U.S. DEPARTMENT OF ENERGY

SAND2013-5182P

Module Level Power Electronics Reliability and Accelerated Testing Standards Development

Topic: [illegible]icroinve[illegible]er & M[illegible]ic[illegible]converter Re[illegible]ability Standards

[illegible]an[illegible] Control Number: 0861-1536

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S[illegible]a National Laboratories

Sandia National Laboratories · TÜVRheinland Precisely Right. · ASU · U · BOSCH · ViaSol Energy Solutions

Outline

- Project Partners Introduction
  – Expertise and Project Focus
- Introduction to Module Level Power Electronics (MLPE)
  – Overall Project Goal
- Proposal Process Flow Detailed Task Discussion
- Overall Project Deliverables

Project Partners

Sandia National Laboratories

- Project management role, technical role
- Impartial chair of MLPE working group

ASU

- Experimental and Computational PoF
- Electrical stress testing

TÜV Rheinland — Precisely Right.

- ANSI approved standard development org
- Temperature and humidity stress testing

University of Utah

- Experimental and Computational PoF
- Electrical stress testing

ViaSol Energy Solutions

- Integrator with large contact network
- PV system reliability and usage

BOSCH

- Formation of testing protocols
- Leverage knowledge of automotive test

Project Partners

Sandia National Laboratories

leads: Jack Flicker, Jennifer Granata

- Experience in inverter reliability testing and standards development at the Distributed Energy Technology Laboratory (DETL)
- 60 years of experience in failure analysis, reliability engineering, and accelerated testing for nuclear weapons, microelectronics, and renewable energies
- Experience applying FMEA to residential and utility scale inverters since 2007
- Extensive history in developing, applying, and analyzing failure models for micro-electronics, power electronics, and PV systems.
- Conducted research in characterization and induced degradation of component level failures in high power converters
- PREDICTs focus: stakeholder outreach, standards development, and unit and component level ALTs with electrical stress

Project Partners

TUV Rheinland PTL, LLC

leads: : Bill Shisler, Jerome Novacek, Zhiwang Zhu

- ANSI approved standards development organization (SDO)
- Experience in standards development and accelerated testing for modules, MLPE, and inverters
- Expert in analysis of failure modes and the associated physics of failure (PoF) models for PV modules
- PREDICTs focus: stakeholder outreach, standards development, and unit level ALTs with temperature, UV, and humidity stress

Project Partners

Robert Bosch ETC, LLC

leads: James Cleveland, Martin Boos, John Haworth, Simon Price

- ISO/IEC 17025-2005 accredited testing center
- Expertise in reliability and lifetime testing of automotive electronics
- History of PoF based simulation, testing, and analysis to support the development and release of new automotive electronic products
- PREDICTs focus: accelerated life test (ALT) planning, utilizing experience in automotive qualifications and reliability testing protocols

Project Partners

Arizona State University

leads: Raha Ayyanar and Rajib Datta

- Academic research group
- Specializes in circuit design of power conversion systems and development of inverter reliability standards
- Characterization and induced degradation of component level failures in high power converters
- Extensive experience in designing and developing PV inverters ranging from microinverters to string inverters to utility scale central inverters
- Modeling of inverters of various designs and applications, including detailed switching level models suitable for reliability studies
- Distribution grid modeling and simulation under high PV penetration

PREDICTs focus: PoF determination using both experimental and computational methods, pre- and post-ALT baseline measurements, and component level ALTs.

Project Partners

University of Utah

lead: Faisal Khan

- The Power Engineering and Automation Research Lab (PEARL) at University of Utah
- Pioneer in characterization and induced degradation of component level failures in high power converters
- Dr. Faisal Khan is a world expert in the design and modeling of capacitor-clamped converters
- Research include power converter design, reliability analysis of power converters, and emerging applications of power converters

PREDICTs focus: PoF determination using experimental methods, pre- and post-ALT baseline measurements, and component level ALTs

Project Partners

ViaSol Energy Solutions

lead: Devarajan Srinivasan

- PV integrator
- Extensive field experience in inverter operation and reliability
- Indoor/outdoor-field testing of PV systems, subsystems, and components at Arizona Public Service and other PV installations

PREDICTs focus: assist working group (WG) develop failure modes and effects analysis (FMEA) by leveraging field experience in inverter operation, power electronics, and PV field reliability

Introduction

- Balance of Systems (BOS) is significant cost of PV plant operations
  - Currently 8-12% of final cost ($0.25/W)
  - Far above DOE goal of $0.10/W by 2017

- Economies of scale driving PV BOS in opposite directions
  - Large centralized inverters (~500 kW)
  - Module level power electronics (MLPE) (~200 W)

- MLPE offer a number of advantages
  - Safety
    - DC to AC conversion at module limits arc faulting
  - Increased component lifetime
    - Lower power handling means smaller components
    - Easier thermal management ⟶ increased component lifetime
  - Increased efficiencies
    - Module-level max power point tracking (MPPT)
    - Eliminates shading problem
    - Eliminates problems due to module mismatch of IV curves

Introduction

- But must overcome some disadvantages
  - Mounted on module backing
    - More extreme diurnal temperature cycling
      - Increased stress on componentry
      - More difficult thermal management
    - Customers require the inverter lifetime = module lifetime (~25 years)
      - Centralized inverters have warranties ~10 years

- One MLPE unit for every module
  - 5,000 units per MW of PV
  - Tens of thousands to millions of MLPE in installation
  - Difficult to impossible to track and repair/replace units as they fail
    - Unique challenge of PV installations operations and maintenance (O&M)

Statistical Reliability and lifetime extension of MLPE devices is critical to successful implementation of O&M schemes for large solar installations

Introduction

- Overwhelming majority of PV research has focused module efficiency and reliability
- These issues largely ignored for BOS
  - PV power electronics industry does not have the extensive, standardized reliability measuring accelerated lifetime tests (ALTs)
    - Ex. PV module industry or mature power electronics industries (e.g. automotive).

Goal: Recommend standard ALT protocols that have been correlated to fielded MLPE failure rates, modes, and environmental stressors

Result: Confidence of system operators, integrators, manufacturers, and financiers is increased ⟶ decreasing the cost of financing and operating large solar installations

Process:

1. Identify MLPE failure modes and unit lifetimes
2. Determine environmental stressors which cause failure modes
3. Develop ALTs which reproduce/exacerbate failure modes
4. Conduct ALTs
5. Verify that ALTs can be correlated to fielded unit lifetimes
6. Submit reliability standard protocol to standards development organizations (SDOs)

Project Process Flow

Task 1: Formation of WG

Formation of MLPE Reliability Working Group (WG)

Failure Modes and Effects Analysis (FMEA)

Task 2: PoF Determination and ALT Development

Determine physics of failure (PoF) of failed units

Determine appropriate ALTs

Task 3: ALT and Data Correlation

Conduct ALTs

Correlate ALT results to FMEA

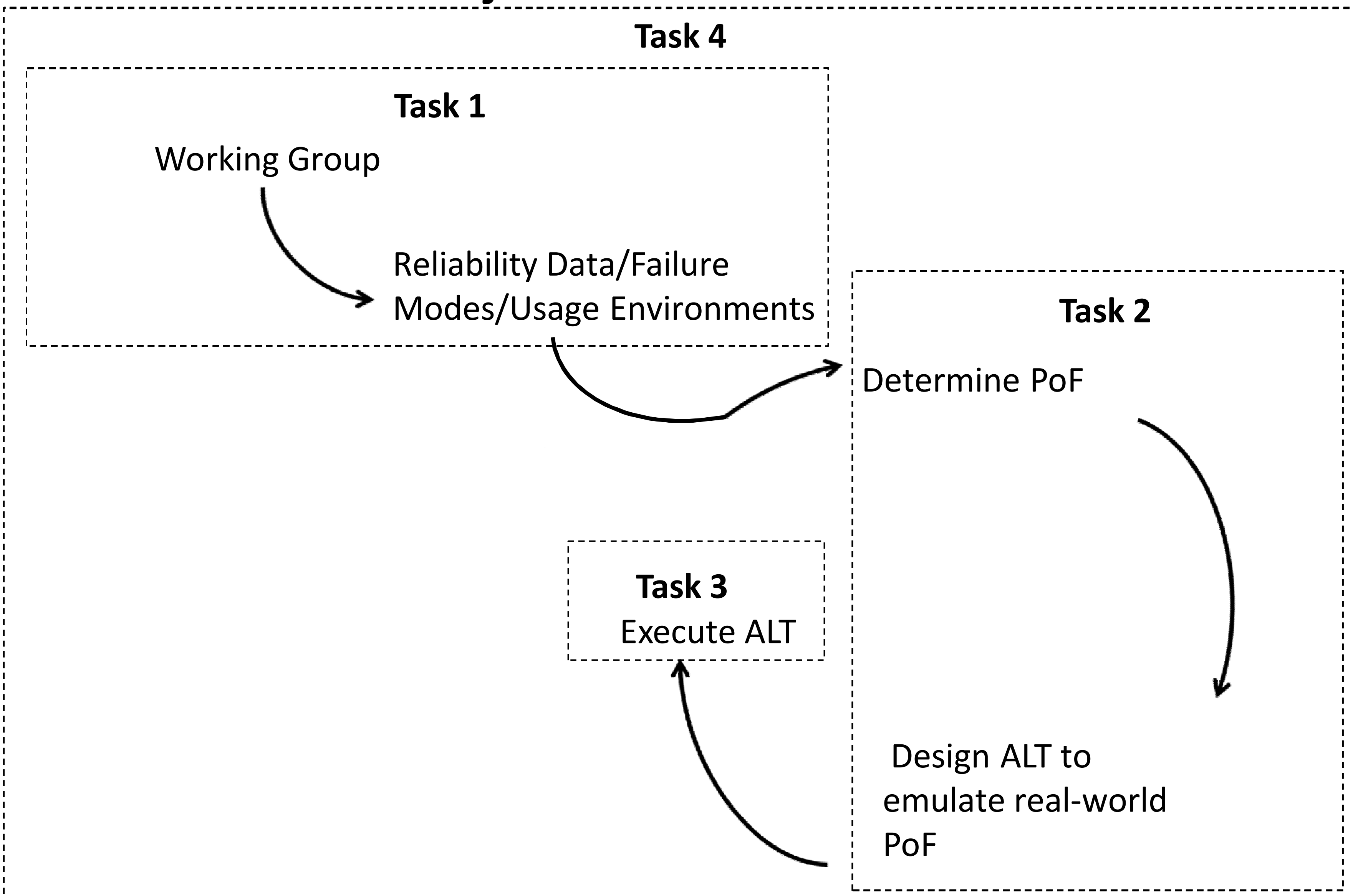
Task 4: Publish Data

Dissemination of Results

Task 5: Standards Development

Submit Draft/Subject standard to SDO

Project Process Flow



Task 1: Formation of WG

Goals: **1.1: Obtain commitments to participate in WG**
1.2: Gather reliability, usage, and environmental data of MLPE units
1.3: Work with WG to perform FMEA on MLPE units
1.4: Publish manufacturer-blinded results of FMEA and reliability data

Results: **1: Development and publication of FMEA of fielded MLPE units**
2: Identification and ranking of field failure modes and at-risk components
3: Identification and ranking of environmental stressors

FMEA

- Systematic method of systems failure analysis
  - Developed by military in 1950s
  - Described by MIL-STD-1629A
  - Extensively used in semiconductor processing, software development, automotive electronics, and other industries
  - Sandia Labs has been applying FMEA to PV systems since 2007

Task 1: Formation of WG

- Successful development and adoption of standard reliability test protocol dependent on:
  - Stakeholder engagement
  - Correlation to real-world failure modes
  - Vendor and technology neutrality

- Stakeholder engagement
  - Members of various organizations with knowledge of MLPE reliability and standards development
    - 1/3 MLPE manufacturers
    - 1/3 PV owners, operators, integrators, installers, and utilities
    - 1/3 universities, national labs, test labs, and independent engineers

- Correlation to real world failures
  - Accurate FMEA ensures that failure root causes and environmental stressors are catalogued and ranked

- Vendor and technology neutrality
  - Samples for test will be obtained from a number of different vendors in WG
  - Test samples will be purchased in the open market as needed to ensure neutrality is observed

Task 1: Formation of WG

Risk Mitigation:

Dependence on WG presents risks to success

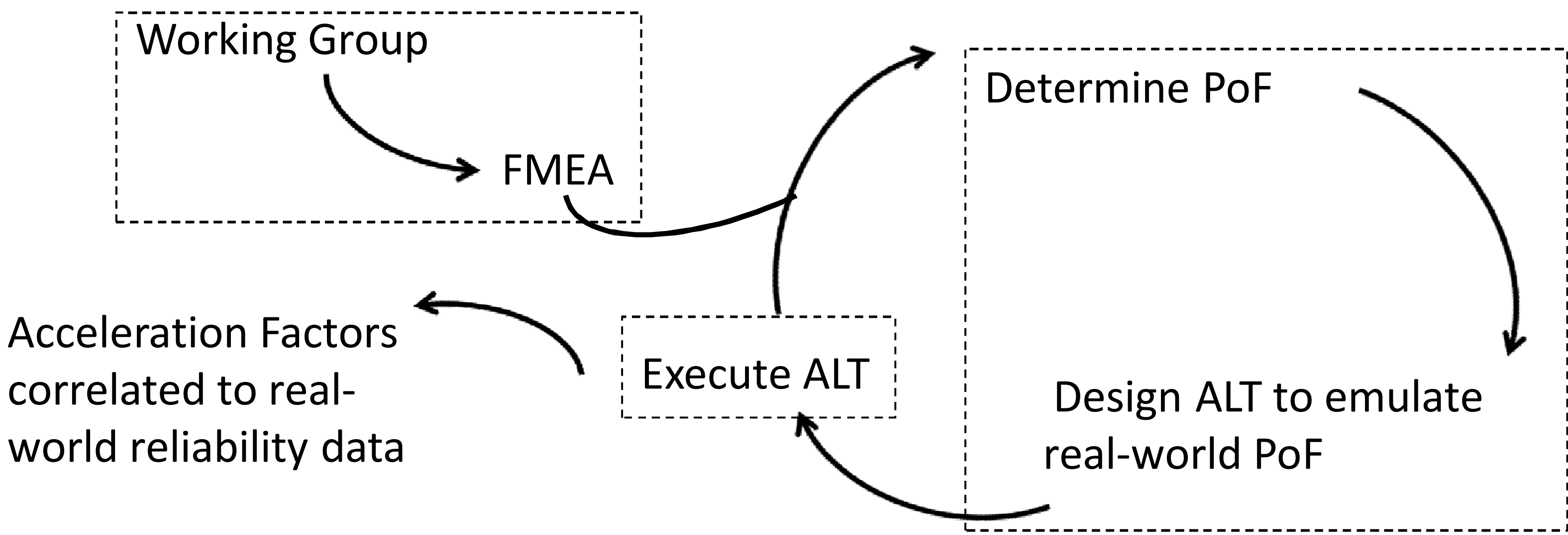
- Project partners involved in concurrent projects with MLPE manufacturers
  - Contact network will be leveraged for the PREDICTs WG.
  - Group members have already begun stakeholder outreach
  - Over a dozen MLPE organizations have agreed to attend meetings, provide MLPE devices to test, and provide usage and lifetime information of fielded MLPE units
    - Burns & McDonnell, Canadian Solar, Celestica, DNV KEMA Renewables, Enphase Energy, First Solar, FM Approvals, NY Solar Energy Society, Power-One, SolarBridge, SolarEdge, Sunset Technology, Varentec, Zep Solar, SalarEdge, Volterra, Tigo, and Petra

- TUV and SNL have worked with manufacturers to publish manufacturer-blinded publications regarding reliability data
  - Data scrubbed of identifying information before being disseminated
  - Negative risk of data-sharing is mitigated due to the anonymity of the data
  - True, unbiased testing of devices alongside competition
    - Advantage of more data for financing, warranty, and product improvements

Task 2: PoF Determination and ALT Planning

Goals: **2.1: Obtain samples of failed units from WG members to carry out PoF analysis**
2.2: Perform PoF analysis utilizing both experimental and simulation techniques
2.3: Determination of environmental stress conditions to replicate PoF

Results: **1: ALT plan which reproduces failures found in fielded MLPE units**
2: Determination of PoF for top 5 MLPE failure modes



Task 2: PoF Determination and ALT Planning

Two common pitfalls of poorly designed ALTs

Lifetime for low/no stress field-use conditions are extrapolated from high stress conditions

Higher stress conditions lead to larger error introduced into the predicted field-use conditions

Short term and long term ALTs are necessary to minimize error in extrapolation to field-use

High stress conditions may induce new failure modes

ALT data will have no correlation to field-use and any extrapolation will be useless.

If ALT PoF is different, ALT must be altered and executed again until the real-world PoF is emulated under stressed conditions in *iterative process*

Task 2: PoF Determination and ALT Planning

PoF

work with manufacturers in the WG to obtain failed units/subunits for PoF analysis

Literature Review

- Take component-level reliability platform
- Mitigates risks associated with unknown PoFs
- Large body on power electronics failure modes

Experimental

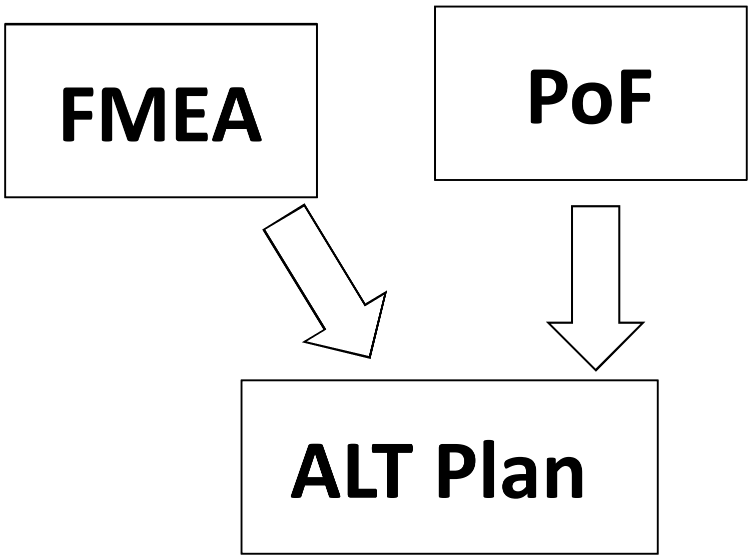
- Chemical depotting and laser ablation
- X-ray computed tomography
- Visual and electrical inspection

Numerical Simulation

Detailed component level models

- Thermal environment
- All relevant parasitics
- PWM and controls process
- Electric grid interactions
- PV panel operation

Task 2: PoF Determination and ALT Planning



Test at least:

- Top 5 failure modes (per FMEA)
- 16 units (1σ) per mode
- Four different stress conditions
- Both whole systems and board/component level
- Utilize both *in situ* and periodic measurements, depending on PoF

Whole units:

- Collection of gross reliability statistics
- Monitoring external parameters of the units (efficiency, DC ripple, THD, AC/DC excursions)
- ID indications of unit degradation

Subsystem level:

- Easier PoF determination
- Straightforward failure modes
- No subsystem interaction

For all failed units, post-mortem analysis will be carried to ensure that the PoF of ALT to failure data from fielded units

Task 3: Accelerated Life Testing and Correlation to Field Reliability

Goals: **3.1: Choose the ALT protocols to implement**
3.2: Obtain a statistically significant number of samples for test from WG or purchase to ensure vendor/technology-neutrality
3.3: Carry out pre- and post-ALT baselines for device operation parameters.
3.4: Carry out ALT to device failure
3.5: Compare ALT protocols and results to reliability standards in other industries

Results: 1: Acceleration factors for ALTs that can correctly predict field-use reliability data
2: Demonstrated ALT protocol that replicates PoF of field-failed units

- ALT will yield an acceleration factor for each failure mode tested
  - Replicate the field-use reliability data provided by the WG
  - Statistical error of less than one standard deviation.

- ALT methodology and acceleration factor
  - Used to determine MLPE reliability with only a small number of ALTs needed.

Task 3: Accelerated Life Testing and Correlation to Field Reliability

- Exact ALT protocol dependent on WG FMEA results
- Prior accelerated testing from the semiconductor, automotive, and utility-solar industries, sort ALT into five core systems elements
- Team members are ideally equipped to conduct ALTs regarding a wide variety of failure modes commonly seen in other industries

System Element	Failure Mechanism	Accelerated Test	Facilities/Capabilities
Enclosure/Interconnect	Mechanical Deformation, Moisture Ingress, Corrosion, Dielectric Breakdown	Thermal cycling (TC)/ Humidity Freeze (HF)/Damp Heat/UV Precondition	TUV/SNL
PCB/Solder system	TCE Mismatch, Electromigration, Corrosion	TC/HF/ Damp Heat/Voltage Stress/Current Stress	TUV/SNL/ASU/Utah
Passive components	Dielectric/Insulation Breakdown	HF/TC/ UV Degradation/ Current Stress/Voltage Stress	TUV/SNL/ASU/Utah
Active Components	Mechanical Wear-Out, etc.	TC/Damp Heat/Extreme Temperature Exposure/ Integrated Power Cycling	TUV/SNL
Integrated Circuit Devices	Hot Carrier Injection (HCI), Time-Dependent Dielectric Breakdown (TDDB), etc.	Voltage Stress/Current Stress	SNL/ASU/Utah

Task 4: Dissemination of Results to Stakeholders

Goals: **4.1: Meet with WG and present results of ALTs.**
4.2: Begin discussions regarding standard reliability testing protocols for MLPE

Results: **1: Presentation of FMEA, ALT protocols and results, and lifetime, usage, and reliability data for MLPE in scientific publications, trade journals, and conferences**
2: Stakeholder Meeting to disseminate ALT results

- Throughout project, all results will be disseminated in various stakeholder forums:
  - WG meetings
  - scientific and trade publications
  - scientific/industry conferences
  - key members' websites

- Results to be published include:
  - Anonymized reliability, usage, lifetime, and environmental MLPE data
  - FMEA analysis of failure modes, environmental stressors, and at-risk components
  - PoF analysis of field-failed MLPE units
  - Acceleration factors and results for ALTs
  - ALT protocols

Task 5: Submission of Reliability Standard Test Protocols to SDOs

Goals: **5.1: Meet with WG and begin development of reliability test protocols.**
5.2: Continue development of standard reliability test protocols and submit draft to SDO for eventual submission to ANSI

Results: 1: Draft standard reliability test protocol to SDO (TUV Rheinland PTL)

- Standard will be drafted through consensus of WG and submitted to ANSI
  - Similar to the flat-plate PV module qualification standard, IEC 61215
  - Content will be based on pre-stress characterization tests, stress-tests, and post-characterization tests to make the pass/fail decisions based on the visual inspections, functionality/safety failures, and relative performance degradations.
  - If ANSI approves within PREDICTs project period, protocol will be released as standard
- ANSI standards development is a very standard process and cannot be expedited (frequently >3 years). If ANSI standard development is longer than PREDICTs project:

1. Release as "subject" or "in draft" standard
   - Long history of ANSI "under development" standards that are widely used in industry in lieu of published standards(ex. UL 8703, UL 2703, UL 3703, UL3730, UL 6703, etc.)
2. Due to consensus of WG, protocol may be released as consortium-based technical specification while undergoing ANSI review

Final Project Deliverables

The five tasks represented here encompass a full accelerated testing plan and results in tangible final deliverables:

1. Collection and dissemination of bulk statistics for lifetime, usage, reliability, and environmental conditions of fielded MLPE units

2. Publication of FMEA featuring a complete, ranked list of MLPE failure modes, at-risk components, and environmental stressors

3. Analysis of failed MLPE units to determine PoF of fielded units

4. Determination of acceleration factors for ALTs of MLPE with a confidence interval of greater than a standard deviation correlated to field-use reliability statistics

5. Submission to SDOs of a reliability standard testing protocol for MLPE which has been vetted and passed by a consensus of the MLPE WG and released for public use as an ANSI standard, SDO approved subject, or consortium approved technical specification

Thank you