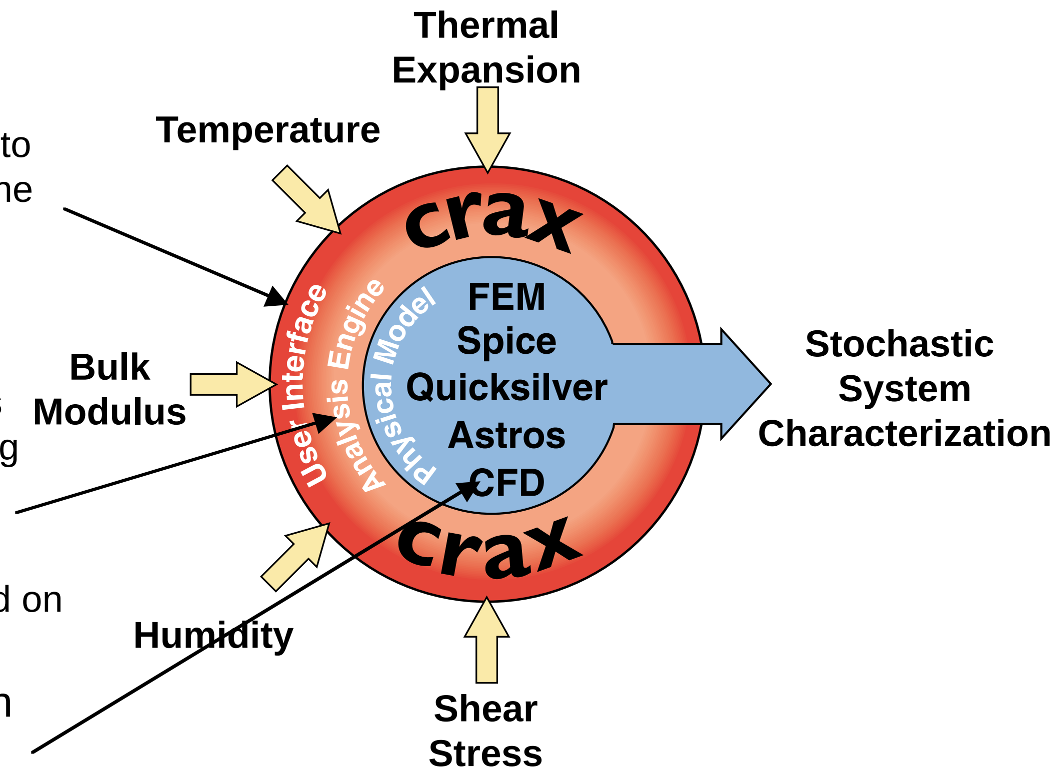
Historical Background

- Cassandra Project started in October 1997
- Objectives of Cassandra Project
  - Assist engineers and managers with
    - analysis of stockpile aging related issues
    - reliability impact of new materials or manufacturing processes
    - characterizing and controlling uncertainty in stockpile decision making
  - Make structural reliability and uncertainty methods accessible to design engineers

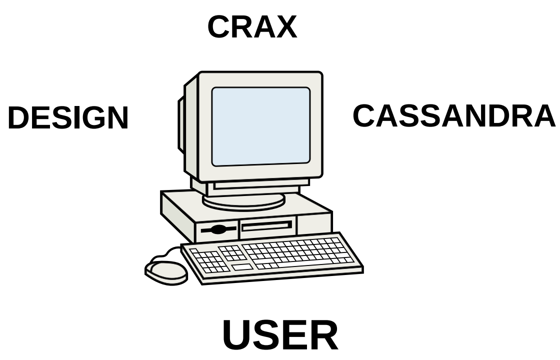
- Historical Footnote: Cassandra was the daughter of Priam, ruler of Troy, and Hecuba. As a child she received the gift of prophecy from the Greek god Apollo. However, the beautiful young woman later refused the advances of Apollo. In his rage, he added to the gift of prophecy the curse that she would never be believed. The people of Troy generally believed her to be insane and felt that she was bringing bad luck to the war effort. Her announcement that there were Greek warriors in the wooden horse fell on deaf ears and Troy was soon sacked and occupied by the Greeks.

Cassandra Structure

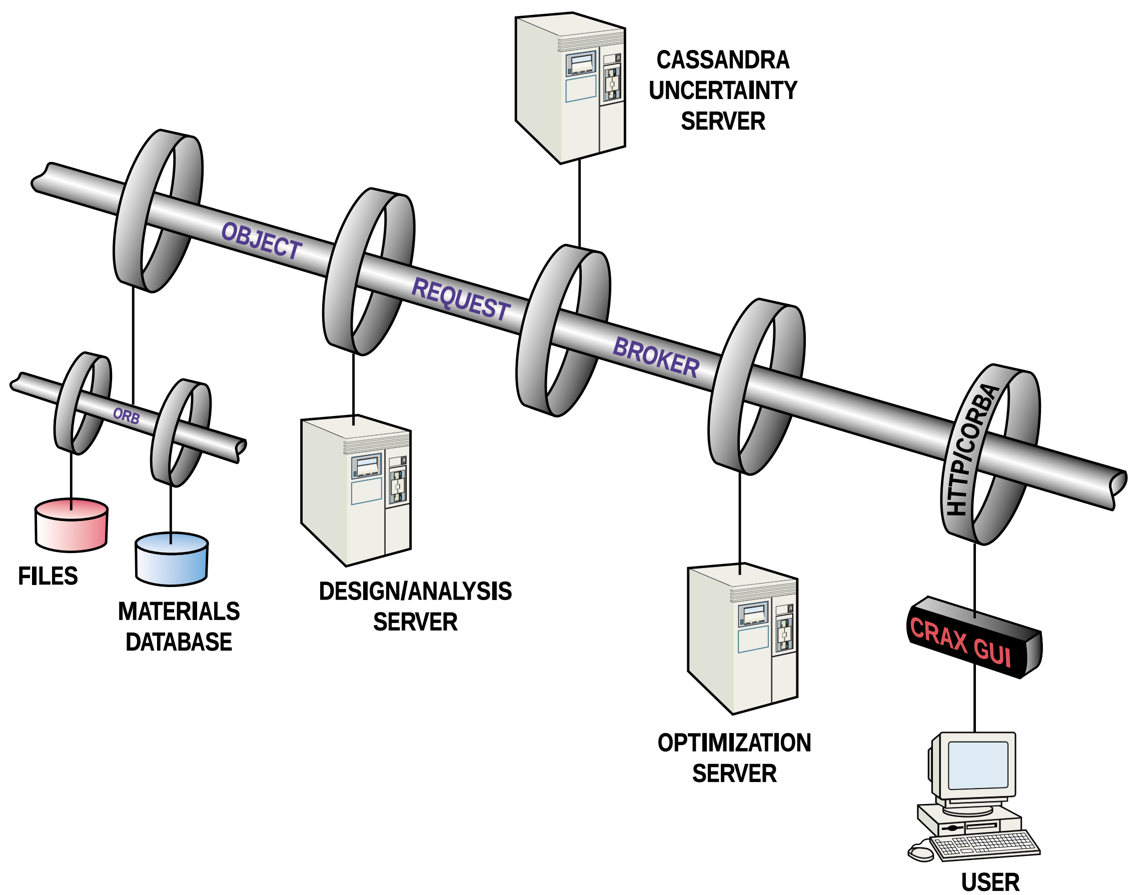
- Three major elements
  - CRAX
    - » Tcl/Tk-based user interface to Cassandra uncertainty engine
    - » Flexible to specific analysis problems
  - Cassandra
    - » Suite of uncertainty analysis routines - analytical/sampling
    - » Infinitely extensible to new methods
    - » Statistical methods validated on all computing platforms
  - Performance characterization
    - » Supplied by user



Processing Architecture



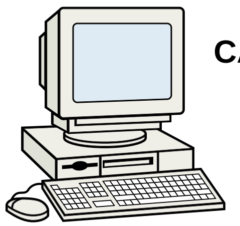
Single Platform



Distributed Processing

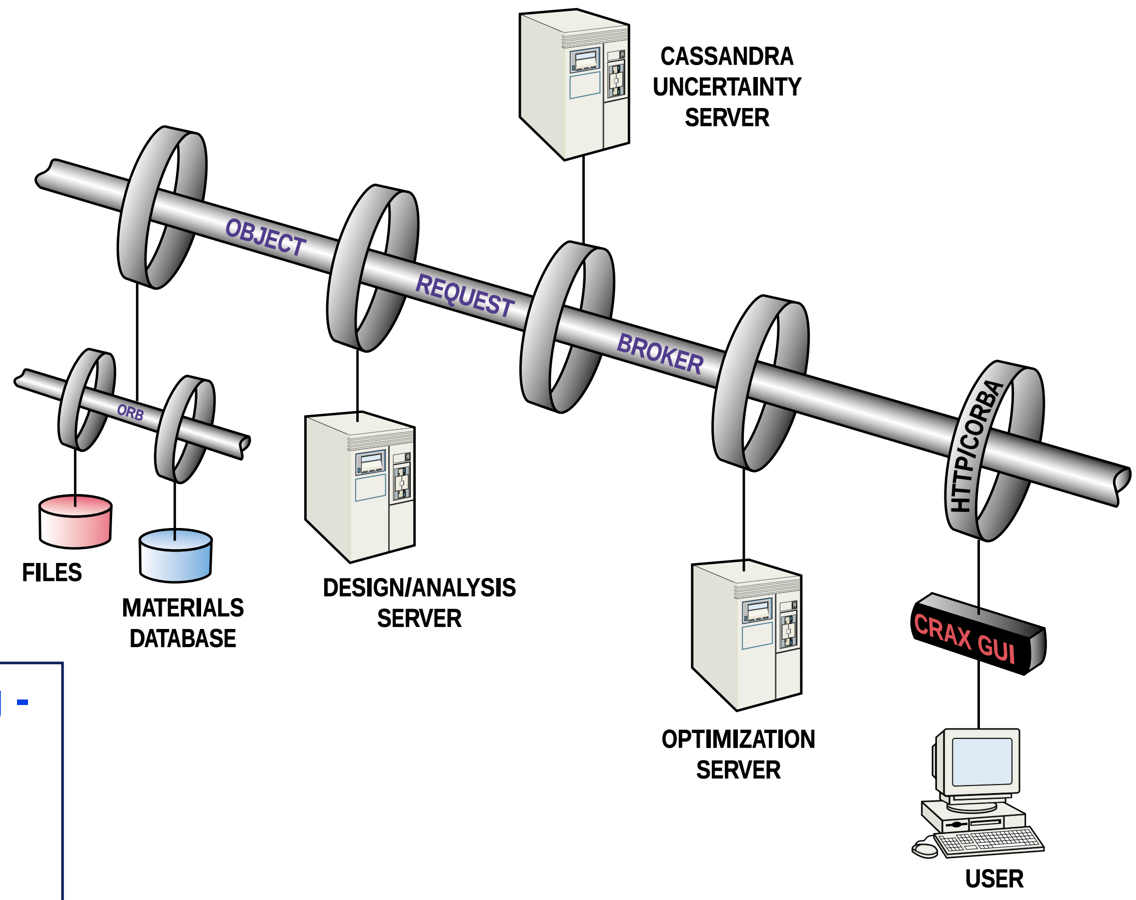
Analysis can be accomplished on single platform or as part of a distributed computational environment and the network configuration describing where computations are conducted can be changed 'on the fly'

Computational Platforms



Single Platform
- •WinNT, Win95
- •Unix (Sun, SG, etc.)
- •Power Mac
- •Linux

Distributed Processing - Any combination of
- •WinNT, Win95
- •Unix (Sun, SG, etc.)
- •Power Mac
- •Linux



Imbedded Uncertainty Analysis Algorithms

- Sampling
  - Pseudo-Monte Carlo
    - » Latin Hypercube
    - » Adaptive Importance Sampling (*)
  - Quasi-Monte Carlo
    - » Hammersley
    - » Halton
      - Normal
      - Skipped (*)
      - Iterative
    - » Sobol
- Analytical
  - Hoenbichler-Rackwitz/Calibration (Linear/Quad)
  - Mean Value (L/Q)
  - AMV (multiple/single pt)
    - » P-value (L/Q)
    - » Z-value (L/Q)
  - AMV+ (multiple/single pt)
    - » P-value (L/Q)
    - » Z-value (L/Q)
  - Tvedt (*)
  - Max-likelihood (*)

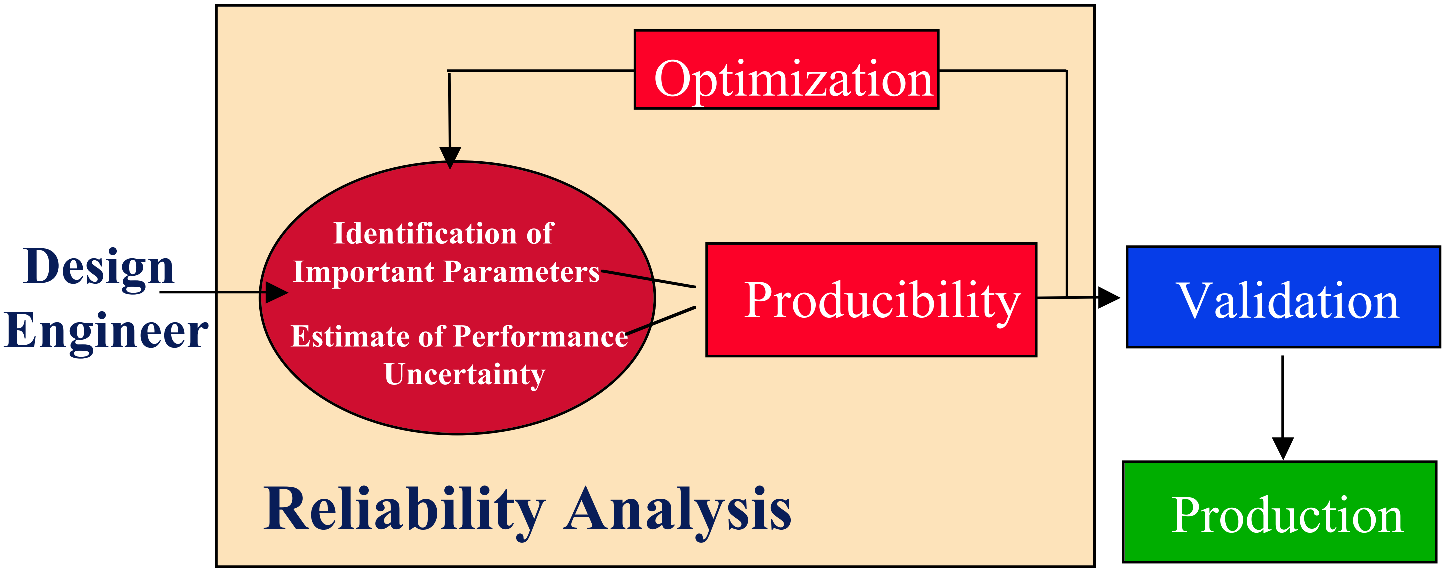
- Field Analysis (α)
  - –Combination of quasi-MC and analytical methods

** Not included in distribution*

Current Applications

- Each problem that has been analyzed has been different however,
- Flexibility is the key asset of both CRAX and Cassandra:
  - Simple to interface with existing codes (commercial and legacy)
  - Easy to extend with new uncertainty/statistical algorithms
  - User interface (CRAX) can be modified very quickly and easily
  - Scalable to whatever computational power is required
- ‘Core’ uncertainty analysis routines remain constant
- Examples
  - Thermo-mechanical fatigue of solder joints
  - Stress voiding of IC interconnects
  - Atmospheric corrosion of electrical components
  - Design of band-pass filter w/ manufacturing variation
  - Optimal lay-up of carbon-carbon composite
  - Aging degradation of polymer seals

Science-based Stockpile Stewardship



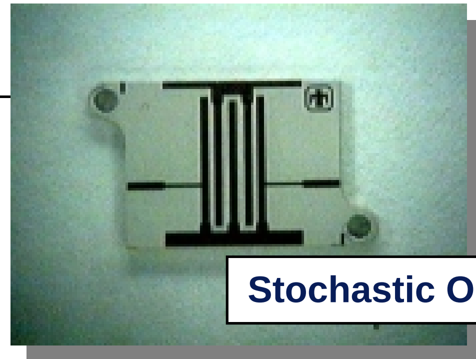
Model Based System Design

Goal: to combine physics based modeling of system performance with manufacturing realities in an effort to design an system which is robust to variations in both operating environment and variations in the manufacturing process.

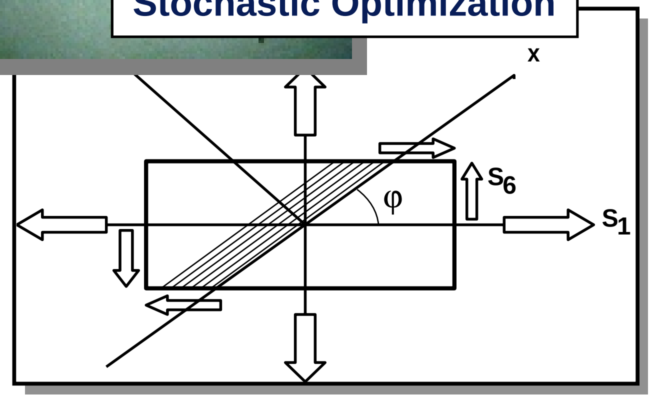
Results:

- **Higher yield from smaller lot production runs**
- **System less sensitive to the effects of age degradation**

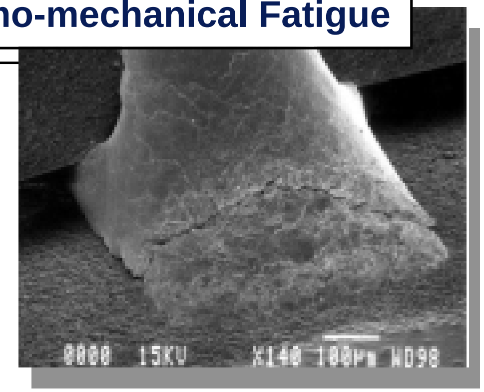
Applications

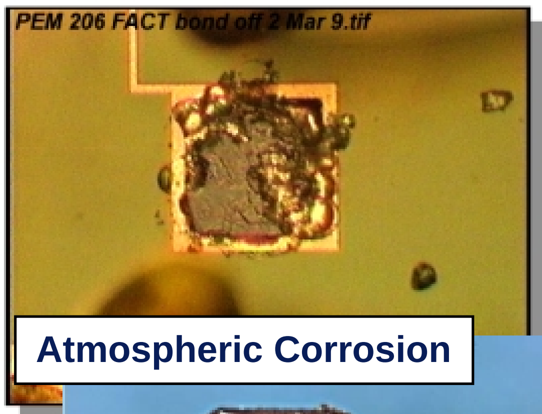


Stochastic Optimization



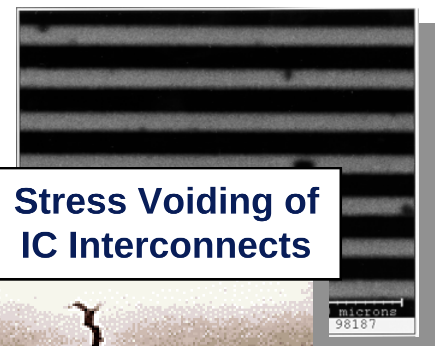
Thermo-mechanical Fatigue

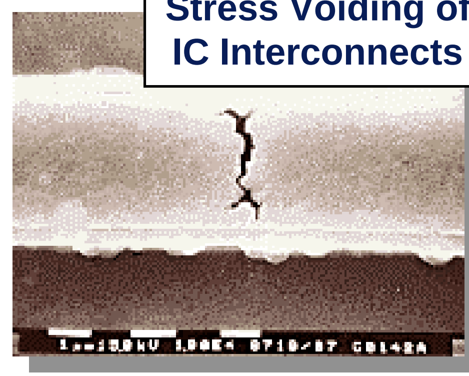




Atmospheric Corrosion

Accelerated Aging Of Polymers





Stress Voiding of IC Interconnects

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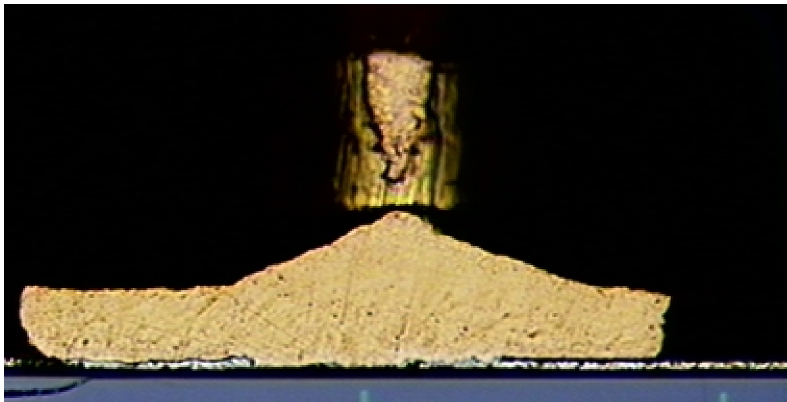
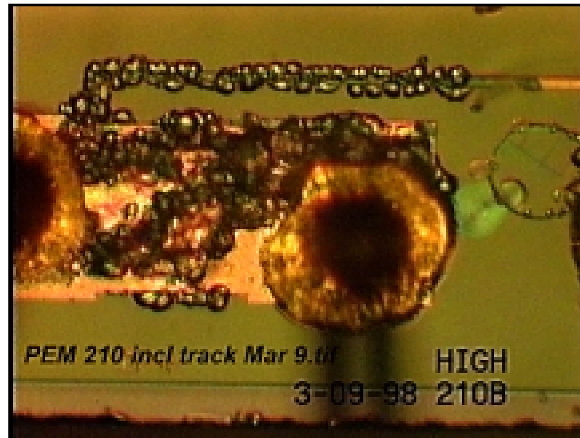
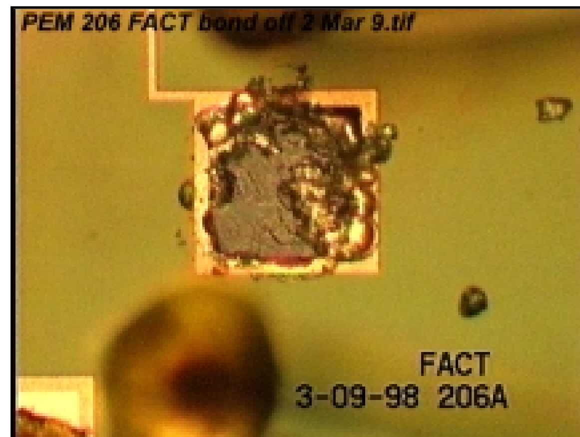
Al Bondpad Corrosion in PEM

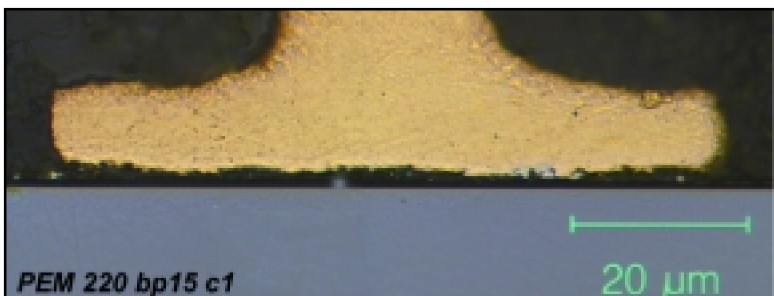




NaCl contaminated
Au/Al wirebond
(6 weeks)

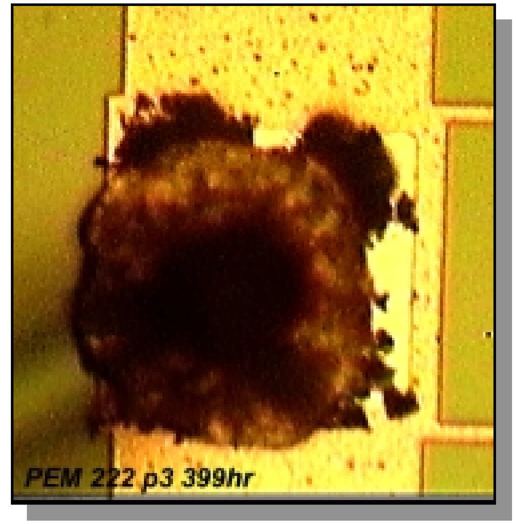
Likely corrosion failure through galvanically assisted attack that initiates in a water-filled crevice

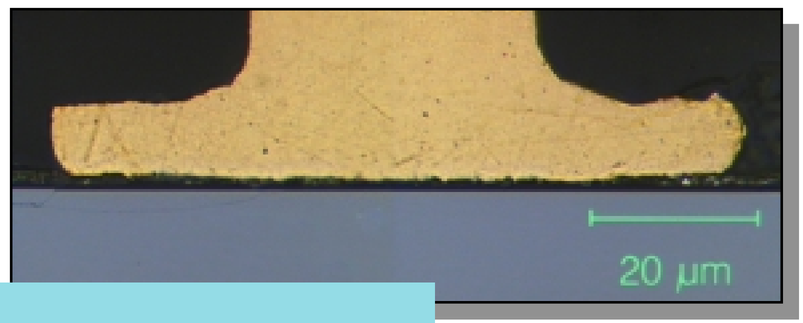




Deterministic Corrosion Model

- **Advantages to early development**
  - — increases experimental efficiency
  - — provides time for addressing unique numerical needs
  - — maintains focal point for ultimate objective
- **Governing equation for intrinsic kinetics**
  - — surface rate constant
  - — environmental parameters
    - » temperature
    - » relative humidity
    - » contamination

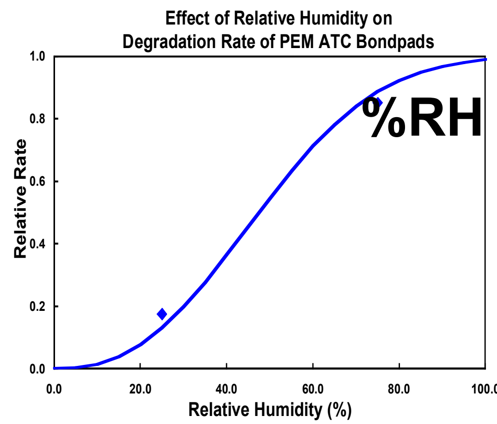


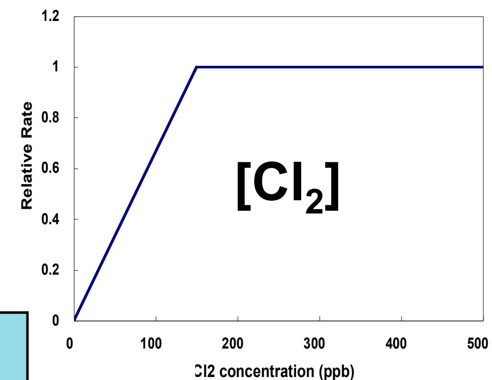


$$CR_{bondpad} = f([Cl_2]) \bullet g(T) \bullet h(RH)$$

Bondpad Performance Equation
Resistance

derived using multi-variable analysis of lumped rate constants





$$R_{BP} = \frac{d(\Delta R/R_o)}{dt} = k_o P_{Cl_2}^{x} \left\{ 1 - \exp\left[-\left(\frac{H}{\eta} \right)^{\beta} \right] \right\} \exp\left[-\frac{E_a}{RT} \right]$$

where $x = 1$, $\beta = 2.5$, $\eta = 55$, $E_a = 17.5$ kcal/mole (0.8 eV)

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Model Parameters and Uncertainty

- Deterministic parameters
  - humidity (β, η)
  - activation energy (E_a)
- Stochastic parameters
  - defects (location and size),
  - ko (includes initiation, spatial, …..)
  - environmental - temperature, relative humidity
  - contaminant concentration ($P[Cl_2]$)

The governing equation for corrosion was be modified to include uncertainty

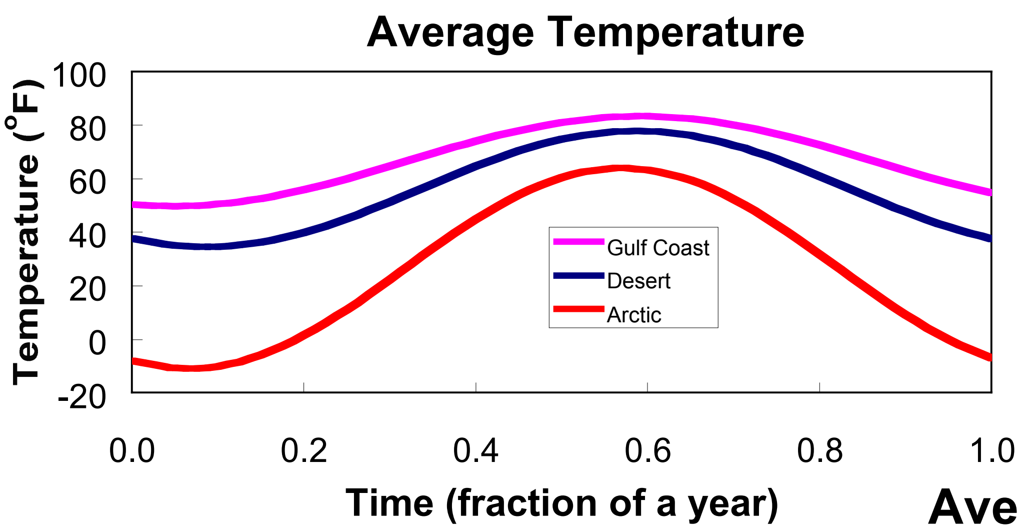
$$R_{BP} = I(\text{defects})k_o(t)P_{Cl_2}\left\{1-\exp\left[-\left(\frac{H(t)}{\eta}\right)^{\beta}\right]\right\}\exp\left[-\frac{E_a}{RT(t)}\right]$$

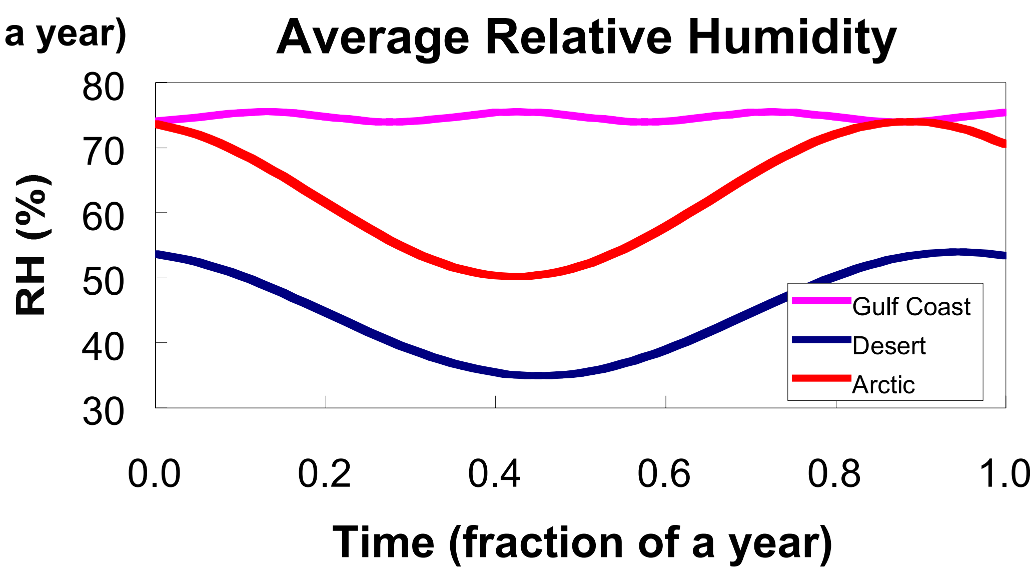
- Random variables -
  - I(defects) : 0 or 1 (3% probability of 1)
  - k_o : lognormal pdf. based on n=70
  - T(.) and H(.) : periodic deterministic variations with Gaussian distributed error - zero mean, unique standard deviation

$$T(t) = T_{\mu} + T_a \sin(\omega_T t + T_0) + \varepsilon_T$$

$$H(t) = H_{\mu} + H_a \sin(\omega_T t + H_0) + \varepsilon_H$$

Sensitivity Analysis
environmental locations: gulf coast, desert, arctic





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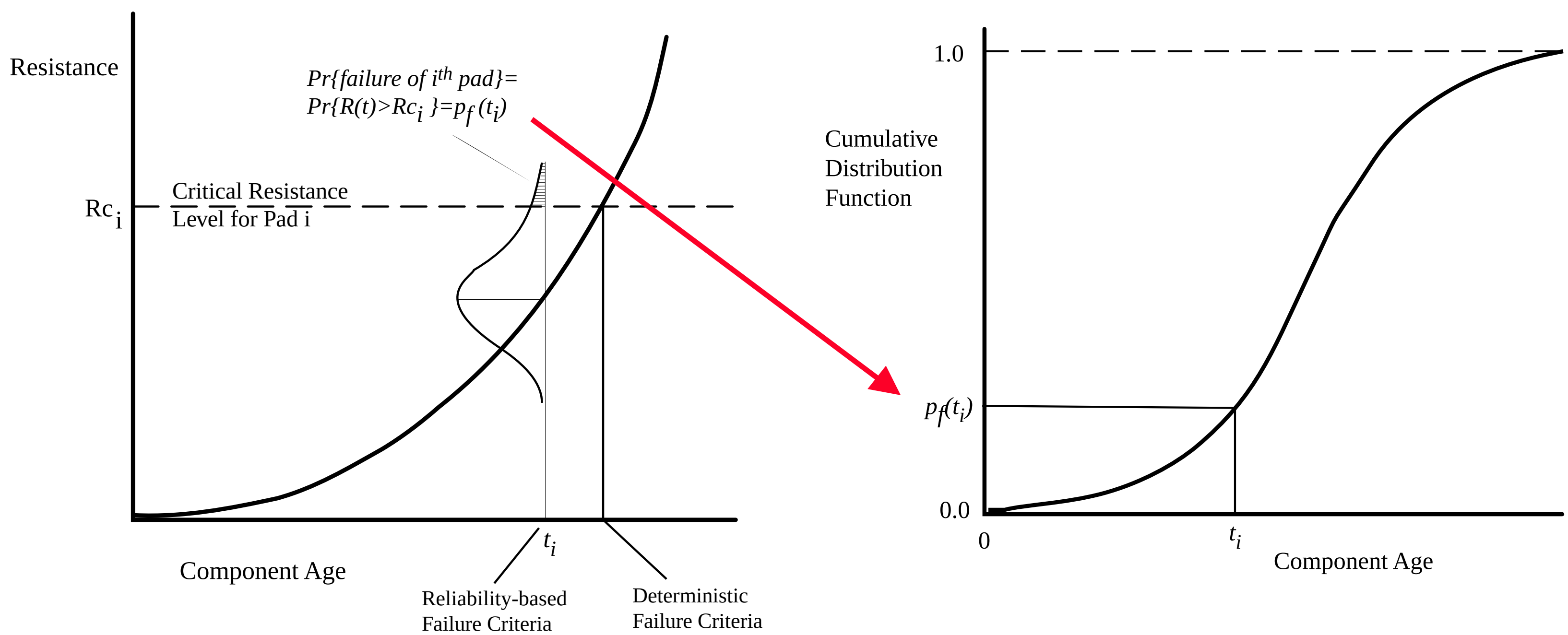
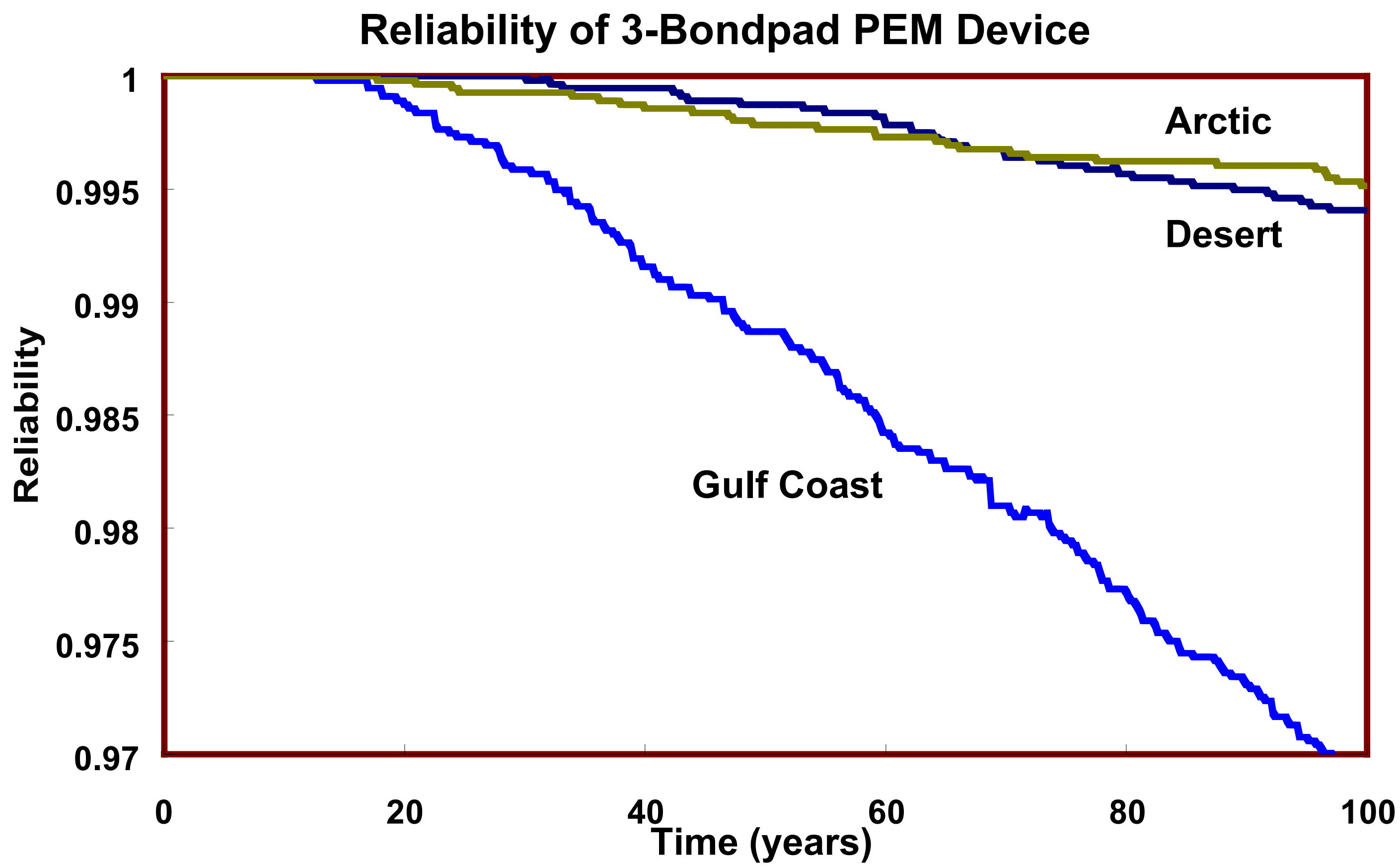
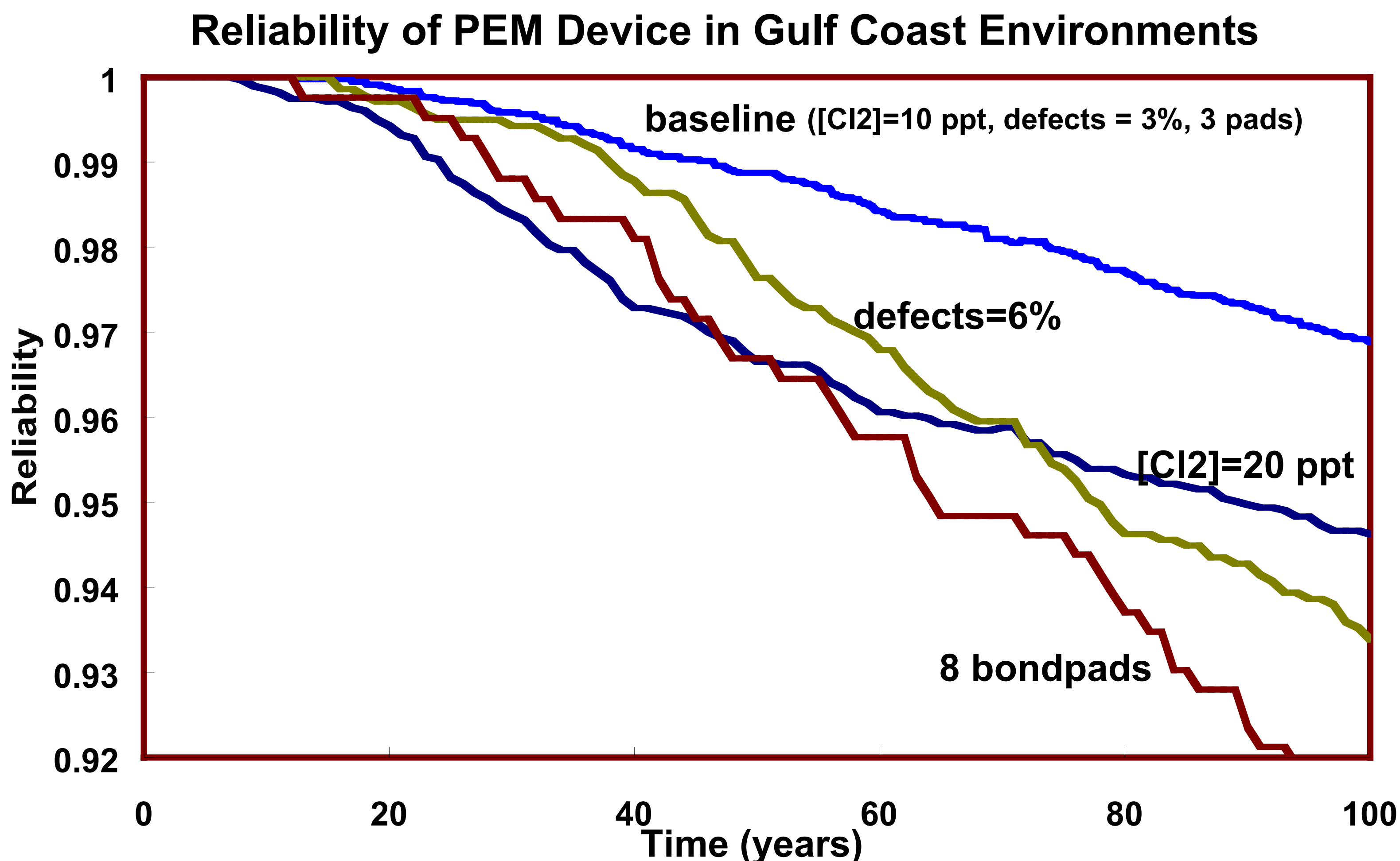
Reliability of Single Bondpad



Reliability Analysis of LM185
failure criterion of 2%



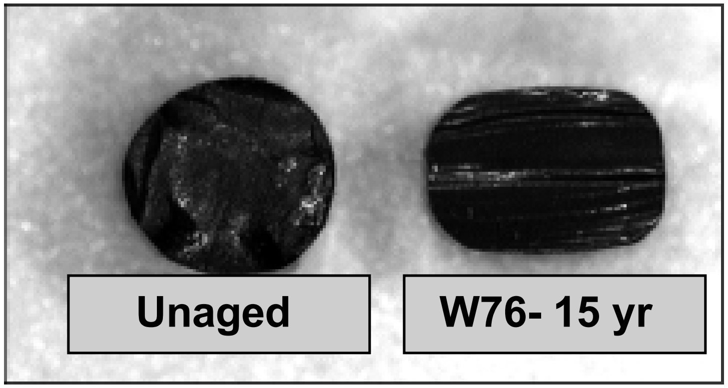
Sensitivity Analysis
parameter variation



Time-dependent degradation of stockpile o-rings (FY97-98)

W76

O-RING CROSS-SECTIONS



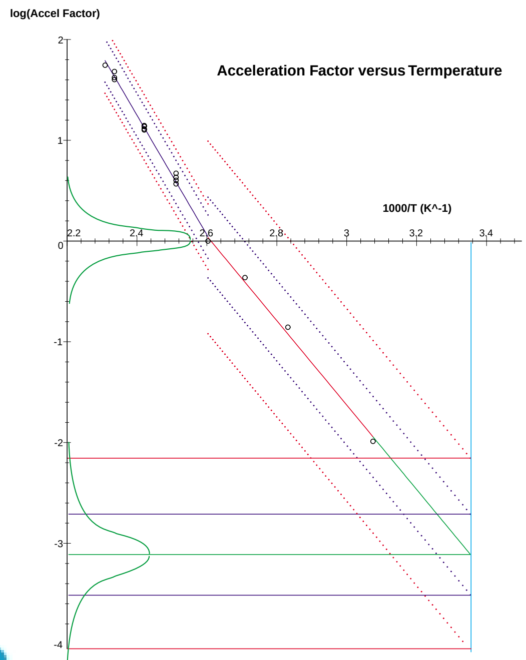
Primary causes:

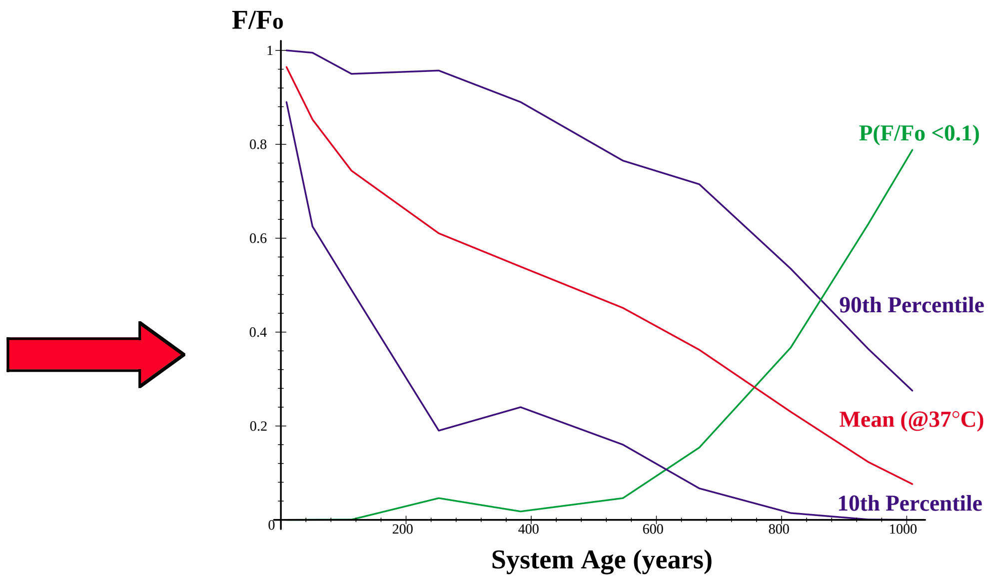
- oxidation
- mechanical stress
- synergism between oxidation and mechanical stress

Time-Temperature-Modality Superposition of Data

The limited amount of data available at lower temperatures results in a wider range of uncertainty regarding the predicted behavior at these lower temperatures

Given acceleration factor predictions, predicted mean compression ratio and associated confidence limits can be developed





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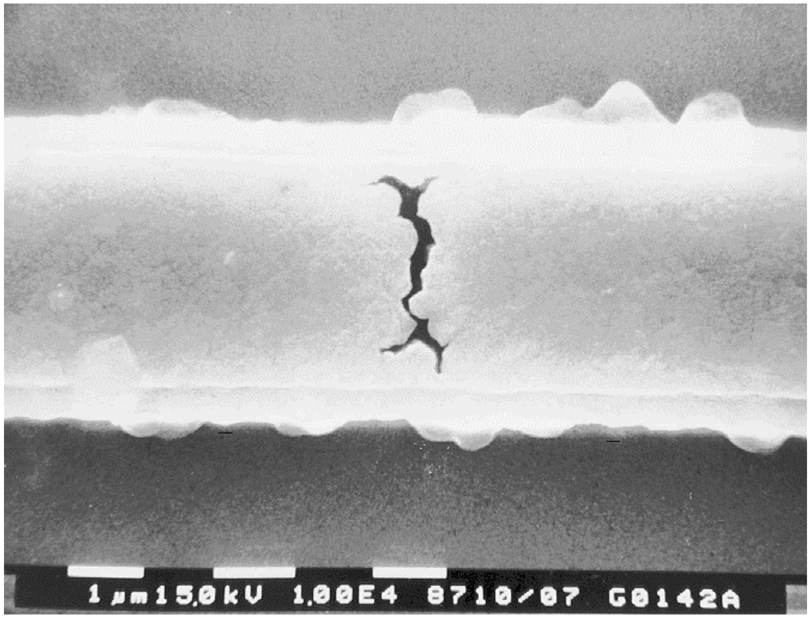
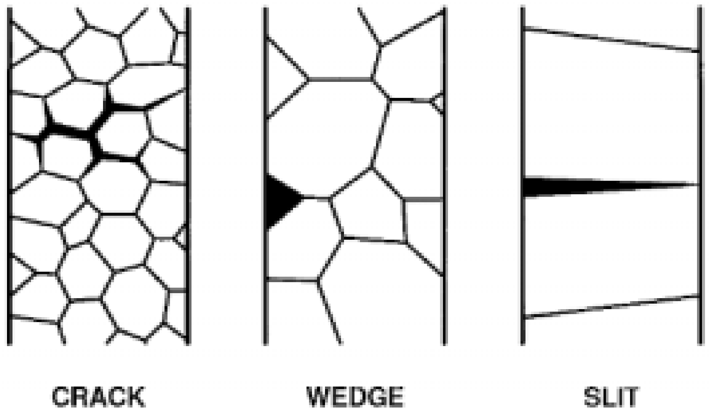
Application - Stress Voiding

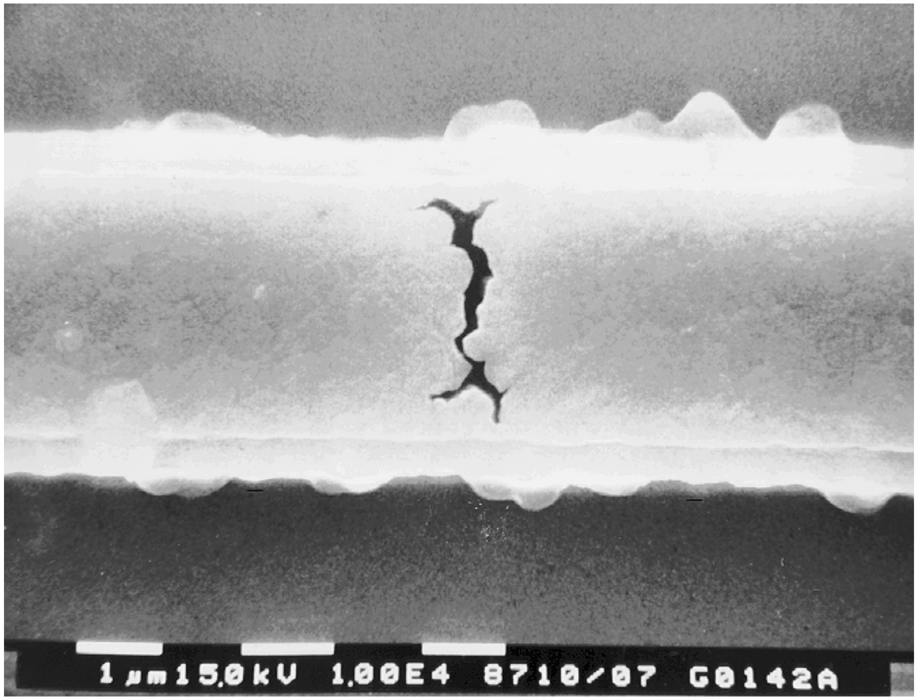
The width of aluminum interconnects in the submicron regime are now becoming common in the integrated circuit industry. This trend has brought a need to assess the reliability of these interconnects as they are affected by a failure mechanism known as stress voiding. Stress gradients in the metallization are caused by mismatch of thermal expansion coefficients and these gradients are known to drive mass transport and void growth. The approach is to view voiding as a nucleation and growth process that leads to failure (open circuit) when the void reaches a critical size.



Void Morphologies

Variety of void types

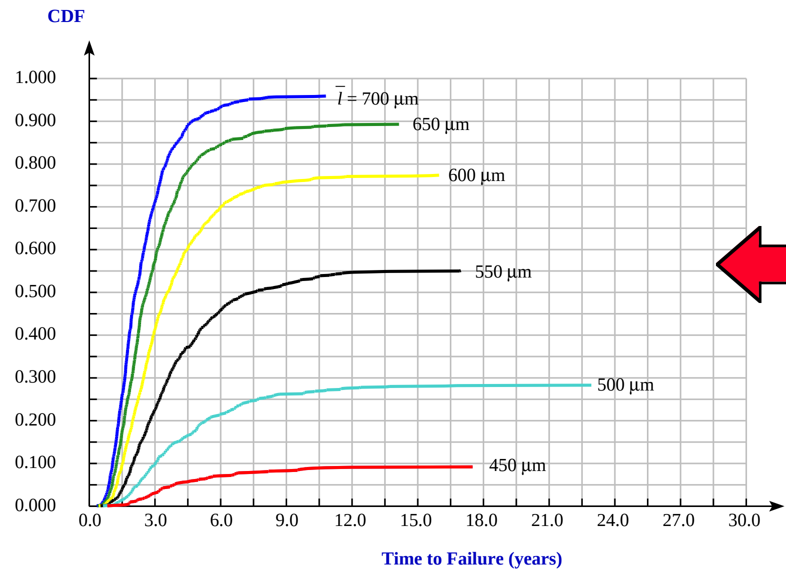




Slit-like crack growing in evaporated *Al* conductor line

Results

impact of mean void spacing and grain size

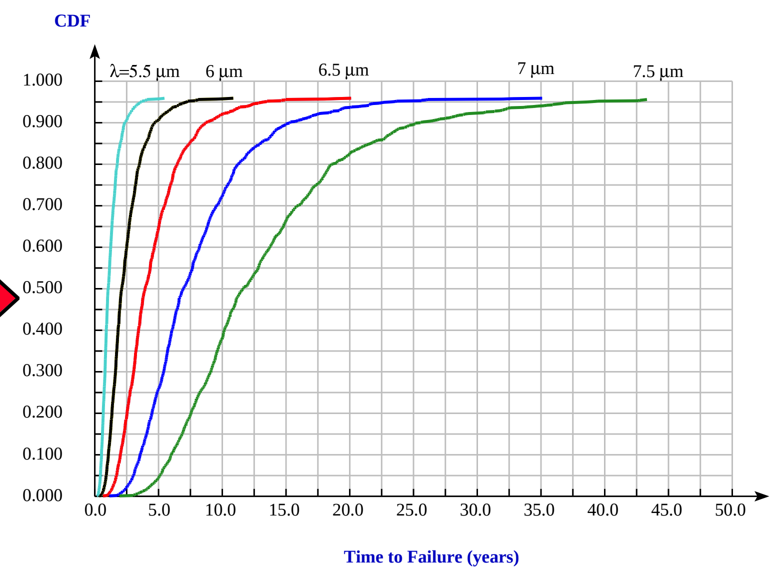


Accurate estimation of mean void spacing critical to accurate reliability characterization

Decreasing long term failure probability with decreasing mean voiding spacing

Grain size does not impact long term reliability

CDF not asymptotic to 1.0



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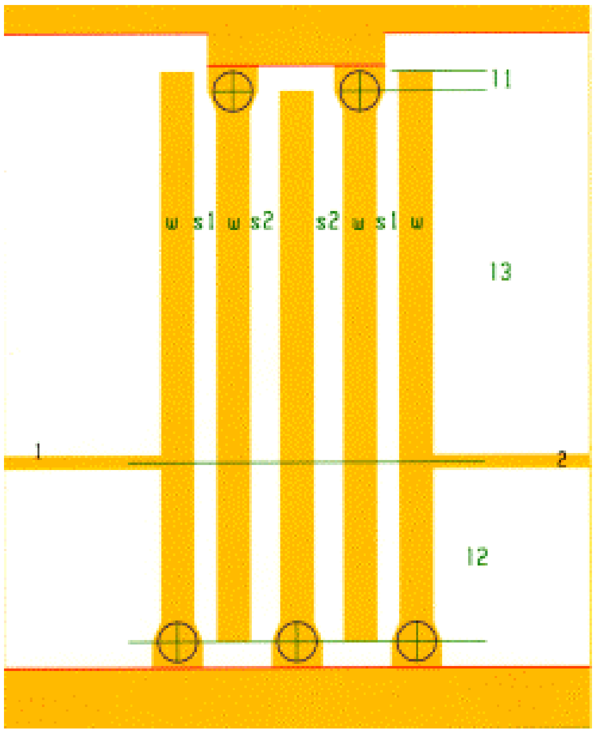
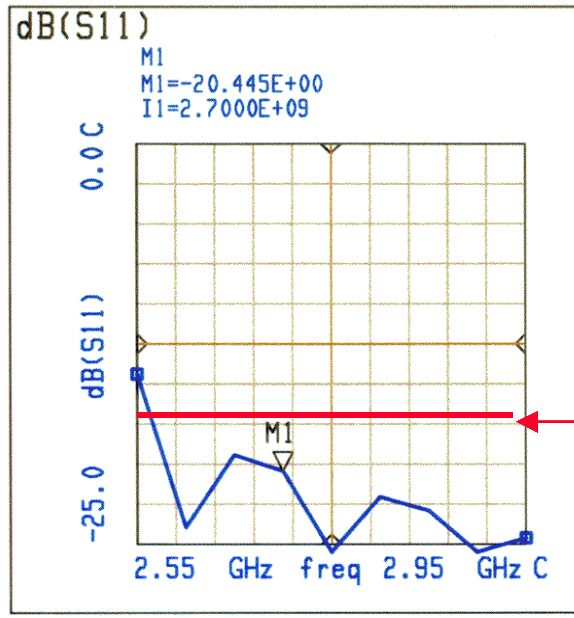
MC3812 (MkV) BPF



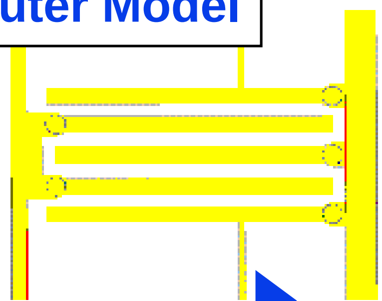


Typical Design Specification

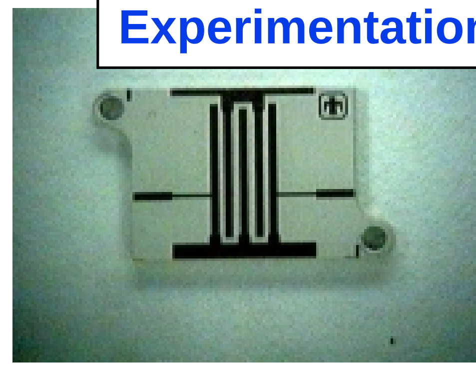
Question: Given uncertainties in material properties and the manufacturing process, what line geometry characteristics provide a BPF design with the highest likelihood of meeting the design specifications in a post-production environment?

Design of Band-pass Filter

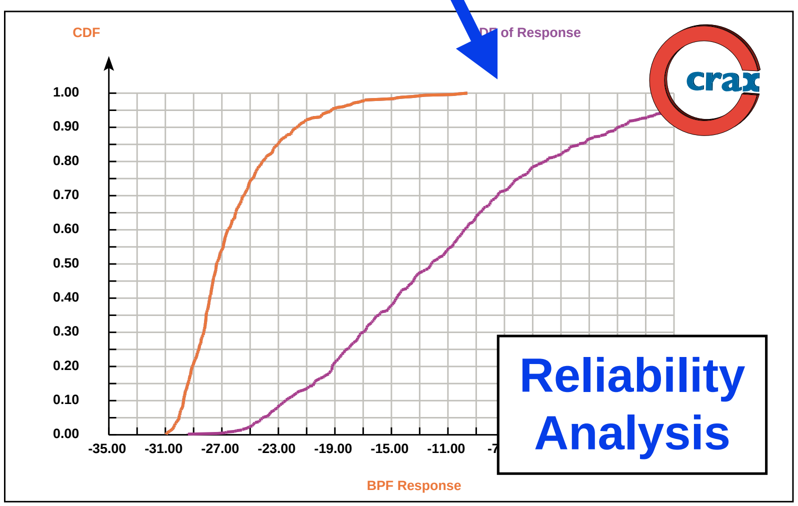
Computer Model



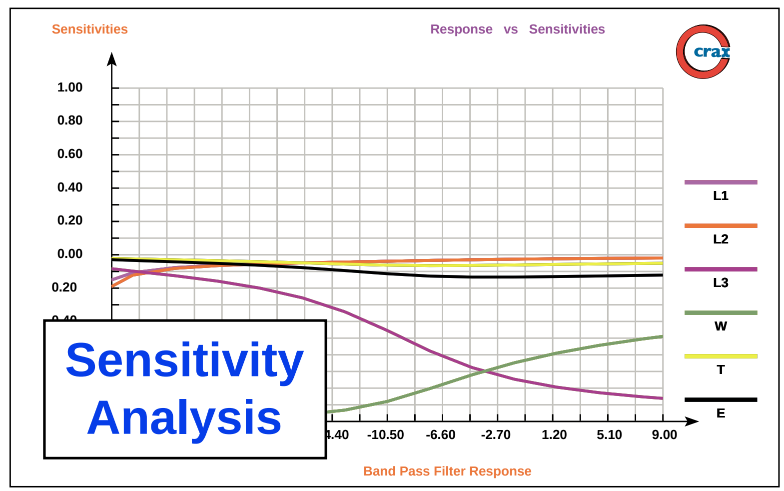
Experimentation



Validation



Reliability Analysis



Sensitivity Analysis

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Summary

- Objectives of Cassandra Project
  - Assist engineers and managers with
    - analysis of stockpile aging related issues
    - reliability impact of new materials or manufacturing processes
    - characterizing and controlling uncertainty in stockpile decision making
  - Make structural reliability and uncertainty methods accessible to design engineers
- Cassandra continues to be developed to provide:
  - a common test vehicle for new and existing uncertainty analysis methods
  - a tool to assist in stockpile reliability evaluation
- Characteristics:
  - Flexible
  - Extensible
  - Scalable
  - Accessible