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FINAL REPORT

PANEL RESULTS OF THE SOLAR THERMAL PROGRAM
RESEARCH REQUIREMENT ASSESSMENT REVIEW

SUBMITTED TO:

U.S. DEPARTMENT OF ENERGY
WASHINGTON, D.C.

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NOVEMBER 1983

MASTER

Energy, Systems, Planning
and Analysis

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SUMMARY AND RECOMMENDATIONS

INTRODUCTION

This report presents the results of an assessment of the research needs of the solar thermal technologies. The assessment was performed for the Office of Program Analysis in the Office of Energy Research (OER) of the Department of Energy by TPI, Inc. as part of the OER's normal responsibility to advise the Secretary of the Department on the research programs within the DOE.

The objectives of the assessment were to identify: research needs by topic and activity, relative priority of research needs, options for performing needed research, potential performers, costs and duration of R&D activities, gaps and duplications within the R&D program, and activities underway that appear to be of low priority.

To achieve these objectives, TPI, Inc. reviewed research programs of the Division of Solar Thermal Technologies within the Office of Renewable Energy and Conservation and the Materials and Advanced Energy Programs of the Office of Basic Energy Sciences. Several recent assessments of solar thermal research needs made within the past two years by various groups were also reviewed, and the key research issues and needs were extracted. A panel of active researchers with distinguished careers in materials science, thermal science, and thermochemistry were selected to review and evaluate this material and make recommendations to OER. A methodology was developed for screening and ranking the research needs in accordance with a set of criteria established jointly by TPI, OER, and the panel. Members of the panel were:

- o Dr. Michael Antal - University of Hawaii
Hawaii Natural Energy Institute (Thermochemistry)
- o Dr. Patrick J. Call - Reference Technology, previously
from the Solar Energy Research Institute (Materials)
- o Dr. Richard Gaggioli - Catholic University
Washington, D.C. (Thermal Sciences)
- o Dr. Roland Winston - University of Chicago
Enrico Fermi Institute (Thermal Sciences)
- o Dr. Mark Wrighton - Massachusetts Institute of Technology
(Photochemistry)

RESULTS

The primary results from the assessment are a set of prioritized activities to meet the most important research needs for solar thermal technologies. These activities belong to four disciplines: materials science, thermal science, thermochemistry, and engineering. Further, priorities associated with the needs for research result from the various activities allow the recommended activities to be grouped into two categories: a core group which should be at the heart of any future program developed by the department, and a set of important needs that should, at least, find their way into a program at some time during its existence. The recommended research program is outlined in Table A, and the complete set of ranked research needs is listed in Table B.

Table A. RECOMMENDED RESEARCH PROGRAM

CORE RESEARCH

HIGH-PRIORITY RESEARCH

Materials

- Degradation Mechanisms

- Analytical Methods
- Interface Science
- Polymers for Mirrors*
- Polymers for Transmitters*

Thermal Science

- Optics

- Direct Absorbers

Thermochemistry

- Photochemical Reactions

- Thermochemical Reactions
- Production of Hydrocarbons

Engineering

- Innovative Design and Evaluation

- Solar Chemical Reactor/
Receiver R & D
- Thermodynamic and Economic
Analysis

* The appropriateness or need for government participation was questioned by the panel.

Table B Research Ranking Summary

<u>Research Area</u>	<u>Weighted Score</u>	Number of no's for Screening Criteria***		
		<u>#1</u>	<u>#2</u>	<u>#3</u>
o Photochemical Reaction	715	0	0	1
o Degradation Mechanisms	708	0	1	0
o Innovative Design & Evaluation	701	0	0	0
o Optics	662	0	0	0

o Thermochemical Reactions	649	0	0	0
o Analytical Methods (Materials)	642	0	1	0
o Interface Studies	638	0	0	1
o Polymers for Mirrors*	612	0	3	0
o Thermodynamic Analysis	609	0	0	0
o Polymers for Transmitters*	582	1	4	0
o Production of Hydrocarbons	542	0	1	0
o Direct Absorbers	538	0	0	0
o Solar Chemical Reactor R&D	536	0	0	0

o Thermochemical Water Splitting	500	0	1	0
o Production of Chemicals	463	0	1	0
o Thermodynamics & Economic Evaluation	463	2	0	0
o Windows for Solar Chemical Reactors	461	0	0	0
o Storage Materials	431	1	0	0
o Containment Material	396	0	1	0
o High-Temperature Heat Exchangers	385	0	2	0
o Metallized Glass Mirrors*	377	2	3	1

*Failed the screening criteria. ***No's indicate the number of panelists who felt the research topic failed three screening criteria: 1) long-term, high-risk research; 2) unlikely to be supported by industry; 3) generic research.

Table B (continued)

<u>Research Area</u>	<u>Weighted Score</u>	<u>Number of No's for Screening Criteria</u>		
		<u>#1</u>	<u>#2</u>	<u>#3</u>
o Absorber Coatings*	366	0	3	2
o High Temperature Receiver Research	362	0	0	0
o Thermal Energy Storage	359	1	1	1
o Transmitting Optical Coatings	(350)**	0	1	1
o Thermodisassociation of Water	345	0	0	1
o Heat Transfer Fluids	303	2	2	0
o Salt Gradient Ponds	300	2	3	3
o Heat and Mass Transport	296	0	0	0

*Failed the screening criteria. **Adjusted score. ***No's indicate the number of panelists who felt the research topic failed three screening criteria: 1) long-term, high-risk research; 2) unlikely to be supported by industry; 3) generic research.

RECOMMENDATIONS

In addition to the identification and ranking of research needs, the expert panel wishes to make a number of general or specific recommendations to DOE which they believe will enhance the chances for a successful research program involving top researchers.

1. DOE should commit itself to a long-range program of fundamental research in support of solar thermal technologies. The research program should have a stable budget of at least the present level for solar research within OER and OST (approx-

mately 10M\$) and a horizon of 10 years or more. The important areas to be covered are as indicated above.

2. The goal of the solar thermal research program should be to support the development of technology that will either a) improve the cost effectiveness of concentrating and converting solar radiation, or b) utilize concentrated solar radiation in ways that take advantage of its unique properties to produce fuels or chemicals.
3. The Solar Thermal Technologies Program should renew its efforts to attract top researchers to the programs and should develop policies that will retain a strong following in the research community. To this end, the panel strongly recommends that future research programs be implemented with:
 - o Stability of goals, funding, and leadership;
 - o Selection of research and researchers based, to a far greater extent, on unsolicited proposals of good ideas and a peer review process of evaluation;
 - o A high-level standing panel of independent scientists and engineers to act as a research advisory board;
 - o Management practices that are appropriate for research projects;
 - o Improved lines of communication with the research community - especially with universities, private research organizations, and professional societies.

I. INTRODUCTION

The Office of Program Analysis (OPA) is charged with providing the Director of the Office of Energy Research (OER) with an objective and independent assessment of energy technologies. These assessments allow the Director of OER to fulfill his responsibilities to advise the Secretary of Energy on the conduct of R&D programs in DOE. TPI has been engaged by OPA to assist this process by conducting an assessment, with the advice of a panel of technical experts, of the research needs and priorities within the solar thermal program. The objectives of this program are to identify:

- o research needs by topic and activity,
- o relative priority of research needs,
- o options for performing needed research,
- o potential performers,
- o costs and duration of R&D activities,
- o gaps and duplication in the R&D program, and
- o activities underway that are deemed to be of low priority.

To achieve these objectives a methodology was developed which fully utilized the expertise of the panel members. This methodology is discussed in the following section.

A detailed description of the solar thermal program is not provided in the text of this report. For the reader unfamiliar with the program, material has been provided in a supplemental report comparing the results of this panel to the existing program. This report and the background material developed for the panel are also available from TPI.

II. METHODOLOGY

The methodology used in prioritizing the research needs of the Solar Thermal Technology Program was comprised of the following five activities:

- o Search the literature to identify recent research conducted in the area and to provide an update on current issues.
- o Select the expert panel members.
- o Develop screening and ranking criteria for qualifying and evaluating research activities.
- o Conduct an expert panel review meeting.
- o Prepare findings, conclusions, and recommendations of the expert panel members.

Each of these activities was governed by guidelines defined by the U.S. Department of Energy's Office of Energy Research. These guidelines required that: the information presented be balanced and up-to-date; the panel members have no conflict of interest and be recognized experts in at least one solar thermal technical area; the screening criteria conform to DOE's and the Administration's policies on the appropriate Federal role in energy R&D; the ranking system be developed with the cooperation of panel members; the panel review meeting be conducted without undue influence by outside interests; and the findings, conclusions, and recommendations be based on the information provided by the experts.

This section will provide a summary of the methodology used in developing the findings, conclusions, and recommendations presented in this document.

II.1 Literature Search

A comprehensive literature search was conducted to assimilate the available information on current and recent activities in the solar thermal research areas of thermochemistry, thermal sciences, and materials. The literature search was conducted through a review of program publications, a computerized literature search, and contacts with knowledgeable individuals involved in the Solar Thermal Research Program, and DOE personnel.

Key documents were obtained and used to update previously available information and to provide a basis for developing an up-to-date information package distributed to the experts.

II.2 Experts Panel

The major driving force in developing the findings, conclusions, and recommendation presented in this document was the information provided by a panel of experts. The experts were selected for their breadth and depth of knowledge of relevant research areas and of the solar thermal program. The panel consisted of:

- o Dr. Michael Antal - University of Hawaii
Hawaii Natural Energy Institute (Thermochemistry)
- o Dr. Patrick J. Call - Reference Technology, previously
from the Solar Energy Research Institute (Materials)

- o Dr. Richard Gaggioli - Catholic University
Washington, D.C. (Thermal Sciences)
- o Dr. Roland Winston - University of Chicago
Enrico Fermi Institute (Thermal Sciences)
- o Dr. Mark Wrighton - Massachusetts Institute of Tech-
nology (Photochemistry)

II.3 Screening and Ranking

The assessment of research needs for the solar thermal technology utilized a project scoring method to evaluate current and potential research areas. The evaluation was conducted in two stages.

In the first stage, panel members were asked to indicate with a "Yes" or "No" whether or not they felt each research area passed the following screening criteria:

- o Long-Term, High-Risk Research
- o Not Likely to be Supported by Industry
- o Generic Research

The second stage was designed to provide a comparative measure of priority. A set of weighted evaluation criteria was developed with the help of the panel and used in ranking the proposed research activity. There were six ranking criteria used in measuring the relative importance of each research activity. The weightings are indicated in parentheses.

- o Potential for fundamental technological advances (4)
- o Potential for reducing the use of non-renewable energy sources (3)
- o Potential for improving cost effectiveness (3)
- o Benefit to research cost ratio (2)
- o Probability of success (2)
- o Scientific merit (4)

To obtain the total aggregate score for a research area, the panel scores for each evaluation criteria were added and then multiplied by the weighting. These weighted scores for the criteria were then summed.

II.4 Expert Panel Meeting

Prior to the meeting, the attendees received an information package based on the earlier literature search. The panel was asked to familiarize itself with the issues and the procedures to be used. The topics presented in the information package were explored during the meeting along with the additional topics suggest by the panel. The DOE Solar Thermal Technologies Division provided a program overview of current DOE activities and goals which brought the panel up-to-date on the program. Each research area identified earlier was discussed, screened, evaluated, and ranked. The results of this exercise are presented in the following sections of this report.

III. RESULTS FROM PANEL ASSESSMENT MEETING

It is neither practical nor desirable to attempt to present in this section all of the discussion which took place on each research area. However, key points will be provided to support the rankings. The results are presented for four general research areas: materials, thermal sciences, thermochemistry, and engineering. A very brief description of the research need is given in this section. The background document supplied to the panel contained a one- or two-page "scope statement" containing the rationale, objectives, research description, effort and probable cost of research to meet each of these needs. Detailed scoring matrices are given in Appendix A for each specific research area to allow the reader to appreciate the variance in scores underlying the total aggregated figure. After a discussion of each general research area is presented, broader issues raised by the panel will be presented.

III.1 Materials Research

The specific research areas considered in this category are briefly described below. Because of its importance to solar thermal energy, optical materials research was considered separately.

III.1.1 General Materials Research

- o Degradation Mechanisms

This area involves the fundamental studies of the change of material characteristics due to interactions with the environment as a function of time. In particular, the effects of radiation, temperature, oxidation, hydrolysis, etc. on the material's ability to fulfill its function is of interest. Durability is a key issue related to degradation.

- o Analytical Methods

Research into methods of visualizing, measuring, and characterizing the fundamental character of materials and especially material interfaces and their interaction with light.

- o Interface Studies

Includes the fundamental physics of interfaces between solids, liquids, and gases. Some overlap with degradation mechanisms.

- o Storage Materials

Research into materials for both sensible and phase change heat storage. Investigation of heat transfer mechanisms, cyclic effects, crystallization mechanisms, etc.

- o Containment Materials (High Temperature)

The study of ceramics, composites, etc. for use in the containment of high temperature corrosive fluids or chemicals.

- o Heat Transfer Fluids

The study of oils, salts, liquid metals, steam/water, and gases for use in industrial process and power cycles. Specifically includes the study of thermodynamic and transport properties as well as corrosion and erosion.

Of the six research areas described above, only one did not appear to meet the screening criteria. The panel gave a total of four "No's" to Heat Transfer Fluids research indicating the panel's belief that (1) industry will probably carry out the necessary research, or (2) the research is not long term or high risk. The other areas all received only one "No" on the screening criteria.

"Degradation Mechanisms" stood out as a clear priority research area within this group with an aggregate score of 708 (see Table 1). The raw scores (Appendix A) indicate a uniform agreement among panel members that this is a high priority area. The next two areas in Table 1, "Analytical Methods" and "Interface Studies," have weighted scores which would indicate a mid-range priority. The raw scores for both areas show wide disparity in the scoring by individual panelists, with scores ranging from 10 to 0 on the same evaluation criteria. The discussion revealed that some of the low scores for "Interface Studies" were a result of the assumption that these topics were a part of "Degradation Materials."

Table 1. General Materials Research

<u>Research Area</u>	<u>Weighted Score</u>	Number of No's for Screening Criteria		
		<u>#1</u>	<u>#2</u>	<u>#3</u>
o Degradation Mechanisms	708	0	1	0
o Analytical Methods	642	0	1	0
o Interface Studies	638	0	0	1
o Storage Materials	431	1	0	0
o Containment Material - High Temperature	396	0	1	0
o Heat Transfer Fluids	303	2	2	0

The remaining three research areas all dealt with more applied research problems which were considered lower priority by the panelists. The research requirements in these areas appear to be a strong function of the operating temperature of the solar collector. As will be discussed in a later section, the panel did not agree on establishing a 2000 F temperature goal for solar thermal collectors and, therefore, many of the potential problems with materials for storage, containment, and fluids in the 2000 F range would not be of interest.

The major emphasis in the materials area was that more basic materials research was needed in the degradation of materials due to exposure to the unique environments of a solar thermal application. It was felt that research into "Degradation Mechanisms" might help bridge the gap between basic energy sciences and solar thermal R&D. It was pointed out that there should be a community

of fundamental researchers dealing with specific technical applications. Coordination with other programs, such as the materials programs of BES and other non-energy technologies, is imperative.

III.1.2 Optical Materials Research

Seven additional materials research needs are evaluated within this category. A brief description of each of the areas is presented below.

- o Polymers for Mirrors
Development of polymer-based mirrors of high efficiency, long life, and low cost. Includes metallized plastic films and protective covering films.
- o Polymers for Transmitters
Includes the development of coatings, adhesives, laminates, copolymerization, additives, etc. for the improvement of the performance of polymer transmitters.
- o Direct Absorbers
Investigation and development of materials used for the direct absorption of high-flux radiation and heat transport. Includes absorbing liquids, particles in gas streams, etc.
- o Windows for Solar Chemical Reactors
Development of window materials which can withstand extremely high radiation flux densities and harsh environments.

- o Metallized Glass Mirrors
Research into the use of thin glass, durability of coating, cleaning, and interface research and development of low-cost alternatives to silver with comparable life.
- o Absorber Coatings
Development and testing of selective surface coatings which can withstand the high temperatures and cycling heat fluxes while providing high efficiency and long life at low cost.
- o Transmitting Optical Coatings
Includes IR and AR coating materials for both glass and polymers.

A number of research areas under Optical Materials Research had serious problems with the screening criteria. Four out of the seven areas had three or more "No's" for a single screening criterion. Two of these, "Polymers for Mirrors" and "Polymers for Transmitters," were the two top ranking research areas in the category. Both had three or more "No's" in the second screening criterion, "Not Supported by Industry," indicating that the panel thought that industry would probably do the R&D without government support. The other two areas, "Metallized Glass Mirrors" and "Absorber Coatings," scored quite low in the ranking and failed to pass the screening criteria, again primarily because of industry activity or potential activity in these areas.

There was not an area of research in this category which scored high enough to be considered a clear standout (see Table 2). Three areas received high scores indicating interest by the

panel, but, as discussed above, two of these failed to pass the screening. The third area, "Direct Absorbers," passed the screening criteria and scored relatively high. However, discussions revealed skepticism with regard to potential applications although scientific merit was considered high.

Research on "Windows for Solar Chemical Reactors" received a moderate aggregate score, although there was wide disagreement on the need for further research in this area. The panel apparently felt that the need for window research and development was based on the premise that attractive processes for producing fuels and chemicals through the direct application of solar radiation, or that production of high temperature working fluids for power production through direct absorption, will require high-temperature, high-flux windows. The research would probably have ranked higher if the panel had greater confidence in those applications. There was also some belief that many of the research objects had been, or would be, met by laser or other military research programs.

Table 2. Optical Materials Research

<u>Research Area</u>	Weighted <u>Score</u>	Number of No's for Screening Criteria		
		<u>#1</u>	<u>#2</u>	<u>#3</u>
o Polymers for Mirrors	612	0	3	0
o Polymers for Transmitters	582	1	4	0
0 Direct Absorbers	538	0	0	0
o Windows for Solar Chemical Reactors	461	0	0	0
o Metallized Glass Mirrors	377	2	3	1
o Absorber Coatings	366	0	3	2
0 Transmitting Optical Coatings	280 (350)*	0	1	1

*One panel member did not provide scores. (Adjusted Score.)

The remainder of the research areas (Metallized Glass Mirrors, Absorber Coatings, and Transmitting Optical Coatings) received very low scores and did poorly on the screening criteria.

III.2 Thermal Science Research

Six areas of research were evaluated in the category of Thermal Science Research.

o Optics

Includes new applications of reflecting, refracting, and defracting optics, such as holographic concentrators, non-imaging concentrators, and dichroic mirrors. Also includes the development of instruments and techniques

for measurement of optical properties and radiation fluxes.

- o High Temperature Heat Exchangers
Includes all work attendant upon developing highly effective, reliable, low-maintenance heat exchangers for high-temperature applications which would include research on surface fouling, heat transfer enhancement, direct contact heat exchange, etc. and would not be limited to the solar receiver.
- o High Temperature Receiver Research
Includes development of basic heat transfer and fluid flow information for a variety of receiver configurations including parallel tube sheet receivers, cavity receivers, direct absorber receivers of both gas and liquid types, and innovative designs.
- o Thermal Energy Storage
Includes the study of all methods of thermal energy storage (latent, sensible) for high temperature applications.
- o Salt-Gradient Solar Ponds
Includes the investigation of the characteristics and control of ponds. Research will be directed primarily at understanding the basic hydrodynamic, optics, and diffusion processes in large area ponds.
- o Heat and Mass Transport
Includes the study and development of advanced techniques for the transport of energy at high temperatures.

Of the six research needs identified in this section, only "Optics" received a high score. Of particular interest to the panel was the development of optical analysis and design methods which could potentially allow design of concentrating structures of four times more concentration than permitted by conventional ray tracing techniques. Improved design techniques could also reduce accuracy requirements for the mirror structures and mechanical components thus, achieving current performance at lower costs. Although Optics Research was given a high score, it was pointed out that holographic imaging had been shown to be impractical and should not be pursued.

The remaining five areas within Thermal Science Research all received quite low scores. There was some concern about industry involvement regarding the development of high temperature heat exchangers. It was also pointed out that if temperatures became too high, heat exchangers would probably be avoided anyway and direct absorption systems developed.

Table 3. Thermal Sciences Research

<u>Research Area</u>	<u>Weighted Score</u>	Number of No's for Screening Criteria		
		<u>#1</u>	<u>#2</u>	<u>#3</u>
o Optics	662	0	0	0
o High-Temperature Heat Exchangers	385	0	2	0
o High-Temperature Receiver Research	362	0	0	0
o Thermal Energy Storage	359	1	1	1
o Salt-Gradient Solar Ponds	300	2	3	3
o Heat and Mass Transport	296	0	0	0

"High Temperature Receiver Research" raised the issue (again) of the desirability of the 2000 F temperature goal. Panel members felt that the applications at these temperatures may not be appropriate for solar. The issue was also raised as to whether Solar Thermal should be investigating medium-high temperatures as well as high temperatures. There was significant disagreement as to whether industry is in fact doing (or will do) this work.

"Thermal Energy Storage" and "Heat and Mass Transport" both received low scores. Although an understanding of these areas is important, it was felt that they had little to offer to high temperature applications. Some engineering work may be required.

"Salt Gradient Ponds" was discussed as a research area, but there was some disagreement as to the appropriateness of this topic in the Solar Thermal Research Program. The area in general received very low scores, as the panel felt that little research was required. It also clearly failed the screening criteria, primarily because of the level of work required to improve the technology (demonstration, engineering), and because the technology appears to be commercially viable (at least in Israel).

III.3 Thermochemistry Research

There were six research areas discussed under this category. Each is briefly discussed below followed by a discussion of the rankings.

- o Photochemical Reaction Studies

- Includes basic studies of the interaction of light with matter to produce chemical changes. Ultimately, this may lead to the identification of attractive means of

producing useful fuels or chemicals from sunlight and abundant feedstock. This could also include photoelectrochemical reaction in cell and colloidal suspensions, and photobiology.

- o Thermochemical Reaction Studies

Includes the identification and evaluation of thermochemical reactions that could beneficially employ solar heating to produce useful fuels or chemicals and the laboratory research necessary to establish the applicability.

- o Production of Hydrocarbons

Includes the thermochemical production of hydrocarbon fuels from sunlight and a variety of feedstocks such as coal, CO₂, and biomass.

- o Thermochemical Water Splitting Processes

Includes development of the processes, systems, and subsystems for the production of hydrogen from multistage, multitemperature chemical reaction.

- o Production of Chemicals

Includes solar thermal driven reactions that could be used for the production of a variety of chemicals, compounds, and metals. The high-temperature clean reaction zone of a large solar furnace may be attractive for producing high-value materials.

- o Thermodisassociation of Water

Includes the development of materials and processes for the separation of hydrogen high-temperature disassociation mixtures.

None of the six research areas described above had significant difficulty with the screening criteria (Table 4). "Thermodynamic and Economic Evaluation" was not considered to be of high risk or long term by two panel members, and all other areas received no more than one "No."

The area "Photochemical Reaction Studies" received a very high score (Table 4). The group agreed that this is a long-term, basic, exploratory-type research area that should be pursued. The fact that photochemical reactions are uniquely dependent upon solar radiation makes the research deserving of more attention. The specific types of photochemical reactions which are worthy of support cannot be specified at this point as they will depend upon the early findings of this exploratory work.

Two other areas received fairly high scores: "Thermochemical Reactions Studies" and "Production of Hydrocarbons". The highest by far of these was "Thermochemical Reactions Studies" which was considered to be of high scientific merit but perhaps of lower potential for success. Research in this area is also not unique to solar, and the panel felt that it should be pursued elsewhere as well.

"Production of Hydrocarbons" is essentially the production of fuels. Some members of the panel felt that the use of solar to convert feedstocks to fuels would be an inefficient use of the feedstock. The interest in this area is in those high-temperature, high solar flux processes which are possible because of solar thermal's unique resource characteristics that have not been discovered yet.

The remaining four research areas, "Thermochemical Water Splitting Process," "Production of Chemicals," "Thermodynamic and

Economic Evaluation," and "Thermodisassociation of Water," all received low scores. Water Splitting was considered an inappropriate use of solar and is based on the hydrogen concept which several members do not support. "Production of Chemicals" included both fuels and special chemicals. However, for high-cost, special chemicals, solar is not of interest by producers. Therefore, the area boiled down to fuel production, which has been treated before.

Table 4. Thermochemistry Research

<u>Research Area</u>	Weighted <u>Score</u>	Number of No's for Screening Criteria		
		<u>#1</u>	<u>#2</u>	<u>#3</u>
o Photochemical Reaction Studies	715	0	0	1
o Thermochemical Reaction Studies	649	0	0	0
o Production of Hydrocarbons	542	0	1	0
o Thermochemical Water Splitting Processes	500	0	1	0
o Production of Chemicals	463	0	1	0
o Thermodisassociation of Water	345	0	0	1

The final area was Thermodisassociation of Water. The low scores reflect a skepticism as to the potential for this approach in generating hydrogen, and again, the viability of a hydrogen economy in general.

III.4 Engineering Research

The three research topics discussed in this section were actually discussed by the panel as part of the three preceeding headings. They are presented here because the panel felt that the work required would add to the fundamental base of engineering knowlege.

- o Innovative Design and Evaluation
Includes research, development, and evaluations of new approaches, configurations, and concepts for more efficient or cost-effective components, subsystems, or systems to transform solar energy into useful thermal energy (exergy). Collectors, receivers, heat exchangers, and heat engines could be included.
- o Thermodynamic and Economic Analysis
Includes the analysis of open and closed systems using First and Second Law analyses, the identification and reduction of irreversibilities, and the thermodynamic and economic optimization of processes and options for the production of process heat, electrical power, fuels, and chemicals from solar.
- o Solar Chemical Reactor Research and Development
Includes the conceptual design and feasibility analysis or verification of reactor/receivers required for attractive thermochemical or photochemical processes.

One area of research in Thermal Sciences received a very high score: Innovative Design and Evaluation (Table 3). There were no problems with the screening criteria for this area. The high

scores reflect the panel's support for research which emphasizes innovation/creativity. It was pointed out that the current approach of issuing PRDA's to solicit innovative ideas is not conducive to quality research, as it encourages the proposal of ideas at a particular point in time. In contrast, a quality research program should rely more heavily on unsolicited proposals which truly represent creative and new ideas.

Two activities related to thermodynamics and economic analysis were discussed and ranked: one, originally in the "Thermal Science" category titled "Thermodynamic Analysis," and one, originally in the "Thermochemistry" category entitled "Thermodynamic and Economic Evaluation". The scores of these two activities are shown separately in Table 5, but they are so closely related that they will be united here and in subsequent discussions.

"Thermodynamic analysis" received a high score, although a significant disparity in scores existed. Most panel members agreed that the detailed analysis, especially Second Law analysis, of the various components of the entire system offers considerable potential for overall performance improvement.

"Thermodynamic and Economic Evaluation" was strongly supported by some panel members and strongly opposed by others. The latter felt that the technology could not be advanced through analysis. The supporters felt that systems could greatly benefit from more rigorous analysis. It was agreed that much of this work was more appropriately categorized programatic analysis and should be pursued in the technology development program. Only novel analysis methods should be pursued as research.

"Solar Chemical Reactor Research and Development" received a high score as well as a considerable amount of discussion. The problems in this area were not clear to all members of the panel. It was pointed out that the design of the reactor is critical to the success of the reaction even if the chemical reactions are well understood. A good reactor must avoid losses, uneven temperatures, transient effects, and ensure that all the solar energy is deposited onto the particles, heat transfer and mass transfer rates, etc. The panel agreed that this was important engineering research. The panel emphasized that this research should not be accomplished by issuing a PRDA and allowing large organizations to perform large-scale research without innovative ideas. It was also recommended that the research be several projects at the \$50,000 to \$100,000/year level and not be a large-scale intensified activity. It was suggested that the research might be too chemical-reaction dependent, but panel members indicated that generic reactor design and research was possible.

Table 5. Engineering Research

<u>Research Area</u>	Number of No's for Weighted Screening Criteria			
	<u>Score</u>	<u>#1</u>	<u>#2</u>	<u>#3</u>
o Innovative Design and Evaluation	701	0	0	0
o Thermodynamic Analysis	609	0	0	0
o Solar Chemical Reactor Research and Development	536	0	0	0
o Thermodynamic and Economic Evaluation	463	2	0	0

IV DISCUSSION

The assessment of research needs for solar thermal technologies, as described in preceding sections, resulted in a set of research activities placed in order of importance to satisfy those needs. It also resulted in a number of recommendations regarding the appropriate goals and objectives for a solar thermal research program and some suggestions for implementing the program in order to assure high quality research. This section discusses the research panel's thinking on the major goals and objectives, discusses the activities appropriate to the highest ranked research needs, and concludes with a brief discussion of the processes and procedures the panel feels will enhance prospects for success.

IV.1 Research Goals and Objectives

o Program Goals

It was obvious that the panel often disagreed with the program goals. In particular, most members questioned the reasonableness of a high temperature (2000 F) goal, and several did not accept the general concept of a hydrogen economy.

The 2000 F goal, although conducive to higher conversion efficiencies of developed systems, seemed to be in conflict with the electric utility established temperature range of 800-1200 F, a result of extensive utility research programs which would also benefit from higher cycle temperatures. The concern was that the high temperature would dictate research areas which had little potential for success and draw resources from the

solar unique problems which must be overcome first, such as cost per unit energy delivered to the receiver.

The hydrogen economy has been long debated. This panel, in general, supported the view that this was not a realistic long-term fuel except, perhaps, for aircraft applications. Therefore, research areas which primarily focused on the production of hydrogen were downgraded.

In a broader sense, the panel discouraged the establishment of quantitative goals but supported the formulation of stable, long-range goals which will provide guidance and confidence to researchers.

IV.2 Research Needs and Appropriate Activities

The assessment of research needs was originally subdivided into three disciplines: materials research, thermal science research, and thermochemical research. During the course of the investigation and the panel deliberations, it became clear that thermochemistry should really be broadened to include photochemistry (and possibly photoelectrochemistry), and that there are important areas of research that are better characterized as engineering research. We have, therefore, divided the discussion and recommendations into four research headings: materials, thermal science, chemistry, and engineering. In each case it might be appropriate to affix the adjective "solar." As it turned out, the research panel ranked one need from each of these categories in the top four. It is evident that the activities that will address these research needs should form the core of the solar thermal research program. They are therefore discussed as a group, i.e., the "core" research. In the remainder of this sec-

tion, the next nine or ten of the highly ranked needs are discussed in the four categories described above.

IV.2.1 Core Research Activities

o Photochemical Reaction Studies

The continuation of long-term, basic, exploratory research received the strongest support from the panel and has been highly ranked in previous assessments. The rationale for this ranking is that the research could broaden the range of applications of an economically viable solar thermal technology, is unique to solar, has high scientific and research content, has reasonable prospects for success, and can be conducted at a low funding level.

Additional justification and more detailed description of the appropriate research activities can be found in the scope statements and supporting documents compiled as background information for the panel. Briefly, however, this activity includes research to understand the combined effects of light and thermal energy on chemical feedstock materials to drive reactions that might yield fuels such as hydrogen, methane, or ethanol; allow energy storage in chemical form; or produce valuable chemicals in industrially attractive processes. Industrially attractive reactions have not been identified to date, but the fact that photosynthesis is the basis of natural conversion of CO₂ to energy-rich carbon compounds suggests that industrial and commercial processes are possible.

The level of research envisioned at this time is quite modest: perhaps 400K per year. The nature of the research is highly exploratory and could take many paths. At this time the critical research issues appear to be those associated with improving the solar response, controlling the back reaction of energetic photoproducts, and finding mechanisms that employ two or more light quanta per fuel molecule to increase the overall solar efficiency.

The solar response of inexpensive, but nearly transparent, starting materials such as water or CO₂ might be achieved by adding sensitizing agents that absorb strongly in the solar spectrum and subsequently channel energy efficiently into chemical reactions in a manner analogous to chlorophyll. The back reaction, which causes the product chemicals to revert to their original state, might be controlled by building in kinetic barriers to retain the thermodynamic dis-equilibrium long enough to allow separation and collection of the desirable products. Multi-photon reactions may require the addition of sensitizing systems that assure a greater utilization of the solar spectrum.

o Degradation Mechanisms in Materials

As a class, materials research was considered most essential to the ultimate success of solar thermal technologies. The underlying reason is that solar equipment, collectors in particular, can only be made cost effective by reducing the amount of material required for construction or by substituting low-cost materials. Both strategies place great demands on the material sciences to characterize the behavior of materials exposed to

solar environments and to understand the limitations so that design safety factors can be reduced without unnecessary failures. This allows material properties to be improved where needed. In the past, all parts of the solar energy program have devoted resources to exposure testing of a wide range of materials, and a fairly extensive database of short-term solar radiation and environmental damage has been developed. However, there has never been a sustained effort to quantitatively understand the physical and chemical changes that occur in materials as a result of such exposure and to relate these changes to the observable changes in material properties.

The understanding of the photodegradation process clearly holds the key to the development or adaption of materials that are stable under exposure to ultraviolet light. Although there has been considerable research in recent years on photodegradation mechanisms in general, there is little information of specific polymers or other materials of interest in solar equipment. Since basic material research programs tend to support the fundamental study of damage mechanisms, it is important for solar research to concentrate on degradation issues that are unique or essential to solar applications. For example, the influence of additional types of stress--high temperature, mechanical stress, dimensional cycling, moisture, etc.--on the UV degradation of polymers is known to be important. Similarly, the degradation of surface properties, including optical properties, of materials subject to solar condition is important.

Even when the mechanisms leading to microscopic damage are understood, it is not generally possible to correlate the microscopic damage with observable macroscopic changes. Such correlations are essential to the successful prediction of service life or design limitation of many materials on the basis of theory or accelerated testing.

Care must be taken to assure degradation mechanism research undertaken by the solar thermal program is germane to solar equipment and essential to advancing the technology. The program cannot afford a truly basic, unconstrained, research effort.

o Innovative Design and Evaluation

The need for research that leads to improved cost effectiveness of solar thermal equipment, especially the solar collectors, has been recognized as paramount by every group that has studied the technology. Economic viability of solar thermal technology will require a number of substantial advancements, but it is clear that the greatest strides must be made in reducing the cost of the collector fields. Current collector designs represent fairly mature and sophisticated engineering, and although costs can be reduced by the economics of mass production and to a degree by engineering refinement, analysts who have examined the requirements for economic success find that these measures may fall short of the necessary cost goals by a factor of two. In order to reduce installed collector costs to something approaching 50 \$/m² will require substitution of materials and innovative design. Material substitution alone is not likely to be successful. There is therefore a real need

to find new ways either to utilize low cost materials in ways that retain high performance or to reduce greatly the amount of material required for essential functions. Both approaches require great leaps in engineering that must be born of creative ideas and forged into practice by thorough research and methodical evaluation.

It is impossible to site examples of the kind of creative thinking that is needed, but one might draw the analogy to the development of ultralight aircraft construction personified by the "Gossamer" series of human-propelled flying machines. Dr. Paul MacReady and his research team proved that strong, light-weight structures could achieve man's age-old dream of self-powered flight. The requirements for solar technology innovation are no less demanding.

Very light-weight structures can be made to assume the precise geometrical configuration required for high-concentration optical systems through careful balance of stresses in tensile members and beams--as in an umbrella--but they must also withstand environmental stresses, remain dimensionally stable for long periods, preserve simplicity and economy of production, and have long lives or low parts replacement costs. Design approaches might include structures that adapt to, rather than resist, forces such as wind, hail, and snow loads; designs that achieve high concentrations through innovative optical design rather than precise surfaces and accurate tracking; designs that allow larger concentrator areas to be driven and controlled by a control device; or immense concentrators made of thin films to be deployed in space. The alternative approach of find-

ing design approaches that allow very inexpensive materials to be substituted for costly ones may also lead to cost breakthroughs. Designs using natural or low-energy products may also have the potential of affecting significant cost reductions without intolerable sacrifices in performance or durability.

The program should always be receptive to good ideas regardless of origin, but the objectives of this type of conceptual research and design evaluation may require a center which maintains a critical mass of talent, resources, and evaluation capability. The total investment in this research will likely be larger than for many of the other research areas in the core program.

o Optics Research

In the opinion of some experts who have reviewed the research needs of solar thermal technologies, the field of optics offers an untapped potential of possible breakthroughs. The argument is that perfect devices, designed according to the rules of classical optics, achieve only a fraction of the thermodynamic limits for concentration or maximum temperature. Techniques are now known that permit much closer approaches to the thermodynamic limit, and there is reason to believe, or hope, that future optic research may open up unforeseen options that would allow either higher performance or less rigid requirements, mirror structure and mechanical components, or both. The pursuit of such breakthroughs was judged to be highly appropriate and beneficial for the solar thermal technologies.

The nature of the research required is, once again, exploratory and encompasses the field of mathematics as

well as physics. It has been pointed out that a parabolic reflector designed according to the classic laws of geometric optics achieves only $1/4$ the thermodynamic limit, i.e. the maximum concentration permitted by the Second Law of Thermodynamics. It is known that the fraction can be improved to $1/2$ through the use of secondary concentrators designed according to the techniques of non-imaging optics. Methods of achieving the full thermodynamic concentration are not known, but are not precluded by physics or mathematics. While the result of this line of research may not be the development of high concentration ratio collectors to achieve super temperatures (the apparent sun surface temperature as seen from earth is about 7000K), a better understanding of optical design could relax the accuracy requirements on the surfaces of reflecting structures of modest concentration ratio to the point where less expensive fabrication methods could be used.

This research, like the search for attractive photochemical reactions, should be dictated by the good ideas available rather than by a specific research objective or budget allocation. Initially, it might be difficult to find more than a handful of researchers who can contribute new ideas in this classical field.

IV.2.2 High Priority Activities to Supplement the Core Research

The research needs discussed below were rated by the panel as only slightly less important than those in the core group. Activities related to meeting these needs would very likely be a part of a comprehensive research program, which might also in-

clude unranked or lower ranked research activities resulting either from programatic necessities or from the presentation of promising proposals.

IV.2.2.1 Materials Research

- o Analytical Methods

Closely related to the need for an understanding of the degradation mechanisms and the effects of solar radiation and the environment on the performance characteristics of materials is the need to develop analytic methods capable of detecting microscopic and subtle macroscopic changes. Although the topic is broad enough to include research into all methods of visualizing, measuring, and quantifying the fundamental character of materials and material interfaces, it is understood that the research objectives would be to quantify the changes that occur when materials and interfaces interact with light. The work would be largely related to and supportive of the research on degradation.

- o Interface Science

Phenomena associated with interfaces are fundamental to virtually all aspects of solar technology. Optical properties are intrinsically surface phenomena--i.e. associated with the solid-gas interface; corrosion is an interface phenomena involving solid-liquid interfaces; and heat, mass, and momentum transfer phenomena occur at solid-liquid, solid-gas, liquid-liquid, gas-gas, and gas-liquid interfaces. Chemical activity and catalytic activity are usually related to surface phenomena at

various types of interfaces. Solar technology needs are largely related to the improvement of surface properties and the reduction of surface degradation, and therefore, research activities should be selected accordingly.

o Polymers for Mirrors

The need for inexpensive, light-weight, highly-reflective, metallized polymer films for the construction of cost-effective collectors has already been discussed. Silvered polymer films are available but are currently expensive and of uncertain durability. The main research requirements are: to characterize the degradation of silvered surfaces in order to screen potential polymers and processes and to identify the important environmental stresses (moisture, UV, pollutants, abrasive particles, etc.); to develop an understanding of the silver polymer interface and to pinpoint key parameters affecting lifetime; and to develop protective coatings for both the front and back surfaces in order to protect the silver layer.

It is expected that industry will take the lead role in development of new polymers and processes. The government program should be restricted to stimulating that development by providing scientific evaluation and feedback at a research (rather than product) level.

The nature of the research required is such that there must be some continuity of effort and funding over a period of several years.

o Polymer Transmitters

High-transmissivity, low-cost, low-weight, long-lived materials are needed for mirrors as protective overcoats; for protective bubbles over heliostats, dishes, and other reflectors; and as glazings for receivers in various types of collectors. Current polymers that are stable in the outdoor environment are typically expensive fluorocarbons. Research directions that should be followed include developing additives or coatings that can protect less expensive polymers from UV damage; lamination of UV resistant polymers with high strength substrates; and the development of new, UV resistant polymers--probably in that order. This research is obviously closely related to work on materials degradation and interface studies, and may be a necessary precursor to the development of polymer mirrors.

IV.2.2.2 Thermal Science Research

Two of the research needs that were originally included in this subheading, Innovative Design and Evaluation, and Thermodynamic Analysis have been moved to the engineering heading. Optics Research was ranked among the first four research needs and has already been discussed under the Core Research section. Thermodynamic Analysis will be discussed in Section IV.2.2.4. The only research need that remains to be discussed in this section is one that was originally categorized as material research. The research on Direct Absorbers involves the fundamental interaction of light with matter, as well as the heat, mass, and momentum exchange between solid or liquid particles and a moving gas, and may involve chemical reaction as well. This complex topic is more appropriately treated as thermal science research.

There are several basic motives for seeking to absorb the solar energy in the working fluid of the process: one is to eliminate or minimize the temperature difference required to transfer heat from the receiver to the working fluid and thereby minimize the entropy production; a second is to take advantage of either photosensitive processes within the working fluid or chemical and/or thermal disequilibrium to drive chemical reactions in the desired direction; still another is to achieve a working fluid temperature higher than the safe operating temperature of structural materials.

The research objectives should be to identify and exploit situations where the availability of a concentrated flux of photons can be used more advantageously than by absorption on an intermediate surface. Coupling this research with the search for attractive photochemical reactions is obviously important.

IV.2.2.3 Thermochemistry Research

Photochemical research was the highest ranking research topic in this category and has already been discussed. The other high-ranking research needs included Thermochemical Reaction Studies and Production of Hydrocarbons, which will be discussed below, and finally, Chemical Reactor Research and Development, which will be discussed in the engineering section.

- o Thermochemical Reaction Research

Research is needed to identify reactions which take advantage of unique properties for use in solar thermal energy systems and to prove their applicability. Studies to date have not identified economically viable

applications of known thermochemical reactors or new reactions with economic potential. The generalized benefits to be derived from commercially successful development, ie. energy transport and distribution, energy storage, augmented heat transfer, and heat pumping, are so significant that it is too soon to "write off" the search or to pursue development based on reactions that appear to have limited commercial potential.

This is also a need that requires exploratory research to identify promising reactions, but there may also be merit to a systematic evaluation of the most promising known systems to see if the barriers can be removed by innovative application of solar energy.

o Production of Hydrocarbons

The production of hydrocarbon fuels such as methane and ethane from abundant and inexpensive feedstocks such as coal, CO₂, peat, and other biomaterials is viewed as an attractive area for solar thermal research because of the possibility of finding processes in which the direct application of sunlight offers unique advantages. Advantages might result from the very rapid heating that could be achieved in a highly concentrated beam of sunlight or as a result of some photochemical reactions. It is clear that this research area is closely related to photochemical and thermochemical reaction studies, to solar chemical reactor R & D, and to direct absorption research. Although research in any of these areas could proceed independently, interaction and coordination is highly desirable in the short term and essential in the long term.

IV.2.2.4 Engineering Research

Although engineering research was not included in the original scope of the evaluation, it became evident that there are real and important technological problems and needs that cannot be met without advances in engineering and design based on sound research. The innovative design and evaluation of new concepts in the concentration and collection of solar radiation has already been discussed as a part of the core research activities. Two additional research needs were regarded as more closely identified with engineering than the other disciplinary categories. They are the research and development of solar chemical reactors and the continuing analysis of solar thermal system thermodynamics and economics.

- o Solar Chemical Reactor R & D

Thermal or photochemical solar reactor/receivers will differ enormously from the boilers, molten salt, liquid metal, or air-cooled Brayton Cycle receivers that have been developed as part of the solar thermal power program.

Thermochemical reactors could be of fairly conventional design, but would have to provide the proper environment for the high-temperature chemistry to occur. This could require careful tailoring of the temperature field, the residence time of the reactants, the location and distribution of catalytic surfaces, the fluid mechanics of the reactants and/or carrier fluids, and the heat transfer processes within the reactor as well as the sound engineering of the structure of the reactor and the proper selection and engineering of materials that

will withstand imposed structural and thermal stress, thermal cycling, and corrosion. As temperatures increase, the use of brittle structural materials--i.e. ceramics, non-metallic, and composites must be considered.

Photochemical reactors and reactors that utilize direct absorption also require provision for the interaction of the concentrated light with the reacting materials or entrained particles. Refractory or air windows must be provided and must be capable of transmitting very high energy fluxes at high temperatures without excessive optical or material losses.

Since it is not yet clear what chemical system and what cycles are likely to be pursued, the research on receiver/reactor design should remain generic, or, at least, should address the problems that will be common to a variety of processes. It might be well to include a review of some of the work that was done in the sixties on high temperature nuclear reactors for propulsion and power applications, the Russian literature and the laser literature. Initial research should be conducted at a laboratory scale, although it is recognized that scale up to commercial size may require several steps.

o Thermodynamic and Thermoeconomic Analysis

Energy technology oriented programs, even those devoted primarily to fundamental long-range research, should be guided by meaningful analysis and interpretation of the programs, accomplishments, and options. This is especially important in the solar thermal energy research program because the utility of the research

eventually depends upon the commercial success of the technology. In our volatile energy economy this requires assessments and projections of the importance of technical developments under condition of highly uncertain market and economic factors. Obviously such analysis should be a part of the technology development program, but research to improve the methods of analysis to make them more useful, reliable, and meaningful should be pursued as a part of the research program.

In particular there is a great need, which applies to all facets of energy analysis and policy, to analyze thoroughly the thermodynamic consequences of energy options from the viewpoint of the Second Law as well as from the First. The use of exergy (available energy or available work) as the quantity of economic value can not only make an enormous difference in the way resources are allocated, it can also reveal serious defects in cycles or processes that may have simple connections or alternatives. The method and units of thermoeconomic accounting can make a tremendous difference in the choice of investment both in capital and research effort. A major objective of the research or thermodynamic and economic analyses for solar thermal energy conversion should be to put the analysis on the soundest possible basis, and to show how complete thermodynamic analysis can pinpoint critical problems and research needs. This is a research need that requires broad programatic support and continuity, but need not use a large fraction of program resources.

IV.3 Research Program

In the past, most of the Solar Thermal Technology Program efforts have been aimed at rather short-term development as a commercialization objective. Research has been undertaken, but only in a highly directed, programatically constrained, and time-limited context. The research needs that have been identified in this assessment are of a more fundamental character and presumably require a program with longer range objectives and more research oriented planning, management, and administration. The evaluation panel, whose members came primarily from the research community, was very outspoken on the need to establish new procedures for implementing the solar thermal research program that would assure attraction of top researchers, encourage creative thinking and submission of good ideas, and permit researchers to devote their talent and effort to the research. Some of the ideas brought up in the panel meeting are discussed below.

- o Planning and Goals

The panel felt the goals for the research programs should be more general and long range than the goals for the technology program. The panel discouraged the establishment of too many specific quantitative goals, e.g. develop a 20 year polymer mirror, but did endorse a few broad long-range goals as ultimate program objectives, eg. .70 \$/peak watt photovoltaic cell or how to concentrate sunlight to produce intermediate-to-high temperatures. Long-term, stable, sensible programatic goals build confidence in the research community.

Similarly, planning should be long term, stable, and broad base. Research breakthroughs cannot be scheduled. Research areas of interest should be identified and made

known to the research community in an interactive process. Periodic review of research accomplishments and opportunities should be as important as identification of programatic needs.

It was suggested that the formation of a high-level standing panel of independent scientists and engineers to act as a research advisory board (and perhaps as peer reviewers) might contribute to the stability and scientific stature of the program.

o Program Implementation

The panel held very strong views on the proper selection and implementation of research work and researchers. It felt that solicitations, i.e. PRDAs, RFPs, etc., for research work stifle creativity and tend to reward the skillful proposal writer rather than the more imaginative and capable investigators. The panel repeatedly expressed its conviction that only broad research areas should be defined and that the actual program content and funding should be determined by the availability of good ideas and capable researchers. The selection process should be much more receptive to unsolicited proposals, and all funded work, including that of the national laboratories, should be subjected to peer review prior to initiation and at periodic intervals, or as it is renewed.

Multi-year funding was also considered to be a necessity to avoid the dissipation of research effort that frequently accompanies the annual struggle for continuation.

- o Research Management

The panel pointed out that a long-term research program should not be expected to contribute to scheduled technology development goals and therefore should not be expected to produce frequent progress reports or meet a milestone schedule. These activities frequently detract significantly from the time available for top researchers to conduct or guide research. The National Science Foundation and the Office of Energy Research's Office of Basic Energy Science were frequently mentioned as role modes for both management and implementation.

- o Quality Assurance

The only way to assure top quality research is to attract the best research talent. Most of the suggestions above have that objective. Perhaps the paramount requirement, however, is to establish a stable program that will allow researchers to pursue long-term, sophisticated research which frequently requires costly facilities, equipment, and specialized knowledge that simply cannot be turned on and off according to yearly fluctuations in program management or funding.

V. CONCLUSIONS

The ranking of the research areas within each category has already been discussed. Here we present an aggregated ranking for all four categories. One recommendation by the panel was that we limit the number of high priority research areas which would allow the focusing of limited funds on the most important areas. In line with this recommendation we have identified only four very high priority areas:

- o Photochemical Reaction Studies
- o Material Degradation Mechanisms
- o Innovative Design and Evaluation
- o Optics Research

Specifically, the program should encourage research in the evaluation of photochemical reactions which take advantage of the unique properties of high-flux radiation; develop a better understanding of degradation mechanisms in materials, particularly polymers promote the development of innovative designs in solar thermal components and systems; and investigate the fundamental optical design and analysis of solar concentrators.

In addition to these prime candidate areas, ten other areas were identified as having high priorities, although two of these failed to pass the screening criteria. These areas are:

- o Thermochemical Reaction Studies
- o Analytical Methods (for Materials)
- o Materials Interface Studies
- o Polymers for Mirrors*
- o Thermodynamic Analysis

- o Polymers for Transmitters*
- o Production of Hydrocarbons
- o Direct Absorbers
- o Solar Chemical Reactor R&D

It is suggested that research in these areas be seriously considered for funding if it is proposed and meets the specific needs of the research area. Proposals for research in those areas with an asterisk should be very carefully evaluated to ensure that the work would have not already been undertaken by industry.

The remaining sixteen research areas (see Table 5) received considerably lower scores and are not considered to be of high priority. Although this does not imply research in these areas should categorically not be funded, it does suggest that research proposals in this area should be carefully scrutinized to determine if they will significantly advance the solar thermal technology through quality research.

*Did not pass the screening criteria.

Table 6. Scoring for All Research Areas

<u>Research Area</u>	<u>Weighted Score</u>	Number of No's for Screening Criteria		
		<u>#1</u>	<u>#2</u>	<u>#3</u>
o Photochemical Reaction	715	0	0	1
o Degradation Mechanisms	708	0	1	0
o Innovative Design & Evaluation	701	0	0	0
o Optics	662	0	0	0

o Thermochemical Reactions	649	0	0	0
o Analytical Methods (Materials)	642	0	1	0
o Interface Studies	638	0	0	1
o Polymers for Mirrors*	612	0	3	0
o Thermodynamic Analysis	609	0	0	0
o Polymers for Transmitters*	582	1	4	0
o Production of Hydrocarbons	542	0	1	0
o Direct Absorbers	538	0	0	0
o Solar Chemical Reactor R&D	536	0	0	0

o Thermochemical Water Splitting	500	0	1	0
o Production of Chemicals	463	0	1	0
o Thermodynamics & Economic Evaluation	463	2	0	0
o Windows for Solar Chemical Reactors	461	0	0	0
o Storage Materials	431	1	0	0
o Containment Material	396	0	1	0
o High-Temperature Heat Exchangers	385	0	2	0
o Metallized Glass Mirrors*	377	2	3	1
o Absorber Coatings*	366	0	3	2

*Failed the screening criteria

Table 6. continued

<u>Research Area</u>	<u>Weighted Score</u>	Number of No's for Screening Criteria		
		<u>#1</u>	<u>#2</u>	<u>#3</u>
o High-Temperature Receiver Research	362	0	0	0
o Thermal Energy Storage	359	1	1	1
o Transmitting Optical Coatings	(350)**	0	1	1
o Thermodisassociation of Water	345	0	0	1
o Heat Transfer Fluids	303	2	2	0
o Salt Gradient Ponds	300	2	3	3
o Heat and Mass Transport	296	0	0	0

*Failed the screening criteria

**Adjusted score.

APPENDIX A

RAW SCORES FOR
EVALUATION CRITERIA

THERMAL AND BASIC MATERIALS RESEARCH

Storage Materials

	Participant #				
	1	2	3	4	5
● Potential for Technological Advance	1	8	8	6	3
● Potential for Reducing Nonrenewable Energy Use	5	8	5	8	1
● Potential for Improving Cost-Effectiveness	1	8	9	8	0
● Benefit to Cost Ratio	1	8	5	4	2
● Probability of Success	1	6	7	4	4
● Scientific Quality	5	6	5	2	3

Heat Transfer Fluids

	Participant #				
	1	2	3	4	5
● Potential for Technological Advance	1	7	6	2	3
● Potential for Reducing Nonrenewable Energy Use	1	6	5	2	1
● Potential for Improving Cost-Effectiveness	1	7	6	2	0
● Benefit to Cost Ratio	1	7	3	2	2
● Probability of Success	1	6	7	0	4
● Scientific Quality	7	5	2	0	3

Containment Materials - High Temperature

	Participant #				
	1	2	3	4	5
● Potential for Technological Advance	5	7	8	6	1
● Potential for Reducing Nonrenewable Energy Use	2	6	3	8	2
● Potential for Improving Cost-Effectiveness	1	6	3	8	1
● Benefit to Cost Ratio	1	6	2	4	2
● Probability of Success	5	7	5	4	2
● Scientific Quality	5	5	7	4	2

Degradation Mechanisms

	Participant #				
	1	2	3	4	5
● Potential for Technological Advance	10	7	8	8	8
● Potential for Reducing Nonrenewable Energy Use	10	7	5	6	8
● Potential for Improving Cost-Effectiveness	10	8	7	8	5
● Benefit to Cost Ratio	10	8	7	8	6
● Probability of Success	10	8	7	8	7
● Scientific Quality	10	7	8	8	8

Interface Studies

	Participant #				
	1	2	3	4	5
● Potential for Technological Advance	10	7	5	10	3
● Potential for Reducing Nonrenewable Energy Use	10	6	5	8	3
● Potential for Improving Cost-Effectiveness	10	6	7	8	3
● Benefit to Cost Ratio	10	6	7	8	3
● Probability of Success	10	7	5	6	4
● Scientific Quality	10	7	7	10	8

Analytical Methods

	Participant #				
	1	2	3	4	5
● Potential for Technological Advance	10	7	5	10	5
● Potential for Reducing Nonrenewable Energy Use	10	8	5	6	0
● Potential for Improving Cost-Effectiveness	10	8	7	8	2
● Benefit to Cost Ratio	10	8	7	8	3
● Probability of Success	10	8	5	8	6
● Scientific Quality	10	8	7	10	4

THERMOCHEMISTRY RESEARCH

Thermochemical Reaction Studies

	Participant #				
	1	2	3	4	5
● Potential for Technological Advance	10	8	9	8	6
● Potential for Reducing Nonrenewable Energy Use	7	6	7	10	5
● Potential for Improving Cost-Effectiveness	5	6	5	8	8
● Benefit to Cost Ratio	5	7	7	8	6
● Probability of Success	3	7	5	8	6
● Scientific Quality	10	8	6	10	6

Photochemical Reaction Studies

	Participant #				
	1	2	3	4	5
● Potential for Technological Advance	10	8	7	8	6
● Potential for Reducing Nonrenewable Energy Use	10	7	7	8	5
● Potential for Improving Cost-Effectiveness	10	7	5	8	8
● Benefit to Cost Ratio	10	7	7	8	6
● Probability of Success	10	6	5	8	6
● Scientific Quality	10	8	9	10	10

Thermochemical Water Splitting

	Participant #				
	1	2	3	4	5
● Potential for Technological Advance	5	7	6	8	3
● Potential for Reducing Nonrenewable Energy Use	3	8	3	10	1
● Potential for Improving Cost-Effectiveness	5	8	3	10	1
● Benefit to Cost Ratio	3	8	5	8	2
● Probability of Success	3	6	7	6	4
● Scientific Quality	3	8	6	8	6

Thermodisassociation of Water

	Participant #				
	1	2	3	4	5
● Potential for Technological Advance	1	8	8	2	0
● Potential for Reducing Nonrenewable Energy Use	1	7	5	2	0
● Potential for Improving Cost-Effectiveness	1	7	6	2	0
● Benefit to Cost Ratio	0	7	8	2	0
● Probability of Success	1	6	8	2	0
● Scientific Quality	5	8	7	6	1

Production of Hydrocarbons

	Participant #				
	1	2	3	4	5
● Potential for Technological Advance	3	8	7	10	3
● Potential for Reducing Nonrenewable Energy Use	2	7	6	10	1
● Potential for Improving Cost-Effectiveness	3	7	5	10	1
● Benefit to Cost Ratio	1	7	6	8	4
● Probability of Success	1	6	8	8	4
● Scientific Quality	8	8	7	10	6

Production of Chemical

	Participant #				
	1	2	3	4	5
● Potential for Technological Advance	3	7	6	10	2
● Potential for Reducing Nonrenewable Energy Use	1	7	3	6	1
● Potential for Improving Cost-Effectiveness	1	6	3	8	1
● Benefit to Cost Ratio	1	6	4	8	1
● Probability of Success	1	6	7	8	4
● Scientific Quality	10	6	5	10	6

Solar Chemical Reactor Research and Development

	Participant #				
	1	2	3	4	5
• Potential for Technological Advance	6	7	7	10	4
• Potential for Reducing Nonrenewable Energy Use	3	6	7	10	1
• Potential for Improving Cost-Effectiveness	3	6	7	10	1
• Benefit to Cost Ratio	6	6	7	8	4
• Probability of Success	7	6	7	8	6
• Scientific Quality	5	6	5	10	1

Thermodynamics and Thermoeconomies

	Participant #				
	1	2	3	4	5
• Potential for Technological Advance	1	9	9	2	0
• Potential for Reducing Nonrenewable Energy Use	1	8	8	4	0
• Potential for Improving Cost-Effectiveness	1	8	9	8	2
• Benefit to Cost Ratio	1	8	8	4	5
• Probability of Success	8	8	8	8	8
• Scientific Quality	5	8	7	4	1

OPTICAL MATERIALS RESEARCH

Polymers for Transmitters

	Participant #				
	1	2	3	4	5
● Potential for Technological Advance	10	6	8	6	6
● Potential for Reducing Nonrenewable Energy Use	5	7	8	4	9
● Potential for Improving Cost-Effectiveness	8	7	8	8	8
● Benefit to Cost Ratio	8	7	5	8	2
● Probability of Success	2	6	6	8	3
● Scientific Quality	7	6	5	2	8

Polymers for Mirrors

	Participant #				
	1	2	3	4	5
● Potential for Technological Advance	10	8	6	8	8
● Potential for Reducing Nonrenewable Energy Use	5	8	7	4	7
● Potential for Improving Cost-Effectiveness	8	8	8	8	9
● Benefit to Cost Ratio	8	8	7	8	5
● Probability of Success	2	7	7	8	2
● Scientific Quality	7	6	5	2	8

Metallized Glass Mirrors

	Participant #				
	1	2	3	4	5
● Potential for Technological Advance	1	7	4	4	3
● Potential for Reducing Nonrenewable Energy Use	5	7	7	6	3
● Potential for Improving Cost-Effectiveness	1	6	5	4	1
● Benefit to Cost Ratio	1	6	5	4	5
● Probability of Success	1	6	5	8	8
● Scientific Quality	5	4	5	0	3

Transmitting Optical Coatings

	Participant #				
	1	2	3	4	5
● Potential for Technological Advance	1	6	6	*	1
● Potential for Reducing Nonrenewable Energy Use	1	7	7		1
● Potential for Improving Cost-Effectiveness	1	7	7		1
● Benefit to Cost Ratio	1	7	8		1
● Probability of Success	1	7	8		1
● Scientific Quality	5	4	5		1

*Did not provide scores for this research area.

Absorber Coatings

	Participant #				
	1	2	3	4	5
● Potential for Technological Advance	1	7	6	2	1
● Potential for Reducing Nonrenewable Energy Use	1	8	7	2	2
● Potential for Improving Cost-Effectiveness	1	8	7	4	2
● Benefit to Cost Ratio	1	8	7	2	3
● Probability of Success	1	8	8	2	6
● Scientific Quality	2	8	5	2	3

Direct Absorbers

	Participant #				
	1	2	3	4	5
● Potential for Technological Advance	5	7	9	8	7
● Potential for Reducing Nonrenewable Energy Use	1	6	8	6	3
● Potential for Improving Cost-Effectiveness	1	6	8	8	3
● Benefit to Cost Ratio	1	6	7	8	3
● Probability of Success	5	7	8	8	3
● Scientific Quality	7	6	7	8	5

Windows for Solar Chemical Reactors

	Participant #				
	1	2	3	4	5
● Potential for Technological Advance	5	6	8	8	4
● Potential for Reducing Nonrenewable Energy Use	1	5	5	6	1
● Potential for Improving Cost-Effectiveness	1	6	5	8	1
● Benefit to Cost Ratio	1	6	8	8	3
● Probability of Success	5	7	6	8	2
● Scientific Quality	7	6	6	6	3

THERMAL SCIENCES RESEARCH

High-Temperature Receiver Research

	Participant #				
	1	2	3	4	5
● Potential for Technological Advance	3	8	5	6	3
● Potential for Reducing Nonrenewable Energy Use	3	7	5	4	1
● Potential for Improving Cost-Effectiveness	1	7	5	4	1
● Benefit to Cost Ratio	1	7	5	4	1
● Probability of Success	3	7	5	6	3
● Scientific Quality	3	7	3	2	1

Salt-Gradient Solar Ponds

	Participant #				
	1	2	3	4	5
● Potential for Technological Advance	0	2	6	2	2
● Potential for Reducing Nonrenewable Energy Use	1	5	6	8	6
● Potential for Improving Cost-Effectiveness	0	5	5	8	2
● Benefit to Cost Ratio	0	5	3	4	3
● Probability of Success	0	4	8	8	6
● Scientific Quality	1	2	3	0	2

Innovative Design and Evaluation

	Participant #				
	1	2	3	4	5
● Potential for Technological Advance	10	10	8	8	10
● Potential for Reducing Nonrenewable Energy Use	5	8	8	8	10
● Potential for Improving Cost-Effectiveness	5	9	8	8	10
● Benefit to Cost Ratio	5	8	5	8	10
● Probability of Success	5	8	7	8	4
● Scientific Quality	10	10	7	8	1

Thermal Energy Storage

	Participant #				
	1	2	3	4	5
● Potential for Technological Advance	1	8	5	6	2
● Potential for Reducing Nonrenewable Energy Use	1	7	5	6	2
● Potential for Improving Cost-Effectiveness	1	7	6	4	0
● Benefit to Cost Ratio	1	7	5	4	0
● Probability of Success	1	7	7	2	3
● Scientific Quality	7	1	3	2	2

High-Temperature Heat Exchangers

	Participant #				
	1	2	3	4	5
● Potential for Technological Advance	1	6	5	8	4
● Potential for Reducing Nonrenewable Energy Use	1	6	5	4	2
● Potential for Improving Cost-Effectiveness	1	6	6	4	2
● Benefit to Cost Ratio	1	6	4	4	2
● Probability of Success	1	6	7	6	4
● Scientific Quality	5	4	3	8	4

Thermodynamic Analysis

	Participant #				
	1	2	3	4	5
● Potential for Technological Advance	5	7	8	8	2
● Potential for Reducing Nonrenewable Energy Use	5	7	7	8	2
● Potential for Improving Cost-Effectiveness	8	7	9	10	2
● Benefit to Cost Ratio	8	7	9	10	4
● Probability of Success	8	8	8	10	1
● Scientific Quality	10	6	8	8	5

Heat and Mass Transport

	Participant #				
	1	2	3	4	5
● Potential for Technological Advance	1	3	4	2	3
● Potential for Reducing Nonrenewable Energy Use	1	3	4	2	3
● Potential for Improving Cost-Effectiveness	1	3	4	2	3
● Benefit to Cost Ratio	1	3	4	2	5
● Probability of Success	1	3	8	2	4
● Scientific Quality	7	6	3	6	3

Optics

	Participant #				
	1	2	3	4	5
● Potential for Technological Advance	7	10	8	8	5
● Potential for Reducing Nonrenewable Energy Use	6	8	8	6	6
● Potential for Improving Cost-Effectiveness	6	9	7	8	8
● Benefit to Cost Ratio	6	9	8	8	6
● Probability of Success	3	8	6	8	3
● Scientific Quality	10	10	7	8	6