The Cassandra Project
Dealing with Uncertainty in an Evolving Stockpile

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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, Hosofier-Lind, Rackwitz, Hoebichler, 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
  - CRAAX
    » 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

Stochastic System Characterization
- Thermal Expansion
- FEM
- Spice
- Quicksilver
- Astros
- CFD

 Bulk Modulus

Temperature

Humidity

Shear Stress
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

**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

- Accelerated Aging Of Polymers
- Atmospheric Corrosion
- Stress Voiding of IC Interconnects
- Thermo-mechanical Fatigue
- Stochastic Optimization

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Al Bondpad Corrosion in PEM

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

\[ \text{CR}_{\text{bondpad}} = f([\text{Cl}_2]) \cdot g(T) \cdot h(RH) \]
Bondpad Performance Equation

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

where \( x = 1, \beta = 2.5, \eta = 55, E_a = 17.5 \text{ kcal/mole (0.8 eV)} \)
Model Parameters and Uncertainty

- Deterministic parameters
  - humidity ($\beta$, $\eta$)
  - activation energy ($E_a$)

- Stochastic parameters
  - defects (location and size),
  - $k_0$ (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 -
  - \( I(\text{defects}) \): 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

Average Temperature

Temperature (°F)

Time (fraction of a year)

Gulf Coast
Desert
Arctic

Average Relative Humidity

RH (%)

Time (fraction of a year)
Reliability of Single Bondpad

Reliability-based Failure Criteria

Deterministic Failure Criteria

\[ Pr[failure \text{ of } i^{th} \text{ pad}] = Pr[R(t) > R_{ci}] = p_f(t_i) \]
Reliability Analysis of LM185
failure criterion of 2%

![Reliability of 3-Bondpad PEM Device](image)

- Arctic
- Desert
- Gulf Coast

Time (years)
Sensitivity Analysis
parameter variation

Reliability of PEM Device in Gulf Coast Environments

- **baseline** ([Cl2]=10 ppt, defects = 3%, 3 pads)
- defects=6%
- [Cl2]=20 ppt
- 8 bondpads

Time (years)

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

Primary causes:
- oxidation
- mechanical stress
- synergism between oxidation and mechanical stress
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.
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
MC3812 (MkV) BPF

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

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- 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