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System Reliability for Utility PV Inverters

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Abstract

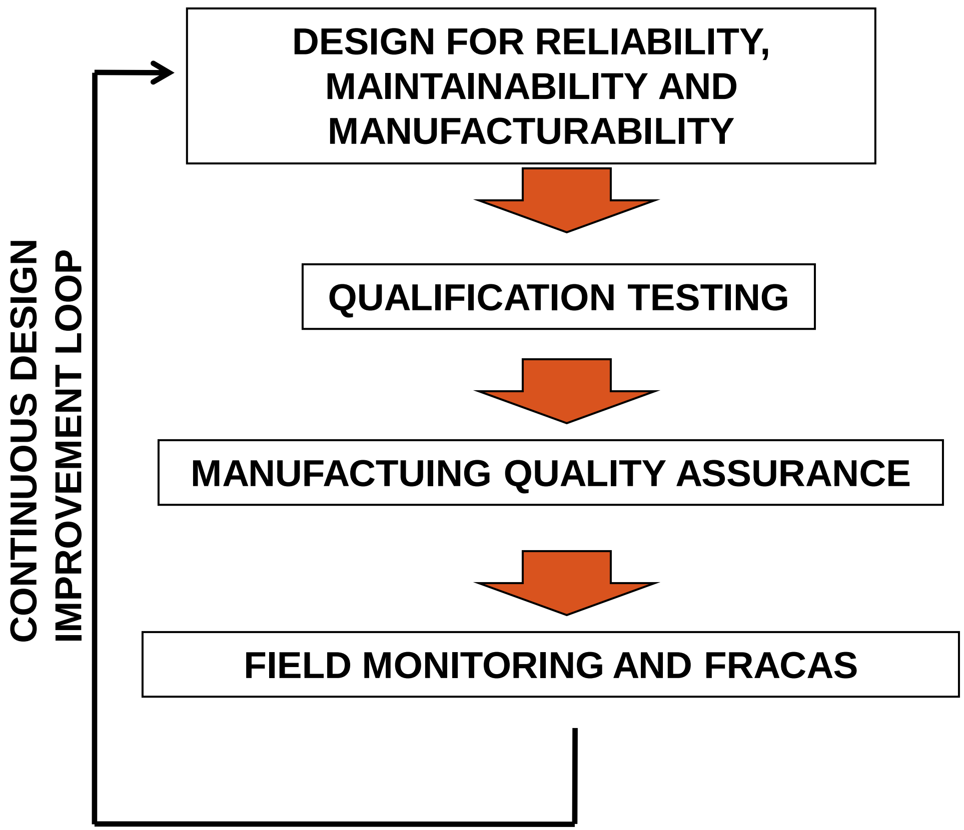
The availability of a PV plant is highly dependent upon the system reliability of the inverter. Systems engineering for PV inverters is accomplished by first performing top down design-for-reliability (DfR) principles including fault tree analysis & reliability prediction methods which result in subsystem reliability allocations. A critical aspect for the design of PV inverters is the ability to simulate both performance as well as environment thereby gaining an understanding for the subsystem and component stress state. Physical testing of the simulation results are accomplished by usage of advanced power supply equipment with the capability to provide both DC and AC performance conditions which represent large scale PV arrays and grid interactions.
Systems reliability analysis provides a basis for subsystem and component technology choices and development. One example of the linkage between simulation and test is applied to the critical inverter subsystem consisting of the IGBT switching subsystem. Simulations and testing to the required performance envelop and environment of operation results in component choices, subsystem design, derating strategies and required cooling methods.

Qualification of inverter reliability is attained by envelope performance testing at environmental extremes to provide for manufacturing burn-in profiles. Durability tests such as system level accelerated life testing (ALT) and component & subsystem highly accelerated life testing (HALT) are key tools to qualify the reliability of new designs. Environmental testing of inverter equipment is performed to ensure that the system availability is maintained over a long lifetime at temperature and humidity variations.

A key aspect for understanding inverter fault modes and the design of efficient maintenance & repair methods is the ability to data mine fielded inverter operation at the component, subsystem, and system level. For that reason, the attainment of high availability is tied to real-time site data acquisition for inverter operational conditions and subsystem states. Actual field performance is fed back into lifetime models used during qualification testing as well as prediction and simulation criteria. Reliability growth is attained by improvements found during prediction, simulation, qualification testing, and field experience.

Methodology - Reliability Assurance Milestones During Inverter Product Lifecycle

- AE uses a closed loop reliability process
- Design for Reliability
  - MTBF, DFMEA, Fault Tree
- Reliability Test
  - ALT, HALT, Thermal, Environmental
- Qualification Test
  - Power profile, efficiency, harmonics, waveform, modulation, control loop, compliance, WCSA, limits, control & communication, burn-in development

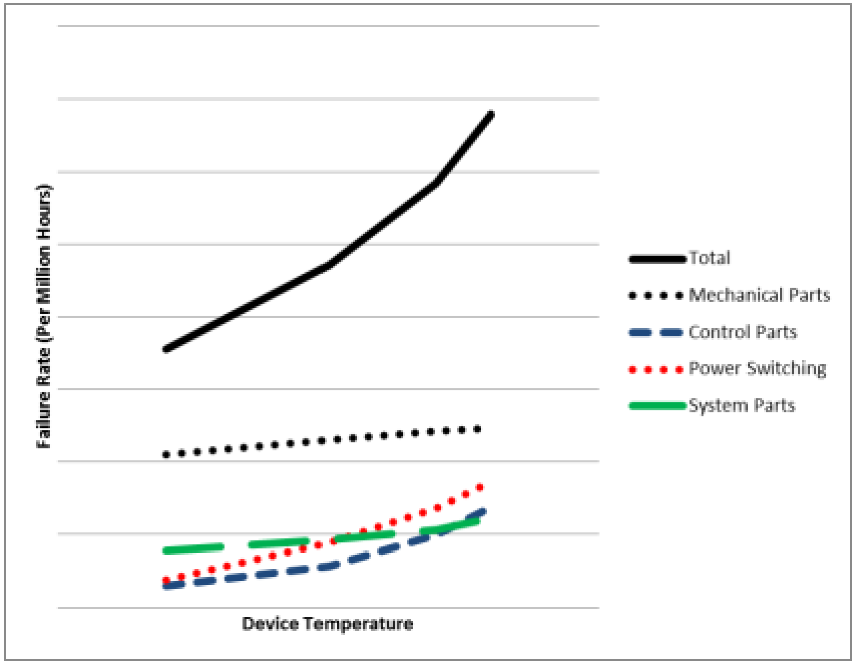


Inverter Reliability Assurance Program

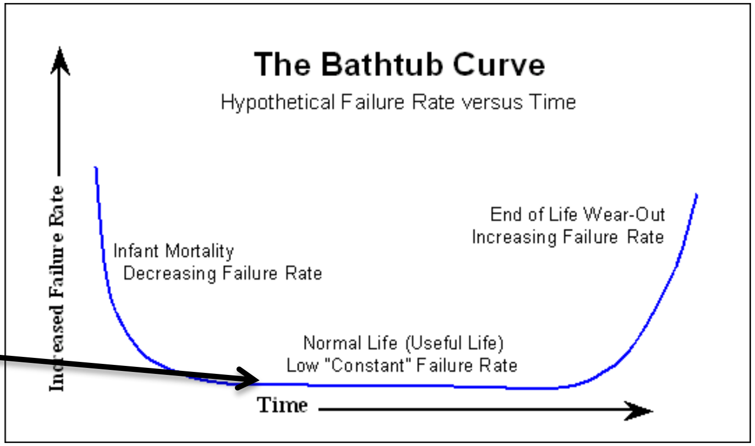
- Design for Reliability (DfR) Focus Areas
  - Modularity; Improves reliability, repair, test, and manufacturing
  - Derating; Component and subassembly derating to reduce operating stress
  - Temperature Management; Achievement of reduced operating temperatures
  - Predictive Methods – MTBF, DFMEA, Fault Tree Assessments
- Reliability Test
  - Verification of potential causes based upon DFMEA
    - Subassembly ALT, Thermal, Thermal Cycle
    - Environmental Testing – Temp/Humidity, Salt Fog
    - HALT
    - System Level ALT
- Experience; Reliability Growth
  - Product lifecycle learning experiences into design
    - Improvements based upon assurance testing and field experience

Design-for-Reliability; Reliability Calculation

- MTBF calculation with software (Such a Windchill) using failure rate libraries (MIL-HDBK-217, Telecordia)
- Provides an understanding for the comparative reliability of different configurations
- Also useful for observing how the reliability is related to cooling efficiency and component stress
- Should not be used as a primary method to predict the actual failure rate



Reliability calculation assesses performance during constant failure rate region



Design-for-Reliability; DFMEA Example

- Team Oriented
- Structured Method, Early Evaluation of Design, Controls to Reduce Risk
- Design FMEA; Detailed, Functional, Interfaces
- RPN Scoring; Severity x Occurrence x Detection

Design Failure Mode Effects Analysis

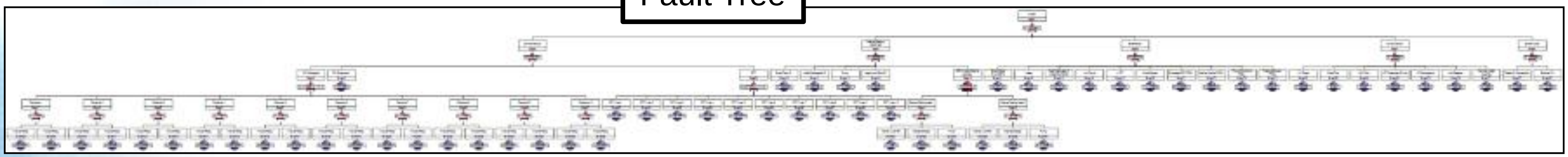
Severity Table Occurrence Table Detection Table

Design Failure Mode and Effect and Analysis		FMEA Number: INVERTER 1	
System:	INVERTER		
Item:	Design Responsibility: System Engineer	Prepared by	Reliability Engineer
P/N:	Updated Date:	DFMEA Date (Orig.) 2/25/14	(Rev) 1
Core Team:	System Eng, Firmware Eng, Power Eng, Mechanical Eng, Quality Eng, Reliability Eng, Manufacturing Eng, Test Eng, Project Mgr		

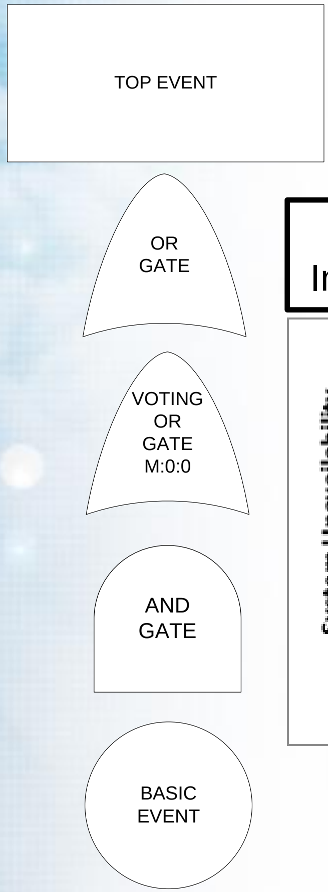
Item No.	Item Function [Item]	Potential Failure Mode	Potential Effect(s) of Failure	Potential Cause(s)/ Mechanism(s) of Failure	Current Design Controls Prevention	Severity	Occurrence	Detection	RPN	Recommended Action(s)	Responsibility & Target Completion Date	Action Results: Action(s) Taken	Action Results: Severity	Action Results: Occurrence	Action Results: Detection	Action Results: RPN
1	Subsystem 1	Overheating	Loss of Power	Thermal, Current Derating	DFMEA, Derating. Fault Tree	8	8	2	128	ALT; Fault Tree Analysis	Pwr Eng, Rel Eng, Test Eng	Subsys ALT complete Derating Met	2	2	2	8

Design-for-Reliability; Fault Tree Analysis Applied to Utility Inverters

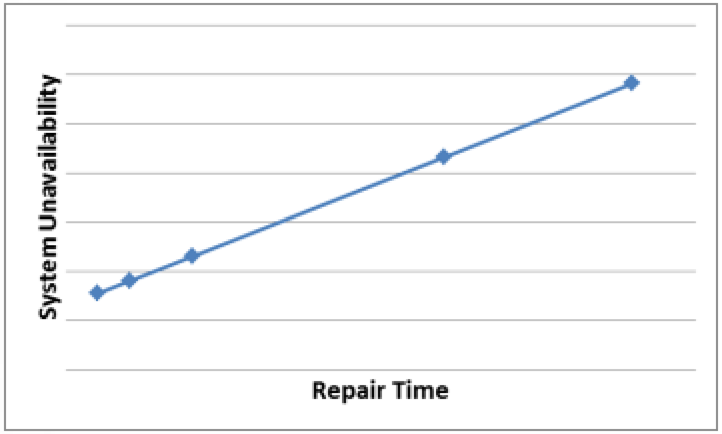
Fault Tree



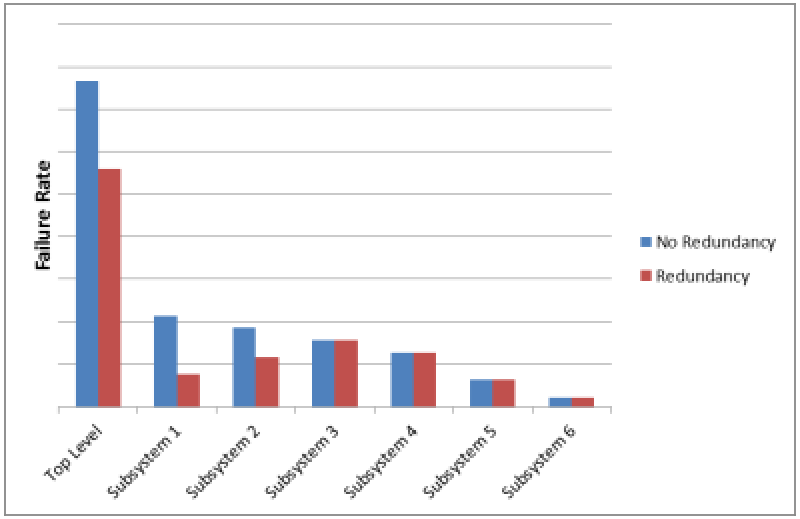
Logic Symbols



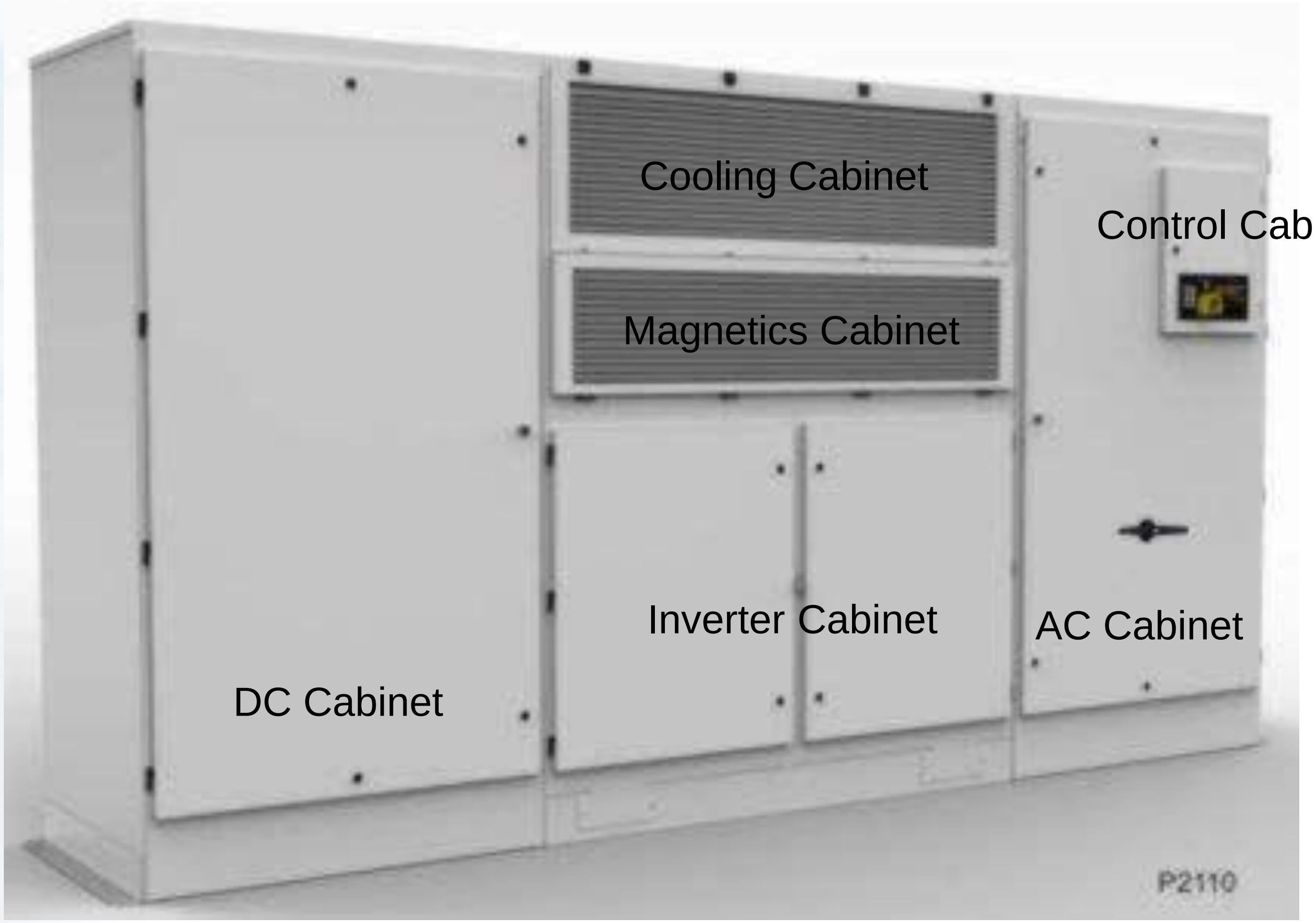
Example of Maintainability Importance with Modularity Improvement



Failure Rate of Subassemblies; Effects of Fault Tolerance

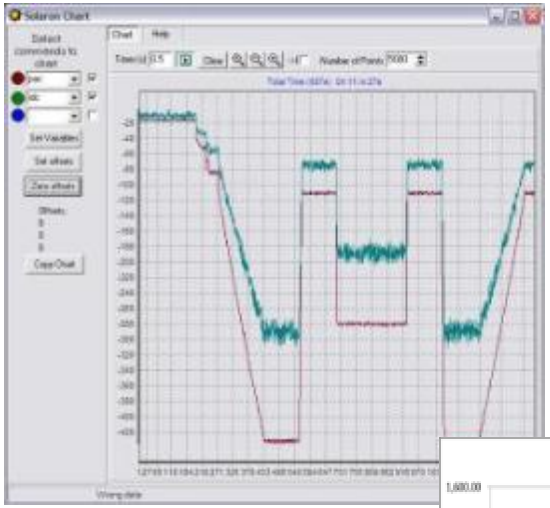


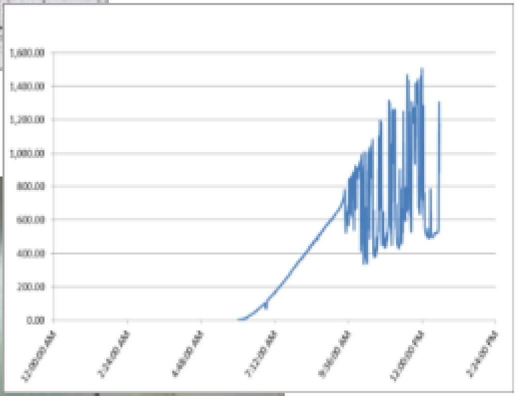
1000NX Modular Design

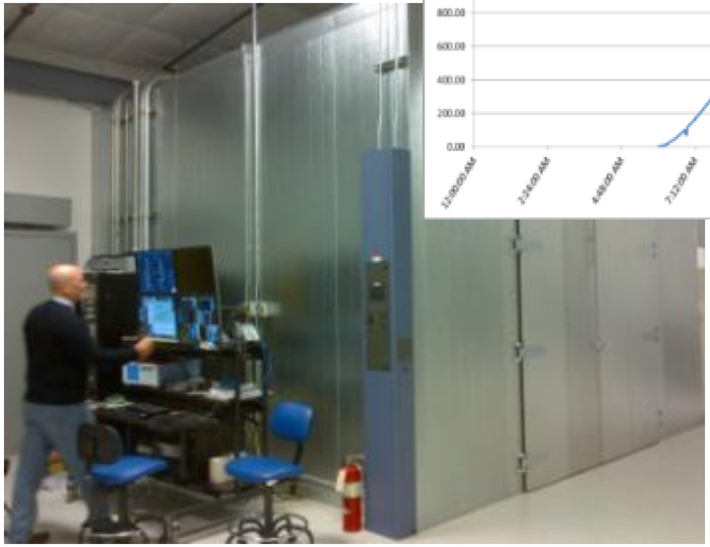


Performance Testing – Solar Simulation

- AE has installed programmable supplies to perform solar simulation testing
- Example of NREL test profile demonstrated with 1000NX
- Example of actual site irradiance data programmed for test



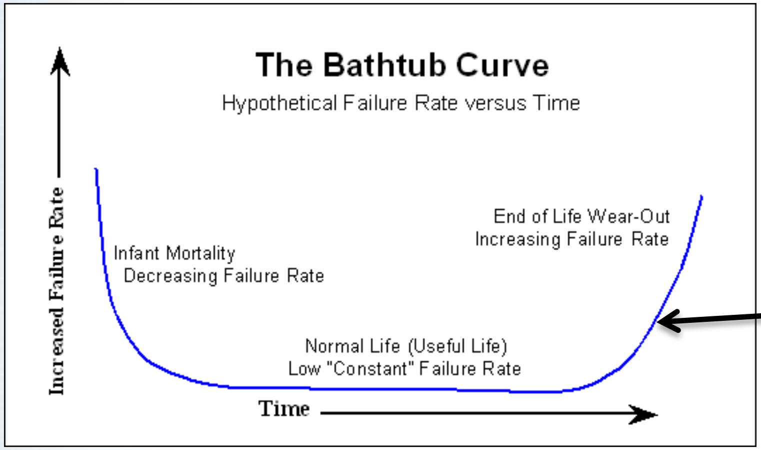




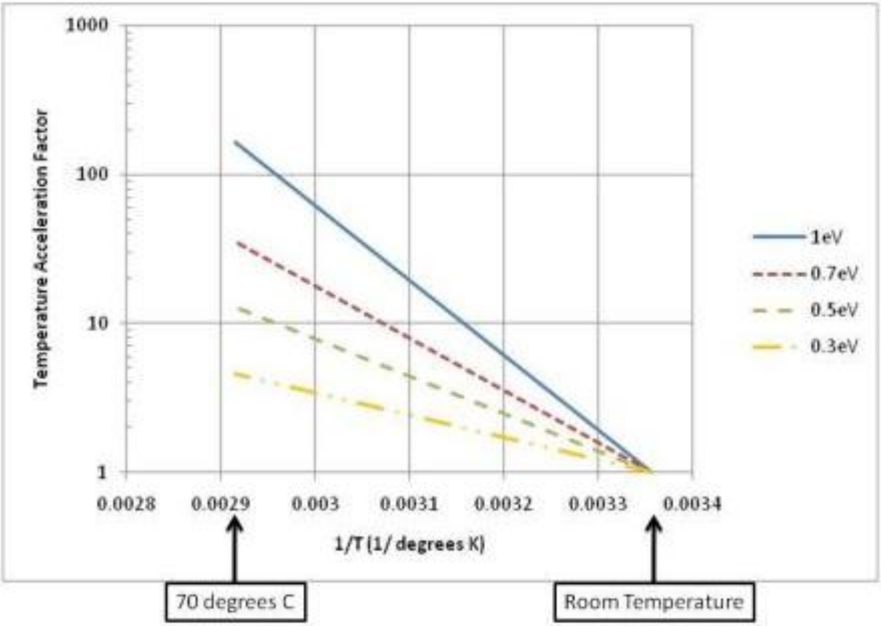
Accelerated Life Test (ALT) – Temperature Acceleration

- Durability tests such as system level accelerated life testing (ALT) and component & subsystem highly accelerated life testing (HALT) are key tools to qualify the reliability of new designs

- The most common temperature acceleration factor AF(T) is based upon the Arrhenius model
  - K_b is the Boltzmann's constant, T_o is the initial ambient temperature in °K, T is the life test temperature in °K, and E_a is the activation energy in eV.



The acceleration factor scales for different activation energies and life test temperatures.

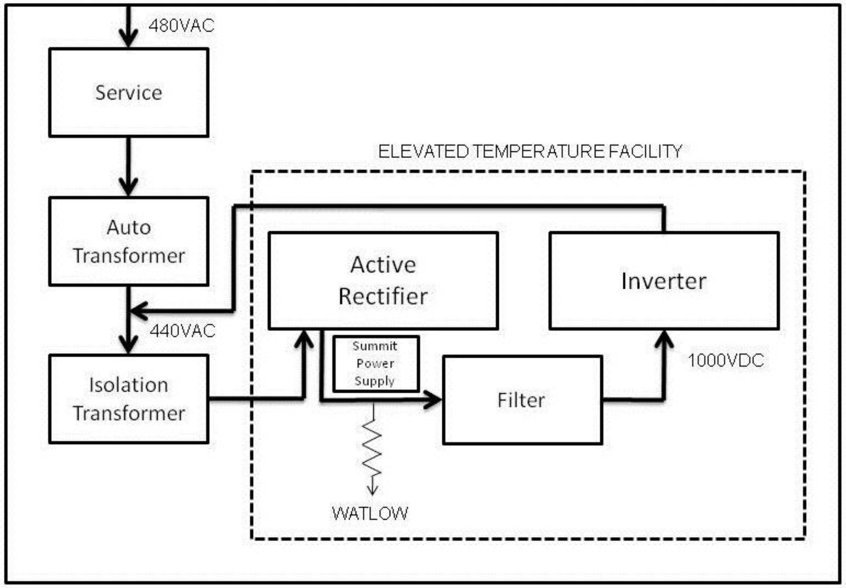


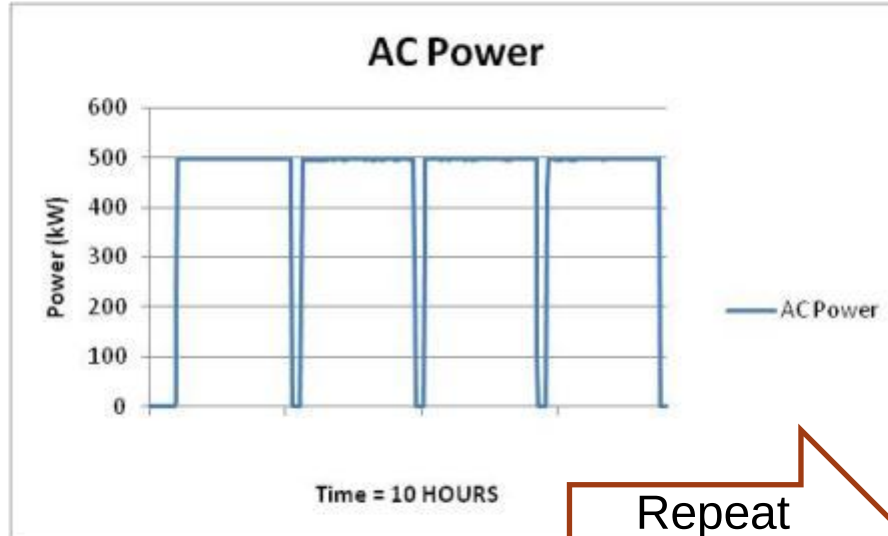
$$\lambda \propto \text{Failures}/(\text{Total Device Hours} \times AF(T))$$

$$AF(T) = \exp[(E_a/K_b)(1/T_o - 1/T)]$$

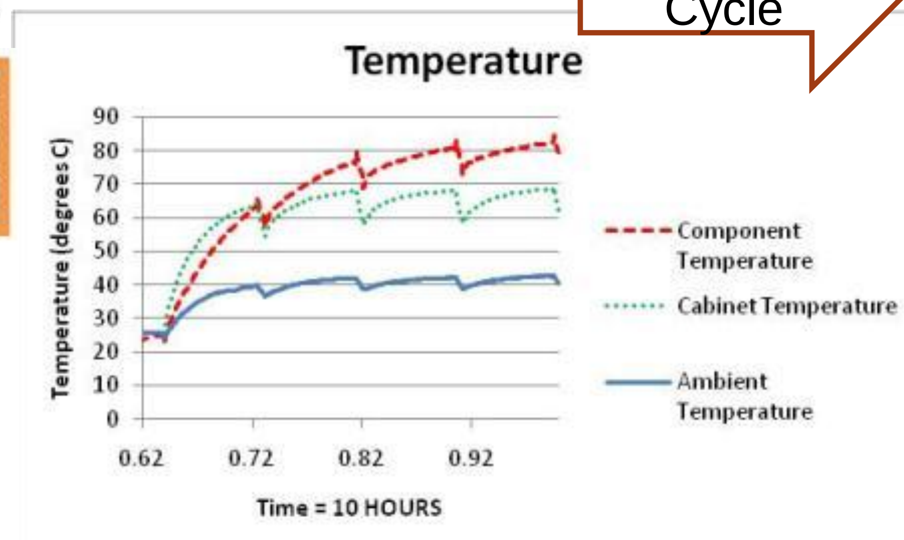
ALT is a gage of the inverter durability to reach end-of-life failure rate region

Life Test Profile Example; System Level ALT





Repeat Cycle



Thermal Qualification – Efficient Cooling Design

- Meet thermal challenges in desert solar site environments
- Thermal characterization has exhibited thermal margins for long lifetime
  - Reliability Rule of Thumb: For every 10degC decrease in temperature, the equipment lifetime is doubled
- Detailed thermal mapping is completed at all operation envelopes

1000NX Installed in Desert

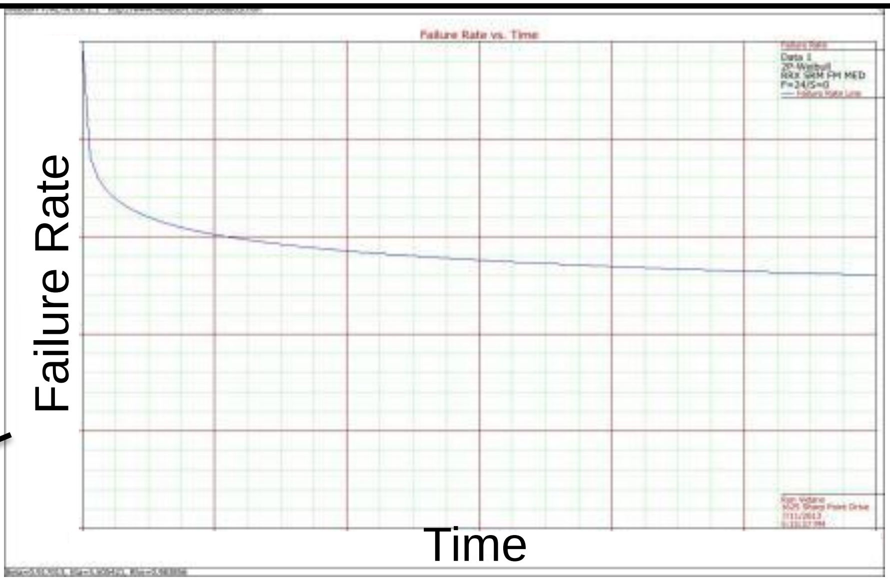
1000NX Tested in Thermal Chamber

Utility Inverter Qualification for a Wide Range of Environments

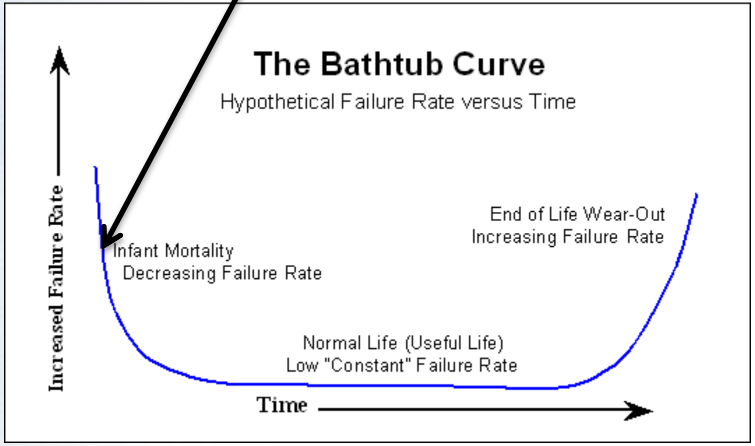
System Level Burn-In for Utility Inverters

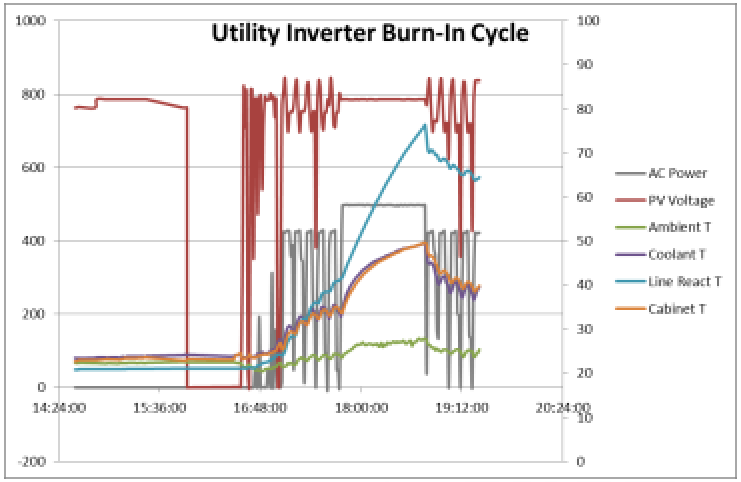
- Burn-in testing takes place at the unit level to stress the components for a designated period time to precipitate component early lifetime mortality - Temperature and Voltage Acceleration Factors
- The burn-in cycle contains voltage and power cycling which is done to ensure that power connections such as the bolted-joint assemblies are robust as well as to test low power electrical connector interfaces

Weibull statistics are accumulated to assess the burn-in cycle



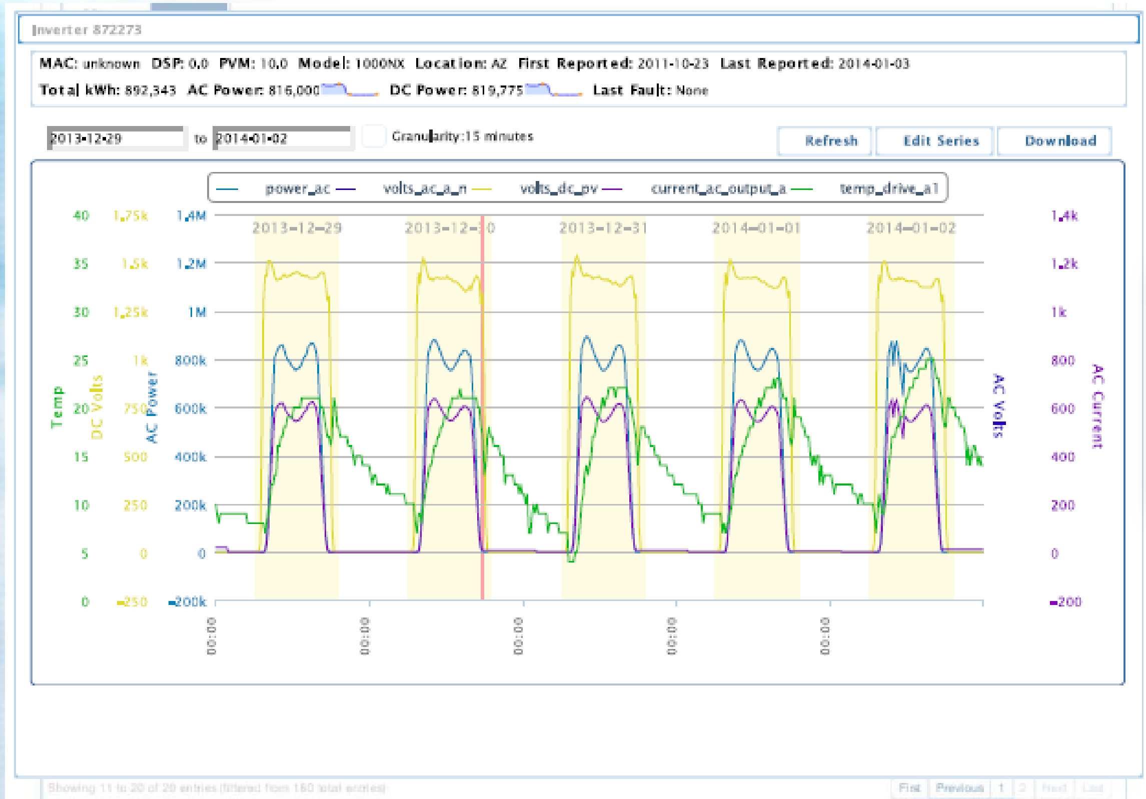
Production Burn-In reduces the number of failures in the early (decreasing failure rate) lifetime region





Inverter Data Monitoring

Example of 1000NX data monitoring – There are 50 performance variables that are constantly monitored



- The attainment of high availability is tied to real-time site data acquisition for inverter operational conditions and subsystem states. Actual field performance is fed back into lifetime models used during qualification testing as well as prediction and simulation criteria.

Conclusion; High Inverter Availability

- Availability is the most important attribute for utility inverters
- High availability is achieved by
  - Design-for-Reliability
  - Design-for-Maintenance
  - Reliability Growth
    - Assurance testing and design improvements
    - Field experience with design improvements

$$\text{Availability} = \frac{\text{Uptime}}{\text{Uptime} + \text{Downtime}}$$

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