1150

COMPENDIUM OF MAJOR ANALYTICAL STUDIES PERFORMED IN THE SOLAR THERMAL TECHNOLOGY PROGRAM DURING THE PERIOD FY 1983 - FY 1986

DRAFT

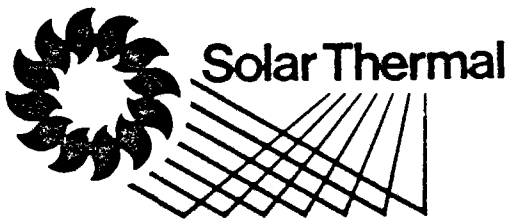
Technical Program Integrator
August 29, 1986

SERI
Solar Energy Research Institute
A Division of Midwest Research Institute
1617 Cole Boulevard
Golden, Colorado 80401

COMPENDIUM OF MAJOR ANALYTICAL STUDIES PERFORMED IN THE SOLAR THERMAL TECHNOLOGY PROGRAM DURING THE PERIOD FY 1983 - FY 1986

DRAFT

Technical Program Integrator
August 29, 1986



SERI
Solar Energy Research Institute
A Division of Midwest Research Institute
1617 Cole Boulevard
Golden, Colorado 80401

TABLE OF CONTENTS

TABLE OF CONTENTS, Continued

TABLE OF CONTENTS, Continued

SECTION 1.0
INTRODUCTION AND BACKGROUND

1.1 OBJECTIVE

The objective of this compendium is to provide summary descriptions of many of the major analytical and comparative studies performed in the DOE Solar Thermal Technology (STT) Program during the period FY 1983 - FY 1986.

For the purposes of this document, a "major analytical study" is a relatively high level systems analysis study--not laboratory/experimental work or hardware R&D--performed in some part of the DOE Solar Thermal Technology Program since FY 1983 and has at least one of the following characteristics or attributes:

(1) The study had an impact on focusing R&D efforts in the STT Program

(2) The study served as a basis for redirecting R&D efforts (for example, redirecting R&D from enclosed concentrators to unenclosed concentrators)

(3) The study was used to determine whether or not a specific application of the technology had promise (for example, whether or not STT systems had promise in generating high-value chemicals)

(4) The study had an impact on initiating major program thrusts (e.g., major thrust in direct absorption receiver R&D)

(5) The study assessed the technical and economic performances of STT systems compared to each other or compared to conventional (i.e., fossil fuel) alternatives.

It is the intention of DOE/HQ to periodically update this Compendium.

1.2 RATIONALE FOR GENERATION OF THE COMPENDIUM/USES OF THE COMPENDIUM

Between FY 1981 (the onset of the Reagan Administration) and FY 1986, annual funding for the DOE Solar Thermal Technology Program has decreased substantially; from about $100,000,000 in FY 1981 to about $26,000,000 in FY 1986. Because of the contraction in funding, it was necessary at times to abruptly terminate many planned R&D efforts and/or redirect funds to those R&D activities considered to have the highest priority.

Also, the number of participants in the Program (universities, industrial firms, national laboratories, nonprofit R&D organizations, etc.) decreased significantly.

In this environment of decreasing resources, together with an array of annual fixed costs (e.g., operation of the Central Receiver Test Facility, etc.), it was not always possible to: (1) systematically bring many R&D projects being terminated to the preferred termination point; (2) adequately document accomplishments and the results and conclusions from R&D being terminated, down-scoped, or redirected; or (3) complete the entire set of R&D activities and systems analysis studies needed by DOE/HQ to make decisions regarding Program thrusts (e.g., evaluate all central receiver concepts to select the one or two concepts for advanced development).

In recognition of the above problems in the Solar Thermal Program, in FY 1985, DOE initiated an effort to:

(1) Systematically document the accomplishments and successes in the STT Program since its inception.

(2) Preserve data--especially in the case of promising R & D that had to be terminated due to lack of funds--so that they will be available if it becomes possible to re-initiate the R & D in the future.

(3) Systematically document work done in the Program to identify promising applications of the technology and potential end users. These studies can be re-visited as the Program evolves and as breakthroughs are attained.

(4) Document, historically, the decisions in the Program regarding major thrusts, the rationales for the decisions and the supporting studies that were used in decision making.

The generation of this compendium is part of the above-mentioned DOE documentation efforts - - especially (3) and (4).

In addition, this Compendium can be used by DOE/HQ and the lead laboratories (i.e., SERI and Sandia National Laboratories/Albuquerque) for the STT Program as a resource in defining and scoping future systems analysis studies. The results of the studies documented in this report are a catalog of systems analysis findings, conclusions and recommendations that can be used as-is or as the starting point for future studies.

1.3 THE DOE SOLAR THERMAL TECHNOLOGY (STT) PROGRAM

The federal program for solar thermal energy R & D is the Solar Thermal Technology Program conducted by the Solar Thermal Technology Division of the U.S. Department of Energy. The Goal of the 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. Research and development functions are assigned to various lead laboratories. The lead laboratories not only conduct in-house R & D - - they also conduct R & D by means of contracts with universities, industrial firms, Federal laboratories and non-profit R & D centers.

Examples of contractors include the following:

R & D Contractor	Type Contractor
o Battelle Pacific Northwest Laboratories	Federal Laboratory
o Lawrence Berkeley Laboratory	Federal Laboratory
o University of Houston	University
o University of Hawaii	University
o Solar Kinetics, Inc.	Industrial Firm
o Martin Marietta	Industrial Firm
o Georgia Tech Research Institute	Nonprofit R&D Center
o Denver Research Institute	Nonprofit R&D Center

At the beginning of FY 1983, the STT Program was organized as follows:

STT Program Functions	Lead Laboratory
o Central Receiver Technology Development Program	Sandia/Livermore (SNLL)
o Distributed Receiver Technology Development Program	Sandia/Albuqueque (SNLA)
o Fuels and Chemicals Program	Jet Propulsion Laboratory (JPL)
o Solar Thermal Research Program	Solar Energy Research Institute (SERI)
o Technical Program Integrator	Sandia/Livermore (SNLL)

During FY 1983, JPL made the decision to withdraw from the Program--to focus on its military and space R & D work. Consequently, the Fuels and Chemical Program was dropped as a separate entity. The various parts were assigned to SNLA, SNLL and SERI.

In FY 1985, the management of Sandia/Livermore made the decision to withdraw as the lead laboratory for the Central Receiver Technology Development Program and from serving as the TPI. In response, DOE combined the central and distributed receiver efforts into the Technology Development Program with Sandia/Albuquerque as the lead laboratory. The TPI function was assigned to SERI. Consequently, in FY 1986, the Solar Thermal Technology Program was structured as follows:

STT Program Function	Lead Laboratory
o Technology Development Program	Sandia/Albuquerque
o Solar Thermal Research Program	SERI
o Technical Program Integrator (TPI)	SERI

Because the number of lead laboratories has decreased from five to two, and because of the decrease in the number of contractors, there is the risk of:

(1) Loss of corporate history.

(2) Loss of data that may be needed in the future.

(3) Loss of expertise.

One of the roles of the TPI is to assist DOE/HQ in preventing (1) and (2).

1.4 METHODOLOGY USED TO GENERATE THE COMPENDIUM

The first step in generating the Compendium was to formulate a definition for the term "major analytical study." The definition is provided in Subsection 1.1. Also, given available funds and time, the Compendium was limited to studies performed or funded by the lead laboratories for the STT Program since October 1983.

Given the definition of the term "major analytical study", the organizations to be included in the Compendium the time frame, the Compendium was assembed using the following approach:

(1) The TPI first constructed a standardized, concise format for documenting each study to be included in the Compendium (see Subsection 1.5).

(2) For each of the five organizations to be included in the Compendium, the TPI generated a computerized bibliographic listing of all known solar thermal reports published by each organization during the period FY 1983 - FY 1986 by querying the NTIS and TIC data bases. Known reports (published or available as drafts) generated in FY 1986 that were not in the NTIS or TIC data bases were manually added to the listings. A total of 395 reports was identified.

(3) For each organization, the bibliographic listings generated in Step (2) above were analyzed manually to identify those that appeared to document a "major analytical study." A total of 51 such reports were identified.

(4) Discussions were then held with present or former staff at each of the five organizations (i.e., persons that were involved in performing major analytical studies) to determine: (i) whether or not the reports compiled in Step (3) resulted from major analytical studies and (ii) to identify additional major analytical studies for which the results were not formally published.

(5) The list of major analytical studies to be covered in the Compendium for each of the five organizations was then generated by combining the results of Steps (3) and (4).

(6) Having identified the major analytical studies to be included in the Compendium, efforts were then devoted to acquiring a copy of each published report and/or unpublished report and/or set of Vugraphs associated with each study.

(7) For each major analytical study, the 3-4 page standardized write-up was then generated by:

- o Obtaining a copy of the relevant report(s) and extracting or synthesizing the required information.
- o Using notes collected during the discussions in Step (4).

1.5 ORGANIZATION OF THE COMPENDIUM

The analytical studies documented in this report are organized as follows:

Organization	Section
o SERI	2.0
o Sandia/Livermore	3.0
o Sandia/Albuquerque	4.0
o Technical Program Integrator	5.0
o Jet Propulsion Laboratory	6.0

For each study documented, the following information is provided in a standardized format:

- Title
- Background (i.e. rationale for performing the study)
- Objective of the Study
- Approach (i.e. methodology)
- Anticipated or Realized Accomplishments
- Deliverables (i.e. major reports)
- Technology Transfer Activities (i.e. papers, articles, presentations)
- Expected or Realized Impact on the STT Program
- How Used to Achieve Impact
- Requestor of the Study
- Approximate Funding

Section 7.0 provides a bibliography of reports resulting from these analytical studies.

SECTION 2.0
SERI MAJOR ANALYTICAL STUDIES

SECTION 2.0 TABLE OF CONTENTS Page

2.1 CONCENTRATORS: CENTRAL RECEIVER SYSTEMS

2.1.1 Analytical Study: Single-Membrane Stretched Membrane Heliostat Systems Analysis and Modeling

Background:

As part of the thrust to conduct research to develop innovative, low-cost, lightweight concentrators--to reduce substantially the capital costs of STT systems--SERI has been conducting research on stretched membrane concentrator concepts since about FY1982. The initial emphasis at SERI was on stretched membrane heliostat concepts having a single membrane. The initial analyses of the concept--as well as the results derived from fabricating, testing and evaluating small-scale models--showed that stretched membrane heliostats had the potential to have the required technical performance while being less expensive (by a factor of about 2) than conventional glass/metal concepts. In order to determine the cost and performance potential of stretched membrane heliostats more accurately, it was necessary to understand the structural response of the membrane/frame combination--specifically, the interaction of the frame and membrane under various pressure (i.e., wind) loads and tension loads. An understanding of the frame and membrane interaction was needed in order to (i) optimize the concept, (ii) establish appropriate design criteria, and (iii) aid potential developers of the concept. Prior to FY1986, SERI did not have the capability to model accurately the structural and optical responses of single membrane stretched membrane heliostats to various loads. Consequently, recognizing the need for this capability, efforts were initiated in FY1984 to develop this modeling capability and utilize the models to aid in understanding frame/membrane response issues.

Objective:

The objectives of this study were to (i) develop an analytical tool (computerized) that modeled the load deformation behavior of a single membrane stretched membrane heliostat reflector module, and (ii) utilize the model to study and acquire an understanding of

the optical and structural load deformation behavior of a uniform pressure loaded reflector module subject to nonaxisymmetric support constraints.

Approach:

The approach was to model the frame/membrane combination for a single membrane module using basic structural analysis principles, and employing large deformation/small strain approximations. The analytical modeling was complemented by a finite element numerical analysis for validation purposes. In addition, the design and fabrication of a two-meter diameter reflector module was carried out to study fabrication and various design limitation issues.

Anticipated or Realized Accomplishments:

The model developed in the study provided the Solar Thermal Technology Program with an accurate and simple method for predicting the structural response of single-membrane stretched membrane reflector modules in which the membrane passes through the frame shear center or in which the membrane is offset but attached so that only radial constaint is experienced. Also, the model provided the Program with a convenient tool for evaluating and screening various design concepts and for performing system trade-off studies. It must be noted that the model was not intended to be used for large deformation situations, stability analyses or for any situations where the assumptions used to construct the model were violated to a significant extent. Utilizing the model, SERI was able to identify a number of important structural response and design considerations that have an impact on the deformation performance and optical accuracy of stretched membrane reflectors.

Deliverables:

Murphy, L. M. and D. v. Sallis, Analytical Modeling and Structural Response of a Stretched Membrane Reflective Module, SERI/TR-253-2101, Golden, CO: Solar Energy Research Institute, June 1984.

Also, a two-meter diameter single membrane module was designed and fabricated.

Technology Transfer Activities:

The above-mentioned report was published and distributed widely in the solar thermal community (distribution list attached to report).

A paper entitled, "Stretched Membrane Heliostat Technology," was accepted for publication in the "Journal of Solar Energy Engineering". The paper summarizes much of the analysis capabilities documented in the report.

Expected or Realized Impact on Program:

This was the first study in the Solar Thermal Technology Program leading to a technical understanding of the structural and optical response of single-membrane models. Because of this study, additional research was devoted to a detailed assessment of the stability of the frame/membrane combination under various loading conditions and constraint configurations. In addition, because of this study, work was initiated in assessing the structural and performance benefits of double-membrane concepts in FY1984 and into FY1985.

How Used to Achieve Impact:

The model developed in this study was a precursor to a more comprehensive and complex structural/optical performance prediction model developed at SERI. It was utilized by the contractors, SERI and Sandia/Livermore to describe the performances of early single-membrane stretched membrane reflectors.

Requested By:

The work was requested by DOE/HQ as part of a more comprehensive task on stretched membrane concentrator research.

Funding:

Funding for this particular study was approximately $100,000 (including the hardware fabrication).

2.1.2 Analytical Study: Single- and Double-Membrane Stretched Membrane Heliostat Systems Analysis and Modeling

Background:

Since FY1982, SERI has been conducting research to demonstrate the technical and economic feasibility of developing low-cost, lightweight, durable solar concentrators utilizing stretched membrane approaches. Until FY1986, the emphasis in this research was on stretched membrane heliostats. Between FY1982 and FY1984, the analytical and experimental work focused on stretched membrane heliostat concepts utilizing a single membrane. As part of that work, a simple analytical model was developed for studying the optical and structural load deformation behavior of uniform pressure loaded single-membrane stretched membrane heliostat reflector modules. The model and the results obtained in using the model to understand the behavior of such reflectors are documented in the report Analytical Modeling and Structural Response of A Stretched Membrane Reflective Module (SERI/TR-253-2101). SERI, in the above report, cautioned that the model was not intended to be used (i) in large deformation situations, (ii) in stability analyses, (iii) in analyzing the behavior of double membrane designs, or (iv) in any situations where the assumptions used in formulating the model were violated to a significant extent. SERI recommended that efforts be devoted to developing a new model or models that could be used for: (1) detailed assessments of the stability of the membrane/frame combination under various loading conditions and constraint configurations (2) assessment of the structure and performance benefits of both single- and double-membrane heliostat reflector modules (in FY1984, SERI had begun to investigate the feasibility of double-membrane systems), (3) assessment of the allowable frame imperfections, (4) assessing the optical advantages of vacuum focusing versus laminate focusing in double membrane approaches and (5) assessment of nonuniform membrane surface loading effects. The subject analytical study, performed as part of the FY1985 Solar Thermal Research Program, evolved from the above-mentioned SERI recommendation.

Objective:

The objectives of this study were (i) to develop a more comprehensive analytical model than the one documented in SERI/TR-253-2101 for describing the response of structural and optical responses of both single and double membrane stretched membrane heliostat

reflector modules and (ii) to utilize the model to understand and estimate the optical and structural performances of such modules to uniform pressure loads normal to the plane of the membrane.

Approach:

The approach taken in this study to develop the analytical model was to utilize the finite deformation variational principle. This principle is routinely used in large deformation analyses for finite element codes to develop an incremental, large deformation, small strain analysis of the optical/structural performance of elastic stretched membrane (either single or double) modules. The NASTRAN finite element modeling approach provided analytical verification of the modeling. In addition, several three-meter diameter modules were designed and fabricated to validate the models and to investigate potentially significant phenomena which might occur that were not considered in the model.

Anticipated or Realized Accomplishments:

SERI developed an analytical model--using a variational approach that uses the concept of potential energy and employs the Rayleigh Reitz procedure--for predicting the load deformation response of single- and double-membrane stretched membrane heliostat reflector modules. This model differs from the above-mentioned earlier model in that (i) it explicitly provides for the analysis of both single- and double-membrane systems (ii) it predicts the coupled membrane/frame response and considers the in-plane stiffness effect of the membrane and nonuniform tension states in the membrane and (iii) it addresses the effect of different membrane attachment schemes.

The model was verified by more detailed NASTRAN finite element analyses to give good approximate predictions of the response of the modules subject to out-of-plane loading and nonuniform frame supports. SERI found that, unlike single-membrane designs, the double-membrane approach couples the in-plane membrane material stiffness with the deformation process even at low pressure loads and low tension levels. Because of the membrane stiffness coupling, the double-membrane module was considerably stiffer than the single-membrane design, thus allowing more pressure loading for a given prescribed maximum out-of-plane deformation. SERI also found that attachment design and stiffness were important design considerations since they determine how effectively the stiffness of the membrane can be coupled with the frame.

Deliverables:

Murphy, L. M., The Variational Approach for Predicting a Low Deformation Response of a Double Stretched Membrane Reflector Module, SERI/TR253-2626, Golden, CO: Solar Energy Research Institute, October 1985.

Three 3-meter diameter single and double membrane modules were designed and fabricated for testing at SERI.

Technology Transfer Activities:

The document was distributed widely within the solar thermal community (a distribution list is attached to the report). In addition, a paper which utilizes many of the results attained with this model has been written and accepted for publication in the Journal of Solar Energy Engineering.

Expected or Realized Impact on Program:

Because of the modeling and experimental work, SERI established qualitatively and quantitatively the advantages of double-membrane stretched membrane heliostat approaches over single-membrane concepts. Consequently, since FY1984, the thrust of the stretched membrane heliostat research has been on double-membrane approaches.

Also, the model was used extensively by the industrial contractors utilized by Sandia/Livermore in developing their respective prototype full-scale commercial stretched membrane heliostat module designs. The experimental modules were tested and results were compared with analysis (see experimental study description).

How Used to Achieve Impact:

The resulting model was utilized in the development of the full-scale prototype stretched membrane heliostat models mentioned earlier. It is a design and evaluation tool that can be made available to heliostat producers.

Requested By:

The study was requested by DOE as part of an overall effort to define the potential cost and performance potential of stretched membrane heliostats as a low-cost heliostat reflector.

Funding:

Funding was approximately $200,000, which included the fabrication of experimental hardware.

2.1.3 Analytical Study: System Performance and Cost Sensitivity Assessments of Stretched Membrane Heliostats Compared to Conventional Glass/Metal Heliostats

Background:

One of the major goals of the Solar Thermal Technology Program is to reduce the installed costs of heliostats for central receiver systems from about $\$150/m^2$ today in mass production to about $\$50\text{-}60/m^2$. This is necessary in order for STT systems to be economically competitive with conventional alternatives for a variety of applications. One of the approaches that show great potential for meeting the $\$50\text{-}60/m^2$ goal while meeting the technical performance requirements is stretched membrane technology. SERI has been investigating this concept since about FY1981. By FY1984, the theoretical, analytical and experimental research had progressed to the point where it was possible to make meaningful comparisons between the capital cost and the technical and economic performances of stretched membrane heliostat concepts compared to conventional glass/metal heliostats. The subject study was performed to make such comparisons on a consistent basis.

Objective:

The objective of this study was assess the capital cost and the technical and economic performances of stretched membrane heliostats compared to conventional glass/metal heliostats. The study also assessed the sensitivity of the performance of a central receiver system (with stretched membrane heliostats) to various system parameters--e.g., application, temperature, heliostat module size, reflector surface quality and focusing capability.

Approach:

The strategy in the study was to assess the cost and analyze technical and economic performances of a central receiver system (for IPH applications) having stretched membrane

heliostats compared to an identical system utilized baseline 100 m^2 glass/metal heliostats. Such assessments were made for systems of different sizes (75, 225 and 450 MW_{thy}) and delivering energy at different temperatures (450°, 750° and 1050°C). The technical performances of the systems were estimated utilizing the central receiver design/analysis models DELSOL2, RADSOLVER and SHAPEFACTOR. The cost data and economic assumptions used in the studies were taken from the document Solar Thermal Technology Five-Year Research and Development Plan (draft) generated by Sandia/Livermore.

Anticipated or Realized Accomplishments

The study showed that, for a wide range of system sizes and energy delivery temperatures, central receiver systems that utilize stretched membrane heliostats can have performance levels that are quite close and possibly slightly better than those utilizing glass/metal heliostats. Furthermore, the analysis of the sensitivity of the technical performances of stretched membrane heliostats to specularity errors showed that if the specularity half cone angle that included 90% of the reflected energy were to be as high as 6 mrad (compared to the FY1984 goal of 2 mrad for silver/polymer reflectors), performance would degrade by only 5% for the 75 MW_{th} system. The degradation would be even less for larger systems.

Deliverables:

Murphy, L. M., et al., System Performance and Cost Sensitivity Comparisons of Stretched Membrane Heliostat Reflectors with Current Generation Glass/Metal Concepts, SERI/TR-253-2694, Golden, CO: Solar Energy Research Institute, December 1985.

Technology Transfer Activities:

In addition to the above mentioned SERI report, the work was presented at the April 1986 ASME Solar Division Conference.

Expected or Realized Impact on Program:

This study established the strong potential for economic feasibility of the stretched membrane heliostat concept, and defined the conditions necessary to achieve that potential. Furthermore, it led to studies in FY1986 to re-assess the specularity requirements for silver/polymer reflector films for stretched membrane heliostats.

How Used to Achieve Impact:

See "Expected or Realized Impact on Program" above.

Requested By:

This study was requested by DOE/HQ.

Funding:

Approximately $60,000 for SERI work.

2.1.4 Analytical Study: Systems Study of the Cost and Performance of Polymer/-Enclosed Heliostats Compared to Glass/Metal Heliostats

Background:

Since concentrators account for about 50% of the capital cost of a solar thermal system, a major thrust of the Solar Thermal Research Program has been to conduct research to identify and assess the technical feasibility of innovative, low-cost concentrators that met the technical performance requirements. During 1976, a moderate effort was undertaken in the STT Program to investigate polymer enclosed heliostat concepts proposed by Boeing and General Electric. The concept appeared to have the potential to significantly reduce costs. However, analysis of the concept at that time showed that there were many uncertainties regarding not only long-term technical performance, but also regarding likely costs. Consequently, work on the concept was terminated. Heliostat R&D then focused exclusively on glass/metal approaches--to develop a heliostat design for the Solar One 10MW Demonstration Project. In February 1980, DOE established a formal Solar Thermal Cost Goals Committee to establish value-based cost goals for both solar thermal systems and concentrators. The committee, in its report in 1982, estimated that if STT systems had a normalized capital cost below $\$115/m^2$ (1982$)--which would correspond to a delivered cost of energy of about $5.80/million BTU--solar thermal technology had the potential to compete with a wide range of fuels in many regions of the country in the 1990-2000 time frame. Since concentrators account for about 50% of the capital cost, in order to attain a normalized system cost of $\$115/m^2$, the installed cost the concentrators must be $\$50\text{-}60/m^2$. At the time of the committee's report, the estimated cost of heliostats in mass production was about $\$150/m^2$ (1982$)--twice that of the goal. Because of (i) advancements in polymer materials technology, (ii) the promising work in progress on polymer mirrors, (iii) the low cost potential of enclosed heliostats and (iv) the need to reduce heliostat costs by 50%, it was decided in FY 1982 to re-examine the technical and economic potential of polymer/enclosed heliostats compared to glass/metal concepts. The subject study, initiated in FY 1982, was completed in FY1983.

Objective:

The objectives of this study were to: (i) evaluate the engineering and economic potential of polymer-based enclosed heliostats from a systems perspective, (ii) assess the cost and performance of enclosed heliostats compared to second generation glass/metal heliostats and (iii) assess prior engineering and materials work and identify R&D issues.

Approach:

SERI began the study with an assessment of prior work on polymer-enclosed heliostats--an assessment of systems studies, work on materials and engineering work. This was followed by development of a conceptual design for a baseline enclosed heliostat--a design with a polymer enclosure and a metallized polymer mirror--and estimation of its cost and technical performance parameters. A second generation glass/metal heliostat was then selected as the alternative. The technical and economic performances of the two heliostat concepts were assessed assuming they were the concentrators in a 30 MW_{th} central receiver system delivery process heat. The assessments were performed using the computer code DELSOL. SERI supplemented the baseline assessment with several sensitivity studies. The assessments were utilized to generate recommendations and conclusions.

Anticipated or Realized Accomplishments:

The study showed that on installed capital cost of $\$50/m^2$ appeared feasible for enclosed heliostats. Also, with enclosed heliostats, the potential existed to reduce the delivered cost of energy by more than 40% compared to a system with second generation glass/metal heliostats. However, attaining the delivered cost of energy target of $5.80/million BTRU would be difficult. The principal reasons for the difficulty were: (i) uncertainties regarding the availability of polymer materials and reflectors having the required mechanical strengths and lifetimes and (ii) uncertainties regarding the optical performance not only of the metallized polymer reflector but also of the enclosure.

The study also showed that if the life of the enclosure was at least five years, improving the optical performance of the polymer materials would have the greatest impact on reducing the delivered cost of energy. The polymer enclosed heliostat concept will be able to attain their ultimate potential in terms of cost and performance only after the identified materials and design issues are resolved. Since long-term materials research was required, SERI concluded that the payoff will be in the long term and accelerated engineering development was not warranted. An important issue not addressed in the study was optical performance degradation.

Deliverables:

Murphy, L. M. et al., A Systems Study of the Polymer/Enclosed Heliostat Concept and a Comparison with Glass/Metal Heliostats, SERI/SP-253-1791, Golden, CO: Solar Energy Research Institute, October 1982.

Technology Transfer Activities:

The results of this work were presented to DOE and Sandia National Laboratories on several occasions.

The briefing package was distributed within the solar thermal community.

Expected or Realized Impact on Program:

Because the study showed that the highest priority polymer research issue was development of a polymer reflector--whether or not it was enclosed-- that had the required optical performance, mechanical properties and durability, DOE/HQ used the study to focus research on metallized polymer reflectors (e.g., stretched membrane) that could be used enclosed or unenclosed. The study also showed that, while enclosed heliostats have significant cost and performance potential that can be attained in the long term, the concept of enclosures have applicability to other concentrator concepts--particularly dishes. Consequently, DOE redirected the work on enclosures for heliostats to enclosures for thermal dishes.

How Used to Achieve Impact:

See "Expected or Realized Impact on Program" above.

Requested By:

This study was requested by DOE/HQ.

Funding:

Funding for this effort was approximately $120,000.

2.1.5 Analytical Study: Analysis of Terminal Concentrators for Central Receivers

Background:

The idea of using terminal (i.e., secondary) concentrators on central receivers has been proposed by a number of researchers since the 1970's. The concept has been examine briefly in several studies. Those studies generally concluded that the large (azimuthal) width of the heliostat field (typically 160^{o}) made the most common types of terminal concentrators impractical. In late 1985, this previous work was reviewed, and a plan was formulated to study the possibility of using concentrators that operated only in two dimensions (i.e., lowering the height of the receiver aperture without affecting its width). This limited terminal concentration concept had not been examined before. It seemed to offer promise for reducing receiver thermal losses without sacrificing interception of the reflected radiation from the field.

Objective:

The objective of this study was to determine if the two-dimensional terminal concentrator concept had potential as a means of improving the technical performances of cavity receivers.

Approach:

The concept was studied using several well-established computer tools, including the central receiver design/analysis tool DELSOL2. The output of the models was combined with a specially developed ray-tracing code that tracked the reflected radiation from the field through the terminal concentrator system and into the aperture. The concept was studied for a baseline 100 MW plant delivering energy at $550^{o}C$.

Anticipated or Realized Accomplishments:

This study demonstrated that there is a limited potential for a plate above the aperture to lower the aperture height without adversely affecting the interception. For the base-line plant, a flat plate terminal concentrator design was determined that would deliver roughly the same energy as the open aperture receiver. However, since the cost of the terminal concentrator would make that system more expensive than the original system, the concept did not appear to be economically feasible under these conditions. However, previous work has demonstrated that the benefits of the terminal concentrator would probably increase with higher delivery temperatures and/or smaller plants.

Deliverables:

A SERI report is being prepared and should be published in the Summer of 1986.

Technology Transfer Activities:

This work will probably be presented at an engineering conference in 1987.

Expected or Realized Impact on Program:

This is the first study of terminal concentrator concepts for central receivers that showed significant promise. The results of the study also pointed to the ranges of system parameters that hold the most promise for future work. The results of the study will be used in planning the FY 1987 Solar Thermal Research Program.

How Used to Achieve Impact:

The results of this study can be utilized in the design of second generation and advanced cavity receiver concepts.

Requested By:

This study was requested by DOE.

Funding:

Approximately $20,000 for SERI in-house R&D.

2.1.6 Analytical Study: Analysis of Wind Loads on Solar Concentrators

Background:

One of the major thrusts in the Solar Thermal Research Program is conducting research to develop innovative low-cost, lightweight, durable solar concentrators--having a specular reflectance of at least 90% and an installed cost of $\$50\text{-}60/m^2$. An important consideration in developing such concentrators is wind loads. Accurate determination of wind loading is a fundamental design consideration in deciding what degree of safety and economy can be achieved in concentrator structures. Various research studies and histories of failures of structures have indicated that repeated wind-induced loads on structures can have damaging effects. This has led to efforts to design structures that resist the repeated loading action of wind--contradicting the more conventional approach of designing based on the static application of a single large wind load derived from the guidelines furnished by the National Building Codes. Experience suggests that unserviceability due to repeated loading effects is a more likely occurrence than unserviceability or collapse from a single application of an exceptionally large load. Examples of the types of structural unserviceability due to repeated wind loading are (1) fatigue failure, (2) foundation settlement, (3) excessive deflection, and (4) induced motion of an acceptable level. As innovative solar concentrator designs evolve that are less robust--in order to reduce the amount of materials, weight and cost--the above issues relating to wind loads become especially important. An issue that SERI had to resolve in assessing wind loads on concentrators was whether or not such assessments could be performed utilizing existing methodologies.

Objective:

The objective of this study was to review and assess the present methodology for predicting and designing for wind loads on solar collectors. Although the emphasis was on heliostats, the work was applicable to troughs, dishes, and large field arrays of photovoltaic cells.

Approach:

The approach was to develop elevation-dependent longitudinal wind velocity profiles for various solar collector exposure conditions. This was followed by a comparative study of the total steady state wind load force coefficients on flat plates with various aspect ratios and various angles of attacks. The coefficients were then compared to the current design codes being used for solar collector design purposes. In addition, a comparative study of the spectra of longitudinal/lateral velocity fluctuations was completed. The spectra were compared with those used for building design purposes. The study did not address the wind-loading effects caused by turbulence (i.e., (i) buffeting, (ii) vortex shedding forces caused by the structure's own wake or (iii) aeroelastic forces induced by the oscillating motion of the structure).

Anticipated or Realized Accomplishments:

The study showed that the present methodology for designing for wind loads using the outlines given by ANSI A58.1-1982 was conservative. A comparative study of the total force coefficient of a flat plate of various aspect ratios and at various angles of attack showed that the values obtained by using the ANSI Code were always higher. SERI also found that the angle of attack that results from the fluctuating vertical wind was considerably smaller than the value suggested by the Code. Because of the findings, SERI recommended that a study be performed to investigate the feasibility of utilizing parameter fences and in-the-field fences around a group of heliostat zones as a means for reducing wind loads.

Deliverables:

Bhaduri, S. and L. M. Murphy, Wind Loading on Solar Collectors, SERI/TR-253-2169, Golden, CO: Solar Energy Research Institute, July 1984.

Technology Transfer Activities:

The above report was published and distributed widely in the solar thermal community.

"Wind Loading on Solar Collectors," a paper condensation of the major report findings, was published and presented at the 1984 ASME Winter Annual Meeting, Paper No. 84-WA/Sol-16.

Expected or Realized Impact on Program:

The work was utilized to gain a better understanding of wind loading on collectors and to complement and guide the efforts at the Colorado State University where experimental work was sponsored to verify the definition of wind load design requirements. In addition, the recommendation to investigate the feasibility of utilizing parameter and internal fences in a heliostat to reduce wind loads resulted in an experimental/wind tunnel simulation project at Colorado State University. That work showed that fences, if properly placed had the potential to significantly reduce wind loads on heliostats.

How Used to Achieve Impact:

See "Expected or Realized Impact on Program" above.

Requested By:

This subtask was requested by the DOE as part of a much larger, more comprehensive task on concentrator research.

Funding:

The funding for this particular work was approximately $35,000, including SERI's effort and the consultant expenses for Dr. Bhaduri from the University of Texas at El Paso.

2.1.7 Analytical Study: Identification and Assessment of Low-Cost Heliostat Communications and Control System Concepts

Background:

One of the major objectives of the Solar Thermal Research Program is to conduct research aimed at reducing the capital costs of central receiver systems. Emphasis in this activity has been on reducing the capital costs of the two most expensive subsystems--concentrators (e.g., heliostats) and receivers. However, there are other opportunities to reduce costs. One such promising opportunity for significantly reducing capital costs is to conduct research to identify low-cost, reliable heliostat communications and control subsystems--the means whereby the heliostats track the sun.

Objective:

The objective of this research was to identify and assess alternative low-cost, reliable heliostat control and communication concepts for central receiver systems--concepts having a potential cost of about $\$15/m^2$ compared to about $\$50/m^2$ for the control and communication subsystem in the Solar One System.

Approach:

Communications between the central computer and the heliostats in the Solar One System is via dedicated buried cable (i.e., via the central computer to a field computer and then to a heliostat computer). However, since the time of the construction of Solar One, several promising potentially lower-costing methods have emerged as a result of new technological developments. The study addressed exploiting these new technological developments to (1) identify alternatives to the buried cable communication system, and (2) assess the feasibility of upgrading the functions and control responsibilities of each of the heliostat microcomputers. Communications alternatives to buried cable were identified and assessed. Several different control strategies were identified and assessed.

Anticipated or Realized Accomplishments:

Four alternatives to buried shielded-cable communication systems were identified and assessed: (1) fiber optics, (2) carrier current, (3) radio frequency (RF), and (4) optical air links using lasers or light-emitting diodes. The RF and optical air link concepts were estimated to have potential costs of $\$9/m^2$ and $\$11/m^2$, respectively. Analysis of the concepts showed that RF and carrier current approaches showed the greatest promise for success. Both utilize established technologies. Because of the potential attractiveness of the RF approach, the researchers completed the design for a prototype RF communication system. Laboratory-scale hardware for the system was fabricated and evaluated.

Five different heliostat control strategies were investigated. Analysis of control functions and hardware showed that it was possible to enhance the computing function of each heliostat microcomputer--to do the following: (a) perform sun vector calculations (now done by the central computer in Solar One), and (b) perform self-calibration calculations and enhance the interrogation potential at the central computer via an adaptive controller. Since their prices were rapidly dropping and special-purpose microcomputers dedicated to control functions were becoming available, the researchers concluded that serious efforts should be devoted to enhancing the responsibilities of the heliostat microcomputers in the field.

Deliverables:

Chen, B. and J. pearson, An Assessment of Heliostat Control System Methods, SERI/TR-253-2390, Golden, CO: Solar Energy Research Institute, 1985.

Technology Transfer Activities:

Pearson, J. and B. Chen, Heliostat Control System Strategies, Proceedings of the ASME Annual Meeting, Boston, MA, American Society of Mechanical Engineers, November 1983.

Expected or Realized Impact on Program:

This research demonstrated that the technology exists to reduce heliostat control and communication subsystem costs from about $\$50/m^2$ (as for the Solar One System) to about $\$15/m^2$, while maintaining the required level of technical performance.

How Used to Achieve Impact:

The schemes identified in this research can be incorporated into the designs for second generation and advanced central receiver systems.

Requested By:

This research was requested and funded by SERI.

Funding:

Total funding of $14,075, distributed as follows:

Institution	Principal Investigator	Funding
John Brown University Siloam Springs, AK	Dr. J. Pearson	$7,575
University of Nebraska/Omaha Omaha, NE	Dr. B. Chen	$6,500

2.1.8 Analytical Study: Analysis of the Cost and Performance of An Inflatable Heliostat Tracking and Support Structure Concept Developed by SERI

Background:

One of the major goals of the Solar Thermal Research Program is to conduct research to reduce the cost and improve the performance of solar thermal systems and broaden the areas where these systems have the potential to approach economic viability. Since concentrators account for 40-50% of the installed cost of a solar thermal system, the most promising means for reducing system cost is to reduce the cost of the concentrators while maintaining high performance. After the reflector module, the greatest cost elements of a complete heliostat are the two-axis drives. In addition to conducting research on innovative low-cost, high performance heliostat reflector modules, in order to reduce the costs of heliostats, SERI has been conducting research on drives. SERI formulated on innovative heliostat drive concept employing an inflated cylindrical sleeve for heliostat support and drive cables attached to the heliostat perimeter. The simplicity and structural efficiency of this concept has the potential to significantly reduce drive costs. A systems study was needed to determine the potential of the concept.

Objective:

The principal objective of this study was to assess the performance and cost of the SERI innovative drive concept compared to the drive assembly used in the ARCO Solar 150m^2 glass/metal heliostat. Another objective was to show that the simplicity and structural efficiency of the concept could lead to significantly reduced drive costs--contributing to meeting the heliostat installed cost goal of \$50-60/m^2.

Approach:

SERI performed a cost analysis of a conceptual model of the inflatable drive designed for a 10-meter diameter stretched membrane heliostat. A cost comparison with the ARCO 150 square meter heliostat was then performed using data obtained from the literature. Next, the central receiver computerized design model, DELSOL2, was used to determine system performance and its sensitivity to a range of tracking errors. These data were

then combined to calculate the allowable change in drive cost in order to maintain a given levelized energy cost as a function of error. Finally, some preliminary structural analysis work was done which was aimed at determining the source and size of the associated tracking errors as well as the range of required articulation.

Anticipated or Realized Accomplishments:

The study showed that the cost of the inflated drive was roughly 56% less than the cost of the comparable current generation heliostat drive/support assembly. This drive cost allows the possibility of achieving total heliostat installed costs of $\$50\text{-}60/m^2$. Secondly, for systems optimized at each level of tracking error, the study showed that system performance was relatively insensitive to tracking errors over the range investigated. In addition, the cost of the inflatable heliostat drive with tracking errors greater than or equal to 2.0 mrad in each axis was shown to be considerably less than the drive cost necessary to maintain the same system levelized energy cost as the baseline system using 0.75 mrad tracking errors.

Deliverables:

Wendelin, T., Cost/Performance Analysis of the SERI Inflatable Heliostat Tracking and Support Structure (Letter Report to be published after patent clearance), Golden, CO: Solar Energy Research Institute, 1986.

Technology Transfer Activities:

A briefing on the SERI inflatable heliostat tracking and support structure was given to DOE officials.

Expected or Realized Impact on Program:

This analysis showed it is possible to achieve lower-costing drives that meet technical performance requirements. This will facilitate attaining the heliostat cost goal of $\$50\text{-}\$60/m^2$.

How Used to Achieve Impact:

The results for this research can be utilized in the design of advanced heliostats to reduce capital costs.

Requested By:

This effort was requested by DOE.

Funding:

Approximately $35,000 was spent on this effort; $30,000 for in-house analysis and $5,000 for a costing consultant (Mr. Conrad Vineyard).

2.2 CONCENTRATORS: DISTRIBUTED RECEIVER SYSTEMS

2.2.1 Analytical Study: Assessment of the Feasibility, Cost and Performance Potential of Polymer Enclosed Thermal Dishes

Background:

During late FY 1982 and into early FY 1983, SERI investigated the feasibility and the cost and performance potential of heliostats enclosed in transparent polymer bubble-like enclosures compared to second generation glass/metal heliostats. The results of that study are documented in the report A Systems Study of the Polymer/Enclosed Heliostat Concept and A Comparison with Glass/Metal Heliostats (SERI/SP-253-1791). That study showed that enclosed heliostats had the potential to deliver thermal energy at a levelized cost significantly below that of second generation glass/metal heliostats if (i) the optical performance of the stretched polymer reflector could be dramatically improved (ii) the optical performance of the enclosure could be dramatically improved and (iii) a five-year dome life could be attained. The study also suggested that enclosures might be feasible for other concentrator concepts--such as dishes--and recommended that this be investigated. In FY 1983 DOE requested that SERI investigate--analytically and experimentally--the performance and cost potential of polymer enclosed thermal dishes (i.e., dishes for process heat applications, rather than for producing electricity). It was believed that if thermal dishes were enclosed, it might be possible to fabricate them using very lightweight structures and thereby reduce their costs significantly. However, the cost implications and performance limitations of polymer enclosed dishes were not understood.

Objective:

The objective of the analytical part of the effort was to assess the technical and economic feasibility of fabricating durable, lightweight thermal dishes enclosed in transparent polymer enclosures to protect the dishes from wind and other loads.

Approach:

Assisted by JPL, SERI reviewed previous thermal dish studies to identify and understand various issues--e.g., beam walk off, optical alignment error, convective plume heating, thermal reradiation, energy transport, etc. This was followed by development of conceptual design for an enclosed dish that allowed for greatly reduced structural weight and cost. The design was assessed regarding its technical and economic performances using an analytical model developed by SERI. An analytical ray trace model was also developed to perform a detailed assessment of the beam walk off/on problem. Numerous trade-off analyses were performed to determine component cost/performance impacts on the delivered cost of energy. SERI also developed several conceptual designs for external receivers (which were consistent with the enclosed dish configuration) and assessed their performance. In parallel with the analytical work, SERI designed, fabricated and evaluated a two-meter diameter polymer enclosure with base attachments.

Anticipated or Realized Accomplishments:

The analytical study showed that an enclosed thermal dish was potential more cost effective than an unenclosed dish if a number of important development issues could be resolved (examples included: (i) optical transmittance of the enclosure, (ii) identification of a material with good tear strength, and (iii) variable pressurizations of the dome, etc). However, the benefits of an enclosed thermal dish did not appear strong enough to make it more cost effective than other solar thermal technologies for system sizes above 5.0MW. Transport costs for thermal dishes were estimated to be exceedingly large. SERI estimated that enclosures would aggravate these high costs, causing some of the anticipated advantages of enclosures to be lost. Furthermore, the analysis showed that a deep profile, unenclosed dish with a f/D (i.e., ratio of focal length to rim diameter) of about 0.25, when coupled with an external receiver, had numerous structural, operational and potential cost reduction benefits for process heat temperatures at or below 540^{o}C.

Deliverables:

Murphy, L. M., et al., Polymer Enclosed Thermal Power Dishes: An Initial Feasibility, Engineering, and Cost Performance Assessment, SERI/SP-253-2197, Golden, CO: Solar Energy Research Institute, December 1983.

A two-meter diameter bubble enclosure was designed, fabricated, and installed at the SERI test facility.

Technology Transfer Activities:

The results of this work were presented to DOE and Sandia National Laboratories at DOE on several occasions.

The briefing package was distributed only within the DOE solar thermal the community.

Expected or Realized Impact on Program:

Because of the findings in this study, DOE terminated R&D on polymer enclosed thermal dishes. Emphasis in the dish program was re-directed to the identification and evaluation of innovative, potentially low-costing unenclosed dishes that could be used for process heat applications or for driving heat engines (e.g., Stirling) to produce electricity.

How Used to Achieve Impact:

The results of the study were used to help DOE formulate a decision to redirect research activity into other potentially more promising areas.

Requested By:

The study was requested by DOE.

Funding:

The funding was approximately $250,000 (including hardware fabrication and testing).

2.2.2 Analytical Study: Systems Assessment of Inflated Conical Concentrators

Background:

One of the continuing efforts in the Solar Thermal Research Program--to make solar thermal systems economically viable--is conducting research to identify and assess the feasibility of innovative, low-cost, lightweight concentrators (of all types) that can meet the technical performance requirements. At the present time, parabolic dishes are accepted as the most promising concentrators for distributed receiver systems. However, the costs of these concentrators are high because of: (i) the requirement for an optically accurate surface (i.e., the surface errors must be small) and (ii) the requirement to withstand weight and wind loads. A solar alternative to the parabolic dish that has the potential to be less costly is an inflated conical concentrator with a reflective surface fabricated from a relatively inexpensive sheet of lightweight, flat polymer material. The conical concentrator concept formulated by SERI is a two-axis tracking concentrator consisting of a conical reflective surface with a linear receiver along the axis of the cone. The reflective surface of the cone forms a 90^{o} angle at the vertex so that all direct insolation is parallel to the cone axis and reflects once off the cone surface at a 45^{o} angle before hitting the receiver. Inflation (using air) of the bag formed by the reflective surface and a transparent plastic cover on the aperture maintains the conical surface. In addition to allowing for inflation of the bag, the cover on the aperture provides environmental protection for the reflective surface.

Objective:

The objective of the study was to conduct a preliminary cost/performance evaluation of such a conical concentrator in order to determine the relevant structural design, fabrication, performance, and cost issues.

Approach:

SERI first formulated conceptual designs for two solar thermal systems having conical concentrators: (i) a system for a 400°C process heat application and (ii) a system for producing electric power. After generating estimates of the capital and O&M costs of these systems, SERI modeled their technical performance using Rabl's method. Their levelized energy costs were calculated and compared to those for a parabolic dish system and a system with trough concentrators. The levelized energy cost for the trough and dish systems were determined assuming the STT Program's long-range goals for those systems were met.

Anticipated or Realized Accomplishments:

The study showed that for the process heat application, the levelized cost of thermal energy for the conical concentrator system ($5.57-6.47/GJ) was significantly lower than that for the parabolic trough system ($9.28/GJ) and comparable to that for the parabolic dish ($6.16/GJ). For Electric power product, the levelized cost of energy for the conical concentrator system ($0.041-0.069/kWh) was estimated to be comparable to that for a 25 kWe parabolic dish/kinematic Stirling system ($0.051/kWh). The sensitivity analyses indicated that the above results were not extremely sensitive to a reasonable range of the following parameters--macroscopic surface errors on the cone reflective surface, receiver emissivity, reflective surface lifetime, etc).

Deliverables:

Short, W. and T. Wendelin, Cost and Performance Analysis of an Inflated Conical Concentrator, SERI/TR-253-2872, Golden, CO: Solar Energy Research Institute, March 1986.

Technology Transfer Activities:

Apart from distribution of the above-mentioned report, SERI has conducted briefings for DOE/HQ.

Expected or Realized Impact on Program:

The work resulted in the development of three prototype conical concentrators. The work is being used in the preparation of a proposal to NASA for a lightweight collector for space applications. The preliminary analysis showed that further investigation of the concept was warrented. This might be done in the FY 1987 Solar Thermal Research Program.

How Used to Achieve Impact:

The results of the study are currently being used only internally at SERI for the NASA proposal as noted above.

Requested By:

The study was requested by DOE as part of the innovative concentrator research.

Funding:

The cost of the study was approximately $65,000 (including hardware fabrication).

2.2.3 Analytical Study: Systems Assessment of Linear Fresnel Lens Concentrators for Solar Thermal Applications

Background:

One of the major thrusts in the Solar Thermal Research Program in FY 1985 and FY 1986 was identifying and assessing the feasibility of new concentrator concepts and optical approaches that had the potential to dramatically improve the optical performance and/or reduce the costs of concentrators compared to current concepts (e.g., reflectors, etc.). One such concept is Fresnel lens concentrators. Flat Fresnel lens were introduced into solar R&D in the mid-1970s to obtain low concentration ratio collectors. At that time, there were problems with the concept because of low optical efficiency due to focusing, transmittance and and manufacturing problems. Since that time, an extensive amount of R&D has been directed toward improving the concentration and optical efficiency of Fresnel lens. Improved manufacturing techniques have also contributed to better performance by allowing more exact prism shaping--it is currently possible to mass produce accurately shaped, transmittance-optimized Fresnel lenses at potentially low costs. Many of the current capabilities of Fresnel lens have resulted from R&D sponsored by the DOE National Photovoltaics (PV) Program. Fresnel lens are being utilized in concentrating PV arrays.

The low-cost potential of Fresnel lens has traditionally been a major reason for their consideration in the STT Program. Other attractive features are low weight, durability, ease of adaption to mass production techniques, and their demonstrated performance and reliability (base on experience gained from PV applications and from a hybrid Fresnel lens solar thermal system developed by ENTECH for DOE). Because of improvements in the technology and the above-mentioned attractive features, SERI conducted a systems study of the concept in late FY 1985.

Objective:

The objective of the study was to provide an objective assessment of the performance and economic potential of linear Fresnel lens solar thermal systems compared to systems

having parabolic trough concentrators--both types of providing thermal energy at temperatures in the range 100^{o}-300^{o}C.

Approach:

For both types of concentrators--Fresnel lens and conventional parabolic troughs--SERI formulated conceptual STT system designs for two applications: (i) a low-temperature water preheat system and (ii) a higher temperature saturated steam system. After generating estimates of the capital and O&M costs for the four systems, SERI assessed their technical performance using the computer SOLIPH. The capital and O&M cost data were generated using both published cost data and cost estimates obtained from manufacturers. The technical performance and cost data were then combined to assess the economic performances of the systems (i.e., levelized cost of energy). The study also included performing sensitivity analyses and identification of R&D issues.

Anticipated or Realized Accomplishments:

The results of the study indicated that the Fresnel lens systems were comparable in performance to troughs over the temperature ranges examined. It should be noted that the specific Fresnel lens concentrator evaluated in this study was the only one available, and it had a maximum temperature lower than typical troughs. Cost estimates indicated that the Fresnel lens collector may be lower in cost than the trough by as much as 25%. This cost advantage was also reflected in a lower levelized energy cost for the Fresnel lens system. SERI concluded that the Fresnel lens technology can, at the minimum, clearly compete with parabolic trough technology in both performance and cost for typical thermal applications.

Deliverables:

Simms, D. A. and A. A. Lewandowski, System Performance and Cost Studies of Linear Concentrating Fresnel Lens Solar Thermal Collectors, SERI/TR-253-2870 (Draft), Golden, CO: Solar Energy Research Institute, to be published in FY 1986.

Technology Transfer Activities:

Lewandowski, A. and David Simms, "An Assessment of Linear Fresnel Lens Concentrators for Thermal Applications," SERI/C-253-0160, paper presented at the Solar Thermal Research Conference, February 19-21, 1986, Golden, CO. This paper has also been submitted to Energy-The International Journal.

Expected or Realized Impact on Program:

Since no research in line-focus technologies is currently being conducted in the STT Program, there will be little immediate Program impact. However, should any further research be conducted in this technology area, the study showed that Fresnel lens systems should be considered, along with the parabolic trough and other line-focus concepts.

How Used to Achieve Impact:

See "Expected or Realized Impact on Program" above.

Requested By:

This study was requested by DOE/HQ.

Funding:

This study costed about $15,000.

2.3 DIRECT ABSORPTION RECEIVERS

2.3.1 Analytical Study: Direct Absorption Receiver Systems Studies - Phase 1 (Generation of Electricity)

Background:

As part of the FY1983 Solar Thermal Research Program, SERI investigated the technical feasibility of high temperature/high flux central receiver systems ("high temperatures" are receiver outlet temperatures above 600°C). The major rationales for the activity were:

- The possibility of significantly better thermodynamic efficiencies at higher temperatures
- The large potential market for process heat at temperatures above 600°C
- The large market potential for fuels and chemicals production at temperatures above 600°C

As part of these efforts, SERI identified the Direct Absorption Receiver (DAR) concept--utilizing a cavity rather than an external receiver--as a promising means for capturing and converting concentrated solar flux into high temperature heat and for operating efficiently at temperatures in the range 900°-1100°C. The heat could be used for co-generation, high temperature process heat, producing electricity or for driving fuels and chemicals production processes.

Initially, the SERI efforts focused on research to provide the scientific and technical base for designing and operating DARs at temperatures in the range of 900°-1100°C. Analytical studies were needed to better identify the potential benefits anticipated from the DAR concept from an overall systems perspective.

Objective:

The principal objective of the Phase I study was to assess the anticipated system performance, capital cost of and levelized cost of energy for a high temperature DAR system for producing electricity compared to a nitrate salt/external receiver central receiver system. Another objective was to identify the design and research issues associated with high temperature direct absorption receivers.

Approach:

In this study, a relatively simple and straightforward systems analysis approach was utilized. Estimates of costs and performance of the components were taken from existing receiver analysis studies and applied to the DAR. Then, those estimates were combined with heliostat field and balance-of-system performance estimates to provide both a design point and an annual performance assessment. This was done for a number of field sizes and operating temperatures. Conversion efficiency to electric power was estimated as a function of temperature. The primary question was whether the increase in conversion efficiency as temperature increases could outweigh the decrease in receiver performance. Cost estimates taken from existing studies were used to determine system installed cost. Levelized energy costs were then determined from the annual performance and installed system cost estimates.

Anticipated or Realized Accomplishments:

Based on the assumptions and limitations in the study, the results indicated that the higher operating temperature capability of the DAR with molten carbonate salt as the working fluid did not result in an advantage in delivered energy cost for electric power applications. Adding storage to the system (increased capacity factor) appeared to offer little advantage in the cost of delivered energy. The DAR receivers appeared, however, to have a potential cost advantage over corresponding metal or ceramic tube receivers.

Deliverables:

Lewandowski, A., et al., Direct Absorption Receiver System Study Phase 1, SERI/SP-253-2438, Golden, CO: Solar Energy Research Institute, August 1984.

Technology Transfer Activities:

Results were presented at the Solar Thermal Research Program Annual Conference, February 20-22, 1985, Lakewood, CO, and published in the proceedings for that conference, SERI/CP-251-2680. Results were also presented to DOE/HQ at the FY 1985 Third Quarter Review.

Expected or Realized Impact on Program:

The study showed that, for producing electricity, a high temperature DAR/central receiver system did not appear to have a significant advantage over lower temperature STT system coupled to a conventional electric power generation subsystem. Because of the study, efforts were shifted toward investigating use of high temperature DAR systems for process heat applications.

How Used to Achieve Impact:

See "Expected or Realized Impact on Program" above.

Requested By:

This study was requested by DOE/HQ.

Funding:

The approximate cost of the study was $30,000.

2.3.2 Analytical Study: Direct Absorption Receiver Systems Studies - Phase 2 (Process Heat Applications)

Background:

As part of the FY1983 Solar Thermal Research Program, SERI initiated investigation of the technical feasibility of high temperature/high flux receivers for central receiver STT systems ("high temperatures" are receiver outlet temperatures above 600°C). As part of this research, SERI identified the Direct Absorption Receiver (DAR) concept--utilizing a cavity rather than an external receiver--as a highly promising means for capturing and converting concentrated solar flux into high temperature heat and for operating efficiently at temperatures in the range 900°C-1100°C. DARs were estimated to offer the following major advantages compared to external receivers utilizing metal or ceramic tubes to convert solar flux into heat:

- Ability to operate at temperatures above 1000°C at low pressures
- Ability to operate at higher absorber flux levels
- Lower cost potential because fabrication and engineering design requirements may be less stringent.

The high temperature heat from a DAR/central receiver system could be utilized for co-generation, process heat applications, producing electricity or for fuels and chemicals production.

In July 1984, SERI completed a systems study ("Direct Absorption Receiver Systems Study - Phase 1") to assess the anticipated system performance and costs of DAR/central receiver systems for producing electricity compared to the performance and costs of central receiver systems with external receivers. The Phase 1 study showed that, for producing electricity, a high temperature DAR/central receiver system did not appear to have a significant advantage over other concepts. In the report documenting the results of the Phase I study, it was recommended that efforts be devoted to determining if the advantages of the DAR concept could be effectively captured in process heat applications. This recommendation was the basis for the Phase 2 study.

Objective:

The objective of the Phase 2 study was to assess the performance potential estimating the capital cost of and levelized cost of energy of a DAR/central receiver system for process heat applications--the receiver outlet temperature being in the range 900°-1200°C (the Phase 1 study addressed electricity generation).

Approach:

This study utilized a relatively simple and straightforward systems analysis approach. Estimates of component technical performance were taken from existing receiver analysis studies and applied to the DAR. They were combined with heliostat field and balance-of-system performance estimates to provide both a design point and an annual performance assessment. This was done for various heliostat field sizes and operating temperatures. Cost estimates, also taken from existing studies, were used to determine system installed cost. Levelized energy costs were then determined from the annual performance and system installed cost estimates.

Anticipated or Realized Accomplishments:

The study showed that DAR systems for process heat applications appear to approach or meet the DOE Five-Year Program Plan levelized energy cost goals for a range of plant sizes and capacity factors at operating temperatures of 900°C and 1200°C. To meet these goals, however, it is critical for the heliostat cost goal (i.e., 50-60/m^2) to be met or exceeded. Adding storage to these systems (i.e., increasing the capacity factor) appeared to offer little advantage in reducing levelized energy cost. The DAR receivers studied appeared, however, to have a potential cost advantage over corresponding ceramic or metal tube receivers.

Deliverables:

Lewandowski, A., et al., Direct Absorption Receiver System Study, Phase 2, SERI/SP-253-2592, Golden, CO: Solar Energy Research Institute, December 1984.

Technology Transfer Activities:

The results of the study were presented at the Solar Thermal Research Program Annual Conference, February 20-22, 1986, Lakewood, CO, and published in the conference proceedings, (SERI/CP-251-2680). The results were also presented to DOE/HQ at the FY 1985 Third Quarter Review.

Expected or Realized Impact on Program:

Although the study showed that DAR/central receiver systems had the potential to approach or meet the levelized cost of energy goals for process heat applications (goals documented in the Five-Year Solar Thermal Technology R&D Program Plan), it was pointed out that there were large uncertainties in the results because of numerous unknowns (e.g., design details, fabrication cost, materials performance, etc.). SERI recommended that a study be performed to determine if the expected operational and cost advantages of DARs running at high temperatures also accrued at lower operating temperatures (i.e., 500-600^{o}C)--a temperature range for which there was less uncertainty regarding costs, materials and performance. As a result of the Phase 2 study, DOE approved a study to analyze intermediate temperature (i.e., 500^{o}-600^{o}C) DAR systems.

Consequently, although the Phase 2 study was not definitive, it became the basis for redirection of the central receiver R&D program from high to intermediate temperatures.

How Used to Achieve Impact:

See "Expected or Realized Impact on Program" above

Requested By:

This study was requested by DOE/HQ.

Funding:

This study cost approximately $30,000.

2.3.3 Analytical Study: Direct Absorption System Studies - Intermediate Temperature (i.e., 550°C) Systems

Background:

During the period FY1983 - FY1985, SERI, as part of the Solar Thermal Research Program, investigated the technical feasibility of high-temperature (i.e., 900°-1100°C) direct absorption receiver (DAR)/central receiver systems for the following applications: (i) producing electricity, (ii) co-generation, (iii) process heat, and (iv) producing fuels and chemicals.

The DAR experimental and theoretical research work was supported by two systems studies to assess the potential benefits of the concept and to identify the R&D issues:

- Direct Absorption Receiver Systems Studies - Phase 1: an assessment of the benefits of the concept in generating electricity compared to systems utilizing salt-in-tube external receivers.
- Direct Absorption Receiver Systems Studies - Phase 2: an assessment of the benefits of the concept for IPH applications compared to systems with salt-in-tube receivers.

Both of these studies showed that DAR systems operating at temperatures in the range 900°-1100°C had technical performances that were potentially better than those for systems utilizing salt-in-tube external receivers operating at temperatures in the range 700°-900°C. However, the performance was not significantly better. On the other hand, DAR receivers appeared to have a clear potential cost advantage. However, there were large uncertainties in the results because of numerous unknowns regarding DARs operating at high temperatures (e.g., materials performance, design details, etc.). Consequently, SERI recommended that a study be performed to determine if the expected technical performance and cost advantages of DARs operating at high temperatures also accrued at intermediate temperatures (i.e., 500°-600°C) applications--a temperature range for which there is less uncertainty with respect to materials performs, costs, etc.

The SERI recommendation to DOE/HQ was the basis for the subject systems study.

Objective:

The objective of this study was to establish the potential merits of the DAR concept as a competitor for supplying energy in the intermediate temperature (550°C) range commonly used in electric generating applications.

Approach:

The first step in the study was to formulate a DAR system concept and a competing central receiver utilizing a salt-in-tube receiver. The system performances of the two conceptual designs were determined using the central receiver design/analysis tool DELSOL2. The costs and economic parameters were drawn from several sources, including the Martin Marietta Saguaro Design, and the draft document Solar Thermal Technology Five-Year Research and Development Plan developed by Sandia National Laboratories/Livermore.

Anticipated or Realized Accomplishments:

The study showed that although the thermal performances of the DAR and salt-in-tube receivers were similar, the DAR concept had the potential to have a significantly better economic performance. For example, the DAR receiver had the potential to reduce the size of the absorber by a factor as large as three--providing significant capital cost savings. SERI estimated that the levelized cost of energy from the DAR system was 17% less than that for the system with the salt-in-tube receiver.

Deliverables:

A SERI-generated letter report was delivered to DOE/HQ in mid-1985. The results of the study were also presented at a DOE Quarterly Review meeting.

Technology Transfer Activities:

Apart from the deliverable mentioned above and briefings for DOE/HQ and Sandia/Livermore, there have been no formal technology transfer activities.

Expected or Realized Impact or Program

The study showed that there were several benefits associated with re-directing the DAR research from emphasis on high temperatures to the more accessible intermediate temperature range. As a result of the study, there were two major impacts:

(a) DOE/HQ approved SERI's undertaking a subsequently systems study of intermediate temperature DAR systems--a study to:

  (i) identify the technical barriers and R&D needed to support development of the concept, and

  (ii) develop a more detailed and accurate understanding of the receiver/optical interface.

(b) The DAR research was redirected to emphasize intermediate temperature systems concepts and applications for the near term. This can be a possible lead-in to high-temperature DAR R&D in the future.

How Used to Achieve Impact:

See "Expected or Realized Impact on Program" above.

Request By:

This study was requested by DOE/HQ.

Funding:

Approximately $60,000 was utilized for SERI in-house effort.

2.3.4 Analytical Study: Direct Absorption Receiver (DAR) Systems Analysis - FY1986

Background:

During FY1985, SERI performed a quick-turnaround systems study of an intermediate temperature (i.e., 550°C) central receiver/DAR system to assess its cost and performance potential in generating electricity compared to a central receiver system that utilized a salt-in-tube receiver. The study showed the following:

- The thermal performances of the DAR and the salt-in-tube (nitrate salt) receivers were similar
- The DAR had the potential to reduce the size of the absorber by a factor of three--providing for the possibility of significant capital cost savings
- The system utilizing the DAR had a levelized cost of energy that was 17% lower than that for the system with the salt-in-tube external receiver.

Because of these findings, SERI recommended that additional, more detailed studies of the DAR concept be performed for intermediate temperature applications--to assess the cost and technical performance potential of the concept and to identify the R&D issues. There were two rationales for the recommendation: (i) intermediate temperature DAR systems are promising in their own right as demonstrated by the results of the FY1985 study and (ii) successful applications at intermediate temperatures could provide the lead-in for conducting R&D on high temperature DAR systems in the future.

The results of the FY1985 study and the SERI recommendation were the basis for undertaking the subject FY1986 systems study.

Objective:

The objectives of this FY1986 work were to study the feasibility of the DAR concept from a systems perspective, to determine the technical barriers, and to identify the research needed to support the eventual development and implementation of the concept. Another objective was to develop a more detailed and accurate understanding

of the receiver/optical interface for central receiver applications which could lead to more effective receiver/field combinations.

Approach:

The strategy in the study was to design a DAR system and assess its cost, technical performance and economic performance compared to a conventional salt-in-tube receiver (i.e., the receiver for the Saguaro project). An engineering study was conducted to establish a viable cavity receiver concept and assess it structural feasibility. After the receiver conceptual design was finalized, detailed cost estimates were generated. The technical and economic performances of the system were assessed using models such as DELSOL 2 and SOLERGY. The results for the cavity receiver were then compared to those for the conventional salt-in-tube receiver. Efforts were then devoted to identifying the research issues.

Anticipated or Realized Accomplishments:

One of the most important accomplishments of this study was formulation of an engineering design for a 100 MW_{th} central receiver system with a cavity DAR that utilizes molten nitrate salt as the thermal fluid and delivers energy at 550°C to an electric power generating plant. The design was formulated for SERI by Solar Power Engineering Company--a spinoff from Martin Marietta of the group that designed the Solar One System. To date, this is the most detailed design for a cavity DAR central receiver system and addresses important issues such as (i) absorber plate design, (ii) absorber plate stresses, (iii) optical darkening of the nitrate salt thermal fluid, and (iv) a recirculation system to reduce temperature gradients on the absorber.

The analysis of the cavity DAR system showed the following: (i) the energy delivered by a cavity DAR should exceed that of a conventional salt-in-tube receiver by about 16%, (ii) the capital cost of a cavity DAR has the potential to be 56% less than that for a salt-in-tube receiver, and (iii) compared to a salt-in-tube receiver, the levelized cost of energy for a system with a cavity DAR should be 20% less.

Deliverables:

Anderson, J. V. et al., DAR Systems Assessment Briefing Package, Golden, CO: solar Energy Research Institute, July 1986.

Technology Transfer Activities:

In addition to the above-mentioned report, efforts will be devoted to briefing DOE/HQ and the R&D community on the results of the study in the Fourth Quarter of FY1986.

Expected or Realized Impact on Program:

Since the results of the study were highly promising, the study will serve to continue the re-orientation of the central receiver R&D efforts towards intermediate temperatures (i.e., above 550°C) and away from high temperatures in the near-term. The conclusions and recommendations from the study will be utilized to plan FY1987 R&D on DAR central receiver systems. In addition, the detailed 100 MW_{th} cavity DAR central receiver concept formulated in this study can be made available for subsequent "what if" system studies to be performed by SERI, SNLA or DOE/HQ.

How Used to Achieve Impact:

See "Expected or Realized Impact on Program" above.

Requested By:

This study was requested by DOE/HQ.

Funding:

Approximately $60,000 for SERI in-house effort and $27,000 for the subcontract with Solar Electric Power Company.

2.4 APPLICATIONS

2.4.1 Analytical Study: Engineering and Systems Analysis of a Hybrid Quantum/-Thermal Process for Fuels and Chemicals Production

Background:

The conversion of solar radiation to useful work can be accomplished (i) by thermal conversion methods (using steam generators, thermoelectrical devices, etc.); (ii) by quantum conversion methods (using photovoltaics, photochemical approaches, etc.); (iii) or by a combination of thermal and quantum methods--so called quantum/thermal hybrid approaches. Emphasis in the Solar Thermal Research Program has been on thermal conversion methods. In FY1983 and FY1984, serious efforts were devoted to assessing the feasibility of quantum/thermal hybrid approaches. At a workshop at SERI in FY1983, the state-of-the-art of combining quantum and thermal systems was reviewed and various quantum/thermal hybrid system concepts were identified. One of the conclusions from the workshop was that a thermal conversion system has a greater maximum conversion system than a quantum system. However, the maximum conversion efficiency of the thermal system occurs at high temperature, while that for a quantum system occurs at ambient temperature. Because costs generally increase with operating temperature, it was not clear from efficiency considerations alone how to optimize a hybrid system. After the workshop, SERI performed preliminary thermodynamic analyses of hybrid systems. Those analyses showed that, under certain operating conditions, a hybrid system has a greater efficiency than either a quantum or a thermal system operating alone. Because of the promising results in FY1983, a more detailed analysis was performed in FY1984.

Objective:

The objectives of this FY1984 systems study were to (i) identify quantum/thermal hybrid system concepts for a specific application; (ii) assess the technical and economic performances of hybrid systems compared to those for conventional alternatives and (iii) identify those hybrid concepts showing the greatest potential. Emphasis in the study was on thermally decoupled quantum/thermal systems. For such systems, the incident solar

radiation is divided between the thermal and quantum processes by a beam splitter on the basis of wavelength. The short waves are collected by the quantum process; the long waves are collected by the thermal process.

Approach:

Since the emphasis was on thermally decoupled approaches, an important consideration was beam splitting. SERI identified, analyzed and compared various methods for beam splitting. The results of that effort were utilized to design and evaluate various solar collectors for a central receiver system. Hydrogen production was selected as the specific application. The conventional alternative was a thermal plant that generated hydrogen by an electrolysis process from electricity obtained using a Rankine cycle system having a molten salt storage subsystem. For the quantum/thermal system, the quantum process selected by SERI generated hydrogen by means of a photoelectrochemical process. The thermal part of the solar system used the same conversion cycle as the conventional alternative. After developing the conventional and quantum/thermal system concepts, SERI generated estimates of their capital and O&M costs and their technical performances. These estimates were then combined in an economic performance assessment of the levelized cost of producing hydrogen.

Anticipated or Realized Accomplishments:

SERI identified four major beam splitting methods: selective absorption, dichroic mirrors, holograms and fluorescent planar mirrors. Of these four, dichroic mirrors and holograms were estimated to be the most efficient. For the quantum/thermal central receiver system, the holographic approach was utilized to formulate a holographic heliostat design. The base case system was a 100 MW_e plant (corresponding to 85 MW_e of equivalent hydrogen output). The economic performance showed that the quantum/thermal solar system was capable of reducing the levelized cost of producing hydrogen by 10% compared to an existing conventional thermal plant--assuming its cost and performance goals could be met. However, because of significant improvements still needed in the photoelectrochemical decomposition of water to make hydrogen, SERI concluded that the R&D needed to make the improvements--in order to attain a 10% cost reduction--was not justified.

Deliverables:

Schell, D. et al., Engineering and Systems Analysis of a Hybrid Quantum/Thermal Process for Fuels and Chemicals Production, SERI/TR-232-2565, Golden, CO: Solar Energy Research Institute, 1984.

Technology Transfer Activities:

Apart from the deliverable above, there have been no formal technology transfer activities.

Expected or Realized Impact on Program:

Because the results of this study showed that quantum/thermal central receiver systems were only marginally better than conventional alternatives and that significant R&D was required, SERI discontinued work in this area and focused on thermal conversion processes.

How Used to Achieve Impact:

See "Expected or Realized Impact on Program" above.

Requested By:

This study was requested by DOE/HQ.

Funding:

The approximate cost was $132,000 for SERI in-house effort.

2.4.2 Analytical Study: Analysis of Nonequilibrium Chemical Reactions with Rapid Heating and Cooling

Background:

As part of the Energy Conversion Technology area of the FY 1985 Solar Thermal Research Program, SERI conducted research to (i) understand the absorption mechanisms by which concentrated solar flux was absorbed by matter and (ii) identify and assess the technical feasibility of promising uses of the phenomenon. One of the unique characteristics of solar energy is that it can be used to control the rate of heating of an absorbing substance. Because it is possible to obtain solar flux densities of the order of 3 megawatts/m^2, and because this energy is available in the form of radiant energy, very rapid heating rates are possible. This feature of solar energy was explored by SERI to study the feasibility of enhancing the yield of a chemical reaction using a rapid solar heating and a rapid quenching process. In the process investigated, the heating rate was so rapid that a chemical equilibrium mixture of products did not have time to be established. Therefore, compared to the rates of the chemical reactions, the concentration of certain species might be enhanced.

Objective

The objective of this study was to investigate the feasibility of enhancing the yield of a chemical reaction by using a solar-driven rapid heating process and a quenching the process. The process examined was the production of nitric oxide (a useful industrial source for producing ammonia) from air.

Approach:

The process selected for investigation was that of producing nitric oxide (NO)--a useful industrial source for producing ammonia--from air. the researchers first modeled analytically the production of nitric oxide from air in a process involving equilibrium conditions. This was followed by the modeling of the process in a non-equilibrium rapid healing and quenching process. The rapid heating was assumed to be accomplished by a

solid particle solar cavity receiver. The air is preheated to 10 atmospheres and 3500°K and is then rapidly heated at 10^9K°/second. The quenching process was assumed to start as the non-equilibrium process brought the mixture to a temperature of 5000°K. The researchers then compared the yields of nitric oxide in the two processes.

Anticipated or Realized Accomplishments:

The study was the first analytical effort that exploited concepts from the SERI-funded research at the Lawrence Berkeley Laboratory on the rapid heating of suspended particles by concentrated solar energy and utilized results from the Sandia/Livermore R&D on solid particle receiver concepts to assess the feasibility of using solar thermal technology to produce a specific chemical compound. The study showed that the nitric oxide yield in air undergoing rapid heating (by concentrated solar flux) in a nonequilibrium process had the potential to be higher than the yield in a equilibrium process operating at the same temperature. The study also showed analytically that small particles suspended in air can be heated at very high heating rates using concentrated solar flux.

Deliverables:

Wang, K. Y. and R. Benito, Nonequilibrium Chemical Reactions with Rapid Heating and Quenching, SERI/TP-252-2956, Golden, CO: Solar Energy Research Institute, June 1986.

Wang, K. Y. and W. W. Yuen, Rapid Heating of A Gas/Small Particles Mixture, SERI/TP-252-2903, Golden, CO: Solar Energy Research Institute, February 1986. (Paper Presented at the 1986 AIAA/ASME Thermophysical and Heat Transfer Conference, Boston, MA, June 2-4, 1986)

Technology Transfer Activities:

In addition to briefings for DOE/HQ, the above mentioned SERI report was submitted for publication in the scientific periodical "Energy: The International Journal."

Expected or Realized Impact on Program:

The study showed that the yield of a specific chemical species produced using a solar-driven nonequilibrium rapid heating and quenching process could be greater than if produced in an equilibrium process operating at the same temperature. However, in order to significantly improve the yield in the nonequilibrium process, the heating and quenching rates would have to be too high--given the state-of-the-art. Consequently, because of this study, the research was re-directed to search for other chemical processes having the potential to increase the yields of valuable chemicals by means of a rapid heating nonequilibrium process.

How Used to Achieve Impact:

See "Expected on Realized Impact on Program" above.

Requested By:

This study was requested by DOE/HQ.

Funding:

The funding for this study was approximately $60,000.

SECTION 3.0
SANDIA/LIVERMORE MAJOR ANALYTICAL STUDIES

(To be completed later)

SECTION 4.0
SANDIA/ALBUQUERQUE MAJOR ANALYTICAL STUDIES

(To be completed later)

SECTION 5.0
TECHNICAL PROGRAM INTEGRATOR (TPI) MAJOR ANALYTICAL STUDIES

(To be completed later)

SECTION 6.0
JET PROPULSION LABORATORY (JPL) MAJOR ANALYTICAL STUDIES

(To be completed later)

SECTION 7.0
MAJOR ANALYTICAL STUDIES BIBLIOGRAPHY

(To be completed later)