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Overview of PV Resources and Capabilities Within the US Department of Energy Solar Program

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DOE's National Laboratories

- US Department of Energy owns a group of "National Laboratories" that conduct R&D not suited for universities or the private sector
- National Renewable Energy Lab (NREL) and Sandia National Labs (SNL) conduct R&D for DOE's Solar Energy Program
- Photovoltaic R&D Program divided into:
  - Fundamental Science
  - Measurements and Characterization
  - Materials and Devices
  - Codes and Standards
  - Test and Evaluation
  - Reliability
  - Manufacturing
  - Modeling
  - Inverters and Balance of Systems
  - Systems Engineering, Diagnostics, and Analysis

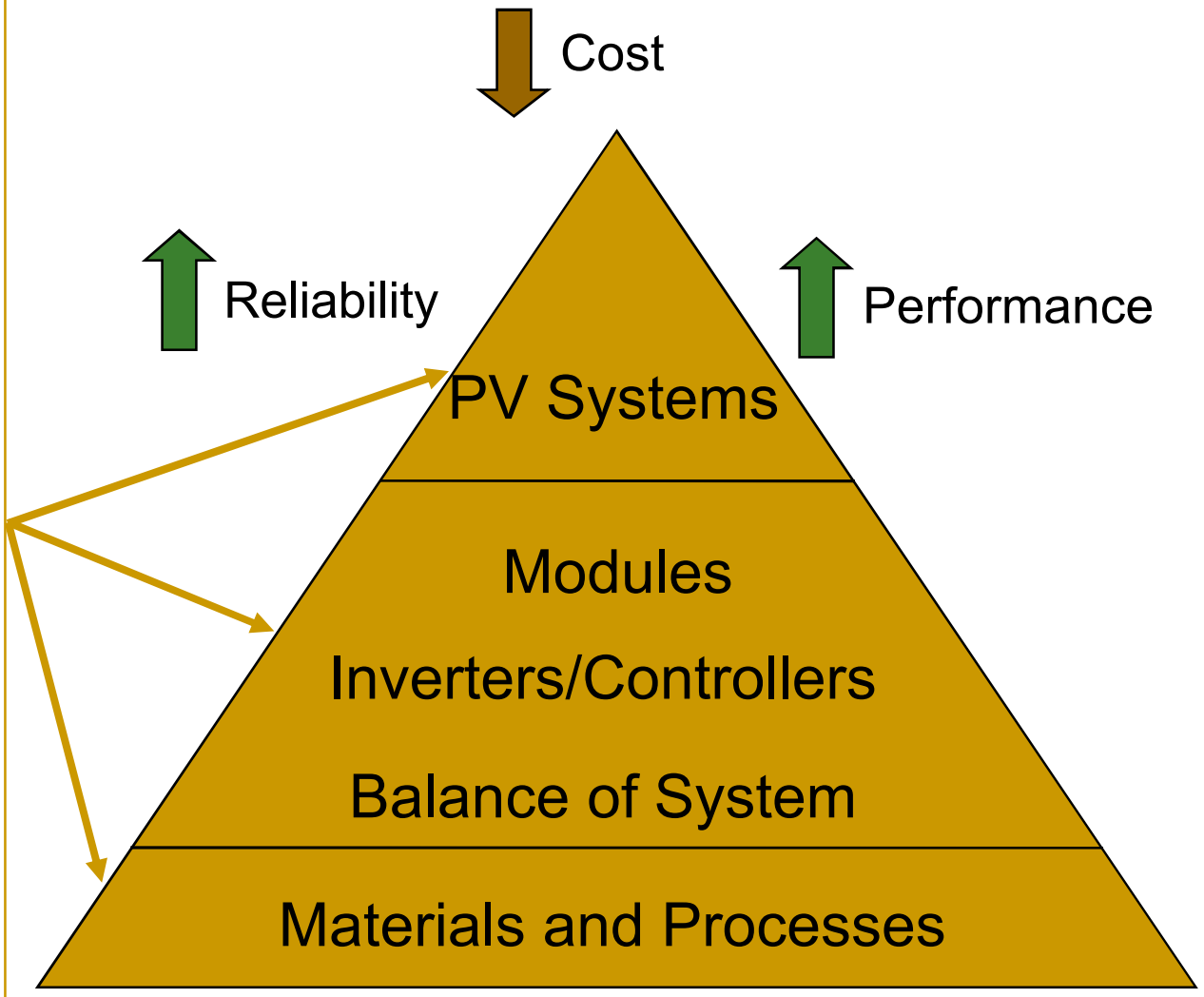
Background

- Sandia is an engineering laboratory primarily focused on reliability aspects for many technology applications
- NREL is primary US laboratory for renewable energy and energy efficiency research and development (R&D).
- Collectively we have >3000 engineers/scientists in the following disciplines:
  - Electrical, mechanical, chemical, and computer engineering
  - Physics, chemistry, materials, mathematics, and other sciences
- Most work is sponsored by DOE and other US agencies
  - Work For Others (WFO) and Cooperative Research And Development Agreements (CRADA) are contractual tools used to work with commercial companies involved in the PV industry

    (US and International Companies)

Systems Driven Approach

- Reliability
- Manufacturing
- Codes & Standards
- Modeling
- Diagnostics
- Lab/Field Tests
- Accelerated Tests
- Failure Analysis
- Qualification and Certification
- Field Evaluations
- Environmental Stress
- System Integration
- Design Verification



Deposition Capabilities

- Plasma-Enhanced Chemical Vapor Deposition (PECVD)
  - Large variety materials
- Pernicka 3 Vacuum Deposition Chamber
  - Deposition of films of metals, conductors and insulators
  - AR coatings, mirrors, lenses, absorbers, light pipes, solid-state drvices
  - Three vacuum coating chambers: load-lock, magnetron sputtering, and ion-assisted e-beam

Encapsulation Research Laboratory

- Analytical Instruments
  - Characterize transmission, absorption
  - Measure emission or excitation spectrum
  - Measures/analyzes color indices of a film
  - Analyze organic/inorganic components
  - Analyze/quantify electroactive components
  - Measure resistance/conductivity of highly resistive films
- Accelerated exposure
  - Solar simulators; UV, full spectrum
- Sample preparation
  - Extruders, roll mill and vacuum laminator

Other Laboratory Capabilities Frequently Used

- Additional analytical/preparation equipment
  - Microscope with digital imaging system
  - Moisture analyzer
  - Balances
  - pH meter
  - Goniometer
  - Ovens and shakers
  - Acoustic (SAM and ultrasonic) testing for adhesion characterization
  - Metallurgical cross-sectioning for solder bond characterization

Vacuum laminator used to prepare samples for exposure testing.

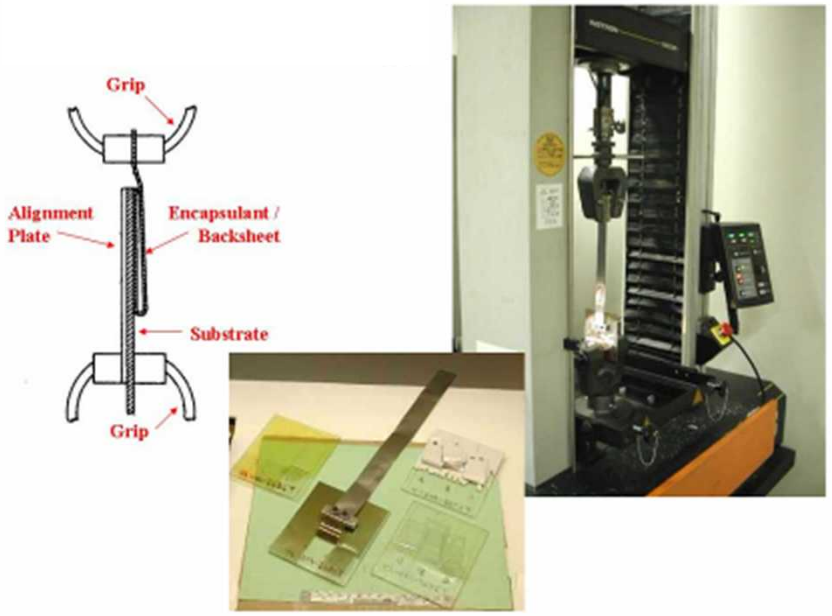
Indoor Accelerated Testing and Exposure

- Single stress and multi-stress controlled chambers test for weathering durability, corrosion, and delamination
  - UV
  - Temperature
  - Humidity
  - Voltage bias
  - Solar simulator
  - Accelerated weathering chambers (light, humidity, temperature)

Environmental Chamber

Optical and Mechanical Characterization

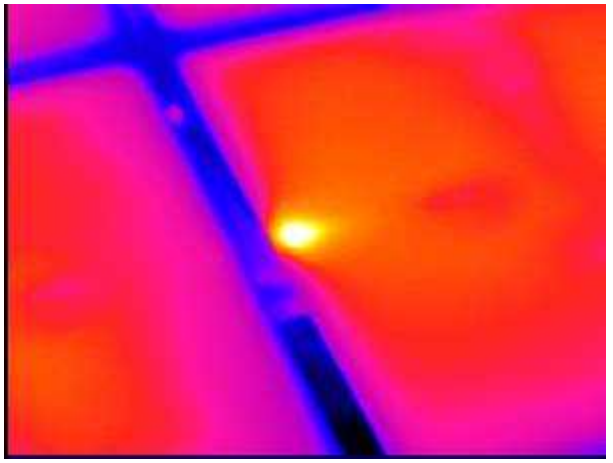
- Instron 5500R Electromechanical test unit
  - Compression, tensile, elastic modulus, creep/relaxation, peel testing, butt joint, and lap-shear adhesion
- Mocon Permatran W 3/31
  - Water vapor transmission rate (WVTR)
- Thermogravimetric analyzer-water diffusivity
- Spectrophotometers
  - Reflectance, transmittance
- Portable Specular Reflectometers



Instron mechanical testing unit used to measure interfacial adhesion properties.

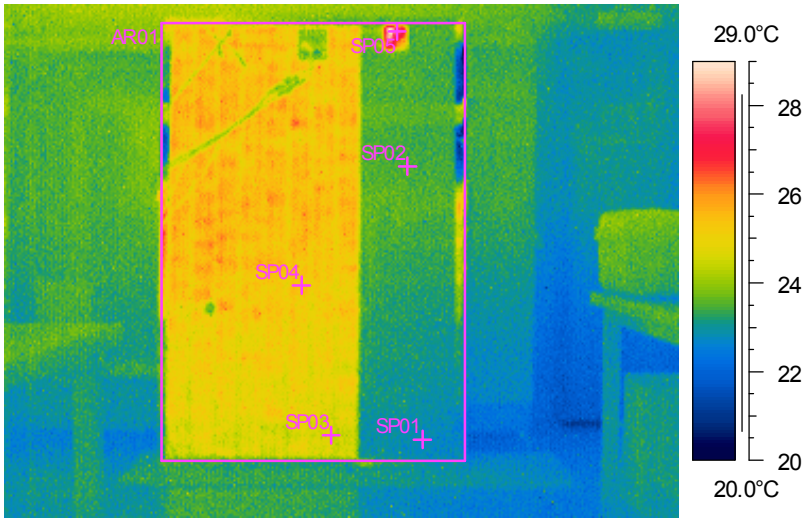
Failure Analysis

- Numerous tools and processes are used
  - IR Camera
  - Dark IV tests
  - Sample extractions
  - Module leakage tests
  - Acoustic imaging
  - X-ray
  - Adhesion tester



IR camera shows hot spot on a module in the field

IR used as a diagnostic in the lab to show a module with one string not producing



Outdoor testing

- Outdoor Accelerated Weathering Tracking System (OATS)
- High Voltage Stress Bed (HVST)
- High accuracy outdoor module performance testing (Albuquerque has ~300 clear test days annually)
- Array and system test beds for performance, durability, optimization, and grid integration studies
- High accuracy meteorological and irradiance monitoring
- Select fielded system monitoring for performance, reliability, and safety studies

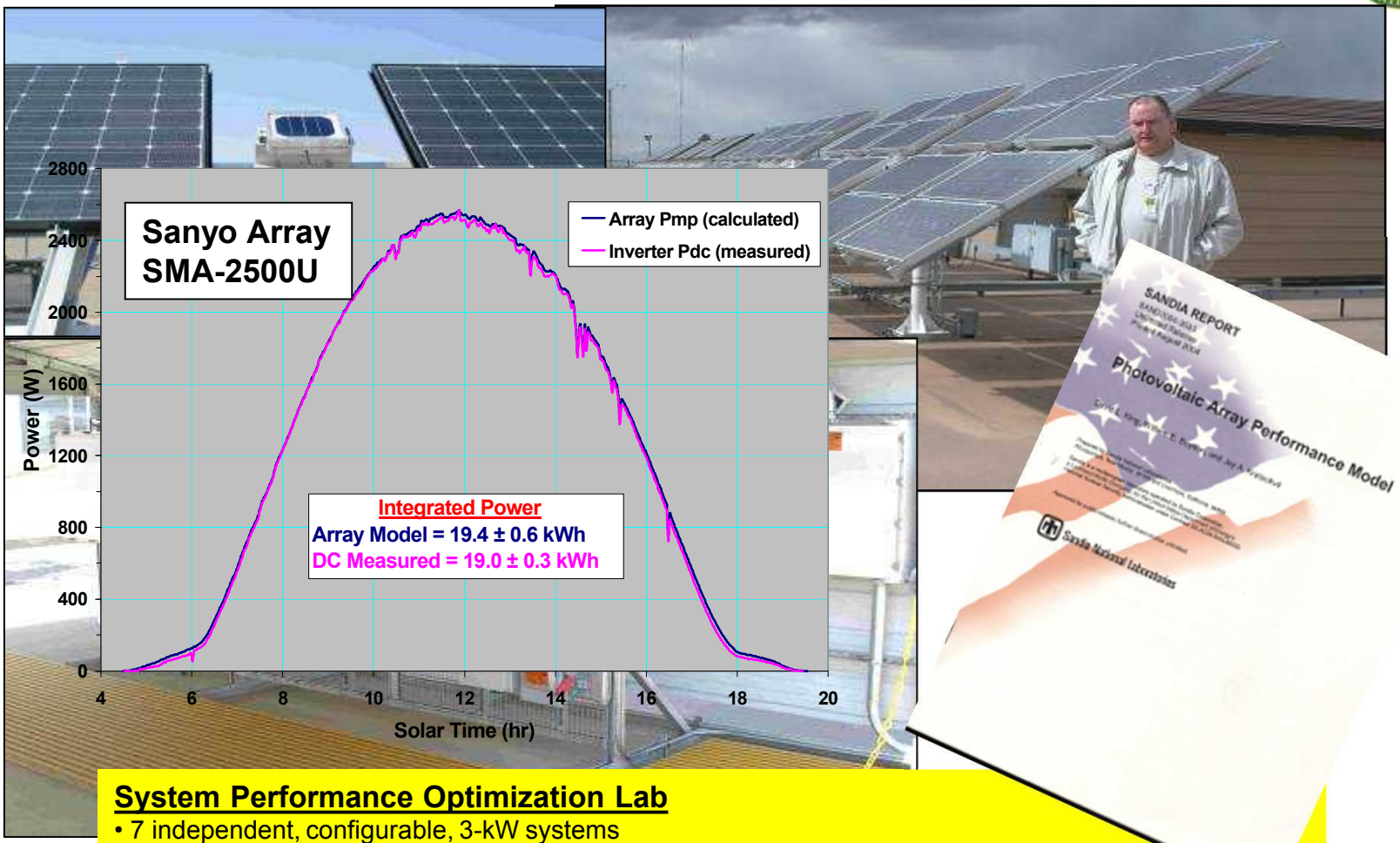
OATS Tracker at NREL

Why are these capabilities so important?

- NREL and Sandia are applying scientific resources to increase the quality of all products being introduced into the market
- NREL and Sandia are applying engineering resources to assure system compatibility with utility grids
- NREL and Sandia are applying analytical resources to develop models that accurately describe cost, performance, and reliability of photovoltaics

The following slides show how we apply capabilities and some results

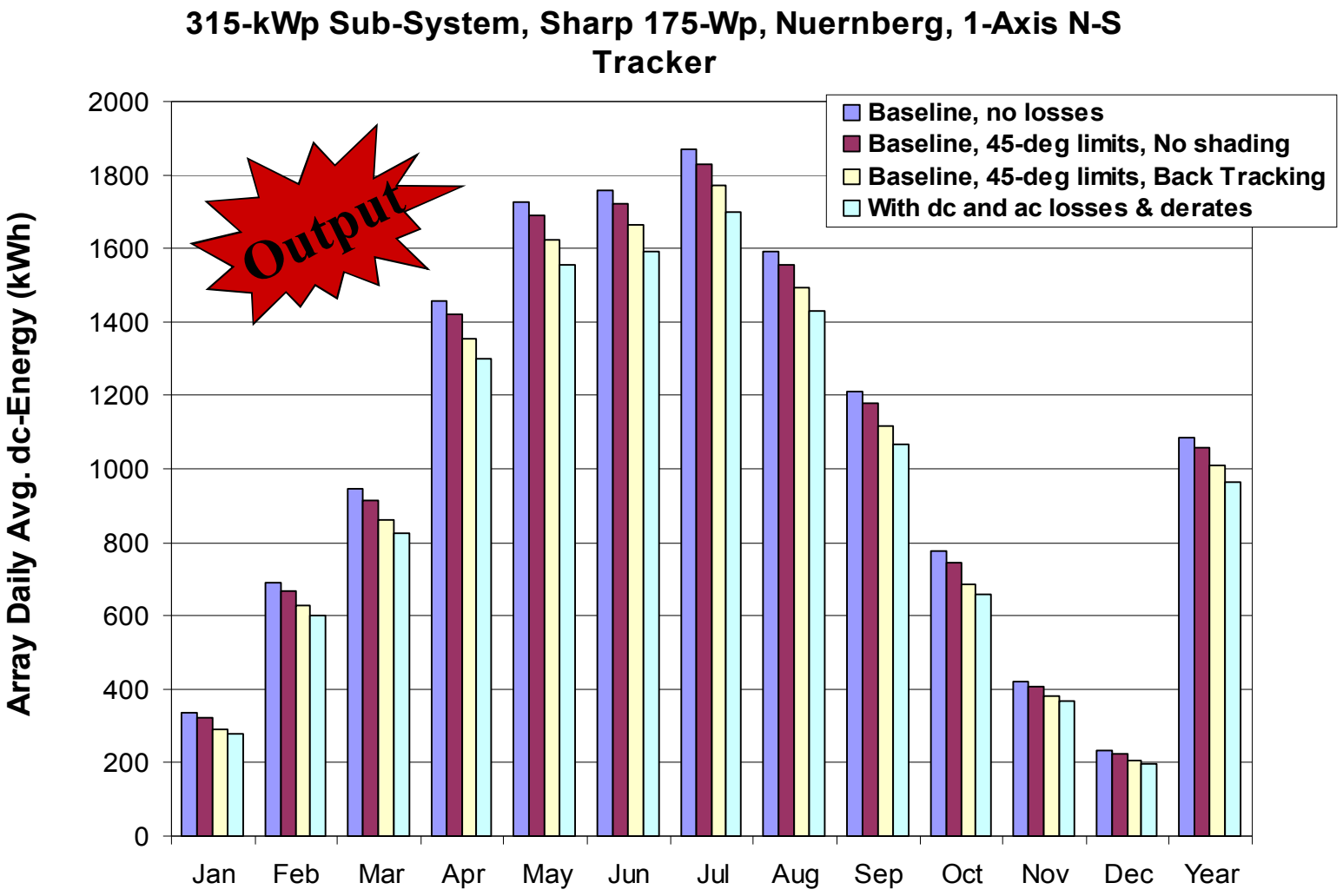
Systems Focus



System Performance Optimization Lab

- 7 independent, configurable, 3-kW systems
- Arrays with variable wiring and orientation
- Grid-connected or off-grid system configurations
- Easy interchange of inverters, charge controllers
- Fully instrumented for detailed energy analysis
- Accurate Sandia array performance model enables characterization of system and component efficiency and quantification of inverter MPPT effectiveness

Energy Modeling



Integrators

Manufacturers

Utilities

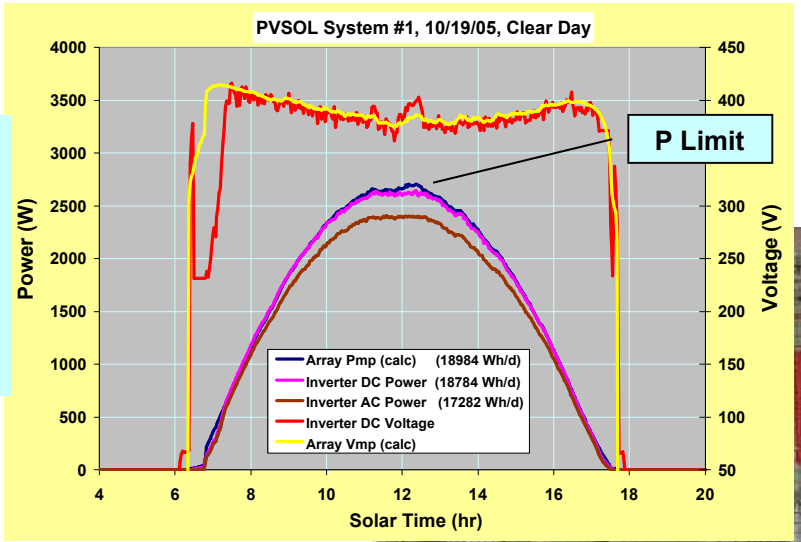
NIST

Researchers

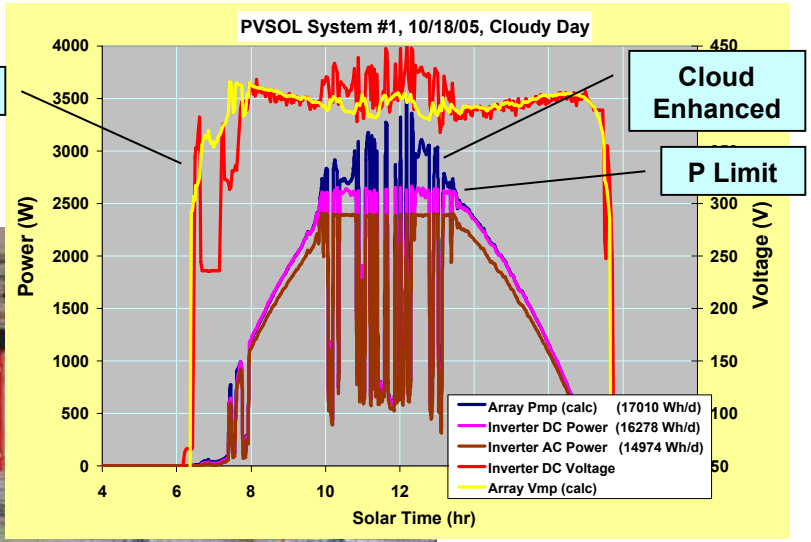
Government

System Analysis & Optimization

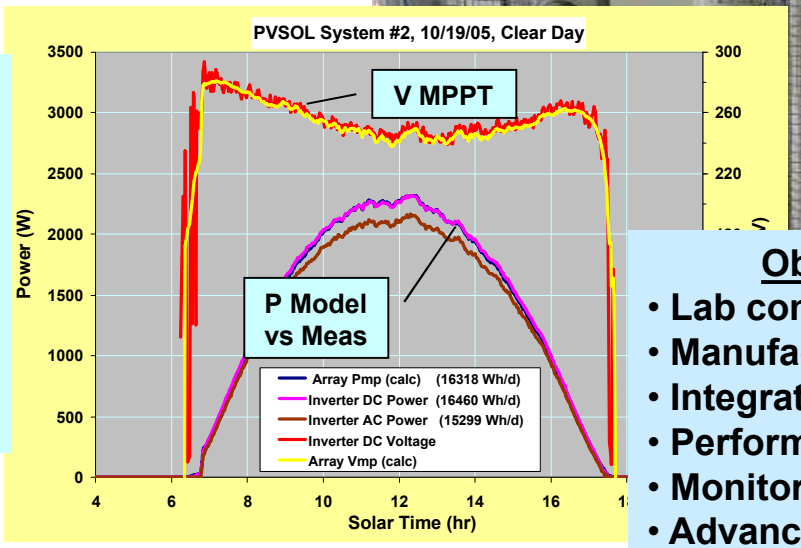
Sanyo - SMA



Start Up



BP Solar - Solectria



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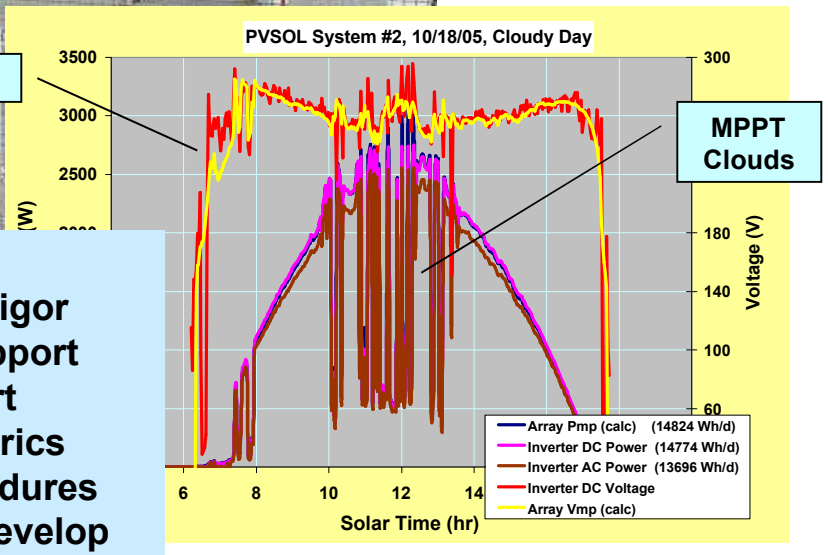
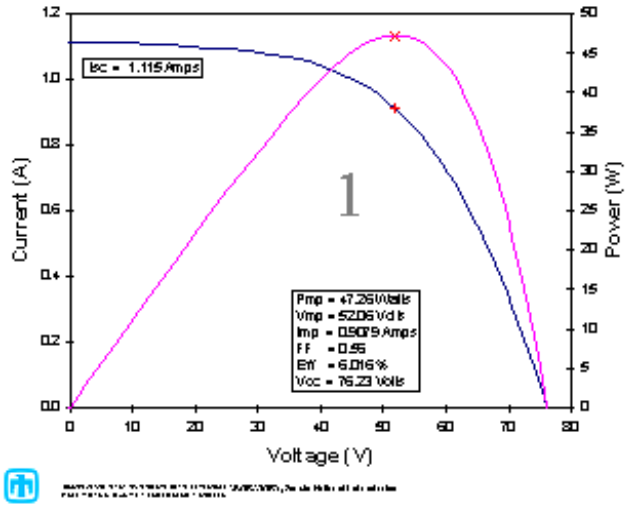


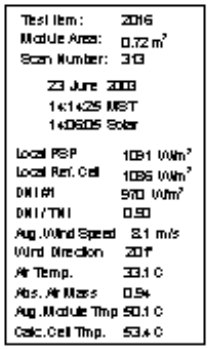
Objectives

- Lab control and rigor
- Manufacturer support
- Integrator support
- Performance metrics
- Monitoring procedures
- Advanced DAS develop
- System reliability

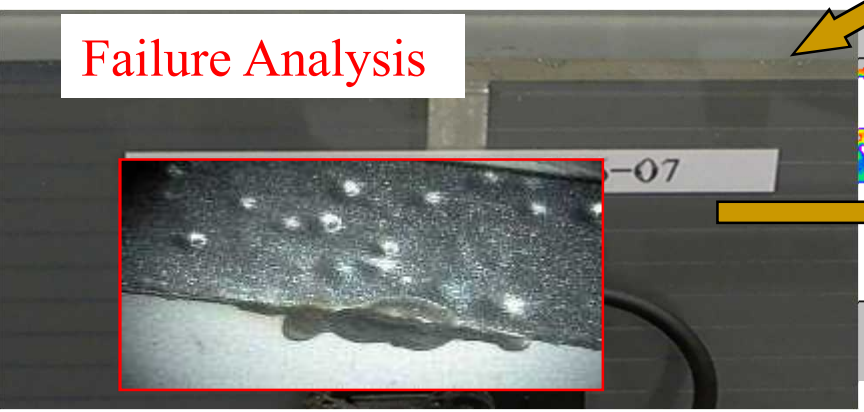
Lab-Field-Lab Studies



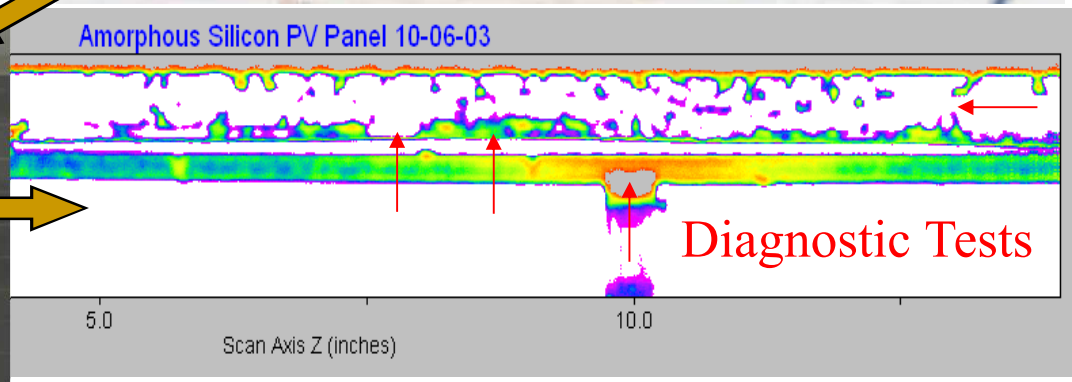
Lab Performance Tests



Field Tests



Failure Analysis



Diagnostic Tests

KW to MW Size Fielded Systems

The Experience Factor

Module and Array Characterization

Fully understand evolving module technology and performance for design

Module R&D

- Benchmark new and improved module technologies entering markets
- Support module performance database
- Accelerate solutions to technology issues in manufactured products

Lab and Field Testing

Module Long Term Exposure

Controlled outdoor exposure to define degradation rates of specific technologies

- Real-time aging of commercially available modules in extreme climates
- Performance, reliability, and/or safety issues
  - Production QC, mechanical failures, moisture intrusion, etc.
- Accelerated exposure test capability (high-voltage bias)

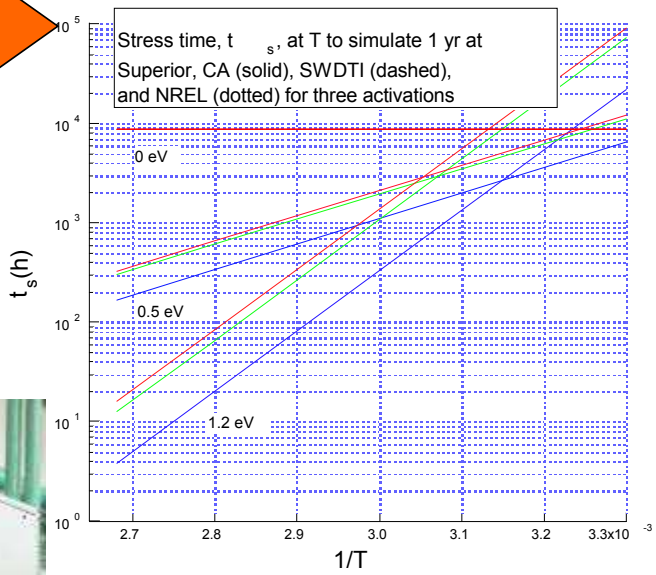
SERES - Hot/Humid Exposure

SWRES - Hot/Dry Exposure

Converging Lab and Field Data

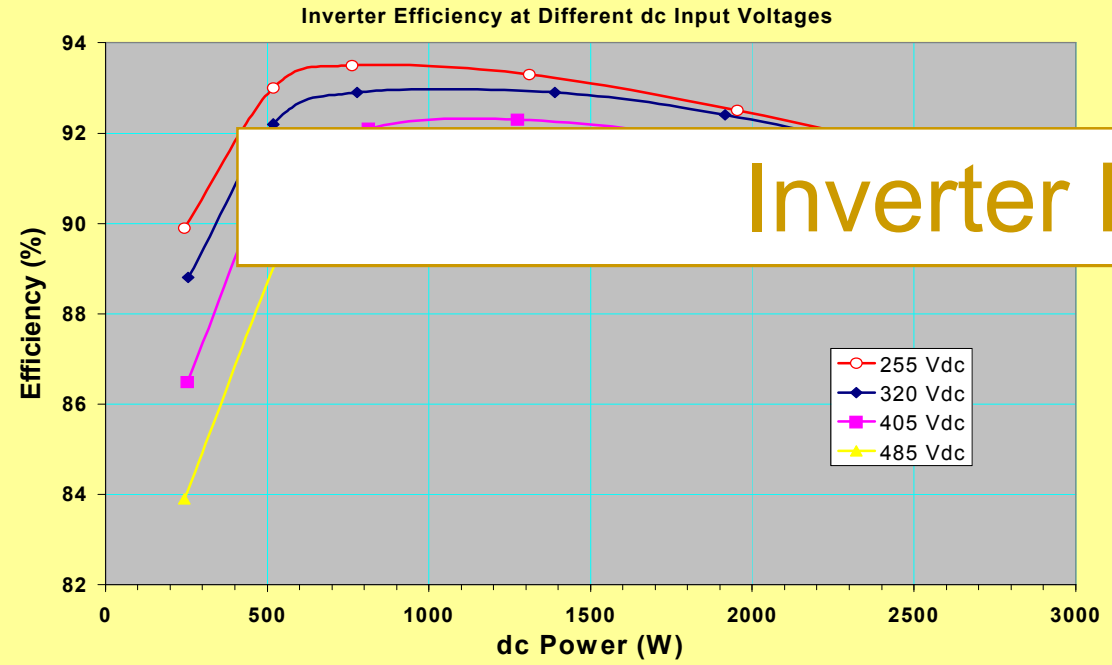
$t_{use}=at_s$

Environmental Chamber Time, t_s LABORATORY



1-Year Use Environment FIELD

Lab Inverter Characterization

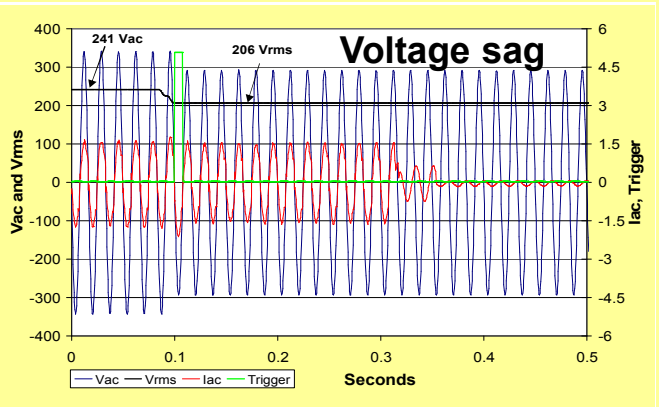


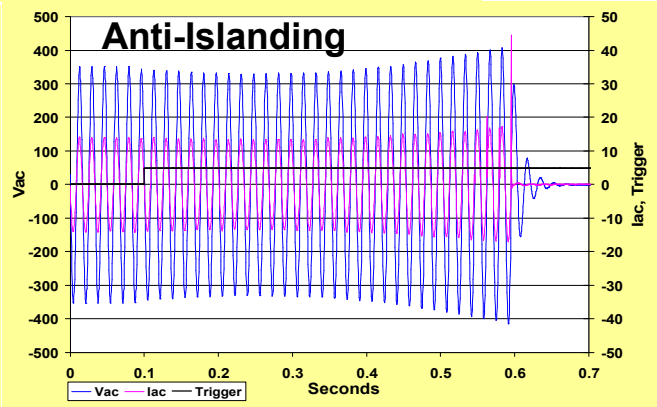
Detailed Lab Testing

- Efficiency (V_{dc}, V_{ac}, T)
- Peak power verification
- Disconnect times
  - AC voltage sag or swell
  - AC Frequency disturbance
  - RLC islanding scenarios
- Harmonic distortion
- RF noise

- Tech support for manufacturers

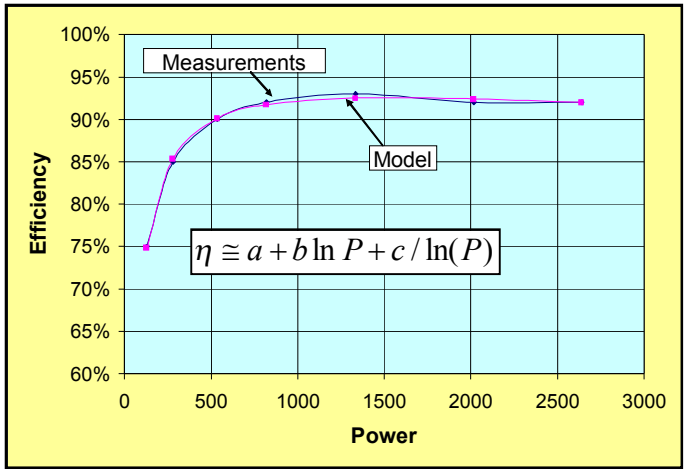
Inverter R&D





PV Inverter Modeling and Reliability

Performance Model



- ✓ Effects prioritized in lab
- ✓ 1st order (Pdc) complete
- ✓ Incorporating into PVSam
- ✓ Refining (Temp, MPPT)

Long-term Characterizations

Purpose

- ✓ Validate SDA model
  - Inverter performance
  - System energy production
  - MPPT and thermal issues
- ✓ Investigate inverter degradation

Status

- ✓ Inverters procured and fielded
- ✓ SNL, FSEC, SWTDI
- ✓ Initial performance evaluated
- ✓ Two inverters failed <24 months
- ✓ Failure analyses being conducted

Long Term Inverter Testing Initiative
Initial Commission Testing
Aaron Murray
Sandia National Laboratories

Confirmed Inverter Types:

Make	Size	Model Number
SMA	2500W	SWR2500
Fronius	3000W	IG3000
PV Powered	2800W	PVP2800
Xantrex	3000W	Xantrex GT 3.0

Test Procedure:...

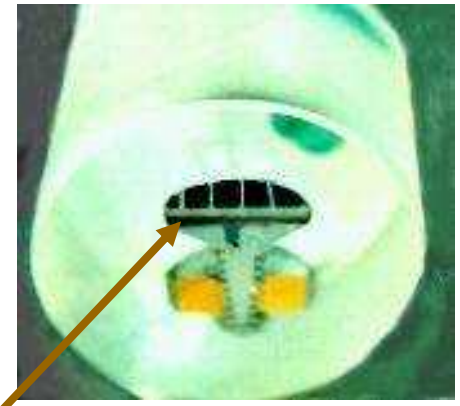
Example: Major Manufacturer Reliability Study

- **Performance assessment— before and "after" to measure affects of degradation**
- **IR imaging— thermal performance and/or failure points, QC check of bypass diode**
- **Dark IV— look at small changes in series resistance, ditto for bypass di**
- **Ul**
  lamination, poor solder bonds, etc.
- **Chemical composition**
  - **LC/PDA/MS and GC/MS—chemical composition before and after aging or outgassing analysis**
  - **Differential Scanning Calorimetry (DSC)—material composition by examining the endothermic and exothermic characteristics as material undergoes a phase change**
  - **Thermogravimetric Analysis (TGA)—measure weight loss in materials that outgas during lamination and/or field exposure**
- **Adhesional Strength—bonded or laminated surfaces**
- **Solder-bond metallography—bond quality, e.g. geometry, voids, intermetallic formation, etc.**

Failure Analysis

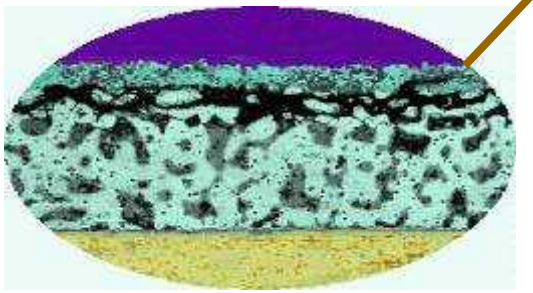
Solder Bond Studies

Solder bond cross-sections are exposed after extraction from modules using a coring method



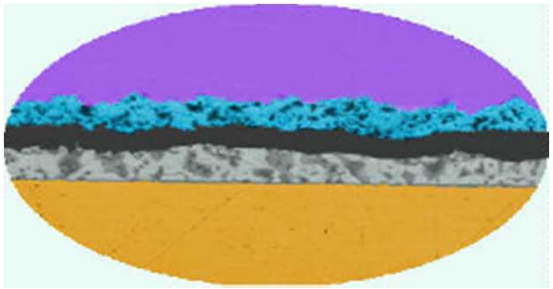
Manufacturing **Field Aging**

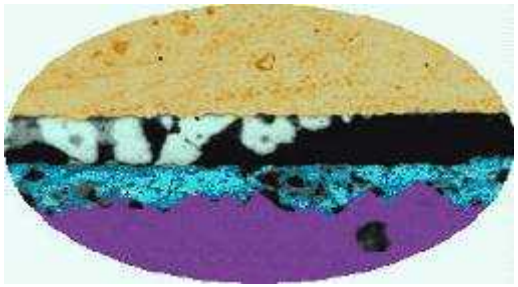
Voids



Cracks

Dewetting

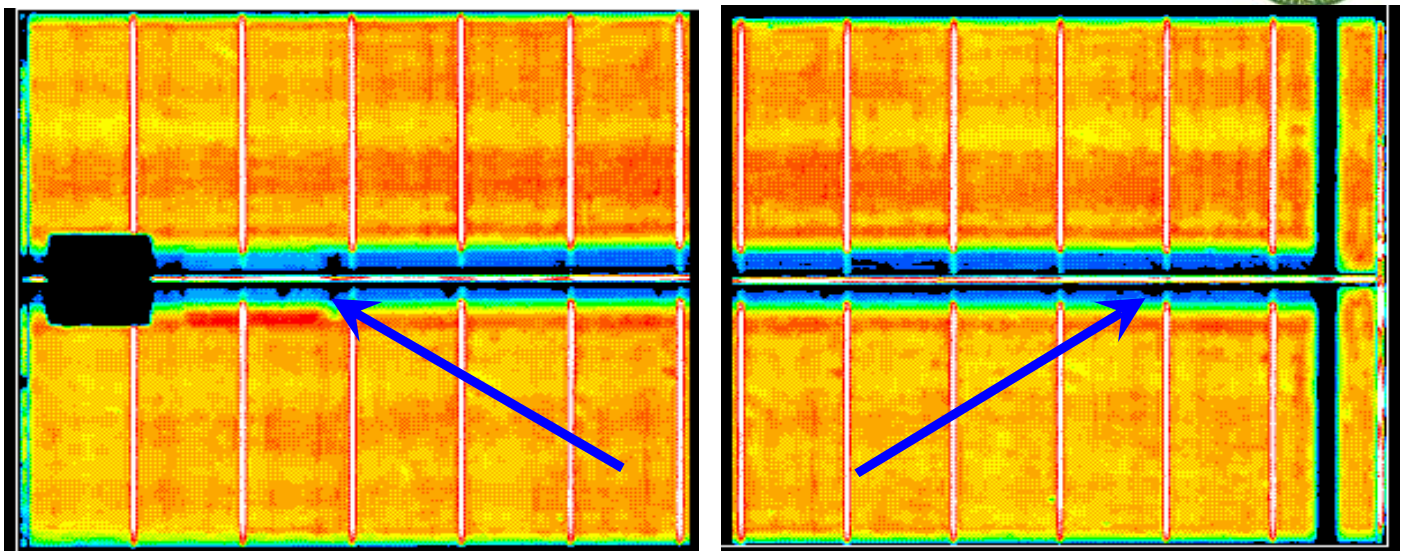




Coarsening

Delamination Studies

Ultrasonic test of a module done in half sections show delaminaton



Adhesion test data is acquired by measuring torque while using a coring technique to extract samples from a PV module

Removing the Barriers

- **Certification of PV Installers**
  - **USA "National Program" established (w/ RESs)**
  - **State and industry support growing**
  - **Will reduce installation and design errors**
  - **Very positive feedback from applicants/certificants**

- **National Electrical Code**
  - **Collaborative SNL/SWRES/Industry Forum**
  - **Key changes describe US market needs to the world**

- **International Codes and Standards**
  - **Module Qualification IEC 61215, UL1703**
  - **Increased effort to actively guide codes and standards by participating in IEC standards writing; e.g. Thin Films and CPV**

Summary