CALCE Simulation Assisted Reliability Assessment (SARA™) Software

Michael Osterman
CALCE Electronic Products and Systems Center
University of Maryland
College Park, Maryland 20742
http://www.calce.umd.edu/software/
CALCE Simulation Assisted Reliability Assessment (SARA®) Software

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- calcePWA Circuit Card Assemblies
  - Thermal Analysis
  - Vibrational Analysis
  - Shock Analysis
  - Failure Analysis

- calceEP Device and Package Failure Analysis

- calceFAST Failure Assessment Software Toolkit

- calceTinWhisker Failure Risk Calculator
Simulation Assisted Reliability Assessment

Virtual Qualification

Design Capture

Failure Risk Identification

Load Transformation

Failure Quantification

Life-Cycle Loads

Ranking of Potential Failure Sites and Mechanisms

Physical Verification: Test Setup, Specimen Characterization, Accelerated Stress Test

Load

Time to Failure

1

2

3

Field
Uses of Virtual Qualification

- Life assessment under anticipated loading conditions
- Design trade-offs
- Accelerated test planning
- Interpretation of accelerated test results with respect to field life
- Remaining life assessment
- Prognostics development
CalcePWA Software Assessment (Military Radio)

Objectives:
- Assess reliability of Control Module in the military environment
- Improve reliability of Control Module

Testing Results:
- 20 pin Leadless Chip Carrier (LCC) was weak in design
- Estimated life under operating conditions - 6.5 years

Analysis Results:
- Model prediction

Testing of CCAs demonstrated failures predicted by CalcePWA Analysis. Redesign of module results in an estimated savings of $27 mil in avoided cost.
Successful Application of calceSARA
Design-Build-Test-Fix vs. Simulation Assisted Design

Program Comparison:
E/E Technology:
Functional/Software Complexity:
Power/Internal Heat:
Packaging:
Supplier:

Results:
# of Total Test Issues Identified:

Pontiac
Grand Am

Pontiac
Aztek

(Development Period - 130 Wks)

Moderate
Proven Tech/Compts - No Electromech.
Moderate
Low Power/Heat
I.P. Mounted Snap Fit, 1 conn.
Supplier A - Highly Capable
Completed 1/98

16

(Development Period - 109 Wks)

More Complex
Proven Tech/Compts + 4 Onboard Relays
More Functions, More Complex
High Power & Thermal Challenges
Console Mnt., Integt’d w/Fuse (NEW)
Supplier A - Highly Capable
Completed 8/99

6

• Product development using simulations produced a more robust design, faster
• First pass issue reductions: 100% E/E circuits, 83% permanent failures, 75% EMI, 63% total
• The more complex module using the simulated assisted design achieved higher quality durability and reliability by beta version in a faster period.
Applications of CALCE Software

Comanche
- Commonality w/ AF F-22
- Commercial ICs Inserted
- $50M O&S savings

JSTARS Ground Station
- PoF Analysis on circuit cards
- Recommended commercial processor circuit card
- $12M Savings

AAAV
Virtual Qualification of circuit cards

GM
83% reduction in design issues
>10% reduction in time to market

Seagate
- Virtual Qualification

Emerson
- Virtual Qualification of CCA
- Failure assessment of a individual component.

VISTA Controls
Conducted virtual qualification of military CCA

Mars Path Finder
Verified robustness of flight CCA

Bradley Fire Support Vehicle
- Identified potential problems
- Increased Reliability

Honeywell
- Virtual qualification of engine controller

Life Cycle PoF Analysis Provides Considerable ROI
System Requirements for CALCE SARA® Software

- Platforms
  - x86-32, x86-64 Hardware, 1.2 GHz or higher recommended
    - MS Windows 2000/XP
    - Windows 8, Windows 7
- Disk Space and Memory
  - 233 MB recommended
  - 2 GB recommended

Testing and development is conducted primarily on a system with a 2.66 GHz Centrino 2, 4 GB, Windows 7
CalceSARA can be downloaded from the CALCE Web Site. The web site provides software, user’s manuals, installation instructions, past workshop materials, and other software documentation. Software is updated approximately every four months.

http://www.calce.umd.edu/software
Installation of calceSARA Release 6.1

The installation of calceSARA 8.0 is facilitated by installation software that takes you step-by-step through the software installation procedure.
Starting calceSARA 8.0

The calceSARA applications are launched like any other Windows application, by selecting the desired application from the list of available tools under calceSARA folder.

CalcePWA, calceFAST, calceEP, and calceWhiskerRiskCalculator, the CALCE Software Update application, and the user documentation can all be launch from the Start Menu.
PWA Failure Assessment Software

calcePWA 8.0

Assessment Management

Interface to CAD

Design Capture

Life Cycle Characterization

Life Expectancy and Failure Assessment

Stress Assessment
calcePWA VQ Inputs

Product Construction Information
- Bill of Materials (BOM) – Parts list with manufacturer and manufacture part number sufficient to obtain mechanical package information for the assembly under review.
- Part layout (x,y, orientation) on the printed wiring assembly may be imported from a CAD intermediate file for the assembly under review.
- Board thickness and material lay-up
- Solder stencil thickness and solder material
- Mechanical support positions on the printed wiring board

Operational and Usage Information
- Operating power of parts within the assembly.
- Expected thermal management of the printed wiring assembly.
- Life expectancy of the assembly under review
- Expected operational temperature cycling
  - Maximum temperature
  - Minimum temperature
- Expected vibration loading
  - Defined PSD normal to the surface of the printed wiring board
- Operation voltage levels of electrolytic capacitors
CALCE VQ Outputs

- Steady State Board and Component Temperatures
- Mode Shapes, Natural Frequencies, Displacement Response to Random Vibration and Shock Loading
- Time to Failure of
  - Package to board interconnects due to temperature cycle and vibration loading
  - PTH under temperature cycle loading
  - Electrolytic Capacitors under steady voltage and temperature operation (calceFAST)
- Probability of failure of
  - Package to board interconnects due to shock loading
  - MLCC under mechanical bending (calceFAST)
- Acceleration Factors between specified test and life conditions.
- Equivalent Life Time for a specified test.
Managing the CCA Virtual Qualification Process

Status of the calcePWA evaluation process can be quickly viewed in this panel.
calcePWA Libraries

To promote reuse of data, the calcePWA software has the following database libraries. Libraries can be build either top down and bottom up.
Printed Wiring Assembly Design Manager

The PWA design manager provides the ability to define and/or modify the PWA model. Model items include board outline, material inserts, layer stack-up, vias, component, part, and materials.
Supported CAD Text File Imports

Import currently available for

- ODB++
- P-CAD
- Veribest
- GENCAD 1.4
- Mentor Neutral File
- Cadance IDF file
- PADS 1.0, 3.5, 4.0 text files
- Zuken-Recal (CADIF) text files

Import typically provides board outline, part list, component list, and component positions referenced to the board outline. The import procedure was developed by extracting data from example text files.
Thermal Assessment

Boundary conditions are applied to each layer.

Unassigned Grid Locations are calculated.

Flood Fill Toggle Button allows for rapid assignment of boundary conditions at the edge of the board.
### Cooling Modes modeled in calcePWA

<table>
<thead>
<tr>
<th>Cooling Mode</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conduction</td>
<td>Internal conduction only</td>
</tr>
<tr>
<td>Conduct_VC</td>
<td>Internal conduction, natural convection with assumed vertical orientation.</td>
</tr>
<tr>
<td>Conduct_VC_Rad</td>
<td>Internal conduction, natural convection with assumed vertical orientation</td>
</tr>
<tr>
<td></td>
<td>with surface radiation.</td>
</tr>
<tr>
<td>Flowover</td>
<td>Internal conduction, surface convection based on defined air flow.</td>
</tr>
<tr>
<td>Conduct_HC</td>
<td>Internal conduction, natural convection with assumed horizontal orientation</td>
</tr>
<tr>
<td></td>
<td>venting of air assumed.</td>
</tr>
<tr>
<td>Conduct_HCNV</td>
<td>Internal conduction, natural convection with assumed horizontal orientation</td>
</tr>
<tr>
<td></td>
<td>no venting of air assumed.</td>
</tr>
<tr>
<td>Conduct_Rad</td>
<td>Internal conduction, surface radiation to enclosure.</td>
</tr>
<tr>
<td>Conduct_HC_Rad</td>
<td>Internal conduction, surface radiation to enclosure, natural convection</td>
</tr>
<tr>
<td></td>
<td>with assumed horizontal orientation, venting of air assumed.</td>
</tr>
<tr>
<td>Conduct_HCNV_Rad</td>
<td>Internal conduction, surface radiation to enclosure, natural convection</td>
</tr>
<tr>
<td></td>
<td>with assumed horizontal orientation, no venting of air assumed.</td>
</tr>
<tr>
<td>ColdPlate</td>
<td>Fin Structure Required. Internal conduction. Internal convection to Air in</td>
</tr>
<tr>
<td></td>
<td>defined fin structure.</td>
</tr>
<tr>
<td>Coldplate_with_NC</td>
<td>Fin Structure Required. Internal conduction. Internal convection to Air in</td>
</tr>
<tr>
<td></td>
<td>defined fin structure. Natural convection with assumed vertical orientation</td>
</tr>
</tbody>
</table>

(* Natural Convection is assumed to occur in the y direction (bottom to top as board appears on the screen)*)
Display of Thermal Analysis Results

CalcePWA Thermal Display Tool presents the results of a thermal analysis.
Determining Component Temperatures

Substrate Temperatures

\[ T_{sub} = T_{layer} + QR_z \]

\[ T_{layer} \] -- Layer temperature below component

\[ R_z = \frac{0.5\Delta Z}{K_cA_c} \]

\[ A_c \] -- Planar component area

Case Temperatures

\[ T_{case} = T_{sub} + QR_{case} \]

\[ R_{case} \] -- Parallel resistance of leads and case to substrate

Junction Temperatures

\[ T_{junction} = T_{case} + Q\Theta_{jc} \]

\[ \Theta_{jc} \] -- User specified

The display tool shows component temperatures calculated from the thermal analysis.
CalcePWA Thermal Analysis Module
Demonstrated for Avionics Printed Wiring Board Assembly

Percentage error between the case temperature predicted by CalcePWA and the experimental data

Analysis results: Thermal analysis software in CalcePWA has been validated against experimental data.

Benefit for the EADS: Development of an optimized plan for accelerated qualification testing
Validation of calcePWA Thermal Analysis

The thermal analysis software in calcePWA has been extensively validated against experimental test data and accepted numerical simulations.

CalcePWA
Thermal Software
Found to be within 5% of experimental test data

Comparison of Component junction temperature (°C) for natural convection case study

<table>
<thead>
<tr>
<th>Component type and power dissipation</th>
<th>calcePWA</th>
<th>Program “PCB EXPLORER”</th>
</tr>
</thead>
<tbody>
<tr>
<td>24 lead DIP (1.56 W) (U55)</td>
<td>124</td>
<td>134</td>
</tr>
<tr>
<td>16 lead DIP (0.32 W) (U38)</td>
<td>79</td>
<td>75</td>
</tr>
</tbody>
</table>

Comparison of Component junction temperature (°C) for flow over case study

<table>
<thead>
<tr>
<th>Component type and power dissipation</th>
<th>calcePWA</th>
<th>Program “PCB EXPLORER”</th>
<th>MRCs SUPERPOSITION METHOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>24 lead DIP (1.56W) (U55)</td>
<td>101</td>
<td>110</td>
<td>108</td>
</tr>
<tr>
<td>16 lead DIP (0.32W) (U38)</td>
<td>67</td>
<td>62</td>
<td>59</td>
</tr>
</tbody>
</table>
Vibration Analysis Manager allows you to assign supports to the board for consideration in the modal analysis and dynamic response. Additional options have been added to toolbar to facilitate use of the software.
Displaying Advanced Vibration Analysis Results

Mode Shapes

Analysis results include:
Mode Shapes,
Natural Frequencies,
Board Displacement,
Board Curvature,
Component Displacement, and
Component Curvatures

Component Curvature

Displacement

Analysis results include:
Mode Shapes,
Natural Frequencies,
Board Displacement,
Board Curvature,
Component Displacement, and
Component Curvatures
Validation of CalcePWA Vibration Analysis

Modal Analysis & Displacement

**ANSYS**

Resonant Frequencies
- 710 Hz
- 1331 Hz
- 1444 Hz

**calcePWA**

Resonant Frequencies
- 724 Hz
- 1348 Hz
- 1399 Hz
Validated against Measured Test Results

BFIST - XM7 Vibration Analysis Results

<table>
<thead>
<tr>
<th>Component</th>
<th>1st Natural Frequency (Hz)</th>
<th>1st Natural Frequency (Hz) SEI ESS Test Data</th>
<th>Max. Displacement (mils) CALCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Video Processor CCA</td>
<td>372</td>
<td>510</td>
<td>.33</td>
</tr>
<tr>
<td>Power Filter CCA</td>
<td>226</td>
<td>230</td>
<td>13.5</td>
</tr>
<tr>
<td>Processor CCA</td>
<td>248</td>
<td>265</td>
<td>.47</td>
</tr>
<tr>
<td>Interface CCA</td>
<td>303</td>
<td>265</td>
<td>.66</td>
</tr>
<tr>
<td>Serial I/O CCA</td>
<td>261</td>
<td>N/A*</td>
<td>.61</td>
</tr>
<tr>
<td>Backplane CCA</td>
<td>417</td>
<td>410</td>
<td>.04</td>
</tr>
</tbody>
</table>

Input frequency to Solder Joint Fatigue is lowest value of CALCE results and ESS test results.

The vibration analysis software in calcePWA has been extensively validated against experimental data and numerical simulations.
Life Assessment

Life assessment in calcePWA is conducted predefined a life cycle profiles

1. Select a predefined life cycle profile

2. Save life assessment problem,

3. solve life assess
Defining the Life Cycle Profile

The Life Cycle Profile Manager allows you to define multiple loading conditions over which that PWA can be analyzed.
PWA Life Assessment

The life assessment module uses the PWA model, results of thermal and vibration simulations defined in a life cycle scenario to determine life expectancy of design.

Color coding to highlight items that fail to meet life expectancy
Available Failure Models

• Thermal Fatigue of Solder Interconnects
  – Most conventional package styles (SOIC, PLCC, QFP, BGA, SOT, HSOP, HSLCC, PGA, DIP, LCCC, LCC)

• Thermal Fatigue of PTH

• Thermal Fatigue of Die to Package Interface

• Vibration Induced Fatigue of Package to Board Interconnects
  – Most conventional package styles (SOIC, PLCC, QFP, BGA, SOT, HSOP, HSLCC, PGA, DIP, LCCC, LCC)

• Mechanical Shock Induced Failure of Package to Board Interconnects
  – Most conventional package styles (SOIC, PLCC, QFP, BGA, SOT, HSOP, HSLCC, PGA, DIP, LCCC, LCC)

• Die Level Electromigration

• Die Level Metallization Corrosion

• Die Level Dielectric Breakdown
Modeling Validation

Interconnect fatigue failure models have been validated though experimental data and detailed numerical simulation. These models are reviewed on a continual basis and updated as necessary.

BGA model has been compared against over 40 measured results obtained from the published papers, conference articles and experiments.
Vibration Testing of 160 IO CABGA Test Boards

Test boards were monitored with accelerometer and four strain gages.

<table>
<thead>
<tr>
<th>Test</th>
<th>Dwell Freq.</th>
<th>Input Acc. (Peak - Peak)</th>
<th>Input Acc. (g)</th>
<th>Resp. Acc. (Peak-Peak)</th>
<th>Resp. Acc. (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>209</td>
<td>20</td>
<td>10</td>
<td>738</td>
<td>369</td>
</tr>
<tr>
<td>P2</td>
<td>210</td>
<td>14</td>
<td>7</td>
<td>596</td>
<td>298</td>
</tr>
<tr>
<td>P3</td>
<td>206</td>
<td>2</td>
<td>1</td>
<td>64</td>
<td>32</td>
</tr>
<tr>
<td>P4</td>
<td>209</td>
<td>6.3</td>
<td>3.15</td>
<td>197</td>
<td>98.5</td>
</tr>
<tr>
<td>P5</td>
<td>205</td>
<td>10.3</td>
<td>5.15</td>
<td>303</td>
<td>151.5</td>
</tr>
<tr>
<td>T1</td>
<td>205</td>
<td>10.3</td>
<td>5.15</td>
<td>393</td>
<td>196.5</td>
</tr>
<tr>
<td>T2</td>
<td>205</td>
<td>6.5</td>
<td>3.25</td>
<td>198</td>
<td>99</td>
</tr>
<tr>
<td>T3</td>
<td>202</td>
<td>6.8</td>
<td>3.4</td>
<td>280</td>
<td>140</td>
</tr>
<tr>
<td>T4</td>
<td>200</td>
<td>8.7</td>
<td>4.35</td>
<td>347</td>
<td>173.5</td>
</tr>
</tbody>
</table>
Comparison of Board Strain versus Input with calcePWA Vibration Module and Test Data

Comparing test strain to measured strain shows relatively good correlation.
Comparison of CTF

These plots contain curves for life expectancy of lead-free (SAC) and SnPb solder interconnects under harmonic load conditions at varying input accelerations generated by the calcePWA software for the CABGA test board. Test results plotted against these curves reveal good agreement.
Validated Temperature Cycle Induced Solder Interconnect Fatigue Model for SAC

2 mm thick board contained PBGA, TSOP, TQFP, CLCC packages. The simulation model was based on a test vehicle used under the JGPP/JCAA Pb-free Solder Test Program. Test assemblies were subjected to a -55 to 125°C temperature cycle and a -20 to 80°C cycle condition.

Model vs. Experiment Data for SN100C

1. M. Osterman, C07-06 CALCE EPSC Project, 2007
3. M. Osterman, C08-08 CALCE EPSC Project, 2008
Probabilistic Physics of Failure (PPOF) Assessment in calcePWA

Evaluate Failure Model

Material Properties

Geometry

Loads

TTF_x

FFOP

Time-to-Failure

Failures
Probability Physics of Failure (PPOF)

- The default failure assessment process in calcePWA is to use nominal values for all parameters with the assumption that the failure assessment results represent time to 50% failure.
- To assess the effect of input variations, you can directly vary inputs and re-run the assessment. This requires modifying model data, regenerating the LCPDB, and re-running the failure assessment.
- The PPOF capability within the calcePWA failure assessment module offers two alternatives: assigned distributions and calculated distributions.
  - Assigned distributions include Weibull and Lognormal which can be applied on a model-by-model basis.
  - Calculated distributions are established by defining distributions to input parameters and using a Monte Carlo technique to establish the failure distribution.
Failure assessment is conducted in the Life Assessment Manager. Assessment is based on the selected Life Cycle Loading Scenario. Probabilistic failure assessment may be conducted by direct assignment of distributions for failure models or through Monte Carlo simulation.
**Supported Distributions**

**Triangular Distribution**

Where:
- \( l \) – Lower variation
- \( u \) – Upper variation

**Example**
- Nominal Value: 5 mm
- Upper: 2 mm
- Lower: -1 mm
- \( a = 4, b = 7 \)

**Uniform Distribution**

**Edit Distribution Dialog**

- Attribute ID: MAX_LENGTH
- Distribution Type: Uniform
- Upper Variation: 2 mm
- Lower Variation: -1 mm

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Center of Advanced Life Cycle Engineering
http://www.calce.umd.edu

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Handling Multiple Environments

Damage is defined as the percent of life consumed. If damage is linearly accumulated, then we define a probabilistic damage index for x percent failure as

\[ D_{P(x)} = \frac{n}{N_{P(x)}} \]

where \( n \) is the applied time (cycles, etc) and \( N_{P(x)} \) is the survivable time (cycles, etc). For multiple environments and the same failure site and mechanism, the total damage is the sum of the damage for the individual environments:

\[ D_{P(x)}^{\text{total}} = \sum_i D_{P(x)}^i \]

Failure occurs when \( D_{P(x)}^{\text{total}} \geq 1 \)
Example of Monte Carlo Analysis

Life Cycle Profile:
1. Temperature Cycle –40 to 100°C (1 CPH) – 12 cycles
2. Shock 20G .5s Half-Sine
3. Random Vib: 0.2 G/Hz (100 to 500 Hz) – 100 hrs
4. Temperature Cycle 0 to 80°C (1 CPD)

Expected life is calculated based on the defined life cycle and assumes that the loading condition persists until failure. The total damage (DR) is based on the defined life cycle loading condition.
Acceleration Factors

In product qualification, it is often impractical to test the system for its full expected lifetime. As a result, high load frequency and load levels may be used. In order to relate the test condition to the anticipated use condition, a failure assessment under both conditions must be completed. If the same failure mechanisms and sites are produced under both conditions, the test and use condition can be related. An acceleration factor is the term used to relate the test and use condition.

\[
AF_{cycle} = \frac{N_{use}}{N_{test}} \quad AF_{time} = \frac{t_{use}}{t_{test}}
\]

The ability to present acceleration factors has been recently added to the calcePWA software. In calcePWA, the acceleration factor is presented in the time domain.
Determining Acceleration Factors in calcePWA

User must create a test profile and a use profile. Both life assessments must be conducted for both profiles. To evaluate the acceleration factor for a particular use and test condition, the user should load the use condition. Next, the user should select the Run \rightarrow Acceleration Factor menu item and use the selection dialog to select the test assessment.
Time Domain Acceleration Factors

The acceleration factors determined in calcePWA are presented in the time domain. As such, the time in test is related to the time under the use condition. Therefore, an acceleration factor of 50 means that a part requiring 2 months for failure under the test would require 100 months to fail under the prescribed use condition. Alternatively, if a part can survive 2 months in test, it should be expected to survive 100 months in the field.
Assessment of Tin Whisker Risk in calcePWA

The calceWhiskerRiskCalculator has been integrated into the calcePWA. The current implementation only considers part self shorting. Later versions will allow for evaluation of part to part shorting.
Importing Components in calceTinWhiskerRiskCalculator

The number of pairs is calculated based on part interconnect format (SIP, DIP, QUAD)

- **SIP**: \( NP = N_{\text{leads}} - 1 \)
- **DIP**: \( NP = 2 \times (N_{\text{leads}}/2 - 1) \)
- **QUAD**: \( NP = 4 \times (N_{\text{leads}}/4 - 1) \)

Conductor spacing gap is determined based on lead width \( W_{\text{lead}} \) and interconnect center line spacing or pitch \( P \)

\[
L_{\text{gap}} = P - W_{\text{lead}}
\]

Conductor area

\[
A_{\text{conduct}} = L_{\text{lead}} \times (T_{\text{lead}} + W_{\text{lead}})
\]

Software will report leaded components that it is unable to determine one or more site parameters.
Risk Assessment Results from calcePWA models

After setting the target life and samples, you can evaluate the whisker risk by selecting Risk->Assessment option. This will evaluate reliability of the system defined by the set of parts under evaluation.
CalceFAST 5.0 (Failure Assessment Software Toolkit) software provides the capability to bypass full scale design modeling and conduct failure assessment using individual failure models. The software implements a failure model plug-in interface and allows the failure model software to be used in calcePWA 5.0 and on the CALCE Web Site.
Expanded Models in calceFAST

Package and device models from CADMP-II are now available in calceFAST.
In the case of multiple attribute sensitivity, the attributes and their assigned values are presented in the text report. The X-axis of the graph defines the percent values over which the selected attributes were varied.
Iso-time to failure assessment provides you with plots that can be used to examine the effect of changes in environment loading conditions versus design parameters. From the example above, a reduction in plating thickness by 0.01mm can reduce the life by 44%.
calceEP Device and Package Level

Toolbox

Package and Device Modeling

Life Cycle Profiling

Package and Device Life Assessment
calceEP Failure Models

Failure models are based on those available in open literature
As well as those internally developed at CALCE. List of supported
failure models will include:

- Electromigration
- Stress Driven Diffusive Voiding (SDDV)
- Time Dependent Dielectric Breakdown (TDDB)
- Metallization Corrosion
- Electrolytic Breakdown
- Dielectric Breakdown
- Die Attach Thermal Fatigue
- Wire Bond Thermal Fatigue
A software package that implements the fixed risk assessment algorithm has been developed. Software allows you to define conductor pairs and select finish type to look up whisker growth or directly define whisker growth parameters.
Conducting A Risk Assessment

The software allows you to define the target life time of the system, desired risk level in parts per million, and the percentage of whisker containment afford by the application of a conformal coat. The target life is used in combination with the database of whisker growth tables to determine the whisker growth characteristics. The risk level is used to define the sample size (i.e. the number of Monte Carlo iteration).
Risk Assessment Results

The software outputs the probability of whisker failure for each conductor pair considered. The probability of failure for each conductor pair is then rolled up to provide the total whisker reliability of the system.