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MISSION ANALYSIS OF PHOTOVOLTAIC SOLAR ENERGY SYSTEMS

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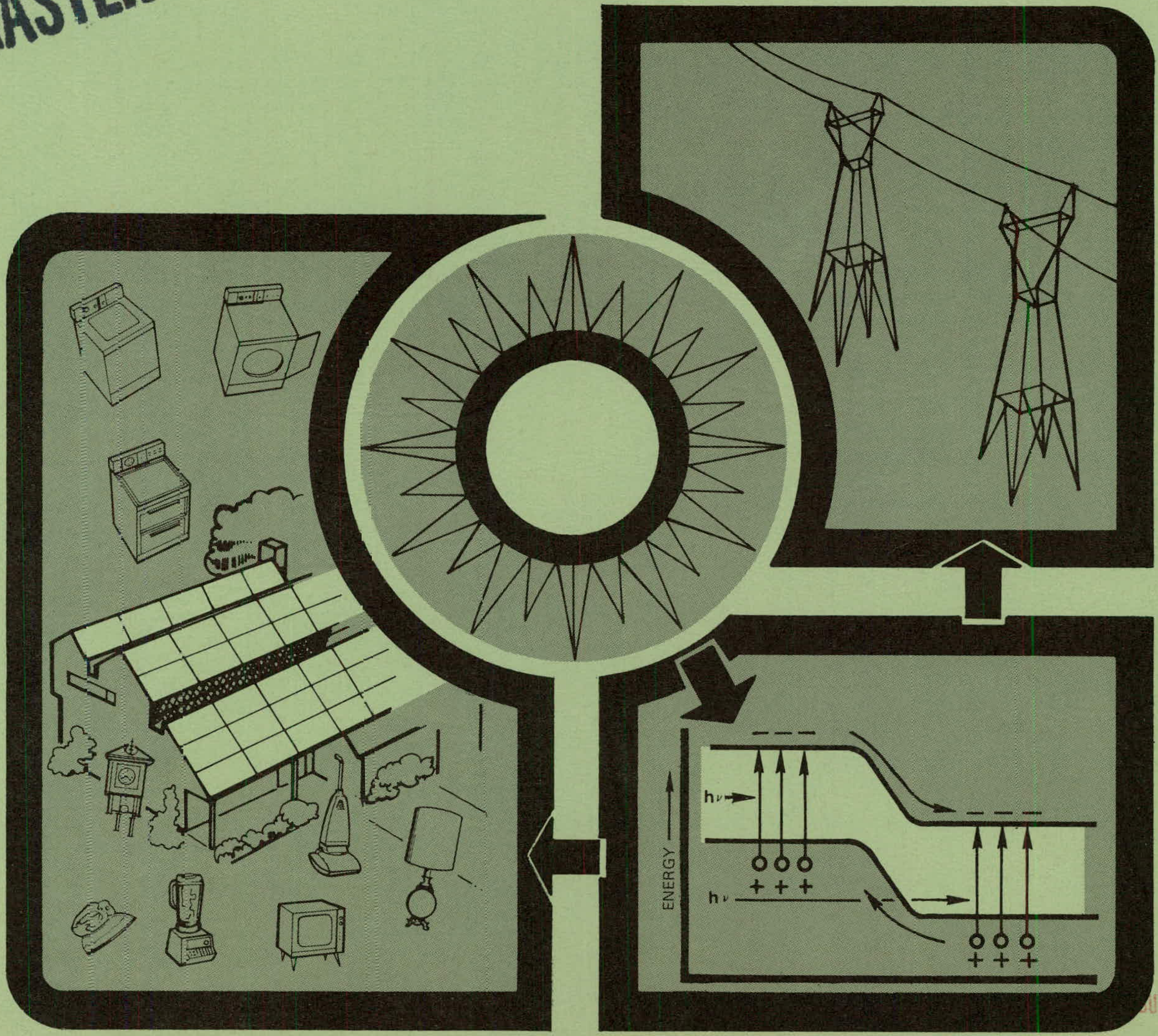
QUARTERLY PROGRESS REPORT
1 JUNE 1976—30 SEPTEMBER 1976



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MISSION ANALYSIS OF PHOTOVOLTAIC SOLAR ENERGY SYSTEMS

Quarterly Progress Report for the Period
1 June 1976 - 30 September 1976

Prepared by

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FOREWORD

This report represents an account of work accomplished during the third quarter of activity under Project Agreement 8, "Mission Analysis of Photovoltaic Solar Energy Systems", on Contract No. E(04-3)-1101 with the United States Energy Research and Development Administration (ERDA). By agreement with the ERDA Program Manager, this report has been written to cover a four-month period in order to bring the reporting period into coincidence with the calendar quarter.

The study is being conducted by the Energy Programs Group of the Energy and Transportation Division of The Aerospace Corporation. Dr. Leonard Magid is the ERDA Program Manager and Dr. A. B. Greenberg, General Manager of the Energy and Transportation Division, is the Principal Investigator. Dr. M. B. Watson is Associate Director of the Energy Programs Group. Dr. Stanley L. Leonard, Director, Photovoltaic Office, provides the program management.

This report was prepared by Dr. S. L. Leonard, Mr. E. J. Rattin, and Mr. B. Siegel. The authors wish to express appreciation for the support of the project by a number of other personnel of The Aerospace Corporation. These include Dr. P. Breisacher, Mr. W. E. Ellis, Mr. J. A. Neiss, Ms. P. L. McGill, Ms. H. Wong, and Mr. H. H. Yoshikawa. The help of Mr. L. J. Clysdale in overseeing the production of the report and of Ms. Kathy Morris in typing the text is also gratefully acknowledged.

ABSTRACT

A substantial shift in the emphasis of the project took place early in the report period. In accordance with the revised work plan, the bulk of the effort during the quarter was devoted to Task 2, Analysis of Major Mid-Term Missions. Progress was also made, however, on Task 3, Review and Updating of the ERDA Technology Implementation Plan, and on Task 4, Critical External Issues, and a start was made on Task 5, the Impact of Incentives. Since the new plan called for phasing out of Task 1, Analysis of Near-Term Missions, and Task 6, Societal Costs of Conventional and Photovoltaic Power Production, relatively little progress was made on these tasks; the small amount of effort that was expended on them was applied to completing the final details of the studies and to beginning the preparation of final reports.

The main examples of progress under Task 2 were: a) completion of the preliminary analysis of central station missions for photovoltaic systems using GaAs arrays in the high-concentration central receiver configuration and b) launching of an investigation of photovoltaic total energy missions. The analysis of central receiver photovoltaic plants led to the conclusion that such plants may well be competitive with solar thermal central receiver plants or with flat-plate photovoltaic plants (for Si array prices of $\$100\text{-}200/\text{kW}_{\text{pk}}$), provided that the thermal energy that is also collected can be sold or used to generate additional electricity in a bottoming-cycle turbine. In that event, they would also be able to compete economically with conventional coal-fired intermediate load power plants, since analyses have found that these latter types of solar plant can be cost-effective in comparison with the conventional alternative.

The investigation of photovoltaic total energy missions was still in the initial phase at the close of the report period. The available data base was explored through literature searches and through contacts with individuals and agencies having information about prospective applications or about related studies. Preliminary criteria for screening candidate applications were established, and a start was made on the screening process, with the objective of selecting one or two preferred candidates for analysis during the final quarter of the project.

Also under Task 2, an investigation was made of the use of electric storage in conjunction with a conventional coal-fired baseload plant to provide intermediate load power. It was found that this alternative is not likely to be a stronger competitor for photovoltaic power than is a combined cycle coal-fired plant designed for intermediate load operation.

A quick study was also made of the sensitivity to the price of fuel of calculations of the cost effectiveness of photovoltaic power plants.

Under Task 3, support was provided to the Systems Development Planning Group in the form of special analyses, participation in the deliberations of the group, and contributions to the preliminary report of the group's activities.

Under Task 4, an investigation was made of the occupational and environmental hazards of the production of GaAs, CdS, and Si arrays. It was concluded that, if the hazards are dealt with in standard ways, there is no likelihood of significant damage to the environment or to the health of the work force. At the close of the quarter a preliminary report had been completed and was under review.

Under Task 5, a new Utility Financial Planning Model that had been developed in a company-funded project was adapted for use in the financial analysis of photovoltaic central station power plants. At the end of the report period, plans were being made to use the new model in evaluating alternative incentive strategies.

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CONTENTS

I. INTRODUCTION

This section of the report contains an account of planned activities for the report period, as modified by a substantial project reorientation that was put into effect early in the period by agreement between The Aerospace Corporation and the Photovoltaic Branch of the ERDA Division of Solar Energy.

Chart 1

REVISED WORK PLAN FOR PERIOD 1 JULY TO 31 DECEMBER 1976

Early in the period covered by this report, it was decided by mutual agreement between The Aerospace Corporation and the responsible ERDA Program Manager that there should be a substantial shift in the emphasis in this project. As is indicated in Chart 1, the principal change was to place the focus of the effort on Task 2, while Tasks 1 and 6 were to be phased out and the remaining tasks somewhat diminished with respect to level of effort. At the same time it was also agreed that it would be appropriate to shift the quarterly reporting date to coincide with the end of the calendar quarter, for better coordination with the regular Quarterly Interface meetings of the ERDA Photovoltaic Program. Accordingly, this report covers the four-month period between 1 June 1976 (the date of the previous report) and 31 September 1976.

Under this revised work plan, the bulk of the increased Task 2 effort is being placed on the first two subtasks listed in Chart 1: central station power and photovoltaic total energy applications. In the case of central station power plants, the thrust of the study has remained essentially the same, centering on a) analyses of photovoltaic plants using very high sunlight concentration, b) investigations of the effect of variations in geographic location on mission cost-effectiveness, and c) studies of the sensitivity of such cost-effectiveness calculations to fuel-price projections or to the introduction of new "conventional" methods for generating intermediate load power (e.g. use of storage with baseload generation). The investigation of photovoltaic total energy systems, however, is a new element in the project, and the main effort during the report period has been spent in such "start-up" activities as searching for background information, developing screening criteria, and carrying out preliminary analyses.

Although most of this report (Charts 3-14) is devoted to a description of progress in the two elements of Task 2 that are described in the preceding paragraph, progress was also made in several other areas. Brief descriptions are included of specific activities under Task 1 (Chart 2) and Task 5 (Chart 15), while progress in Tasks 3 and 4 is summarized in the text accompanying Chart 16. The report concludes (Chart 17) with an account of planned activities for the next quarter.

Revised Work Plan for Period 1 July to 31 December 1976

TASK 1 ANALYSIS OF NEAR-TERM MISSIONS

TASK 2 ANALYSIS OF MAJOR MID-TERM MISSIONS

- CENTRAL STATION POWER
- PHOTOVOLTAIC TOTAL ENERGY APPLICATIONS
- INTERMEDIATE-TO-LARGE LOAD CENTER MISSIONS

TASK 3 REVIEW AND UPDATING OF ERDA TECHNOLOGY IMPLEMENTATION PLAN

TASK 4 CRITICAL EXTERNAL ISSUES

TASK 5 IMPACT OF INCENTIVES

TASK 6 SOCIETAL COST OF CONVENTIONAL AND PHOTOVOLTAIC POWER PRODUCTION

EMPHASIS

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Chart 1

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II. PROGRESS

This section contains a discussion of the progress that has been made during the reporting period.

Chart 2

TASK 1: ANALYSIS OF NEAR-TERM APPLICATIONS

The status of the Task 1 activity is summarized in Chart 2. In accordance with the revised work plan, the active search for new near-term photovoltaic markets was concluded early in the report period. It was necessary, however, to continue to expend a limited amount of effort on the task in order to complete investigations that had been started earlier and to begin preparation of a final report.

In the course of the study, approximately 200 groupings of potential photovoltaic power applications were identified and examined in greater or lesser detail. All of these were domestic civilian applications; the survey did not extend to military or foreign markets.* As has been reported earlier (References 1 and 2) a number of likely markets in the 1978-1985 time period were uncovered. In most cases they represented remote or semi-remote applications in which the alternative sources of power were either primary batteries or gasoline or diesel motor generators. It was estimated that the total 1980-1985 market for photovoltaic arrays for use in such applications could reach an average of between 15 and 20 MW_{pk}/year and that the most promising sales areas would be in communications systems (especially microwave and radio relays), impressed-current cathodic protection (of gas well heads, pipelines, highway bridge decking), illuminated highway signs and traffic control systems in locations remote from utility power, and, perhaps, railroad grade crossing protection in similar locations.

Although they are not likely to represent a really substantial addition to the total domestic market for arrays, photovoltaic applications on U. S. Indian Reservations are of particular interest. Because of the similarity between electric power needs on such reservations and those in developing countries, any successful demonstration of a photovoltaic system on a reservation would have considerable potential for increasing foreign sales of arrays, in addition to serving the dual purpose of stimulating domestic sales and helping to meet reservation needs. For that reason, a number of contacts have been made with representatives of U. S. Indian tribes. Several of these contacts have occurred as a result of the circulation by the Bureau of Indian Affairs (BIA) of an Aerospace Corporation questionnaire to 19 Arizona tribes, on a trial basis. So far, responses have been received from the San Carlos Apache, the Papago, and the Havasupai Tribes. Other contacts made more directly have included

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*A separate, more intensive market study, covering military (DoD) and foreign (worldwide) markets as well as those in the domestic civilian sector, will shortly be under way under ERDA sponsorship.

the Navaho Tribe and BIA personnel at the Southern and Northern Pueblo Agencies as well as the Albuquerque and Phoenix headquarters of the BIA. Tribal applications for photovoltaic power which are already economically viable (or nearly so) are in the communications area, and possibly also in shallow well water pumping. Potentially viable applications range widely over community refrigeration and lighting, cottage industry power, tourist accommodations, school electrification, and trickle irrigation. In several instances, the advantage of photovoltaic power would lie in the lower skill level associated with its maintenance and operation, as compared to engine-generated power, rather than in a direct economic benefit.

Although it is badly needed, no evidence was found of a centralized activity to assess power requirements in furtherance of tribal economic development, or to optimize application of alternative power sources to satisfy these requirements. Several of the tribes, however, are already participating in solar thermal demonstration projects, with the aid of local academic institutions and of ERDA National Laboratories in the area.

Task 1 Analysis of Near-Term Applications

STATUS

- ACTIVE SEARCH FOR NEW MARKETS CONCLUDED IN JULY
  - INVESTIGATIONS INITIATED EARLIER BEING COMPLETED
  - FINAL REPORT IN PREPARATION
  - CONCLUSION: NEAR-TERM DOMESTIC CIVILIAN MARKET COULD REACH 15-20 MW_{pk}/yr IN THE 1980-1985 PERIOD
    - MILITARY, FOREIGN MARKETS NOT INCLUDED, MAY WELL BE APPRECIABLY LARGER - TO BE SUBJECT OF SEPARATE ERDA MARKET STUDY

- INFORMATION BEING ACCUMULATED ABOUT POTENTIAL MARKETS ON U.S. INDIAN RESERVATIONS
  - AEROSPACE QUESTIONNAIRE CIRCULATED BY BUREAU OF INDIAN AFFAIRS TO 19 ARIZONA TRIBES
    - REPLIES TO DATE (3) EXPRESS GREAT INTEREST IN PHOTOVOLTAIC POWER FOR WATER PUMPING, REFRIGERATION AND VILLAGE ELECTRIFICATION, TOURIST FACILITY POWER
  - SIGNIFICANT PARALLELS TO APPLICATIONS IN DEVELOPING COUNTRIES KNOWN TO EXIST
    - DEMONSTRATIONS ON RESERVATIONS SHOULD MAKE GOOD TEST BEDS FOR SYSTEMS WITH POTENTIAL EXPORT MARKET

Chart 2

Chart 3

PHOTOVOLTAIC CENTRAL RECEIVER SYSTEMS: OPTIONS

As was indicated in the Introduction, the focus of the effort on Task 2, Major Mid-Term Missions, during the report period has been on a) central station power applications and b) photovoltaic total energy missions. Chart 3 introduces one part of the central station mission study, a preliminary investigation of the use of intense sunlight concentration in photovoltaic central power plants. The specific concept that was analyzed combines the high efficiency and heat tolerance of GaAs solar cells with the very high concentration ratios ($X \sim 1000$) that are achievable in the central receiver configuration. In this configuration, multiple images of the sun are focussed by a large field of steerable flat mirrors onto the surface of a cylindrical receiver mounted on top of a tower. GaAs solar arrays are attached to the exterior surface of the receiver, and array cooling is provided by a high-speed flow of water (inlet temperature 20°C) in a narrow annular channel on the inner side of the receiver surface. It was assumed that the individual cells were coated on the rear with a layer of tin (to form the rear ohmic contact) and were then attached by a thin layer of adhesive to the aluminum surface of the receiver. In the analysis, the maximum permissible temperature of any portion of the array was taken to be 200°C, on the basis of manufacturer information indicating that higher array temperatures could reduce cell life.

As is indicated in Chart 3, three different design options were considered, for three different modes of operation: a) generate photovoltaic electric power for sale, b) provide both photovoltaic electricity and thermal energy for sale, and c) provide photovoltaic power and, by the addition of a low temperature turbine, use the thermal energy in the array coolant to generate additional electricity. In the first case, the system would be designed for maximum net photovoltaic power (power generated minus power consumed in pumping the coolant). In the second case, the design would again be optimized for maximum net photovoltaic power, but with the additional condition that the outlet water temperature would be high enough for the intended application of the thermal energy. In the third case, one would design for maximum net electric output, including the output of the bottoming cycle turbine.

Photovoltaic Central Receiver Systems

OPTIONS

- GENERATE PHOTOVOLTAIC POWER ONLY

  DESIGN FOR MAXIMUM NET ELECTRICAL POWER (power generated - coolant pumping power). DUMP COOLANT HEAT VIA DRY COOLING TOWER

- GENERATE PHOTOVOLTAIC POWER, SELL COOLANT HEAT (PHOTOVOLTAIC + THERMAL)

  DESIGN FOR MAXIMUM NET ELECTRICAL POWER, SELECT COOLANT CHANNEL GEOMETRY AND/OR VARY MASS FLOW FOR GIVEN CHANNEL GEOMETRY TO PROVIDE REQUIRED COOLANT MAXIMUM TEMPERATURES (150°F - 350°F feasible)

- GENERATE PHOTOVOLTAIC POWER, USE COOLANT HEAT IN A BOTTOMING CYCLE (PHOTOVOLTAIC + THERMAL ELECTRIC)

  DESIGN FOR MAXIMUM NET POWER (photovoltaic power + thermal electric power - coolant pumping power)

Chart 3

Chart 4

PHOTOVOLTAIC CENTRAL RECEIVER POWER PLANT CHARACTERISTICS

The figures in Chart 4 display some of the principal characteristics of photovoltaic central receiver plants designed for the three different modes of operation that were discussed in the text accompanying Chart 3. These graphs present the results of calculations for the maximum-insolation case where the GaAs arrays are illuminated by sunlight with an intensity of 1 MW/m^2 (corresponding to an effective concentration ratio of ~1000).

The photovoltaic-only system represented by the graph on the left in Chart 4 is designed to provide maximum photovoltaic power (power generated minus coolant pumping power), and the heat absorbed by the coolant is dumped to the atmosphere. Each point on the curve corresponds to a different width for the annular cooling channel (and therefore to a different system design) and represents system performance for optimum choices of operating parameters, particularly coolant flow rate. As the graph indicates, maximum system efficiency (the ratio of net electrical power to insolation on the array) occurs at an average array temperature of about 70°C and a maximum (outlet) coolant temperature in the neighborhood of 41°C. (This maximum point also corresponds to a channel width of 5 cm and a coolant flow rate of 120 gallons per minute per square meter of array.) As the average array temperature decreases, the channel width and coolant flow rate for maximum efficiency both increase, and eventually the increase in coolant pump power exceeds the increase in array electrical output.

The heat energy available in the coolant of a GaAs array is typically 3 to 6 times greater than the photovoltaic electrical energy and could potentially be sold to generate revenue. The middle figure of Chart 4 shows that the temperature of this heat energy may be varied significantly for a given system, without greatly changing electrical efficiency, by varying the coolant flow rate. For example, with a 1 cm coolant channel, dropping the flow rate from 50 to 25 gallons per minute per square meter of array would increase maximum water temperature from 70°C to 150°C with virtually no change in efficiency. Heat energy at these temperatures could be used for space heating and cooling and in various industrial processes. A photovoltaic central receiver may therefore be operated to provide thermal energy at customer specified temperatures (up to about 175°C) without significantly affecting electrical power generation.

Coolant heat energy may also be used to generate additional electricity by use of a turbine "bottoming cycle." The right-hand figure on Chart 4 shows system efficiency for a combined photovoltaic/thermal electric system as a function of average array temperature, where the turbine inlet temperature is assumed to be 14°C below the coolant maximum temperature. In this case an overall efficiency of ~24% can be achieved (photovoltaic plus thermal electric power generated minus coolant pumping power divided by insolation on the array). Such an efficiency occurs at an average array temperature of approximately 130°C, maximum water temperature of 167°C, coolant channel width of 0.6 cm and a flow rate of 16.5 gallons per minute per square meter. Again each point on the photovoltaic or combined photovoltaic and thermal electric curves corresponds to an optimum system design with specified values of channel width and flow rate. Points corresponding to larger channel widths also correspond to higher average array temperature in this graph. Thus, as one moves to the left in the figure, toward lower average array temperatures, the channel width decreases and the heat transfer coefficient rises. As a result, the temperature difference between cooling water and array decreases rapidly enough so that the water temperature can actually increase slightly even though the array temperature drops. Eventually, however, the increase in coolant pump power exceeds both the increase in photovoltaic power resulting from the lower average array temperature and the increase in thermal electric power resulting from the higher water temperature. The optimum design conditions for this combined photovoltaic/thermal electric system are in striking contrast to those for the photovoltaic-only system. These differences are summarized in the following table:

	Combined	Photovoltaic Only
Maximum Array Temperature °C	200 (Assumed Limit)	81
Average Array Temperature °C	130	70
Maximum Water Temperature °C	167	41
Channel Width, cm	0.6	5.0
Flow Rate, gpm/m^2	16.5	120

Additional analyses have shown that slight improvements in overall efficiency (1-3%) can be achieved by allowing higher maximum array temperatures, by using working or coolant fluids other than water, or by modifying assumed turbine operating conditions.

Photovoltaic Central Receiver Power Plant Characteristics

Concentration ratio: 1000 Insolation on array: $1 MW/m^2$
Water cooled GaAs solar cells Water inlet temperature: 20°C
Maximum array temperature: 200°C

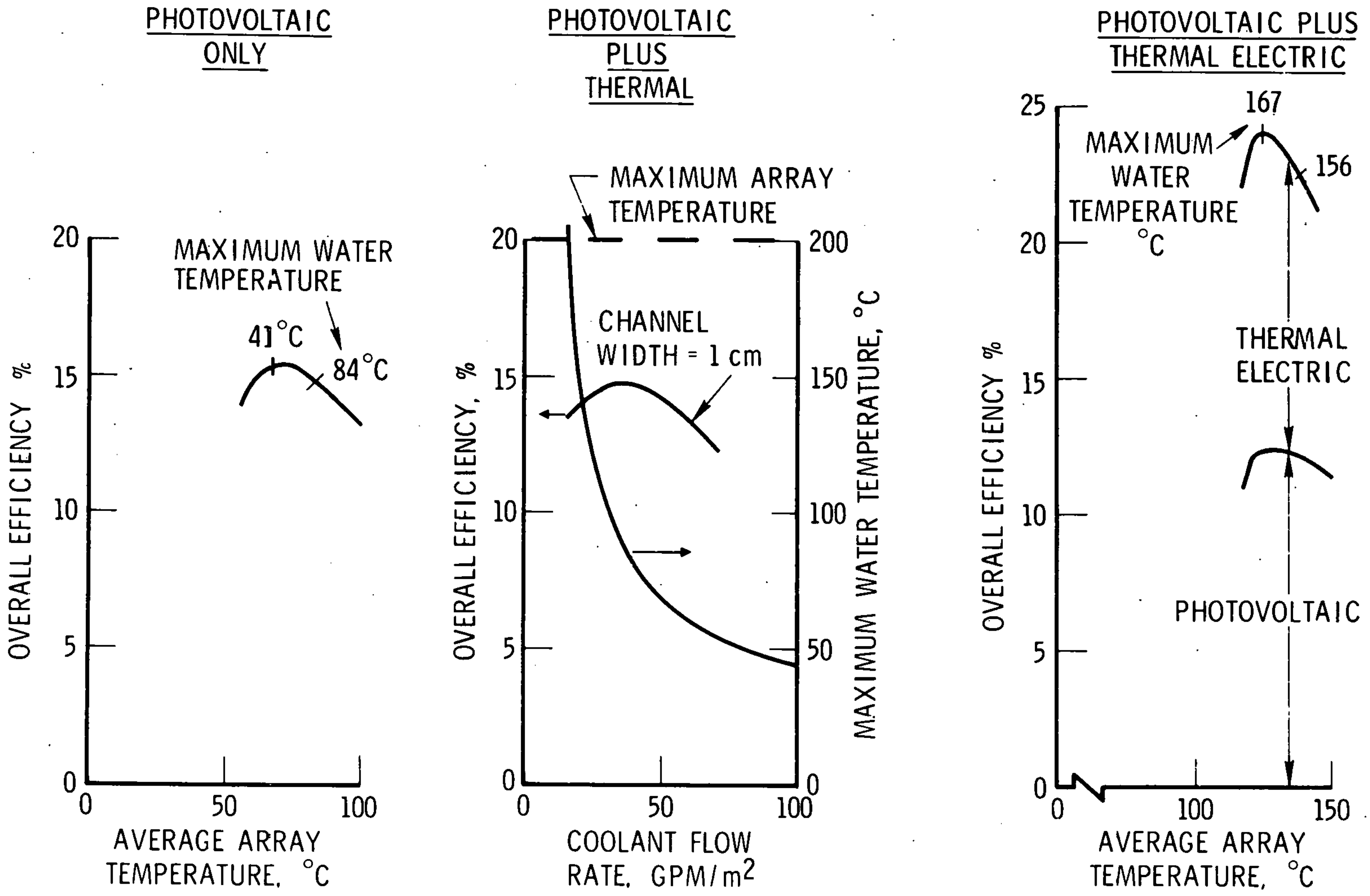


Chart 4

Chart 5

PHOTOVOLTAIC CENTRAL RECEIVER POWER PLANT: PHOTOVOLTAIC/THERMAL ELECTRIC OPERATION OPTIONS

The graphs in the preceding chart all represented system performance characteristics under maximum insolation (1 MW/m^2) conditions. Some additional analyses were made of the overall efficiency of the combined photovoltaic/thermal electric system as a function of insolation intensity. The system design in this case was that corresponding to the maximum-efficiency point in the right-hand graph of Chart 4 (0. 6 cm coolant channel width). It was assumed that, as the insolation intensity decreases, average and maximum array temperatures and the maximum coolant temperature are controlled by varying the coolant flow rate.

The graphs in Chart 5 display the results of these analyses, for three different operational approaches: 1) constant coolant flow rate, 2) constant coolant maximum temperature, and 3) constant maximum array temperature. Of the three approaches, operation at constant coolant maximum temperature (center graph) appears to be the most desirable and results in essentially constant efficiency down to an array insolation of 0.4 MW/m^2. This result occurs primarily because photovoltaic efficiency improves slightly at lower insolation (lower average array temperature) while the thermal electric efficiency remains constant (constant turbine inlet temperature). In the constant flow-rate case (left-hand chart), the rapid drop in system efficiency is due primarily to the decrease in thermal electric output resulting from reductions in maximum coolant temperature. This decrease far outweighs the improvement in photovoltaic efficiency that occurs because of reductions in average array temperature. When the system is operated at constant maximum array temperature (right-hand graph), the flow rate must be decreased as insolation drops. As a result, the maximum coolant temperature increases above the turbine inlet design temperature (167°C at 1 MW/m^2) resulting in reduced turbine efficiency. This reduction in turbine efficiency more than compensates for the slight increase in array efficiency caused by the drop in average array temperature with decreasing insolation.

This combined photovoltaic/thermal electric system requires further investigation in at least two areas:

(1) System performance and economics are greatly affected by the design, efficiency, and cost of the low temperature turbine system used in converting coolant thermal

energy to electric power. Such factors as the appropriate turbine size, outlet conditions, and variation in efficiency with insolation, inlet temperature, and flow rate need to be examined in greater detail. Consideration should also be given to the desirability of using a low boiling point secondary fluid to drive the turbine, rather than using the array coolant. In addition, better information is needed about turbine development and capital costs and on the costs of operation and maintenance.

(2) Simulation of system operation is needed in order to provide information on the appropriate mix of electrical and thermal storage and to define operational strategies for maximizing net electrical output over a significant period (e.g., one year of operation.)

Photovoltaic Central Receiver Power Plant

PHOTOVOLTAIC PLUS THERMAL ELECTRIC OPERATION OPTIONS

[Concentration ratio: 1000
Design point: 1 MW/m^2 of insolation on array]

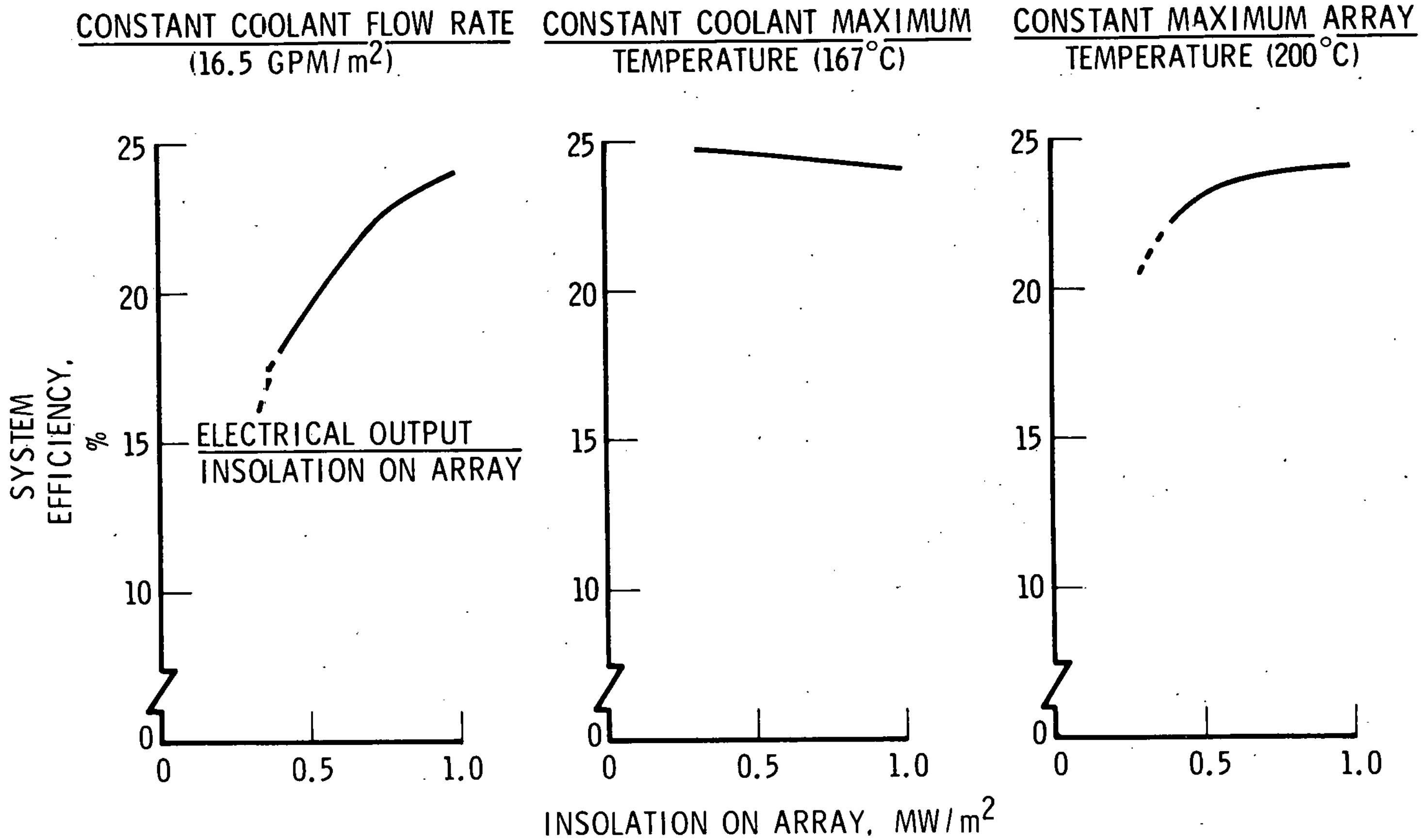


Chart 5

Chart 6

INTERMEDIATE LOAD SOLAR POWER PLANTS: COST COMPARISON

Preliminary estimates have been made of the capital costs of photovoltaic central receiver plants designed for operation in the three modes indicated in Charts 3 and 4 and of the associated busbar energy costs. The cost figures are displayed in Chart 6 (which is an updated version of a chart presented in an earlier report), along with the corresponding figures for a solar thermal central receiver plant and for a photovoltaic plant using flat-plate collectors. (In this latter case, the system cost figures are shown for two different prices for flat-plate arrays, $\$100/kW_{pk}$ and $\$500/kW_{pk}$.)

All of the plants represented in the chart are rated at 100 MW and have essentially the same performance characteristics, with plant capacity factors of ~ 0.4 when operated at Inyokern, California. All are assumed to go on line in 1990, and the subsystem cost figures are estimates based on projections to high-volume production in that future period. In addition to the basic plant cost (the sum of the costs of the installed subsystems) figures are given for the total plant cost, including spares, contingencies, indirect costs, and interest during construction. Two sets of busbar energy cost figures are given. The first set represents the required revenue during the first year of commercial operation (1991), while the second set represents the levelized value, calculated by the customary levelized fixed charge approach, as described in Reference 3. (In this case the fixed charge rate has been set equal to 0.15 and the levelized operation and maintenance cost has been assumed to be 3 mills/kWh.) In the photovoltaic plus thermal case the revenues from the sale of the thermal energy (at a net price, after distribution and storage, of $\$2/10^6$ Btu, with an assumed escalation rate of 4% after 1990) are also shown, expressed in mills per kWh of electric energy sold; the sum of the electric and thermal revenue is just sufficient to defray the cost of the plant, including interest and return on equity, and to pay all other operating and capital-related costs. All of these costs are expressed in <u>1976</u> dollars.

The cost figures shown for the flat-plate photovoltaic power plant and for the solar thermal plant are based on the results of earlier studies. Those for the flat-plate photovoltaic system are essentially the same as those obtained in the NSF-sponsored Photovoltaic Mission Analysis study that was the forerunner of the current program, except that the assumed cost for array support structure has been increased from $\$15/m^2$ to $\$20/m^2$. The solar thermal results have been abstracted from the Aerospace Corporation's on-going Solar Thermal Mission Analysis program.

The cost figures shown for the central receiver photovoltaic plants are not based on a detailed system simulation but instead were derived in an approximate manner from the system simulation computations carried out for the other two cases. From the analysis of solar thermal central receiver performance, values were derived for the overall (annual average) efficiency of the central receiver collector system, taking into account reflection losses and shading and blocking of adjacent heliostats. The annual average normal incidence insolation for Inyokern (8.8 kWh/day) was then multiplied by the collector efficiency figure (62%) to yield a value for the average amount of collected radiation (5.4 kWh/day). On the basis of this figure and the corresponding figure for the annual average amount of collected radiation in the flat-plate case (7.2 kWh/day), and taking into account the different conversion efficiencies of silicon and gallium arsenide arrays, a determination was made of the collector area that would lead to the same annual array output in the central receiver photovoltaic plant as in the flat-plate plant. (Array packing factors of 0.9 were assumed for each type of array and the 70°C efficiencies were assumed to be 10% and 17.5% for silicon and gallium arsenide cells, respectively.) The cost figures for the heliostat field ($\$62/m^2$) and the receiver towers were taken to be the same as in the solar thermal case; the gallium arsenide array price was assumed to be $\$10,000/m^2$, on the basis of manufacturer estimates.

The system labeled "Photovoltaic Alone" has been designed to provide maximum net photovoltaic power. System design conditions are the same as shown in Chart 4 (70°C average array temperature, 41°C maximum water temperature, 5 cm coolant channel).

For the photovoltaic plus thermal systems, where it is assumed that the coolant heat is sold for some purpose, it has been assumed that a maximum coolant temperature of 100°C is required. In this case, at an insolation intensity of 1 MW/m^2, the average array temperature is also 100°C (system conversion efficiency of 14.6%) when the coolant channel width is 1 cm. With such a system, water temperatures up to 150°C can be achieved by reducing the coolant flow rate without exceeding the assumed maximum array temperature of 200°C, or significantly reducing system conversion efficiency.

The combined photovoltaic/thermal electric system has been designed as was shown in Chart 4. Storage for this system is assumed to be in the form of batteries and no thermal storage is provided. It is assumed that the turbine system continually generates all of the electric energy it can produce and dispatches it into the grid. The electric energy from the photovoltaic arrays is used to bring the total output up to 100 MW, with any excess stored for later use. (This may not be the appropriate storage configuration for this system; simulation computations would be needed in order to define the optimum combination of electrical and thermal storage.)

The inferences that have been drawn from these estimated cost figures are presented in the next chart (Chart 7).

Intermediate Load Solar Power Plants

COST COMPARISON

	PHOTOVOLTAIC FLAT PLATE		CENTRAL RECEIVER SYSTEMS				
			SOLAR THERMAL	PHOTOVOLTAIC ALONE	PHOTOVOLTAIC THERMAL ELECTRIC	PHOTOVOLTAIC PLUS THERMAL 50%*	100%*
COLLECTOR AREA (m^2)	$2(10^6)$	$2(10^6)$	$1(10^6)$	$1.62(10^6)$	$1.18(10^6)$	$1.75(10^6)$	$1.75(10^6)$
CONCENTRATION RATIO	1	1	600	1000	1000	1000	1000
CELL MATERIAL	Si	Si	--	GaAs	GaAs	GaAs	GaAs
STORAGE CAPACITY (kWh/kW_{rated})	6	6	6	6	6	6	6
1990 CAPITAL COSTS ($\$/kW_{rated}$)							
COLLECTOR	400	400	620	1010	732	1085	1085
ARRAY	225 †	1125 ††	--	162	118	175	175
STORAGE	120	120	121	120	120	120	120
POWER CONDITIONING	35	35	--	35	35	35	35
BALANCE OF PLANT	65	65	315	79	97	79	79
TOTAL BASIC PLANT	845	1745	1056	1406	1102	1494	1494
TOTAL PLANT (including spares, contingencies, interest during construction)	1310	2705	1647	2179	1708	2316	2316
BUSBAR ENERGY COSTS (mills/kWh)							
ELECTRIC 1991	48	99	60	80	62	71	57
LEVELIZED	59	119	74	96	76	80	59
THERMAL 1991	--	--	--	--	--	14**	28**
LEVELIZED	--	--	--	--	--	22**	43**

PLANT CAPACITY FACTOR = 0.4
GaAs ARRAY PRICE: $\$10,000/m^2$
ALL COSTS IN 1976 DOLLARS

*Fraction of heat sold at a net price (after distribution/storage cost) of $\$2/10^6$ Btu

**Value of thermal energy assumed to escalate at 4% after 1990

† Array price = $\$100/kW_{pk}$

†† Array price = $\$500/kW_{pk}$

Chart 6

Chart 7

PHOTOVOLTAIC CENTRAL RECEIVER POWER PLANTS: PRELIMINARY CONCLUSIONS

The analyses that have been outlined in the preceding four charts have led to the tentative conclusions summarized in Chart 7. Although the preliminary and approximate nature of the analyses precludes any final judgments, they do strongly indicate that, far from being clearly superior to the solar thermal and flat-plate photovoltaic alternatives, the central receiver photovoltaic concepts actually appear somewhat inferior unless profitable use is made of the thermal energy that is also collected. When allowance is made for the sale of the thermal energy or for its use in generating additional electricity, however, the differences in busbar energy costs become smaller than the uncertainties in the analysis, and the central receiver photovoltaic plants may well be competitive with the other solar energy alternatives considered. More detailed analyses are required in order to settle the issue finally; of particular importance are the cost and performance of the bottoming-cycle turbine, the cost of storage and distribution of thermal energy, the appropriate mixes of electric and thermal storage, and the existence and nature of potential markets for the thermal energy.

Photovoltaic Central Receiver Power Plants

PRELIMINARY CONCLUSIONS

- SALE OF COOLANT HEAT OR USE OF SUCH HEAT TO GENERATE ADDITIONAL ELECTRICITY COULD MAKE GaAs PHOTOVOLTAIC CENTRAL RECEIVER COMPETITIVE WITH SOLAR THERMAL OR FLAT PLATE PHOTOVOLTAIC SYSTEMS (\$100/kW_{pk} array) IN CENTRAL STATION APPLICATIONS
- PHOTOVOLTAIC CENTRAL RECEIVER SYSTEMS APPEAR SUFFICIENTLY ATTRACTIVE TO JUSTIFY FURTHER MORE DETAILED ANALYSES TO:
  - DEVELOP MORE RELIABLE COST INFORMATION
  - DEFINE SYSTEM EQUIPMENT AND OPERATIONAL REQUIREMENTS
  - INVESTIGATE FEASIBLE USES OF WASTE HEAT

Chart 7

Chart 8

COST EFFECTIVENESS OF SOLAR POWER PLANTS AS A FUNCTION OF FUEL PRICE, ESCALATION: LEVELIZED FIXED CHARGE APPROACH

It is obvious that the ability of any type of solar power plant to compete economically with conventional fossil-fuel-fired power generation depends very strongly on the cost of the fossil fuels. (In the case of nuclear generation, the fuel-price influence is weaker, but solar plants are ill-adapted to provide baseload power generation and are therefore not likely to compete with nuclear plants in any case.) The graphs in Chart 8 are intended to illustrate this dependence and to permit the rapid identification of the fuel price/escalation conditions under which a given solar plant concept might be economically competitive with conventional generation.

The upper two figures in Chart 8 constitute a graphical representation of the levelized fixed charge method of determining the "levelized" busbar cost of electric energy, exclusive of fuel. In the levelized fixed charge approach, which is in common use in the electric utility industry and has been adopted by ERDA's Division of Solar Energy (Reference 3), the busbar energy cost is determined by the requirement that the annual income from the sale of energy be constant (levelized) and that this stream of constant annual receipts over the life of the plant be exactly enough to defray the total cost of constructing the plant, operating and maintaining it over its service life, and paying the expected return on the capital investment.

This relationship can be expressed in the simple form

$$\text{BBEC (mills/kWh)} = \frac{(C)\,(FCR)}{8.76\ PCF} + \overline{O\&M} + \overline{FL}$$

where C is the total capital cost of the plant as of the first year of commercial operation (including interest during construction) expressed in dollars per rated kW of plant capacity; FCR is the fixed charge rate, which depends on the internal cost of capital to the utility system (the after-tax discount rate); PCF is the plant capacity factor, the ratio of the total annual output of the plant (in kWh) to the output which would have been produced if the plant had operated at full rated capacity for all 8760 hours of the year; $\overline{O\&M}$ is the levelized cost (exclusive of fuel) of operating and maintaining the plant, expressed in mills/kWh: and $\overline{FL}$ is the levelized cost of fuel, also expressed in mills/kWh. In constructing the graphs in Chart 8, the simplifying assumption was made that the $\overline{O\&M}$ for any type of power plant is ~ 3 mills/kWh. Although the fixed charge rate, FCR, for a given utility depends on its individual financial structure, typical values are in the 0.15-0.18 range.

The lower two graphs in the chart permit quick graphical determination of $\overline{FL}$ on the basis of assumed values for the base-year price of fuel, FL_o (in dollars per 10^6 Btu), for the fuel-price escalation rate, g, and for the after-tax discount rate, k. The relationship is

$$\overline{FL} = CRF_{k,N} \cdot FL_o \cdot HR \cdot \left(\frac{1+g}{k-g}\right)\left[1-\left(\frac{1+g}{1+k}\right)^{N}\right] \cdot 10^{-3}$$

where $CRF_{k,N} = k\,(1-(1+k)^{-N})^{-1}$ is the capital recovery factor, the uniform annual payment, as a fraction of the original principal, that will fully repay a loan, including all interest, in N years at an interest rate of k. The remainder of the expression represents the present value cost, as of the year of start-up, of all the fuel that is used over the N years of plant service; HR is the heat rate, the ratio of thermal energy consumption to electric energy output. The graphs in Chart 8 are based on the choices: N = 30 years and HR = 10,000 Btu/kWh.

To use this chart, one first must determine the total capital cost figures for the solar and conventional plants that are to be compared, as of the beginning of commercial operation, including interest during construction and, in the case of the solar plant, the total capital cost of the required backup capacity. He then enters the chart at the appropriate points on the abscissa of the upper right-hand graph and proceeds vertically to the line for the assumed fixed charge rate and then horizontally across into the upper left-hand chart. At the intersections with the line representing the plant capacity factor, he drops vertically to the abscissa to determine the corresponding values for the busbar cost of energy, exclusive of fuel. If the solar plant is to compete economically with the conventional plant, $\overline{FL}$ must be equal to or greater than the difference in the fuel-less busbar energy cost figures.

The lower two graphs then permit the identification of the various fuel price/escalation scenarios that will result in the required value of $\overline{FL}$. The lower left-hand chart is entered at the point on the horizontal axis corresponding to this required $\overline{FL}$, the intersections of the vertical line from this point with the various FL_o lines identify the required values for the levelizing fuel-price multiplier that is required in each case. One then proceeds horizontally across into the lower right-hand graph to intersect with a vertical line drawn from the assumed value of the after-tax discount rate, k. Interpolation between the curves in this graph then permits an estimate of the fuel escalation rate that, in conjunction with the corresponding FL_o value, will yield the required $\overline{FL}$. For each value of the k on the abscissa scale in the lower right-hand graph the corresponding values of $CRF_{k,N}$ (for N=30) and FCR are also shown. (The determination of FCR from the value of k requires that some assumptions be made about the effective income tax rate, τ, and about other tax and insurance costs; the assumptions made in constructing the chart were the same as those used in the nominal case discussed in Reference 3; τ was taken to be 0.4 and the other tax and insurance costs were assumed equal to 0.0225 times the capital cost.)

In using the chart, one should, of course, choose a value for k (in the lower right-hand graph) that corresponds to the same value of FCR that was chosen in using the upper right-hand graph. It may also be objected that k and g are not completely independent, that g is coupled to some extent to the general inflation rate and that this rate influences the prevailing value of k, the expected internal rate of return on capital in a utility system. It seems likely, however, that the fuel escalation rate will be somewhat greater than that of general inflation and that, for example, a value of k = 0.08 (a rate of return that corresponds to relatively mild inflation, 3 or 4%) could conceivably coexist with fuel escalation rates of 8% or more.

Cost Effectiveness of Solar Power Plants as a Function of Fuel Price and Escalation

LEVELIZED FIXED CHARGE APPROACH

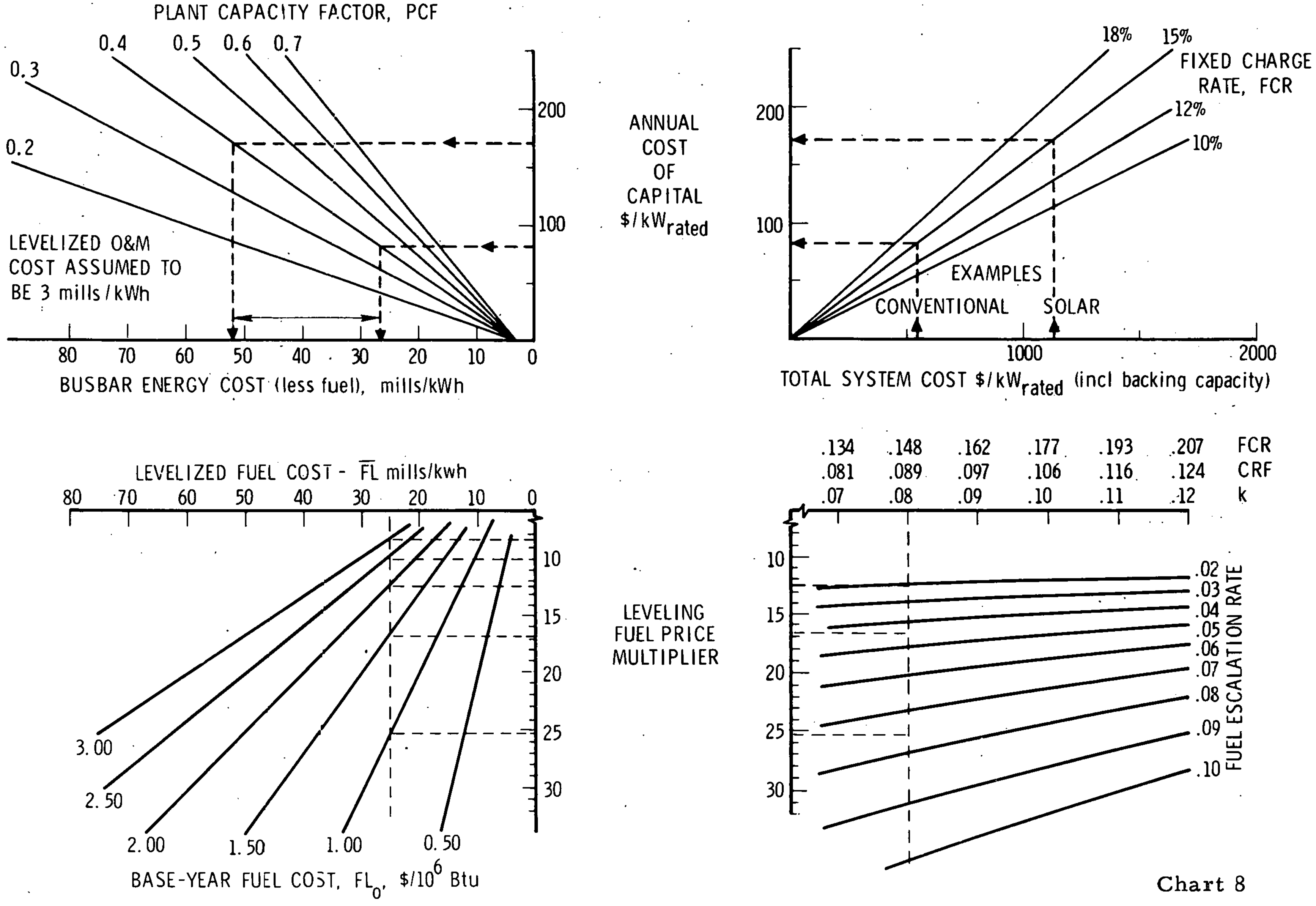


Chart 8

Chart 9

COMPOSITE INTERMEDIATE LOAD POWER PLANT

In evaluating the cost effectiveness of photovoltaic power plants, it has usually been assumed that the appropriate type of plant to consider as the conventional alternative would be a new coal-fired combined-cycle plant designed for intermediate load service. The analyses have showed that, when array prices reach the $100-300/kW$_{pk}$ range, photovoltaic power plants will be able to compete economically with conventional plants of this type and that the most cost-effective photovoltaic plant design is one incorporating about 5 hours of electric storage, provided that storage costs can be brought down to about $20/kWh. It has been widely recognized, however, that when storage costs reach this level it may be economically advantageous to meet intermediate load power requirements by increasing baseload capacity and storing some of the baseload output for use during periods when system demand is above the baseload level. In that event, the cost-effectiveness of a photovoltaic plant should be determined by comparing the busbar cost of photovoltaic electric power with that of intermediate load power produced by such a baseload-plus-storage combination. Chart 9 presents the results of a preliminary analysis of this concept.

The analysis considered the hypothetical situation in which a 1000 MW baseload coal plant, operating at a plant capacity factor of 0.8, is combined with a storage facility in such a way that the combination functions as an intermediate load plant with an overall plant capacity factor of 0.4. The operational mode is illustrated schematically in the lower left-hand part of Chart 9. It is postulated that, except for scheduled and unscheduled periods of shut-down, the baseload plant operates 24 hours per day at full rated capacity. During late-evening and early-morning hours, its output is dispatched entirely to storage. Then, during the high-demand day-time and early-evening hours, the output from the baseload plant is combined with power extracted from storage (minus losses) and dispatched to the load. When allowance is made for losses (storage in-out efficiency ~0.75; rectification-inversion efficiency ~0.85), the average power that can be extracted from the storage facility is ~635 MW, so that the total composite power output is 1635 MW. The daily plant capacity factor in this case is 0.5, but since the baseload plant operates only 80% of the time, the annual average PCF value for the composite plant is 0.4.

If the storage capacity is rated in terms of the amount of energy that can be inserted into it, this rated value must be $12\ (10^6)\ (0.75)^{1/2}\ (0.85)^{1/2}$ or $9.6\ (10^6)$ kWh. (This calculation assumes that the rectification and inversion efficiencies are equal and that the efficiency of inserting DC energy into storage equals the efficiency of extracting it again.) This represents 15 kWh per kW of rated output.

On the basis of the levelized fixed charge approach discussed in connection with the preceding chart, the levelized busbar cost of energy from the baseload plant is $12.6 + \overline{FL}$ mills/kWh, where $\overline{FL}$ is the levelized cost of fuel (in mills/kWh). (In this calculation the levelized fixed charge rate was set at 0.15 and the levelized O&M cost was assumed to be 3 mills/kWh.) One can use the same approach to calculate the incremental cost for each kWh that is dispatched from storage. Three different unit cost figures for storage were considered (as shown in the upper center portion of Chart 9), and the basic cost of the remainder of the storage plant (including rectification/inversion equipment) was assumed to be $\$100/\text{kW}_{\text{rated}}$. The basic plant cost figures were multiplied by 1.55 in order to allow for spares, contingencies, indirect costs, and interest during construction. (This ratio is the one that emerged in the earlier Aerospace Corporation studies of flat-plate photovoltaic power plants.)

When the total cost of all the energy delivered to the load is divided by the number of delivered kWh, the levelized busbar costs shown in the upper right-hand box of Chart 9 are obtained. The levelized fixed charge approach was then used to calculate the cost of power from a photovoltaic plant with 5 hours of storage and the same plant capacity factor, as a function of solar plant capital cost, for the three different unit storage-cost figures considered in the composite-plant case. (Again, FCR was taken to be 0.15 and the levelized O&M cost to be 3 mills/kWh.) It was then a simple process to determine the value of $\overline{FL}$ for which the busbar cost of energy from the photovoltaic plant was equal to that from the composite plant, as a function separately of the unit storage cost and the cost of the remainder of the solar plant (total cost less storage).

The results of these computations are shown in the graph in the lower right-hand section of Chart 9. In particular, in the case where the storage cost is $20/kWh and the total solar plant cost (less storage) is $\sim\$1000/\text{kW}_{\text{rated}}$, the solar plant can compete with the composite plant when $\overline{FL} \sim 21$ mills/kWh. This example corresponds to that highlighted in Chart 8 (where the total solar plant cost, including storage, was $\sim\$1150/\text{kW}_{\text{rated}}$). In that example, it was found that the solar plant could compete with a conventional coal-fired intermediate-load plant (at $550/kW) only when $\overline{FL}$ reached ~25 mills/kWh. It is thus apparent that, even when unit storage costs are as low as $20/kWh, a composite plant like the one discussed here would not prove to be a stronger competitor for intermediate-load photovoltaic power generation than would the conventional intermediate-load plant. (This result is, of course, confirmed by a direct comparison of the two fossil-fuel concepts.)

Composite Intermediate Load Power Plant

CONVENTIONAL BASELOAD PLANT PLUS STORAGE

A PRELIMINARY LOOK

BASELOAD COAL PLANT

1000 MW
PCF = 0.8

TOTAL CAPITAL COST = $450/kW

$\overline{BBEC} = 12.6 + \overline{FL}$ mills/kWh

+

STORAGE PLANT

635 MW
PCF = 0.4

STORAGE CAPACITY = 15 kWh/kW

BATTERY COST $/kWH	BASIC PLANT COST $/kW	TOTAL PLANT COST $/kW	$\Delta\overline{BBEC}$ mills/kWh
20	400	620	29.5
50	850	1320	59.5
100	1600	2480	109.2

=

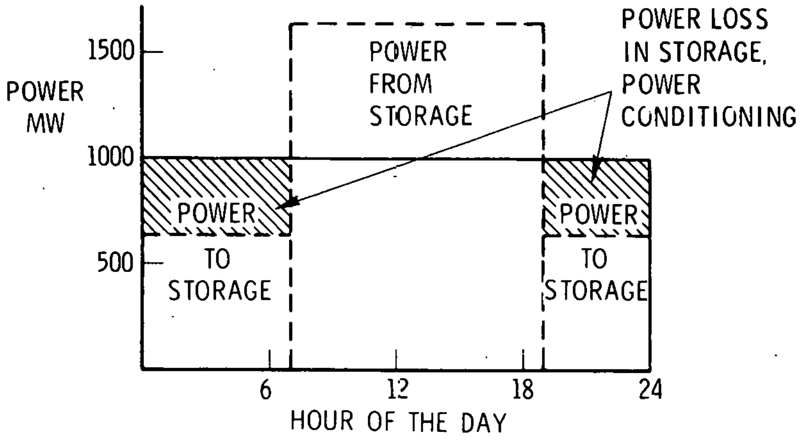
COMPOSITE PLANT

1635 MW
PCF = 0.4

$\overline{BBEC}$ mills/kWh

$26.9 + 1.22\,\overline{FL}$
$38.5 + 1.22\,\overline{FL}$
$57.8 + 1.22\,\overline{FL}$

COMPOSITE PLANT OPERATION



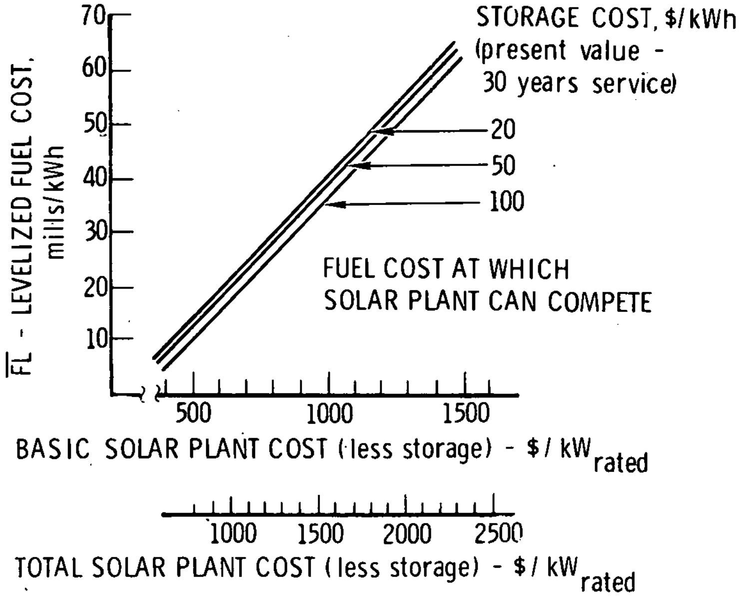


Chart 9

Chart 10

TOTAL ENERGY MISSIONS

The second major area of concentration of the Task 2 effort during the report period has been the start-up phase of an investigation of applications for photovoltaic total energy systems (PTES). These are systems in which a) photovoltaic solar energy conversion is used to supply electric power to meet the electric demand at a single load point (or group of related load points) and b) the thermal energy that is also collected is used to meet a colocated or nearby thermal demand. The objective of the mission analysis in this case is, as in the case of other types of photovoltaic missions, the identification of the most promising applications and the determination of the conditions under which PTES would be cost-effective in these applications. The emphasis of the study is on missions that will be technically and economically feasible in the post-1986 period.

Because of the multidimensional character of the problem, analysis of PTES missions requires consideration of a large number of parameters. Chart 10 illustrates some examples of the many interactive factors that must be taken into account. Not only is there a wide range of potential applications to be evaluated, but a variety of system concepts, operational concepts, and design concepts must be considered in each case. The questions as to the type of collector (flat-plate or concentrator) and the amount and type of storage (electric and/or thermal) to be provided are of particular interest, as is the decision as to which type of load -- electrical or thermal, baseload or peaking -- is to govern the design. The analytical procedure that is adopted must be able to cope with such questions as these, both in terms of their technical effects and their implications for the economics.

Study of Total Energy Missions is Multi-Dimensional

APPLICATIONS

RESIDENTIAL
- MULTIFAMILY
- MILIT BARRACKS
- NEW CITIES

INDUSTRIAL
- CHEMICALS,
- TEXTILES

COMMERCIAL
- OFFICES
- STORES
- HOTELS

INSTITUTIONAL
- SCHOOLS,
- LIBRARIES,
- GOVERNMENT BUILDINGS

AGRICULTURAL
- CROP DRYING,
- MILK PROCESSING

INSTALLATION
- NEW
- RETROFIT

SYSTEM CONCEPTS

STAND ALONE
- STORAGE
- NO STORAGE

BACK-UP
- GRID
- HEAT ENGINE

SITING

LOCATION
- URBAN
- RURAL

REGIONS
- INSOLATION
- THERMAL DEMAND
- etc.

OTHERS

- UTILITY INTERFACES
- IMPACT ASSESSMENT
- OWNERSHIP STRUCTURES

OPERATIONAL CONCEPTS

DESIGN TO LOAD
- ELECTRICAL
- THERMAL
- PEAKING
- BASELOAD

DUTY CYCLE
- SEASONAL
- SOLAR MATCH
- OTHER

DESIGN CONCEPTS

FLAT PLATE
- Si, CdS

CONCENTRATION
- ARRAY MATERIAL
- CONCENTRATOR TYPES

POWER UTILIZATION

- LIGHTING,
- HEATING,
- COOLING,
- PROCESS

Chart 10

Chart 11

PHOTOVOLTAIC TOTAL ENERGY MISSION ANALYSIS

The general methodology that has been selected for analyzing PTES missions is basically the same as the one that has been used in analyses of other solar energy missions, with somewhat increased complexity as a result of the addition of thermal supply and demand questions to the problem. This procedure is illustrated in schematic flow-diagram form in Chart 11. The first step, and the one to which much of the early effort on the task has been applied, is to establish a data base, containing information about candidate types of applications (physical characteristics, geographic distribution, electric and thermal loads, estimated market size, etc.). In this phase of the effort, as many as possible potential applications are identified for at least preliminary scrutiny.

The next step is to develop and apply appropriate initial screening criteria to identify those candidates that are technically feasible, that are likely to be cost-effective in the post-1986 period, and that represent markets that are large enough to be significant in relation to the total energy consumption in the U.S. These criteria must, of course, include an assessment of the degree to which application requirements (especially the magnitude and timing of electrical and thermal demands) match the capabilities of PTES.

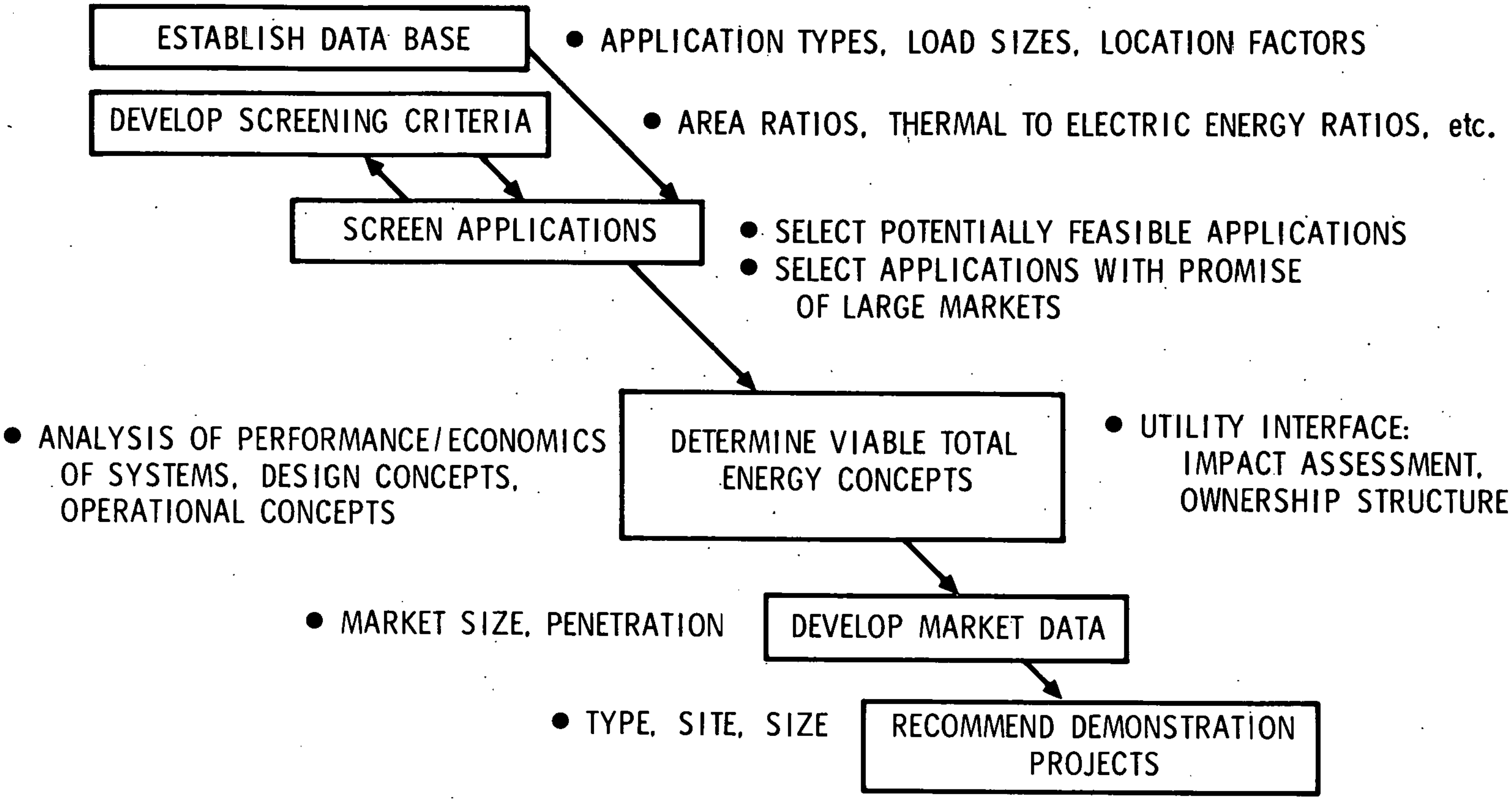
At the close of the report period, the assembly of the data base was nearing completion (although additional information will, of course, continue to be sought), and the preliminary screening was under way.

The next step in the process, and the one on which by far the greater part of the effort will be spent, will be the detailed analysis of the leading candidates among the applications that survive the initial screening. Computer simulation procedures will be used to evaluate the performance of the PTES systems in the application, as a function of system parameters, and these results will serve as inputs, along with system cost estimates, to an economic analysis that will determine the economic viability of the use of PTES in the application. Conversely, these economic analyses will also determine subsystem cost/performance goals that must be met if economic viability is to be achieved.

Finally, for the most promising applications, more refined estimates will be made of the total size of the associated market and of the expected degree (and timing) of PTES penetration of this market. Recommendations will also be made of appropriate and attractive demonstration projects.

Photovoltaic Total Energy Mission Analysis

- RATIONALE: UTILIZATION OF WASTE HEAT MAY MAKE PHOTOVOLTAIC POWER COMPETITIVE AT HIGHER ARRAY COST
- APPROACH:



ESTABLISH DATA BASE
- APPLICATION TYPES, LOAD SIZES, LOCATION FACTORS

DEVELOP SCREENING CRITERIA
- AREA RATIOS, THERMAL TO ELECTRIC ENERGY RATIOS, etc.

SCREEN APPLICATIONS
- SELECT POTENTIALLY FEASIBLE APPLICATIONS
- SELECT APPLICATIONS WITH PROMISE OF LARGE MARKETS

DETERMINE VIABLE TOTAL ENERGY CONCEPTS
- ANALYSIS OF PERFORMANCE/ECONOMICS OF SYSTEMS, DESIGN CONCEPTS, OPERATIONAL CONCEPTS
- UTILITY INTERFACE: IMPACT ASSESSMENT, OWNERSHIP STRUCTURE

DEVELOP MARKET DATA
- MARKET SIZE, PENETRATION

RECOMMEND DEMONSTRATION PROJECTS
- TYPE, SITE, SIZE

Chart 11

Chart 12

PHOTOVOLTAIC TOTAL ENERGY MISSIONS: AVAILABLE DATA BASE

The extent of the available data base that has been identified and is being utilized in this study is indicated in Chart 12. In order to locate and tap these sources of information an extensive literature search was carried out and contacts were made (both by telephone and in person) with personnel of such sponsoring agencies as the Department of Housing and Urban Development (HUD), the National Bureau of Standards (NBS), the California State Energy Commission, and various divisions of ERDA. In addition, principal investigators in various studies were contacted and reports of completed studies were acquired.

It was found that a considerable amount of information appears to be available on heating and cooling requirements for buildings, and on prior and current installations of conventional total energy systems. The heating and cooling data generally do not include electrical power needs, even when all-electric buildings are described, because power for machinery other than for refrigeration or heating systems, and sometimes lighting, is not normally inventoried for such studies.

There is also an extensive literature on industrial process heat requirements, but again, concurrent electrical load data is usually not provided. The studies by Battelle Memorial Institute and Intertechnology Corporation for ERDA's Division of Heating and Cooling may provide some relevant data, but they are not yet complete and reports are not available.

Although HUD was, and is currently, sponsoring studies of total energy systems and both studies and demonstrations of modular integrated utility systems (MIUS), these systems have been generally applied to multifamily residential complexes. (MIUS is a total energy system which satisfies excess thermal demands by burning waste materials in a supplemental boiler or gas generator.) Only a relatively small amount of market data in useful form has been obtained in these HUD studies because building statistics derived for these studies generally show square feet of floor area per geographic division only, in addition to data on heating and cooling requirements. These statistics do not provide such important information (for PTES applications) as the number of buildings of a particular type in a geographic division, the number of floors per building, the total ground area available, the electrical power needs other than those for heating and cooling, and so forth.

Much useful information on industrial and commercial electric and thermal loads is being generated by the McDonnell Douglas and Atomics International studies for the Total Energy Project of the Solar Thermal Systems Branch of the ERDA Division of Solar Energy. The Atomics International study has not as yet addressed PTES and will not make it a major portion of its work but will emphasize instead solar thermal total energy concepts. Particularly close contact and cooperation will be maintained with this program and, of course, with the ERDA-sponsored solar thermal total energy study at The Aerospace Corporation.

Photovoltaic Total Energy Missions

AVAILABLE DATA BASE

	DATA SOURCES, PROGRAMS	COMMENTS
BUILDING COOLING & HEATING	EPRI SPONSORED ERDA SPONSORED HUD SPONSORED	ONGOING PROGRAMS PRODUCING CONSIDERABLE REQUIREMENTS & MARKET DATA
	LITERATURE	● EXTENSIVE LITERATURE
INDUSTRIAL PROCESS HEAT	ERDA SPONSORED	● BATTELLE, INTERTECHNOLOGY CORP. - ONLY WORK SPECIFIC TO SOLAR ENERGY ● SOME MARKET DATA AVAILABLE
	LITERATURE	● EXTENSIVE LITERATURE, e.g., GEOTHERMAL & NUCLEAR PLANT HEAT UTILIZATION, CHEMICAL PROCESS DATA
CONVENTIONAL TOTAL ENERGY SYSTEMS	HUD SPONSORED	● DEMONSTRATION PROJECTS IN PROGRESS ● LITTLE MARKET SIZE DATA
	UTILITIES/PRIVATE	● GAS, DIESEL TOTAL ENERGY SYSTEMS, DISTRICT HEATING
	LITERATURE	● EXTENSIVE
SOLAR THERMAL TOTAL ENERGY SYSTEMS	ERDA SPONSORED	● ONGOING PROGRAMS: AEROSPACE CORPORATION - SOLAR THERMAL MISSION ANALYSIS McDONNELL DOUGLAS - INDUSTRIAL ATOMICS INTERNATIONAL - COMMERCIAL SANDIA - COLLEGE CAMPUS AMERICAN TECHNOLOGICAL UNIV - FT HOOD
	HUD SPONSORED	● PAST PROGRAM: A. D. LITTLE - RESIDENTIAL
PHOTOVOLTAIC TOTAL ENERGY SYSTEMS	ERDA SPONSORED	● ONGOING PROGRAMS: ATOMICS INTERNATIONAL - COMMERCIAL SANDIA - SYSTEM ANALYSIS

Chart 12

Chart 13

PHOTOVOLTAIC TOTAL ENERGY MISSIONS: BASIC ENERGY BALANCE CHARACTERISTICS

At the close of the report period, a start was being made on the task of selecting, from many potential candidates, those PTES applications that will be subjected to more detailed analysis. Chart 13 illustrates some very simple but fundamental properties that are inherent to photovoltaic total energy systems, at least to those in which the same solar collector is used to provide the electrical and thermal energy.

Because the conversion efficiency of a photovoltaic array decreases fairly rapidly as the temperature increases, the ratio of electrical to thermal output can be varied over a fairly wide range. The absolute value, however, remains small. (Or, conversely, the thermal to electrical ratio is large, 3 to 5, at low array temperatures and increases as the array temperature is allowed to rise.) The absolute amount of thermal output, on the other hand, is relatively insensitive to array temperature, increasing by ~10% as the array temperature is increased from $0^{\circ}C$ to $200^{\circ}C$. The analysis of any PTES application must take these basic characteristics into account. For example, in those numerous cases where the ratio of thermal demand to electrical demand is smaller than 3, the matching of PTES supply to the demand will be less than optimum.

Photovoltaic Total Energy Systems

BASIC ENERGY BALANCE CHARACTERISTICS

- ELECTRICAL/THERMAL RATIO RELATIVELY SMALL
- THERMAL OUTPUT INSENSITIVE TO ARRAY TEMPERATURE

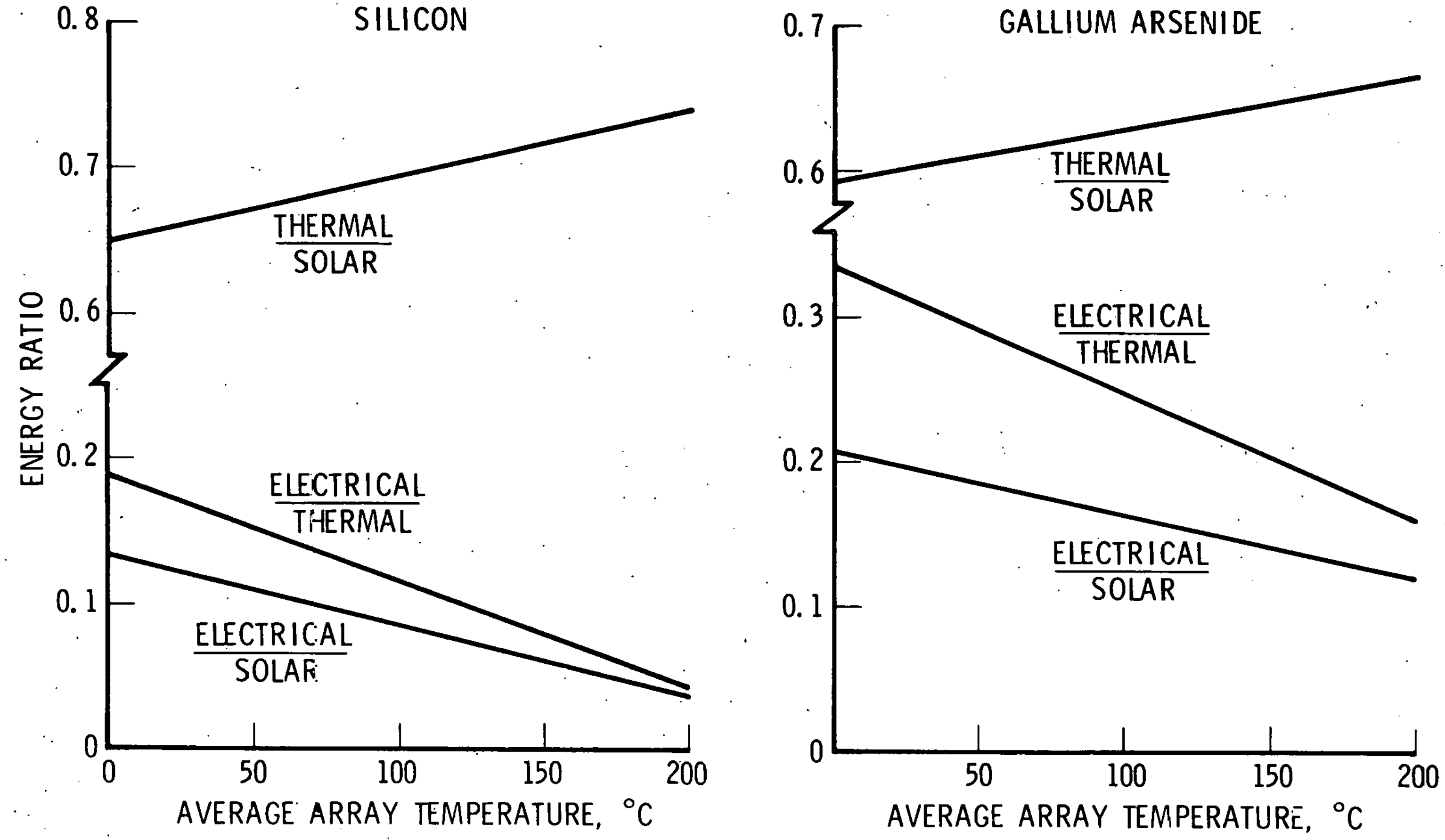


Chart 13

Chart 14

PHOTOVOLTAIC TOTAL ENERGY MISSIONS: CANDIDATE SCREENING CRITERIA

In connection with the preceding chart (Chart 13) the point was made that the selection of promising PTES applications must take into account the extent to which the thermal/electrical demand ratio in the application matches the inherent PTES thermal/electrical supply ratio. In addition to this basic criterion, however, a number of additional criteria must be applied in order to screen the large number of possible applications and to select the strongest candidates for further study. Chart 14 provides examples of the criteria that have been identified and are being applied, to the extent possible, in the preliminary screening that is now under way. As the process proceeds, it is likely that other criteria will be identified; it is also possible that one or more of those on the chart will be dropped because of the unavailability of the required data.

Most of the criteria listed in Chart 14 are self-explanatory, but some amplification may be useful in several cases. The "benefit ratio" will be important in those cases (e.g., a high-rise building) where the utilization of PTES would require the acquisition of additional land to accommodate solar collectors. In this case, in addition to the cost of the land, one should include in the economic assessment the revenue that could be realized from an alternative use of the land. The "aspect ratio" is a measure of the degree to which the total energy supply (which, in the case of solar energy, is proportional to the total area of the site) is matched to the demand (which is usually proportional to floor area). Uniformity in an application is important in that architectural and engineering costs could be substantially reduced if many identical (or nearly identical) systems were required (e.g., in supplying energy to the individual members of a chain of franchised restaurants).

Photovoltaic Total Energy Missions

CANDIDATE SCREENING CRITERIA

- ECONOMIC
  - PRELIMINARY MARKET ESTIMATE - ESTIMATED NUMBER OF LOAD POINTS, GROWTH POTENTIAL
  - GEOGRAPHIC DISTRIBUTION - NATIONAL, REGIONAL
  - BENEFIT RATIO - ENERGY SAVINGS/REVENUE FOR ALTERNATE LAND USE
  - PAYOUT TIME - COST BREAKEVEN WITH CONVENTIONAL ALTERNATIVE
- TECHNICAL
  - "ASPECT RATIO" - BUILDING FLOOR AREA/SITE AREA
  - ENERGY RATIO - THERMAL LOAD/ELECTRICAL LOAD
  - STORAGE REQUIREMENTS - DEPENDENCE ON DUTY CYCLE, DIURNAL MATCH
  - MINIMUM SIZE - DEPENDENCE ON BUILDING TYPE, UTILIZATION, DUTY CYCLE, ETC.
  - UNIFORMITY - SIMILARITY IN LOAD REQUIREMENTS, BUILDING DESIGN

Chart 14

Chart 15

UTILITY FINANCIAL PLANNING MODEL

During the report period, a start was also made on Task 5, the Impact of Incentives. The first step was to adapt to the specific case of photovoltaic power plants a general Utility Financial Planning Model whose construction was nearing completion in an Aerospace Corporation company-financed project. This new model (which replaces the Aerospace Corporation Power Plant Economic Model used in earlier studies) is illustrated in block-diagram form in Chart 15. It treats cash flows, taxes, depreciation, working capital allocations, and allowed revenues in a manner which is consistent with the way in which power plant economics are viewed by regulatory agencies. The model is therefore particularly well suited for use in evaluating alternative incentive strategies.

A central element of the model is the determination of the revenue stream through separate computations of a) the rate base, the utility's net investment at a given time as determined in accordance with regulatory practice; b) the allowable rate of return on rate base; and c) the total operating expenses. A provision is also made for the cost of periodic replacement of major plant subsystems. The determination of the total construction cost, as of the beginning of commercial operation, is carried out in the same manner as in the earlier Power Plant Economic Model (Reference 4) and takes into account spares, contingencies, indirect costs, and interest and escalation during construction.

At the close of the report period, the adaptation of the new financial model to the photovoltaic case was in the final check-out phase and its application to the evaluation of alternative incentive strategies was about to begin.

Utility Financial Planning Model

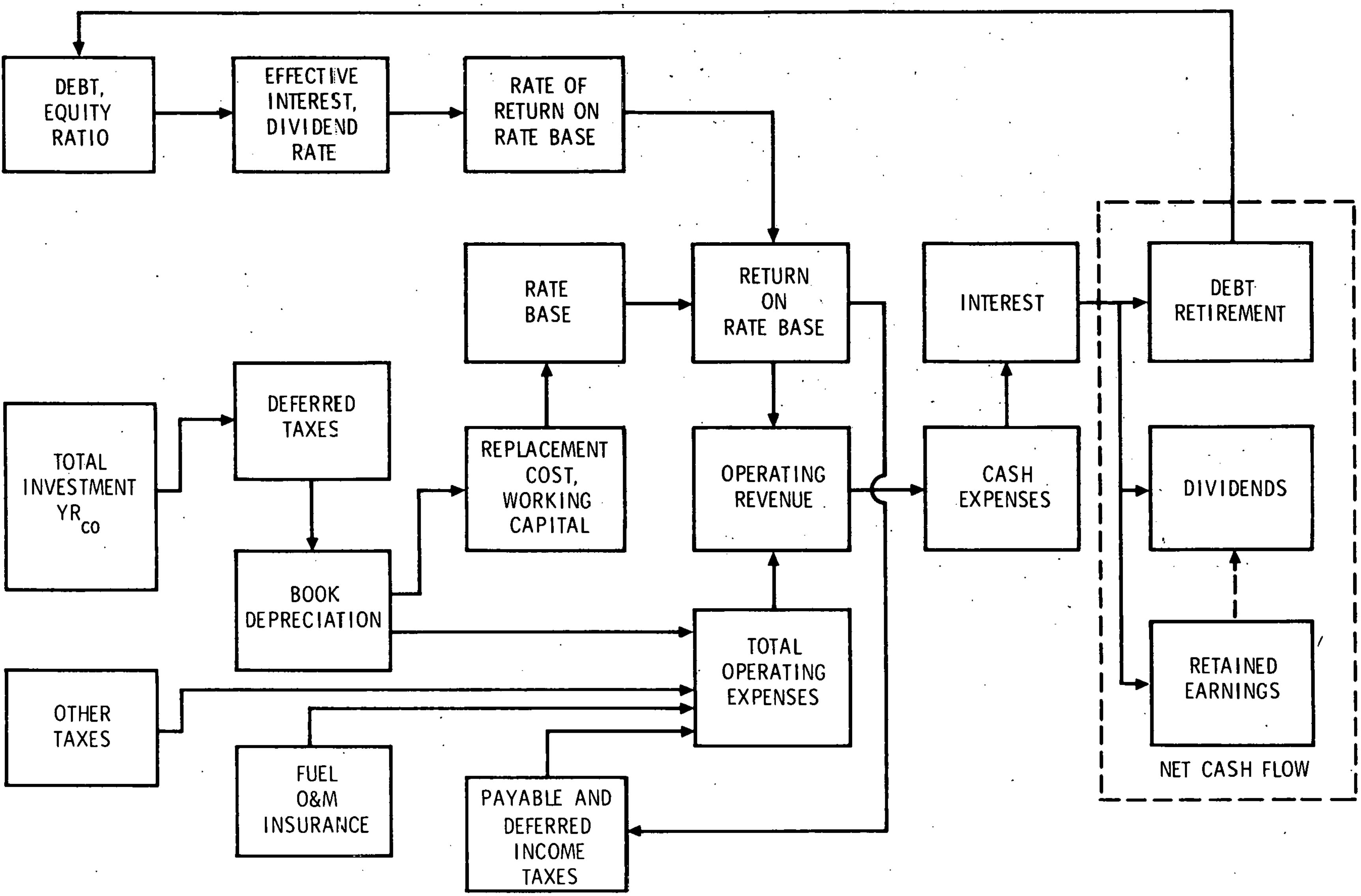


Chart 15

Chart 16

ACCOMPLISHMENTS: 1 JUNE - 30 SEPTEMBER 1976

The progress that has been made during the report period is summarized in Chart 16. Most of the activity has been devoted to Tasks 1, 2, and 5, and the accomplishments in these three tasks have been documented in greater detail in the preceding charts and in the accompanying text. Although no charts were prepared to illustrate it, progress was also made in the other tasks and is reported here.

The main thrust of the Task 3 effort during this period has been directed toward supporting the special Systems Development Planning Group that was set up at the close of the preceding quarter. Support of the activities of this group has required the carrying out of special analyses, attendance at a number of deliberative meetings, and preparation of a contribution to the preliminary report that was submitted in September.

Under Task 4, a study was made of the occupational and environmental safety and health hazards associated with the manufacture of GaAs, CdS, and Si solar cells. The conclusion was reached that, although local problems could arise if adequate preparations are not made to handle many of the toxic materials involved, experience gained in the chemical industry should permit even a greatly expanded solar cell industry to conduct all processing steps without damage to the environment or to the health and safety of the associated work force. A preliminary report on this study has been prepared. After some additions and revisions, it will be incorporated in the final report on the project.

In accordance with the revised work plan (as presented in Chart 1), effort on Task 6 was phased out early in the quarter with the completion of the analysis of the non-internalized societal costs of coal-fired power generation. A report on this study is in preparation and will also be included in the final report on the project.

Accomplishments: 1 June - 30 September 1976

TASK 1 ANALYSIS OF NEAR-TERM MISSIONS
- SURVEY CONCLUDED. REPORT IN PREPARATION
- SURVEY QUESTIONNAIRE ON INDIAN RESERVATION APPLICATIONS PREPARED FOR CIRCULATION BY BUREAU OF INDIAN AFFIARS; REPLIES BEING RECEIVED

TASK 2 ANALYSIS OF MAJOR MID-TERM MISSIONS
- STUDY OF CENTRAL STATION MISSIONS CONTINUED
  - COST-EFFECTIVENESS CRITERIA EXAMINED
  - PRELIMINARY ANALYSIS OF CENTRAL RECEIVER SYSTEMS EXTENDED
- INVESTIGATION OF PHOTOVOLTAIC TOTAL ENERGY MISSION BEGUN
  - APPROACH SELECTED
  - EXPLORATION OF DATA BASE INITIATED

TASK 3 REVIEW AND UPDATING OF ERDA TECHNOLOGY IMPLEMENTATION PLAN
- SUPPORT PROVIDED TO SYSTEMS DEVELOPMENT PLANNING GROUP

TASK 4 CRITICAL EXTERNAL ISSUES
- INVESTIGATION OF ENVIRONMENTAL/OCCUPATIONAL HAZARDS OF ARRAY PRODUCTION NEARING COMPLETION

TASK 5 IMPACT OF INCENTIVES
- NEW UTILITY FINANCIAL PLANNING MODEL OPERATIONAL

TASK 6 SOCIETAL COSTS OF CONVENTIONAL AND PHOTOVOLTAIC POWER PRODUCTION
- STUDY OF SOCIETAL COSTS OF COAL-FIRED GENERATION COMPLETED. REPORT IN PREPARATION

Chart 16

III. PLANS

This section contains a summary of planned activities during the next quarter.

Chart 17

PLANNED ACTIVITIES: 1 OCTOBER - 31 DECEMBER 1976

The activities that are planned for the final quarter of the project are listed in Chart 17. The main emphasis will continue to be on the several elements of Task 2, but progress will also continue to be made on Tasks 3, 4, and 5. Although there are no plans for substantive work on Tasks 1 and 6, some effort will be devoted to the preparation of reports on results already achieved.

Under Task 2, the analysis of central station missions will concentrate on a study of the cost-effectiveness of both flat-plate and concentrating (for at least one type of concentrator) photovoltaic power plants in five different geographical areas of the U.S. Similar analyses will also be carried out for plants with several different types of concentrator but sited in the same area.

The investigation of photovoltaic total energy missions will also continue. One or two candidate applications will be selected and subjected to preliminary analysis. At the same time, work will proceed on the development of the computer simulation capability that will be required for detailed analyses, but it is unlikely that this capability will be fully operational before the end of the quarter.

A start will also be made on an investigation of intermediate-to-large (i.e., $>100\ \text{kW}_{pk}$) load center applications for photovoltaic electricity. One or two examples of promising applications will be identified and subjected to preliminary analysis.

Under Task 3, support will continue to be given, as required, to the ongoing activities of the System Development Planning Group and an effort will be made to update the estimates of the size of the near-term and mid-term markets for photovoltaic arrays.

Under Task 4, the report on the study of the environmental and occupational hazards of array production will be completed and a renewed effort will be made to resolve the question of the real-world feasibility of feeding excess on-site photovoltaic power back into the utility grid.

Under Task 5, the new Utility Financial Planning Model will be used in a quantitative evaluation of a number of suggested incentive strategies.

Planned Activities: 1 October - 31 December 1976

TASK 1 ANALYSIS OF NEAR-TERM MISSIONS
- PREPARE REPORT ON MARKET SURVEY

TASK 2 ANALYSIS OF MAJOR MID-TERM MISSIONS
- CONTINUE ANALYSIS OF CENTRAL STATION MISSIONS
  - EFFECTS OF GEOGRAPHICAL VARIATIONS
  - EFFECT OF CONCENTRATION TYPE, CONCENTRATION RATIO
- CONTINUE INVESTIGATION OF TOTAL ENERGY MISSIONS
  - PRELIMINARY MARKET SURVEY
    - SEARCH LITERATURE, RESULTS OF RELATED STUDIES
    - ESTABLISH DATA BASE (load characteristics, etc.)
  - SELECT ONE OR TWO CANDIDATES FOR INITIAL ANALYSIS
  - DEVELOP TECHNICAL/ECONOMIC ANALYSIS PROCEDURE
- BEGIN INVESTIGATION OF INTERMEDIATE-TO-LARGE LOAD CENTER APPLICATIONS FOR PHOTOVOLTAIC ELECTRICITY
  - START MARKET SURVEY, MAKE INITIAL IDENTIFICATION OF PROMISING APPLICATIONS
  - CARRY OUT PRELIMINARY ANALYSIS OF ONE OR TWO EXAMPLES

TASK 3 REVIEW AND UPDATING OF ERDA TECHNOLOGY IMPLEMENTATION PLAN
- UPDATE ESTIMATES OF NEAR-TERM, MID-TERM MARKET
- SUPPORT SYSTEM DEVELOPMENT PLANNING GROUP

TASK 4 CRITICAL EXTERNAL ISSUES
- COMPLETE STUDY OF OBSTACLES TO FEEDBACK OF EXCESS ON-SITE POWER TO GRID
- COMPLETE STUDY OF ENVIRONMENTAL/OCCUPATIONAL HAZARDS OF ARRAY PRODUCTION

TASK 5 IMPACT OF INCENTIVES
- UTILIZE UTILITY FINANCIAL MODEL TO ASSESS IMPACT OF SEVERAL INCENTIVE STRATEGIES

TASK 6 SOCIETAL COST OF CONVENTIONAL AND PHOTOVOLTAIC POWER PRODUCTION
- COMPLETE REPORT ON SOCIETAL COSTS OF COAL-FIRED GENERATION

Chart 17

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IV. REFERENCES

1. Energy and Transportation Division, "Mission Analysis of Photovoltaic Solar Energy Systems, Quarterly Progress Report for the Period 1 December 1975 - 29 February 1976", ATR-76(7574-07)-1, The Aerospace Corporation, 1 March 1976.

2. S. L. Leonard, P. K. Munjal, and E. J. Rattin, "Mission Analysis of Photovoltaic Solar Energy Systems, Quarterly Progress Report for the Period 1 March 1976 - 31 May 1976", SAN/1101-76/1, ATR-76(7574-07)-2, The Aerospace Corporation, June 1976.

3. J. W. Doane, R. P. O'Toole, R. G. Chamberlain, P. B. Bos, and P. D. Maycock, "The Cost of Energy From Utility-Owned Solar Electric Systems, A Required Methodology for ERDA/EPRI Evaluations", JPL 5040-29, ERDA/JPL-1012-76/3, Jet Propulsion Laboratory, California Institute of Technology, June 1976.

4. Energy and Resources Division, "Power Plant Economic Model", ATR-74(7417-16)-1, The Aerospace Corporation, 1 June 1974.