SANDIA REPORT

SAND87–0131 • UC–55a
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Printed June 1987

Proceedings of the Concentrating Solar Collector Workshop: Key Technical Issues

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Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
for the United States Department of Energy
under Contract DE-AC04-76DP00789

SF2900Q(8-81)

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes
Printed copy: A04
Microfiche copy: A01

SAND87-0131
Unlimited Release
Printed June 1987

Distribution
Category UC-55A

PROCEEDINGS OF THE CONCENTRATING SOLAR COLLECTOR WORKSHOP: KEY TECHNICAL ISSUES*

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ABSTRACT

This report comprises the proceedings of a solar thermal workshop on the key technical issues involved in the research and development of concentrating solar collectors. The workshop was held at Sandia National Laboratories on October 7 and 8, 1986. The major topic areas were solar concentrator optics, soiling of optical surfaces, windloads on collectors, and solar receiver issues.

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*SAND87-0131. This work was supported by the U.S. Department of Energy (U.S. DOE) under Contract DE-AC04-76DP00789.

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FOREWORD

The research and development described in this document was conducted within the U. S. Department of Energy's (DOE) Solar Thermal Technology Program. The goal of the Solar Thermal Technology Program is to advance the engineering and scientific understanding of solar thermal technology, and to establish the technology base from which private industry can develop solar thermal power production options for introduction into the competitive energy market.

Solar thermal technology concentrates solar radiation by means of tracking mirrors or lenses onto a receiver where the solar energy is absorbed as heat and converted into electricity or incorporated into products as process heat. The two primary solar thermal technologies, central receivers and distributed receivers, employ various point and line-focus optics to concentrate sunlight. Current central receiver systems use fields of heliostats (two-axis tracking mirrors) to focus the sun's radiant energy onto a single tower-mounted receiver. Parabolic dishes up to 17 meters in diameter track the sun in two axes and use mirrors to focus radiant energy onto a receiver. Troughs and bowls are line-focus tracking reflectors that concentrate sunlight onto receiver tubes along their focal lines. Concentrating collector modules can be used alone or in a multi-module system. The concentrated radiant energy absorbed by the solar thermal receiver is transported to the conversion process by a circulating working fluid. Receiver temperatures range from 100C in low-temperature troughs to over 1500C in dish and central receiver systems.

The Solar Thermal Technology Program is directing efforts to advance and improve promising system concepts through the research and development of solar thermal materials, components, and subsystems, and the testing and performance evaluation of subsystems and systems. These efforts are carried out through the technical direction of DOE and its network of national laboratories who work with private industry. Together they have established a comprehensive, goal directed program to improve performance and provide technically proven options for eventual incorporation into the nation's energy supply.

To be successful in contributing to an adequate national energy supply at reasonable cost, solar thermal energy must eventually be economically competitive with a variety of other energy sources. Components and system-level performance targets have been developed as quantitative program goals. The performance targets are used in planning research and development activities, measuring progress, assessing alternative technology options, and making optimal component developments. These targets will be pursued vigorously to insure a successful program.

Communication between the participants is a vital element of any R&D project. A continuous sharing of ideas, problems, methodologies, definitions, and progress is necessary to assure efficient use of resources. To stimulate this sharing process, a formal conference or workshop in which developers and other experts meet in numbers not practical on a day-to-day basis can be very useful. This workshop constitutes such a meeting. The scope was intentionally limited to solar thermal concentrators and receivers so that a thorough examination of the key technical issues would be possible in a limited time. The major component of solar thermal technology is the concentrator -- the device that serves to focus incident solar radiation onto an appropriate receiver where solar energy is converted to thermal energy in a heat transfer fluid. The receiver is also a critical component because it operates at high temperature and must be capable of converting concentrated radiant energy to heat efficiently and economically.

The authors would like to express appreciation for the support of Marty Murphy, Solar Energy Research Institute, and Craig Tyner, Sandia National Laboratories, who helped organize and conduct the sessions on concentrators and receivers, respectively.

INTRODUCTION AND SUMMARY

The Concentrating Solar Collector Workshop: Key Technical Issues was held at the Solar Thermal Test Facility in Albuquerque, New Mexico, on October 7 and 8, 1986. The workshop was sponsored by the Department of Energy's Solar Thermal Technology Program and was hosted by Sandia National Laboratories.

The workshop dealt with technical issues involving the concentrator and receiver subsystems of a solar energy system. The solar technologies involved in the workshop included Distributed Receivers (DR), Central Receivers (CR), and Photovoltaics (PV). Photovoltaic technology was included because there is a strong concentrator development activity in that program and because many of the issues and problems are common to both solar thermal and photovoltaic technologies. This workshop constituted the first time that developers in these three technologies had formally met to discuss common issues. The workshop was divided into three sessions. The session titles and the technologies represented in each session were as follows:

- Solar Concentrator Optics and Soiling; DR, CR, PV
- Windloads on Collectors; DR, CR, PV
- Solar Receiver Issues; DR, CR.

The purpose of the workshop was to attempt to reach consensus on key technical issues, to identify uncertainties in technical areas that must be reduced for solar technologies to reach long-term goals of performance and cost, and to identify R&D needs not currently being addressed or current activities that could be redirected to more effectively reduce technical uncertainties.

Invited attendees included presenters, members of review panels, and observers. In each session presentations were made -- generally by participants from the programs' lead laboratories, Sandia Albuquerque, Sandia Livermore, and SERI. These presentations described the status, development strategy, technical results, and problems within a specific technical program area. The review panels were composed of program contractors and non-program experts in the field of interest for each session, e.g. aerodynamics or thermal science authorities for the windloading or receiver sessions respectively. Observers included DOE, SNLA, and SERI managers and staff, others with a strong programmatic interest, and presenters/panelists from other sessions.

The format of the workshop was as follows:

- The presenters addressed the review panel whose members asked questions to clarify or add detail to the presentations, raise additional issues, or question conclusions reached in the presentations.

- Observers were allowed to ask questions or provide comments only when recognized by the session chairman.

- The session assistant chairman took notes on topics to be evaluated later in the closed review panel meetings. These topics were typically uncertainties, definitions, technical issues, or candidates for additional R&D.

- After each session a closed panel meeting, led by the session chairman, was held for the purpose of discussing and reaching consensus on the topics identified during the session. After discussion, the panel members rated each issue relative to its importance in the solar thermal program and its technical uncertainty. The product of the importance and uncertainty was used as a measure of the relative need for program development support to a given issue.

The major points upon which the review panels reached consensus are summarized as follows:

Session I: Concentrating Collector Optics and Soiling

1. The development of stretched membrane concentrators is important for the improved performance and reduced cost of solar collectors.

2. The development of comparative costing and annual performance analysis techniques would be useful for the evaluation of alternative collectors and systems.

3. Reflective concentrators are appropriate for high concentration ratio solar thermal applications, and refractive, Fresnel lens concentrators are better suited for lower concentration PV applications.

4. Soiling of concentrator optical surfaces can cause substantial degradation in collector performance. Soiling mechanisms and the cost-effective cleaning of optical surfaces are two issues that warrant further attention.

5. The development of a device to measure slope errors would be very useful to industry.

6. The degradation of optical materials, in particular polymer films, in the natural environment is a critical issue for future collector development.

Session II: Solar Receiver Issues

1. The understanding of thermal loss mechanisms and the implementation of experimental techniques to separate the various loss mechanisms were identified as key issues.

2. Operational effects such as transients, thermal mass, control strategies, and reliability were all identified as key issues bearing on annual thermal efficiency.

3. Establishing receiver tube life evaluation criteria, long-term testing, and understanding cost make-up in receivers, were specifically identified as key issues.

4. Advanced receiver designs such as direct absorption and reflux receivers were identified as approaches capable of providing substantial improvements in performance/cost ratios. Continued development of such concepts were considered to be key needs.

Session III: Windloads on Collectors

1. Survival windloads drive the structural design of concentrating solar collectors.

2. Wind tunnel measurements can probably predict drag, lift, and moment coefficients for solar collectors within 10 to 15%.

3. Additional wind tunnel testing on generic concentrator designs is needed to further quantify mean pressure distributions, fluctuating pressure distributions, and peak loads.

4. Because of the large, long-term level of effort required to obtain good field data and the questionable ability to reduce the uncertainty of coefficients below current levels, field-scale experiments for windloading are probably not required at this time.

The balance of this report details the results of the review panel for each session. Appendix A is the Workshop Agenda. Appendix B includes a list of all workshop participants. Appendix C lists the composition and affiliation of the members of the three panels. Appendix D contains the detailed assessments of the review panel members.

SESSION I: CONCENTRATING COLLECTOR OPTICS AND SOILING

Introduction

The workshop session on Solar Collector Optics was conducted on Tuesday, October 7, 1986, at Sandia's Solar Thermal Test Facility in Albuquerque, New Mexico. The thirteen members of the Technical Review Panel heard presentations by Sandia and SERI personnel in the four general areas of reflective optics, refractive optics, soiling of optical surfaces, and measurements associated with concentrating solar collectors. Issues critical to the development of collector optical systems were identified and, significantly, many are currently being investigated in the DOE Solar Thermal Program.

At the end of the day, the Technical Review Panel convened to rate the relative importance to the development of concentrating collectors of "key" issues that had been identified during the presentations. The figure of merit used in these evaluations is the product of the priority to the program (rated from 1 to 5, 5 being a high priority) and the technical uncertainty associated with the particular issue (also rated from 1 to 5 with 5 again being a high uncertainty). Therefore an issue of very high priority to the program and about which very little is known would receive the highest possible rating of 25, whereas an issue of lower priority or one that is understood would receive a lesser score. The detailed results of this evaluation are shown in Table D-1. The values assigned to each issue by the panelists are shown for each of the 42 issues within ten topic areas. The total score for each issue has been normalized in the last column by dividing it by the highest score received by any one issue, in this case the 206 points received by stretched membrane facet size and slope errors. The last column in Table D-1 is the average of the normalized ratings of the issues within a given topic area. The topic rankings are summarized in Table I-1 in descending order of relative importance to the Solar Thermal Program as determined by the review panelists.

An examination of the last column of Table I-1 indicates that the highest topic ranking is for the stretched membrane concentrator issues, at 99%, and the second highest ranking is for collector comparative cost estimates, at 88%. There is a grouping of categories, including definitions, annual performance, soiling, measurements, secondary concentrators, and code validation in the high 60 and low 70% range. The two lowest ranked topics in terms of their priority and uncertainty are collector error budgets and Fresnel optics as applied to distributed receiver systems, at 59 and 57%, respectively.

An important question was raised regarding the sessions selected for the workshop. The point was made by members of the review panel and the general audience that the workshop focus was too narrow in that it centered on components and subsystems. Of particular concern to the collector optics review panelists was the exclusion of the receiver from discussions on solar collector optics. In defense of the organization of the workshop, it should be noted that it was never intended that the topic areas be evaluated independently of other subsystems or components. However, workshop organizers considered it necessary to limit the session topics in order to permit an in-depth treatment of a relatively small number of critical issues.

TABLE I-1

SOLAR COLLECTOR OPTICS SESSION
TOPIC RANKING

Topic	Normalized Score
Stretched Membrane Concentrators	99%
Comparative Collector Costs	88%
Soiling of Concentrator Surfaces	75%
Secondary Concentrators	74%
Concentrating Collector Measurements	73%
Concentrator Annual Performance	71%
Optical Computer Code Verification	69%
Definitions	67%
Solar Collector Error Budgets	59%
Fresnel Optics in Distributed Systems	57%

The following is a summary of workshop discussions with an emphasis on those issues and topic areas that received an evaluation score greater than 80%. The summary is organized into four sections: reflective and refractive optics, soiling of optical surfaces, and solar collector measurements.

Reflective Optics

In the reflective optics area some of the issues discussed were stretched membrane concentrators, cost estimation, performance measures for solar collectors, and material lifetimes. The stretched membrane collector area received the highest overall rating (99%) of the ten topics covered in the optics sessions. It is clear, since stretched membrane heliostat and dish concentrator development received the highest ranking from the review panel, that the present emphasis on this area within the Solar Thermal Program is strongly supported.

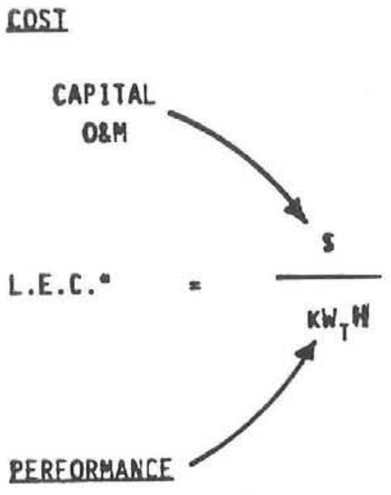
Discussion on stretched membrane concentrators centered around performance and cost issues. There was interest in determining the optimum size of a stretched membrane facet and developing techniques for characterizing the performance of the facets. These questions are being addressed in the current program. Further discussion was more general and treated the question of the "best" performance measure which should be applied to all solar collectors. Some of the key points on measures of performance for collectors are presented below.

The only issue discussed in the Solar Collector Optics Session of the workshop on which the panelists were in unanimous agreement was the best measure of solar collector performance -- the levelized energy cost (L.E.C.). The equation for determining the L.E.C. and a discussion of it are shown in Figure I-1. Briefly stated, the L.E.C. is the cost required to produce a given unit of energy, in this case a thermal kilowatt hour, spread evenly over the lifetime of a system. The three elements which influence the L.E.C. are the capital cost, operation and maintenance costs, and annualized thermal output. The costs include the purchase price of the plant, installation costs, the cost of money, the cost of operation, and the cost of maintaining the equipment. The estimation of these costs is difficult and, because the system designer is likely to know the most about the design, cost predictions have often been left to the individual contractors. The uncertainty associated with mass production cost estimates as well as performance predictions can be very high because of a large range in the variables. An approach used in the past is to assume that, since solar collector materials and fabrication techniques are similar, the costs will be approximately proportional to the weight of the collector. Neither of these two approaches to estimating the collector cost is completely satisfactory.

Of particular concern to the review panel was the practice of basing capital, operation and maintenance costs on the design (and perhaps, the production) of a single prototype collector. It is generally accepted that solar collector costs cannot be predicted in an absolute sense and that contractor-produced estimates may not reflect similar assumptions and may not therefore be comparable. One possible solution to this problem that was raised during discussions is the use of third-party cost estimates made from a common, established set of assumptions for the system cost variables. This would include such variables as discount rates, internal rates of return, material costs, fabrication costs, and reliability predictions based on the parts count, the type, and complexity of subsystems.

A second area of extensive discussion by the review panel was the development of annual solar collector performance predictions from instantaneous performance measures. Instantaneous concentrator optical efficiency can be accurately predicted and, in the case of prototype collectors, measured. There are a number of ray trace and cone optics computer codes that can be used to predict the performance of a reflective optical concentrator. These codes use information such as the sunshape, optical surface specularity, slope errors, and sun-tracking methodology to develop detailed flux density profiles in the receiver aperture plane. Optical efficiency measurements on prototype collectors can be made calorimetrically or with radiometer and scatter-plate flux mappers. These profiles can then be integrated to

ULTIMATE PERFORMANCE MEASURE



- AT A SPECIFIED OR KNOWN RECEIVER TEMPERATURE

* L.E.C. IS LEVELIZED ENERGY COST

FIGURE I-1. LEVELIZED ENERGY COSTS
(From "Point-Focus Collectors in the Solar Thermal Program" by T. R. Mancini)

The numerator of the Levelized Energy Cost* (L.E.C.) is the cost associated with the purchase price of the plant, the installation costs, the cost of money, and the cost of operating and maintaining the equipment. The denominator is the system performance, probably derived from a systems model in which the capacity rating of the system is determined and derated based on weather, downtime, etc. to achieve an "attainable capacity factor" for the plant. Both the numerator and denominator in the equation for the L.E.C. are "annualized" or "levelized" over the lifetime of the plant (often assumed to be 20 years). The reliability of the system components affects the L.E.C. in that a system that is unreliable will have greater downtime and require additional maintenance costs. An unreliable system will also perform below the design level; resulting in an additional increase in the L.E.C.

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*A good reference on the L.E.C. is The Cost of Energy From Utility-Owned Solar Electric Systems, ERDA/JPL-1012-76/3 by Doane, J. W., et. al.

provide optical efficiency as a function of receiver aperture radius. Examples of some instantaneous solar collector optical efficiencies are shown in Figure I-2.

The review panel discussions centered on the question: "How is instantaneous solar collector performance translated into an annual measure?" There are a number of variables that affect solar collector performance. Because only the concentrator optical efficiency is under consideration, transient effects such as would be experienced in the receiver need not be considered here. For all practical purposes, the concentrator responds instantaneously to a change in the solar intensity or sunshape and this is directly translated into a change in the flux-density profile and hence, the optical efficiency. This substantially simplifies the analysis, but then the question becomes: How are such variables as solar intensity, sun shape, wind, intermittent cloud cover, rain, snow, the reliability of the system, soiling and rainwash of the optical surface, degradation of the optical surface, etc. factored into the equation to reduce the instantaneous efficiency to an annual performance measure?

Several possible answers to the question posed above were discussed by the Solar Collector Optics Review Panel. One suggestion was the use of Typical Meteorological Year (TMY) data for a selected site for all system simulations. In this way an annualized performance could be generated which would have some basis for comparison of the performance of different systems. A second suggestion was that a given site be selected and actual data from that site be used to simulate performance. The major point to come out of this is the need to standardize the basis for both performance and cost comparisons.

Refractive Collector Optics

Refractive optics received the lowest score (57%) of the 10 topic areas ranked by the review panel. The only issue within this topic to receive a rating greater than 60% dealt with the appropriate scale for refractive collectors in solar thermal applications (it received a score of 78%). This particular issue is presently being treated in some detail by the Solar Energy Research Institute.

Refractive optics, more specifically Fresnel lenses, are used extensively in the photovoltaic program and much of the workshop discussion centered around the application of Fresnel optics in the Solar Thermal Program as well. Figures I-3 and I-4 show Fresnel lenses as applied to photovoltaic and solar thermal systems, respectively, and discuss some of the issues involved in the two technologies.

It is noteworthy that the review panel does not believe that current Fresnel lens technology can be cost effective in its application to point-focus collectors in the Distributed Receiver Project. The chromatic aberration, important to PV in creating uniform flux densities and constant voltage drops across the cells, results in large receiver apertures being required for solar thermal applications. This, coupled with the reduced optical performance of Fresnel optics (80% versus 90% for reflective systems) and

INSTANTANEOUS OPTICAL EFFICIENCIES
OF SOME POINT-FOCUS COLLECTORS

TEST BED CONCENTRATORS I & II	.90
VANGUARD	~.90
MCDONNELL-DOUGLAS	~.90
PDC-1	.76
SHENANDOAH	~.73
PKI 135	.80
LEC 460	.73
ACUREX INNOVATIVE	.91*
LEC 1700 INNOVATIVE	.90*

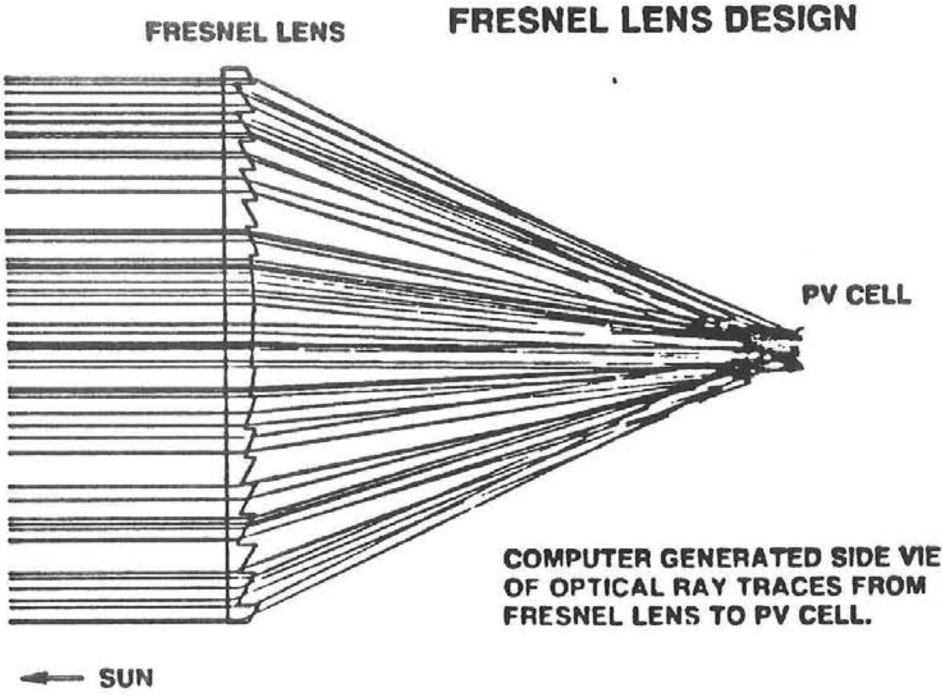
*PREDICTED PERFORMANCE

FIGURE I-2. INSTANTANEOUS SOLAR COLLECTOR OPTICAL EFFICIENCY (From "Point-Focus Collectors in the Solar Thermal Program" by T. R. Mancini)

Instantaneous optical efficiencies for 10 reflective solar collectors are listed above. Eight of the 10 reported values are actual, measured optical efficiencies. The other two optical efficiencies are predictions based on simulations of the prototype designs. The real issue is how to "adjust" this well understood instantaneous value to account for the annual performance one is likely to see in a solar collector.

PHOTOVOLTAIC CONCENTRATOR RESEARCH

FRESNEL LENS DESIGN

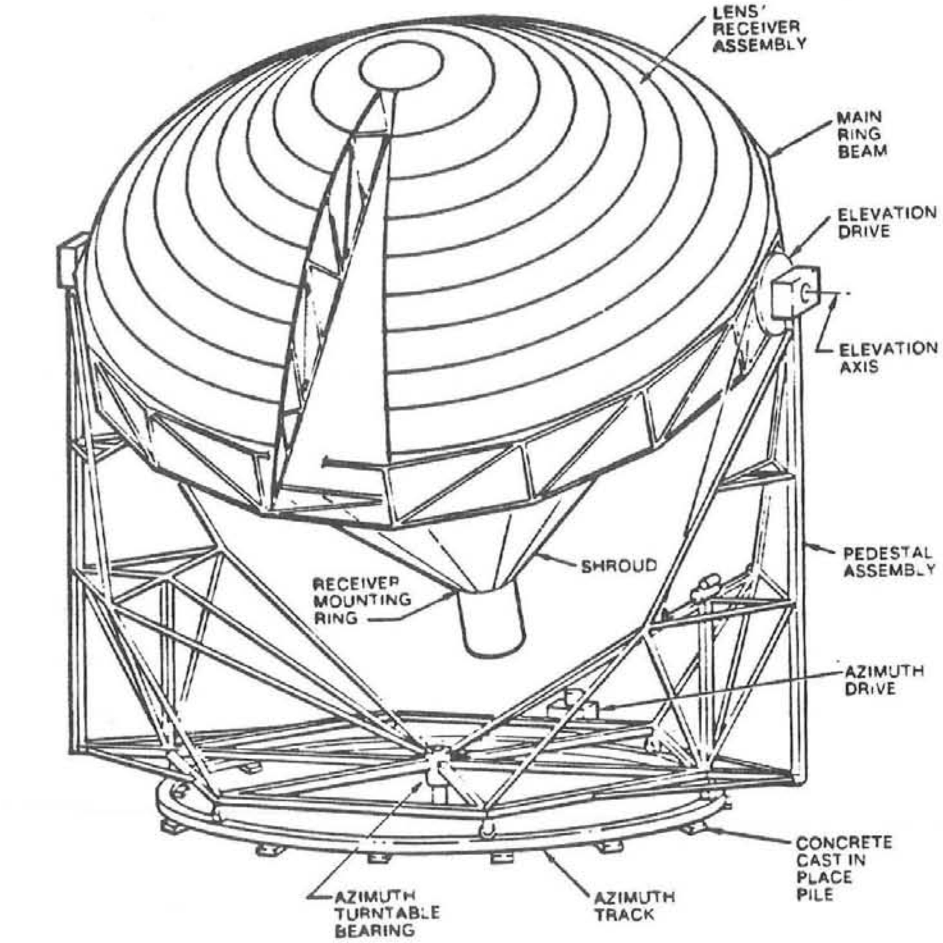


COMPUTER GENERATED SIDE VIEW OF OPTICAL RAY TRACES FROM FRESNEL LENS TO PV CELL.

OPTICAL EFFICIENCY	~ 80%	ELEMENT SIZE	.3 BY .3 M
f/D	~ 1	NO. OF ELEMENTS	~ 20
CONCENTRATION RATIO	100 - 300	ASSEMBLY SIZE	.6 BY 3 M

FIGURE I-3. FRESNEL LENS FOR PV SYSTEM (From "Refractive Point-Focus Solar Collectors" by C. Stillwell)

The schematic demonstrates how a point-focus Fresnel lens is used in a concentrating photovoltaic system. Because of chromatic aberration (the separation of the incident solar energy into its respective constituents by wavelength), the image size is larger than that of a comparable reflected image and necessitates the use of a larger receiver aperture. PV makes use of the chromatic aberration to produce the more uniform flux density distribution required by the solar cells for efficient operation by overlapping the images. The resulting receiver aperture must be even larger in order to achieve high optical efficiency.



OPTICAL EFFICIENCY	~ 75%	ELEMENT SIZE	.6 BY .6 M
f/D	~ .8	NO. OF ELEMENTS	~ 500
CONCENTRATION RATIO	~ 1500	ASSEMBLY SIZE	14 M DIA.

FIGURE I-4. SOLAR THERMAL FRESNEL LENS SYSTEM DESIGN
(From Entech, Inc., Innovative Concentrator)

This is a sketch of a solar thermal point-focus concentrating collector using Fresnel optics. The concentration ratio is about an order of magnitude greater in a solar thermal application than for photovoltaics. Compared to the typical PV concentrator shown in Figure I-3, this collector is much larger being approximately 150 m^2 in area. Lens element size is presently limited by manufacturing techniques to about 1 m square for both PV and solar thermal applications. Larger Fresnel optical concentrators must be assembled from a number of the smaller lens elements.

the complex (and potentially costly) collector assemblies, results in Fresnel optics generally not being very attractive for large, point-focus solar thermal applications.

Soiling of Concentrator Surfaces

Soiling of concentrator optical surfaces was the topic rated third by the review panel, at 75%, behind stretched membrane concentrators and comparative cost analysis. Listed in Figure I-5 are eight solar installations and a brief comment for each on the types of cleaning results and soiling problems. An examination of Figure I-5 results in two observations. First, soiling is very strongly location dependent and second, it can cause a substantial degradation in system performance.

Panel discussions addressed such issues as the variability of the contaminants that can affect soiling rates and the types of products that will form on the surface of the optical concentrator. Because of the scope of the problem, there was no consensus on a viable approach to its solution. Discussion then switched to methods for cleaning the solar collector optical surfaces. These included wash trucks at Solar One, spray washes, mechanical washing techniques using brushes, snow cleaning, chemical cleaning agents, and rainwash. As shown in Figure I-6, rainwash is one of the more effective methods for cleaning a solar collector surface and it is the most cost-effective approach. The question of the economics of cleaning was raised and is illustrated in the hypothetical example shown in Figure I-7. This figure shows that the economics of generating electricity is improved with increased frequency of cleaning and that this improvement continues all the way to weekly cleaning frequency. Nevertheless, it was generally argued that no general guidelines could be reached regarding frequency of cleaning because of the variability and scope of the parameters involved. Plant operators will generally determine the economic viability of cleaning based on the specific site, local contaminants, performance degradation, frequency of rainfall, and the cost of cleaning the collector field.

At this point in the discussion, the emphasis shifted to issues the review panel felt warrant further investigation. Soiling mechanisms due to common contaminants, soiling avoidance techniques, the evaluation of cleaning agents, and long-term material degradation due to soiling all received high rankings from the panel. No consensus was reached as a result of discussions on the soiling of collector surfaces, but rather, issues that may warrant further study were identified.

Concentrating Collector Measurements

A number of measurement techniques applied to point-focus concentrators were presented to the review panel and audience by SERI and SNL staff. These included calorimetric measurement techniques, radiometer and video flux mappers, reverse image methods and others for evaluating the optical and thermal performance of a collector. Two major issues were raised in this area: industry would like to have an easy-to-use field (or at least shop) instrument to measure slope error; and life-cycle optical materials testing

SUMMARY OF SOILING AND CLEANING EXPERIENCE

PROJECT	COLLECTORS	COMMENTS
BUNGE CORP. DECATUR, AL	FLAT PLATE	HEAVY WAXY RESIDUE - SOYBEAN PROCESSING
JOHNSON & JOHNSON SHERMAN, TX	ACUREX PARABOLIC W/COILZAK	REFLECTIVITY DEGRADED FROM .69 TO .31; RESTORED TO .57 BY CLEANING
LONE STAR BREWERY SAN ANTONIO, TX	SKI PARABOLIC W/FEK 244	REFLECTIVITY DEGRADED FROM .722 TO .535 IN 8 MONTHS
SOUTHERN UNION REFINING CO., LOVINGTON, NM	SKI PARABOLIC W/FEK 244	COLLECTOR FIELD MOVED TO AVOID SOILING. INITIALLY LOCATED DOWNWIND FROM COOLING TOWERS
RIEGEL TEXTILES LA FRANCE, SC	FLAT PLATE	COLLECTORS, LOW TO GROUND, COVERED BY CUDZU VINES
CATERPILLAR TRACTOR CO. SAN LEANDRO, CA	SKI PARABOLIC W/FEK 244	SYSTEM EFFICIENCY DEGRADED FROM 19% TO 10% IN ONE MONTH; AFTER CLEANING 28%
INDUSTRIAL SOLAR TECH., AURORA, CO	IST PARABOLIC W/ECP300	REFLECTIVITY DEGRADED FROM .975 TO .68 IN 3 MONTHS; AFTER CLEANING .945
SEGS II DAGGETT, CA	LUZ PARABOLIC 165,000 M^2	FULL TIME WASHING CREW ON 2-WEEK CYCLE. EQUIPMENT AND PERSONNEL PROBLEMS

FIGURE I-5. SUMMARY OF SOLAR COLLECTOR CLEANING EXPERIENCE
(From "Soiling of Solar Collectors" by E. L. Harley)

This figure lists a number of solar collector locations and briefly comments on the experiences associated with soiling and cleaning of the optical surfaces at each. It emphasizes the site dependence and performance degradation of optical surface soiling. Examining in slightly more detail some of the entries in this figure, one finds examples of some of the issues that must be confronted in evaluating and implementing a cleaning strategy. Cleaning strategies ranged from cases in which the systems were never cleaned or inverted for rainwash to those in which systems were washed during rainstorms as well as subjected to a regular cleaning cycle. At some sites, such as the Caterpillar Tractor Co. in San Leandro, California, a strong case could be made for a regular wash cycle. For other sites such as Solar One in Barstow, California, regular wash cycles may not be justified and natural rain wash may be the most cost effective cleaning method. The SERI-IST tests in Aurora, Colorado, indicated that with soiling, the 15 milliradian (mr) specular reflectivity degraded the same amount as the 25 mr value implying that, at least down to 15 mr, the specularity will degrade at the same rate as the total hemispherical value.

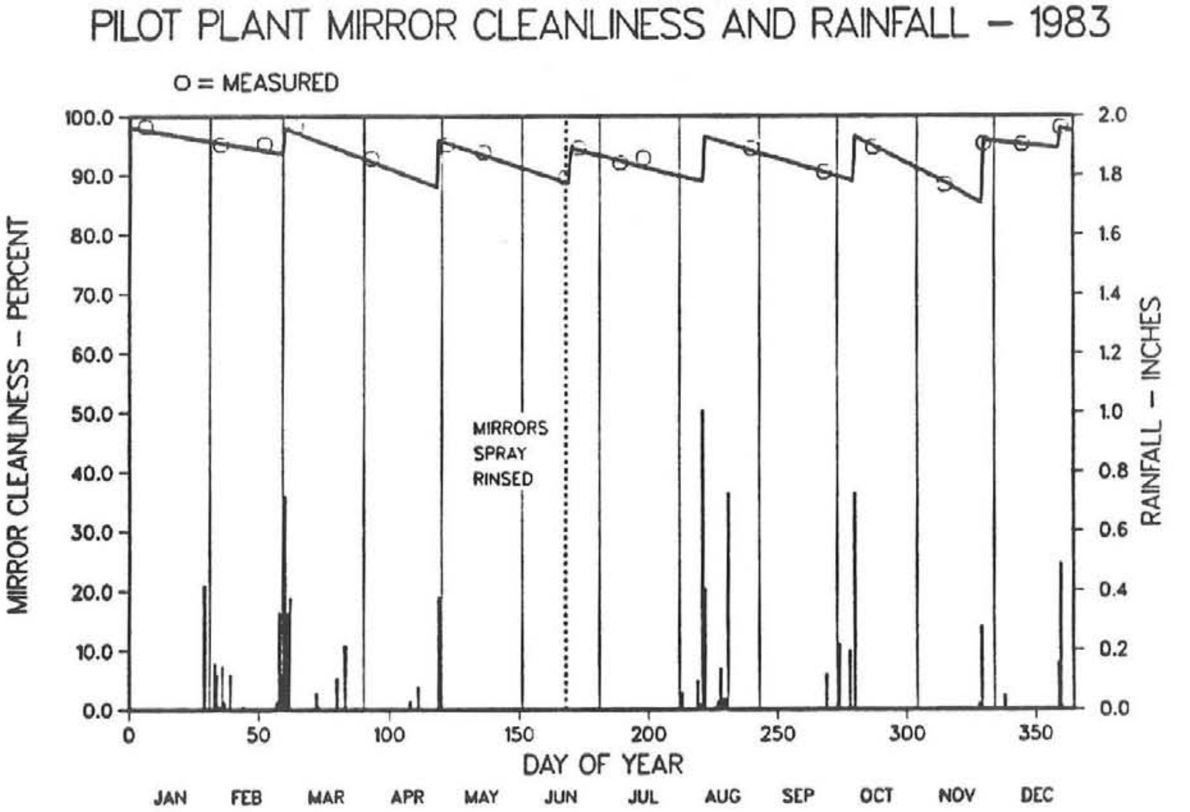


FIGURE I-6. SOLAR ONE MIRROR CLEANING
(From "Soiling of Solar Collectors" by A. Baker)

This figure demonstrates the degradation due to soiling of the heliostats at Solar One in Barstow, California. It is interesting to note the almost constant performance degradation rate of 5% per month between rain wash or cleaning events. Solar One has relied on a number of schemes for cleaning the heliostats including rain, spray and rinse, and spray and wash with a brush truck. Future considerations for cleaning are high pressure spray, vibration wash, and chemical wash and rinse.

SOLAR ENERGY SYSTEM PARAMETERS

COST ANALYSIS - HYPOTHETICAL

1. SYSTEM -- LINE FOCUS ELECTRIC GENERATION
2. AREA -- 165,000 M^2 (SEGSII)
3. ANNUAL PRODUCTION -- 33.36 x 10^6 KWHRS (ESTIMATED FROM PREDICTIONS FOR SOUTHERN UNION REFINING CO.)
4. CAPITAL COST -- $120 x 10^6 (400/KWE; $727/$M^2$)
5. O&M -- LESS COLLECTOR WASHING - $0.6 x 10^6 (1/2% OF CAPITAL COST)
   COLLECTOR WASHING - $87,100 (13 MEN @ $3.35/HR, 2000 HRS)
   - $169,000 (13 MEN @ $6.50/HR, 2000 HRS)

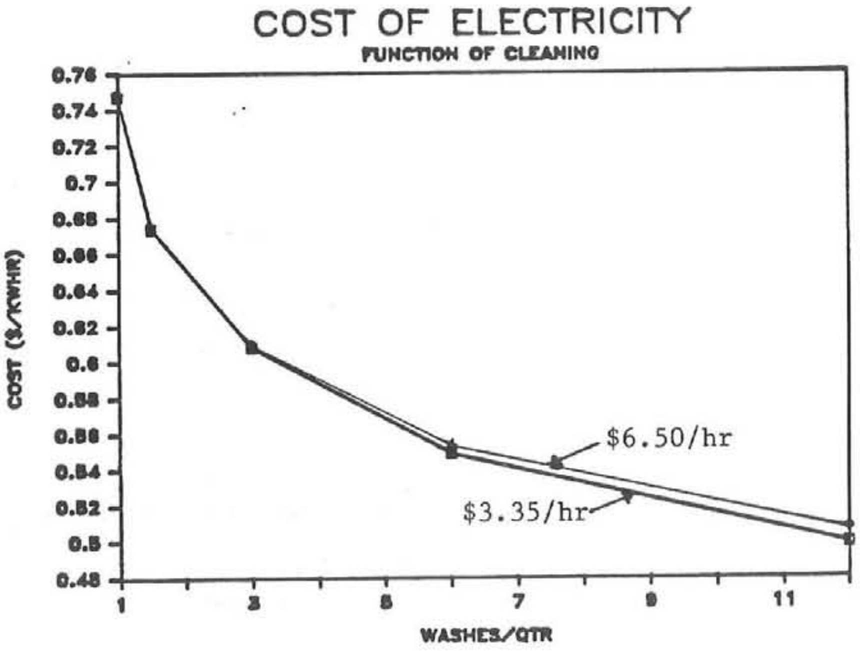


FIGURE I-7. HYPOTHETICAL CLEANING COST STUDY
(From "Soiling of Solar Collectors" by E. L. Harley)

This figure demonstrates the type of economic analysis that might indicate the feasibility of cleaning at a specific solar site. The information at the top of the figure is the economic input to the model, and the curves represent the cost of generated electric power as a function of cleaning frequency for two labor rates. It is worth noting that in this hypothetical example the production cost of electric power is only slightly affected by a doubling in the cleaning labor rate. Furthermore, cleaning cycles up to a frequency of once per week result in a reduction in the cost of power generation. This is a hypothetical example and has been included to demonstrate the dependence of the decision to clean the collectors on the site, system cost, management perspective etc.

is important to assess the viability of using these materials in concentrators.

The field measurement of slope error received a 98% rating in the review panel evaluation. This issue is in part being addressed by SERI in the development of an instrument for making specular reflectivity measurements in the mm to cm sample size range. The relationship of this measurement technique to the laboratory based bidirectional reflectometer and the field scale reverse imaging or distant observer method is shown in Figure I-8.

The second issue of life-cycle materials testing is a very important one. Polymer optical surfaces are becoming increasingly important to the Solar Thermal Program and, while their performance is presently being evaluated by the national laboratories, it is crucial to the further development of concentrating collectors that questions about their lifetimes in various environments be answered. The review panel felt that a better understanding of the environmental degradation of optical materials is critical to the development of high performance solar concentrators.

Summary

Although a number of topics and issues were discussed in the Solar Collector Optics Session of the workshop, the following six points surfaced throughout the discussions and in the evaluations of the review panel.

1. The development of stretched membrane concentrators is important for the improved performance and reduced cost of solar collectors.
2. The development of comparative costing and annual performance analysis techniques would be useful for the evaluation of alternative collectors and systems.
3. Reflective concentrators are appropriate for high concentration ratio solar thermal applications, and refractive, Fresnel lens concentrators are better suited for lower concentration PV applications.
4. Soiling of concentrator optical surfaces can cause substantial degradation in collector performance. Soiling mechanisms and the cost-effective cleaning of optical surfaces are two issues that warrant further attention.
5. The development of a device to measure slope errors would be very useful to industry.
6. The degradation of optical materials, in particular polymer films, in the natural environment is a critical issue for future collector development.

Optical Surface Characterization

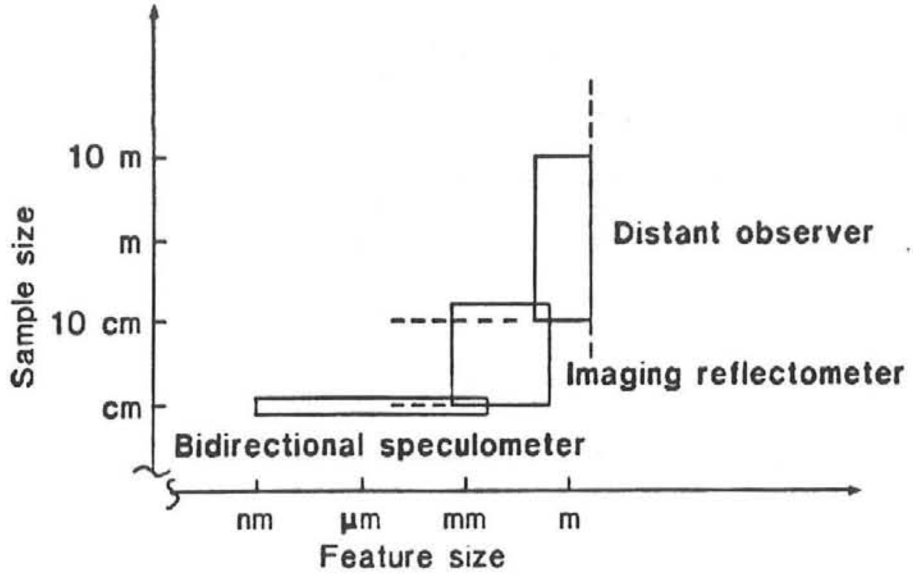


FIGURE I-8. OPTICAL SURFACE CHARACTERIZATION
(From "Measurement Techniques and Uncertainties in Testing of Point-Focus Collectors" by A. Lewandowski)

This figure demonstrates the range of sample size and the relative size of the feature that contributes to the reflectivity value or characterization of a specific measurement technique. The distant observer or reverse imaging method is used to view a target located at the focus of the concentrator by looking back into the concentrator from a large distance. The method can be used to provide either a qualitative or, given the appropriate image analysis capability, a quantitative measure of the expected total concentrator slope error and intercept factor. In the other limit, a bidirectional reflectometer can characterize the local specularity on a reflective surface. Between these two extremes is a region of interest to the solar designer, where moderate size features representative of the relative effectiveness of the optical material "stack" lie. SERI is presently working on an instrument that will make measurements in this range.

SESSION II: SOLAR RECEIVER ISSUES

Introduction

The workshop session on Solar Receiver Issues was held Wednesday, October 8, 1986, at Sandia's Solar Thermal Test Facility in Albuquerque, New Mexico. The 11 members of the Technical Review Panel heard presentations on thermal performance, reliability issues, and on advanced receiver design issues. As expected, a great deal of material was discussed, with varying degrees of consensus among panelists.

As in Session I, the Technical Review Panel convened at the end of the day to refine the list of topics and issues identified during the presentations and discussions and to rate their relative importance. The detailed results of this evaluation are shown in Table D-2, Solar Receiver Issues of Appendix D.

Table D-2 shows the values assigned to each technical topic and issue by the panelists. Unlike Session I, however, the panelists separated the topics and issues into near- and long-term and independently scored the overall topics as well as the issues within a topic. The normalized total score in the last column of Table D-2 is the topic's total score divided by the highest score received by any topic, in this case 166 points received for prediction of annual and off-peak performance. Note that there is a substantial degree of variation in the sub-issues identified by the panel. The relative ranking of the receiver technical topics is summarized in Table II-1.

An important point raised during this session was the systems and operational aspect of solar thermal design. A similar discussion took place during the optics session. It was pointed out that the receiver is but one component in a solar thermal system that must operate in a transient environment. Understanding the systems implications of solar receiver design was suggested as a potential workshop subject by itself. The importance of being able to predict annual and off-peak performance and understanding operational effects on solar receivers (100% and 89%, Table II-1) assigned by the panel are indicative of the importance of systems aspects of receiver technology development.

The following is a summary of session discussions with the emphasis on topic areas rated highest by the panel. The summary is organized into near-term and long-term topics.

TABLE II-1

SOLAR RECEIVER ISSUES SESSION
TOPIC RANKING

Topic	Normalized Score
Prediction of Annual & Off-Peak Performance	100%
Advanced Design Feasibility	99%
Reliability	90%
Understanding Operational Effects on Energy	89%
Understanding Scale-up of Parameters	85%
Understanding Cost	85%
Advanced Applications Receivers	81%
Thermal Losses	78%
Loss Mitigation	64%
Surface Coatings	60%
Hybridization (Near Term)	45%
Hybridization (Long Term)	35%

Near-Term Topics

Prediction of Performance -- An understanding of the heat loss mechanisms was identified as a key technical need. Relative to modeling, it was pointed out that extensive modeling efforts were conducted in the early years of the program and that comprehensive receiver models of various levels of sophistication already exist. There was consensus that what is really needed is to validate the models that exist and to insure that modeling and experimental efforts be conducted in concert with each other. A typical comment was, "When we do experimental programs . . . we (should) try to do a balanced effort . . . and make sure that we're not just generating data that doesn't do anything or that we're just not generating models that can't be validated."

Development of experimental techniques for evaluating receiver losses, especially techniques for differentiating between loss mechanisms, is more important than new theories or sophisticated three dimensional computer codes. Although there was consensus that the existing theories could use improvement, there was also consensus that more and better correlation with experimental results would be required first.

Temperature measurement in a solar flux environment, temperature gradients through Pyromark paint, measurement of the energy available to the receiver, and the problems inherent in accurate calorimetric measurements were pointed out as difficulties in obtaining good experimental results. One presentation showed how multiple tests can statistically reduce measurement uncertainty (see Figure II-1). The consensus was that the Solar Thermal Program should continue to pursue better temperature and flux measurement techniques.

Wind effects on heat loss were discussed but with little consensus on the magnitude of this effect on performance. Although the wind issue has been studied carefully in the Central Receiver Project with the conclusion that forced convection is not a significant factor, there is qualitative evidence in dish testing that wind-induced heat loss can be significant. The need to develop a fundamental understanding of this issue, and of how forced convection heat loss varies with receiver size and design was suggested as a key component in understanding thermal loss mechanisms.

Even though we cannot always measure steady-state heat loss accurately, it generally represents a relatively small fraction of the energy available to the concentrator, and we can generally predict it to within ±25% (see Figure II-2). Failure to appreciate operational effects can have a more detrimental outcome. Understanding operational losses was, therefore, judged to be more important than understanding steady-state heat loss mechanisms. Solar thermal energy systems operate in a transient environment. They must be able to respond to diurnal cycles and clouds in an efficient way. A lack of consideration of these issues has resulted in many systems that do not operate up to the designer's expectations. The response to transients, the significance of receiver thermal mass, and control strategies were highlighted as very important issues. Scheduled maintenance during natural outage periods, such as night time or cloudy days, was also identified as an important operational consideration.

The ability to predict annual energy production is the ultimate objective of performance calculations and was the highest scored technical category. There was strong consensus that the Solar Thermal Program should develop the tools and expertise to make annual and off-peak performance predictions. This aspect of receiver performance emphasizes the need for good systems analysis and the interdependence of concentrator, receiver, heat load, and control strategy.

Reliability -- Reliability, according to the panel, is the most uncertain among important technical issues facing the solar thermal community. In addition to the need for good reliability engineering from the beginning (see Figure II-3), tube life (for the nearer term tube receivers) is a major consideration. Tube life is, perhaps, the biggest technical concern for the utility participants in the Central Receiver Project. The validity of using the nuclear based code case N-47 for solar thermal applications is in doubt. The need to develop confidence through long-term testing was the most highly scored technical issue at 178. The tradeoffs in designing tube receivers for long life are discussed in Figure II-4.

IEA sodium external receiver has peak steady-state nominal efficiency of over 95%

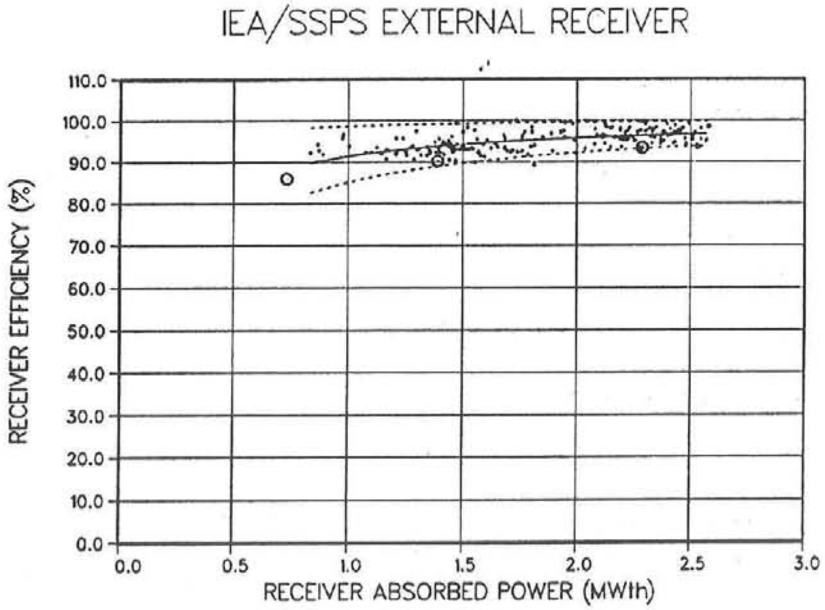


Figure II-1. IEA/SSPS RECEIVER PERFORMANCE
(From "Receiver Experience" by Al Baker)

This figure shows a plot of receiver efficiency vs. receiver absorbed power for the sodium external receiver in the International Energy Association's Central Receiver System in Almeria, Spain. By utilizing large amounts of statistical data, uncertainties in calculating losses can be reduced. The high efficiency for this receiver is a consequence of using sodium, with its high heat transfer coefficient. The receiver can be made much smaller than permitted by other heat transfer fluids such as steam and molten salt. Conduction, convection, and radiation losses (for external receivers) can be reduced. Smaller receivers are also less expensive.

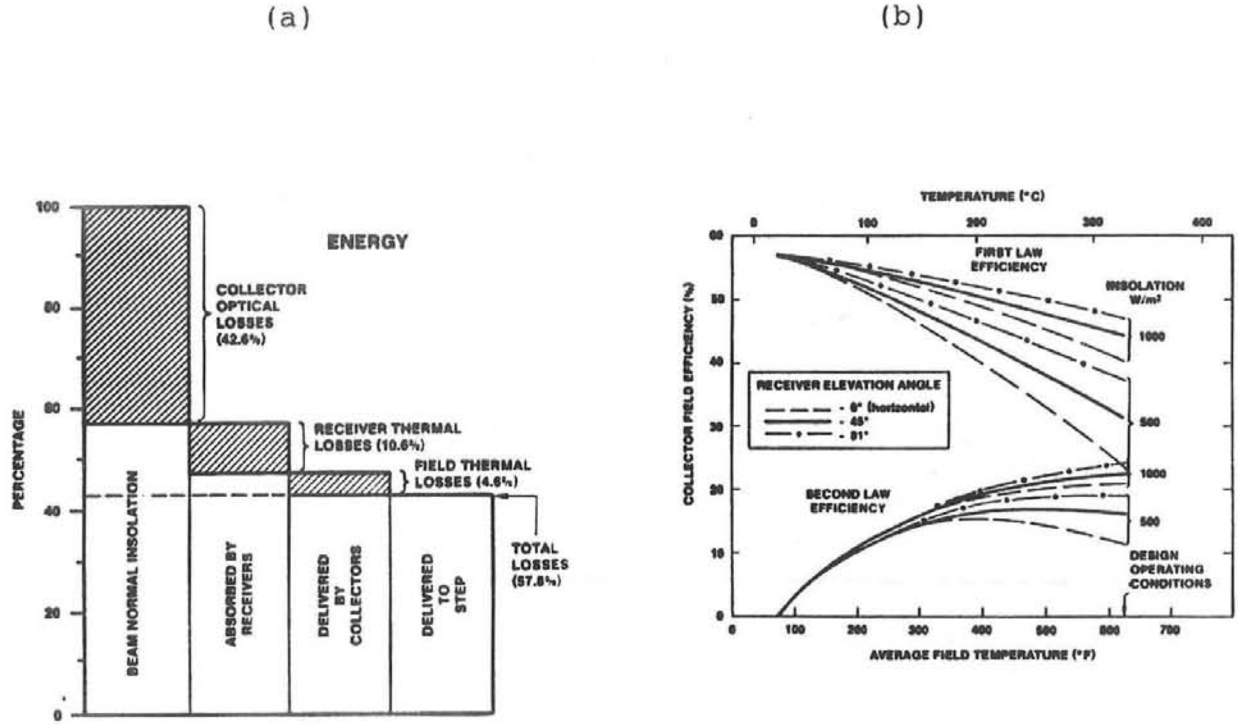


Figure II-2. SHENANDOAH SYSTEM LOSS MEASUREMENTS
(From "Thermal Losses from Receivers: Experimental Examples," by Bill Stine)

This is a waterfall diagram (a) of energy flows & losses in the Shenandoah Solar Total Energy Project. Note that receiver losses represent an important but relatively small fraction of the total losses.

Collector field efficiency vs. average field temperature (b) for three receiver elevation angles indicates that convective losses increase substantially as the receiver attitude approaches horizontal. The results are presented on a first and second law basis. The second law analysis provides important insights into some operational considerations. At the lower insolation level, receiver loss is a higher fraction of the total and is therefore more significant.

Module Failure Summations by System for January 1, 1983, Through July 31, 1984

SOLAR ONE

System	Failures	Component Problems	Transducer Problems	Failures Resulting in >8-hr Outage
1 Receiver	17	98	86	4
2 Main stream	2	14	3	1
3 Stream turbine	4	64	29	1
4 Thermal storage and admission steam	7	82	48	0
5 Auxiliary system	2	2	1	0
6 Feedwater	3	24	11	2
7 Condensate	1	25	19	0
8 Cooling water/sampling	5	16	10	0
9 Water quality control	13	72	31	4
10 Raw and service water	1	9	0	0
11 Compressed air	4	50	4	1
12 Nitrogen	0	6	1	0
13 Fire protection	1	36	1	0
14 Drains, sumps, and waste disposal	2	30	3	0
15 Heating ventilating and air conditioning	1	22	3	0
16 Electrical power	8	39	5	3
17 Computer system	17	188	0	6
18 Miscellaneous support	4	18	10	0
Total for entire plant	92	795	265	22
Entire Plant: critical modules only (145 total)	69	603	221	22

Figure II-3. SOLAR ONE FAILURE SUMMATIONS
(From "The Reliability of Solar One" by John Nagel)

Summary table of major module failures at Solar One for January 1, 1983, through July 31, 1984. Reliability engineering from design through testing is something that should receive more attention. Scheduling maintenance during natural downtimes when possible, investigating parallel and standby contingency configurations, having reliable command and control systems, and setting up critical transducers in parallel with voting logic, are approaches for improving reliability. Better documentation for projects like Solar One can help identify the reliability "weak links" and guide future designs.

Receiver area decreases as peak flux increases

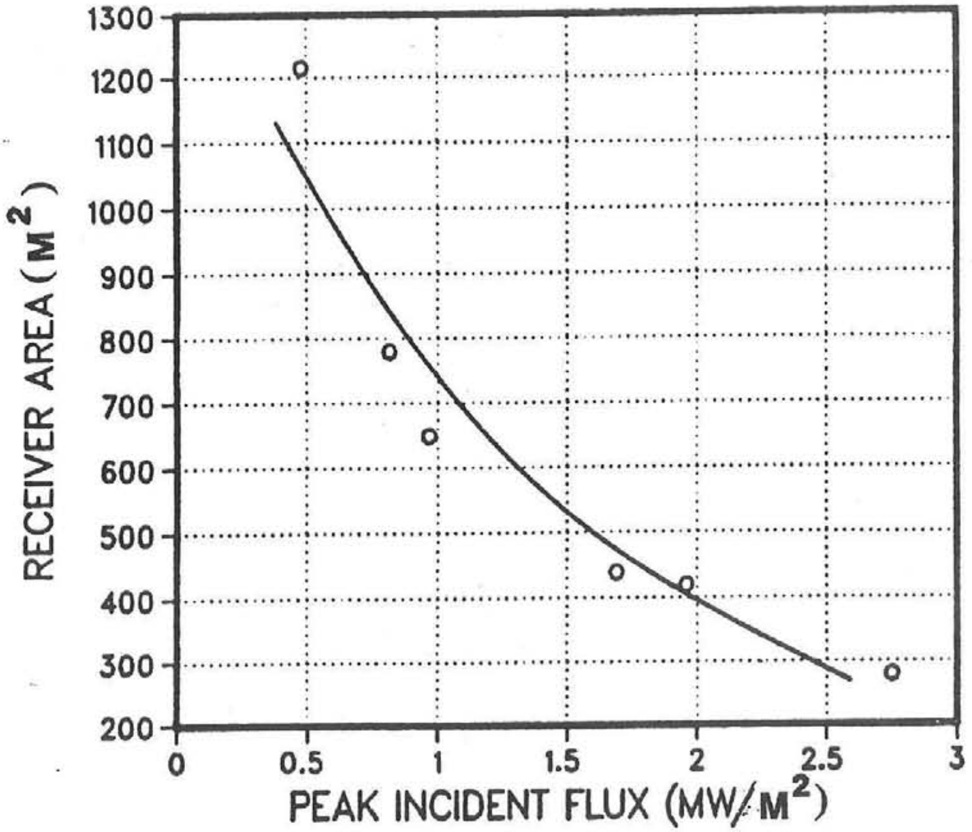


Figure II-4. RECEIVER AREA VS. FLUX
From "Receiver Tube Life Considerations," by Bruce Kistler)

High flux intensities permit the construction of lower absorption area (smaller) receivers that have distinct performance and cost advantages. High peak flux intensities, however, can have catastrophic effects on tube life. The existing guidelines for predicting tube life, ASME code case N-47, are based on nuclear applications and are not readily applicable to solar design. Learning how to predict tube life and long-term testing are needed to insure that receivers can be designed for a specified lifetime while not being too conservative (expensive).

<u>Costs</u> -- Costs, capital and O&M, because of their impact on levelized energy cost were also identified as an important issue. Understanding cost makeup by breaking down the components (already being done with heliostats) was suggested. An identification of the major cost components would provide insights into cost reduction targets. Although cost issues are difficult to evaluate <u>a priori</u> and always tend to be nebulous until something is actually built, there was a strong consensus that cost issues are a priority because cost is the term in the LEC calculation that can be impacted most by R&D.

Long-Term Topics

Advanced receiver designs such as direct absorption (Figure II-5) and reflux receivers (Figure II-6) were identified as approaches capable of providing technical breakthroughs. Their inherent simplicity and potential for high efficiency, high reliability, and low cost make them very attractive. There was consensus that the program should attempt to establish the feasibility of the most promising advanced receiver concepts and vigorously pursue them. Receivers and processes capable of utilizing high temperatures (Figure II-7) and/or photon-specific reactions were identified as having a great deal of potential and also high technical uncertainty. They are also very controversial, with sharply divided opinions as to whether they should be pursued within the Solar Thermal Program.

Thermal loss mitigation schemes, on the other hand, were determined to be less important and better understood. Fossil fuel hybridization of receivers was given relatively low priority.

Summary

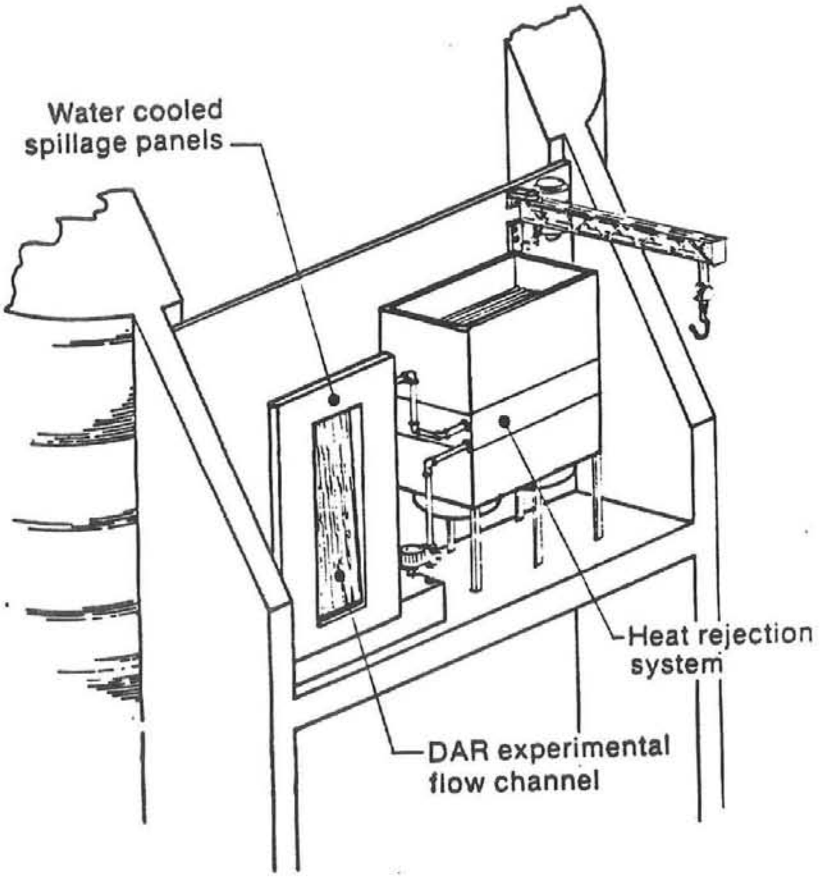
The issues identified and discussed by the presenters, panelists, and audience covered a great deal of fertile ground and helped to put into perspective the technical issues facing the development of solar thermal receivers. It is significant, however, that the technical concerns expressed by the panel and their recommended priorities are in good agreement with those already established within the Solar Thermal Program.

1. The understanding of thermal loss mechanisms and the implementation of experimental techniques to separate the various loss mechanisms were identified as key issues.

2. Operational effects such as transients, thermal mass, control strategies, and reliability were all identified as key issues bearing on annual thermal efficiency.

3. Establishing receiver tube life evaluation criteria, long-term testing, and understanding cost make-up in receivers, were specifically identified as key issues.

4. Advanced receiver designs such as direct absorption and reflux receivers were identified as approaches capable of providing substantial improvements in performance/cost ratios. Continued development of such concepts were considered to be key needs.

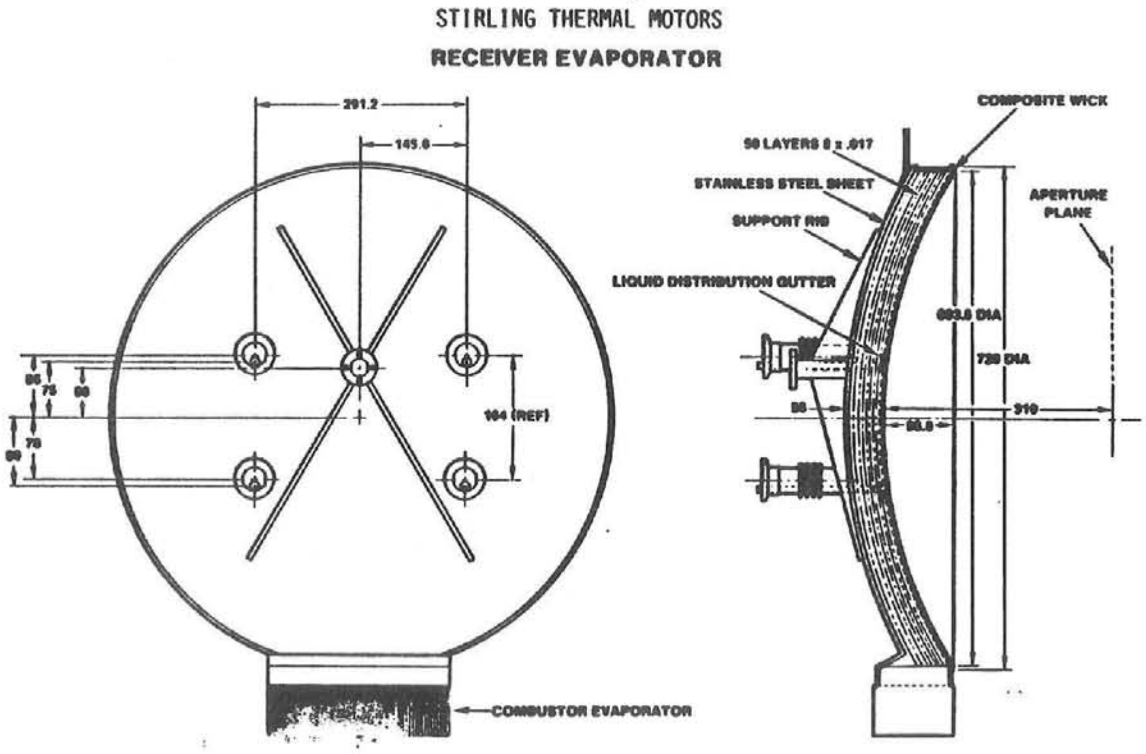


DIRECT ABSORPTION RECEIVER

Panel Research Experiment at the CRTF

Figure II-5. CRTF DAR EXPERIMENT
(From "Molten Nitrate Salt Direct Absorption Receivers" by Craig Tyner)

Sketch of the proposed direct absorption receiver (DAR) panel test scheduled for testing and evaluation at the CRTF. Advanced receiver concepts like DAR have the potential to improve performance, reduce cost, and increase reliability compared to conventional tube receivers. Since the DAR has no tubes, tube life, a critical issue for tube receivers, is not an issue. Proving the feasibility of advanced receiver concepts like DAR should be a priority, according to the panel.



Schematic Drawing of a Reflux-Heat Pipe Solar Receiver for a Kinematic Stirling Engine by Stirling Thermal Motors.

Figure II-6. A KINEMATIC STIRLING ENGINE BY STIRLING THERMAL MOTORS (From "Advanced Dish Receivers" by Rich Diver)

This design and similar designs by Mechanical Technology, Inc., and Stirling Technology Company for free-piston Stirling engines are major departures from the demonstrations of Stirling dish-electric technology by United Stirling, Advanco, and McDonnell-Douglas. Advanced receiver design concepts trade uncertainties in one area against uncertainties in another. Designs that account for and take advantage of the characteristics of concentrated solar flux are capable of providing breakthroughs.

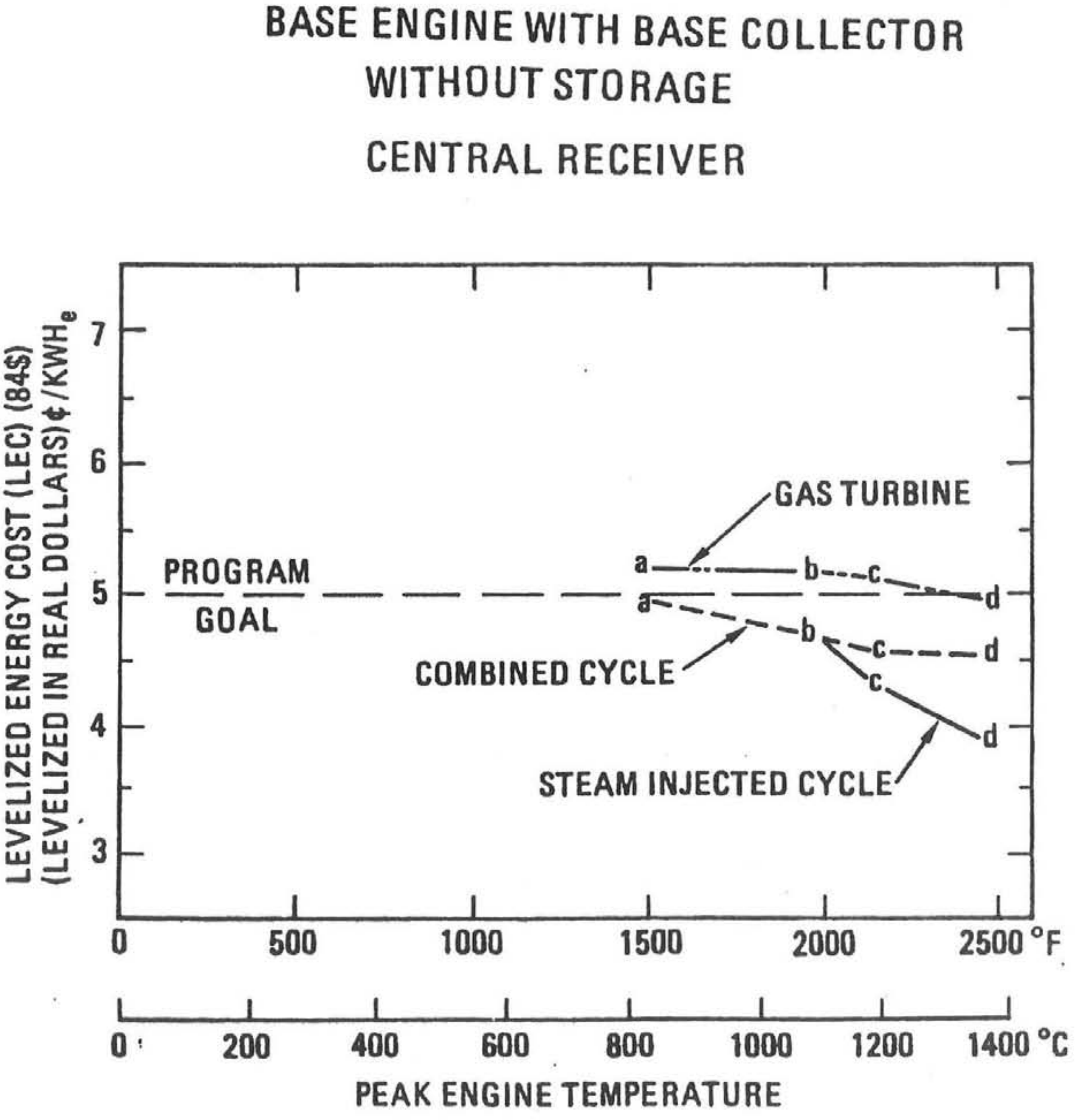


Figure 11-7. ENGINE TEMPERATURE VS. LEVELIZED ENERGY COST (From "High Temperature Applications Study: The Bottom Line of Electric Power" by Robert Copeland)

This figure shows levelized energy cost (the bottom-line cost of producing electric power) vs. peak engine temperature for three gas turbine based power cycles. Conventional steam cycle systems are capable of producing the solar thermal program goal at substantially lower temperatures (~1000 F). The results from this study suggest that reductions in LEC are possible but that significant high temperature receiver technology development will be required.

SESSION III: WINDLOADS ON COLLECTORS

Introduction

The workshop session on Windloads on Collectors was conducted in the afternoon of Wednesday, October 8, 1986, the second of the two-day workshop. Discussion in this session was more directed than in other sessions because of the specific nature of the topic and the similarity of the needs of the three solar technologies: Central and Distributed Receivers and Photovoltaics. The following three questions were addressed by the presenters and the eight members of the review panel.

How important are windloads to the design of solar concentrators?

What level of uncertainty exists with regard to drag and moment coefficients for concentrating collectors?

Can we presently design concentrating collectors for windloads using moment and drag coefficients without penalizing them through overdesign?

The two presentations made during this session centered on the available design data from wind tunnel testing and the need for full-scale field experiments to verify and supplement this data base. In fact, the main issue of this Workshop session can be summarized by the question: Are full-scale field experiments needed to narrow the technical uncertainties associated with drag and moment coefficients from wind tunnel testing of collector models?

At the end of the session, the review panel convened and evaluated four topic areas, which were subdivided into 23 issues. The four topic areas and the results of the review panel's evaluation are summarized in Table III-1 and the underlying issues are listed in detail in Appendix Table D-3.

TABLE III-1

WINDLOADS ON COLLECTORS SESSION
TOPIC RANKING

Topic	Normalized Score
Required Data for Design	67%
Wind Resource Assessment	66%
Requirement for Full-Scale Field Testing	46%
Field Hardware Characterization	39%

None of the four topic areas received an overall ranking above 70%. An examination of Table D-3 shows that only three issues, mean pressure distributions, fluctuating pressure distributions, and peak loads, received rankings above 75%.

The following section is a brief presentation of review panel discussions surrounding the central issue of the uncertainty of wind tunnel generated windload data and the need for full-scale field experiments.

Windload Issues

The review panel and those in attendance at the Windloads on Collectors session of the workshop were in unanimous agreement that windloads drive the structural design of solar collectors. Furthermore, survival windloads are more important than operational conditions in most concentrating collector designs. Having established this point, the group then moved on to a discussion of methods for calculating windloads, wind tunnel data, and full-scale field tests.

The windloads on solar collectors are calculated by applying lift, drag and moment coefficients, and wind velocity profiles to generate survival and operational loads on collectors. In the discussion, questions were raised about how "good" the coefficients are and about the conditions used for operational and survival winds. The review panel's evaluation (Appendix D-3) showed only three issues with rankings greater than 75% and all three--peak loads (100%), fluctuating pressure distributions (91%), and mean pressure distributions (87%)--are related to the coefficients and loading. All remaining issues, including the need for field test data, were considered to be of low priority relative to these three issues.

Review panel discussions highlighted the fact that windload calculations for uniform, steady fluid flow are well characterized. That is, drag coefficients etc. have been measured by many different researchers for a variety of geometries and flow conditions. The unsteady nature of the flow field in the atmospheric shear layer adds significant complication to the calculation of windloading, however. Unsteady effects have been treated using either a gust-factor or a peak-load-factor approach where the mean forces are modified to account for the variation in the wind speed. These two approaches are described below.

The two methods used to calculate the windloads as a result of unsteady boundary layer shear flows are the gust-factor and peak-load-factor approaches. In both methods the appropriate drag and moment coefficients come from measurements made for a model in a boundary layer wind tunnel. In the gust-factor approach the load calculated from the mean wind is multiplied by the gust factor, the ratio of the peak wind speed to the mean wind speed, to arrive at an equivalent loading condition. This method appears to work well for quasi-steady or slowly varying wind loading situations. In the peak-load-factor approach the mean force is modified by the addition of the product of a peak load factor and the standard deviation of the force. The peak factor is the difference between the peak and mean loads divided by the rms deviation. The peak load factor method for predicting unsteady loads is good for situations in which the structure may interact with the fluid flow field due to wake excitation. This approach is more applicable to solar collector wind load analysis because, unlike buildings, solar collectors may interact with the vortex shedding and wake fluid flow. In this case the fluctuations in the load are not always proportional to the mean load. The peak-load-factor approach tends to predict higher loads than the gust-factor method and, as yet, there has been no validation or refutation of either procedure.

Independent of which method is used for the calculation of unsteady wind loads in the atmospheric boundary layer, the coefficients are derived from measurements made in the wind tunnel. Some of the problems associated with the scaling of wind tunnel tests and the subsequent interpretation of data are indicated in Figure III-1. In spite of these problems, good agreement between model and full-scale tests has been observed for buildings. This is shown in Figure III-2. Experts generally agree that wind tunnel predictions for tall buildings are possible within 10 to 15%.

Also required for the prediction of loads on solar collectors is information regarding the local wind speed at the site of the collector. Some discussion in this workshop session was devoted to sources of wind velocity data. This was not given a priority ranking by the evaluation panel.

Wind Tunnel Tests

The presentation and discussion shifted to work that has been performed in the wind tunnel at Colorado State University by Prof. John Paterka. A significant amount of work has been done to measure the loads on heliostats at various locations within the collector field and on wind abatement techniques. Only a few measurements have been made for the loads on dish collectors. The effect of fences within a heliostat field and location of a heliostat within the field are shown in Figures III-3 and III-4. Figures III-5 and III-6 show hinge moment coefficients for a heliostat and a dish collector, respectively. These figures serve to emphasize the large differences that exist between uniform flow analysis and turbulent shear flow analysis. Another variable, which is not obvious in the figures, is the geometry of the concentrating collector. Figure III-6 is for a specific collector design that has a slot in part of the dish. This slot has a large effect on the drag and moment measurements made in the wind tunnel.

Following the presentation on wind tunnel measurements, the review panel discussed at length the need for field-scale windload measurements. The discussion followed a number of paths but the consensus was that wind tunnel measurements for solar concentrators can probably be made to within 10 and 15%. Because of the difficulty and time required to make good field-scale measurements, it is probably not justified to undertake these experiments at this time. This opinion is reflected in the low rating of 46% that the field test issue (Appendix D-3) received in the evaluation process.

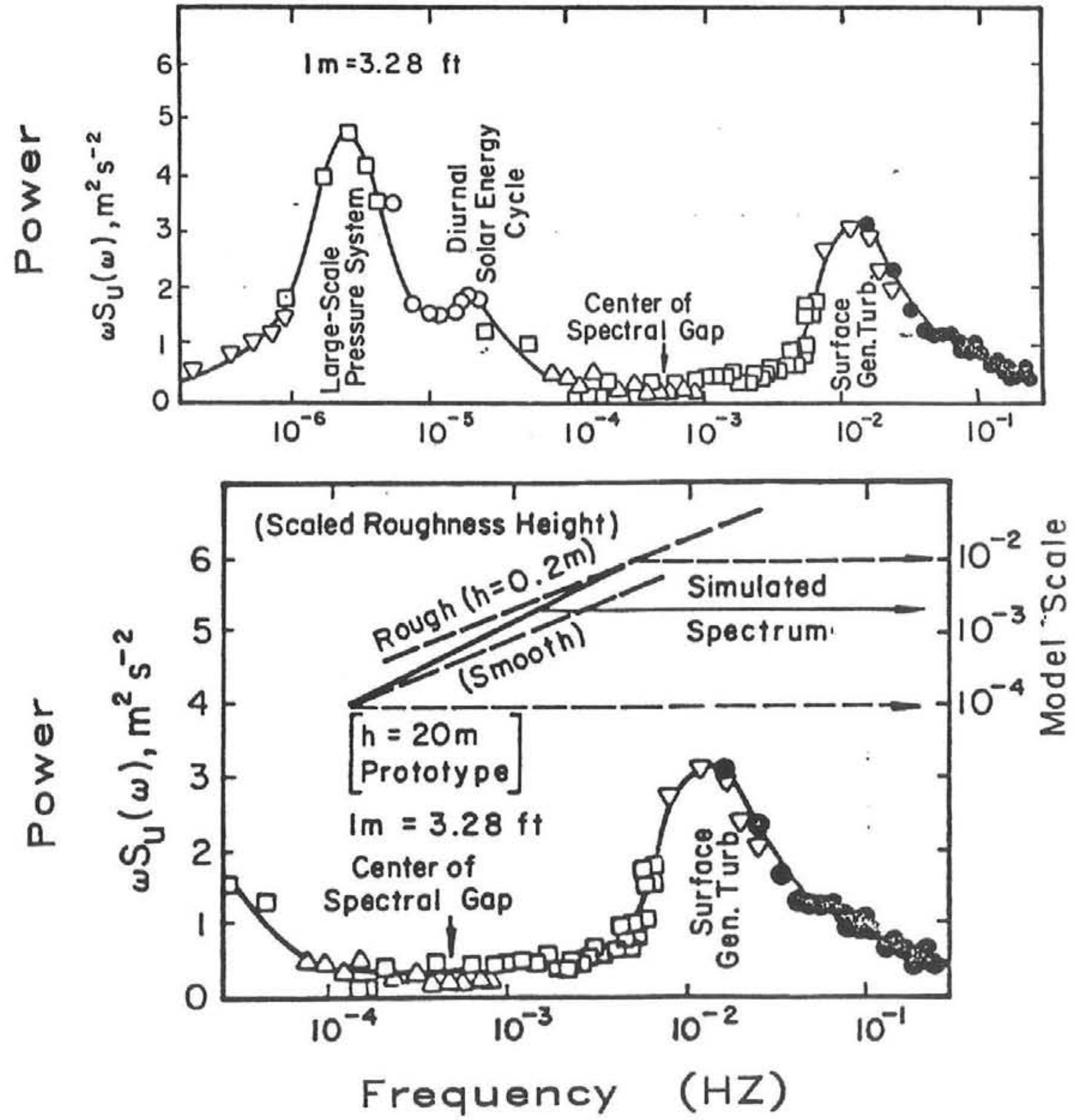


FIGURE III-1. BOUNDARY LAYER WIND SPECTRUM AT 100M (from "Windloading on Solar Collectors" by J. Paterka)

The top figure is the boundary layer wind spectrum at 100m due to van der Hoven. The lower figure is the high frequency part of the spectrum. The low frequency part of the spectrum below the spectral gap cannot be modeled in the wind tunnel. In fact, the lower figure demonstrates that the scale for the wind tunnel models and the range of the spectrum simulated for a prototype 20m high. The model scale varies by two orders of magnitude. Furthermore, the dynamic characteristics of the model must be taken into consideration in the reduction of the data since there is presently no scaling for dynamic similarity in the wind tunnel.

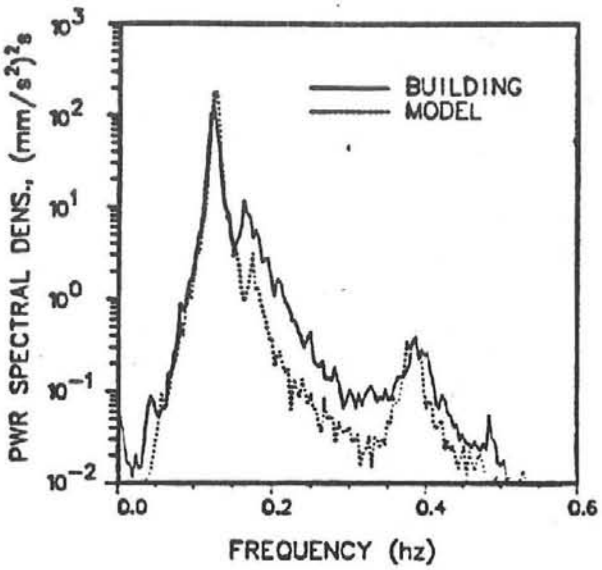


FIGURE III-2. COMPARISON OF TRANSLATIONAL MODES FOR A TALL BUILDING BY DALGLEISH
(From "Windloads on Solar Collectors" by J. Paterka)

This figure demonstrates the excellent agreement obtained between wind tunnel and full-scale tests for a tall building. Experts generally agree that the behavior of tall buildings can be predicted from wind tunnel measurements to within 10 to 15%.

Several references for wind loading are:

"Aerodynamics of Buildings" by J. E. Cermak, Annual Review of Fluid Mechanics, Vol. 8, Annual Reviews Inc., Palo Alto, California, 1976.

Wind Loading on Solar Concentrators: Some General Considerations by E. J. Roschke, DOE/JPL-1060-66, Jet Propulsion Laboratory, Pasadena, California, May 1984.

Wind Load Reduction for Heliostats by J. A. Paterka, et. al., SERI/STR-253-2859, DE86010703, Solar Energy Research Institute, Golden, Colorado, May 1986.

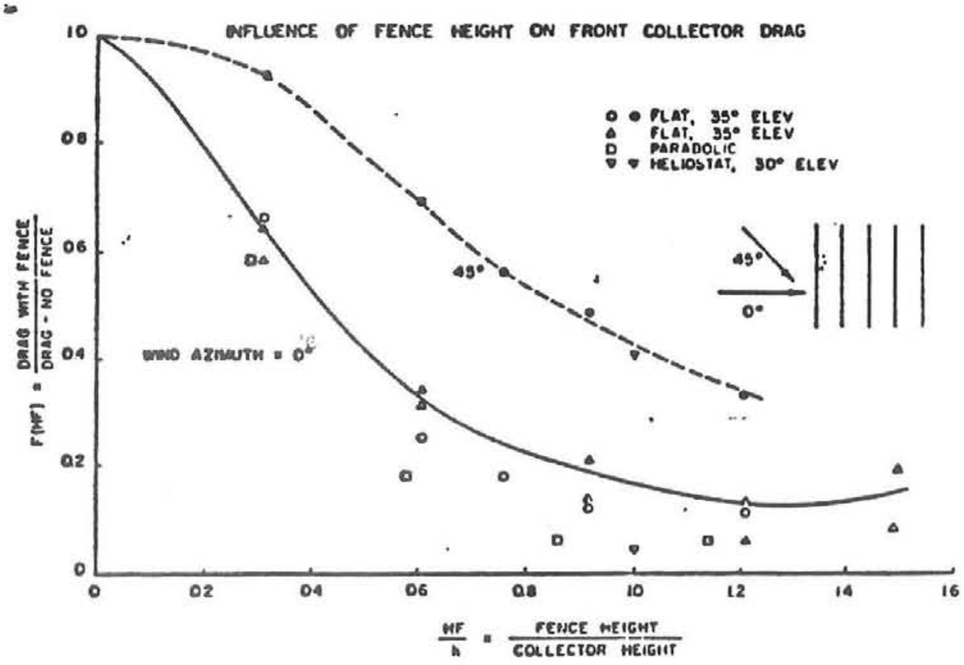


FIGURE III-3. HELIOSTAT WIND ABATEMENT USING FENCES
(From "Windloads on Solar Collectors" by J. Paterka)

This figure shows the effect of various fence heights on the frontal drag of a solar collector. Fences can reduce the drag by a factor of two or three depending on the orientation of the collector.

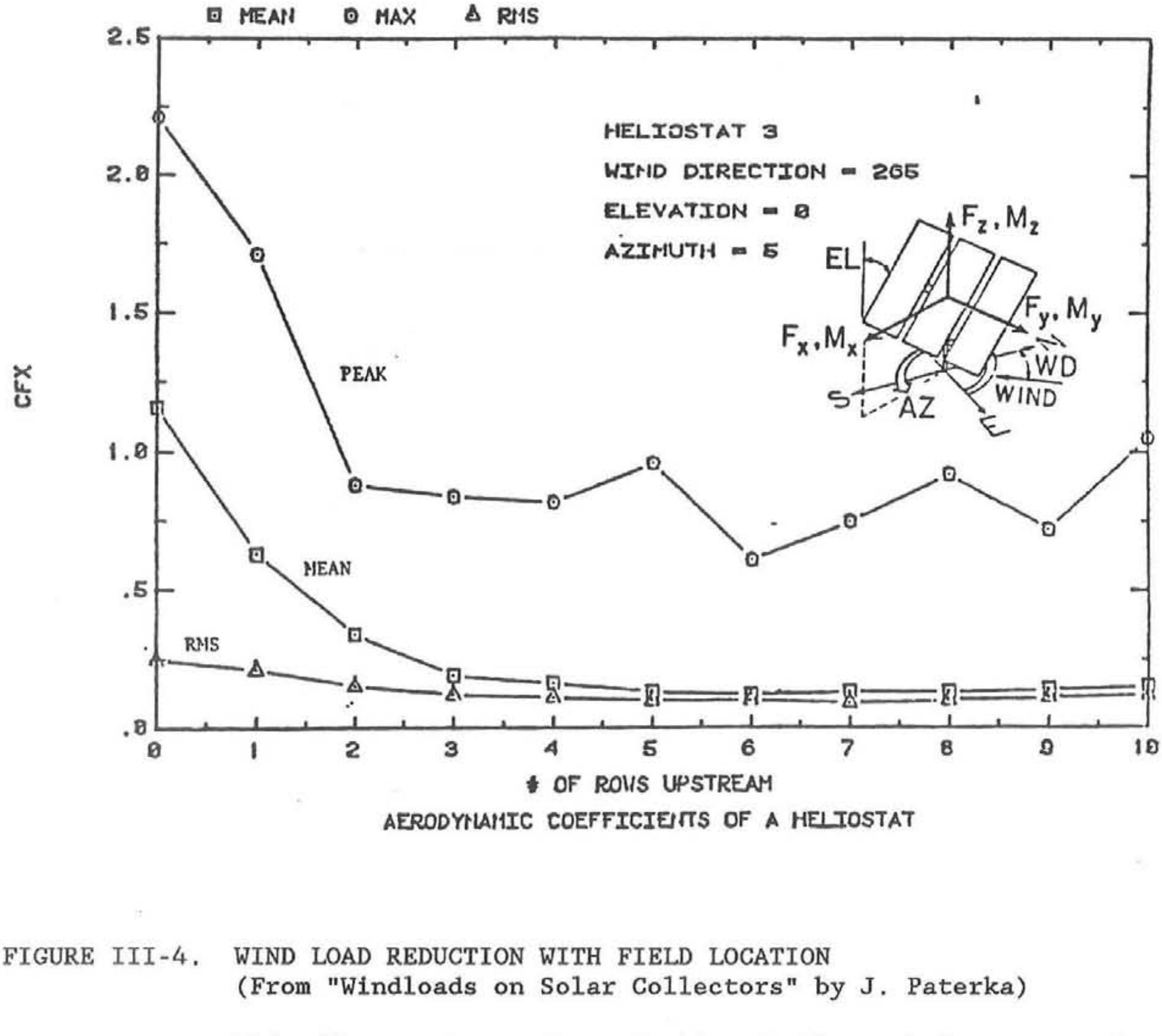


FIGURE III-4. WIND LOAD REDUCTION WITH FIELD LOCATION
(From "Windloads on Solar Collectors" by J. Paterka)

This figure shows the reduction in the peak drag, mean drag and rms drag with position in a heliostat field. The drag in the third row has been reduced in peak value by 66%, in the mean by 69%, and rms by 30%. This figure suggests that location within a collector field will greatly affect the loads a solar collector will experience.

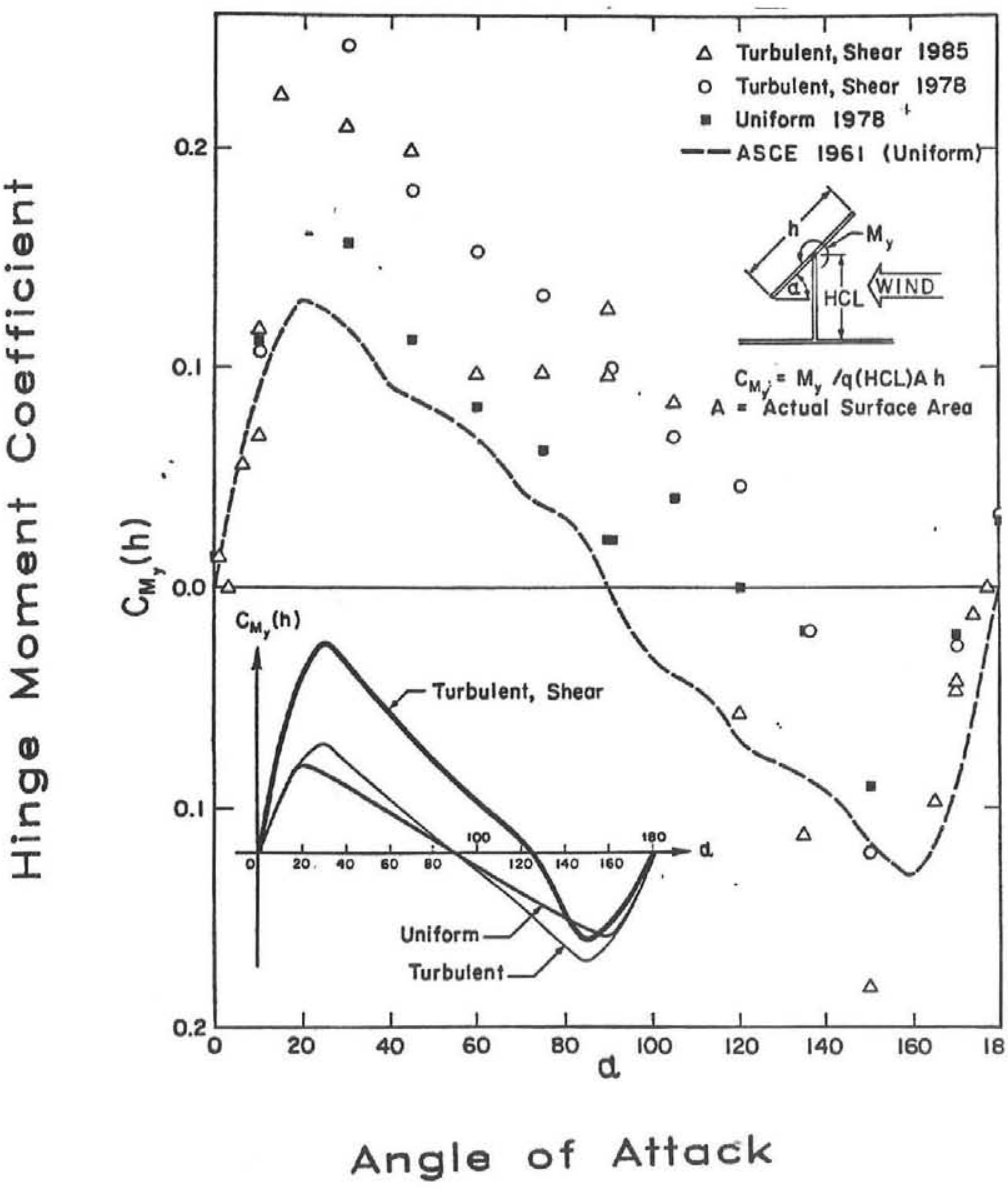


FIGURE III-5. HINGE MOMENT COEFFICIENT FOR A HELIOSTAT
(From "Windloads on Solar Collectors" by J. Paterka)

The hinge moment is one of the critical loads that the designer of a concentrating collector must consider in the drive and structural support system design. This figure shows the vast difference between the ASCE uniform flow criteria for windload design, the uniform flow data from wind tunnel tests, and turbulent shear flow data for a heliostat. Note that a factor of two can exist and a change in the sign of the moment coefficient (difference in the direction of the moment) can exist between uniform flow and turbulent shear flow data.

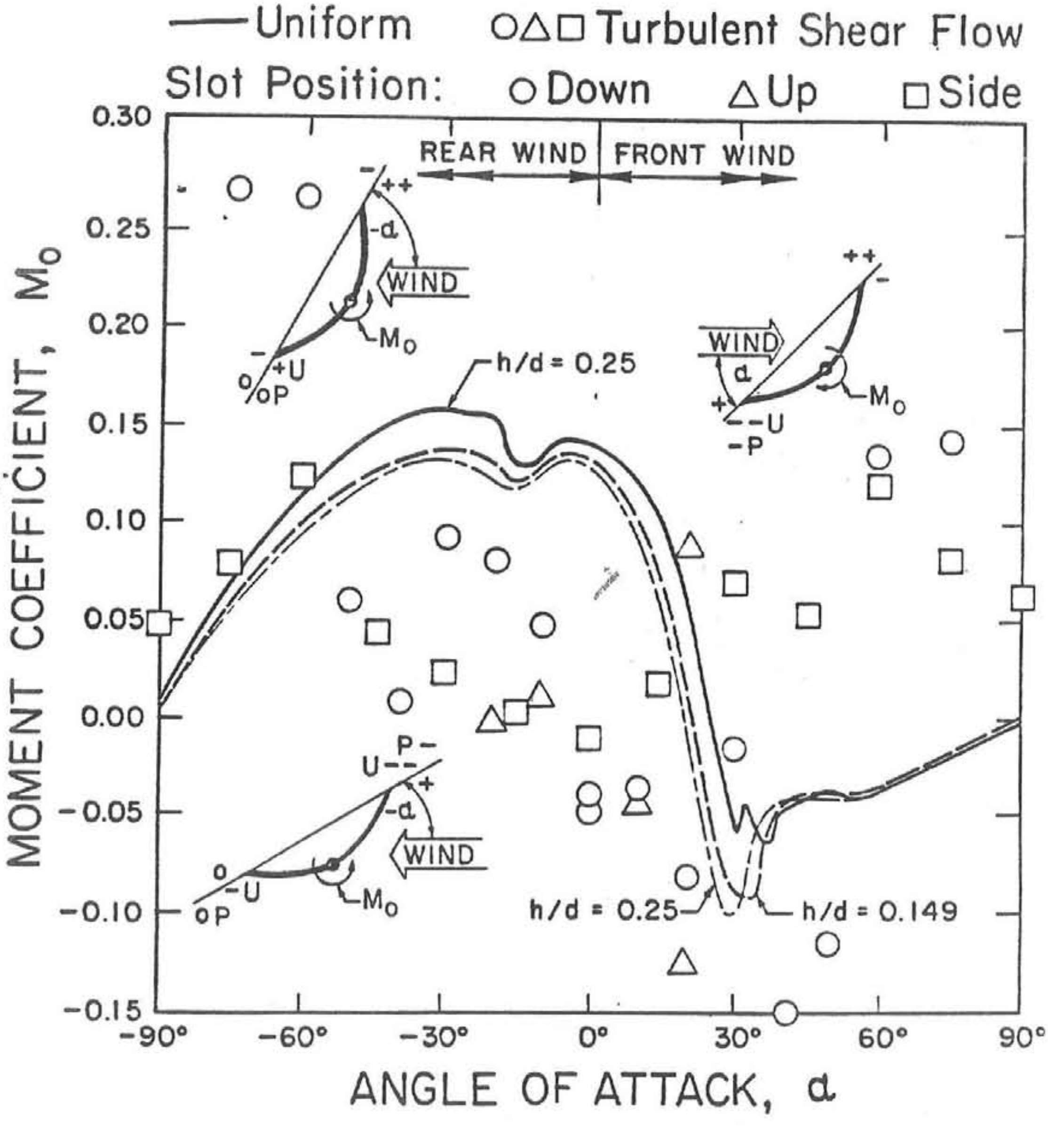


FIGURE III-6. HINGE MOMENT COEFFICIENT FOR A DISH COLLECTOR (From "Windloads on Solar Collectors" by J. Paterka)

This figure is similar to Figure III-5 with the exception that it is for a dish collector of a very specific design. Even larger discrepancies between predicted and wind tunnel data are experienced in this figure, as large as a factor of 5 or 6. At angles of attack greater than 30 degrees, there is a difference in sign between the measurements and the predictions. This curve is for a porous solar collector with an open slot. A concentrator having a different geometry will not have these same moment coefficients.

Summary

The following four issues summarize the consensus of the review panel for windloads on collectors.

1. Survival windloads drive the structural design of concentrating solar collectors.
2. Wind tunnel measurements can probably predict drag, lift, and moment coefficients for solar collectors within 10 to 15%.
3. Additional wind tunnel testing on generic concentrator designs is needed to further quantify mean pressure distributions, fluctuating pressure distributions, and peak loads.
4. Because of the large, long-term level of effort required to obtain good field data and the questionable ability to reduce the uncertainty of coefficients below current levels, field-scale experiments for windloading are probably not required at this time.

APPENDIX A

Final Agenda

WORKSHOP

CONCENTRATING SOLAR COLLECTORS: KEY TECHNICAL ISSUES

October 7 and 8, 1986
Albuquerque, New Mexico

Tuesday, October 7

8:30	J. Leonard, SNLA Workshop Chairman	Welcoming Remarks
8:40	F. Morse, DOE/HQ	Introductory Address

SOLAR COLLECTOR OPTICS:

Session Organizers: L. Murphy, SERI and
T. Mancini, SNLA

REFLECTIVE OPTICS

8:50	L. Murphy, SERI	Introductory Remarks on Concentrating Collectors
9:00	T. Mancini, SNLA	Point-Focus Collectors in the Solar Thermal Program--Definitions, Performance Parameters, Experience gained, Uncertainties associated with "key" collector issues, etc.
9:40	QUESTIONS, ANSWERS, AND DISCUSSION	
10:30	Coffee Break	
10:45	A. Baker, SNLL	Heliostats -- Performance, Cost, Uncertainties, Experience gained, etc.
11:15	QUESTIONS, ANSWERS, AND DISCUSSION	
12:00	LUNCH	

AGENDA (Continued)

	REFRACTIVE OPTICS	
1:00	C. Stillwell, SNLA	Refractive Point-Focus Solar Collectors -- Performance criteria and evaluation of experience gained in the SNLA PV Program
1:30	QUESTIONS, ANSWERS, AND DISCUSSION	
	SOILING	
2:00	A. Baker, SNLL E. Harley, SNLA C. Stillwell, SNLA	Soiling of Concentrating Solar Collectors
	MEASUREMENT	
2:40	C. Cameron, SNLA A. Lewandowski, SERI	Measurement techniques and uncertainties in Testing of Point-Focus Collectors
3:30	Coffee Break	
3:45	QUESTIONS, ANSWERS AND DISCUSSION	
4:30	Review Panel Convenes	

Wednesday, October 8

SOLAR RECEIVER ISSUES:
Session Organizers: R. Diver and
C. Tyner, SNLA

8:30	R. Diver	Introduction to Receiver Issues
	PERFORMANCE	
8:35	W. Stine, Cal Poly	Thermal Losses from receivers: experimental examples
9:00	A. Baker, SNLL	Receiver Experience -- Technical issues raised by testing at Solar One, MSEE, IEA, etc., concentrating on losses, measurement uncertainties, etc.
9:30	R. Copeland, SERI	High Temperature Receivers - Technical Uncertainties and Opportunities
10:00	Coffee Break	

AGENDA (continued)

10:30	QUESTIONS, ANSWERS AND DISCUSSION	
	RELIABILITY	
11:30	J. Nagel, SNLA	The Reliability of Solar One: includes general methodology, confidence levels
12:00	LUNCH	
1:00	B. Kistler, SNLL	Receiver Tube Life Considerations
1:30	QUESTIONS, ANSWERS, AND DISCUSSION	
	ADVANCED DESIGNS/ANALYTICAL METHODOLOGY	
2:00	C. Tyner, SNLA	The Direct Absorption Receiver
2:30	R. Diver, SNLA	Advanced Dish Receivers
3:00	QUESTIONS, ANSWERS AND DISCUSSION	
3:30	Coffee Break	
3:45	Review Panel Convenes:	

1:00 P.M. Wednesday, October 8

WINDLOADS ON COLLECTORS:
Session Organizers: T. Mancini, SNLA and
L. Murphy, SERI

1:00	T. Mancini, SNLA	Introductory Remarks on Wind Loads
1:10	J. Paterka, CSU	Windloading on Solar Collectors - Heliostat, PV, and Solar Thermal dish collector wind loads; uniform vs. boundary layer flows; turbulence intensity effects; scaling; dynamics etc.
2:15	QUESTIONS, ANSWERS, AND DISCUSSION	
2:45	J. Strachan, SNLA	SNLA Wind Field Test Experiments
3:15	Coffee Break	
3:30	QUESTIONS, ANSWERS, AND DISCUSSION	
4:15	Review Panel Convenes	

APPENDIX B

CONCENTRATING SOLAR COLLECTORS: KEY TECHNICAL ISSUES WORKSHOP

October 7 and 8, 1986

Attendees

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R. Appledorn, 3M
D. Arvizu, SNLA

B. Barber, B-N
A. Baker, SNLL
D. Bielenberg, SPECO
E. Boes, SNLA
R. Boehm, U of Utah
B. Butler, SAIC

C. Cameron, SNLA
D. Carroll, Alpha Solarco
H. Coleman, DOE/HQ
R. Copeland, SERI

H. Dehne, Acurex
P. Delaquil, Bechtel
E. DeMeo, EPRI
R. Diver, SNLA
F. Durgin, MIT
V. Dugan, SNLA

C. Garcia, DOE/AL
D. Gorman, Advanced Thermal Systems
D. Graves, DOE/AL

E. Harley, SNLA
W. Hesse, ENTECH
T. Hillesland, PG&E
J. Holmes, SNLA
R. Houser, SNLA
A. Hunt, LBL
J. Hutchison, SKI

J. Kesseli, Sanders
B. Kistler, SNLL

N. Lackey, DOE/AL
J. Leonard, SNLA
A. Lewandowski, SERI

R. Mahoney, SNLA
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M. McGlaun, LaJet
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J. Otts, SNLA

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D. Reda, SNLA
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C. Stillwell, SNLA
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D. Thornburg, APS
T. Tracey, Consultant
C. Tyner, SNLA

L. Vant-Hull, U of Houston

H. Walter, Fresnel Optics
E. Weber, APS
D. White, SKI
C. Williams, LaJet

D. Young, B&W

APPENDIX C

Optics Review Panel

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T. Mancini	Co-chairman
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D. Bielenberg	SPECO
B. Butler	SAIC
H. Dehne	Acurex
E. DeMeo	EPRI
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C. Williams	LaJet

Receiver Review Panel

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C. Tyner	Co-chairman
R. Boehm	U of Utah
P. Delaquil	Bechtel
T. Hillesland	PG&E
A. Hunt	LBL
J. Kesseli	Sanders
B. Mikic	MIT
P. Skvarna	SCE
D. Smith	B&W
W. Stine	Cal Poly
T. Tracey	Consultant
E. Weber	APS

Wind Loading Review Panel

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L. Murphy	Co-chairman
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F. Durgin	MIT
A. Lewandowski	SERI
A. Maish	SNLA
M. McGlaun	LaJet
M. O'Neill	ENTECH
D. Reda	SNLA
R. Reese	SNLA
D. White	SKI

APPENDIX D

TABLE D-1

SOLAR COLLECTOR OPTICS
TECHNICAL REVIEW PANEL RANKINGS

TOPIC/ISSUE	REVIEWER ASSIGNED PRIORITY X UNCERTAINTY PRODUCT												TOTAL	NRMLZD TOTAL	AVERAGE NRML TTL
DEFINITIONS															67%
Instantaneous Optical Efficiency	3	15	10	0	20	12	15	4	20	25	9	12	145	70%	
Annual Optical Efficiency	12	15	10	4	20	25	9	9	20	25	9	16	174	84%	
Slope Error	25	15	12	2	25	9	12	6	9	9	9	20	153	74%	
Specularity	25	15	12	4	16	9	4	12	9	6	9	5	126	61%	
Sunshape	25	15	12	2	12	12	9	4	4	12	12	12	131	64%	
Concentration Ratio	9	15	8	2	20	6	5	3	6	6	12	9	101	49%	
CONCENTRATOR ANNUAL PERFORMANCE															71%
Sunshape and TMY Data	20	12	12	6	12	16	12	4	25	16	15	9	159	77%	
Specularity	25	12	12	4	16	16	9	3	9	4	16	6	132	64%	
Site Dependence	9	20	4	2	6	15	9	1	16	9	25	6	122	59%	
Receiver/Concentrator Interaction	9	15	15	12	20	20	12	1	12	20	25	12	173	84%	
SOLAR COLLECTOR ERROR BUDGETS															59%
Solar Collector Figure	25	12	9	9	9	25	15	2	9	16	12	12	155	75%	
Thermal Effects on Errors	20	12	9	6	12	9	9	2	4	16	4	12	115	56%	
Humidity Effects on Errors	12	12	9	2	6	8	9	9	4	4	4	8	87	42%	
Gravity Effects on Errors	8	25	9	6	6	6	9	2	6	6	4	8	95	46%	
Tracking Errors	16	12	12	3	12	16	16	1	9	16	4	9	126	61%	
Concentrator Slope Errors	20	9	12	6	20	16	20	6	12	12	4	15	152	74%	
Errors due to Facet Size	9	9	4	6	12	25	15	6	9	8	12	5	120	58%	
COMPARATIVE COLLECTOR COSTS															88%
Capital Cost of Collectors	25	20	25	16	6	16	25	3	20	0	4	20	180	87%	
Operational and Maintenence Costs	25	15	25	20	4	25	25	8	20	0	4	20	191	93%	
Drive Cost Reductions	9	25	25	9	6	20	20	12	25	9	4	6	170	83%	
STRETCHED MEMBRANE CONCENTRATORS															99%
Facet Size and Slope Errors	25	15	25	9	12	25	25	20	9	9	16	16	206	100%	
Cost/Performance vs. Size	25	15	25	8	6	25	25	16	9	16	16	16	202	98%	
FRESNEL OPTICS IN DISTRIBUTED SYSTEMS															57%
Chromatic Aberration	8	8	9	1	16	9	12	1	0	16	6	4	90	44%	
Slope Error Sensitivities	9	8	9	6	25	9	16	1	0	20	6	10	119	58%	
Secondary Concentrators For	9	8	6	1	16	8	16	1	0	16	9	6	96	47%	
Scale for Thermal Applications	25	8	25	6	25	8	20	1	0	6	16	20	160	78%	
Optical Errors of Fresnel Collector	25	8	9	3	25	9	15	1	0	12	9	4	120	58%	
SOILING OF CONCENTRATOR SURFACES															75%
Short Term Degradation	25	9	20	2	2	8	20	1	3	9	12	8	119	58%	
Long Term Degradation	25	9	25	6	12	20	25	6	3	16	12	16	175	85%	
Value of Cleaning Optical Surfaces	15	9	15	2	6	8	10	2	9	25	12	16	129	63%	
Cleaning Agents for Optical Surface	25	9	16	9	12	12	20	6	25	6	16	8	164	80%	
Collector Surface Treatments	25	20	16	12	6	20	16	0	15	25	16	12	183	89%	
Soiling Avoidance Schemes	9	16	9	12	9	25	15	2	9	12	20	4	142	69%	
Soiling Mechanisms on Materials	25	20	9	12	6	25	16	4	6	16	20	12	171	83%	
Mechanical Cleaning Damage	25	16	9	8	8	12	12	8	4	12	20	12	146	71%	
CONCENTRATING COLLECTOR MEASUREMENTS															73%
Surface Imperfections/Figure	20	9	9	6	6	12	20	9	4	16	15	9	135	66%	
Field Slope Error Measurement	25	12	9	16	6	25	16	6	25	25	20	16	201	98%	
Central Receiver Flux Mapper	15	15	25	16	4	8	9	4	1	12	20	9	138	67%	
Fresnel Measurement Techniques	0	8	9	3	12	6	15	0	0	9	20	8	90	44%	
Life-Cycle Materials Performance	20	9	25	12	4	25	16	12	20	20	4	25	192	93%	
SECONDARY CONCENTRATORS	25	20	6	4	12	8	20	2	25	16	10	4	152	74%	74%
OPTICAL COMPUTER CODE VERIFICATION	25	9	15	12	6	0	9	4	9	25	12	16	142	69%	69%

APPENDIX D

TABLE D-2

SOLAR RECEIVER ISSUES
TECHNICAL REVIEW PANEL RANKINGS

TOPIC/ISSUE	REVIEWER ASSIGNED PRIORITY X UNCERTAINTY PRODUCT											TOTAL	NORMALIZED TOTAL	
	NEAR TERM													
THERMAL LOSSES	14	6	20	12	12	9	12	9	11	12	12	129	78%	
Comprehensive Heat Loss Understanding	15	9	16	12	20	12	12	9	9	16	16	146		82%
Model Validation	12	14	16	16	8	16	9	9	12	20	12	144		81%
Instrumentation	12	16	12	12	10	16	16	9	16	16	16	151		85%
· Surface Temps.	16	20	9	12	10	15	16	9	16	15	15	153		86%
· Flux	12	9	9	12	10	12	16	9	16	16	12	133		75%
· Input Power	9	9	9	12	10	16	16	9	16	9	16	131		74%
SURFACE COATINGS	12	6	15	6	8	15	9	0	9	12	8	100	60%	
Understanding Pyromark Properties	12	6	12	6	4	12	12	0	9	12	20	105		59%
New Coatings	12	6	20	6	12	9	9	0	9	12	15	110		62%
UNDERSTANDING OPERATIONAL EFFECTS ON ENERGY	9	6	20	20	10	20	9	1	25	12	16	148	89%	
Transient Responses	16	6	20	16	10	20	9	1	20	16	20	154		87%
Thermal Mass	4	8	16	9	11	9	4	1	4	9	12	87		49%
Control Strategies	9	6	20	16	11	16	9	0	25	12	20	144		81%
Parasitics	12	4	10	20	12	20	8	0	25	4	16	131		74%
· Heat Trace	16	4	8	16	12	16	8	0	25	6	9	120		67%
· Pumping	6	4	6	9	12	12	8	0	25	6	12	100		56%
· Overnight Conditioning	12	6	6	16	12	6	8	0	25	6	16	113		63%
RELIABILITY	14	6	15	25	3	20	16	25	11	0	15	150	90%	
Reliability Documentation	12	4	8	25	3	1	16	25	2	0	15	111		62%
Receiver Tube Life (tubes, fasteners, materials, 9 Cr/Mo)	16	4	6	16	3	20	12	25	9	0	20	131		74%
Long-Term Testing	25	6	20	25	3	25	12	25	12	0	25	178		100%
PREDICTION OF ANNUAL & OFF-PEAK PERFORMANCE	20	6	25	25	9	25	12	8	16	0	20	166	100%	
UNDERSTANDING SCALE-UP OF PARAMETERS	12	6	25	25	12	25	12	0	9	0	15	141	85%	
UNDERSTANDING COST	13	6	15	25	8	12	12	25	10	0	15	141	85%	
Capital	16	6	12	25	8	16	12	25	20	0	15	155		87%
O&M	9	6	12	25	8	16	12	25	6	0	15	134		75%
Cost Reduction	15	9	25	25	8	16	12	25	10	0	15	160		90%
HYBRIDIZATION	4	6	12	12	1	4	6	25	1	0	4	75	45%	
	LONG-TERM													
ADVANCED DESIGN FEASIBILITY	12	25	15	20	15	15	16	1	20	5	21	165	99%	
High-Temperature Receivers	6	20	10	16	15	12	16	1	20	5	25	146		82%
High-Flux Recievers	9	20	10	16	15	12	16	1	16	5	25	145		81%
D.A.R.	16	20	10	25	15	16	16	1	16	0	20	155		87%
Photon-Specific	16	25	10	25	15	2	16	1	25	0	15	150		84%
ADVANCED APPLICATIONS RECEIVERS	12	25	12	16	7	4	12	15	12	0	20	135	81%	
Fuels & Chemicals	16	20	10	16	5	4	12	15	9	0	20	127		71%
Advanced Power Systems	12	16	10	16	15	4	12	15	16	0	25	141		79%
High-Temp. Process Heat	9	12	10	16	1	4	12	15	1	0	15	95		53%
LOSS MITIGATION	8	10	6	16	15	9	9	4	6	12	12	107	64%	
Terminal Concentrators	6	6	6	16	15	8	9	5	2	12	15	100		56%
Windows	4	20	6	12	6	4	9	1	16	9	16	103		58%
Air Curtains	14	6	6	12	15	12	9	5	1	12	15	107		60%
HYBRIDIZATION	12	6	3	9	1	3	9	5	1	0	9	58	35%	

TABLE D-3
WINDLOADS ON COLLECTORS
TECHNICAL REVIEW PANEL RANKINGS

TOPIC/ISSUE	REVIEWER ASSIGNED PRIORITY X UNCERTAINTY PRODUCT							TOTAL	NRMLZD TOTAL	AVERAGE NRML TTL
REQUIREMENT FOR FULL-SCALE FIELD TESTING										46%
Turbulence Intensity as f(t)	6	9	16	25	1	4	20	81	70%	
Non-scalable Reynolds No. Effects	4	2	25	25	1	2	15	74	64%	
Uncertain Geometeries	4	2	4	9	1	8	25	53	46%	
Other Uncertainties	5	2	0	0	1	6	16	30	26%	
Cost/Benefit	4	4	0	0	1	4	6	19	17%	
Confirmation Tests	3	6	9	15	1	6	20	60	52%	
REQUIRED DATA FOR DESIGN										67%
Mean Pressure Distributions	25	1	10	16	16	12	20	100	87%	
Fluctuating Pressure Distributions	20	1	15	16	16	12	25	105	91%	
Peak Loads	16	20	15	20	12	12	20	115	100%	
Load Spectrum (Freq.)	16	16	15	0	6	4	20	77	67%	
Mode Shapes	12	16	0	0	9	6	12	55	48%	
Mean Loads (3 components)	9	3	4	12	6	6	20	60	52%	
Mean Moments (3 components)	9	3	4	12	6	6	20	60	52%	
Unsteady Loads	15	0	16	0	0	6	25	62	54%	
Test to Failure	16	25	5	0	12	4	8	70	61%	
Verify or Establish Safety Factors	16	25	5	0	4	4	12	66	57%	
WIND RESOURCE ASSESSMENT										66%
Mean Wind Distrigution	6	12	8	15	9	6	15	71	62%	
Peak Wind Distribution	9	12	8	15	9	8	20	81	70%	
Probabilistic Wind Distribution	6	4	8	15	20	8	25	86	75%	
Design Windspeed Specifications	8	9	10	15	6	4	12	64	56%	
FIELD HARDWARE CHARACTERIZATION										39%
Field Test	3	0	15	0	6	4	20	48	42%	
Simple Instrumentation	4	0	8	0	0	4	20	36	31%	
Probabilistic Failure Analysis	6	0	5	0	12	4	25	52	45%	

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1820	R. E. Whan
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1830	M. J. Davis
1832	W. B. Jones
1840	R. J. Eagan
1841	R. B. Diegle
1842	R. E. Loehman
1846	D. H. Doughty
2520	N. J. Magnani
2525	R. P. Clark
2540	G. N. Beeler
2541	J. P. Abbin
3141	S. A. Landenberger (5)
3151	W. L. Garner (3)
3154	C. H. Dalin (28) for DOE/OSTI
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6200	V. L. Dugan
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