PV MODULE INTRACONNECT THERMOMECHANICAL DURABILITY DAMAGE PREDICTION MODEL

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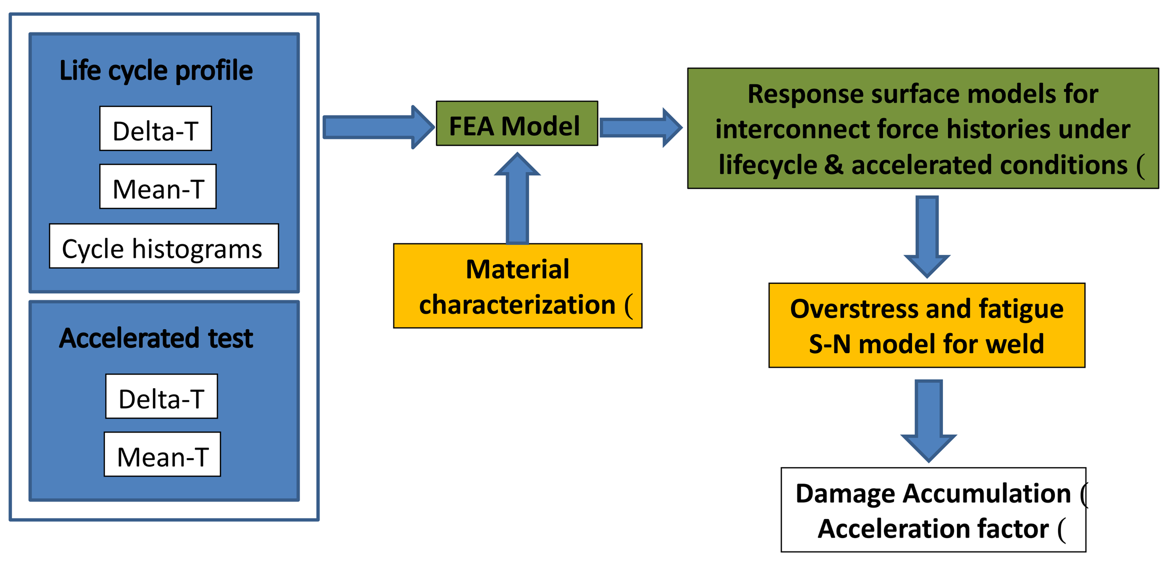
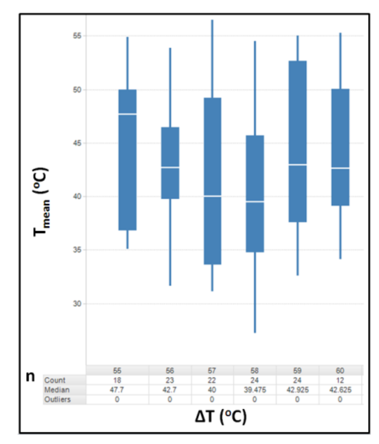
Outline of Methodology



Thermal Cycle Design Space

- Continuous temperature readings taken at various geographic locations
- 3 parameter Rainflow algorithm used to reduce raw data to significant cycles
- Temperature data quantified in terms of cyclic T_{mean} and ΔT
- Design space generated to describe life cycle profiles
- Accelerated profile: -40°C to 90°C

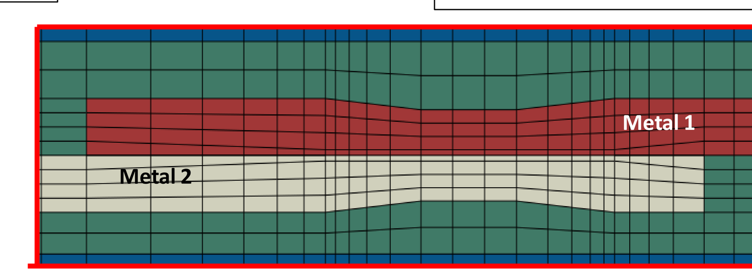


T_{mean} (°C) ↑					
	38.0, 79.0	47.5, 79.0	57.0, 79.0	66.5, 79.0	76.0, 79.0
	38.0, 56.25	47.5, 56.25	57.0, 56.25	66.5, 56.25	76.0, 56.25
	38.0, 33.5	47.5, 33.5	57.0, 33.5	66.5, 33.5	76.0, 33.5
	38.0, 10.75	47.5, 10.75	57.0, 10.75	66.5, 10.75	76.0, 10.75
T_{mean} (°C)	38.0, -12.0	47.5, -12.0	57.0, -12.0	66.5, -12.0	76.0, -12.0
ΔT, T_{mean}	ΔT (°C) →				

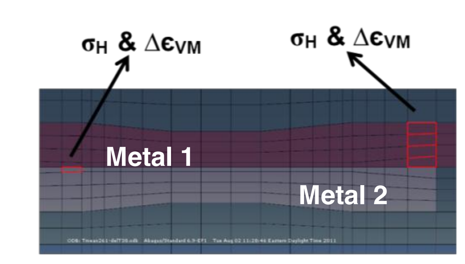
FEA Model - Intraconnect

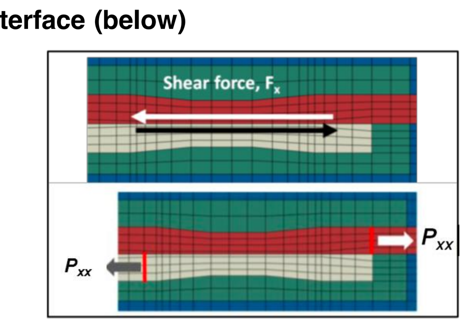
Schematic

Localized view of FEA model developed of intraconnect interface within assembly



- Shear, peel, and axial forces estimated using FEA
- Parameters monitored at intraconnect interface (below)



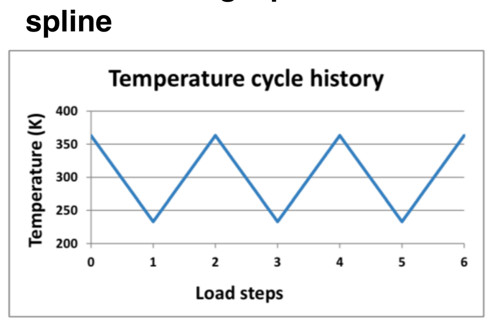


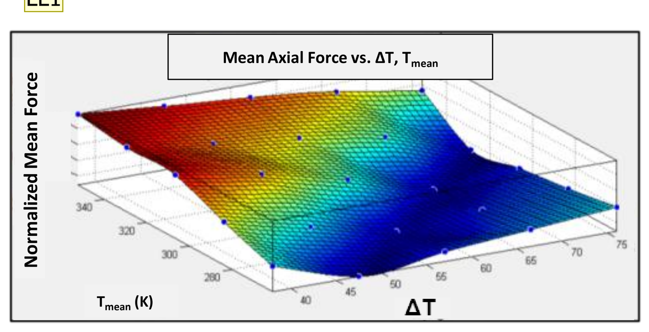
Response Surface Models

- FEA model run for all combinations within design space as well as accelerated profile (90°C to -40°C)
- Response surface models generated (as a function of T_{mean} and ΔT) for all parameters monitored at intraconnect interface using a piecewise cubic spline

T_{mean} (°C) ↑					
	38.0, 79.0	47.5, 79.0	57.0, 79.0	66.5, 79.0	76.0, 79.0
	38.0, 56.25	47.5, 56.25	57.0, 56.25	66.5, 56.25	76.0, 56.25
	38.0, 33.5	47.5, 33.5	57.0, 33.5	66.5, 33.5	76.0, 33.5
	38.0, 10.75	47.5, 10.75	57.0, 10.75	66.5, 10.75	76.0, 10.75
T_{mean} (°C)	38.0, -12.0	47.5, -12.0	57.0, -12.0	66.5, -12.0	76.0, -12.0
ΔT, T_{mean}	ΔT (°C) →				

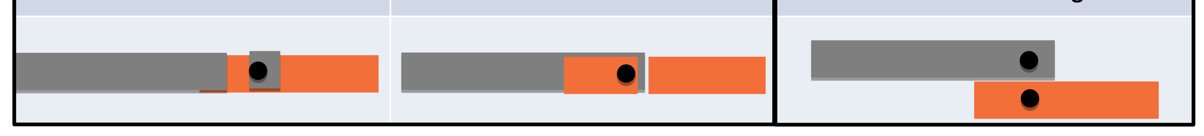
LL1

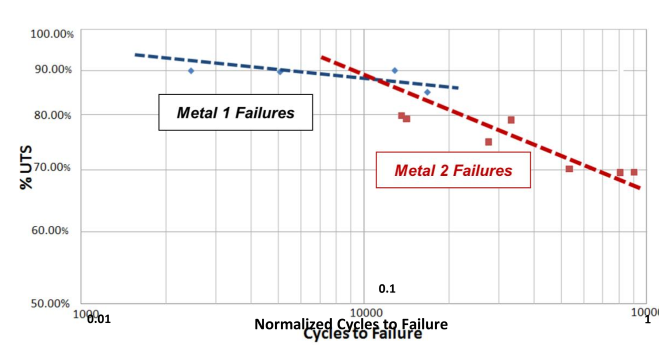




Mechanical Failure Modes

Failure Model 1 (FM1)	Failure Mode 2 (FM2)	Failure Mode 3 (FM3)
Room Temperature Max Load: 90% of P_{ult} Normalized N_f: 0.0683 Failure Site: **Metal 1**	Room Temperature Max Load: 70% of P_{ult} Normalized N_f: 1 Failure Site: **Metal 2**	Room Temperature Max Load: 90% of P_{ult} Normalized N_f: 0.00825 Failure Site: **Interconnect Region**

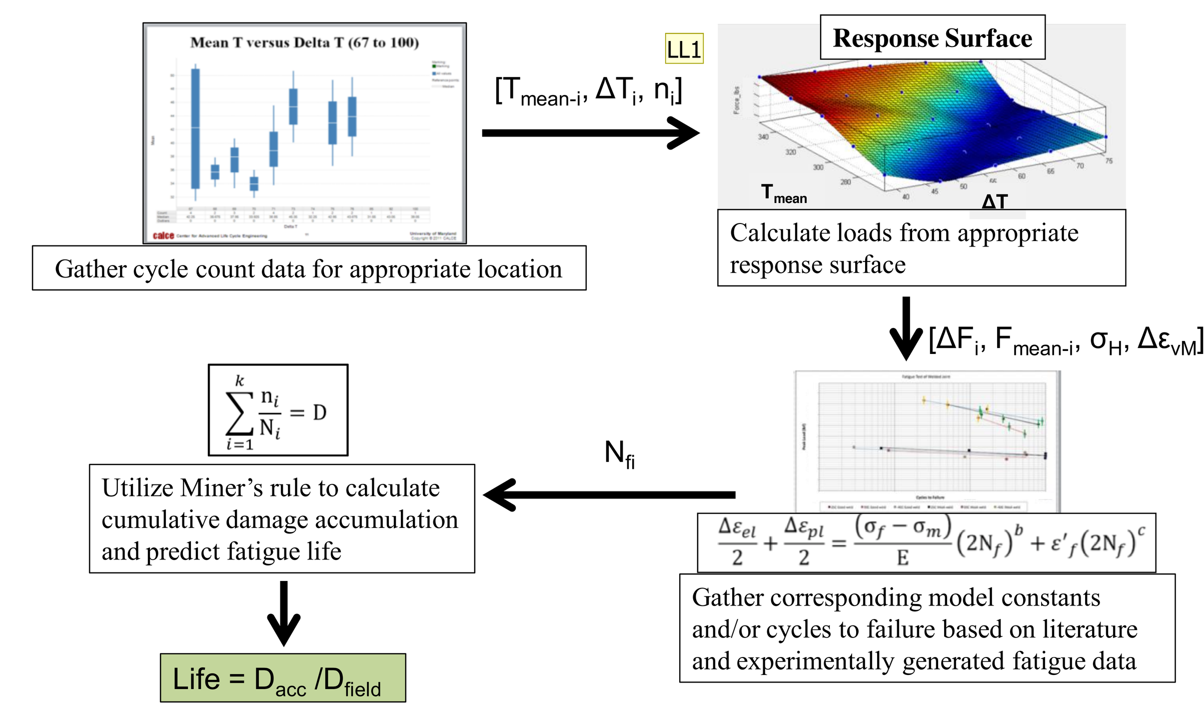




Competing fatigue curves seen for different failure modes (

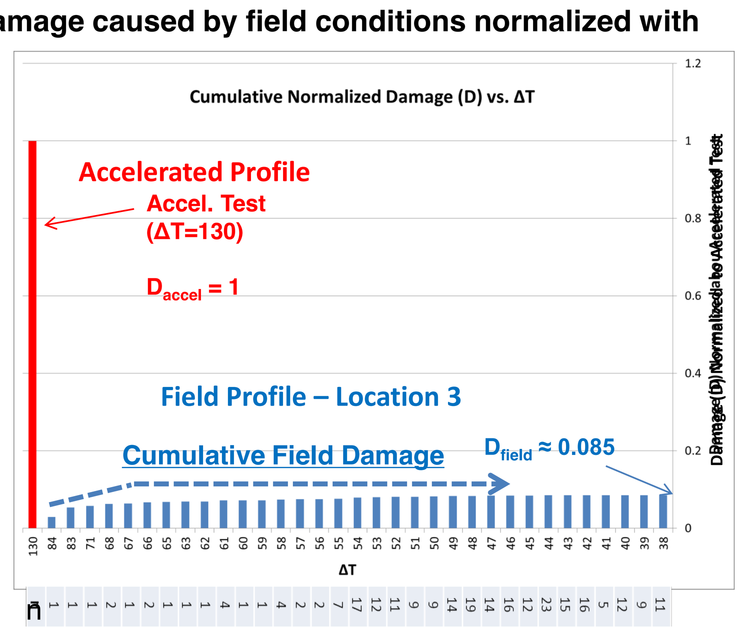
NOTE: Plot generated while testing was in progress and does not contain all fatigue data

Damage Accumulation: Approach



FM1: Damage Modeling

- Plot shows a cumulative damage caused by field conditions normalized with respect to accelerated test
- ♦ Majority of damage accumulated from the first few largest ΔT values
- ♦ Cycles with smaller ΔTs that have a higher cycle count in the field (i.e. higher **n value**) still contribute less damage cumulatively than a small number of the highest ΔT cycles



FM1: Acceleration Factor

$$\frac{\Delta\varepsilon_{el}}{2}+\frac{\Delta\varepsilon_{pl}}{2}=\frac{(\sigma_f-\sigma_m)}{E}(2N_f)^b+\varepsilon'_f(2N_f)^c$$

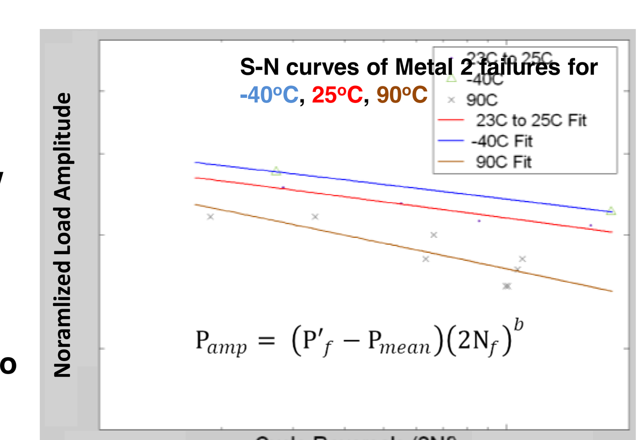
- Sensitivity study of model coefficients σ_f' and ε_f' (i.e. fatigue curve intercept)
- Values chosen based on values for σ_f' and ε_f' in literature
- N_f values changed by as much as a factor of 2 for most severe field conditions

Combinations	
σ_f' (MPa)	ε_f'
135	0.10
139	0.13
142	0.14

	Location 1	Location 2	Location 3
AF	5.7-6.1x	2.7-2.9x	11.7-12.9x

FM2: Damage Modeling

- S-N curves generated for metal 2 failure
- The fatigue strength coefficient (P'_f) is modeled using a power-law dependence on temperature and the fatigue exponent b is modeled using a log-linear dependence on temperature
- This allows for fatigue constants to be estimated at any T_{mean} in the field environment.



P_{amp}	Load Amplitude
P'_f	Fatigue strength coefficent
P_{mean}	Mean Load
N_f	Cycles to Failure
b	Fatigue exponent

FM2: Acceleration Factor

Linear damage superposition (Miner's rule) used to calculated damage accumulation:

1. FEA & Response Surface Models used to extract stress/strain histories at interconnect
2. N_f values calculated using extracted data and fatigue model(s) for all field conditions at each location
3. Cumulative damage index calculated from field conditions (D_{field})
4. Acceleration factor (AF) calculated by comparing damage index ratio of single accelerated cycle 'D_{acc}' to all field cycles 'D_{field}'
5. Repeatable for any field location where cycle history is known

$$D=\sum\frac{n}{N_f} \qquad AF=\frac{D_{acc}}{D_{field}}$$

	Location 1	Location 2	Location 3
AF	~13x	~5x	~21x

Summary

- A method for determining the durability of a PV module intraconnect was established
- The life prediction approach consisted of four parts:
  1) collection and qualification of temperature history data from life cycle environments
  2) experimental characterization of intraconnect fatigue data
  3) thermal cycle modeling using 2D and 3D FEA
  4) damage accumulation modeling to assess product durability
- A 3 parameter Rainflow algorithm was used to reduce module temperature data to significant cycles of Tmean and ΔT
- FEA models were developed and used to generate response surface models as a function of Tmean and ΔT over a 2D design space
- Damage was calculated using the Coffin-Manson relation with model constants from both literature and fatigue test coupons
- AF values were generated comparing relative damage index between field environments and an accelerated thermal cycle profile (90C to -40C)

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