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Assessment of the Technology Required to Develop Photovoltaic Power Systems for Large-Scale National Energy Applications

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Preface

This publication represents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract No. NAS 7-100, sponsored by the National Aeronautics & Space Administration. This report is being submitted to the National Science Foundation in partial fulfillment of NSF Grant No. AG-485. It includes evaluations, conclusions, and recommendations which culminate in a program plan, a milestone schedule, and funding requirements for the first 5-year phase of the development.

The principal author of this report is Dr. Ralph Lutwack, Member of the Technical Staff of the Spacecraft Power Section. Some suggestions of Mr. John V. Goldsmith, Supervisor of the Solar Energy Group of the Spacecraft Power Section, were used. The manuscript was edited by Ms. Dorris Wallenbrock of the Technical Information and Documentation Division.

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Foreword

This document is submitted to the National Science Foundation (NSF) by the Jet Propulsion Laboratory (JPL) in partial fulfillment of the contract to participate in the technical assessment for Photovoltaic Conversion Technology. The assessment described here includes perspectives of the overall program and of each of its phases. Task objectives, milestones, program phasing, implementation approach, descriptions and schedules for deliverable items, and stipulations of the resources required are considered. A framework in which a photovoltaic conversion development program can be operated and the information needed to integrate the tasks are discussed. The Laboratory believes that the comprehensive program, which is constructed from this assessment, is commensurate with the magnitude and importance of the NSF Photovoltaic Energy Conversion Program.

In the course of performing this assessment JPL evaluated published studies and documents, such as the recommendations of the Interagency Panel for Terrestrial Applications of Solar Energy and the summaries of the workshops at the NSF Conference on Photovoltaic Conversion for Terrestrial Applications held at Cherry Hill, New Jersey, October 23–25, 1973. Evaluations of solar cell systems, technology developments, and program projections by members of the Solar Energy Conversion Group at JPL were amalgamated with this information to yield the resulting program plans and schedules.

The recommended program contains subprograms for technology development, demonstration projects, and systems analyses, the guideline being the establishment of the practicability of photovoltaic conversion systems for large-scale terrestrial power applications. The scope of the program is limited by considerations of the status of the technology for individual photovoltaic candidates, schedule requirements, and funding limitations. As a consequence, the program for the development of the single-crystal *Si* system has been emphasized, but provisions for development programs for other candidates have been included.

The conclusions and recommendations of this report are applicable to the operation and direction of the program within the boundaries of the assumed conditions of objectives, schedules, and funding. Reevaluations and revisions will be needed in the event any of these becomes inappropriate in the future.

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Abstract

A technical assessment of a program to develop photovoltaic power system technology for large-scale national energy applications has been made by analyzing and judging the alternative candidate photovoltaic systems and development tasks. A program plan was constructed based on achieving the 10-year objective of a program to establish the practicability of large-scale terrestrial power installations using photovoltaic conversion arrays costing <$0.50/peak W. Guidelines for the tasks of a 5-year program were derived from a set of 5-year objectives deduced from the 10-year objective.

This report indicates the need for an early emphasis on the development of the single-crystal Si photovoltaic system for commercial utilization; a production goal of 5×10^9 peak W/year of $0.50 cells was projected for the year 1985. The developments of other photovoltaic conversion systems were assigned to longer range development roles. The status of the technology developments and the applicability of solar arrays in particular power installations, ranging from houses to central power plants, was scheduled to be verified in a series of demonstration projects. The budget recommended for the first 5-year phase of the program is $268.5M.

Assessment of the Technology Required to Develop Photovoltaic Power Systems for Large-Scale National Energy Applications

I. Summary

This report contains a technical assessment of a program to develop photovoltaic conversion system technology for large-scale terrestrial energy applications. The assessment was initiated by defining the long-term objective of a program to achieve economic practicability for photovoltaic conversion systems for terrestrial applications. A list of technology requirements and program limitations, which provide generalized descriptions of the requisites of the program, was employed in the definition. Objectives of a near-term, 5-year program were then delineated, based on the long-term objective. This set of objectives was used to derive interim objectives and interim goals. The technical assessment, which in turn becomes the basis for formulating a program containing descriptions of technology development tasks, program milestones, funding requirements, and a management organizational plan, was obtained, finally, from considerations of the 10-year objective, the 5-year objectives, the interim objectives, and the interim goals.

The reports, conclusions, and recommendations of an Interagency Panel for Terrestrial Applications of Solar Energy, of an NSF-sponsored Conference on Photovoltaic Conversion of Solar Energy for Terrestrial Applications held at Cherry Hill, New Jersey, October 23–25, 1973, and of the publication "The Nation's Energy Future" by Dr. D. L. Ray were analyzed and evaluated. These critiques were utilized in the assessment, in which the criterion of optimizing the probability of achieving the 5-year objectives of the program was applied.

The objective of the first 10-year effort is the establishment of the practicability of large-scale terrestrial power installations using photovoltaic conversion arrays costing <$0.50/peak W.

In order to meet the long-term objective, the following 5-year objectives are specified:

(1) The determination of the feasibility of the technology necessary for fabricating solar cell modules, which will result in an array costing <$0.50/peak W. This implies:

(a) Establishing that these solar arrays have satisfactory lifetime electrical performance characteristics under terrestrial environmental conditions

such that the degradation of electric power output is less than 5% over a 20-year period.

(b) Requiring the installation of a pilot plant for the production of low-cost, solar cell grade, polycrystalline Si.

(2) The institution of facilities and tasks to perform the tests and evaluations required for the development program and to provide the data for the systems studies.

(3) The performance of a sufficient number of systems studies to ensure the availability of the information needed to design technically and economically acceptable power systems.

(4) The conducting of a research program to provide the basis for advanced technology developments.

This set of objectives should serve as the precedent for another set of objectives, which will need to be defined for the second 5-year interval in the 10-year program.

The list of generalized technical requirements and program limitations, which was used as the precedent for the 10-year objective, also served as a guide in the assessment of the technology and in constructing milestone and funding requirements. This list reflects the essence of the program objectives and summarizes the general programmatic considerations and the consequences of these objectives. It contains the following items:

(1) A power installation based on a photovoltaic conversion system must be economically competitive.

(2) The feasibility of the technology for a potentially economically competitive system must be demonstrable within 5 years.

(3) The commercial practicability of a photovoltaic conversion system should be established within 10 years.

(4) Fundamental and applied research and development tasks must be conducted vigorously throughout the program to ensure the scientific and technological bases, which may lead to technically and economically superior systems.

(5) The financial support will come primarily from NSF. There may be complementary programs supported by private industry. To increase the participation of industry, it will be necessary to communicate the progress and problems of the NSF program; one way to do this is through demonstration projects.

(6) The probability of developing practical technology would be increased by arrangements with power utility organizations for cooperative programs.

Using the definitions of an interim objective as being essential to the success of the 10-year program and of an interim goal as being contributory but not essential to the achievement of the 10-year program objective, sets of interim objectives and interim goals were created to provide an elaboration of the plan for the program for each of the 10 years. A list of interim objectives and interim goals is provided in Table 1.

In the conclusions and recommendations of the technical assessment, derived by the procedure and under the conditions cited above, the primary effort is assigned to the development of the single-crystal Si solar cell system. In support of this effort, separate tasks for power system studies and for operating a national laboratory directed to insolation, testing, and evaluation are also described.

The subprogram for developing single-crystal Si array technology contains five key tasks: (1) low-cost, high-volume production of polycrystal Si material; (2) low-cost, high-volume, large area single crystal Si production; (3) continuous, automated, low-cost, high-rate cell and array fabrication; (4) satisfactory long-lifetime encapsulation; and (5) improved cell efficiency. The development of a suitable process for single-crystal Si production is considered to be crucial to achieving the program objectives; the edge-defined, film-fed growth (EFG) procedure, which is being investigated, has the potential for meeting these requirements. The manufacturing steps, which begin with the processing of single-crystal ribbons and end with the fabrication of solar cell arrays, must be automated to make the array fabrication sequence economically feasible.

The primary role for the single-crystal Si solar cell system is apparent from the selection of interim program objectives, as given in Table 1, and from the designation of the critical milestones for the 10-year program, which are presented in Fig. 1. Further evidence is provided in Table 2, which shows the budget for a program constructed from the JPL assessment. The program, with a funding total of $268.5M for 5 years, emphasizes the development of the single-crystal Si solar cell system and includes major sections for power system design, material characterization and device-performance evaluation, and demonstration projects. It is believed that reductions in funding below the levels proposed will result in compromises in

Table 1. Interim objectives and goals

Fiscal Year	Objectives	Goals
1975	Initiate programs in the following areas: Production of low-cost polycrystal Si material Development of continuous, multiple ribbons of single-crystal Si Development of processes for continuous cell production from single-crystal Si sheets Development of long-lifetime encapsulation materials and packaging designs Study of power system requirements Study of electric power performance of solar cells used in terrestrial applications Continue development of single-crystal Si ribbon process: Establishment of at least one suitable die material Evaluation of physical and electrical properties of prototype solar cells	Initiate, or continue, long-range programs in the following areas: Single-crystal Si cells Development of web single-crystal sheets Investigations directed toward improvement of efficiency of energy conversion Other materials and services Development of techniques for fabricating polycrystal Si cells Investigation of properties of polycrystal Si cells Investigations of degradation and reliability problems of CdS/Cu_2S cells Studies of several potential photovoltaic conversion systems Initiate program to demonstrate feasibility for production of wafer-cell arrays at < \$5/peak W: Development of scale-up and automation processes Evaluation of production potential of automated processes using Czochralski ingots
1976	Select process for high-volume production of low cost polycrystal Si material Complete preliminary specifications for power system requirements and economic analysis of several applications of photovoltaic arrays Initiate demonstrations of continuous growth and multiple growth processes for single-crystal Si ribbon Initiate study to optimize production of Si ribbon cells Define standard procedures for device evaluation and calibrate cells for terrestrial performance evaluations	Develop substrate materials for polycrystal Si cells Fabricate development model, 3% efficient, stable CdS/Cu_2S cells Establish feasibility of technology for \$5/peak W, single-crystal Si wafer cell Begin construction of 100-kW modules from single-crystal Si wafer cells for use as demonstration units Complete analysis and define specifications for solar concentration for photovoltaic systems
1977	Complete design of production plant for polycrystal Si material Demonstrate feasibility of continuous ribbon technology Define processes for ribbon-cell fabrication Complete specifications and design for encapsulation of ribbon-cell arrays	Establish that development model CdS/Cu_2S cells have satisfactory stability and reliability characteristics Demonstrate technical feasibility for polycrystals Si cells Complete specifications for insolation measurements and solar cell and array evaluation procedures
1979	Place on-stream small-scale plant for production of polycrystal Si material Demonstrate technology for multiple growth of Si ribbon Complete study for automating ribbon cell processing	Achieve production of \$2.50/peak W for Si wafer cells Select systems out of category of other materials and services for continued research and development
1982	Place on-stream small-scale production plant for ribbon Si Place on-stream small-scale production plant for ribbon Si cells and arrays Initiate design of large-scale production plant for ribbon Si cells and arrays	Place on-stream small-scale production plant for 5% efficient polycrystal Si cells
1983	Achieve production of < \$0.50/peak W modules	Demonstrate technology for 10% efficient polycrystal Si cells

Table 2. 5-year budget[a] recommended in JPL assessment

	Fiscal Year				
	1975	1976	1977	1978	1979
Single-crystal Si cell (ribbon)	4.0	12.5	24.0	31.0	46.0
Single-crystal Si cell (wafer)	1.5	6.5	7.0	6.0	2.0
Polycrystal Si cell	0.5	2.0	3.5	3.5	3.5
CdS/Cu_2S cell	1.0	4.5	8.5	9.5	9.5
Other materials and devices	0.75	3.5	4.0	3.0	3.0
Isolation, testing, and evaluation	2.5	4.5	6.0	5.5	5.[illegible]
Systems	1.25	6.5	11.0	13.0	13.0
Totals	10.5	40.0	64.0	71.5	82.5
Cumulative totals	10.5	50.5	114.5	186.0	268.5

[a]In $\$10^6$.

the overall program scheduling and, consequently, in a marked decrease in the probability of a successful program.

The thin-film, photovoltaic conversion systems of CdS/Cu_2S, polycrystal Si, GaAs, and CdTe; organic systems; and other novel systems are among those placed in the category of candidates whose technical capabilities are yet to be demonstrated. The development subprograms for these systems are for investigations which are directed to establishing technology credibility as a prerequisite for the development of practical devices. Accordingly, the CdS/Cu_2S subprogram comprises studies of degradation and efficiency problems; there are studies of efficiency, of the effects of grain boundaries, and of junction formation in the polycrystal Si effort; and the physical and electrical characteristics of other potential photovoltaic conversion systems are to be the subjects of a research and development task.

The plan for a FY75 program, which is presented in Table 3, conforms to the proposal for the 5-year program.

A potential program organization structure is outlined in Fig. 2. This is a functional arrangement which comprises four major sections: (1) Single-Crystal Si Solar Array Mission, (2) Systems, (3) Insolation and Evaluations, and (4) Photovoltaic Conversion Systems—Advanced Development.

An appendix which contains a discussion of the need for technical evaluation laboratories is included as a supplement to the report.

II. Introduction

The practical generation of electricity from solar energy for terrestrial applications using photovoltaic conversion technology cannot be achieved until solar cell modules and systems can be produced at low cost and in adequate volume, and solar cell power plants can be installed and operated at commercially competitive prices. There is no solar cell which meets these requirements today. However, some solar cells have been shown to have properties which make them suitable candidates for development programs directed to obtaining a satisfactory photovoltaic conversion system. As a prerequisite to instituting these programs, it is necessary to perform an assessment of the candidates in which the potential of each is evaluated; the structure and magnitude of research, development, and engineering programs needed to establish the technology feasibility of each system are estimated; and milestones and funding levels are formulated.

The single-crystal Si solar cell is the primary candidate by virtue of its many attributes. In this case, the theory and technology are well developed, the conversion efficiency is high, the material is abundantly available, and the technical goals are well defined. The relatively high level of technological maturity attained for this system is evidenced by the increase in conversion efficiency to about 16.5% at Air Mass 1 (AM1) from 5% for the early cells developed in 1954. Solar modules with conversion efficiencies of about 11% are available today at less than \$50/W for small orders. The present annual U.S. production of single-crystal Si devices is equivalent to

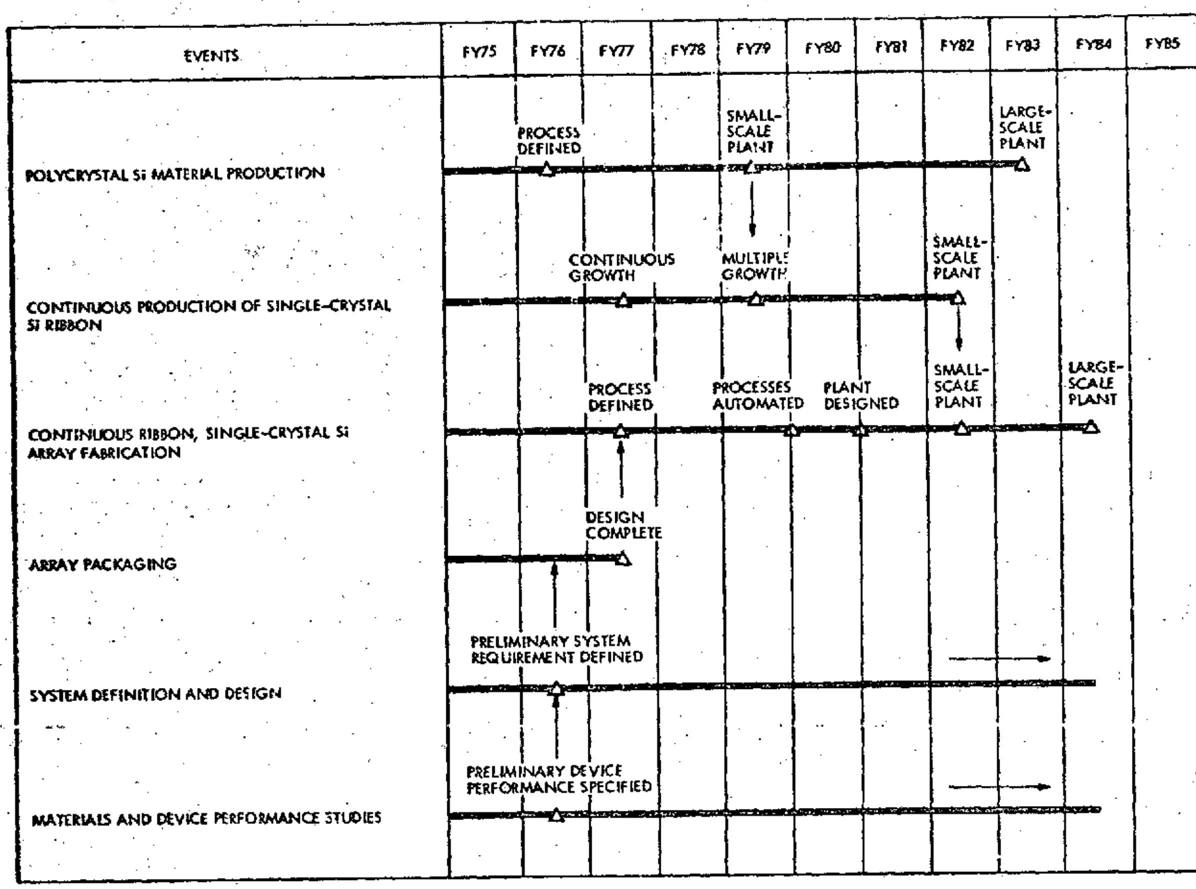


Fig. 1. Critical program milestones to reach NSF objective of \$0.50/peak W solar arrays for solar photovoltaic power systems in 10 years

approximately 60 kW; 90% of these devices are used in the space program.

Although much of the development to date has been restricted to the single-crystal Si technology, research and development of other promising photovoltaic conversion systems have been accomplished to a lesser extent. These systems have the potential for high-volume production and for costs less than the single-crystal Si module, but they require far more extensive basic research and development programs.

In general, the prospects for producing satisfactory low-cost solar modules are good. Even without further technology advancements, significant cost reductions are obtainable by the application of mass production techniques. If the changes are instituted to meet a market of 1000 kW or more, per year, a decrease in price to \$20/W for the single-crystal Si array is predicted. A decrease to \$5/W has been extrapolated for an anticipated market in excess of 1000 kW per year if automation procedures are utilized in production. A price for a module of less than \$0.50/W has been projected for both the single-crystal Si and CdS/Cu_2S systems if adequate development programs are pursued.

At an array price of less than \$0.50/W, the generation of electric power by photovoltaic conversion would be commercially competitive in many situations. Accordingly, the 10-year objective of this program is the establishment of the practicability of <\$0.50/W solar arrays for terrestrial power plants. The probability of the availability of these low-cost solar energy conversion components should act as a strong incentive to involve power utility participation in the development of photovoltaic conversion devices for large-scale power applications.

Table 3. Suggested tasks for FY75

- *Single-crystal Si solar array mission*
  - Single-crystal Si ribbon cell
    - Polycrystal Si material
      - Process definition study—3 parallel programs
    - Single-crystal Si ribbon
      - Ribbon-process development—2 parallel programs
      - Ribbon-process research
      - EFG die investigation
      - Process control
    - Other single-crystal Si sheet
    - Cell manufacture
      - Process development—3 parallel programs
      - Ribbon cell fabrication R&D
    - Array manufacture
      - Process development
      - Encapsulation materials investigation—3 parallel programs
  - Supporting developments
    - Development of improved cells—3 parallel programs
    - Study of requirements for demonstration projects
  - Wafer cell manufacture
    - Development of processes for high-volume production
    - Production engineering for high-volume production
- *Photovoltaic conversion systems—advanced development*
  - Polycrystal Si cell
    - Studies of properties and techniques for preparation—3 parallel programs
    - Investigation of substrate materials
  - CdS/Cu_2S cell
    - Investigations of stability problem—3 parallel programs
    - Study of encapsulant materials
  - Other materials and devices, investigations of physical and photovoltaic properties—7 to 10 efforts
  - Advanced research and development
- *Systems*
  - Studies, designs, and analyses: studies of concentrator designs and systems, photovoltaic performance in systems, power conditioning requirements, energy storage, interfaces with power grids, and total energy systems—3 parallel programs
  - Applications projects, design studies for applications projects
- *Insolation and evaluations*
  - Insolation data
    - Investigations to develop hardware and software
    - Evaluations of measuring equipment
  - Evaluations of materials and devices
    - Investigations to certify tests and apparatus
    - Purchases and evaluations of equipment and initial policy
    - Operation of facility

III. Basis for Technical Assessment

The primary aim of the NSF Photovoltaic Conversion Program is to establish the conversion of solar energy by photovoltaic devices as a technically and commercially practical means of providing electric power for terrestrial applications. In addition, it is intended that the Program will act as (1) a bridge between the scientific and industrial communities to facilitate the transfer of technology developments and (2) a means of maintaining a vigorous research and advanced development program in the photovoltaic field To provide direction for the program, a far-term, 10-year objective has been defined, and near-term, 5-year objectives have been based on it. The 5-year objectives act as the framework for the technology assessment and for formulating program milestones and budgets.

Implicit in the definition of the 10-year objective is a list of technology requirements and program limitations which was used to provide generalized descriptions of the requisites of the program. Having defined the 10-year objective, a set of interim objectives and interim goals was formulated. This set was used to furnish the premises for the assessment of the scheduling of the technology development tasks. Finally, the criterion that the 10-year and 5-year objectives were to be achieved in a cost-effective, integrated operation was used as the basis for the assessment of the funding requirements for the overall program.

A. Technical Requirements and Program Limitations

The definition of the 10-year objective is based on the recognition that the NSF program needs to conform to a particular set of technical requirements and program limitations, including the following:

(1) A power installation based on a photovoltaic conversion system must be economically competitive.

(2) The feasibility of the technology for a potential economically competitive photovoltaic conversion system must be demonstrable within 5 years.

(3) The commercial practicability of an economically competitive photovoltaic conversion system must be established within 10 years.

(4) Fundamental and applied research and development tasks must be conducted vigorously throughout this program to ensure progress in science and technology so as to provide the basis for systems which may become technically superior and more economical.

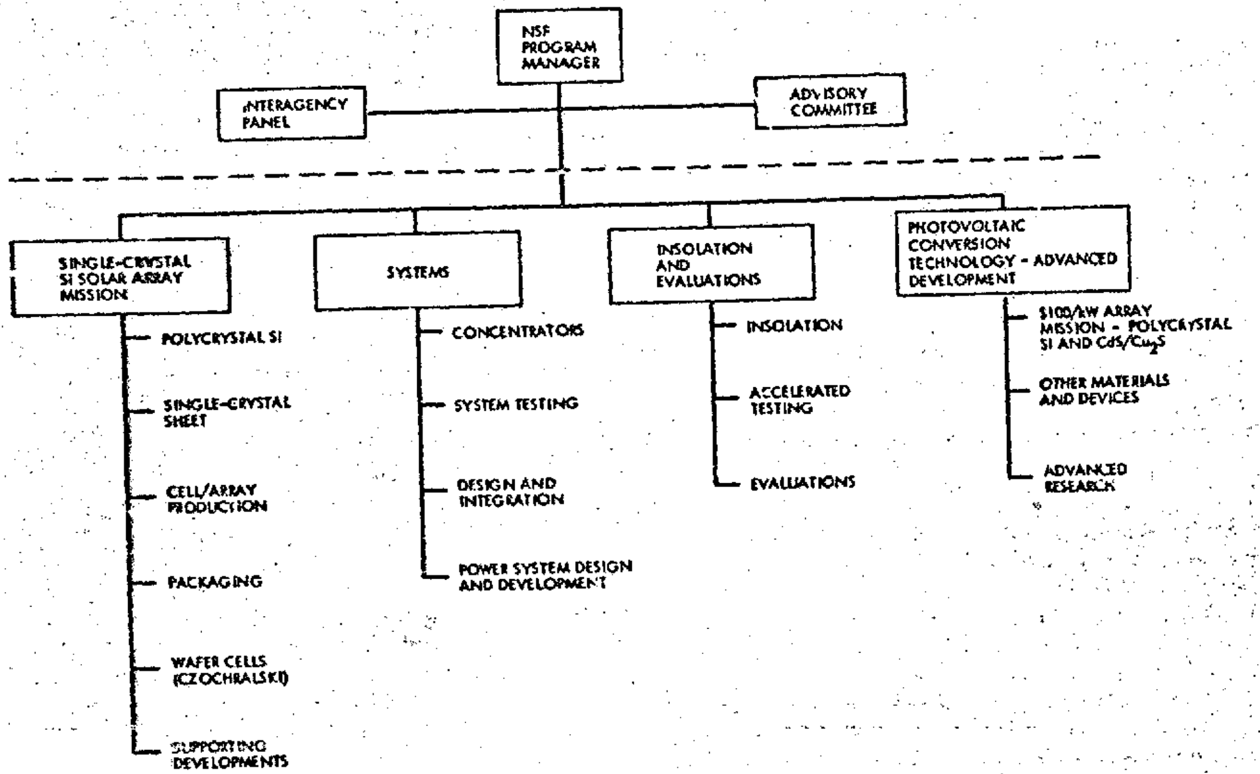


Fig. 7. Management organization chart

(5) The financial support for the program will come primarily from the National Science Foundation. There may be complementary programs supported by private industry. To increase the participation of industry, it is necessary to communicate the progress and problems of the NSF program through meaningful demonstration projects.

B. 10-Year Objective

The far-term, 10-year objective has been based on the foregoing set of requirements and is defined to be the establishment of the practicability of large-scale terrestrial power installations using photovoltaic conversion arrays costing <\$0.50/W.

C. 5-Year Objectives

The near-term, 5-year objectives were derived using the 10-year objective as the primary guideline for the program. The near-term objectives are:

(1) The determination of the feasibility of the technology necessary for fabricating solar cell modules, which will result in an array costing <\$0.50/peak watt. This implies (a) establishing that these solar arrays have satisfactory lifetime electrical performance characteristics under terrestrial environmental conditions such that the degradation of electric power output is less than 5% over a 20-year period, and (b) requiring the installation of a small-scale plant for the production of low-cost, solar cell grade polycrystalline Si.

(2) The institution of facilities and tasks to perform the tests and evaluations required for the development program and to provide the data for the systems studies.

(3) The performance of sufficient systems studies to ensure the availability of the information needed to design technically and economically acceptable power systems.

(4) The conducting of a research program to provide the basis for advanced technology developments.

D. Interim Objectives and Interim Goals

A set of interim objectives and goals was created for use in categorizing the technology needs and scheduling the program. In this context, an interim objective has been defined as being essential to the success of the program, whereas achieving an interim goal is considered to be desirable but not vital to the achievement of the 10-year objective. However, the interim goals are also directed in large part to the advancement of photovoltaic conversion technology and to the attainment of the technical development commensurate with establishing the feasibility of \$0.10/W arrays. For instance, the development of 20% conversion efficiency devices could be designated as an interim goal, although reaching this efficiency mark is not essential to attaining the 10-year program objective. The identification of these interim objectives and goals was an aid in judging the relative importance of specific tasks during the technology assessment as well as serving as a premise for the overall program schedule.

E. Funding Consideration

In the course of analyzing the funding requirements for the program, the funding levels recommended in the reports of the Interagency Panel and of the NSF Workshops were examined. These budgets had been formulated under the general guideline of separately optimizing the contributions of the individual subprograms toward achieving the 5- and 10-year objectives of the program. It was concluded that a procedure of simply using the sum of these recommendations is not commensurate with the prudent funding of an integrated program. This conclusion follows from the recognition that the structure of the total program should be based on the premise of maximizing the probability of achieving the objectives of the overall program. As a consequence of this optimization criterion, constraints were imposed on formulating the strategy of the overall program. These constraints were employed in turn in the assessments of the technology development plans for the subprograms. Thus, in effect, this optimization criterion was used to set priorities among the subprograms and their tasks as well as to define the technology development goals and limitations for specific subprograms. Accordingly, the allocations of the funding levels were, in turn, dependent on the judgments of the relative importance of the technical and schedule aspects of each task to the objectives and schedule of the overall program.

IV. Technical Assessment

The selection of the particular photovoltaic conversion systems and the formulation of the technology development tasks to be included in a terrestrial energy program should be effected so as to maximize the probabilities of attaining each of the near-term objectives. In the selection procedure, it is necessary to judge the alternative systems, taking into account the need to consider the economic, technical, and organizational factors; the obligation to allocate resources of funds, facilities, and manpower in more than one objective area and in different time frames; the uncertainties of estimating the outcome of a particular set of decisions; and the availability of more alternative options than can be used. To give proper consideration to these various factors and relationships, and in an effort to provide a reasonable basis for the program, assessments have been made of the state-of-the-art. In the course of these evaluations, special consideration was given to the conclusions and recommendations of the Interagency Panel for Terrestrial Applications of Solar Energy, of the workshops at the NSF Conference on Photovoltaic Conversion for Terrestrial Applications held at Cherry Hill, New Jersey, and of the section on photovoltaic conversion in "The Nation's Energy Future" by Dr. D. L. Ray.

The assessments have been accomplished on the basis that, while the primary, immediate need is to achieve the technical and economic optimization requirements, as stated in the 5-year objectives, there are requisites for the overall program extending beyond the near-term periods. These requisites are to establish photovoltaic conversion systems as being practical for on-site and central power installations and in doing so to demonstrate that commercial, production, and social demands can be fulfilled satisfactorily.

A summary of these assessments is presented in the following section.

A. Assessment of Summaries of Workshops at NSF Cherry Hill Conference

A workshop Conference on Photovoltaic Conversion of Solar Energy for Terrestrial Applications, held on October 23–25, 1973, at Cherry Hill, New Jersey, was organized by JPL and sponsored by NSF. The agenda consisted of workshop discussions, panel discussions, and presentations and discussions of invited papers. The workshop subjects were single-crystal Si solar cells; polycrystal Si solar cells; CdS/Cu_2S solar cells; other materials and devices; systems; and insolation, testing, and evaluation.

The following general objectives were posed for the workshops: (1) to provide the research and technology base required for the economic terrestrial application of solar energy and to foster the implementation of practical systems to the state required for commercial utilization; (2) to develop at the earliest feasible time the potential of solar energy applications as large-scale alternative energy sources; and (3) to provide a firm technical, environmental, social, and economic basis for evaluating the role of solar energy utilization in U.S. energy planning.

Assessments of the summaries of the workshops follow.

1. Single-Crystal Si Solar Cell

a. Abstract of Workshop Report. Four key elements for a technology development program were cited in the report of this workshop: low-cost polycrystal Si material; low-cost single-crystal Si sheet; automated solar cell and array manufacture; and improved solar cell conversion efficiency. Several conclusions and recommendations were reported: (1) Low-cost polycrystal Si material may be obtainable by modifying the presently used processing of $SiHCl_3$ or by developing a different process, for example by using SiH_4. Three- to five-fold decreases in the price of solar cell grade polycrystal Si were predicted to be attainable based on a program involving a phase for a study process development, production engineering, and an experimental pilot plant, which was scheduled to be in operation in 1979. This phase was budgeted at \$5.8M. In a second phase, a production plant, capable of producing solar cell grade polycrystal Si equivalent to 5×10^8 peak W annually starting in 1985, was budgeted at \$50M. (2) The EFG ribbon process is crucial to the overall program to produce low-cost single-crystal Si cells. This process has the potential for effecting the needed cost reductions and being concordant with the high-rate production of cells. Since the consensus was that only a five-fold cost decrease is possible using the web dendrite process (the Czochralski process was declared to be only capable of a two-fold decrease), the primary effort should be expended on the EFG development, where a budget of \$5M for R&D, \$15M for scaling up technology, and \$30M for a full-scale production plant was recommended. (3) A continuous, automated, high-rate cell fabrication process is required to achieve the necessary cost reductions. The recommended budget included \$6M for process definition, \$12M for a pilot plant, \$1M for packaging, and \$80M for a factory. (4) An efficiency of 19% (AM1) should be the goal for a high-volume, low-cost cell. A supporting R&D program of \$3 to 5M was recommended.

b. Critique by JPL. The areas for research and development were separated and clearly defined in this workshop summary. The conclusions that the development of a new single-crystal process, such as EFG, is crucial and that the cell and array manufacture must be automated seem to be peremptory. In general, the recommended program seems to be well matched to the program objectives.

In view of the importance assigned to the development programs for the EFG process and for automating all fabrication, these two efforts should be pursued with the top priority for the available funding. The task for the development of a process for low-cost, high-volume production of polycrystal Si is also of considerable importance and should proceed at the recommended level, if possible. Consequently, the task for supporting developments would be the most vulnerable to fund-cutting, if any is necessary, at the start of the program.

In the sequencing of the program, the milestones for the technical development of the ribbon process, for the definition of the processes for cell fabrication automation, and for the complete design for the encapsulation packaging are shown to fall due in the middle of FY77. This seems to imply that there would be little dependence of the process developments for cell automation on the characteristics of the ribbon and encapsulation processes. Although it might seem that the ribbon production can be described in a general sense early in the development, nevertheless, the probable interdependence of these development subprograms should be recognized. Accordingly, a great emphasis needs to be placed on the ribbon process development at the early stages of the program in order to meet the schedule for the cell production subprogram. The timing for the integration of the encapsulation development into the overall schedule needs to be given serious attention.

There were no provisions in this program for the development of encapsulation techniques for arrays, although notice was taken of the need to resolve this problem. A separate task for this purpose should be included in the program.

2. CdS/Cu_2S Solar Cells

a. Abstract of Workshop Report. In the report of this workshop, the emphasis was placed on the descriptions of the low-cost and high-volume production potentials of the CdS/Cu_2S cell. The technology problems of conversion efficiency, performance degradation, and production cell uniformity were concisely stated, but the milestone chart contained production goals only. Lifetime, degradation, production yield, and photovoltaic conversion efficiency were designated as problem areas. Other II-IV combinations, such as CdTe and CdTe/CdS, were recommended for further study. An extensive R&D program for the CdS/Cu_2S cells, culminating in the commercial production of high-reliability, low-cost cells by 1985, was advised. Milestones were set at \$4/W devices by the end of 1975, continuous-batch production of $\leq$\$2/W devices at the end of 1977, a pilot plant for continuous production at $\leq \$1/W$ at the end of 1979, and a production capability of 9.3×10^6 m^2/year at \$0.20/W at the end of 1984. The budget through 1979 was set at \$65.5M, with an additional \$120M budgeted through 1985.

b. Critique by JPL. The report of this workshop was considered optimistic. Although problem areas were mentioned, the emphasis was placed on developing processes to meet mass production and cost goals. Indeed, the linking of statements concerning degradation and reliability problems, with brief presentations of preliminary results from investigations of these problem areas, tended to lessen anxiety about the seriousness of the technical issues. Descriptions of the problem areas and the use of milestones for technology goals to solve the problems would have provided a base for correlating the technology development and engineering phases with the defined production goals. Indeed, the precedence of a problem-solving phase to the phase for the development of production processes should be clearly stated by inserting technology development goals into the milestone chart. The proposed budget would be reduced as a result of an emphasis being placed on the solution of the technology problems in the first years of the program and of the decision to make the single-crystal Si cell the primary candidate for this program.

3. Polycrystal Si Solar Cells

a. Abstract of Workshop Report. The major problems listed by the workshop can be categorized as those dealing with energy conversion and those involving production of devices. In the first category, tasks were assigned to investigations of grain boundary effects, grain size, energy conversion efficiency, and electrical performance characteristics. The second category included tasks for large-area production on suitable substrates, encapsulation and contact techniques, and low-cost polycrystal Si material production. The objectives were set up for the demonstration of 5% efficiency in 1979 and pilot plant capabilities of 10,000 m^2/year in 1982 and 100,000 m^2/year in 1984. A \$14M budget was recommended to achieve the first objective, and there were additional budgets of \$18M and \$12M for each of the other milestones.

b. Critique by JPL. The relatively primitive stage of technology development, the complexity of the problems, the necessary technology breakthroughs, and the program objectives were explicitly described. The milestone chart, which included the objectives, would have been more meaningful had some of the interdependencies of the R&D tasks been shown. The workshop evidently intended to use the omission of milestones for other R&D tasks as a means of emphasizing the present rudimentary nature of the polycrystal Si solar cell technology.

4. Other Materials and Devices

a. Abstract of the Workshop Report. The workshop recommended that exploratory studies be undertaken on a large number of alternative materials and devices, the first step being a weeding-out process of perhaps 3 years. It was advocated that additional funds be used at the end of this first period to pursue the research and development of the remaining promising materials and devices. The materials suggested for consideration were Cu_2O, GaAs, CdTe, $CuInS_2$, $CuAlS_2$, and Zn_3As_2. The devices considered included cells based on Schottky barriers, solar thermal-photovoltaic and semiconductor-electrolyte systems, photosynthetic barriers, and electromagnetic wave converters. Among the conclusions were statements that no program based on single-crystal cells should be initiated unless there is a high probability of obtaining a low-cost material; Schottky, metal-insulator-semiconductor (MIS), and other barriers are more suitable for thin-film, polycrystal solar cells than are diffusion barriers; organic semiconductor and semiconductor-electrolyte systems should be investigated in view of the low cost potential; material availability studies should be prerequisites to the commitment of funds for developing solar cell system candidates; and a national thin-film diagnostic center should be instituted. A budget of \$7.7M was recommended for the 3-year weeding-out phase and an additional \$8.6M for the following 2 years to establish at least one high-potential alternative system.

b. Critique by JPL. Investigations of novel systems should be part of a dynamic program, although the primary positions would be for systems with a well established technology, such as single-crystal Si. It should be noted that the probability of encountering UV degradation problems in the novel systems which include organic materials should be given serious consideration in the preliminary weeding-out process. Otherwise, the conclusions and recommendations of this workshop seem to be comprehensive and appropriate.

5. Insolation, Testing, and Evaluation

a. Abstract of Workshop Report. The workshop recommended the creation of centers for determining terrestrial insolation and for testing and evaluations. Included in the insolation segment were tasks for establishing insolation system requirements and for the design and operation of hardware and software to collect, analyze, and distribute insolation data. The center for testing and evaluations was assigned the duties of defining standard tests, specifying the conditions for accelerated life testing, conducting an activity for developing measurements and procedures, and conducting and coordinating measurements and evaluations for the NSF program. In the recommended budget, using the assumption that existing facilities would be converted into centers, a 5-year funding of $9.8M was allocated for the insolation area and $9.2M for testing and evaluations. No funds were included for the operation of the network to measure insolation.

b. Critique by JPL. The recommendations seem to cover the needs of the program. The necessity of obtaining data in an independent, objective, and controlled manner was not stressed, however. The research and development of procedures and apparatus for testing and evaluations seem to be properly emphasized, but the total funding may be inadequate.

6. Systems

a. Abstract of Workshop Report. The workshop on systems noted the importance of performing systems studies early in the program to enable a feedback of information to the various technology development tasks, a rather desperate need for insolation data suitable for systems analyses, the advantages resulting from evaluating a demonstration project, and the desirability of using large arrays for environmental testing. Four areas were defined: (1) system studies, (2) investigations of the advantages and limitations of concentration for photovoltaic conversion systems, (3) data gathering and analysis of 100-kW field test power systems, and (4) preliminary design for a MW power system. The budgeting was $10M over a 5-year period for the first area, $0.5M over 2 years for the second, $2.75M over 3 years for the third, and $2M over 2 years, starting in FY78, for the fourth.

b. Critique by JPL. The tasks were all defined and seemed to be appropriate to a systems subprogram. The hope expressed of obtaining a significant level of funding of this effort by utilities early in the program does not seem to be realistic in view of the history which indicates that a stage of demonstrable profit and commercial practicability is a requirement for investment by utilities.

B. Assessment of the Report, "The Nation's Energy Future"

1. Abstract of Report. A solar energy development program, in which extremely limited funding for photovoltaic conversion was recommended, was part of this report, released in December 1973. The 5-year budget was $35.8M. In this very sparse budget, the lion's share is for the single-crystal Si system.

2. Critique by JPL. The consequences of the funding constriction are the exorcising of most of the supporting technology development, the exclusion of the development of alternative systems, and drastic reductions in the levels of effort directed toward establishing the feasibility of technology for a $0.50/W single-crystal Si solar array. Hence, the scope of this proposed program is certainly not commensurate with an advocacy of photovoltaic conversion as a reasonable means of supplying a significant portion of the nation's future energy. Instead, the program to develop photovoltaic conversion systems for terrestrial applications is decreased so drastically in this report that it does not even provide for an adequate budget for optimizing the development of the single-crystal Si solar cell system, which remains as the sole objective.

C. Assessment of the Report by the Interagency Panel for Terrestrial Applications of Solar Energy

The panel considered a program plan divided into two areas. To the area for the Research and Development of Photovoltaic Arrays for Terrestrial Applications were assigned subprograms for Si solar cell arrays, CdS solar cell arrays, and other materials and devices. The other area, which was devoted to the Application of Photovoltaic Energy Conversion Systems to the power needs of the nation, was composed of subprograms for on-site power, for central power, and for test and evaluations laboratories.

In this plan, the subprogram for Si solar cells contains sections for the single-crystal and polycrystal Si cells as well as for the Si wafer cell. The subprograms for on-site and central power systems are separate parts of an effort, which is parallel in intent to the NSF Workshop on systems. In the following assessment, the titles of the NSF Workshops will be used to allow for more accessible comparisons. The differences in the composition, emphasis, conclusions, and recommendations of the Interagency Panel subprograms vis-a-vis the NSF workshops will be noted.

1. Single-Crystal Si Solar Cells

a. Abstract of Report. The following are the main tasks: (1) Automation of presently used processes for wafer cells with the goal of establishing the reduction of array costs to about $5.00/W by proof-of-concept experiments. A milestone of an operational pilot plant capable of producing arrays equivalent to 1 MW/year was budgeted at $12M, with tasks for development and engineering funded at a total of $23M until 1979. Putting a demonstration plant capable of 5 to 10 MW/year into operation in 1978 was also included as a milestone. (2) Developments of the single-crystal Si ribbon process, of a new process for the production of low-cost polycrystal Si material, and of automated, low-cost cell and array manufacturing methods. A budget of $86M was recommended for a program for ribbon processing. This program has the objectives of establishing technology feasibility in 1978 and of completing the engineering development in 1979. Technology feasibility for a $0.50/W array is to be demonstrated in 1979. Milestones were set for a pilot plant (10 MW/year) in 1983 and for a commercial production capability of 1000 MW/year in 1985.

b. Critique by JPL. Except for some differences in milestone dates, these tasks are in large part the same as those recommended by the workshop. The main differences lie in the emphasis here on a separate subprogram for wafer cells and on the large-scale production of $5/W arrays from wafer cells by 1978. The arrays are intended for use in fabricating power installations, which are needed for systems studies and evaluations. Some of the techniques which would be developed to effect the mass production of $5/W wafer cell arrays might be applicable to the automated production of single-crystal Si ribbon cells and arrays. Accordingly, the possible adoption of these techniques should be continually analyzed, starting in the first stage of the ribbon cell program, by reviewing the processes being developed and installed to increase the production capacities of the wafer-cell plants and examining them in the context of the objectives of the ribbon cell tasks.

2. CdS/Cu_2S Solar Cells

a. Abstract of Report. The problem areas of stability and reproducibility were cited as well as the need to develop automated processes and a better means for attaching the grids. The development of automation in a 2- to 3-year period is to follow after a 2-year phase to deal with the problems. A pilot line will be used in 1979 to demonstrate the feasibility of automated procedures to produce stable, reliable, reproducible arrays at $0.25/W. The milestones include installations for a pilot plant at 1 MW/year in 1979, a demonstration plant for 10 MW/year in 1982, and a commercial plant for >1000 MW/year in 1985. The budget through 1979 is $36.2M.

b. Critique by JPL. The recommended concentration on solving the problems of stability and reproducibility before phasing in the development of automated processes for fabrication of cells seems appropriate. The recognition that the problems of degradation and reproducibility are severe and may prove to be difficult to solve is appropriately reflected in the milestone schedule. The institution of a pilot plant should follow the successful resolution of the technology problems; a production capability of 1 MW/year in 1979 is likely to be difficult to realize in view of the need to precede the production engineering task with the demonstration that the problems of stability and reproducibility have been solved. The recommended budget would in turn be reduced by the rescheduling of the installation of production facilities.

3. Polycrystal Si Solar Cells

a. Abstract of Report. The potential of providing $0.10 to $0.30/W arrays was ascribed to polycrystal Si solar cells. The need to develop processes for low-cost films, performing basic studies as a first phase and continuing the development phase through 1978, was stated. The program, with a budget of $15M through 1979, provides for device testing in 1979.

b. Critique by JPL. The milestone schedule appears to provide a suitable period to establish feasibility.

4. Other Materials and Devices

a. Abstract of Report. A program involving the evaluations of the physical, chemical, and photovoltaic conversion properties of potential materials and devices was recommended. The list of materials included III-V compounds, such as GaAs, In_3P_2, and Ca_3P_2; organic compounds; and inorganic compounds, such as Cu_2O, PbO, and ZnO. The milestones are a demonstration by 1977 that some candidates have suitable properties, a demonstration by 1979 that at least one candidate has promising photovoltaic conversion properties, and the confirmation of the economic advantages of at least one candidate by 1981. The recommended budget through 1979 is $25.1M.

b. Critique by JPL. This subprogram for the research and development of novel photovoltaic conversion devices, which should certainly be included in the overall program, requires that judicious selections of candidates be made. Particular care must be taken in the selection procedure to ensure that the constraints not be construed as inhibiting the concept that the program is open to proposals of novel and radical ideas for photovoltaic conversion systems. Hence, the advocated screening process seems to be reasonable. Evaluation criteria will need to be well defined so that a rational plan can be established to judge proposals as well as to evaluate contract progress.

5. Insolation, Testing, and Evaluation

a. Abstract of Report. Milestones were set for establishing a network in 1975 for collecting insolation data, a laboratory characterizing and analyzing materials in 1975, a laboratory for calibration and standardization in 1976, and a facility for environmental testing in 1976. A budget of $18.33 was recommended for these purposes.

b. Critique by JPL. The tasks described are necessary to accomplish the program. The recommendations for this subprogram seem to cover the needs, but the recommended budget may be inadequate.

6. Systems

a. Abstract of Report. Two separate areas were covered: on-site power and central power. The development of photovoltaic conversion systems for on-site power utilization in homes, or similar applications, includes efforts to (1) study, design, optimize, and evaluate arrays and associated hardware built into homes in various places in the U.S.; (2) investigate the tradeoffs of incorporating photovoltaic conversion devices into heating and air conditioning systems; and (3) study the applicability of a tie-in of photovoltaic conversion systems, which are built into homes and are of about 10-kW capacity, into electric utility grids. The milestones for this program are the completion of the system design in 1977 and the installation of systems by 1979. The budget through 1979 contains a development and engineering phase at $8.05M, a pilot plant at $2.7M, and a demonstration plant at $3.15M.

In the program for central power plants, milestones were set for an economic feasibility study in 1976, for the initiation of subsystem design in 1977, for the design phase in 1979, and for integration into structures starting in 1982. The budget through 1979 is $20M.

b. Critique by JPL. The systems subprogram of the panel is far more strongly oriented to fabricating and evaluating power installations than is that of the workshop. Whereas the workshop recommended the design, construction and testing of two 100-kW systems, the panel proposed the on-site and central power projects cited above. The information to be gained from the studies and analyses of these projects can be advantageously used in the other technology development subprograms. The proposed extent of these projects and the corresponding level of funding seem reasonable. The subprogram should be begun at the same time as the initiation of the technology development programs so as to provide the valuable feedback data from the systems analyses.

D. Assessment by JPL

This technical assessment for a photovoltaic conversion development plan is based on the following premises: (1) The 10-year objective is to be used as the dominant guideline for the overall program; (2) the near-term, 5-year objectives are those given above. (3) The program will continue beyond the near-term period, and consequently, the near-term program plan should contain provisions for performing research and development subprograms directed to applicability for goals and objectives of the medium- and far-term periods beyond 5 years. (4) The selection of tasks and the allocation of funds for the individual subprograms are based on the maxim that the overall program should be constructed using the criterion of optimizing the probability of achieving the program objectives.

This assessment is also based on the concept that the stated objectives are immutable and that future funding changes will be reflected in adjustments in milestone dates. In contrast, the approach which would permit a dependence of the objectives on future funding levels has been rejected. A concerted effort will be required to maintain the validity of this basic concept.

A procedure of approximating the effects of different levels of funding on the probability of achieving the technology and array price objectives of the program was used. The consequences of the budget analyses are evident from the nature of the assessments. The effects are also manifested in the resultant program, which is described below.

The assessment has been simplified by an arbitrary partitioning of the overall program and the assignment of the technology development tasks to four separate divisions. In this way, the individual goals and objectives of particular subprograms can be more easily identified, thereby facilitating the definitions of the appropriate requisites for particular evaluations of technology development priorities, scheduling, and funding. A further consequence of this partitioning is to provide a structure both for setting up milestones and for establishing a suitable management organization.

The four divisions created by the partitioning are:

(1) Single-crystal Si solar array mission

(2) Photovoltaic conversion systems—advanced development

(3) Systems

(4) Insolation and evaluations

Descriptions of the assessments pertinent to these divisions are presented below.

1. Single-Crystal Si Solar Array Mission. The mission-oriented division is directed to the advancement of photovoltaic converter technologies which have reached the stage of maturity required to make them practical candidates for utilization in large-scale terrestrial power installations. Many of the tasks in this division will deal with developing low-cost, high-volume production techniques.

The major emphasis at the start of the program will be on the development of the single-crystal Si system, as reflected in the title of this division. For purposes of this discussion, the Si program has been divided into parts for the production of solar-cell-grade polycrystal Si material, the production of solar arrays fabricated from single-crystal Si ribbons, the increased production of single-crystal Si wafer cells, and the installation and evaluation of demonstration projects. However, although this set of tasks serves adequately for discussion purposes, different groupings of the production sequence may prove to be more commercially practical; for example, it may be more expeditious and cheaper to combine the productions of single-crystal Si ribbons and of the cells and arrays into one integrated fabrication process. Decisions of this type will follow from the results of product engineering and mass production analyses.

Multiple technology development efforts to achieve a task objective should be conducted whenever possible. The selection of the alternative approaches would follow from studies of the technical tradeoffs and considerations of the relative importance of the tasks as well as from the requirements of the technology development schedule. Some of the proposed options are presented in this section of the assessment. The instances in which parallel efforts are recommended will be explicitly stated in Section V.

The alternative processes which should be considered for the production of solar-cell-grade polycrystal Si material are (1) modifications in the process to reduce $SiHCl_3$ by H_2 so as to increase the efficiency of the reaction, thereby reducing the extent of recycling; (2) the possible exploitation of the advantages of using SiH_4; and (3) purification of Si using an electrolytic process. Concurrently, studies of the dependence of the characteristics of the cell on the presence and concentrations of particular impurities and of the tradeoffs of the overall performance and economics should be carried out.

The EFG technique is presently the most likely candidate to effect sufficiently large cost reductions in the production of single-crystal Si to be commensurate with the overall objective. The EFG process, or any other process for producing single-crystal Si, must not only have the features of large-volume production at an acceptable cost but, in addition, should be adaptable to large-area conversion into cells. This requirement must be maintained as a guideline throughout the subprogram to develop a satisfactory single-crystal process. For the present, the successful development of the EFG process is crucial to the program, as was stated unequivocally as a conclusion of the NSF Workshop.

A concurrent investigation of the web dendrite process, which is directed toward establishing the production volume and cost capabilities as well as the possible technological advantages is recommended, although the conclusion of the NSF Workshop was that only a 5-fold cost reduction from the present cost could be obtained by developing this method.

The fabrication of cells involves many separate processes which have heretofore been performed on a batch process schedule. A consensus conclusion is that the only means of effecting the necessary cost reduction is to automate the cell production. However, considerable process technology development and production engineering are required to form the basis for the automation design. Consequently, the processes for the continuous production of large-area, single-crystal Si; for fabricating junctions, contacts, and antireflection coatings, and for the encapsulation of arrays must be modified or developed in a manner to ensure an automated, integrated fabrication process for solar cell arrays. A continuing production-audit feedback should be included in the design to ensure that improvements which could lead to increases in production volume and decreases in cost of the production arrays will be expeditiously evaluated and promptly incorporated if appropriate. Hopefully, use can be made of the considerable experience of the semiconductor industry in all of the aspects of incorporating automation production.

The fabrication of solar arrays from solar cells consists of the processes for electrically connecting the solar cells, physically attaching and arranging the cells to form the array, and encapsulating the array to protect the cells and electrical conversions against weathering effects. Automation of these processes is required to assure high-volume and low-cost production. Concurrently, the repetitive production on a volume basis of solar arrays as a consequence of automation will result in good quality control, since the quality checks and functional tests specified for the designed array can be incorporated into the overall automated production plan. A well-designed quality assurance program can be strictly maintained in this manner.

The encapsulation is designed to protect the underlying array without decreasing the amount of light transmitted to the solar cell surfaces. It affords this protection by preventing the transport of substances, such as O_2, H_2O, H_2S, various salts, fungi, and bacteria, which can cause corrosion of the electrical connections and deterioration of the physical and chemical properties of cell and array materials. The consequences of time-dependent changes on the permeability properties of the encapsulants as well as the rates of the corrosion and deterioration reactions must be tested and evaluated.

The encapsulant itself must also be stable to the environmental conditions of temperature, UV radiation, and microorganisms, in addition to the substances for which it is to act as a transport-barrier. It must also be nonflammable. If the encapsulation material is polymeric, as it probably will be, the stability can be obtained by the addition of various substances to prevent deterioration, discoloration, and embrittlement. Since oxidation, the primary cause of these failure modes, is initiated by the presence of chromophoric impurities, which absorb in the UV and lead to polymeric degradation reactions (depolymerization, scission of the polymer chains, and cross linking), the addition of colorless UV absorbers, which absorb in the UV and transform the incident UV radiation into innocuous long-wavelength light, can be used to protect against oxidation reactions. Biocides can be incorporated to exclude microbial attack on the residual plasticizer and surfactant substances. The need for any additive will, of course, be decreased by quality control programs to minimize the presence of any foreign materials which could participate in the initiation of oxidative or microorganism reactions.

After a satisfactory encapsulant material has been developed and certified, an encapsulation process must be designed to be compatible with the overall automated production plan. This step will involve process development as well as a production engineering effort, which will necessarily be closely integrated into the production engineering and automation phase of the cell and array fabrication.

2. Photovoltaic Conversion Systems—Advanced Development. The photovoltaic conversion systems—advanced development division contains tasks for the development of new converter technologies, which have the potential of yielding devices with significantly improved performance, along with a vigorous research subprogram. The research effort should include both applied research and pure research tasks. (As used here, the term applied research denotes research efforts which are directly related to and guided by specified technological goals, and the term pure research refers to those efforts which should be free of utilitarian control. Applied research tasks are closely controlled when the goals are precisely defined. Despite the freedom implicit in the definition, pure research should be directed to the extent necessary to provide scientific foundations for the technology development program.) The information derived from these tasks will form the foundation for the subsequent development, fabrication, and evaluation process for polycrystal Si cells and arrays.

Among the technical problem areas which should be investigated are (1) the effects of grain size and boundaries on cell efficiency; (2) the devising of suitable substrates which have the potential for high-volume, large-area, low-cost depositions of Si; (3) the electrical performance characteristics as functions of the physical properties of the Si film; and (4) the technology for junction formation, contacts and encapsulation. A separate task is for the development of large-area technology to overcome the disadvantage of low efficiencies. Finally, a task for product engineering is included based on the assumption that the technology can be developed to a level commensurate with undertaking such an effort.

Another segment of this subprogram is devoted to research and development tasks to prepare the technical foundations for the CdS/Cu_2S solar cell system. Separate tasks are needed for studies of (1) the conversion mechanism, (2) the nature of the degradation mechanisms and the rates of degradation processes, (3) the conversion efficiency, and (4) electrical performance characteristics. Despite the considerable information which has been obtained regarding these matters, these investigations are needed to provide a solid base for the development and engineering tasks associated with cell and module manufacture. The problem areas in the production area include device design, yield, uniformity, reliability, and encapsulation. Some initial research and development in these production areas can proceed at relatively low levels concurrently with the tasks for the more basic investigations. However, the solution of the degradation-lifetime issues is of crucial importance in the effort to prepare the

CdS/Cu_2S conversion system to meet the objectives of the NSF program. Accordingly, the emphasis should be on these topics until the satisfactory resolution of them permits a shifting of tasks and funding to the other areas. Hence, the content and starting times for the production engineering tasks should be postponed, and the schedule should be dependent on the progress achieved in the phase for studies and analyses.

The essentials of the subprograms involving tasks for other materials and devices have been well described in the discussions of the workshop and panel summaries. The JPL assessment concurs with the essentials of these recommendations. In summary, the first phase should be devoted to an evaluation of selected proposals for novel systems and after a 3-year period for R&D and evaluations, at least one should be qualified for further investigation.

The vigor of the division for photovoltaic conversion systems—advanced development will in large part depend upon maintaining a strong subprogram to investigate new ideas and proposals for novel systems. The research subprogram containing tasks for pure and applied research should be carried on continually throughout the program so as to provide the necessary scientific and engineering support.

3. Systems. The systems division is directed to the integration of conversion devices into commercially attractive power sources. The development, design, and evaluation of power-conditioning, power subsystems, power systems, and system-structures should be undertaken as tasks in this division. The power-conditioning task should involve the design, fabrication, and evaluation of circuits for specific power needs. These needs are to be defined as part of the assignment for performing configuration designs and system requirement analyses directed toward providing a basis for specifying the technology, hardware, and power-conditioning requisites. The specifications are to follow from analyses of load profiles; subsystem performance capabilities; and technology, time, and funding constraints. The preliminary design and evaluation of the on-site and central power installations can be accomplished on reduced-size models.

In-depth analyses and tradeoff studies are to be performed as prerequisites for decisions regarding power system projects. The structuring of these projects, which can be utilized to provide valuable engineering data, should be contingent upon a careful evaluation of the information obtained in the precedent studies.

Power system projects will be designed, installed, and evaluated. The designs will be based upon previous studies and analyses. The intent of these projects is to demonstrate the applicability of solar photovoltaic conversion power-generating systems as well as to provide operating experience and engineering information which will be derived from phases of design, operation, and evaluation. The conclusions and recommendations will also provide needed feedback for the technology development tasks.

These activities should be supported by studies of the social and economic factors involved in the production and utilization of photovoltaic conversion systems for on-site (10 kW) and central power (1 to 100 MW) installations.

This division should also include a task for the study, development, and evaluation of concentration collectors in an effort to determine the merits of using concentrators as a means of improving the collection efficiency of solar array assemblies. Tradeoffs should be compared for the area, light, and cost effectiveness factors vis-a-vis any technical and engineering drawbacks. The effects of the concentration of solar energy intensity on the physical properties and the performance characteristics of the candidate photovoltaic conversion systems need to be investigated. These studies should include: the effect of light intensity on the intrinsic characteristics of the cell; the relationship of electrical performance and intensity; the heating consequences of concentration and the effects of temperature on cell performance, degradation mechanisms and rates, and effective lifetime; optimization of design and integration of the collector into the conversion system; and product engineering. Those activities which deal primarily with the effects of concentration on particular cells should be investigated as parts of the subprogram for the specific photovoltaic conversion system candidate; the activities which are primarily for the study and development of concentration collectors should be performed in the systems division.

4. Insolation and Evaluations. The division for insolation and evaluations includes the tasks for the measurements and analyses of insolation data and the measurements, testing, evaluations, and analyses of photovoltaic conversion materials and devices.

A major task of this division is to meet the requirements for measurements, tests, and evaluations of materials and devices at various stages in the subprograms. A national laboratory should be established for coordinating and directing these activities for the overall program as well as for conducting an independent testing program to complement the testing, quality assurance, and evaluation procedures of the contractors. The charter of this laboratory should contain assignments for performing independent diagnostic studies and evaluations of materials and of the structural, chemical, and electronic properties of devices; for standardizing solar cells; for developing and instituting standardized procedures and test facilities, especially for investigations of the effects of particular terrestrial environmental conditions and of lifetime performance characteristics; for determining the electrical performance characteristics of the devices; and for establishing and utilizing the procedures and documentation needed to compare the status of the technology for each photovoltaic conversion system subprogram relative to the program objectives. A complementary statement of the need for independent technical evaluation laboratories is presented in the Appendix.

A concerted effort must be made to establish and operate a suitable number of well designed insolation data acquisition installations capable of supplying the insolation data required for the design of solar cell arrays and solar power systems. In addition, the procedures for the analysis and the dissemination of the data must be instituted.

V. Program Milestones and Funding Requirements

A sequence, starting with the definitions of the 10-year objectives, the 5-year objectives, and the interim objectives and goals and ending with the assessments of the conclusions and recommendations of the Interagency Panel and of the NSF Workshop Conference, has led to the JPL assessment, which has been presented within the format of a program partitioned into four divisions. The elements of this sequence and the JPL assessment are now used to form the requisite basis for the formulation of the composition, milestones, and funding requirements of the program directed to the accomplishment of the defined 5- and 10-year objectives.

In addition to the assessments, a further basis for the formulation of the detailed structure of the program, involving task objectives, schedules, and funding for each of the subprograms, was derived from comparisons of the recommendations for milestones and funding by the panel and the workshops and from the conclusions obtained using a set of evaluation criteria. The program was constructed from this assembly of evaluations.

The program is structured on the premise that a concomitant guideline to the maximization of the probability of achieving the program objectives is the condition of cost-effectiveness. (The term cost-effectiveness, as used in the context of this proposed program, denotes that the budget to meet the program schedule was generated under the constraint of funding realistic levels of activities for the various tasks, where the estimates for the realistic levels are for the most part based on experience in managing developments of photovoltaic conversion systems.)

The tasks and subprograms included in the program were assigned priorities, and these were used to establish milestones, schedules, and funding levels. This program, together with the Management Plan, described in Section VI, comprises the conclusions and recommendations of the report.

A. Basis for Program Formulation

The three segments of the basis for formulating the program are the technology assessments, the conclusions derived from comparisons of the milestones and funding of the programs proposed by the panel and the workshops, and the conclusions obtained from a set of evaluation criteria.

1. The Technology Assessment Basis. The abstracts and critiques of the technology development programs proposed by the panel and by the workshops and the technology assessment by JPL were described in Section IV.

2. Comparisons of Recommended Milestones and Budgets. The milestones and budgets recommended by the panel and by the workshops were examined from the perspective of the conclusions of the technology assessment. To provide greater visibility to the data used for comparisons, composite milestone charts were prepared from the panel and workshop summaries; these are shown in Figs. 3 and 4, respectively. The differences in the milestone schedules were detected and examined in task-by-task analyses. There are two major dissimilarities:

(1) Only the panel program contains a provision for the continued development and production of wafer-type single-crystal Si cells from Czochralski ingots. The cells are for use in the power system installations. The production goals are 1 MW/year in FY77 and 5 to 10 MW/year by FY79.

(2) The systems subprogram in the panel program is divided into the two sections: on-site power and central power. Each of these sections has separate milestones for the steps of system design, installation, and evaluation. In contrast, the systems subprogram recommended by the workshops pro-

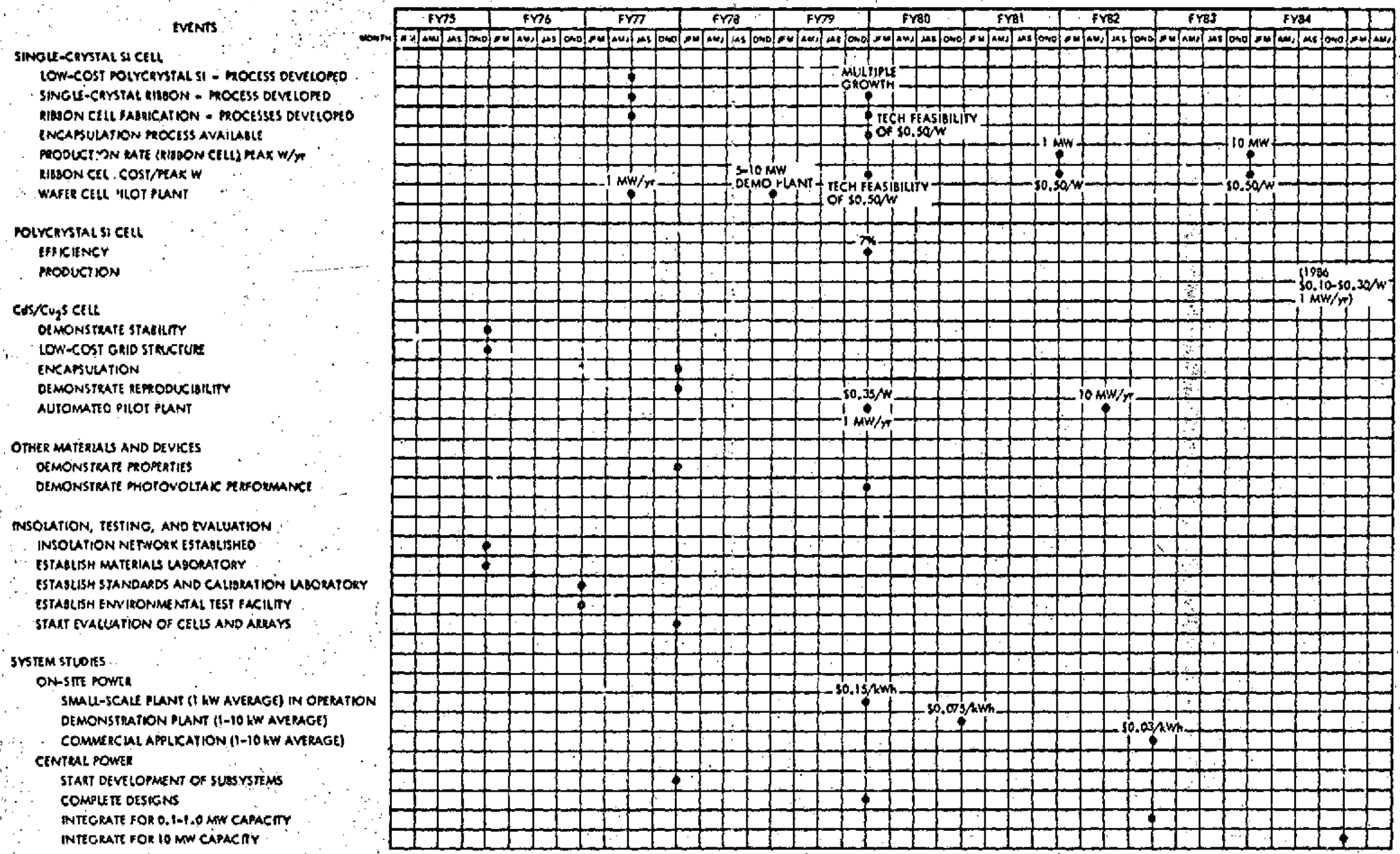


Fig. 3. Milestone schedule recommended by interagency panel

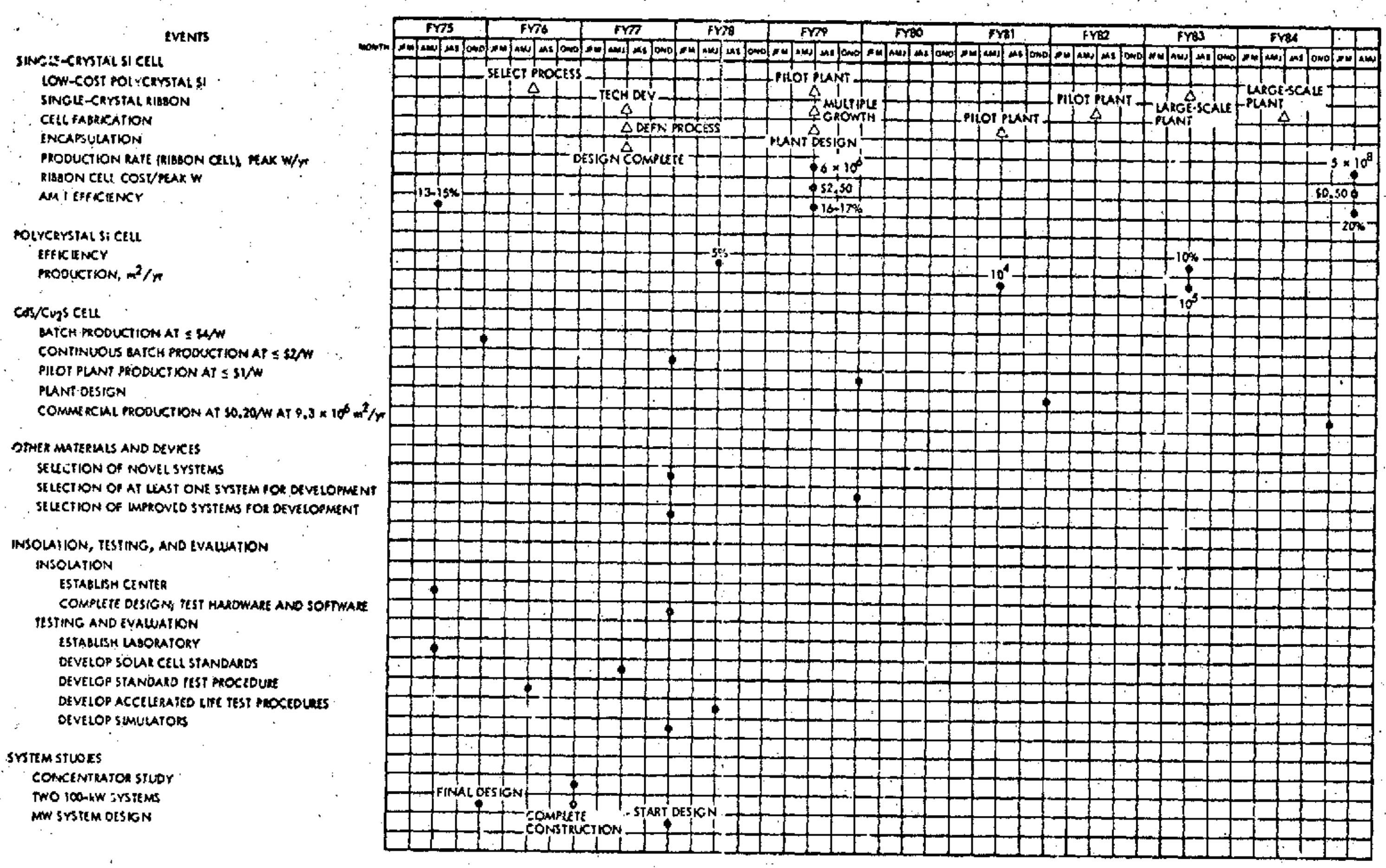


Fig. 4. Milestone schedule recommended by workshops

vides for power test systems within a single subprogram organization. The tasks included in these subprograms were discussed under the pertinent sections in the technical assessment.

To illustrate the significant dissimilitudes more clearly, the milestone schedules have also been compiled in a different format in Table 4. Direct comparisons can be made more readily using this outline. Some of the distinctions are presented below:

(1) Single-crystal Si cell

(a) The panel recommended the construction of production plants for wafer cells. These would have capacities of 1 MW/year in FY77 and 5 to 10 MW per year in FY79. The Workshop did not include a subprogram for wafer cells.

(b) To satisfy the need for low-cost, high-volume production of polycrystal Si material, the workshop recommended the installation of a pilot plant in FY79 and a large-scale plant in FY84, whereas the panel had provisions for a large-scale plant in FY79.

(c) The panel provided for a pilot plant and a demonstration plant for the fabrication of ribbon cell arrays in FY81 and FY83, respectively, and implicitly included the large-scale production of ribbon Si in these installations. In contrast, the workshop explicitly recommended the institution of a pilot plant in FY82 and a large-scale plant in FY84 for the production of ribbon Si. In addition, a large-scale plant for cell manufacture was set for FY84.

(2) CdS/Cu_2S cell. The panel set milestones for demonstrating CdS/Cu_2S cell stability by FY76, for achieving a suitable encapsulation technique and cell fabrication reproducibility by FY78, and for cell production capabilities of 1 MW/year at \$0.35/W by 1979, 10 MW/year by 1982, and >1000 MW/year by 1985. In contrast, the workshop mainly gave explicit milestones in terms of production capabilities only: ≤\$4/W by FY76, ≤\$2/W by FY78, and ≤\$1/W by FY80. However, a production capability of 9.3×10^6 m^2/year (equivalent to 186 MW/year at 10% efficiency) was set for FY85.

(3) Polycrystal Si cell. The workshop set a milestone of 10^5 m^2/year of 10% efficient cells for FY83. This corresponds to 2 MW peak power per year. The panel, in comparison, had a milestone of 1 MW/year of \$0.10 to \$0.30/W cells with an efficiency goal of 7% for FY80.

(4) Systems. The workshop recommended the construction of two 100-kW systems by FY77 and the design of a 1-MW system by FY78. On the other hand, the panel divided the subprogram into sections for on-site (about 10 kW) and central power (about 0.1 to 10 MW) systems. For the first section, the panel set milestones of a completed system design by 1977, of \$0.15/kWh at 1 kW average output by 1979, of \$0.075/kWh at 1 to 10 kW average output by 1980, and of \$0.03/kWh at 1 to 10 kW average output by 1982. For the second section, the milestones were a system design by 1979 and construction of a 0.1- to 1-MW system by 1982 and of a 10-MW system by 1985.

The divergences in the recommended budgets correspond, for the most part, to these program milestone differences.

3. Evaluations Using a Set of Criteria. Supporting evidence for the formulation of the overall program was provided using a set of evaluation criteria. The list of criteria and the corresponding data are presented in Table 5. It is apparent that the character of the data varies from being precisely quantitative to be completely qualitative. Accordingly, weighting factors were not used. Thus, the conclusions derived from these evaluations can also vary in degree of definition.

The information in Table 5 supports the conclusions that the single-crystal Si solar cell should be the primary candidate for this program by virtue of the attributes of material availability, level of technology development, and intrinsic material and device properties. The conclusion that the price of the solar cells is the major hindrance to the widespread commercial utilization of this cell in terrestrial applications is corroborated.

B. Elements of the Program

The elements of the program were selected from appraisals using the assembly of evaluations described above, taking into consideration the constraints of time and funding. The conclusions are as follows:

(1) The primary candidate at the outset of the program should be the single-crystal Si cell, and all of the tasks involved in this subprogram should be initiated as soon as possible at the recommended levels.

(2) An intense systems assessment subprogram for defining program goals, analyzing photovoltaic conversion systems, evaluating technology advances in relation to power system requirements, and providing information for on-site and central power

Table 4. Comparison of program milestones

Subprogram	Program	Fiscal year 1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985
Single-crystal Si solar array												
Polycrystal Si material												
1. Select process	P[a]			1		3						
2. Small-scale plant	W[b]		1			2				3		
3. Large-scale plant	J[c]		1			2				3		
Single-crystal ribbon												
1. Continuous growth	P			1-2-3								
2. Multiple growth	W			1		2			3		4	
3. Small-scale plant	J			1		2			3			
4. Large-scale plant												
Ribbon cell												
1. Select processes	P			1				3		4		
2. Adapt to automation	W			1		2		3			4	
3. Small-scale plant	J			1		2			3		4	
4. Large-scale plant												
Wafer cells												
1. Adapt to automation	P			2								
2. 200 kW at < $5/peak W	W											
3. 200 kW at < $2.50/peak W	J		1	2		3						
Photovoltaic conversion system—advanced development												
CdS/Cu_2S solar cell												
1. Establish lifetime technology	P	1		2		4						
2. Establish reliability of process	W	$4/W		$2/W		3,$1/W					5	
3. Automated fabrication	J			1,2		3						
4. Small-scale plant												
5. Demonstrate < $0.20/peak W												
Polycrystal Si solar cell												
1. Establish technology	P			1		3						6
2. Certify 5% efficient cells	W				1,2			6		5,7		
3. Certify 7% efficient cells	J			1	2		4					
4. Production process established												
5. Certify 10% efficient cells												
6. Small-scale plant												
7. Large-scale plant												
Other materials and devices												
1. Candidates screened	P			1		2						
2. R&D of selected systems	W			1		2						
	J			1		2						
Systems												
1. Preliminary power system	P					8,9			10			
specifications	W		1,3	4		2,5						
2. Detailed power system	J		3	1	6		7					
specifications												
3. Concentrated analysis and evaluation												

[a]Panel.
[b]Workshop.
[c]JPL.

Table 4 (contd)

Subprogram	Program	Fiscal year										
		1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985
4. Preliminary design of MW system												
5. Operate 100-kW systems												
6. Design and install 200-kW system												
7. Design and install 400-kW system												
8. On-site systems installed												
9. Central power system design												
10. Integrate central power systems												
Insolation and evaluations												
1. Insolation program	P	2		5								
defined	W			1,3	4							
2. Insolation facilities installed	J	5	2	3	4							
3. Tests and evaluations defined												
4. Accelerated testing defined												
5. Evaluation facilities installed												

installations should be continued throughout the program.

(3) The subprograms for the thin film CdS/Cu_2S and Si cells are promising but should be limited initially to tasks for research to solve fundamental technological problems. This phase should be followed by tasks directed to the development of fabrication processes and the production engineering of devices.

(4) A subprogram for the research and development of the other materials and devices category should involve a preliminary screening/evaluation phase to be followed by an effort for research and development of at least one promising candidate.

(5) The tasks in the subprogram for the testing and evaluation of materials and devices and for the gathering and analysis of insolation data will be necessary for the success of the overall program and hence should be considered as integral, and not as optional, sections of the program.

A program plan which incorporates these conclusions has been devised. This plan is composed of the milestone and funding schedules for the four major sections of the program: single-crystal Si solar array mission, systems, insolation and evaluations, and photovoltaic conversion systems—advanced development.

The milestone schedule for the program is given in Fig. 5, where the separate schedules and the interrelationships of the tasks for each section are explicitly shown.

C. Single-Crystal Si Solar Array Mission

The emphasis on the development of the low-cost, single-crystal Si array technology is apparent from the milestone schedule of the overall plan as given in Fig. 5. The crucial role assigned to the ribbon single-crystal Si solar cell subprogram is obvious from these milestones and the funding, which has been specified. The 5-year objectives of the investigations of this section are:

(1) Plant production of low-cost polycrystalline Si material.

(2) Demonstration of the achievement of continuous growth and of multiple ribbon processing.

(3) Proof of availability of an encapsulant material and a packaging technique suitable for long-life solar arrays.

(4) Design of automation processes for the production of single-crystal Si solar arrays.

(5) Completion of studies comprising detailed solar photovoltaic system designs analyses.

(6) Production of <$5/W wafer cells.

(7) Completion of the installation and evaluation of a demonstration project.

The importance of immediate starts in FY75 for each of the seven tasks as well as the stress placed on the tasks for the ribbon production of single-crystal Si and the automated production of solar cells and arrays are distinctly indicated. The tasks for securing the high-volume production of solar cell grade polycrystal Si at

Table 5. Evaluation criteria

a. General

Criteria	Cells		
	Single-crystal Si	Thin-film Si	CdS/Cu_2S
Chemical and physical properties of materials			
Susceptibility to corrosion and UV degradation	Unknown	Unknown	Unknown
Toxicity[a]	Unknown	Unknown	High
Status of commercial readiness			
Scientific development	High	Low	Low
Cell development	Wafer–high Ribbon–new	Low	Starting
Production rate	60 kW/yr	—	—
Production array costs	\$20–\$50/yr	—	—
Cell characteristics in terrestrial environment			
Degradation of performance	Low or none	Unknown	Variable to high
Conversion efficiency	13–15%	Up to 6%	Up to 8.3%
Electrical performance	Very good	Unknown	Variable
Temperature range	$0 < T < 60°C$	Unknown	$0 < T < 60°C$
Lifetime	~10 yr	Unknown	Unknown
Technology development required			
Basic technology	Available	Needed	Needed
Production engineering	Needed	Needed	Needed
Estimate of difficulty			
Probability of successful development			
Mass production potential			
Difficulty of developing production process			
Probability of successful development			
Cost for 10-yr development program	\$250M[b]	\$43M[c]	\$163.5M[d]
Production potential, peak W/yr for 1984	5×10^8, 20% eff.	10^7/line, 10% eff.	9.3×10^8, 10% eff.

[a]Ref. 1.
[b]Ref. 2.
[c]Ref. 3.
[d]Ref. 4.

markedly reduced costs and for fabricating suitable encapsulation materials are also important in meeting the program goals. The achievement of a production capability of 500 MW/year for \$500/peak kW arrays is set for FY84.

The identification of the tasks for the ribbon cell development is explicit and detailed so as to provide a high visibility for this prime candidate. The three-step effort for producing solar cell grade polycrystal Si material culminates in the installation of a production facility. The concentrated program for the ribbon development comprises a 3-year process development phase; a phase to establish the multiple growth process, which overlaps the process development task, is scheduled for 4 years; and a phase for production engineering, which involves the conversion to fabrication processes suitable for mass production, overlaps the multiple growth and production engineering tasks. The tasks for the ribbon cell manufacture have overlapping tasks for process development and production engineering. Separate tasks are contained in an array manufacture program, which includes the development of an encapsulation process and the design of a production facility in addition to array process development and array production engineering tasks.

Table 5 (contd)

b. Availability of Materials

Solar cell	Element	U.S. production[a]	World production[a]	U.S. reserves[a]	World reserves[a]	Cost, $/kg	MT/MW[b]
Single-crystal Si	Si	750 (1973)[c] 1250 (1974)[c]			[d]	60	11.5[e]
CdS/Cu_2S	Cd	3×10^{3}[f]	17.1×10^{3}[f]	205×10^{3}[f]	850×10^{3}[f]	7[f] 20[g]	3.7[h]
	Cu	1.83×10^{6}[i]	8.05×10^{6}[i]	91×10^{6}[i]	407×10^{6}[i]	1.50[i]	0.22[j]
Thin-film Si	Si	750 (1973)[c] 1250 (1974)[c]		[d]	[d]		2.3[k]
GaAs	Ga	0.3[l]	1.0[l]	2.7×10^{3}[m]	110×10^{3}[m]	600	2.5[n]
	As	19×10^{3}[o]	52×10^{3}[o]	1.43×10^{6}[i]	19.4×10^{6}[i]	0.14[o]	2.6[n]
CdTe	Cd	3×10^{3}[f]	17.1×10^{3}[f]	205×10^{3}[f]	850×10^{3}[f]	7[f]	1.4[q]
	Te	1×10^{3}[p]	1.92×10^{2}[p]	7.5×10^{3}[p]	34×10^{3}[p]	15.40[p]	1.7[q]
$CuInSe_2$	Cu	1.83×10^{6}[i]	8.05×10^{6}[i]	91×10^{6}[i]	407×10^{6}[i]	1.50[i]	0.53[r]
	In			5.3×10^{2}[o]	31.8×10^{2}[o]	225[o]	0.97[r]
	Se	3.4×10^{2}[p]	1.02×10^{3}[p]	24.5×10^{3}[p]	10.9×10^{4}[p]	30[g]	1.3[r]

[a]All weights are in metric tons (MT = 10^3 kg).

[b]Densities taken from Ref. 5.

[c]Ref. 6.

[d]Essentially unlimited.

[e]200×10^{-4} cm thick, 20% efficiency, 2.32 g/cm^3.

[f]Ref. 7.

[g]Ref. 8.

[h]20×10^{-4} cm thick, 10% efficiency, 4.82 g/cm^3.

[i]Ref. 9.

[j]1×10^{-4} cm thick, 10% efficiency, 5.6 g/cm^3.

[k]20×10^{-4} cm thick, 10% efficiency, 2.32 g/cm^3.

[l]Ref. 10.

[m]Ref. 11.

[n]20×10^{-4} cm thick, 10% efficiency, 5.32 g/cm^3.

[o]Ref. 12.

[p]Ref. 13.

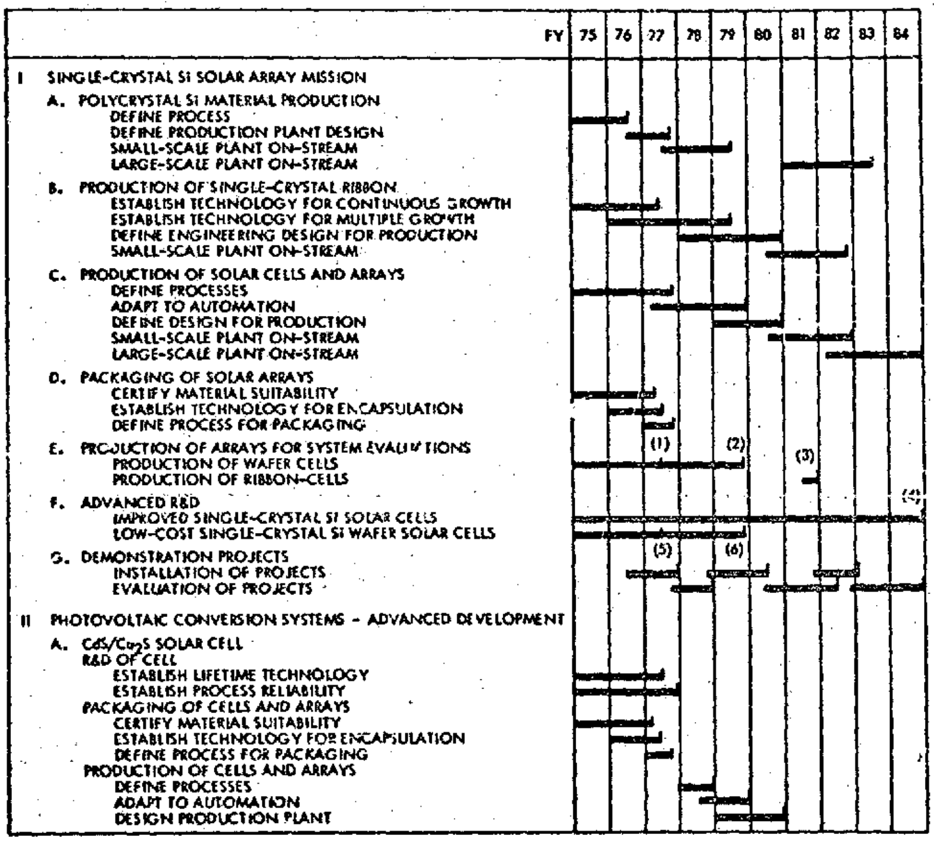
[q]10×10^{-4} cm thick, 10% efficiency, 6.2 g/cm^3.

[r]10×10^{-4} cm thick, 10% efficiency, 5.65 g/cm^3.

In the case of the wafer cell subprogram, price objectives were defined concurrently with the milestones for different levels of production. The successive objectives of $5 and $2.50/peak W should be achieved as consequences of introducing automation procedures into the cell fabrication process and of the economics of large purchases. Accordingly, an interval for developing suitable fabrication techniques will be a necessary prerequisite for the conversion to automation. The time and funds required to accomplish this conversion will be lessened if some of the automation procedures utilized in the semiconductor industry are applicable.

The process development and production engineering tasks for the wafer cell extend over the 5-year period, with the greatest emphasis being in the first 2 years. A task for the construction of production facilities involves a design and installation period spread over three years, starting in FY76. Finally, provisions are made for the purchase of cells to obtain the arrays required for systems installations. Additional purchases of cells for the purposes of evaluating development, engineering, and production model cells may be required.

The subprogram for demonstration projects contains tasks for the design and installation of photovoltaic conversion systems, the size of which will be increased as the solar cells become available. These systems are not identical with those contained in the systems section. Here, the systems will be used for studies that will be conducted in close collaboration with the ribbon cell and wafer cell development subprograms. The purpose of the studies will be to field test solar cell and array hardware so that the feedback of the performance data will be expedited. A concurrent purpose will be to use the systems as demonstrations of the state-of-the-art of solar array technology and photovoltaic conversion power systems.



NOTES:

(1) \$5/W

(2) \$2.50/W

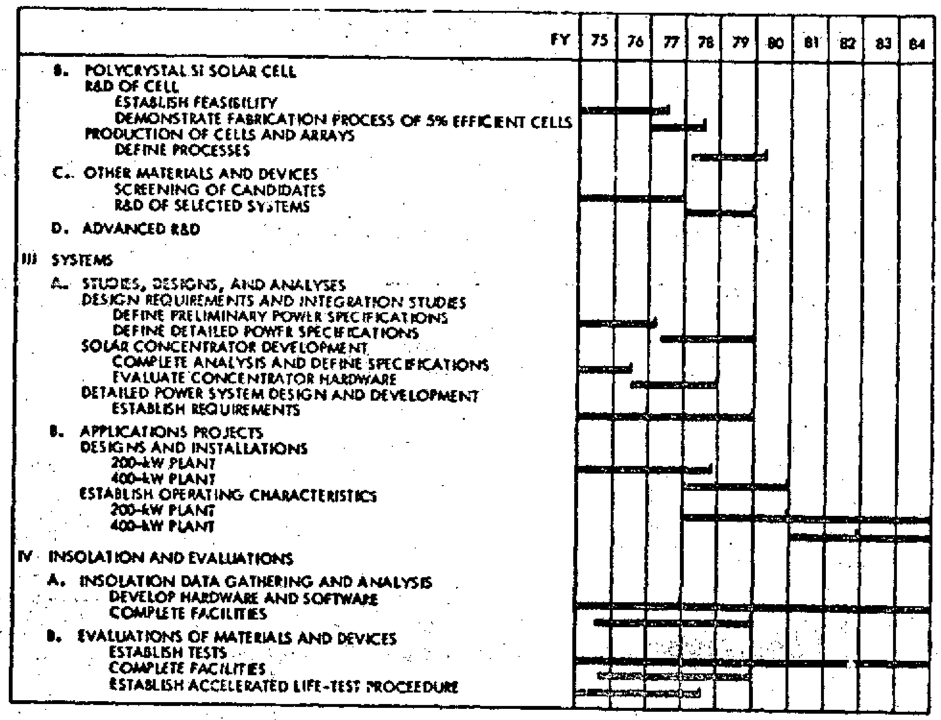
(3) WAFER CELLS AT \$2/W (PEAK POWER) PLUS SMALL QUANTITY OF DEVELOPMENT AND ENGINEERING MODEL RIBBON CELLS AND ARRAYS

(4) 20% CONVERSION EFFICIENCY

(5) \$5/W (PEAK POWER)

(6) \$2.5/W (PEAK POWER)

Fig. 5. Milestone schedule, JPL-recommended program



FY
75
76
77
78
79
80
81
82
83
84
B. POLYCRYSTAL SI SOLAR CELL
R&D OF CELL
ESTABLISH FEASIBILITY
DEMONSTRATE FABRICATION PROCESS OF 5% EFFICIENT CELLS
PRODUCTION OF CELLS AND ARRAYS
DEFINE PROCESSES
C. OTHER MATERIALS AND DEVICES
SCREENING OF CANDIDATES
R&D OF SELECTED SYSTEMS
D. ADVANCED R&D
III SYSTEMS
A. STUDIES, DESIGNS, AND ANALYSES
DESIGN REQUIREMENTS AND INTEGRATION STUDIES
DEFINE PRELIMINARY POWER SPECIFICATIONS
DEFINE DETAILED POWER SPECIFICATIONS
SOLAR CONCENTRATOR DEVELOPMENT
COMPLETE ANALYSIS AND DEFINE SPECIFICATIONS
EVALUATE CONCENTRATOR HARDWARE
DETAILED POWER SYSTEM DESIGN AND DEVELOPMENT
ESTABLISH REQUIREMENTS
B. APPLICATIONS PROJECTS
DESIGNS AND INSTALLATIONS
200-kW PLANT
400-kW PLANT
ESTABLISH OPERATING CHARACTERISTICS
200-kW PLANT
400-kW PLANT
IV INSOLATION AND EVALUATIONS
A. INSOLATION DATA GATHERING AND ANALYSIS
DEVELOP HARDWARE AND SOFTWARE
COMPLETE FACILITIES
B. EVALUATIONS OF MATERIALS AND DEVICES
ESTABLISH TESTS
COMPLETE FACILITIES
ESTABLISH ACCELERATED LIFE-TEST PROCEDURE

Fig. 5 (contd)

D. Photovoltaic Conversion Systems—Advanced Development

In addition to the research and development efforts to advance the scientific and technology bases of photovoltaic conversion systems, this section contains the subprograms for the CdS/Cu_2S cell, polycrystal Si cell, and other materials and devices that were relegated to subordinate positions in the program by the conclusions derived in the technical assessment.

1. CdS/Cu_2S Solar Cell. The initial program for the CdS/Cu_2S cell encompasses research and development tasks to prepare the foundations for production engineering. Investigations directed to the solution of the degradation, lifetime, reliability, and efficiency problems should comprise the first phase effort. A change of emphasis to tasks for device design, fabrication, and evaluation should follow the satisfactory resolution of these problems. In the first phase, the milestones for the accomplishment of these technology investigations and for the development of a suitable encapsulant are set for FY77. The next phase, which is devoted to the process development and production engineering for the cell and the array, culminates in FY79, with a task for the design of a production facility.

2. Polycrystal Si Solar Cell. The subprogram for thin-film, polycrystal Si cells is directed toward research and development tasks to prepare the technological foundations for a subsequent phase for cell and array fabrication and evaluation. The studies should involve performing basic research and technology developments, increasing the conversion efficiency, and devising a suitable encapsulation technique. The resolution of the critical technical unknowns and the development of the basic technology should precede investigations of fabrication procedures and production engineering. This initial phase is for 4 years. The task for production engineering is scheduled to begin in FY78.

3. Other Materials and Devices. The first phase of this subprogram should be devoted to the research directed to determine the physical, chemical, and photovoltaic characteristics of several novel solar energy conversion systems. This in effect will constitute a screening process. Suitable candidates would then be selected for further research and development efforts.

4. Research and Advanced Development. A section of this subprogram will be devoted to the pure research and applied research tasks described in Section IV.D.2.

E. Systems

The subprogram for systems is partitioned into the subdivisions of studies, designs, and analyses, and applications projects.

1. Studies, Designs, and Analyses. This subdivision comprises three tasks: design requirements and integration studies, solar concentrator development, and detailed power system design and development. The tasks are integrated so that the preliminary and the detailed specifications formulated in the task for design requirements and integration studies and the conclusions derived in the solar concentrator development task will be used as the foundation for the power system design of the third task. These designs and the developments of power systems will incorporate efforts for power conditioning, energy storage, interfaces with solar heating and air-conditioning systems, tie-ins to power grids, and total energy systems.

2. Applications Projects. The subdivision for applications projects contains two tasks. One task provides for the designs and installations of solar power plants which utilize the wafer-type Si cells, and the second is for the operation and evaluations of the plants. The first plant will be for 200 kW and is scheduled for completion in FY77. The second plant, to be installed in FY80, will be for 400 kW.

F. Insolation and Evaluations

The subprogram for insolation and evaluations comprises two main subdivisions: insolation data gathering and analysis, and evaluations of materials and devices.

1. Insolation Data Gathering and Analysis. The charter of this section is for obtaining, analyzing, and disseminating insolation data, which are required for system studies and for parts of the technology development program. The development of the hardware and software will continue over the 5-year period. Operation of the facilities is scheduled to begin in FY77.

2. Evaluations of Materials and Devices. In order to meet the requirements for the evaluations of materials and devices at all stages of the program, a national laboratory should be instituted for coordinating and directing these activities at the facilities of the contractors as well as for conducting an independent testing program. A separate task for accelerated environmental testing will be directed to the determination of the long-term effects of particular environmental conditions on the physical, chemical, and electrical properties of solar arrays. Intensive investigations will be needed to validate the procedures for accelerated testing.

G. The Integrated Program

Segments of the integrated 5-year program directed to accomplishing the 5- and 10-year objectives of the NSF Program for Photovoltaic Conversion for Terrestrial Applications have been presented in the form of narratives and milestone schedules for the subprograms. The coordination of the separate subprograms into an integrated program so that the overall program objectives are attained through the orderly achievement of the objectives of the subprograms was implicit in the milestone chart of Fig. 5.

An explicit description of the flows and interrelationships of the subprograms is displayed in Fig. 6. Here, for example, the sequential dependence of the milestones in the single-crystal Si cell mission and the interfaces of this subprogram with other sections of the program are shown. The milestone for the specification of the processes for automating cell and array production is shown to be dependent upon the resolution of the encapsulation design problem and the establishment of the feasibility of the multiple growth of single-crystal Si ribbon; the capability for manufacturing multiple growth ribbon, in turn, depends on the increased production of polycrystal Si. Also shown in this figure are the interfaces of the single-crystal Si cell mission with the photovoltaic conversion systems—advanced development through the research and development tasks for advanced technology and with the insolation and evaluation subprogram through the environmental testing and other evaluations. Corresponding interrelationships between other subprograms can be derived from this figure.

A chronological listing of the key milestones of the composite program can also be used to illustrate the interfaces of the elements of the program. The integrated structure of the program can be fashioned by reference to Fig. 6. A compilation of these milestones includes the following:

(1) FY76, completion of a preliminary system analysis.

(2) FY76, definition of a process for the high-volume production of low-cost polycrystal Si material.

(3) FY76, demonstration of the process for continuous growth of ribbon single-crystal Si.

(4) FY77, demonstration of a suitable solar array encapsulation procedure.

(5) FY77, completion of development of processes for automation of single-crystal Si ribbon cell and array fabrication.

(6) FY79, completion of production engineering for automation of single-crystal Si ribbon cell and array fabrication.

(7) FY79, demonstration of the process for multiple growth of ribbon single-crystal Si.

(8) FY79, completion of design of plant for automated production of single-crystal Si ribbon cell and arrays.

(9) FY79, demonstration of technology feasibility of a thin-film solar cell (CdS/Cu_2S or polycrystal Si).

VI. Management Plan

A. Approach

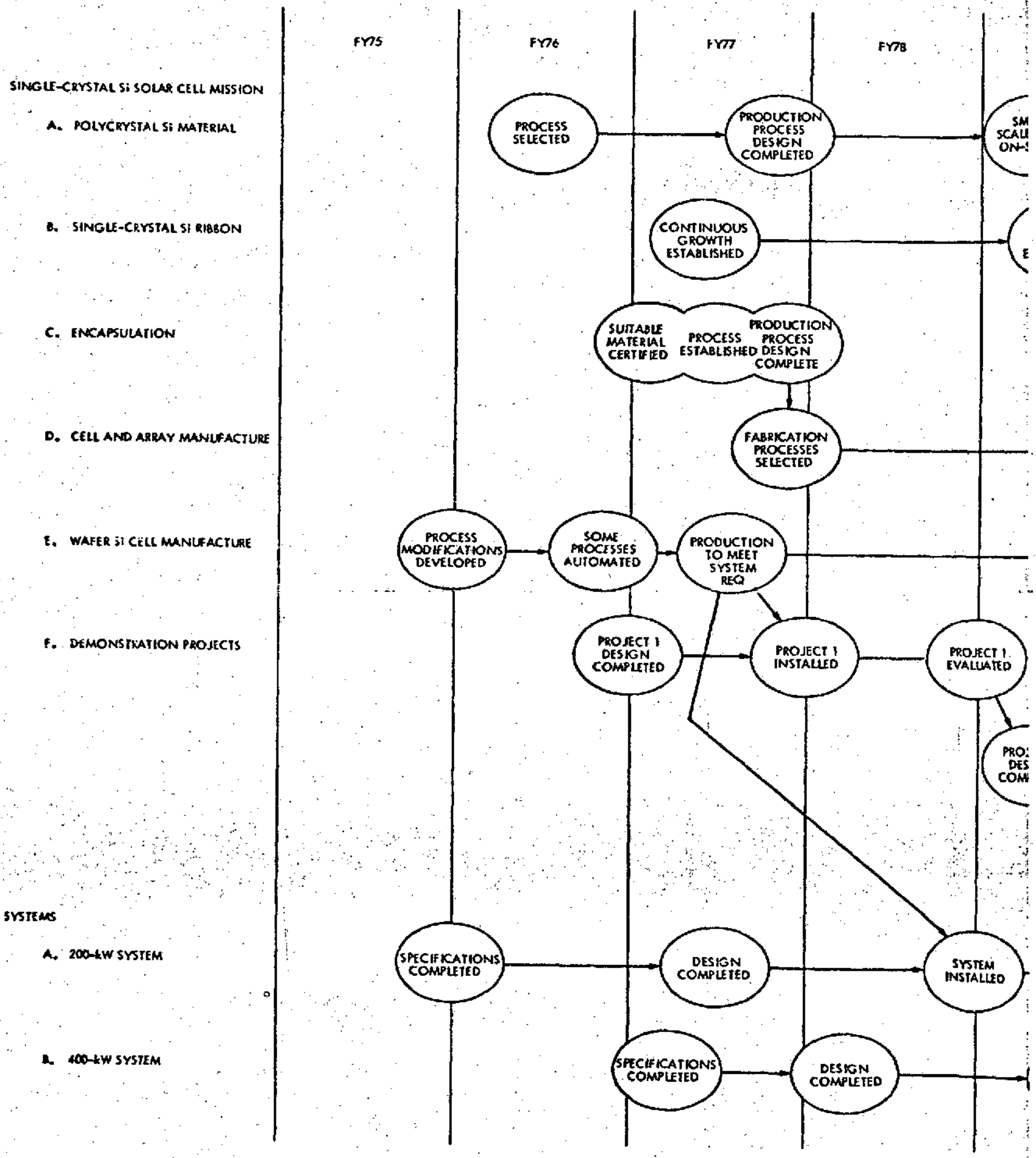
A program management structure to ensure the continual technical review and tight control of the technology developments, financial affairs, and schedules has been formulated as a complement to the technical assessment. The management roles have been described, the areas of responsibility and authority have been defined, and the management interfaces have been set up to ensure that the objectives of the program are achieved in a technically competent, economically responsive, and timely manner.

B. Organizational Structure

A functional type of management structure is recommended for the program organization. As shown in Fig. 2, a program manager is responsible for all aspects of the program. The program is managed in four divisions, which are defined as single-crystal Si solar array mission, systems, insolation and evaluations, and photovoltaic conversion systems—advanced development. The roles, objectives, and operational modes are different in each area, and this partition provides a practical means for management control of the subprograms. In addition, an independent advisory group is placed in a staff position to the program manager. This arrangement has the advantage of allowing direct interaction among the sections, each of which has a carefully defined charter of responsibility and authority.

C. Management Responsibilities

1. Manager of the Program. The responsibility for the program and the authority to direct it are assigned to the Manager of the Photovoltaic Conversion (MPCP). The final decisions for the approval of new, or major changes in, projects, technology development and research programs, budgets, and manpower are vested in the MPCP.


FY75
FY76
FY77
FY78
SINGLE-CRYSTAL Si SOLAR CELL MISSION
A. POLYCRYSTAL Si MATERIAL
B. SINGLE-CRYSTAL Si RIBBON
C. ENCAPSULATION
D. CELL AND ARRAY MANUFACTURE
E. WAFER Si CELL MANUFACTURE
F. DEMONSTRATION PROJECTS
SYSTEMS
A. 200-kW SYSTEM
B. 400-kW SYSTEM
PROCESS SELECTED
PRODUCTION PROCESS DESIGN COMPLETED
CONTINUOUS GROWTH ESTABLISHED
SUITABLE MATERIAL CERTIFIED
PROCESS ESTABLISHED
PRODUCTION PROCESS DESIGN COMPLETE
FABRICATION PROCESSES SELECTED
PROCESS MODIFICATIONS DEVELOPED
SOME PROCESSES AUTOMATED
PRODUCTION TO MEET SYSTEM REQ
PROJECT 1 DESIGN COMPLETED
PROJECT 1 INSTALLED
PROJECT 1 EVALUATED
SPECIFICATIONS COMPLETED
DESIGN COMPLETED
SYSTEM INSTALLED
SPECIFICATIONS COMPLETED
DESIGN COMPLETED

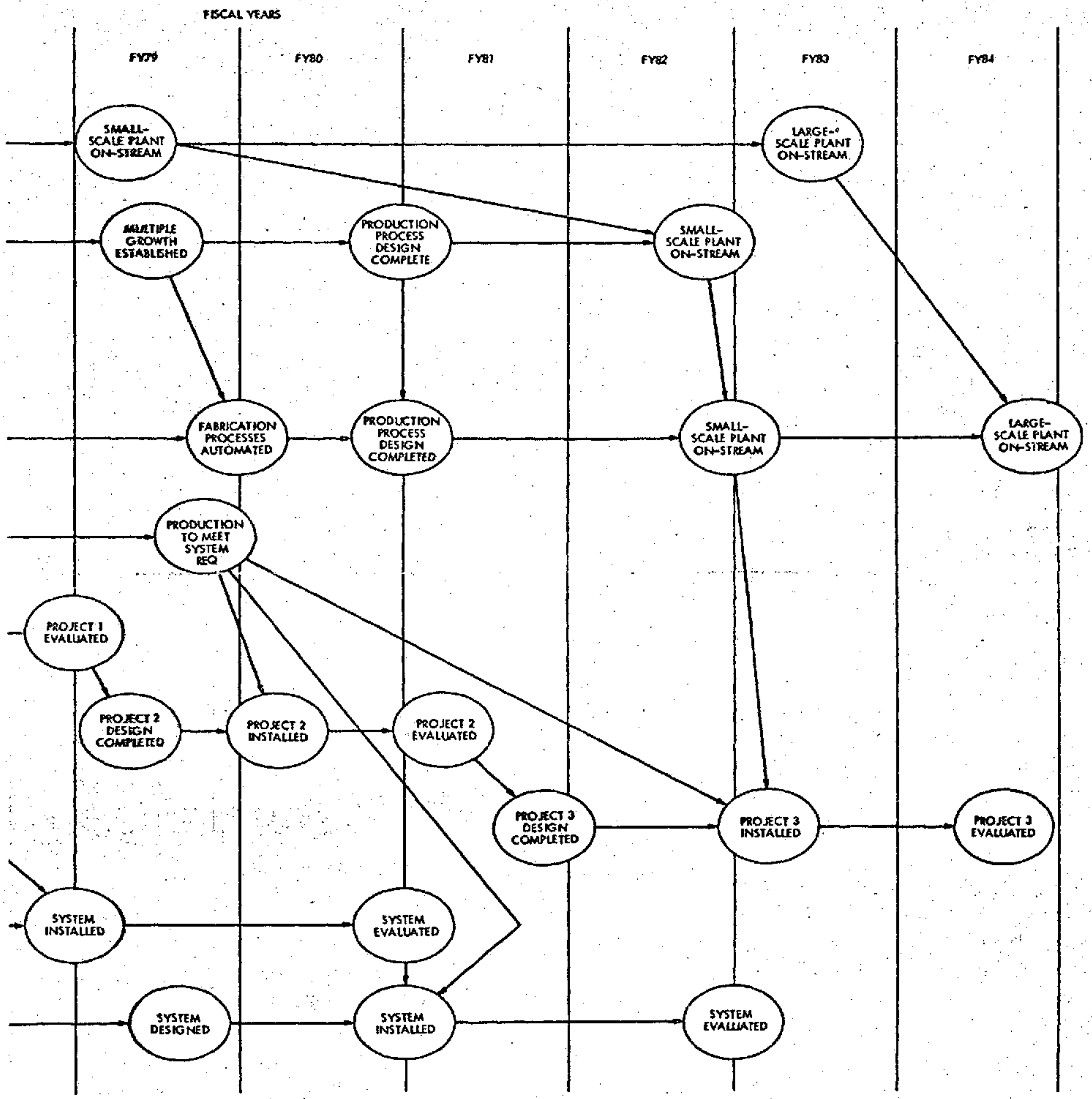


Fig. 6. Key events in program recommended by JPL

LDOUT FRAME 2

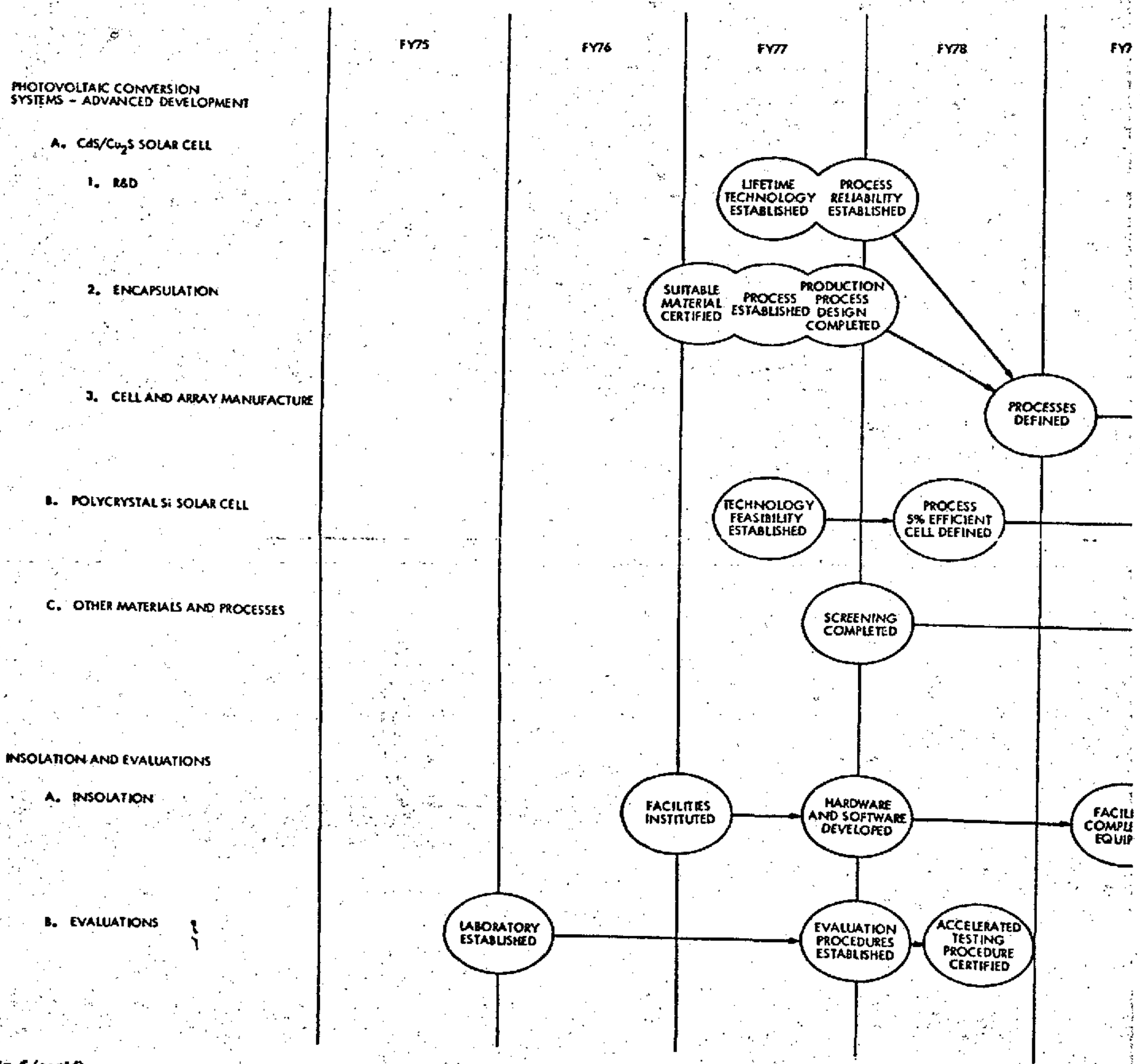
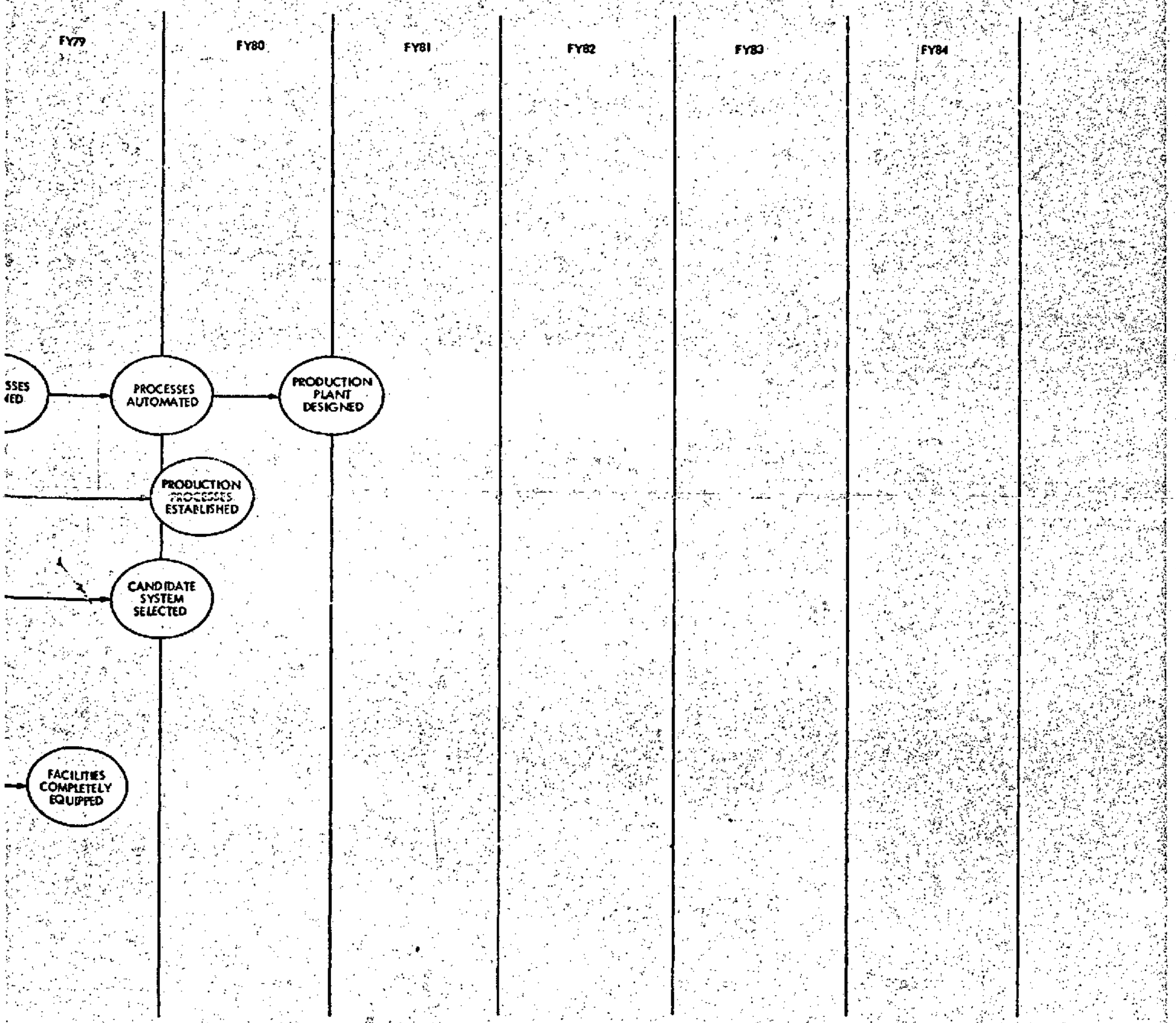

FY75
FY76
FY77
FY78
FY7
PHOTOVOLTAIC CONVERSION SYSTEMS - ADVANCED DEVELOPMENT
A. CdS/Cu2S SOLAR CELL
1. R&D
2. ENCAPSULATION
3. CELL AND ARRAY MANUFACTURE
B. POLYCRYSTAL Si SOLAR CELL
C. OTHER MATERIALS AND PROCESSES
INSOLATION AND EVALUATIONS
A. INSOLATION
B. EVALUATIONS
LIFETIME TECHNOLOGY ESTABLISHED
PROCESS RELIABILITY ESTABLISHED
SUITABLE MATERIAL CERTIFIED
PROCESS ESTABLISHED
PRODUCTION PROCESS DESIGN COMPLETED
PROCESSES DEFINED
TECHNOLOGY FEASIBILITY ESTABLISHED
PROCESS 5% EFFICIENT CELL DEFINED
SCREENING COMPLETED
FACILITIES INSTITUTED
HARDWARE AND SOFTWARE DEVELOPED
LABORATORY ESTABLISHED
EVALUATION PROCEDURES ESTABLISHED
ACCELERATED TESTING PROCEDURE CERTIFIED

Fig. 6 (contd)



FOLDOUT FRAME 2

In the performance of this decision duty, he will review the progress, the resources, and the status of the tasks of the program on a regular basis; coordinate the preparation of plans to achieve the objectives of the program; analyze information relevant to the program objectives and achievements; review and assign the responsibility to conduct studies evaluating technical feasibility and cost-effectiveness; be responsible for the overall management of funding and manpower resources, for the direction of technology development and project activities, and for the program administration; formulate and propose an integrated program of technology development, economic and social studies, and project efforts; and formulate and recommend the funding and manpower resources required for the Photovoltaic Conversion Program.

The MPCP may utilize advisory committees to assist him in reviews and evaluations and to advise him in the performance of his duties. These committees, which, for example, may in part consist of a power engineer, an economist, a solar cell scientist, and a production engineer, are to be staffed either by volunteers or by paid consultants. The committee personnel can be drawn from universities, industrial laboratories, consultant firms, and government laboratories and agencies. To ensure that independent advice and critiques are provided, it is important that these advisory committees be separate from the staffs comprising the management of the program. The committees will meet at the discretion of the MPCP, and the funds for this activity should be included as a specific item in the budget.

2. Section Management

a. Single-Crystal Si Solar Array Mission. This section has the responsibility for the program of research, development, and engineering tasks directed to achieve the objective of proving the practicability of \$0.50/W arrays fabricated from single-crystal Si. This section comprises four groups: solar energy conversion, production engineering, quality assurance, and systems engineering. The activities of the first two groups involve (1) conducting applied research and development; (2) conducting investigations, designs, development, fabrication, and qualifications of cells and arrays; and (3) developing and establishing mass production procedures for fabricating cells and arrays so that the cost goal can be reached. The quality assurance group has the charter for specifying, maintaining, and controlling all involvements of reliability and quality assurance measures in this program. The systems engineering group has the responsibility for the direction of activities associated with power systems development and engineering, such as power conditioning, systems design and analysis, and systems structure.

b. Systems Section. The systems section is responsible for the activities associated with the requirements for power conditioning, power systems, and systems structure. Assigned to the power conditioning activity is the development of materials and circuits for power conversion. These efforts involve conceptual designs and modeling followed by circuit designs, fabrication, and testing. In the power systems activity, there are tasks for preliminary configuration designs, definition of requirements for systems analyses, and estimates of hardware requirements; for defining subsystem and system performance specifications from load profile analyses, margin analyses, reliability estimates, and computer program outputs; for performing subsystem and system designs using syntheses, tradeoffs, analyses, tests, evaluations, and reviews; for establishing and controlling interfaces in the system; and for developing new power system concepts. The systems structures activity comprises the tasks pertinent to the design, fabrication, installation, testing, and evaluation of the terrestrial power systems utilizing photovoltaic conversion.

c. Insolation and Evaluations Section. The responsibility for obtaining and processing insolation data and for all testing and evaluation activities is assigned to this section. The evaluation assignment is divided into two main areas: testing and evaluation as part of contractual agreements and the operation of national laboratories.

In order to direct and control the efforts in the first evaluation area, the measurement procedures, evaluation criteria, and documentation must be specified for each contract, and this phase of the contract must be monitored diligently. The quality assurance procedures and policies of the program will be used for establishing the guidelines and conditions for each contract, and the contract monitoring will be supported by the insolation and evaluations section in formulating and carrying out the testing and evaluation directives of the program. They will participate in this process by ensuring the correctness of the provisions in the contracts; supporting the monitors with technical information regarding measurement equipment, procedures, and evaluations; and providing the interface between the contractual activities and those delegated to the national laboratories.

The remaining evaluation area of responsibility is the operation of the national laboratories. The activities of this area include performing studies to determine the measurement requirements for particular subprograms by conducting a research program to develop innovative measurement techniques and instruments; making independent measurements on the materials, devices, and processes of the contracts; and coordinating the collection, analyses, and dissemination of data and conclusions.

The responsibility for the management of insolation data includes the activities of installing and maintaining insolation stations and gathering, evaluating, processing, and distributing insolation data.

d. Photovoltaic Conversion Systems -Advanced Development. This section is given the responsibility for all activities involved in conducting a long-range research and advanced development program for photovoltaic conversion systems. As in the case of the solar energy conversion group, the efforts may involve basic research on material properties, diffusion characteristics, properties of junctions, carrier lifetimes, spectral response, and energy efficiency of cells; development of the techniques for purification of materials, diffusion of doping agents, and fabrication of cells; and the design, fabrication, and evaluation of cells and arrays. In addition, the section will act as a focal point for the transfer of technology from universities, industry, and government laboratories and will plan and hold seminars in the fields of science and engineering of photovoltaic conversion for terrestrial applications. The program of this section expressly includes basic and applied research and development subprograms consisting of both theoretical and experimental investigations of photovoltaic conversion technology areas with relatively low levels of scientific and technical maturity. Since the goals of the section are to obtain information and to develop new concepts for photovoltaic conversion, the transfer of these products to the rest of the program will in some cases provide technical support for tasks currently in the program. On the other hand, the consequence may be major changes in the overall program, such as the introduction of entirely different photovoltaic conversion systems.

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Appendix

Need for Technical Evaluation Laboratories

The NSF Program for Photovoltaic Conversion extends from basic research studies to proof of concept experiments on production solar arrays. Throughout the program, it will be necessary to make various kinds of measurements on solar cells, arrays, and power systems. These will include measurements of intrinsic physical and chemical properties, semiconductor behavior, and electrical performance characteristics. At many stages of the various tasks of the R&D and project types of programs, there will be requirements to compile, correlate, and evaluate data.

Many of these activities will be performed by the contractors engaged in carrying out the provisions of the contracts for research, development, design, fabrication, and evaluation. The cognizant technical and project engineers will monitor these measurements and evaluations. Despite careful control of measurement procedures and the critical evaluation of these data, however, there remains a need to perform the same types of measurements and data evaluations in laboratories which are physically independent of those of the contractors. This need is of critical importance in assuring that independent and consistently accurate and reliable data are expeditiously obtained. This conclusion will require setting up a national laboratory or a series of national laboratories which have the requisite capabilities. The primary goal of these laboratories will be to ensure the validity and objectivity of the quantitative information which will become the basis for task evaluations and for program decisions.

The existing laboratory facilities of various government agencies should be incorporated into this measurement and evaluation organization to the greatest degree practical, recognizing that there will be other commitments and conflicting schedules. To accomplish a coordinated, controlled utilization of these facilities will require that an extensive inventory be made of the physical resources, equipment, manpower, and work loads. Interagency contractual agreements will be necessary to assure the primacy of the scheduling obligations to the NSF program. The requirements for additional facilities will be determined after listing the measurement requirements and inventorying the available facilities.

The following objectives should govern the operating procedures of the laboratories: (1) To provide the independent, objective measurements and evaluations necessary in all phases of the research, development, engineering, and product fabrication tasks of the program so as to maintain the continuity of the overall program and the unimpeded flow of the work. (2) To provide the data and analyses which can be used to construct the information basis for making decisions regarding the tasks, schedules, and funding of the program. (3) To ensure that the measurements, evaluations, and analyses of the quality assurance program are performed with the highest level of accuracy, objectivity, and reproducibility. These objectives can be accomplished with technical effectiveness and economic efficiency in a laboratory organization which assigns, controls, and coordinates all scientific and engineering measurements.

The operating procedures of these laboratories should be controlled so that the measurement techniques are well documented and standardized; the facilities are fully utilized in an economical manner; innovative measurement techniques and apparatus are explored; schedules for measurements are coordinated and directed to yield systematically obtained, timely data; and the information is made readily available. Since these laboratories are to be operated in support of and in collaboration with the contractual measurement requirements, all facilities and the manpower needed to make measurements at each level of the research, development, and fabrication of solar cells and arrays should be provided. The technical aspects and the contractual arrangements should be under the direct control of the individual sections of the program, which have the complete responsibility and authority to establish the specifications as to the instrumentation, equipment, measurement procedures, data handling, and reporting. A separate schedule should be established for periodic reviews of measurement procedures and of the summaries and conclusions derived from the data. Similar critiques should also be included in the other technical reviews of the program.

A strong, effective laboratory organization can be maintained by operating this measurement and evaluation function within a controlled structure which is responsive to the NSF. It is important that the priority status of the NSF program be a contractual requirement which is continually reviewed and enforced.

Epilogue

This technical assessment, which includes a program plan, milestones, schedules, and funding requirements, was based on a technical analysis and evaluation by JPL and made use of reviews of the literature including critiques of the conclusions and recommendations of the Interagency Panel for Terrestrial Applications of Solar Energy and the NSF Conference on Photovoltaic Conversion of Solar Energy for Terrestrial Applications. The premises for the assessment were taken to be the 5- and 10-year objectives of a program to develop photovoltaic devices for commercial utilization and a cost-effective constraint. It is evident that some parts of this assessment will be affected by changes in any of these factors. Hence, a conclusion of this report is that technical assessments should be performed throughout the program as a task of the program so that variations in the scientific foundations and technology readiness as well as in the objectives and budgets can be used to maintain a currently effective program. Independent assessments, periodically scheduled, are recommended. These could advantageously be assigned as a task for an advisory committee.

One concern, discussed frequently in the workshop and panel meetings at the NSF Conference, was that some elements of industry and the electric utilities will not become involved in this development program early enough to significantly affect the course or duration of the program and that these delays will lessen the chances of reaching the goals of commercial utilization of photovoltaic conversion devices. The general conclusion was that earlier participation would be expected if the program was supported by a firm, long-term commitment by the government—a commitment which states unequivocally that the development of photovoltaic conversion of solar energy for terrestrial applications is a national, long-term goal. Such a declaration would provide a strong impetus at the start of the program by encouraging the participation of many research and development laboratories and industries.

Based on this governmental commitment, also, the private investments necessary for the commercial institution of photovoltaic conversion hardware would very likely be consigned at a much earlier stage of the development. These two consequences of a commitment declaration should substantially strengthen and accelerate the overall program. Hence, the immediate, unequivocal, firm commitment by the government to a long-term, adequately funded program to establish the commercial practicability of photovoltaic conversion of solar energy for terrestrial applications is a recommendation of this report.

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