DfR Solutions
reliability designed, reliability delivered

Meeting the Target of 25 Year Reliability in Solar Electronics

SAMPE Dallas

April 11, 2013

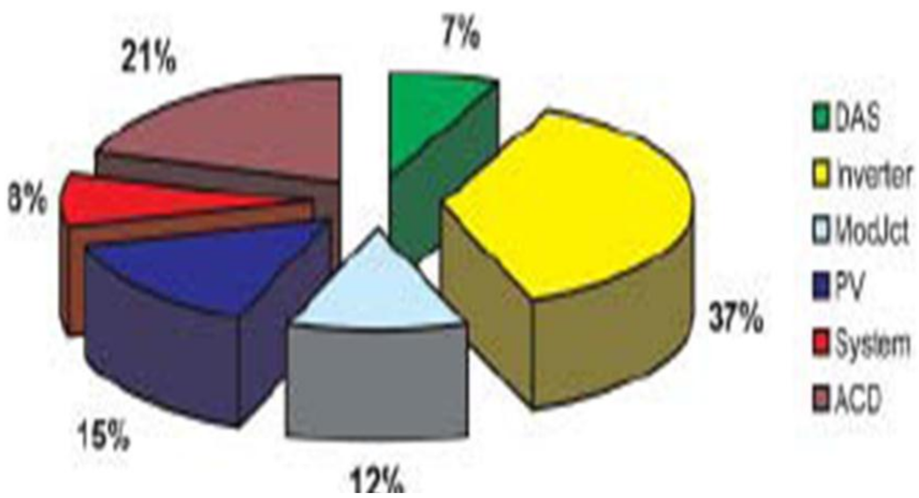
Cheryl Tulkoff, ctulkoff@dfrsolutions.com

Perspective on Desired Product Lifetimes

- Low-End Consumer Products (Toys, etc.)
  - Do they ever work?

Cell Phones:	18 to 36 months
Laptop Computers:	24 to 36 months
Desktop Computers:	24 to 60 months
Medical (External):	5 to 10 years
Medical (Internal):	7 years
High-End Servers:	7 to 10 years
Industrial Controls:	7 to 15 years
Appliances:	7 to 15 years
Automotive:	10 to 15 years (warranty)
Avionics (Civil):	10 to 20 years
Solar Electronics	**25 years**
Telecommunications:	10 to 30 years

Leading Causes of "Hard" Photovoltaic (PV) System Failures

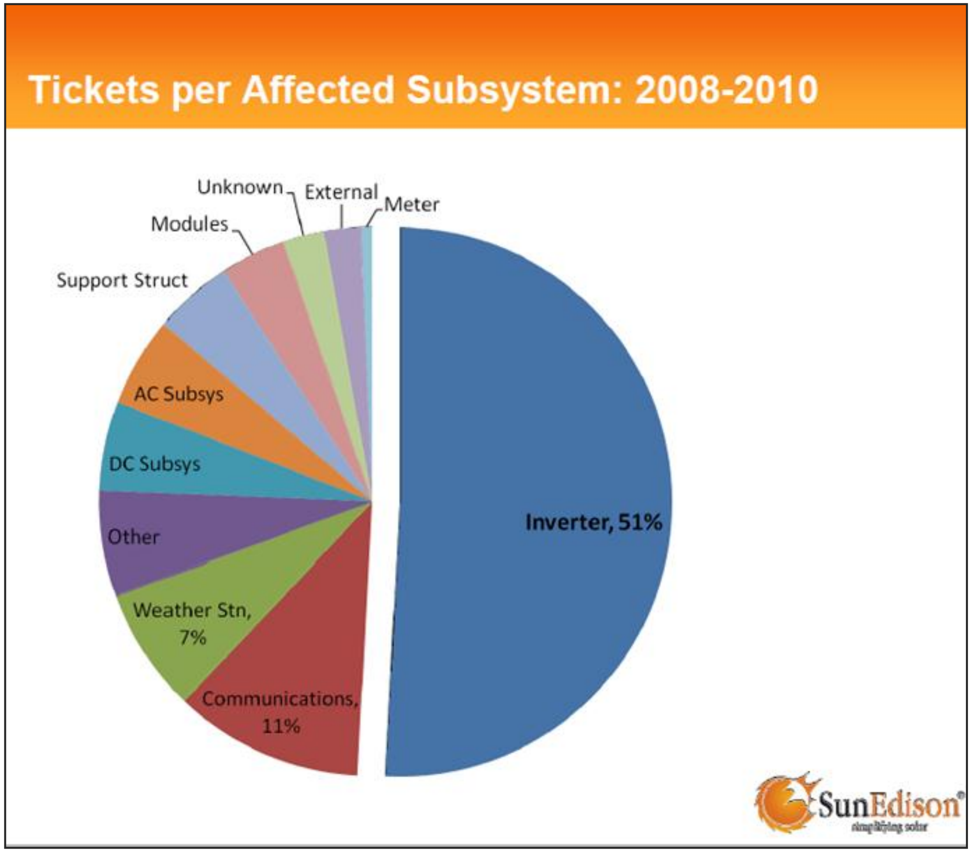


J. Granata, Sandia; 2009 PV Reliability Conference

IGBT = insulated gate bipolar transistor

- Central Inverter: 37% from 2009 Sandia Study
  - IGBT most common component
- 3 basic fail categories
  - Manufacturing Quality
  - Inadequate Design
  - Defective Electronic Components

Leading Causes of "Hard" PV System Failures



Central Inverter: 51% from Sun Edison 2008-2010 study

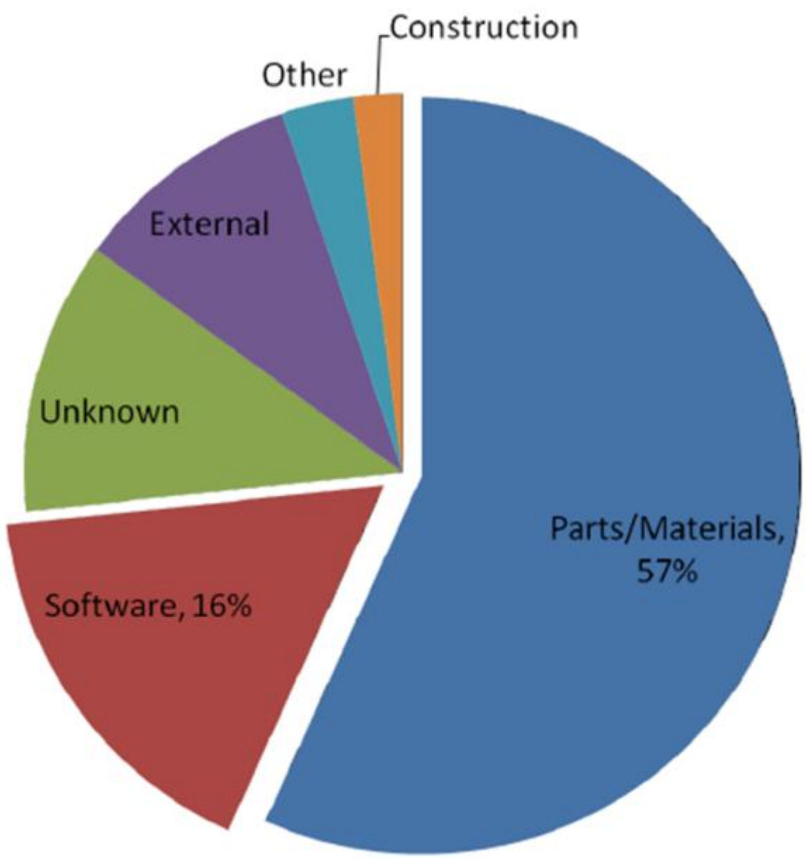
Communications: 11%

Weather Station: 7%

"Owner/Operator Perspective on Reliability Customer Needs and Field Data", Sandia National Laboratories, Utility-Scale Grid-Tied PV Inverter Reliability Workshop, January 2011.

Leading Root Causes of "Hard" PV Inverter Failures

Inverter Tickets per Root Cause: 2008-2010



Parts & Materials: 57%

Software: 16%

SunEdison

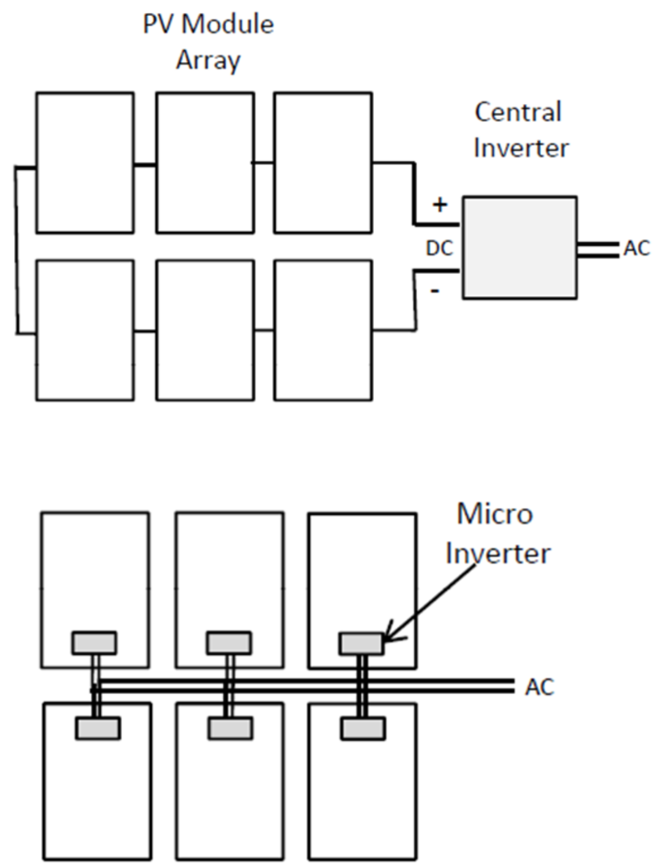
DfR Solutions

Quick Inverter Overview

- Inverters perform two key functions
  - Converts the direct current (DC) coming from the panels to the alternating current (AC) used by the electric grid
  - Perform algorithms to maximize the power produced by the system.

Micro-Inverters versus Central Inverters

- Better Reliability & Availability
  - Lack of single failure point
  - Longer warranty: 15-25 years versus 5-10 years
- Lower DC Voltages, less vulnerable to arcing
- Optimized Maximum Power Point Tracking (MPPT) per module
- PV Module level real-time monitoring



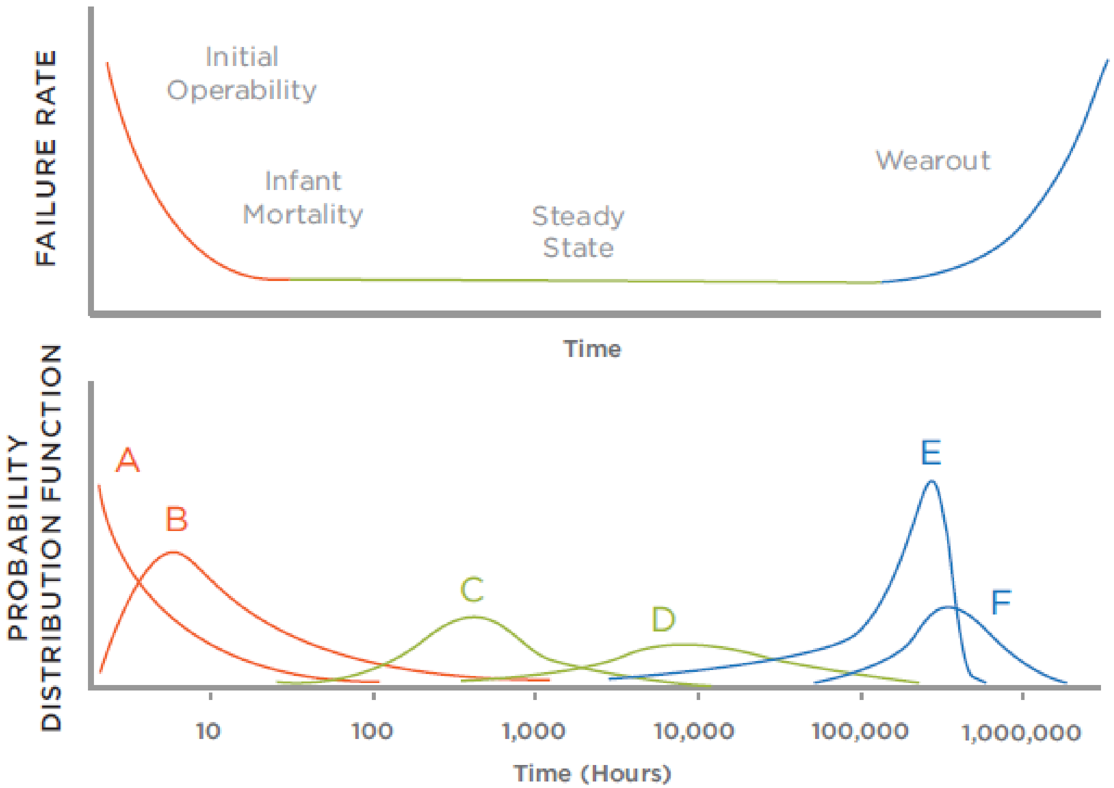
Images courtesy of Paul Parker, SolarBridge

Micro-Inverters

- The electronic components used in a micro-inverter are commercial off-the-shelf (COTS)
  - Parts designed for consumer electronics but need to survive 25 years in solar installations
  - Outdoor/Partially Protected & Temp Not Controlled

5110 Roanoke Place, Suite 101, College Park, MD 20740 | 301-474-0607 | www.dfrsolutions.com

Inverter Component Failures



Infant Mortality:
A. Weak Solder Joints
B. Cracked Ceramic Capacitor

Steady State:
C. FET Single Event Burnout
D. Corrosion

Wearout:
E. Electrolytic Capacitor Degradation
F. Non Compliant Solder Joints (BGA,etc.)

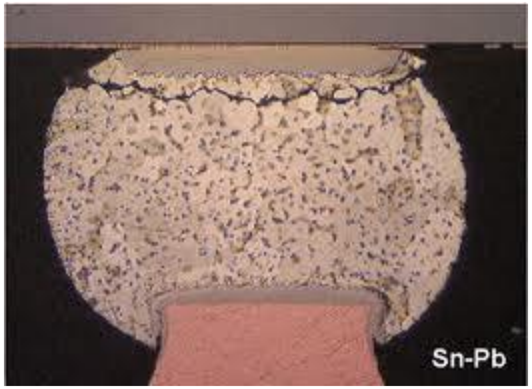
Image Courtesy of SolarBridge

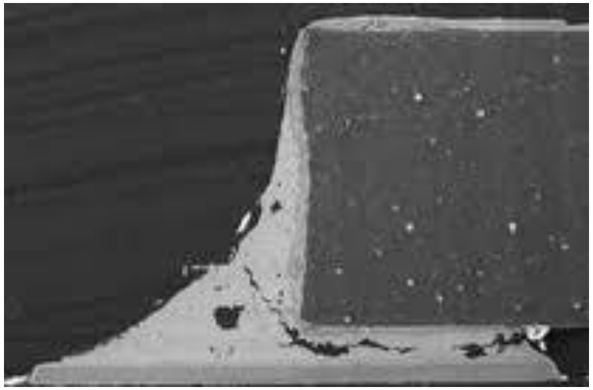
Inverter Field Failure Mechanisms

- Solder joint fatigue failure
- Plated through hole fatigue failure
- Conductive anodic filament formation (CAF)
- Shock or Vibration (shipping and in use)
- Component wear out
- Potting Induced Failure

Solder Fatigue

- Solder joints “wear out” or fatigue and fail under the long term influence of temperature cycling and mechanical stresses.

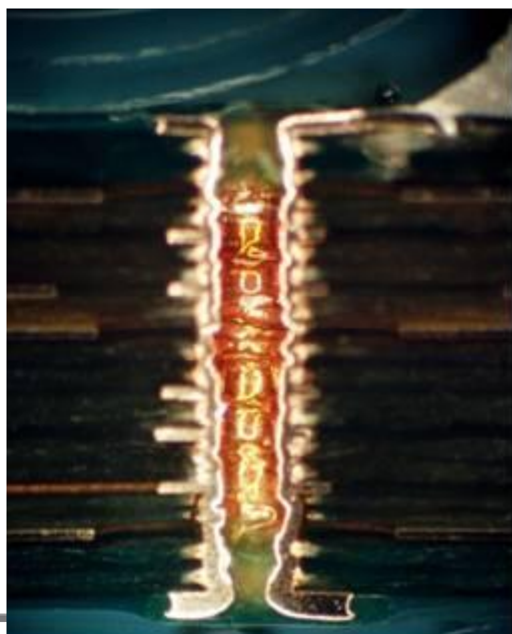


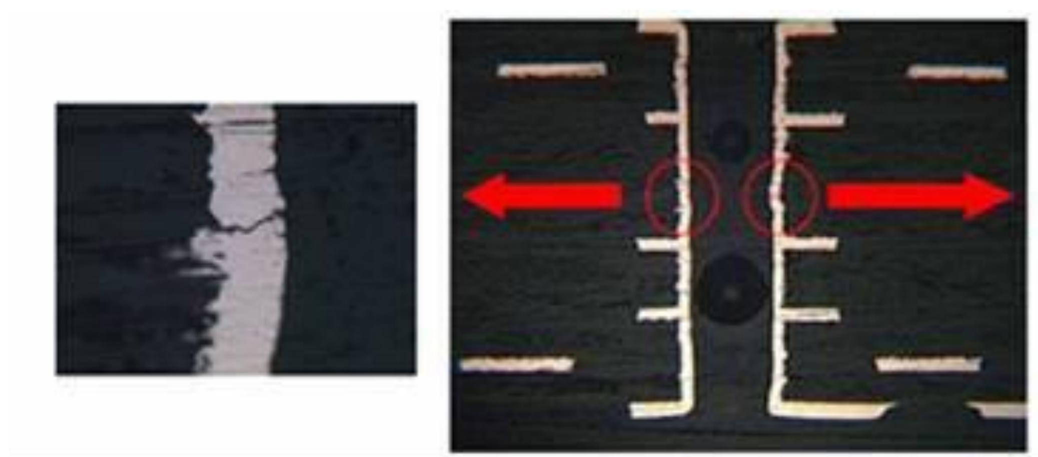


DfR Solutions

Plated Through Hole Fatigue

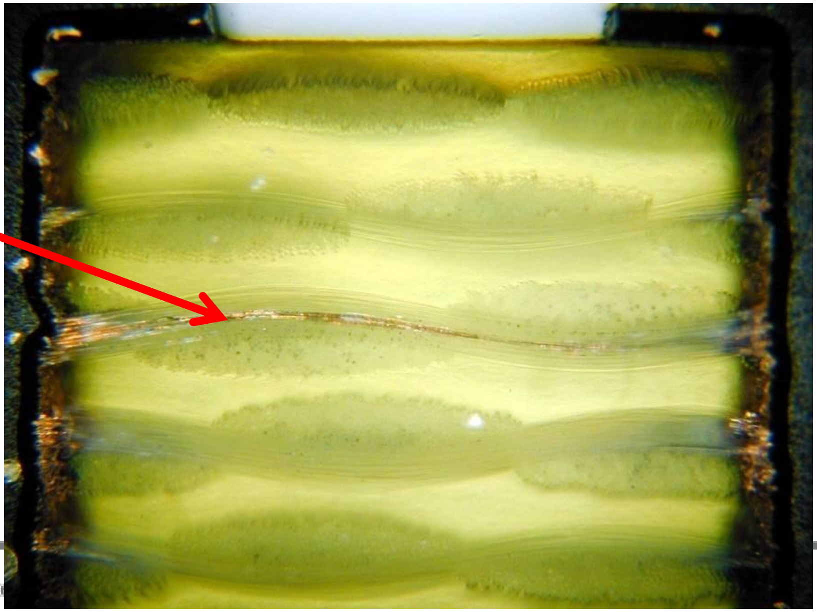
- When a printed circuit board experiences temperature cycling, expansion/contraction in the z-direction is much higher than that in the x-y plane
- High stress can build up in the copper via barrels resulting in cracking near the center of the barrel as shown in the cross section photos below.





Conductive Anodic Filament Formation (CAF)

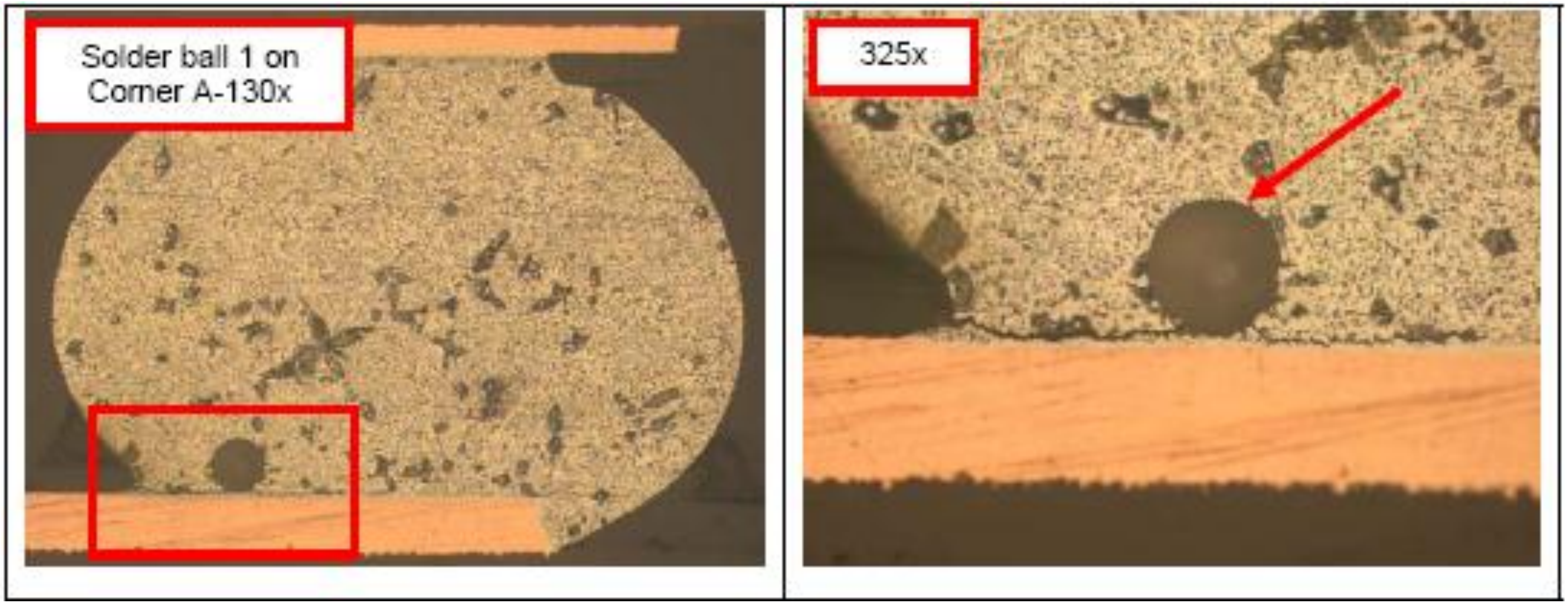
- CAF formation is a risk when Plated Through Holes (PTH) or vias are so close together that damage from drilling can open up a pathway between vias.
- Copper from the via can migrate along the pathway and eventually cause shorting.



DfR Solutions

Failure after Exposure to Vibration

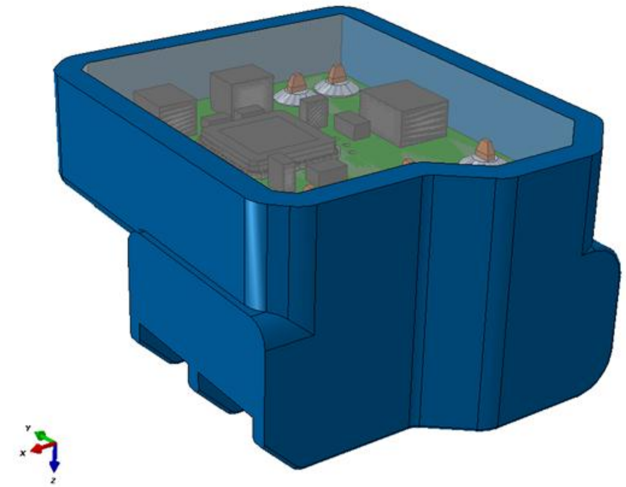
- Mechanical shock and vibration also leads to solder joint failures
- Can occur during transportation, installation or use



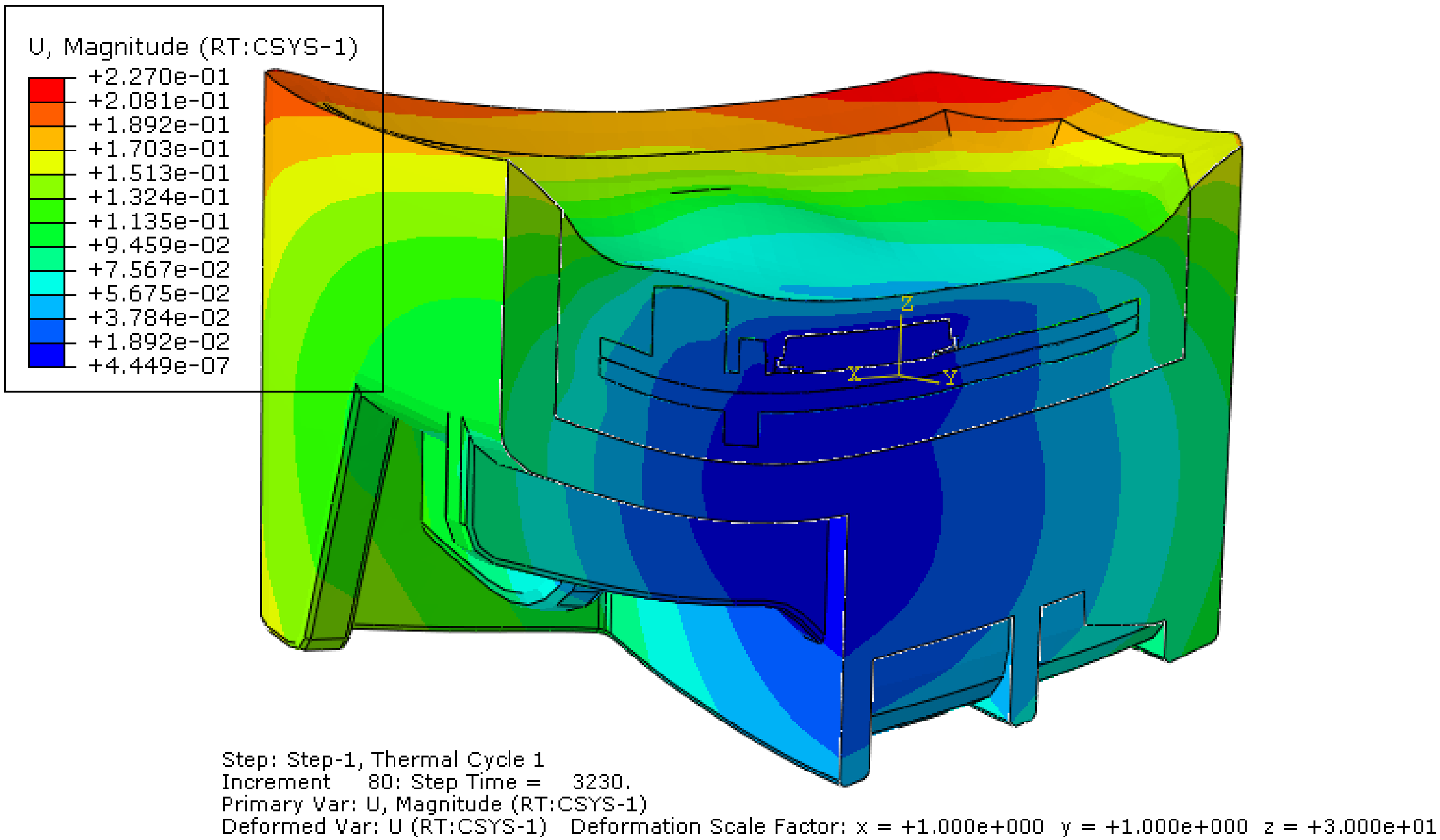
5110 Roanoke Place, Suite 101, College Park, MD 20740 | 301-474-0607 | www.dfrsolutions.com

Potting Electronic Assemblies

- Potting is the process of filling an electronic assembly with a resin compound
- Provides resistance to shock and vibration, and excludes moisture and corrosives.



Printed Circuit Board Warpage due to Potting Shrinkage



DfR Solutions
reliability designed, reliability delivered

An Effective Means to Model the Life of Solar Inverter Electronics

Solar Micro-Inverter Requirements

- The electronic components used in a micro-inverter are off-the-shelf
  - Designed for consumer electronics.
- How will these electronic assemblies survive the demands of the solar industry?

	Consumer Electronics	Micro-Inverter Electronics
Expected Life	5-7 years	20-25 years
User Environment	Indoor/Protected Temp Controlled	Outdoor/Partially Protected Temp Not Controlled

Solar Micro-Inverter Environment

- Extreme hot and cold locations (AZ to AK)
- Exposure to moisture/humidity
- Large diurnal thermal cycle events (daily)
- Largest temp swings occur in desert locations where it can reach 64C in the direct sun down to 23C at night (Δ41C)

DfR Solutions

NREL – Solar Panel Data

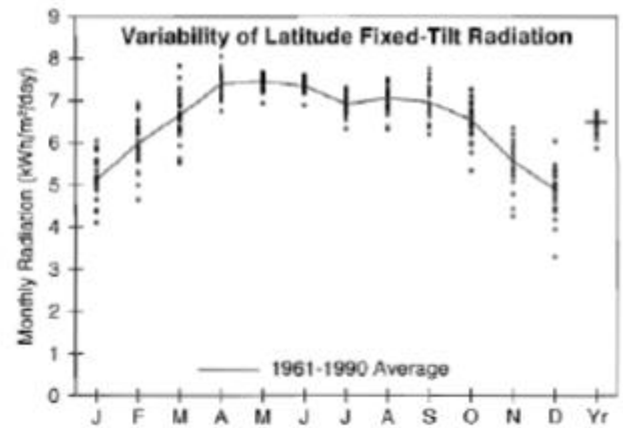
- Diurnal Cycles for Each Month

Phoenix, AZ

WBAN NO. 23183

LATITUDE: 33.43° N
LONGITUDE: 112.02° W
ELEVATION: 339 meters
MEAN PRESSURE: 974 millibars

STATION TYPE: Primary

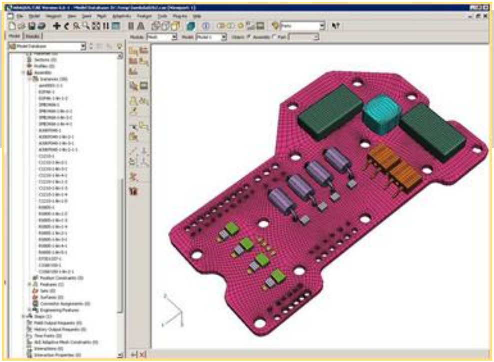


[illegible]	Min/Max	3.5/6.5	3.7/7.5	4.5/8.6	6.7/10.3	7.1/9.9	8.0/10.1	5.8/9.0	5.7/8.6	5.5/8.7	4.4/7.9	3.1/7.1	2.8/6.8	5.8/7.4

Temperature (°C)	12.0	14.3	16.8	21.1	26.0	31.2	34.2	33.1	29.8	23.6	16.6	12.3	22.6
Daily Minimum Temp	5.1	7.1	9.3	12.9	17.7	22.7	27.2	26.2	22.7	16.0	9.4	5.4	15.2
Daily Maximum Temp	18.8	21.5	24.2	29.2	34.2	39.7	41.1	39.8	36.8	31.2	23.8	19.0	29.9
Record Minimum Temp	-8.3	-5.6	-3.9	0.0	4.4	10.0	16.1	15.6	8.3	1.1	-3.9	-5.6	-8.3
Record Maximum Temp	31.1	33.3	37.8	40.6	45.0	50.0	47.8	46.7	47.8	41.7	33.9	31.1	50.0
HDD, Base 18.3°C	201	126	101	42	4	0	0	0	0	9	74	192	750
CDD, Base 18.3°C	4	12	53	123	242	387	491	457	343	173	23	4	2312
Relative Humidity (%)	51	44	39	28	22	19	32	36	36	37	44	52	37
Wind Speed (m/s)	2.5	2.8	3.2	3.4	3.4	3.2	3.4	3.2	3.0	2.8	2.6	2.5	3.0

What can be done?

- How can a micro-inverter supplier design the product to meet the requirements AND convince the customer of this?
- New method to model the reliability of an electronic assembly in a variety of conditions based on the design (before building anything).
- Design for Reliability (DfR) concepts and Physics of Failure (PoF) are used. .
- A comprehensive software package was developed to simplify this modeling, making it available to design engineers.



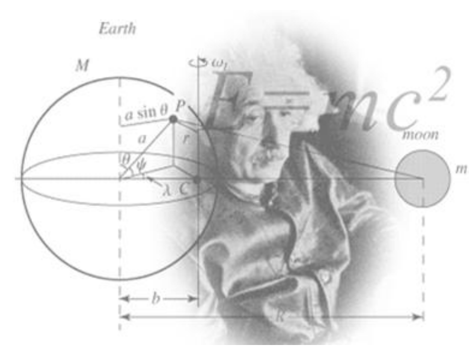
Design for Reliability (DfR)

- DfR: A process for ensuring the reliability of a product or system during the design stage *before* physical prototype

- Reliability: The measure of a product's ability to
  - …perform the specified function
  - …at the customer (with their use environment)
  - …over the desired lifetime

Physics of Failure (PoF)

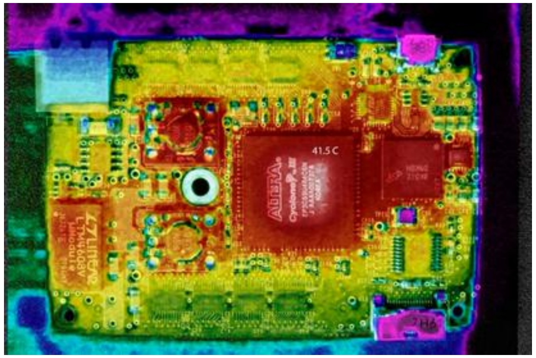
- PoF Definition: The use of science (physics, chemistry, etc.) to capture an understanding of failure mechanisms and evaluate useful life under actual operating conditions
- Using PoF, design, perform, and interpret the results of *accelerated* life tests
  - Starting at design stage
  - Continuing throughout the lifecycle of the product



- Start with standard industry specifications
  - Modify or exceed them
  - Tailor test strategies specifically for the individual product design and materials, the use environment, and reliability needs

Physics of Failure Definitions

- Failure of a physical device or structure (i.e. hardware) can be attributed to the gradual or rapid degradation of the material(s) in the device in response to the stress or combination of stresses the device is exposed to, such as:
  - Thermal, Electrical, Chemical, Moisture, Vibration, Shock, Mechanical Loads . . .



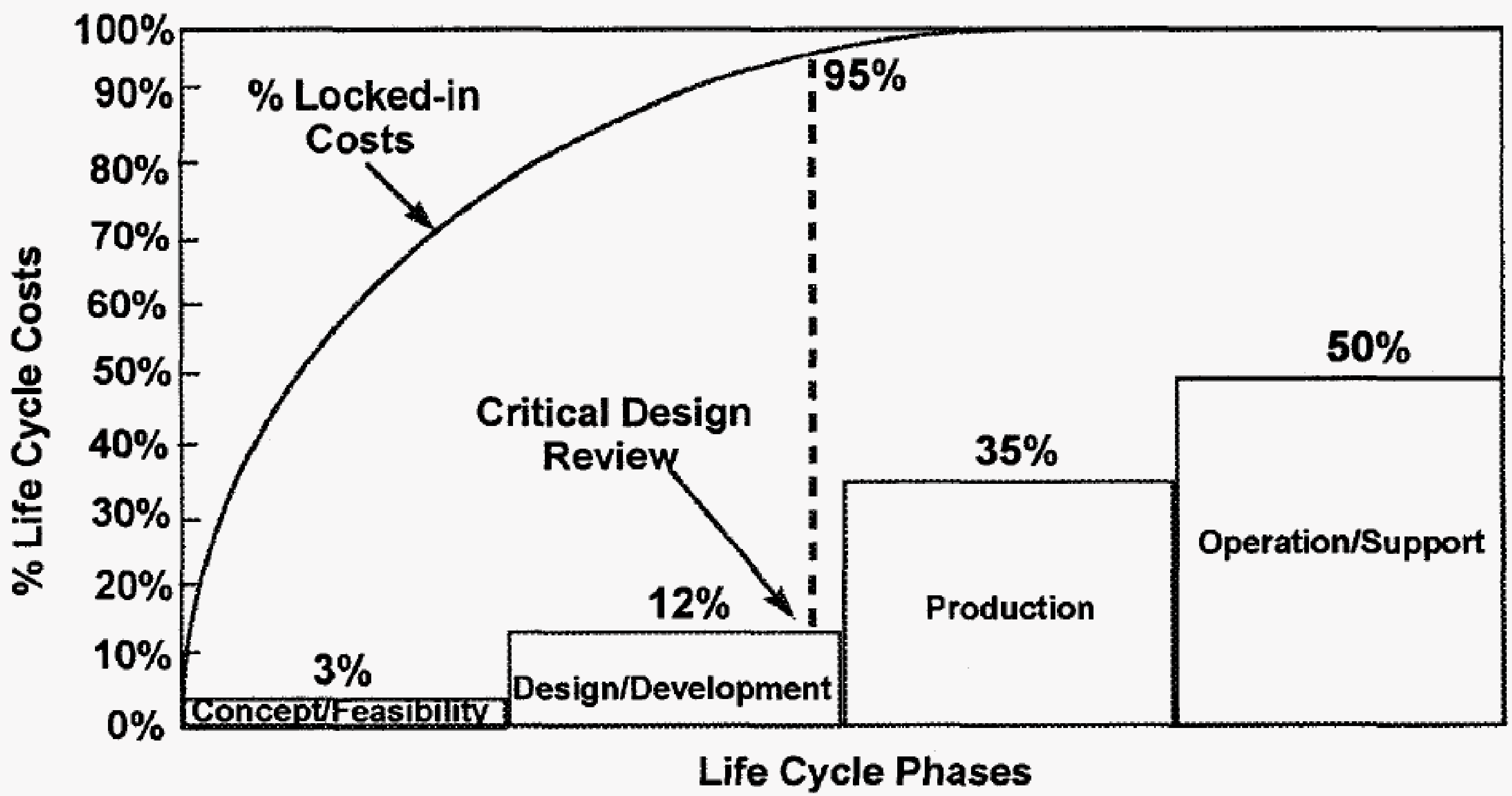
- Failures May Occur:
  - Prematurely
  - Gradually
  - Erratically

Are there Methods to Model these Failure Mechanisms?

- Yes!
- Algorithms exist to estimate the failure rate from solder joint fatigue for different types of components.
- IPC TR-579 models Pin Through Hole & via reliability
- Risk for Conductive Anodic Filaments can be determined
- Finite Element Analysis can be used for Shock & Vibration risk.
- MTBF (Mean Time Between Failure) calculations can be performed to estimate component failure rates

Why is modeling reliability early important?

Reduce Costs by Improving Reliability Upfront

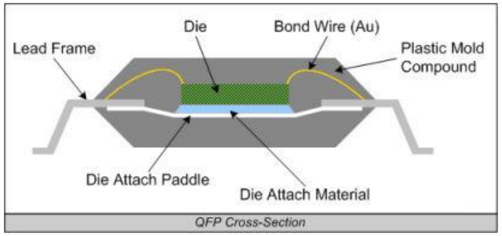


Architectural Design for Reliability, R. Cranwell and R. Hunter, Sandia Labs, 1997

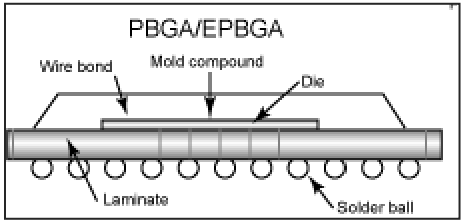
Solder Joint (SJ) Wearout

- Elimination of leaded devices
  - Provides lower RC and higher package densities
  - Reduces compliance

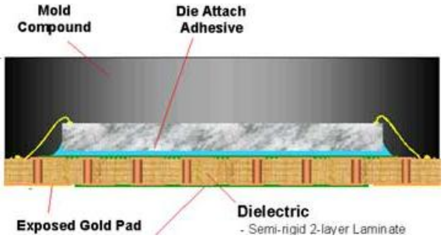
Cycles to failure
-40 to 125C



QFP: >10,000



BGA: 3,000 to 8,000



QFN: 1,000 to 3,000

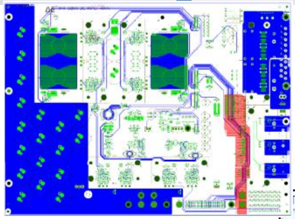
CSP / Flip Chip: <1,000

DfR Solutions

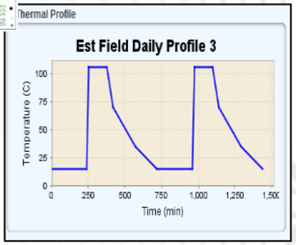
Software Modeling

- Tool predicts failures from
  - Solder joint wear-out from thermal cycling (SAC305 or eutectic SnPb solders)
  - Plated through hole fatigue
  - Conductive anodic filament formation
  - MIL Handbook 217 MTBF calculations are also generated
- Software uses Finite Element Analysis to determine
  - Board deflection and solder joint failure from mechanical vibration
  - The natural frequencies for the board based on the mount points.
  - Board deflection due to shock events

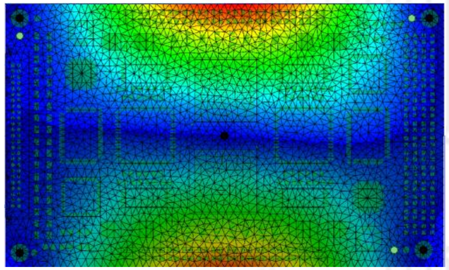
The 4 Parts of a Sherlock Analysis



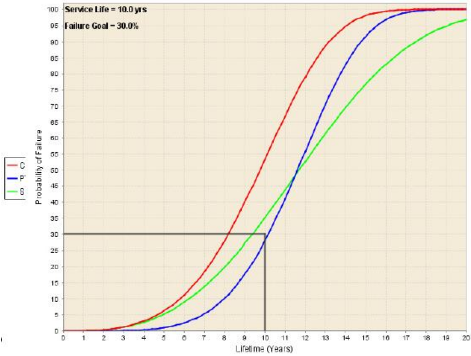
1) **Design Capture** - provide industry standard inputs to the modeling software and calculation tools



2) **Life-Cycle Characterization** - define the reliability/durability objectives and expected environmental & usage conditions (Field or Test) under which the device is required to operate

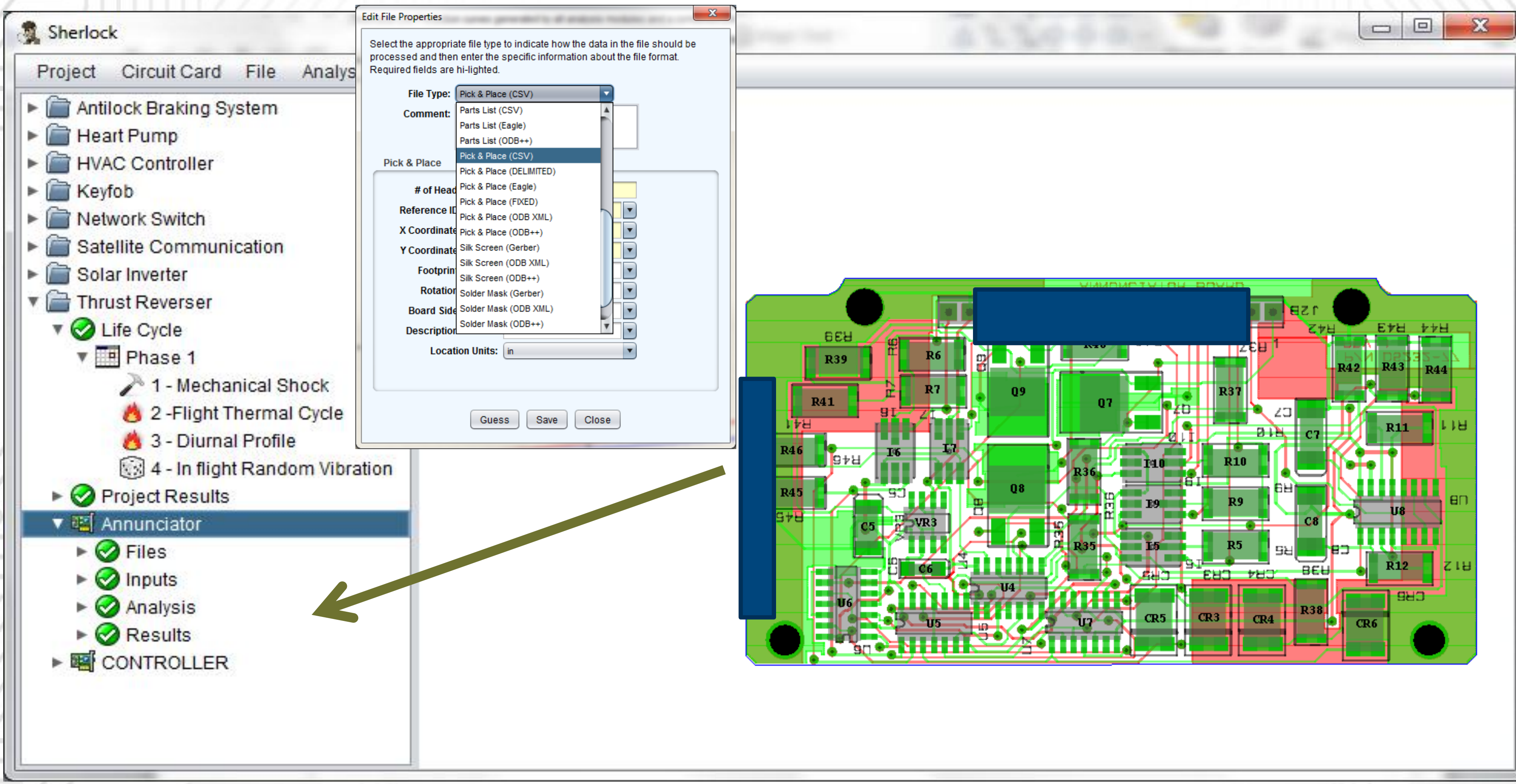


3) **Load Transformation** – automated calculations that translates and distributes the environmental and operational loads across a circuit board to the individual parts



4) **PoF Durability Simulation/Reliability Analysis & Risk Assessment** – Performs a design and application specific durability simulation to calculates life expectations, reliability distributions & prioritizes risks by applying PoF algorithms to the PCBA model

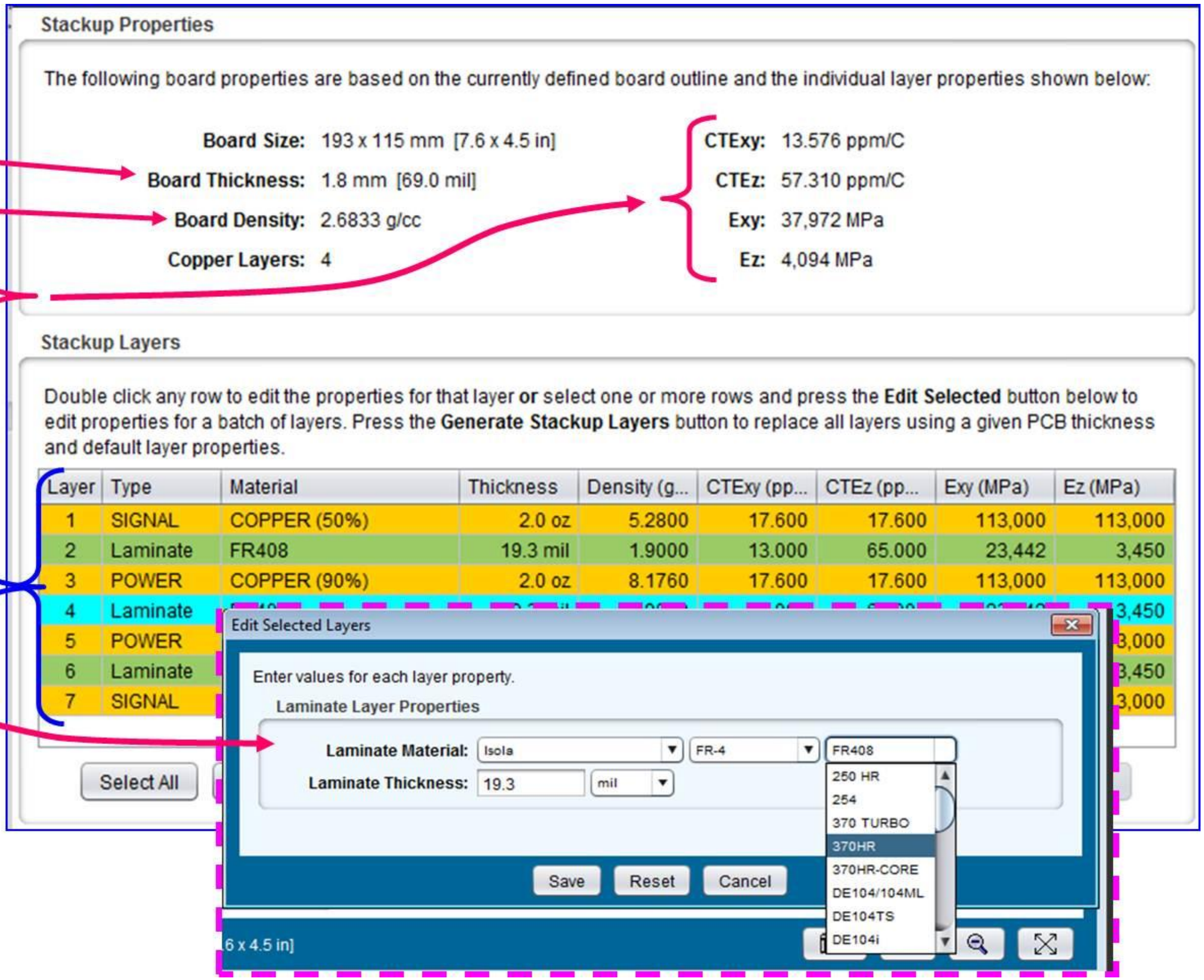
Design Capture



- Imports standard PCB CAD/CAM design files (Gerber / ODB++) to automatically create a CAE virtual circuit board model

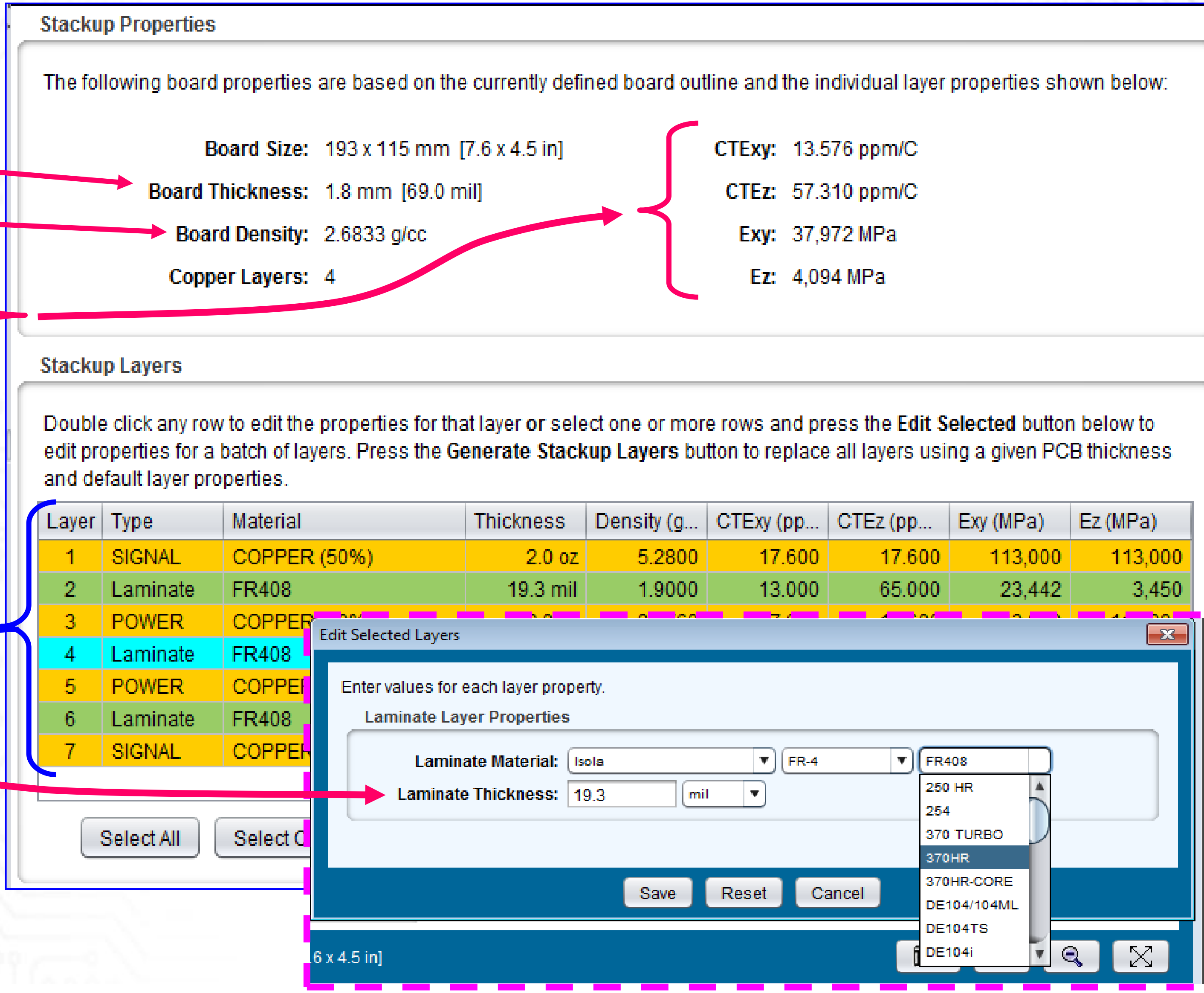
Printed Circuit Board Details Required for Modeling

Calculates
- Thickness
- Density
- CTE x-y
- CTE z
- Modulus x-y
- Modulus z
- From the material properties of each layer
- Using the Built in Laminate Data Library

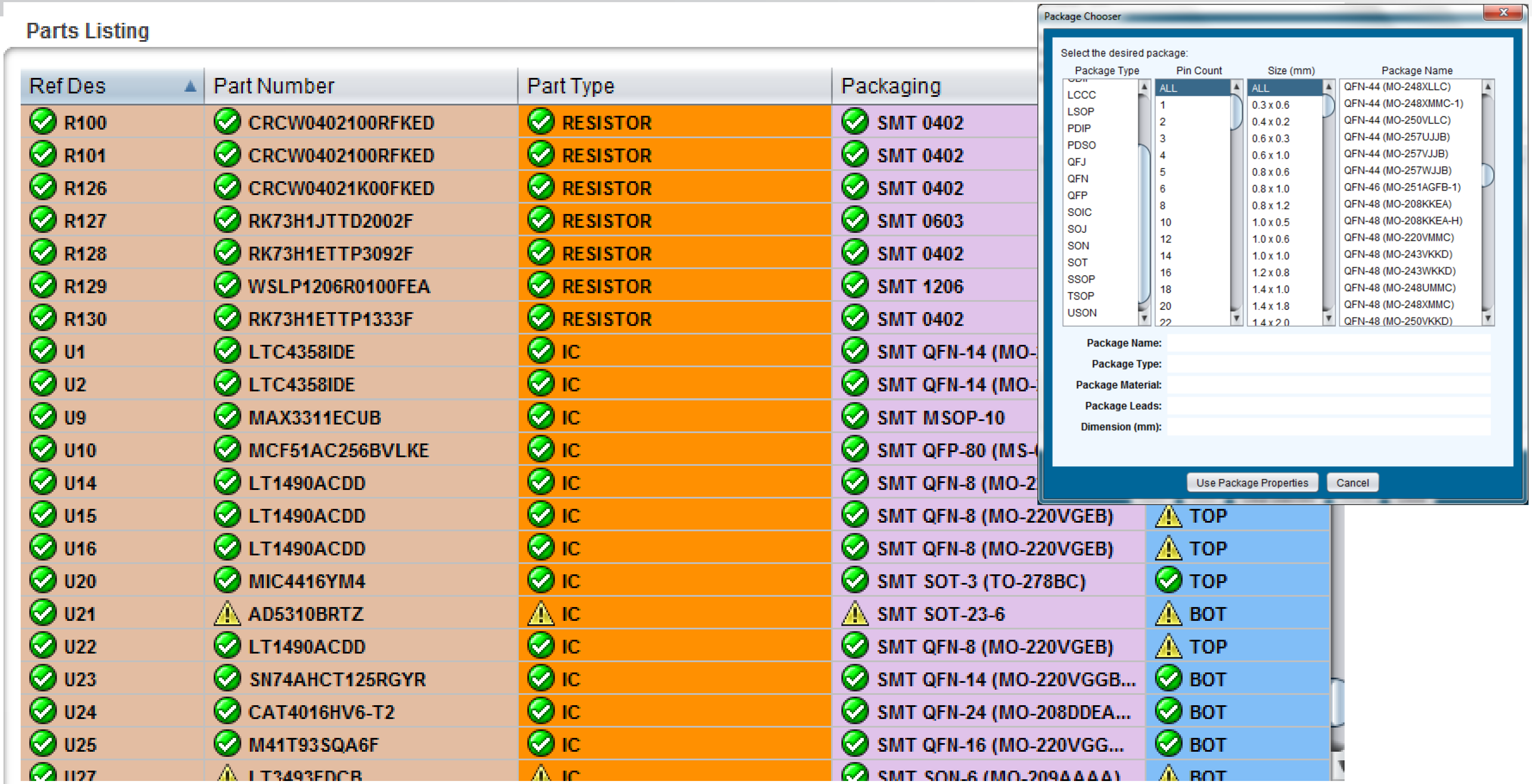


Design Capture – Printed Circuit Board Laminate & Layers

Calculates
- Thickness
- Density
- CTE x-y
- CTE z
- Modulus x-y
- Modulus z
- From the material properties of each layer
- Using the Built in Laminate Data Library



Establish Part Parameters



Parts Listing

Ref Des	Part Number	Part Type	Packaging	
R100	CRCW0402100RFKED	RESISTOR	SMT 0402	
R101	CRCW0402100RFKED	RESISTOR	SMT 0402	
R126	CRCW04021K00FKED	RESISTOR	SMT 0402	
R127	RK73H1JTTD2002F	RESISTOR	SMT 0603	
R128	RK73H1ETTP3092F	RESISTOR	SMT 0402	
R129	WSLP1206R0100FEA	RESISTOR	SMT 1206	
R130	RK73H1ETTP1333F	RESISTOR	SMT 0402	
U1	LTC4358IDE	IC	SMT QFN-14 (MO-	
U2	LTC4358IDE	IC	SMT QFN-14 (MO-	
U9	MAX3311ECUB	IC	SMT MSOP-10	
U10	MCF51AC256BVLKE	IC	SMT QFP-80 (MS-	
U14	LT1490ACDD	IC	SMT QFN-8 (MO-2	
U15	LT1490ACDD	IC	SMT QFN-8 (MO-220VGEB)	TOP
U16	LT1490ACDD	IC	SMT QFN-8 (MO-220VGEB)	TOP
U20	MIC4416YM4	IC	SMT SOT-3 (TO-278BC)	TOP
U21	AD5310BRTZ	IC	SMT SOT-23-6	BOT
U22	LT1490ACDD	IC	SMT QFN-8 (MO-220VGEB)	TOP
U23	SN74AHCT125RGYR	IC	SMT QFN-14 (MO-220VGGB...	BOT
U24	CAT4016HV6-T2	IC	SMT QFN-24 (MO-208DDEA...	BOT
U25	M41T93SQA6F	IC	SMT QFN-16 (MO-220VGG...	BOT
U27	LT3493EDCB	IC	SMT SON-6 (MO-209AAAA)	BOT

- Components identified along with packaging properties.
- Minimizes data entry through intelligent parsing and embedded package and material databases

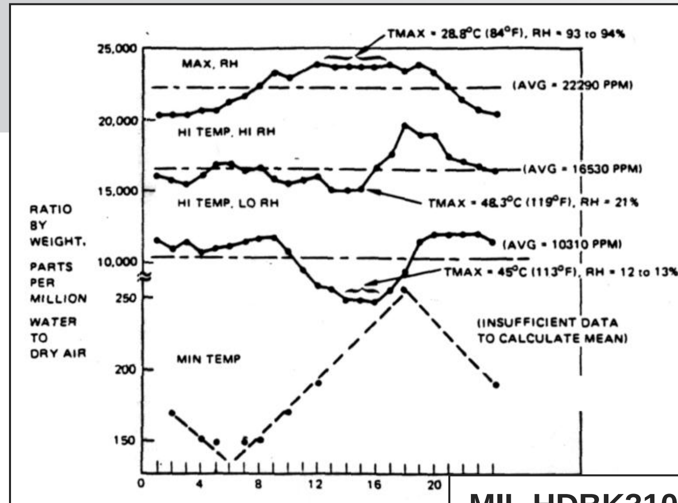
DfR Solutions

Define Reliability Goals

- Identify and document two key metrics
  - *Desired lifetime*
    - Defined as time the *customer* is satisfied with
    - Should be actively used in development of part and product qualification
  - *Product performance*
    - Returns during the warranty period
    - Survivability over lifetime at a set confidence level
    - MTBF or MTTF (try to avoid unless required by customer)

Identify Use Environment

- Old School Approach: Use of industry/military specifications
  - Military, IPC, Telcordia, ASTM…..
- Advantages
  - No additional cost!
  - Sometimes very comprehensive
  - Agreement throughout the industry
  - Missing information? Consider standards from other industries
- Disadvantages
  - Most more than 20 years old
  - Always less or greater than actual (by how much, unknown)



MIL HDBK310

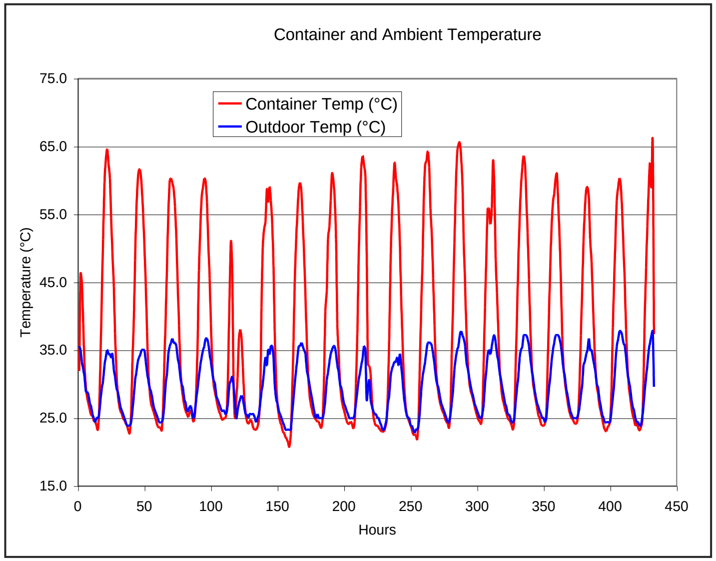
USE CATEGORY	WORST-CASE USE ENVIRONMENT Tmin °C	Tmax °C	$\Delta T^{(1)}$ °C	t_D hrs	Cycles/ year	Typical Years of Service	Approx. Accept. Failure Risk, %	ACCELERATED TESTING Tmin °C	Tmax °C	$\Delta T^{(2)}$ °C	t_D min
1) CONSUMER	0	+60	35	12	365	1-3	1	+25	+100	75	15
2) COMPUTERS	+15	+60	20	2	1460	5	0.1	+25	+100	75	15
3) TELECOM	- 40	+85	35	12	365	7-20	0.01	0	+100	100	15
4) COMMERCIAL AIRCRAFT	-55	+95	20	12	365	20	0.001	0	+100	100	15
5) INDUSTRIAL & AUTOMOTIVE PASSENGER COMPARTMENT	-55	+95	20 &40 &60 &80	12 12 12 12	185 100 60 20	10	0.1	0	+100	100 & COLD(3)	15
6) MILITARY GROUND & SHIP	-55	+95	40 &60	12 12	100 265	10	0.1	0	+100	100 & COLD(3)	15
7) SPACE leo geo	-55	+95	3 to 100	1 12	8760 365	5-30	0.001	0	+100	100 & COLD(3)	15
8) MILITARY AVIONICS a b c	-55	+95	40 60 80 &20	2 2 2 1	365 365 365 365	10	0.01	0	+100	100 & COLD(3)	15
9) AUTOMOTIVE UNDER HOOD	-55	+125	60 &100 &140	1 1 2	1000 300 40	5	0.1	0	+100	100	15

IPC SM785

DfR Solutions

Use Environment (cont.)

- Approach 2: Based on actual measurements of similar products in similar environments
  - Determine average and realistic worst-case
  - Identify all failure-inducing loads
  - Include all environments
    - Manufacturing
    - Transportation
    - Storage
    - Field

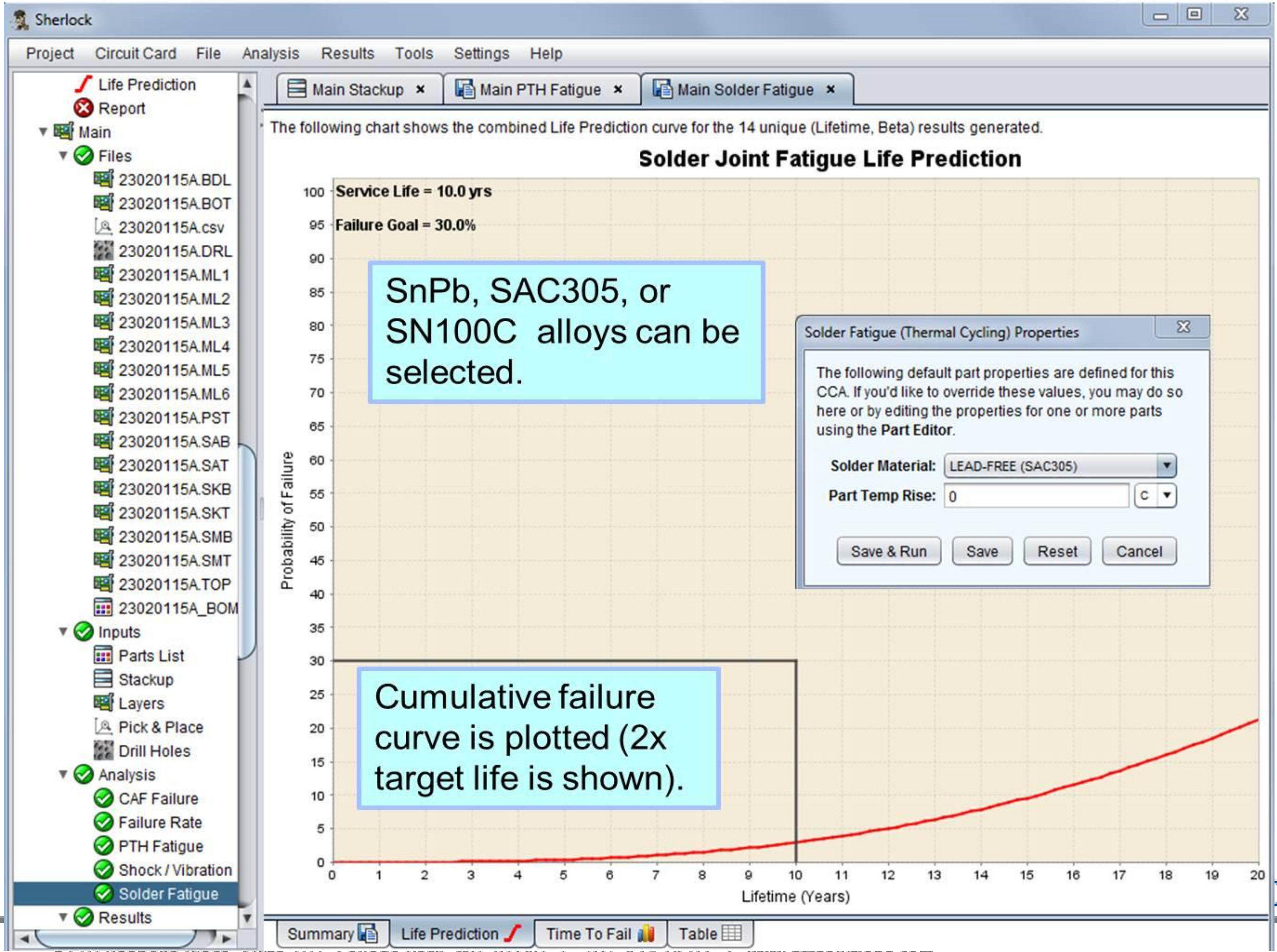


DfR Solutions

Environment Profiles in Sherlock

- Define Thermal, Vibration & Shock Stress Profiles

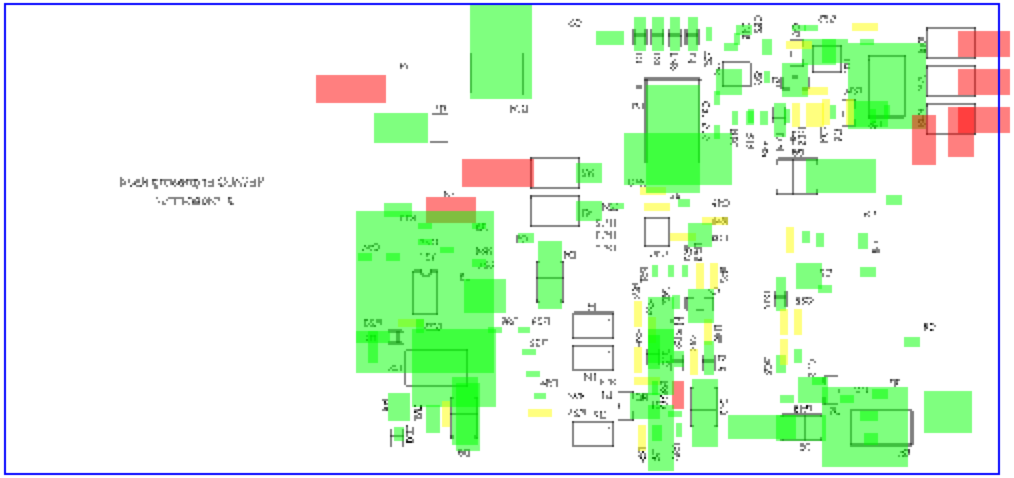
Thermal Cycle Fatigue Analysis – Example Plot



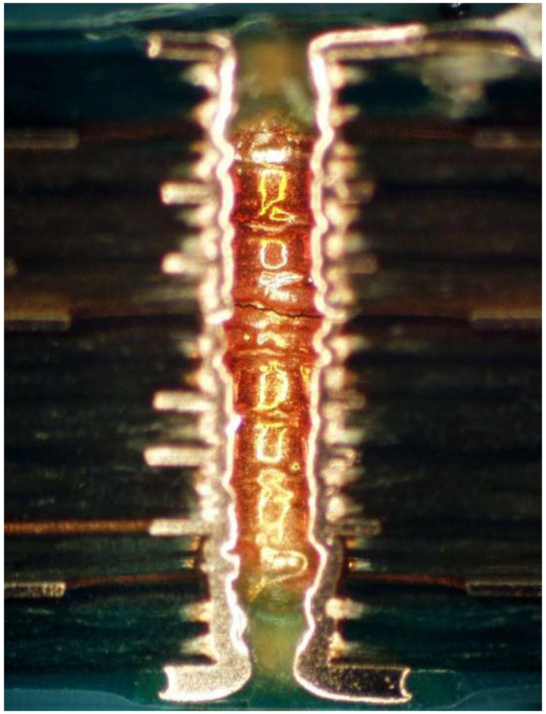
Highest Risk Components

- Large Resistors provide the weakest solder joints in this example.

RefDes	Package	Part Type	Part Number	Solder	Temp Rise	Cycles to Fail ▲	TTF (yrs)	Score
R3	2512	RESISTOR	47	SAC305	0.0	75,290	34.46	1.9
R4	2512	RESISTOR	100	SAC305	0.0	75,290	34.46	1.9
R9	1210	RESISTOR	Not_Stuffed	SAC305	0.0	78,735	36.03	2.4
R17	1210	RESISTOR	0.43_1/2W_1_	SAC305	0.0	78,735	36.03	2.4
R18	1210	RESISTOR	_Table_1	SAC305	0.0	78,735	36.03	2.4
R43	1210	RESISTOR	430	SAC305	0.0	78,735	36.03	2.4
R44	1210	RESISTOR	430	SAC305	0.0	78,735	36.03	2.4
R45	1210	RESISTOR	430	SAC305	0.0	78,735	36.03	2.4
R39	0805_-_R:...	RESISTOR	47k	SAC305	0.0	123,549	56.54	8.3
R14	0603_-_R:...	RESISTOR	4.02k_0.1_	SAC305	0.0	>124,545	>57	10.0
R23	0603_-_R:...	RESISTOR	75k	SAC				
R24	0603_-_R:...	RESISTOR	47k	SAC				
R26	0603_-_R:...	RESISTOR	1k	SAC				
R27	0603_-_R:...	RESISTOR	_Table_1	SAC				
R28	0603_-_R:...	RESISTOR	1.3k	SAC				
R29	0603_-_R:...	RESISTOR	5.1k	SAC				
R40	0603_-_R:...	RESISTOR	27k_1_	SAC				
R41	0603_-_R:...	RESISTOR	40.2k_1_	SAC				
R42	0603_-_R:...	RESISTOR	40.2k_1_	SAC				



Plated Through-Hole Reliability Modeling

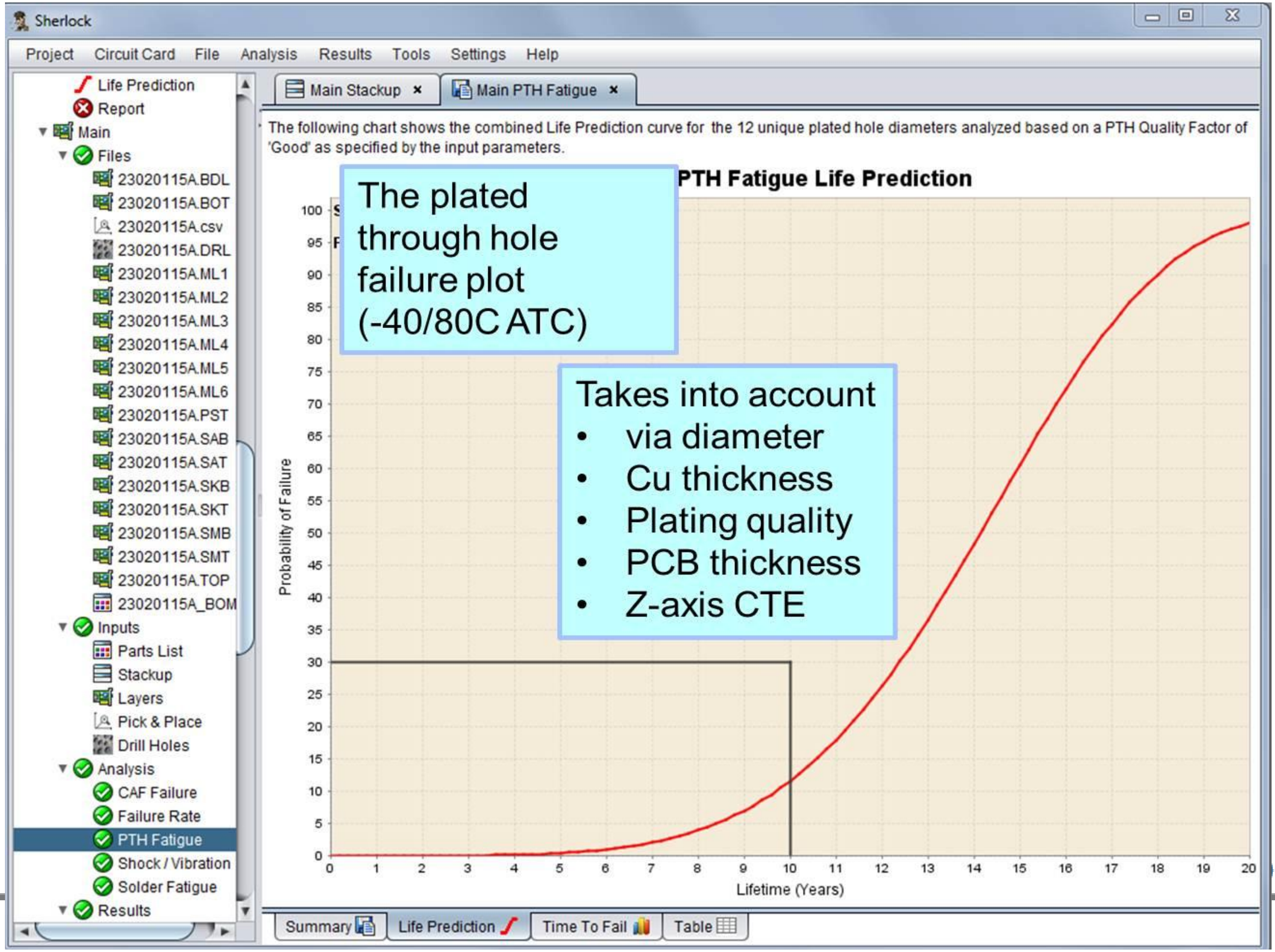


When a PCB experiences thermal cycling, the expansion/ contraction in the z-direction is much higher than that in the x-y plane.

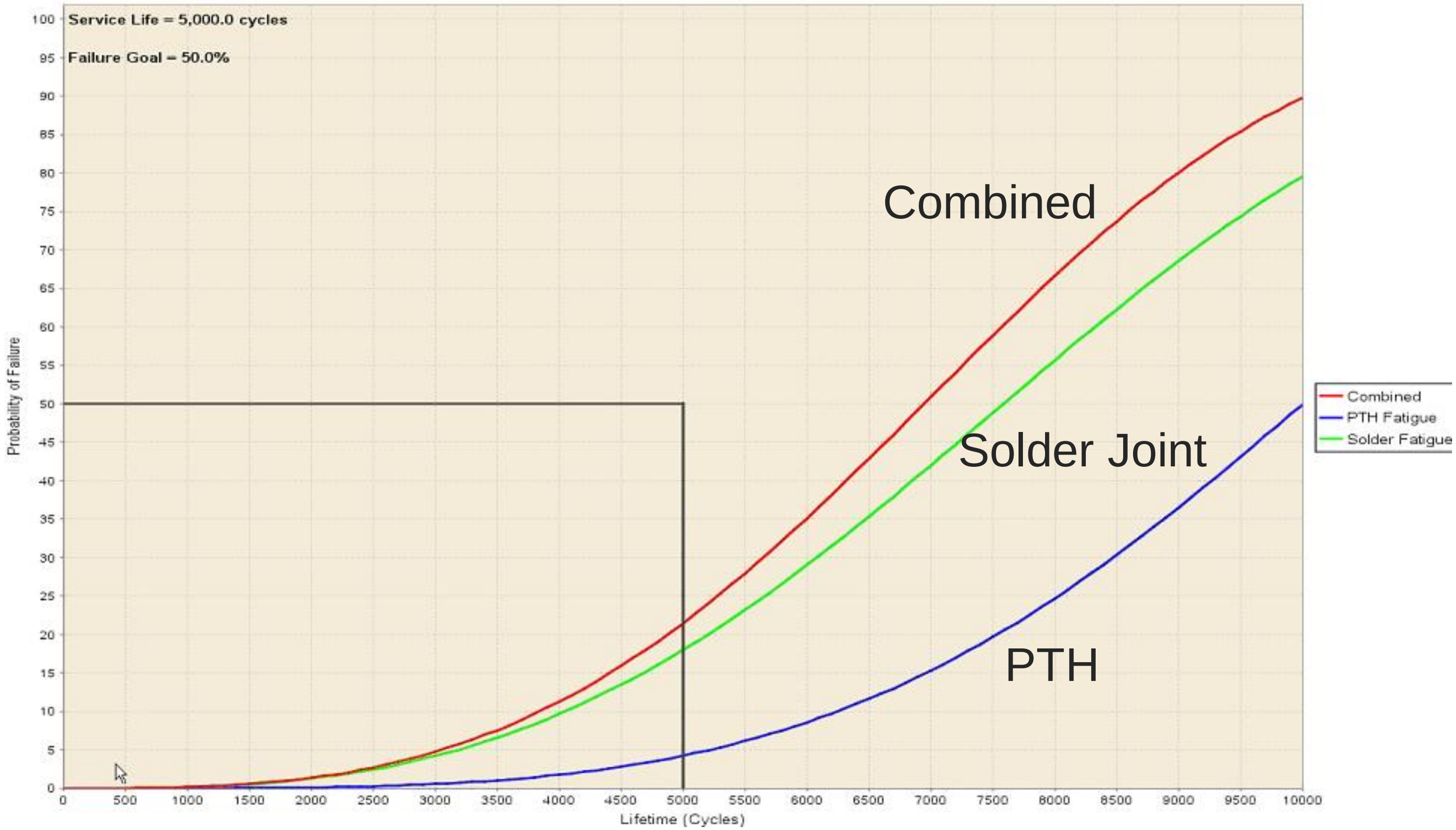
The glass fibers constrain the board in the x-y plane but not through the thickness.

As a result, a great deal of stress can be built up in the copper via barrels resulting in eventual cracking near the center of the barrel as shown in the cross section photos.

PTH Fatigue Results - Example



Combined (SJ & PTH) Lifetime Prediction

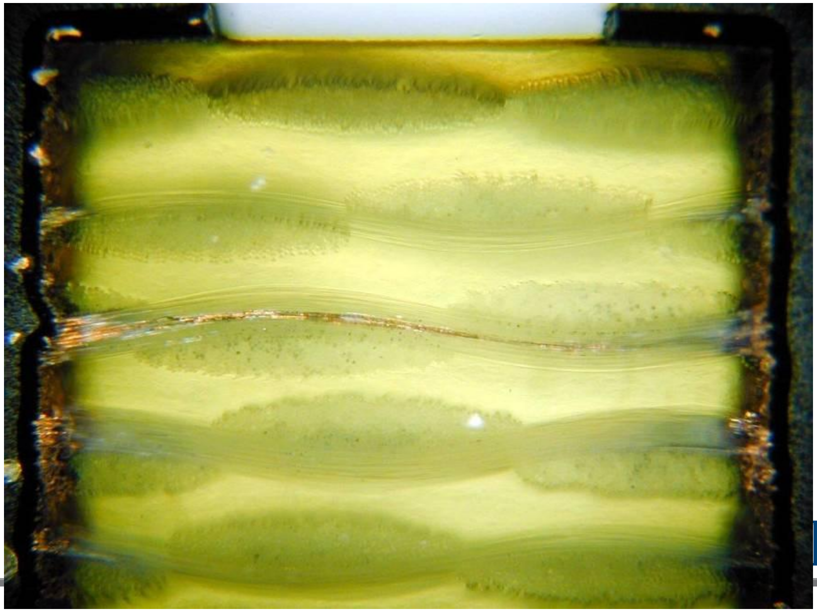


- Combines analysis results into overall failure prediction curve

DfR Solutions

Risk for Conductive Anodic Filament Formation (CAF)

- CAF formation becomes a risk when plated through hole vias are so close together that damage from drilling can open up a pathway between vias.
- Copper from the via can migrate along the pathway and eventually cause shorting.



CAF Analysis

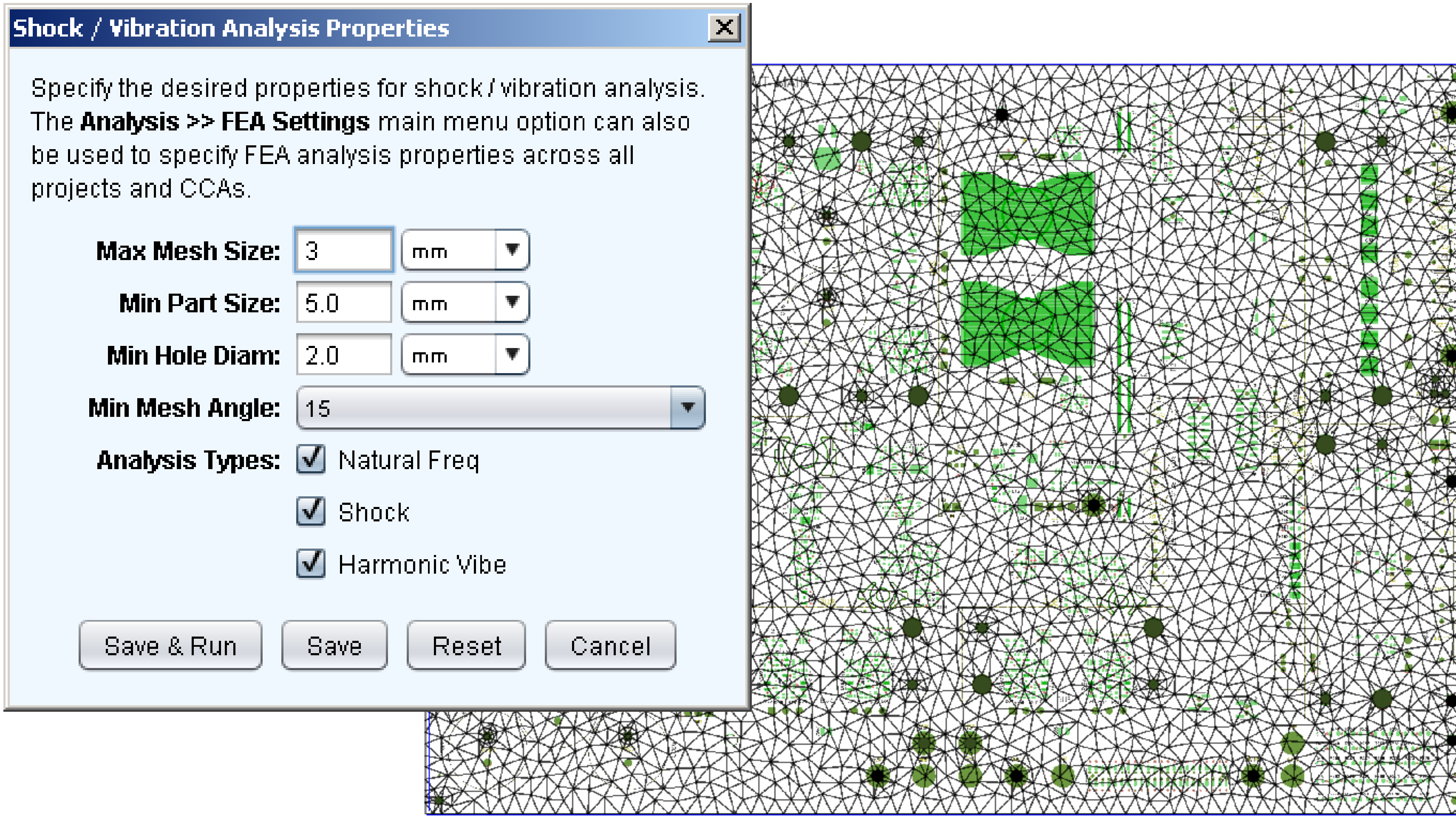
- The primary variables that effect the probability of CAF formation are:
  - Distance between vias
  - Damage during drilling process
  - Temperature and humidity conditions
  - Voltage differential between vias
- The analysis takes into account the first two variables only (measures distance between all PTH pairs).
- Vias identified as being too close are flagged.

CAF Analysis

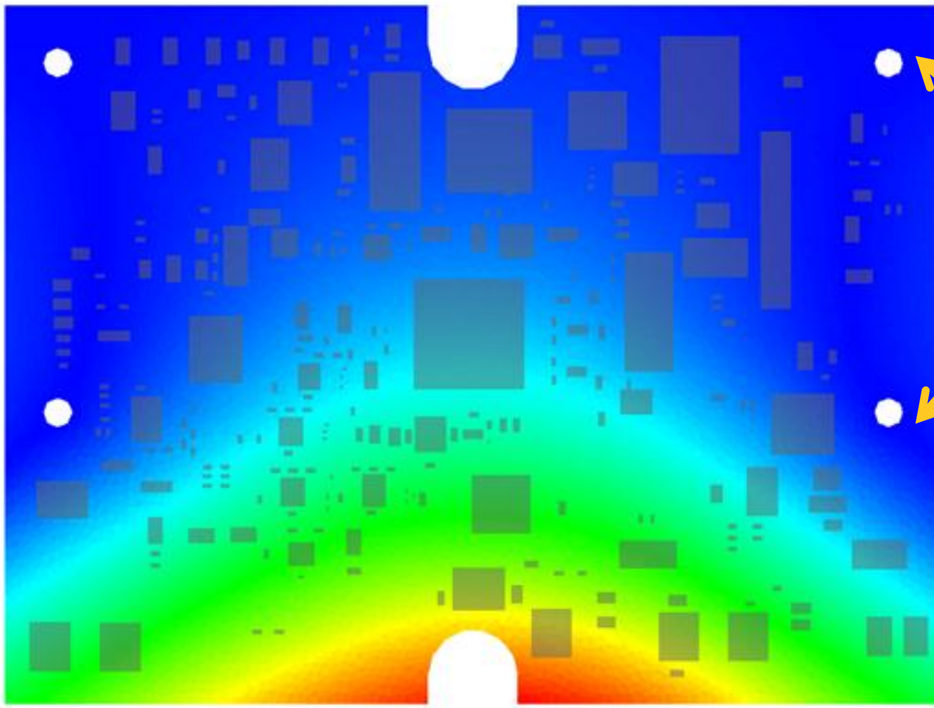
- Software will flag vias at high risk for CAF formation

Finite Element Analysis

- PCBA Example with Mesh Outlined



Natural Frequencies are Calculated



MPs

Figure 19: 1st natural frequency 299.6 Hz, red denotes areas of highest deflection

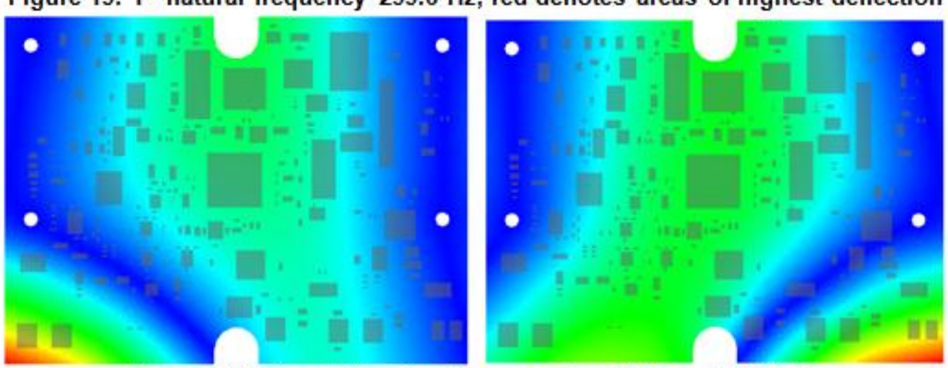


Figure 20: 2nd and 3rd natural frequencies 478.6 and 511.6 Hz

Select the number of natural frequencies to look for within the desired frequency range.

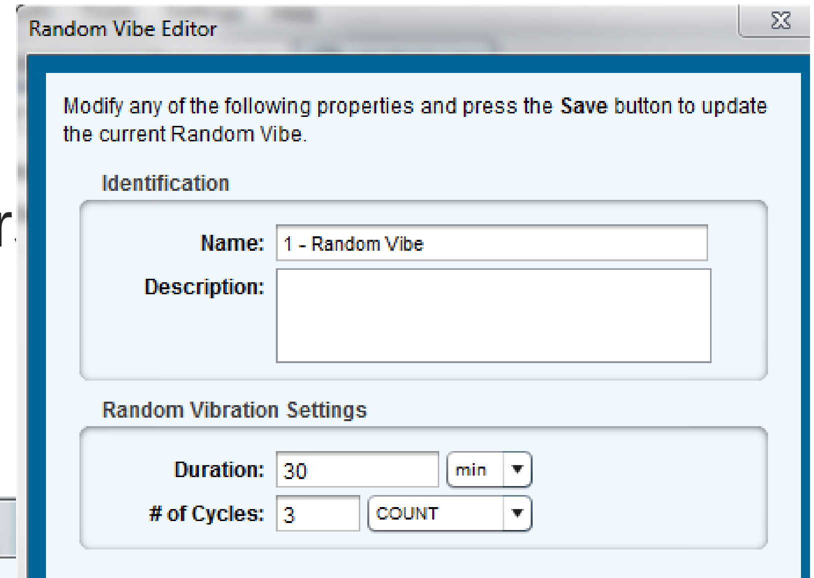
Components in high strain regions are at risk.

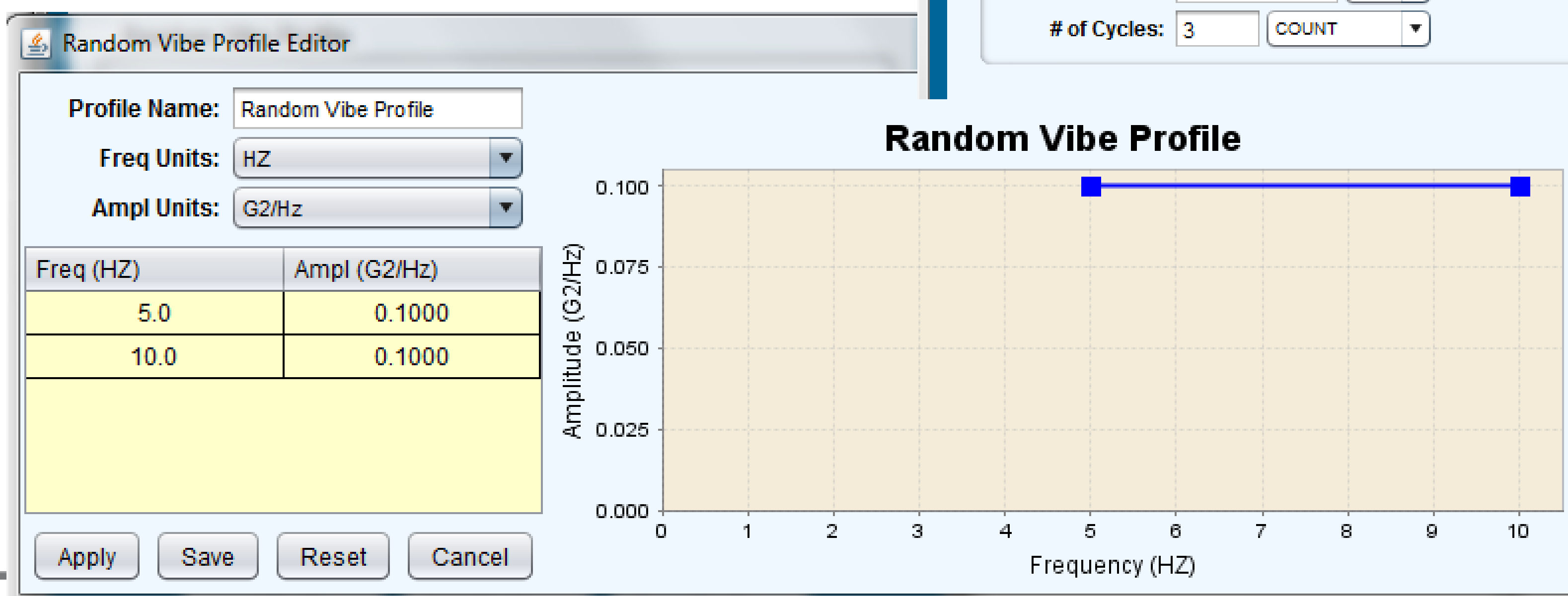
- Move the components
- Move/add mounting points.

Vibration Environment

Complex vibration profiles can be modeled.

- Qualification test parameters
- Shipping/Transportation
- Field conditions





Random Vibration Strain

Random Vibration

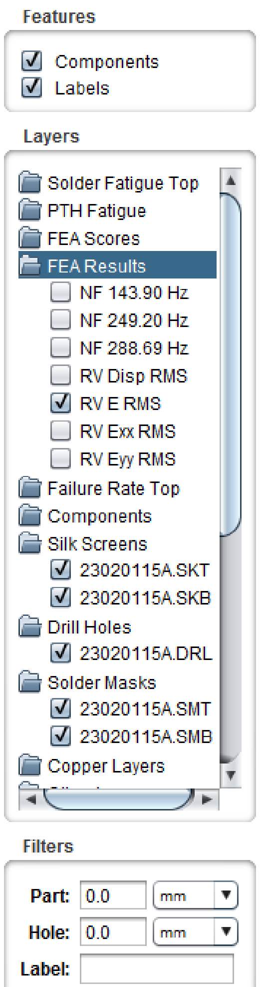
Duty Cycle (%): 10

Power Spectral Density:

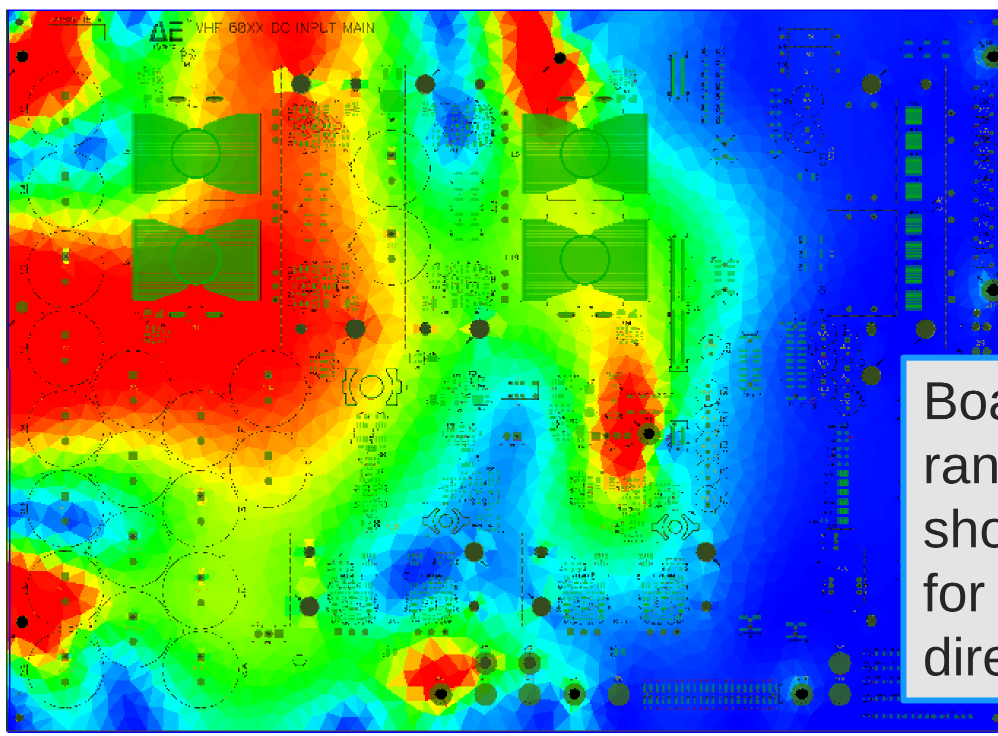
Amplitude	Units	Freq	Units
0.002868	G2/Hz	5.0	Hz
0.002868	G2/Hz	120.0	Hz

Load ... | Add Row | Delete Row | Save ...

Vibration set to simulate shipping



Random Vibration



Strain Range [3.5e-22, 1.8e-5]

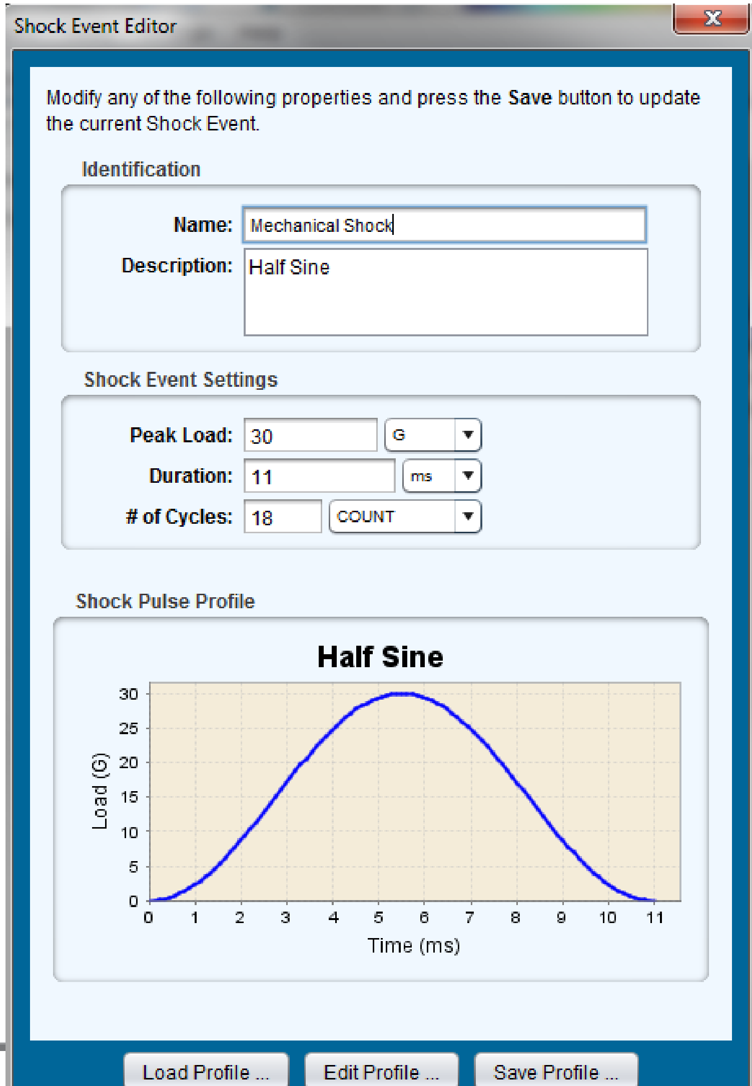
Board strain from random vibration is shown (calculated for x, y, and z directions)

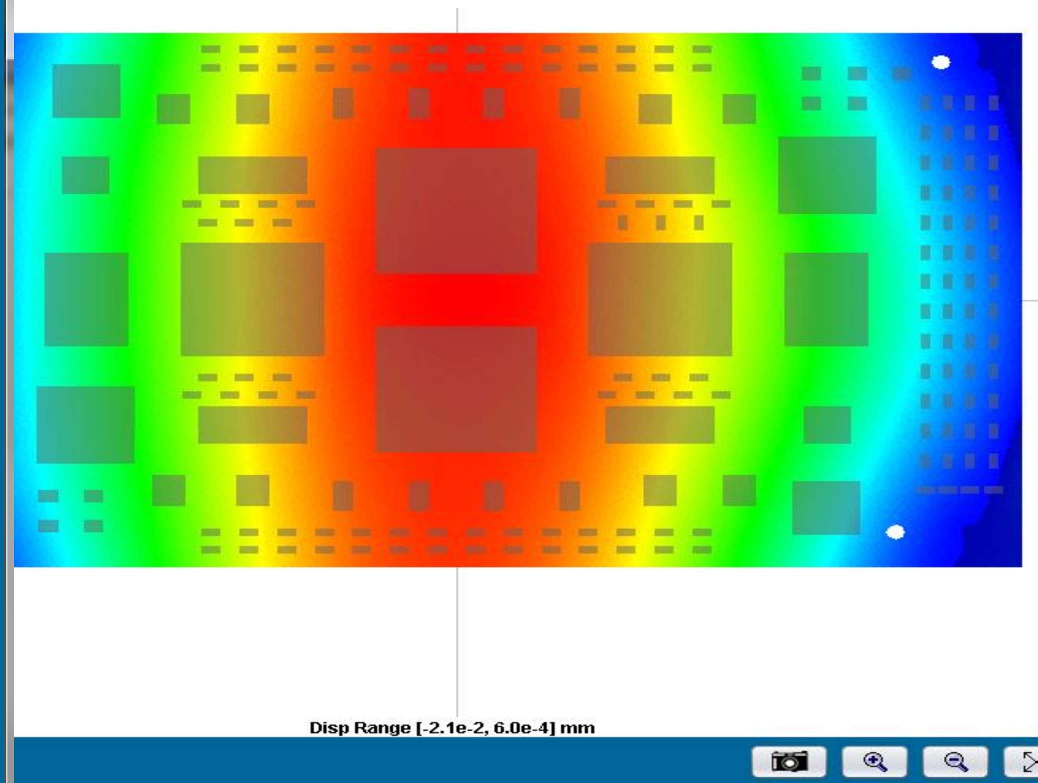
Solutions

Software Shock

- Implements Shock based upon a critical board level strain
- Will not predict how many drops to failure
- Either the design is robust with regards to the expected shock environment or it is not
- Additional work being initiated to investigate corner staking patterns and material influences

Shock Results - Example





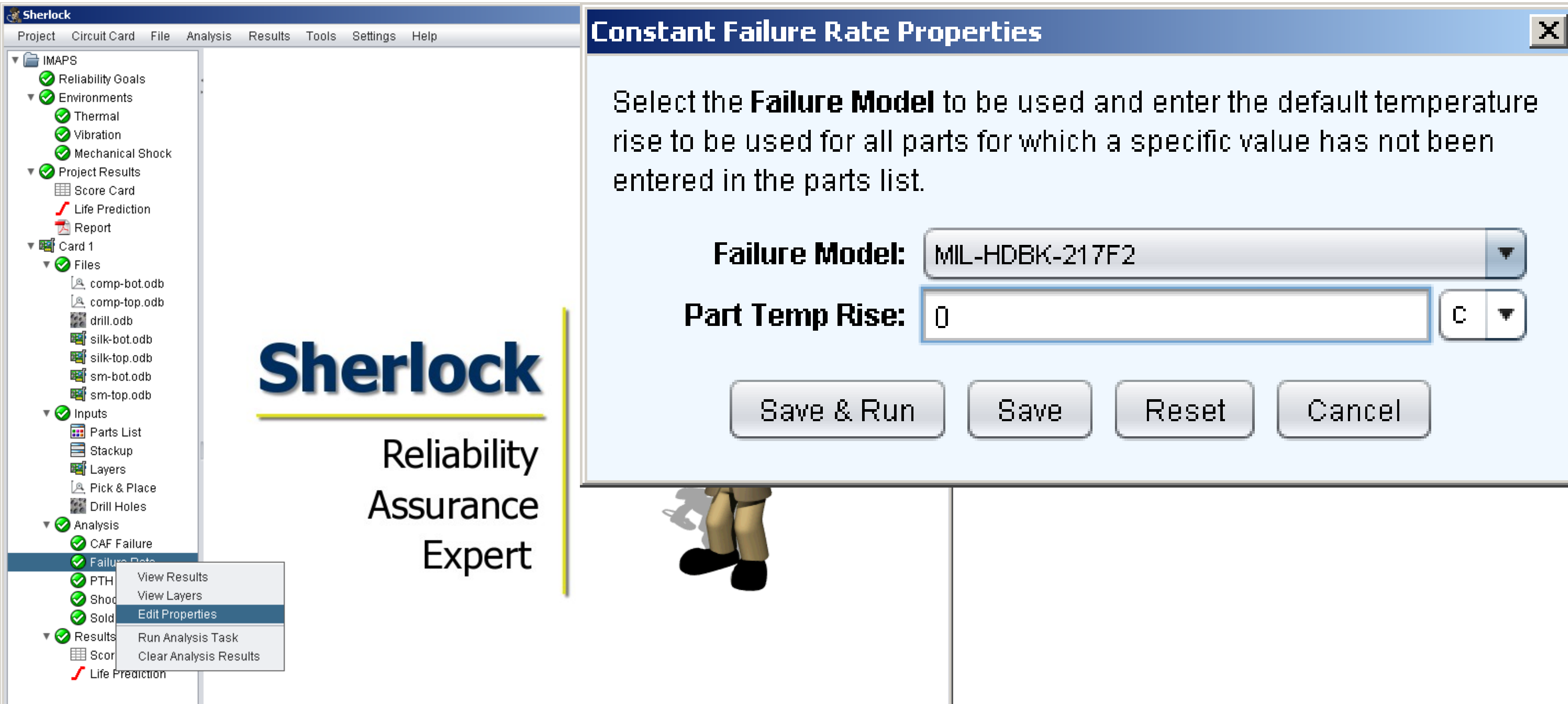
Shock Results – Component Breakdown

Components listed in order of maximum strain experienced.

Card 1 Shock / Vibration

RefDes	Package	Part Type	Material	Max Disp	Max Strain	Score
U1	QFJ-20	IC	OVERMOLD-LEADED	9.0E-3	5.2E-4	2.7
U2	QFJ-20	IC	OVERMOLD-LEADED	8.6E-3	4.9E-4	3.4
Q14	DPAK	TRANSIST...	OVERMOLD-LEADED	1.3E-2	4.0E-4	5.6
U7	QFP-100 (MS-026...	IC	OVERMOLD-LEADED	1.0E-2	3.9E-4	5.6
U11	LCCC-44	IC	ALUMINA	1.1E-2	3.9E-4	5.7
Q16	DPAK	TRANSIST...	OVERMOLD-LEADED	1.2E-2	3.8E-4	5.9
U12	LCCC-44	IC	ALUMINA	1.2E-2	3.8E-4	6.0
U8	QFP-100 (MS-026...	IC	OVERMOLD-LEADED	1.2E-2	3.8E-4	6.0
Q10	DPAK	TRANSIST...	OVERMOLD-LEADED	1.6E-2	3.2E-4	7.2
U13	TSOP-32 (MO-142...	IC	OVERMOLD-LEADED	1.8E-2	3.2E-4	7.2
Q13	DPAK	TRANSIST...	OVERMOLD-LEADED	1.3E-2	3.2E-4	7.3
Q12	DPAK	TRANSIST...	OVERMOLD-LEADED	1.2E-2	3.2E-4	7.3
U15	TSOP-32 (MO-142...	IC	OVERMOLD-LEADED	1.8E-2	3.1E-4	7.4
U14	TSOP-32 (MO-142...	IC	OVERMOLD-LEADED	1.8E-2	3.1E-4	7.4
Q15	DPAK	TRANSIST...	OVERMOLD-LEADED	1.7E-2	3.1E-4	7.5
U6	QFN-80 (MO-239...	IC	OVERMOLD-QFN	9.6E-3	3.1E-4	7.5
U5	QFN-80 (MO-239...	IC	OVERMOLD-QFN	9.1E-3	3.0E-4	7.6
Q9	DPAK	TRANSIST...	OVERMOLD-LEADED	1.6E-2	3.0E-4	7.7

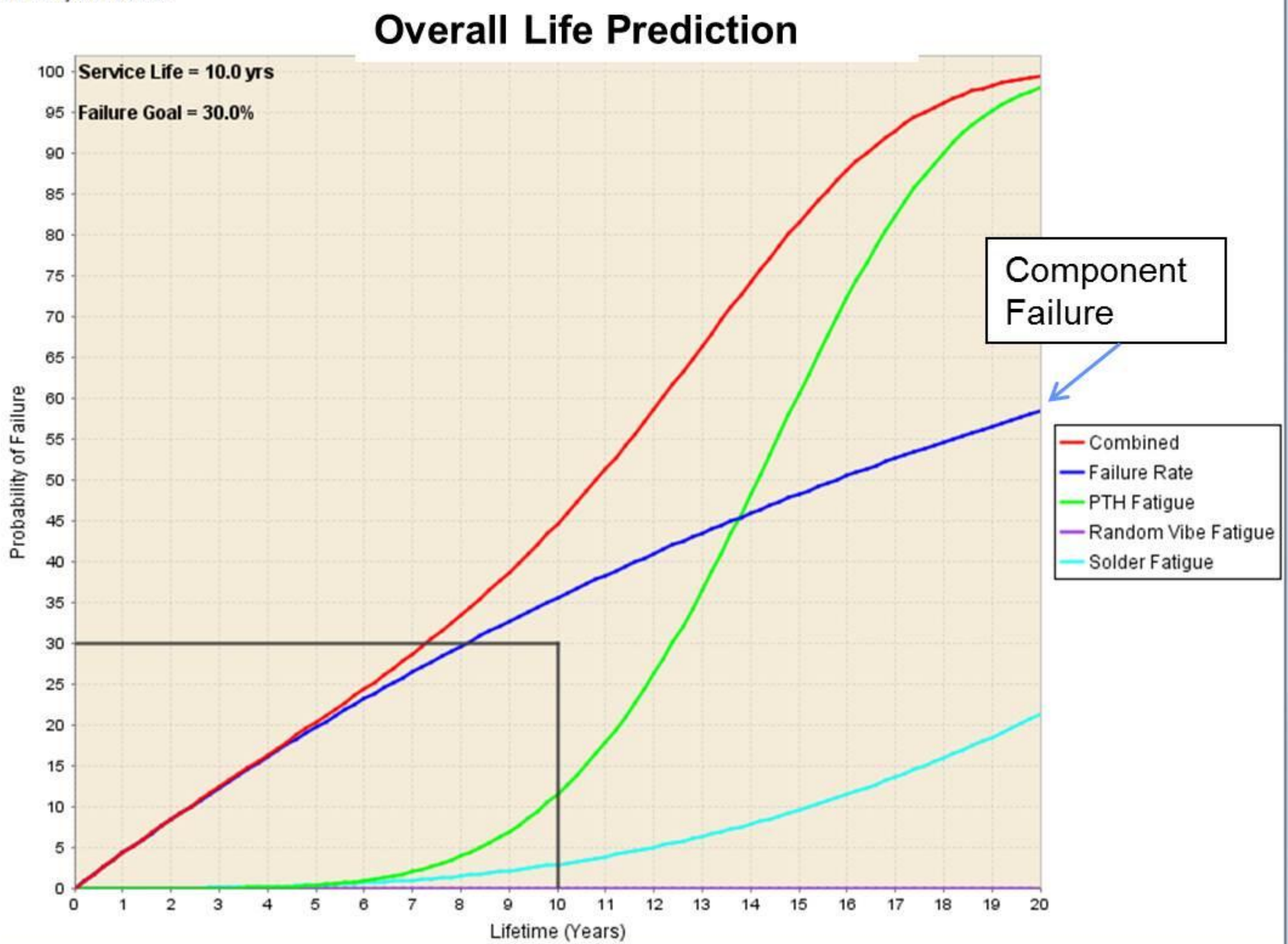
Constant Failure Rate Module – Components (Mil-HNDBK-217F)



This takes into account the failure rate of the components themselves.

Combined Failure Rate is Provided

The following chart shows the individual Life Prediction curves generated by all analysis modules and a combined Life Prediction curve based on all the analysis results.



Summary

- It is important to eliminate design flaws early in development.
- Micro-Inverters must survive a challenging environment for long periods of time.
- A software tool is now available to model the primary failure mechanisms so that inverter electronics can be made more reliable.
- Sherlock modeling will enable a number of “what if” scenarios.
  - Changing package types
  - Changing location of components
  - Changing the mount point locations
  - Changing laminate type, etc.
- The software can also be used to determine the TC test conditions that best simulate the field use conditions.
- Micro-Inverter designs can be built with more confidence that they will survive the challenging environments where they are placed.

Questions?

Thank you for your attention.

Any questions?

ctulkoff@dfrsolutions.com

DfR Solutions