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CSP Training Module 3: Modeling CSP Plants

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Agenda

- 1. Basic Theory of Operation
- 2. Fuel
- 3. Modeling CSP plants
- 4. Basic construction and Design
- 5. Startup and Shutdown
- 6. Major System Operations
- 7. Plant Operation influences on the grid
- 8. Response to Weather Changes
- 9. Water Chemistry
- 10. Plant Performance Measurements
- 11. Safety Concerns

3. Modeling CSP plants

- Types of Models and Their Purpose
  - Plant level models
    - Energy flow
    - Trade studies
  - System level
    - Optical Performance
    - Physical subsystem
    - Detailed performance
  - Component level
    - Design level
    - FEA
    - CFD
- Waterfall efficiency
  - Conversion Efficiencies and soiling effects

Plant Level Models

- Purpose:
  - To model the entire plant and understand it performance on a macro level.
  - Conduct trade-off studies on the effects of design or operational parameters on the output or economics of the plant
  - Compare performance to actual operation and understand discrepancies
- Examples
  - SOLERGY – use to conduct plant annual energy production for different dispatch strategies.
  - DELSOL – use for performance and optimization of complete system. It models heliostats, receiver, BOP, and calculates LCOE
  - SAM – use to conduct plant annual energy analysis, economic analysis, and plant optimization

Plant Level Models

- SOLERGY
  - Basic Features:
    - Estimates the annual performance of a solar thermal electric power plant.
    - Quasisteady-state plant model with a constant (but user-variable) time step.
  - Accounts for the following factors on the annual electrical output:
    - Energy losses and delays incurred in start-up
    - Effects of ambient weather conditions on plant operation and efficiency
    - Effects of hold time
    - Charge and discharge rates on deliverable energy from storage
    - Subsystem maximum and minimum power limits
    - Parasitic power requirements
  - First law thermodynamics analysis (conservation of energy):
    - Solar energy incident on the heliostats is followed through the plant and reduced by losses as it, passes through the various subsystems
    - Actual fluid temperatures and flow rates are not computed.
  - Written in FORTRAN

Plant Level Models

- DELSOL
  - Basic Features
    - Performance and design optimization code
    - Uses an analytical Hermite polynomial expansion/convolution-of moments method for predicting images from heliostats
    - Computationally efficient
    - Calculates time varying effects of Insolation, cosine, shadowing and blocking, and spillage
    - And time independent effects attributable to atmospheric attenuation, mirror reflectivity, receiver reflectivity, receiver radiation and convection, and piping losses.
  - Used to evaluate:
    - LCOE for a variety of technical options and range of sizes,
    - Effects of heliostat parameters on system cost and performance.
  - Original code written in FORTRAN

Plant Level Models

- Solar Advisory Model
  - Basic Features
    - Performance and financial model designed to facilitate decision making
    - Makes performance predictions and cost of energy estimates based on installation and operating costs and system design parameters
    - User friendly interface
  - Includes performance models for the following technologies:
    - Photovoltaic systems (flat-plate and concentrating)
    - Parabolic trough concentrating solar power systems
    - Power tower concentrating solar power systems (molten salt and direct steam)
    - Linear Fresnel concentrating solar power systems
    - Dish-Stirling concentrating solar power systems
    - Conventional fossil-fuel thermal systems
    - Solar water heating for residential or commercial buildings
    - Large and small wind power projects
    - Geothermal power and geothermal co-production
    - Biomass power
  - Can use sliders to conduct parametric studies
  - Has some optimization functions (e.g., field layout for specific receiver design)

System Level Models

- Models that give a physical representation of the behavior on a system in the plant
  - Heliostat field: field layout, optical performance, blocking, shading, cosine, spillage, optimization
  - Receiver: process flow, thermal hydraulic analysis, thermal loss, efficiency, transient behavior
  - Thermal storage: sizing, charging/discharging strategies, heat loss, optimization, transient behavior
  - Power block: heat balance diagrams, optimization of configuration (e.g., number and configuration of feedwater heaters), pressures, temperatures, startup, transients
  - Balance of Plant: auxiliary power consumption
- Models provide input to Plant Level Models
- Important for plant system design, especially at interfaces
- Typically in-house, though many commercial packages available for elements

Component Level Models

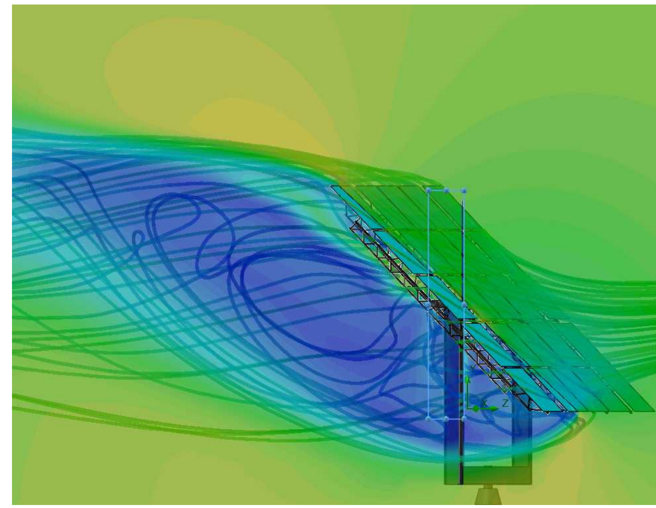
- Component-level models are typically used to develop designs or confirm compliance with design
- Examples:
  - Finite element analysis (FEA) to determine high stress locations, fatigue life, minimize failures
  - Computational fluid dynamics (CFD) to understand the impact of wind loads on heliostats and heat loss from receiver surfaces.
- Provides feedback to design, but also can provide limits on operational parameters
  - Ramp rates during startup
  - Temperature, pressure, and flow limits
- Process requirement can feed down to component level models. Design limits can also feed up to process limits.
  - Rate of change of flux due to clouds will impact the receiver HTF temperature ramp rate
  - Similarly, thermo-mechanical LCF of the receiver material will limit the allowable steady-state flux

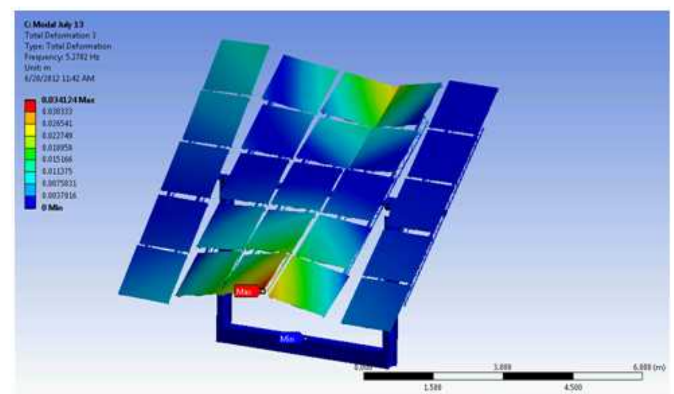
Example of CFD and FEA

<u>Goal</u>: These tests and analyses will improve our understanding of the impact of wind loads on heliostats, which will lead to improved structural designs that can dampen or mitigate wind-induced vibrations and loads, ultimately leading to improved optical accuracy, structural reliability, and reduced costs.

<u>Innovation</u>:

- Use of full-scale heliostats (vs. wind-tunnel tests with scaled plastic models) for testing and model validation
- Application of modal analyses to assess dynamic (vs. static) impacts of wind on structural fatigue and optical performance
- Assessment of spatial and temporal effects in a field of heliostats





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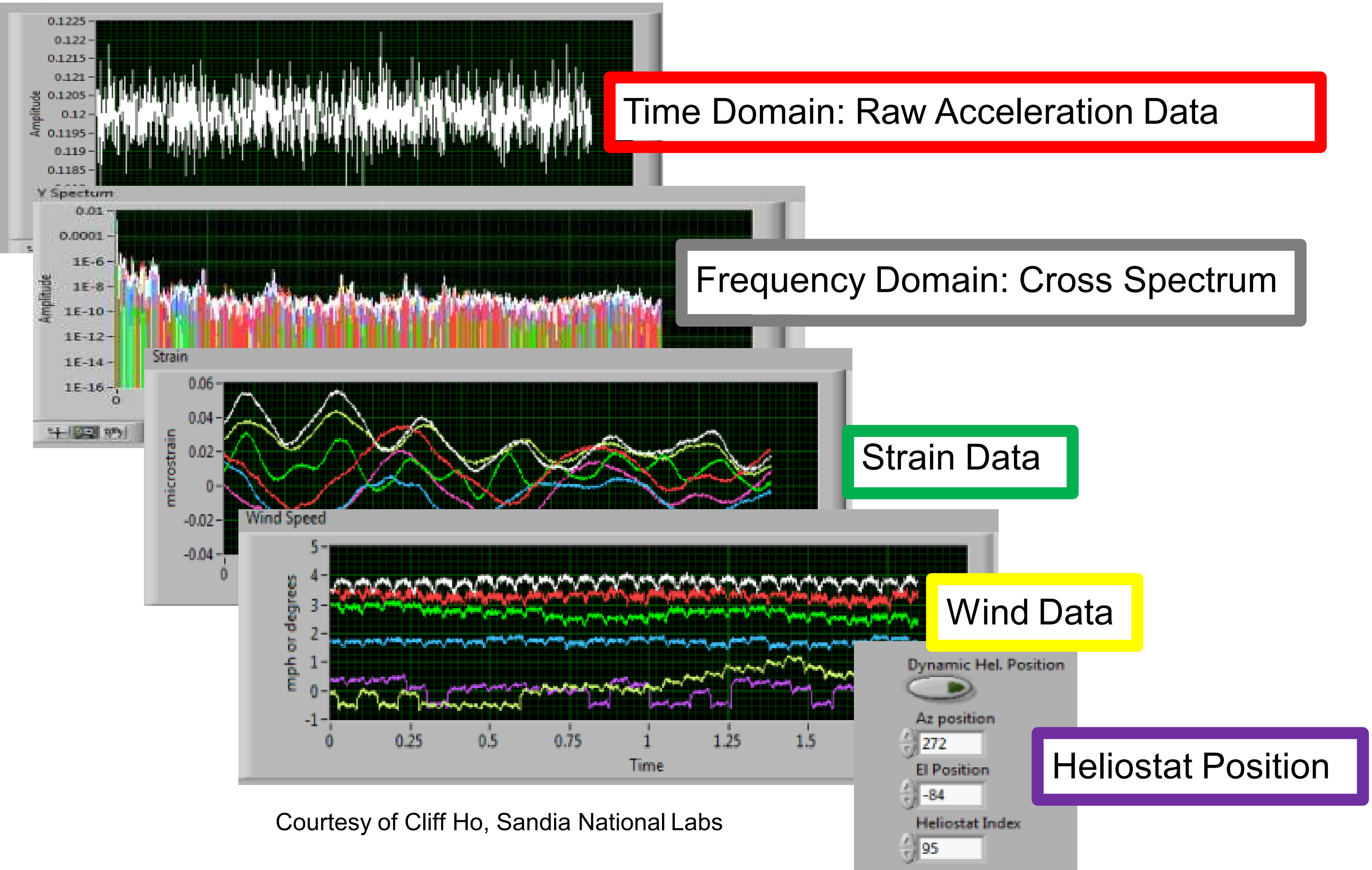
Approach

1. Merged Acceleration, Strain, and Wind data acquisition programs into one operational program
2. Mounted sensors on 10 heliostats
3. Conduct wind load analyses with DAQ
4. Conduct modal analyses with DAQ

Merged DAQ Capabilities



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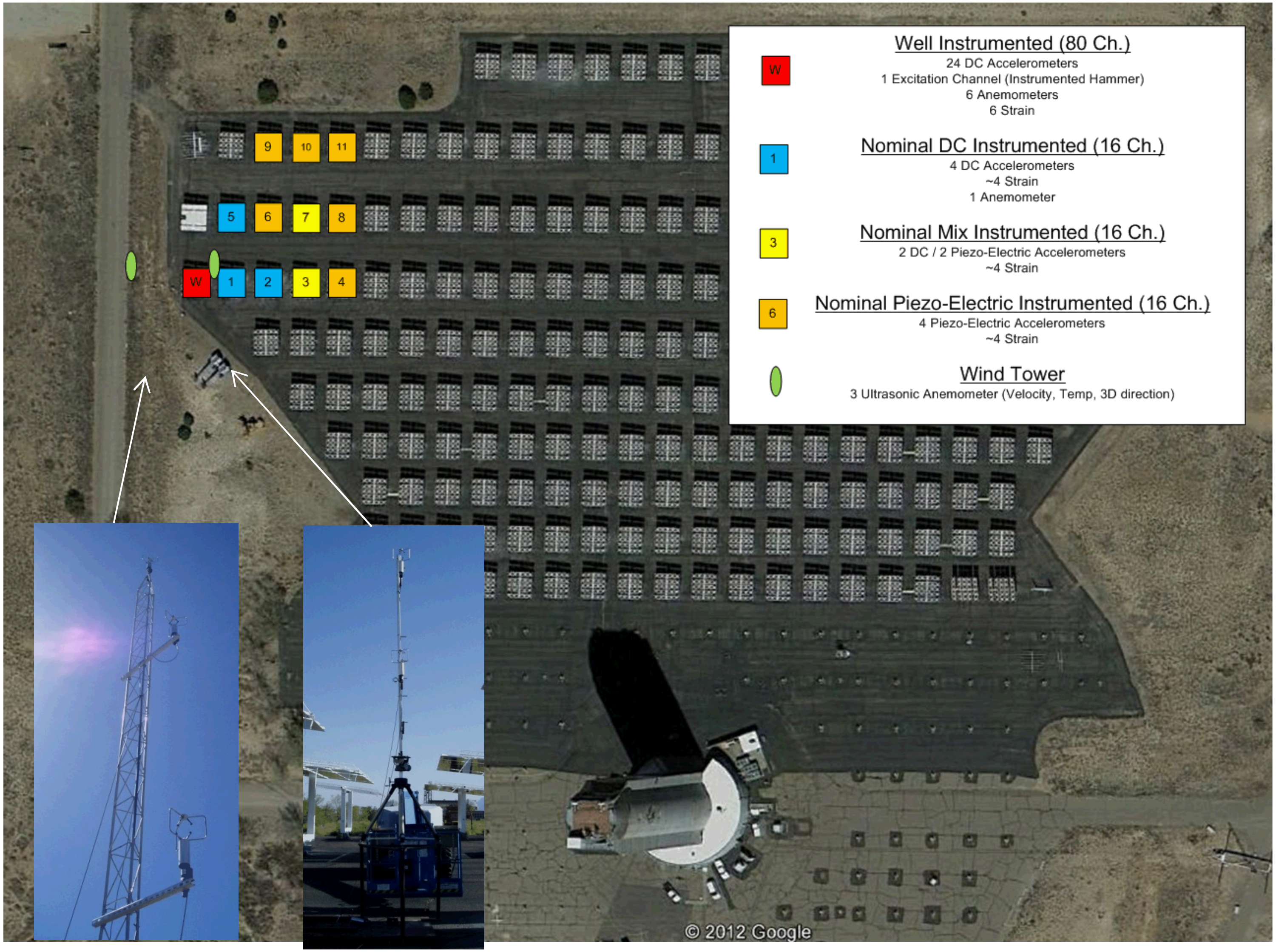
Heliostat Instrumentation



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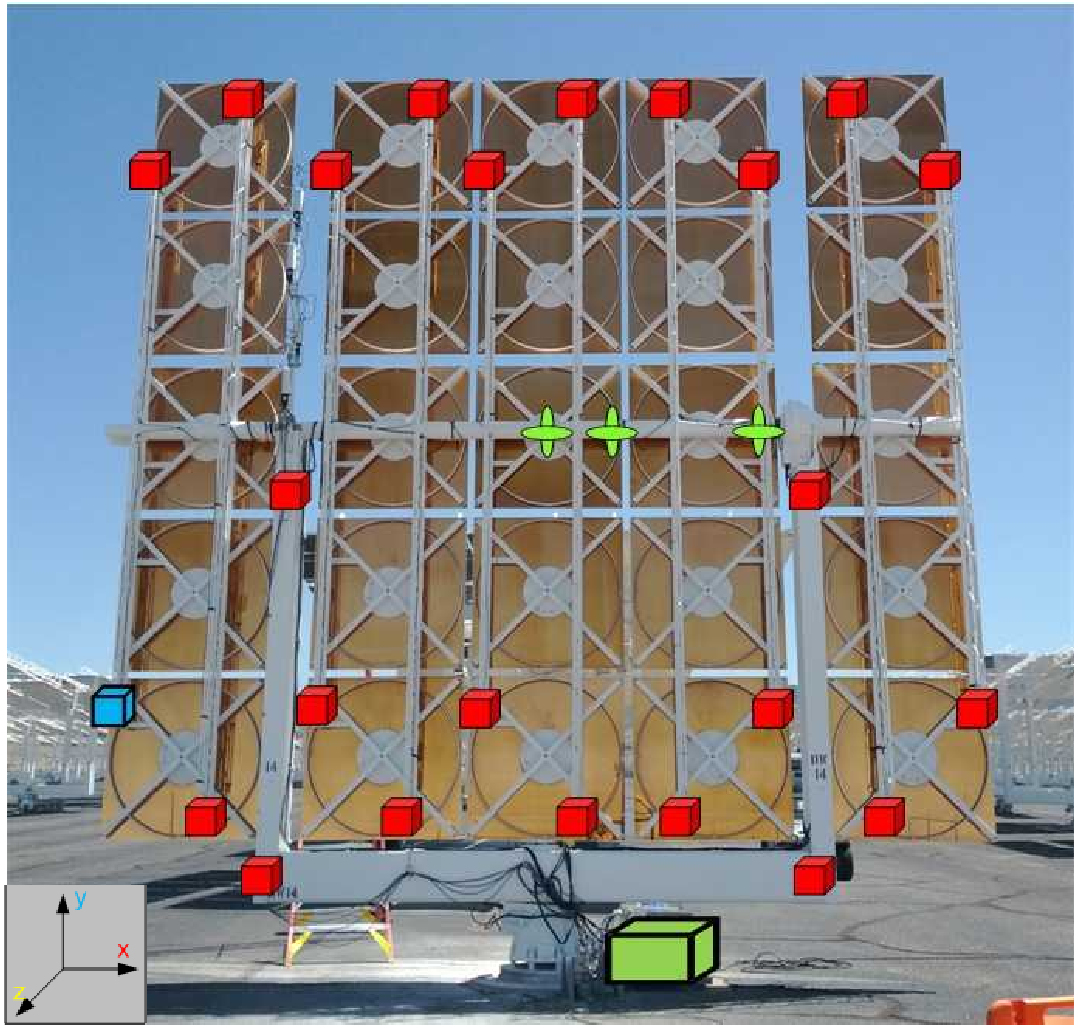
Well Instrumented Heliostat



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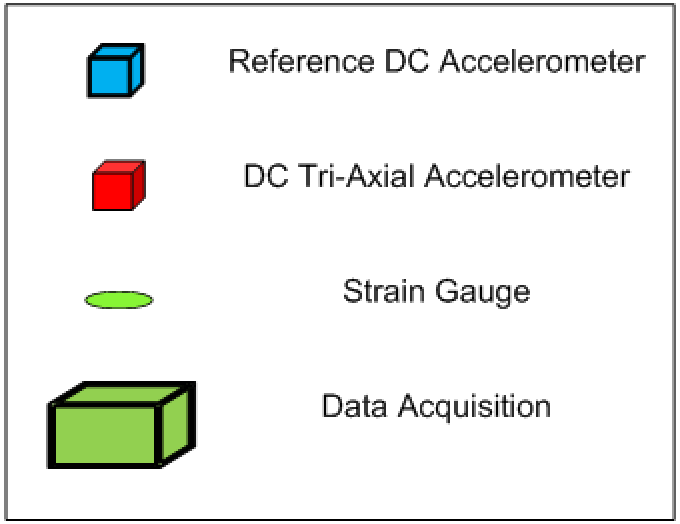
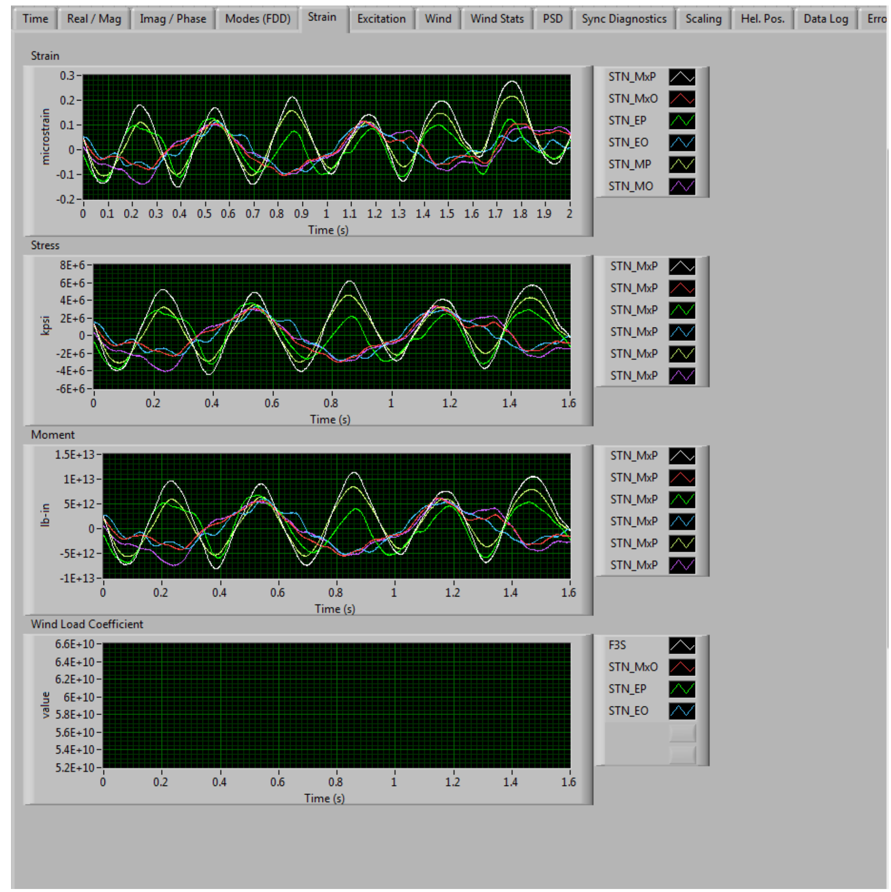


- 24 Tri-axial DC Accelerometers
- 6 Strain Gauges
- 6 Ultrasonic Anemometer (Not Shown)

Wind Load Analyses

1. Measure strain
2. Convert strain to stress via Young's Modulus and empirical constants
3. Determine moment from stress via known methods and empirical models
4. Use wind and heliostat position data to determine wind loads



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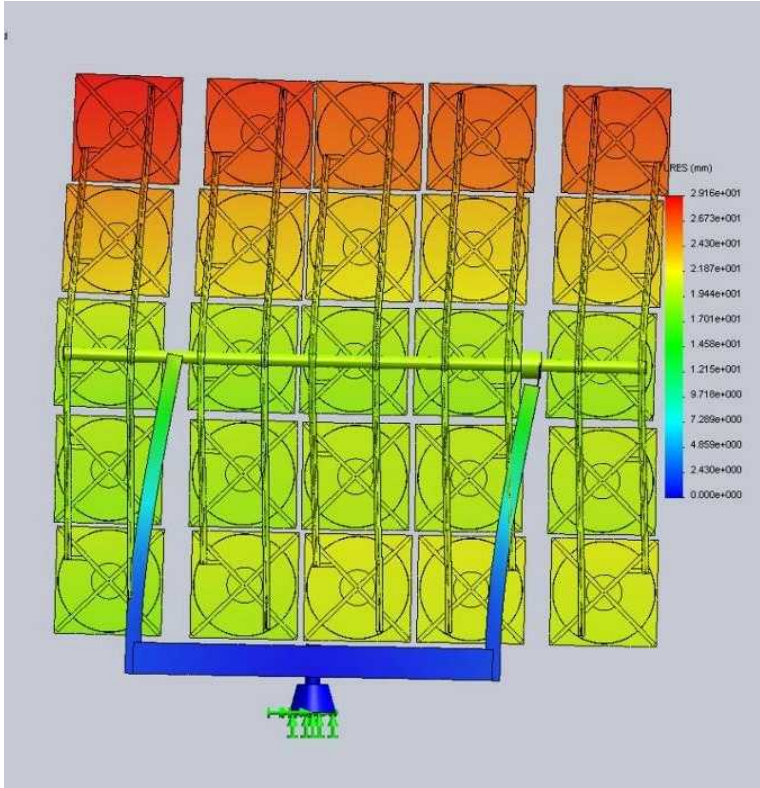
Modal Analyses

1. Measure Acceleration
2. Frequency Domain Analysis
3. Modal Parameter Identification
    1. Mode shapes
    2. Natural Frequencies
    3. Damping
4. Impact on fatigue and optics



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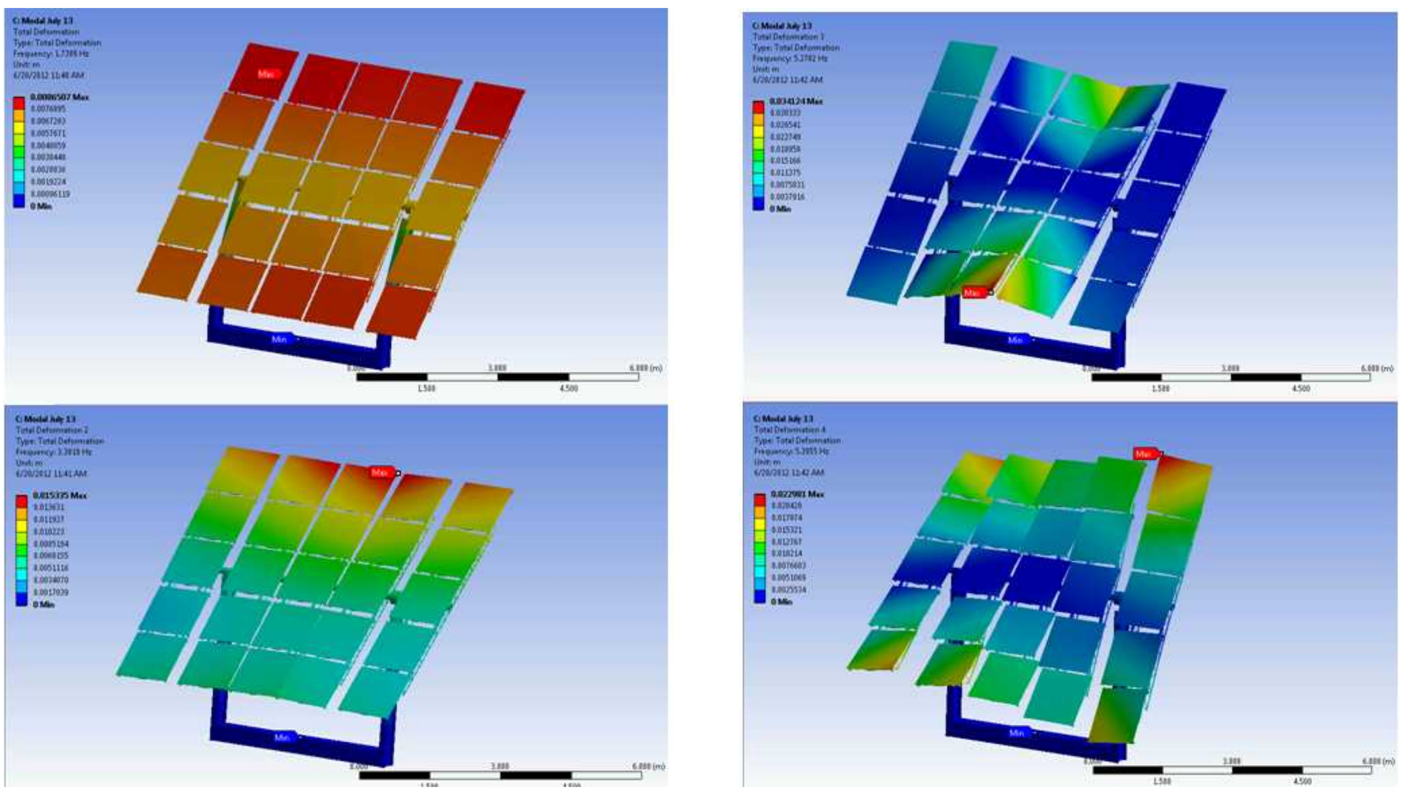
Modal Analysis of NSTTF Heliostat

- First 20 modes, between 1.8 and 7.7 Hz

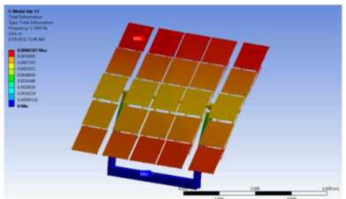


Clockwise from top left: Mode 1, 1.74 Hz; Mode 12, 5.27 Hz; Mode 13, 5.39 Hz; Mode 2, 3.30 Hz

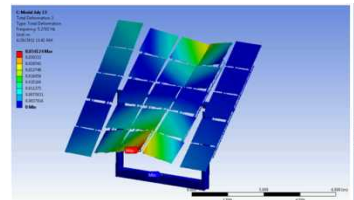
Courtesy of Cliff Ho, Sandia National Labs

Beam Shape Characterization: NSTTF Heliostat

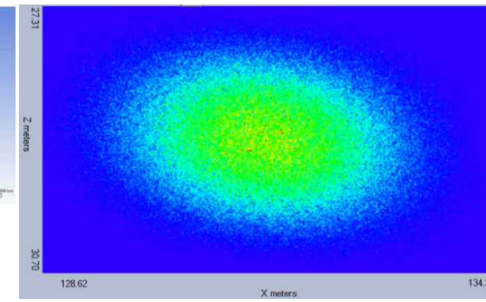
Deformed beam shapes from modal study

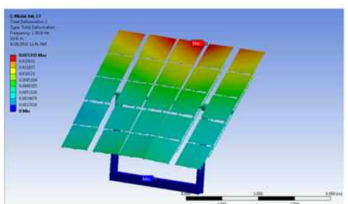


Mode 1

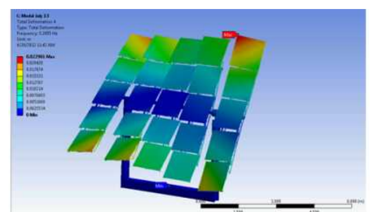


Mode 12





Mode 2



Mode 13

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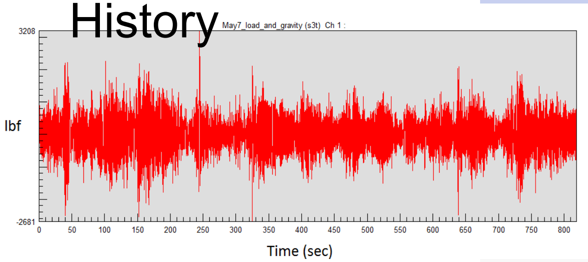
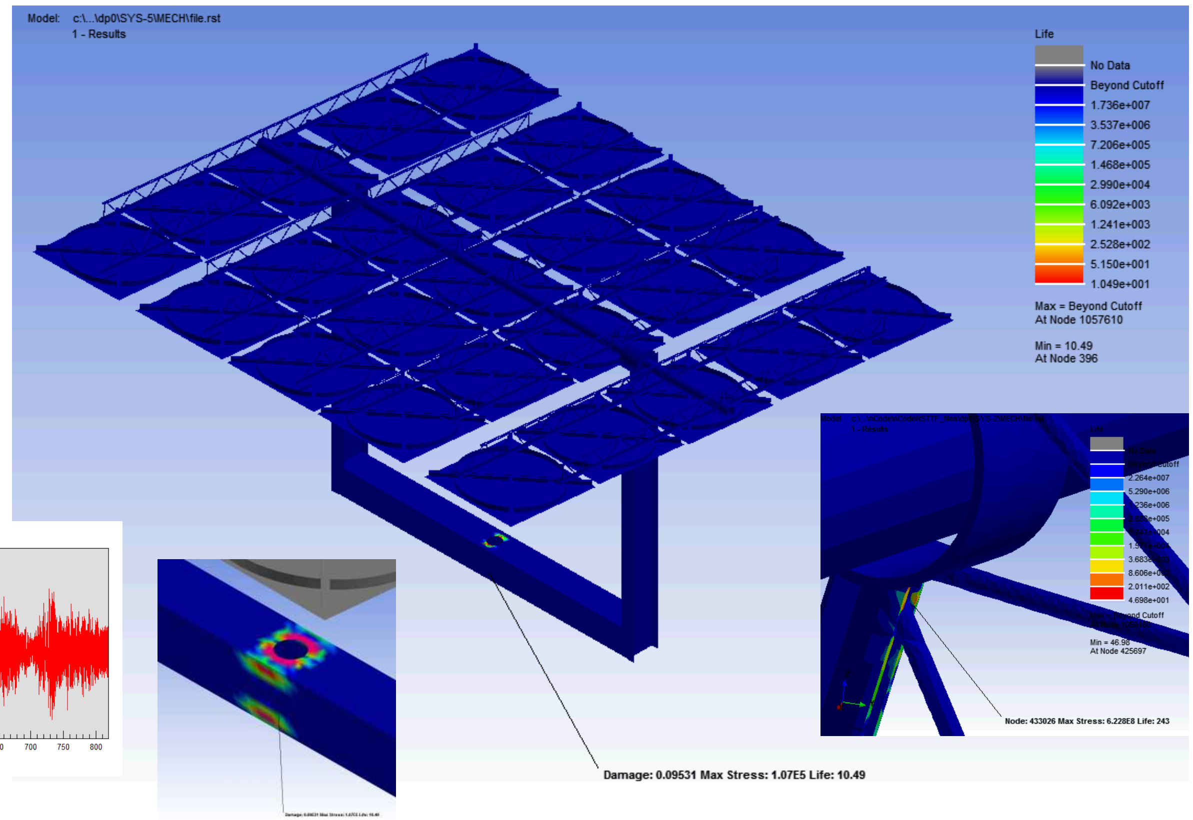
- Fatigue analysis of NSTTF Heliostat
  - Simplified wind load histories extracted from instrumented heliostat applied to FEA models

Load History





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Waterfall Efficiency

- Describes the flow of energy from direct normal irradiance through each step of its conversion to electricity

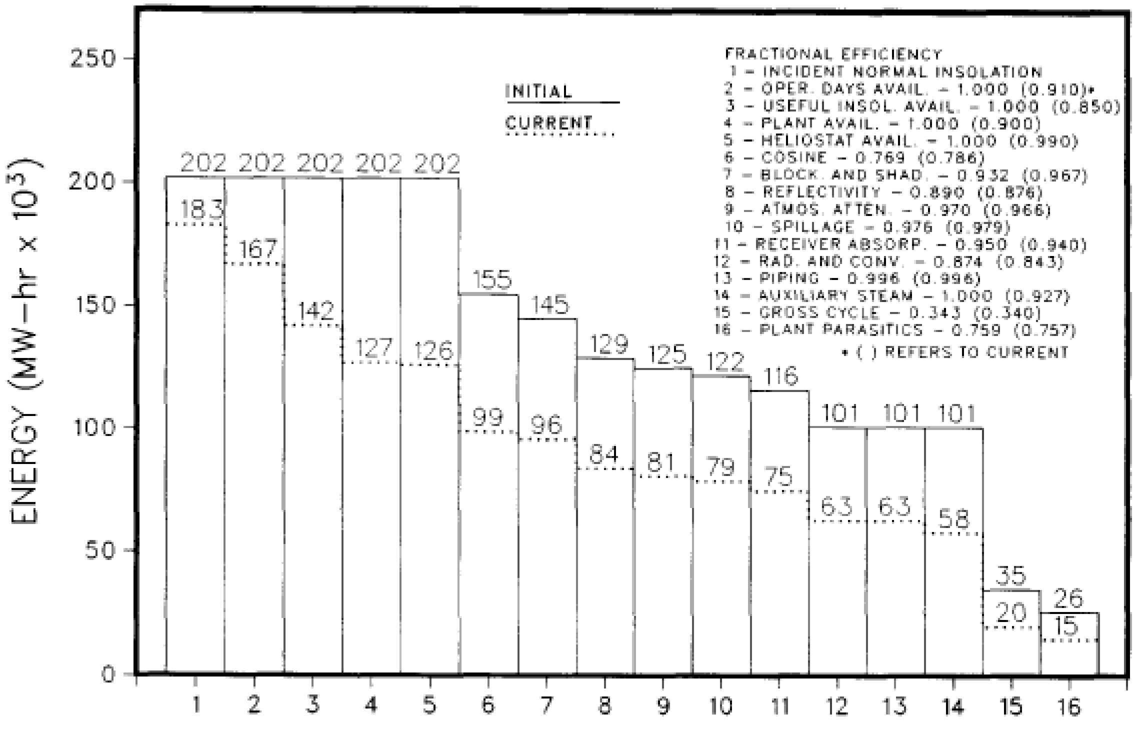


Figure 4-1. Comparison of Initial and Current Pilot Plant System Efficiency and Annual Energy Predictions

Source: L.G. Radosevich, *Final Report on the Power Production Phase of the 10 MWe Solar Thermal Central Receiver Pilot Plant*, SAND87-8022, March 1988

Definition of Each Efficiency Element

- 1. Incident Normal Insolation: Annual direct normal insolation times the heliostat reflective surface area.
- 2. Operating Days Insolation Availability- The fraction of the annual horizon-to-horizon insolation that is available on the days when the plant was operating or could have operated. The difference between the total (365 day) horizon-to-horizon insolation and the operating days insolation is the insolation occurring on the plant's non-operating days - that is, days when insolation levels were too low or wind speeds were too high.
- 3. Useful Insolation Availability -Useful insolation when the irradiance is above a certain threshold (e.g., 500W/m^2) on the plant's operating days.

Definition of Each Efficiency Element

- 4. Plant Availability - The fraction of daylight hours that the plant is available to operate, assuming good weather conditions. Thus, plant availability reflects scheduled and unscheduled plant maintenance outages but does not reflect weather outages. (Any overlap between maintenance and weather outages is considered to be a weather outage.)
- 5. Heliostat Availability- Fraction of the heliostat field that is operational.
- 6. Cosine – Cosine angle between the mirror normal and sun or target vector.
- 7. Blocking and Shadowing – Fraction of energy that is lost due to blocking reflected light from heliostats in the path of a reflected beam and shading from an adjacent heliostat.

Definition of Each Efficiency Element

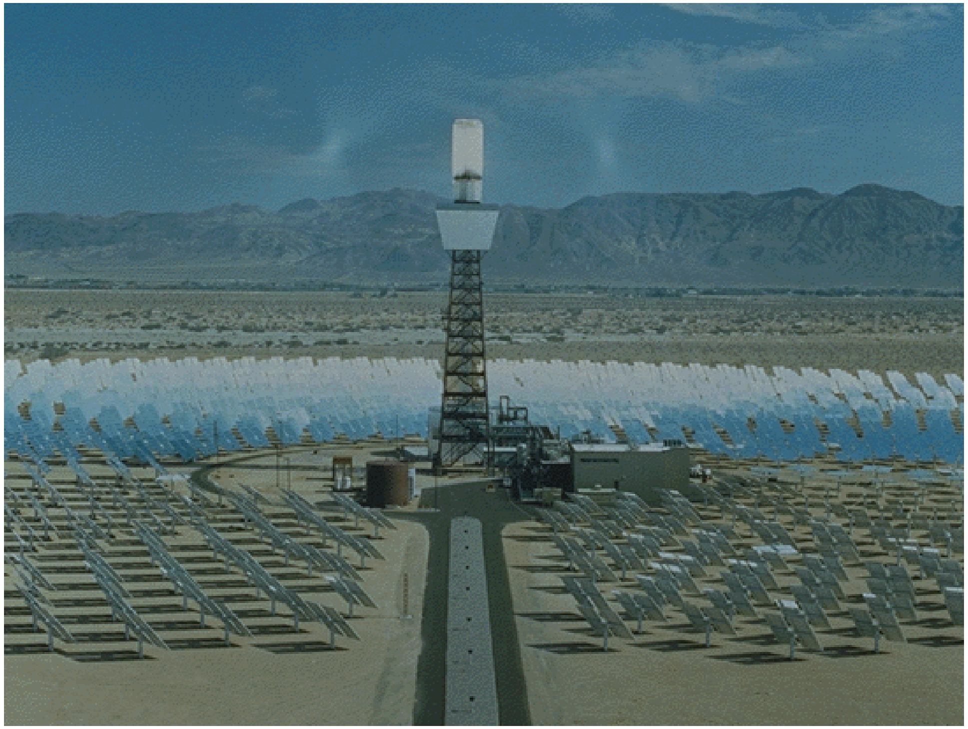
- 8. Reflectance – Product of the clean reflectance (reflectance of the heliostats when completely clean) and cleanliness (percent of clean reflectance – a measure of soiling)
- 9. Atmospheric Attenuation - Atmospheric attenuation is the reduction of energy as it passes between the heliostat and the receiver due to particulates, humidity and aerosols.
- 10. Spillage – Fraction of the light reflected from the heliostat field that misses the receiver.
- 11. Receiver Absorptance- Fraction of incident energy that is absorbed by the receiver surface.
- 12. Radiation and Convection- Radiation is the fraction of the absorbed energy that is lost to thermal radiation. Convection is the fraction of the absorbed energy lost to forced and natural convection.

Definition of Each Efficiency Element

- 13. Piping – Fraction of energy lost due to piping thermal losses
- 14. Auxiliary Steam – Fraction of energy used for auxiliary steam functions (e.g., steam seals or for charge thermal storage, if applicable)
- 15. Gross Cycle – Gross cycle efficiency (efficiency of converting thermal energy to electrical energy). Accounts for startup energy required to heat up and sync turbine.
- 16. Plant Parasitics – Electrical energy consumed by the plant.

Solar One Data

- Solar One
  - 10 MWe Solar Central Receiver Pilot Plant
  - Joint project between US DOE, SCE, and others
  - Located Daggett, CA
  - Operated from 1984-1988
  - Very well documented
  - Detailed data is **publically** available in many reports
- Once-through-to-superheat receiver
  - 100 bar
  - 960 C
- Oil/Rock Thermocline Storage
  - 4 hours at 7 MWe
- 10 MW Non-reheat Rankine Steam Turbine



Three Years of Data from Solar One

Table 4-2
Effects of Actual Plant Conditions on Pilot Plant System Efficiency and Annual Energy Output

Item	First Year Efficiency (Fraction)	First Year Energy (MW-hr x 10^3)	Second Year Efficiency (Fraction)	Second Year Energy (MW-hr x10^3)	Third Year Efficiency (Fraction)	Third Year Energy (MW-hr x10^3)
Incident Normal Insolation		170		181		174
Operating Days Availability	0.900	153	0.900	163	0.900	157
Useful Insolation Availability	0.840	129	0.840	137	0.840	132
Plant Availability	0.800	103	0.830	114	0.820	108
Heliostat Availability	0.967	99	0.982	112	0.988	107
Cosine	0.786	78	0.786	88	0.786	84
Blocking and Shadowing	0.967	76	0.967	85	0.967	81
Reflectance	0.808	61	0.840	71	0.790	64
Atmospheric Attenuation	0.966	59	0.966	69	0.966	62
Spillage	0.979	58	0.979	67	0.979	61
Receiver Absorptance	0.880	51	0.910	61	0.940	57
Radiation and Convection	0.803	41	0.812	50	0.812	46
Piping	0.996	41	0.996	50	0.996	46
Auxiliary Steam	0.886	36	0.909	45	0.998	46
Gross Cycle	0.328	12	0.335	15	0.333	15
Plant Parasitics	0.600	7	0.676	10	0.652	10
Overall	0.042	7	0.056	10	0.057	10

Source: L.G. Radosevich, *Final Report on the Power Production Phase of the 10 MWe Solar Thermal Central Receiver Pilot Plant*, SAND87-8022, March 1988

Initial Annual Efficiencies and Updated Values Based on Experience

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Table 4-1
Comparison of Initial and Current Pilot Plant System Efficiency and Annual Energy Predictions

Item	Initial		Current	
	Efficiency (Fraction)	Energy (MW-hr x 10^3)	Efficiency (Fraction)	Energy (MW-hr x 10^3)
Incident Normal Insolation		202		183
Operating Days Availability	1.000	202	0.910	167
Useful Insolation Availability	1.000	202	0.850	142
Plant Availability	1.000	202	0.900	127
Heliostat Availability	1.000	202	0.990	126
Cosine	0.769	155	0.786	99
Blocking and Shadowing	0.932	145	0.967	96
Reflectance	0.890	129	0.876	84
Atmospheric Attenuation	0.970	125	0.966	81
Spillage	0.976	122	0.979	79
Receiver Absorptance	0.950	116	0.940	75
Radiation and Convection	0.874	101	0.843	63
Piping	0.996	101	0.996	63
Auxiliary Steam	1.000	101	0.927	58
Gross Cycle	0.343	35	0.340	20
Plant Parasitics	0.759	26	0.757	15
Overall	0.130	26	0.082	15

Source: L.G. Radosevich, *Final Report on the Power Production Phase of the 10 MWe Solar Thermal Central Receiver Pilot Plant*, SAND87-8022, March 1988

Mirror Soiling - Cleanliness

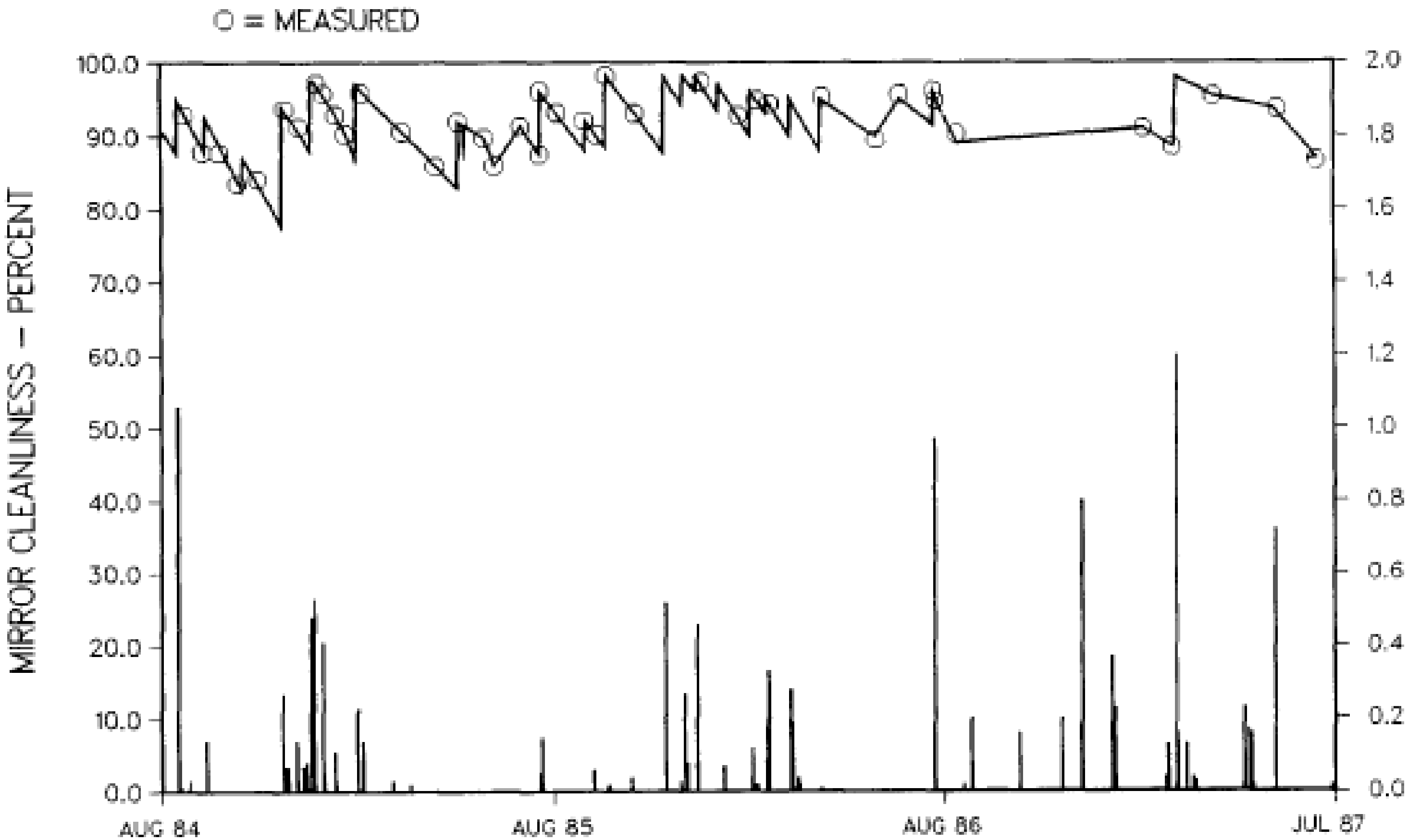

Figure 5–2. Pilot Plant Mirror Cleanliness and Rainfall

Source: L.G. Radosevich, *Final Report on the Power Production Phase of the 10 MWe Solar Thermal Central Receiver Pilot Plant*, SAND87-8022, March 1988