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PROGRAM SUMMARY REPORT

SOLAR-THERMAL POWER
TECHNICAL AND MANAGEMENT SUPPORT

See Ltr. Dtd. 3/8/79

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1. INTRODUCTION

The work described in this Program Summary Report was performed under DOE Contract ET-78-C-03-2225 and covers the period 15 July 1978 through 11 March 1979. The period of 15 January 1979 through 11 March 1979 was covered by a no-cost extension to the basic contract approved by the DOE San Francisco Operations Office on 28 February 1979. The contract number was changed to 03-79ET00711.501 by DOE/SAN at the time the extension was approved.

The objective of this effort was to provide technical and management support to the Assistant Director for Thermal Power Systems in the DOE Division of Central Solar Technology (CST). This support, which was covered by a single task, fell into the following three areas:

- Preparation of technical inputs for special management reviews
- Evaluation and analysis of advanced concepts and planning studies, as required by CST
- Provision of other technical support to CST in the preparation, review, and documentation of the Thermal Power Systems Program

Section 2, Task Descriptions, contains brief descriptions of each of the six activities carried out on this contract. Appendix A, contains a draft of the Goals and Requirements Section of the Integrated Solar Thermal/Industrial Process Heat Program Plan. This draft was prepared by The Aerospace Corporation in response to a request by DOE but was not included in the Plan. The Section is included here to formally document this activity.

2. TASK DESCRIPTIONS

This section contains brief descriptions of each of the six support activities carried out by The Aerospace Corporation on this contract. The first activity, preparation of the significant development weekly reports, spanned the entire contract period. Preparation of briefings for the Solar Thermal Power Systems Program occurred during the first four months of the contract. The preparation of the first Annual Thermal Power Systems Technical Progress Report, which has been a continuing effort since September, has required varying degrees of effort during this period. The remaining three activities were short duration efforts which occurred at different times during the contract period of performance.

2.1 SIGNIFICANT DEVELOPMENT WEEKLY REPORTS

Significant Development Weekly Reports represent the primary means of documenting significant events in the Solar Thermal Power Systems Program for higher levels of management within the Office of Solar, Geothermal, and Electric Storage Systems of the Department of Energy.

Information was compiled weekly from the San Francisco Operations Office, Sandia Livermore Laboratories, and The Aerospace Corporation for the preparation of 35 Significant Development Weekly Reports for the Large Power Systems Branch. Inputs were also collected from the Jet Propulsion Laboratory and Sandia Livermore Laboratories for the Advanced Technology Significant Development Weekly Report.

2.2 THERMAL POWER SYSTEMS PROGRAM BRIEFING PREPARATION

An important aspect of any program is the prompt and lucid communication of programmatic information to higher management, both within and without the program office, and to interested persons not connected with the program. The Aerospace Corporation was asked to prepare a "general purpose" briefing, which would describe all elements of the Solar Thermal Power Systems Program in a form which would be intelligible to the general public.

Work was started on this briefing in June 1978 under the preceding contract (ET-76-C-03-1101). The original 80 vugraphs were complemented by 64 additional vugraphs prepared during the first three months of the current contract. In general, these additional vugraphs either provided greater detail in various program areas or consolidated generic information into a single chart. Vugraphs covering a particular portion of the Solar Thermal Power Systems Program can be augmented by additional charts of a more technical nature for special purpose use.

A briefing was prepared for the Assistant Director for Thermal Power Systems in November 1978 to highlight the accomplishments of each project in the Solar Thermal Power Systems Program. This briefing was intended as an interim means of describing the Program accomplishments until the Annual Technical Progress Report (see Section 2.6) became available.

2.3 INTEGRATED SOLAR THERMAL/INDUSTRIAL PROCESS HEAT PROGRAM PLAN

Prior to the formation of the Department of Energy in 1977, all solar energy activities were the responsibility of the Assistant Administrator for Solar, Geothermal, and Advanced Energy Systems in the Energy Research and Development Administration (ERDA). When DOE was formed, the solar energy effort was split into two areas, one reporting to the Assistant Secretary for Energy Technology (ET) and the other reporting to the Assistant Secretary for Conservation and Solar Application (CSA). The industrial process heat activity in ERDA became the responsibility of the Agricultural and Industrial Applications Branch of CSA, but was supported partially by funds from ET. It was necessary to coordinate the technology development between the two organizations and to document these jointly shared responsibilities in an Integrated Program Plan. The Aerospace Corporation was requested to assist in the preparation of the Plan by the Assistant Director for Thermal Power Systems (ET) and the Chief of the Agricultural and Industrial Applications Branch (CSA).

The Aerospace Corporation was specifically requested to prepare a draft of the Goals and Requirements section of the Program Plan. The inputs were submitted to DOE on 31 August 1978 by letter from H. M. Webb of

Aerospace to J. Dollard, the CSA Branch Chief. A copy of the submittal is shown in Appendix A.

The goals and requirements were formulated to achieve the program objective of "the earliest possible commercialization of solar thermal energy systems". Goals were selected to: (1) permit competitive production in the pre-1985 time period of trough collectors, using existing technology, to generate low-temperature energy and (2) allow competitive production in the pre-1990 time period of the developing central receiver systems for the generation of high-temperature energy. To achieve these goals, both programs may require tax credit incentives of 50-60 percent for a period of 5-10 years. The tax incentive program is intended to expand production volumes to the point that the sales will reduce equipment costs to a level where incentives will no longer be required.

2.4 REVIEW OF THE STORAGE TECHNOLOGY DEVELOPMENT PROGRAM FOR THERMAL POWER SYSTEMS

A portion of the Storage Technology Program within the Division of Energy Storage Systems (ET) is intended to support the energy storage requirements of the Solar Thermal Power Systems Program within the Division of Central Solar Technology. A draft of the Program Plan for Storage Technology Development for Thermal Power Systems was prepared by another DOE contractor. The Aerospace Corporation was requested to review the draft Plan by the DOE Project Manager at the NASA Lewis Research Center to ensure that the Plan properly reflected CST's needs. Comments on the draft Plan were transmitted to DOE on 9 October 1978 by letter from M. B. Watson to the contractor, with information copies to the Assistant Director for Thermal Power Systems (CST) and to the NASA Lewis Project Director. It was felt that the Plan was technically shallow and programmatically confusing. The following points of major concern were identified:

- Conversion of the Storage Technology Program into an independent Storage System Development Program directly tied to Thermal Power Systems projects (including several that may not be pursued) does not appear desirable. It was suggested that further guidance from DOE on this approach may be required.

- The plan implied that receiver and conversion equipment design/development activities might be undertaken as part of the Storage Program, which seems unnecessarily duplicative.
- The motivation for considering substantial funding of the Program by Thermal Power Systems (CST) with management by Storage (ESS) was initiated to increase the responsiveness of the Storage Program to the needs of the Thermal Power Systems Program. The management approach proposed in the plan did not recognize the need for greater interaction between the two programs.
- More than 50 percent of the funding in the proposed program was assigned to three program elements which are the least defined and appear to be the least responsive to the priority needs of the Thermal Power Systems Program.

2.5 REVIEW OF THE THERMAL POWER SYSTEMS MULTIYEAR PLAN

A Multiyear Plan was prepared by the Assistant Director for Thermal Power Systems to describe the planned technology development activities in the Solar Thermal Power Systems Program as a means of communicating information about the Program to DOE decision-makers and to other interested parties. The Plan focuses on applications and solar thermal systems having favorable conditions for early market penetration. A draft of the Thermal Power Systems Multiyear Plan was reviewed at the request of the Assistant Director. Comments were transmitted to him by letter from M. B. Watson on 16 November 1978.

In summary, the draft appeared to represent a good first effort. However, the Plan appeared to be too long and, in some areas, used well-turned phrases to transition across some issues which could have been addressed more directly, even though complete answers to these issues are not available in all cases. The following significant comments were made with respect to the Plan:

- The correlation of various program element descriptive material with the program structure was poor and led to confusion.
- Bowl collector systems should not be singled out as a separate application concept any more than any other collector concept, the Crosbyton Project notwithstanding.
- The strategy was quite vague and did not address meaningful issues. Perhaps a better approach would have been to discuss the strategy in terms of several needs such as:

- Reduce the cost of current technology systems
 - Develop experience with attractive applications
 - Explore alternate and advanced technology systems
 - Encourage the development of industrial manufacturing facilities
 - Promote the development of an industrial/institutional infrastructure essential to effective commercialization
 - Build an awareness of viable solar thermal system options among potential users
- While the concept of Technology Readiness was introduced, it was not defined. Definition of Technical Readiness and Commercial Readiness, and the distinction between the two, could lead to a better understanding of the rationale for many of the technology development activities and system experiments without the need to introduce the "quads" type of argument.
 - The setting of cost goals is desirable, but the goals were too fine-grained in time (three goals in 8 years). In addition, some of the goals for various types of systems appeared to be inconsistent.
 - Cost-effectiveness should not be an objective of the first-of-a-kind large scale experiments such as Barstow or Ft. Hood. The real value of these experiments is in understanding total system performance and external interface interactions.
 - The measurement of progress described in the Plan is a major step forward. If the specific management areas can be correlated with key milestones, there will be much more confidence that the Plan will be responsive to evolving needs and technical accomplishments.

2.6 ANNUAL THERMAL POWER SYSTEMS TECHNICAL PROGRESS REPORT

The preparation of the first Annual Thermal Power Systems Technical Progress Report consumed the lion's share of effort expended on this contract. Work began in July with the preparation of a schedule and guidelines to be used in the preparation of inputs to the Report. The guidelines were issued in late August to all organizations responsible for preparing inputs to the Report with the request that the information be available at the annual program review at the end of September. Most of the inputs which were received were not usable and, more importantly, many inputs were not received because of the short time allowed for their preparation. Delays in receiving the inputs from all of the Program

Managers and the poor quality of a few inputs led to a slip in the desired target date for a final draft of the Annual Technical Progress Report from 15 November to early 1979. During an internal review of an early partial draft of the Report by DOE on 22 December, it was decided to rewrite the Report to shorten it significantly; to proceed with the Report omitting those sections which still had not been submitted to DOE; and to provide a copy of the revised Report to DOE as soon as possible. The final draft of the revised Report was submitted to DOE on 16 February for review and was also sent to each Program Manager who had provided inputs to the Report for a review of his section. Comments are due back to DOE by 9 March. A camera-ready copy of the Annual Report is expected to be available for final approval by DOE approximately four weeks after the receipt of the review comments if no major revision of the Report is required.

APPENDIX A. DRAFT OF GOALS AND REQUIREMENTS SECTION OF THE INTEGRATED
INDUSTRIAL PROCESS HEAT/SOLAR THERMAL PROGRAM PLAN PREPARED BY
THE AEROSPACE CORPORATION

The Aerospace Corporation was requested to prepare a draft of the Goals and Requirements section of the Integrated Industrial Process Heat/Solar Thermal Program Plan, by the DOE Program Managers. The Aerospace approach to goals and requirements laid out a methodology for achieving these goals over a period of time. The decision was made by DOE to use a different approach which merely stated the goals without indicating how they were to be achieved.

Since preparation of the Goals and Requirements draft required an appreciable effort and since this material has not been documented elsewhere by The Aerospace Corporation, the draft of the Goals and Requirements section is reproduced in this Appendix as a matter of record.

SECTION II. GOALS AND REQUIREMENTS

2.0 INTRODUCTION

The goals and requirements presented in this section are aimed at achieving the program objective, "the earliest possible commercialization of solar thermal energy conversion systems". The strategy employed to achieve this objective is two-fold. First, to integrate the development of solar industrial process heat systems with the other solar thermal program elements, i.e., solar thermal electric and solar thermal total energy systems, to achieve an earlier commercialization for all solar thermal equipments than could be achieved with separate development efforts. Second, to identify tax incentives required to reduce economic risk for industry and utility users and thus stimulate the earliest commercialization. The economic methodology employed in this section determines the required level and period of incentives necessary for commercialization of program elements.

The commercialization program will distribute solar technology throughout industry as it is developed maximizing industrial participation in the development efforts. Initial emphasis will be to distribute the existing trough collector technology focused on industrial process heat applications which are less sophisticated and less demanding than electric utility applications. Industrial process heat systems will be aimed at the repowering market in the oil or gas fuel saver mode. The process heat repowering market is the simplest and least costly type of solar thermal system, requiring neither thermal storage nor thermal to mechanical or electrical conversion subsystems. The process heat systems are aimed at reduction of solar collector system cost. Later, as the storage and energy conversion technology are developed solar thermal electric systems can more easily enter the commercial market, capitalizing on the reduced collector cost achieved through earlier introduction in the process heat market.

2.1 METHODOLOGY

The text that follows presents a simple economic methodology defining the incentives and cost sharing requirements for an integrated solar thermal program. The methodology combines solar system learning curves, potential market, and system performance in an iterative fashion to calculate the projected capital investment required for energy systems in future years. This projected capital investment is then combined with the other factors of money, system lifetime, and investment tax credit incentives to obtain the delivered cost of solar energy. Solar energy cost is then compared with the cost of competing fuels to evaluate the value of incentives. Appropriate investment tax credit incentive levels and time period requirements can then be identified. Government cost sharing required to maintain production in the pre-incentive period can also be estimated.

Figure 1 presents the solar system learning curves based on Government buys of trough collector systems and central receiver systems. The ordinate and abscissa of the figure are expressed in total solar system cost in dollars per square foot of collector area and cumulative collector area production base in millions of square feet. The trough system costs have been calculated for industrial process heat systems with thermal storage and thermal to mechanical electric conversion costs deleted. Central receiver solar thermal system costs are similarly adapted from STTF and pilot plant data. Projections of market growth of solar thermal systems are presented in Figure 2. The initial growth represents actual installations while the balance of the curves are forecasts of market penetration. Three individual markets are shown: the low-temperature process heat, below 550°F; the high-temperature process heat, between 550 - 1100°F (these are similar and represented by one curve); and the electric power market. The curves are based on achieving a 1 1/2 Quad penetration each in the low-temperature and high-temperature process heat market and 3/4 Quad penetration of the electric power market by year 2000. These data are consistent with independent studies of Sandia Laboratories, Mitre, and The Aerospace Corporation.

Figure 1. Solar System Learning Curves

Figure 2. Market Potential

The information from Figures 1 and 2 have been combined to project solar system costs for future years. Cost curves are shown for trough collector systems and for central receiver systems. Trough collector systems are shown in Figure 3A for the low-temperature industrial process heat market using 93% and 90% learning curves. Central receiver system curves using 90% learning curves are shown in Figure 3B. The upper curve is for the central receiver system and the electric utility market while the lower curve indicates the lower costs achievable by penetrating the combined electric utility and high-temperature process heat markets.

Figure 3A. Projected Solar System Costs

Figure 3B. Projected Solar System Costs
Central Receiver Systems

Figure 4 presents the solar system performance increase anticipated in future years as the technology is developed and the performance is expressed in BTUs per square foot per year as a function of time. A direct normal insolation mean daily value of 0.5 kWhr/ft^2 was used to calculate the system performance. For the continental U. S. the direct normal insolation ranges from a high of 0.7 kWhr/ft^2 in the sunbelt (Eastern California, Nevada, Arizona, New Mexico, and Western Texas) to a low of 0.3 kWhr/ft^2 in the Pacific Northwest (Washington) and New England (Maine, Massachusetts and New York). Therefore, the 0.5 kWhr/ft^2 performance used represents a nominal value for the U.S. When the performance improvements from Figure 4 are combined with solar system capital costs from Figure 3, factors of money, and a 20-year amortization period the solar energy production cost can be calculated.

Figure 4. System Performance

This information is presented in Figures 5, 6, and 7 for three types of solar systems; a 450°F trough, a 550°F trough, and a high-temperature central receiver. The trough collector systems in Figures 5 and 6 have been evaluated for three levels of investment tax credit (10%, 30%, and 50%), demonstrating the benefit of increased incentive levels.

A comparison of the production cost of solar energy for central receiver systems entering the electric utility market only or the combined electric utility and high-temperature process heat markets is presented in Figure 7. The comparison for a standard 10% investment tax credit is illustrative of the advantages of a larger market to drive down costs. By the early nineties, a 20 percent energy cost reduction can be recognized by an integrated pursuit of both electric utility and process heat markets.

Figure 5. Levelized Costs (1977 \$)
450° F Troughs

Figure 6. Levelized Costs (1977 \$)
550° F Troughs

Figure 7. Levelized Energy Costs (1977 \$)
550°F to 1100°F Central Receiver

The delivered fossil fuel prices are presented in Figure 8. These fuel prices are nominal values for the U.S. as delivered to industry. The low coal and residual oil prices are the DOE standards fuel prices recommended for evaluation of new energy systems and then converted to 20-year levelized costs expressed in 1977 dollars for direct comparison with solar energy production costs. The efficiency of modern large fossil systems that burn these fuels is usually above 95%. Moreover, due to these extremely high efficiencies the small increased cost caused by these small conversion losses has been ignored. The high coal price curve represents not the average price but the most recent premium price paid for a clean low sulfur content high BTU coal needed to make the environmental standards in some regions of the U.S. Similar price variations exist for low sulfur residual fuel oil. Other regional price variations exist for coal due to regional differences in the costs of mining and shipping. However, these cost variations have been omitted for clarity.

Figure 8. Delivered Fossil Fuel Prices
20-Year Levelized Costs (1977 \$)

Finally, an energy cost comparison of fossil fuel and solar energy systems is presented in Figure 9. The solid lines present the fossil fuel energy costs and the two families of broken line curves represent the Trough Collector Low-Temperature Process Heat Systems, and the Central Receiver Electric and High-Temperature Process Heat Systems. The nominal solar cost curves shown are for a direct normal insolation value of $0.5 \text{ kWhr/ft}^2/\text{day}$ and for a 60% investment tax credit for an initial five year period from 1981 thru 1985. Then starting in 1986 reduction of the investment tax credit to 40% and continuing thru 2000 at the 40% level. The shaded band indicates the range of solar energy costs as the U.S. insolation level is varied from $0.7 \text{ kWhr/ft}^2/\text{day}$ in the Southwest to the nominal $0.5 \text{ kWhr/ft}^2/\text{day}$ for the U.S.

Assuming the implementation of a 60% investment tax credit (ITC) as incentive solar energy production costs for trough collector low temperature process heat systems could drop below residual fuel energy

Figure 9. Energy Cost Comparison
20 Year Levelized Costs (1977 \$)

costs in the southwestern U. S. in 1981 and in the central states in 1982. If the 60% investment tax credit were maintained trough collector systems could penetrate the states with less favorable insolation in the mid to late 1980 time period; however, if the ITC is reduced from 60% to 40% in 1986 the continued growth in these less favorable insolation regions would be delayed for several years. Central receiver systems utilizing a 60% ITC would just become competitive with residual oil in the highest insolation areas of the U.S. in 1986, and reduction of ITC below the 60% level would postpone the commercialization of central receiver systems to the post 1990 time period. If costs of the solar systems were equal to the cost of conventional energy sources this alone would not be sufficient inducement for industry to adopt a new system due to the added risk associated with the new technology. Therefore, for commercialization of solar systems to occur when costs are equal to conventional energy sources some additional incentives in the form of fossil fuel priorities will be required to trigger the commercialization of solar thermal systems.

2.2 RECOMMENDED GOALS AND REQUIREMENTS

The recommended goals and requirements have been formulated to achieve the program objective, "the earliest possible commercialization of solar thermal energy systems". A goal has been selected that will allow the competitive production of already developed trough collector low-temperature energy with residual oil fossil energy in high to medium insolation regions of the U.S. in the pre-1985 time period. To achieve this goal a requirement exists for an incentive program to establish economic parity between solar and fossil energy sources allowing normal marketing (sales) of solar systems. After some period of time the production volumes resulting from the sales will reduce equipment costs to a point where incentives are no longer required. For trough collectors an incentive such as a 50% to 60% investment tax credit will be required for a minimum period of five to ten years. Similarly, a goal has been selected that will allow the competitive production of currently developing central receiver high-temperature energy systems with residual oil in high to medium insolation regions of the U.S. in the pre-1990 time period. The central receiver equipments will probably require a 60% level investment tax credit incentive for a ten year period. These requirements assume adoption of an incentive program by Congress by 1981 and a Government/industry cost shared program to maintain solar system equipment production during the pre-incentive period.