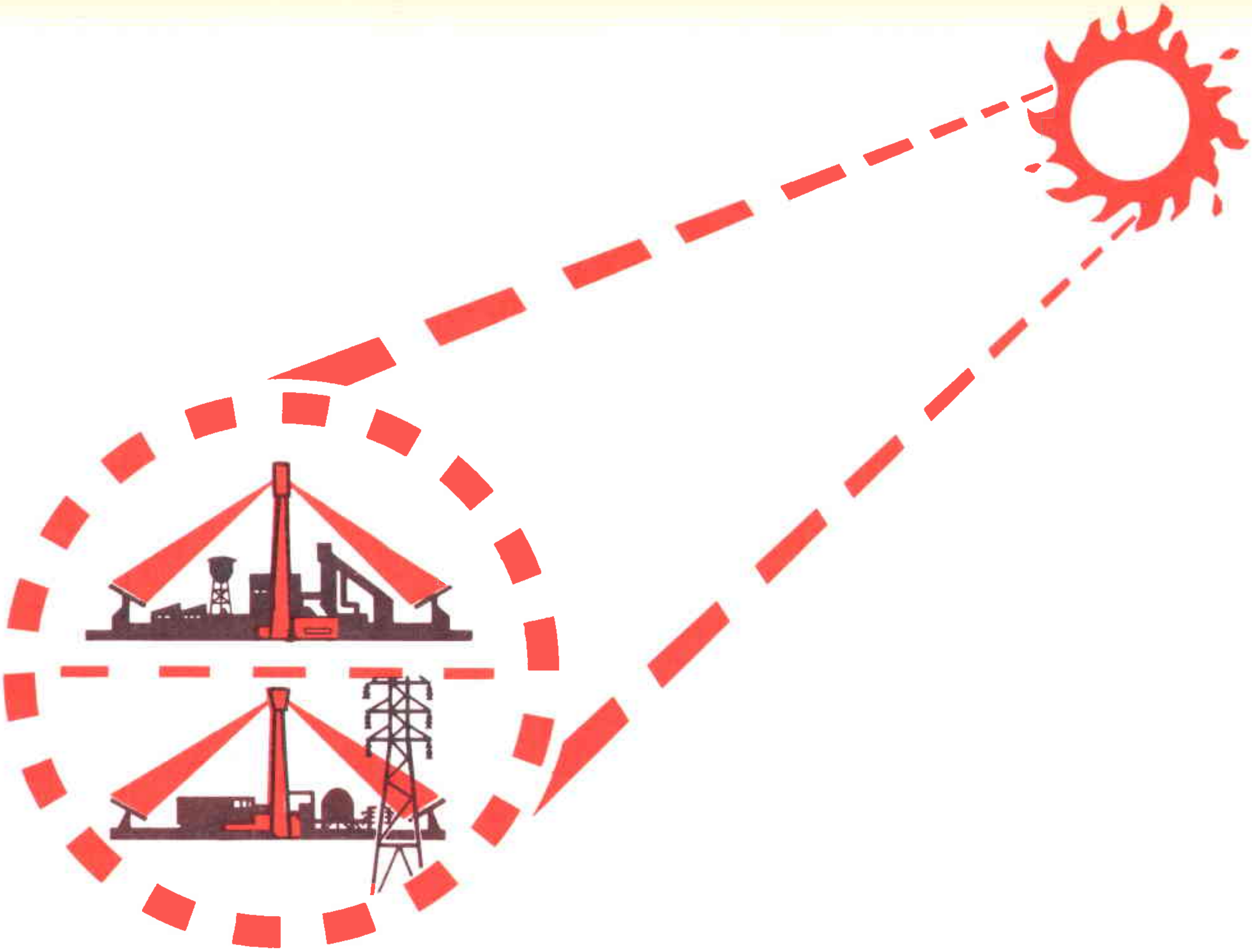
1060

SOLAR FUELS AND CHEMICALS

Annual Operating Plan
Fiscal Year 1984



U.S. DEPARTMENT OF ENERGY

San Francisco
Operations
Office

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SECTION I

GOALS, OBJECTIVES AND STRATEGY

A. BACKGROUND

The Solar Fuels and Chemicals program develops the technology of operating chemical processes using concentrated solar heat. Because the effeciency of energy usage increases with increasing temperature, high-temperature chemical processing is emphasized. Prior to FY83, the effort concentrated on a number of proof-of-concept experiments which demonstrated the technical feasibility of utilizing direct solar radiation to produce fuels and chemicals. In addition, a number of studies were conducted, focusing both on near- to-midterm technology for early commercial demonstration by the fuel and chemical industry, and on far-term applications using very high temperatures and direct solar flux.

The early proof-of-concept experiments included tests on the gasification of coal and biomass, the pyrolysis of oil shale, and the high-temperature processing of inorganic chemicals such as calcium carbide and zinc sulfate. These experiments pointed to many of the key technical development areas needed to adapt solar thermal technology to fuels and chemicals processes. These include fundamentals such as (1) improved characterization of heat and mass transfer, (2) behavior of high-temperature materials, catalysts under thermal cycling, and process stability, and (3) improved understanding of kinetics and thermodynamics of high-temperature reactions.

Several analytical assessments of the application of solar thermal technology were conducted, the most recent being one carried out by Black and Veatch Consulting Engineers and the Ralph M. Parsons Company for DOE/SAN. This work concluded that, for near-term applications, solar thermal technology would not be competitive in the conventional chemical industry. They recommended that research and engineering efforts be concentrated in advanced processes, and be developed in parallel with high-temperature solar capabilities.

A few conceptual studies of larger chemical systems driven by solar thermal energy have been conducted. PFR Energy Systems (1980) studied the repowering of an ammonia plant using solar heat to reform methane to hydrogen. The study concluded that the system could be economically attractive if the high-temperature receiver technology were available. Westinghouse Electric Company (1979) studied the production of hydrogen by a thermochemical cycle based on the decomposition of sulfuric acid. Their design required transfer of heat from a central tower using a high-pressure helium heat transfer loop. The study concluded that the process was feasible, and produced excellent engineering designs of the high-temperature reactors.

While the proof-of-concept studies showed the possibility of using solar energy in chemical processes, the engineering studies showed that fundamental engineering research was required to understand the interaction of the solar heat source with chemical processes. The primary needs were in understanding the role of transient heat supply on the processes, and in understanding the effects of rapid heat and mass transfer required by the high solar fluxes. For some classes of reactions, chiefly those involving pyrolysis of solids or complex liquids, the high incident fluxes may be beneficial to the processes.

Early in FY83, a plan was developed which will guide the research on the adaptation of central tower technology to chemical processes. This plan provides for the operation of an integrated system research experiment. The technology leading to this experiment will resolve the major questions of materials, process control, process stability, and interfacing of complex processes with solar energy. As part of this plan, a series of experiments was begun to prove the engineering feasibility of operating chemical reactions in the solar environment. An experiment was completed at the Advanced Components Test Facility in Atlanta in which a catalytic reactor was operated at over 815°C (1500°F). This test, conducted by GA Technologies, Inc., proved the technical feasibility of using high-alloy metal reactors for a variety of chemical operations in a solar tower. The basics of reactor design and integration with a solar cavity were proved. This effort will continue in FY84 with the operation of a more sophisticated experiment which will test pressurized operation, reactor/receiver efficiency, and reactor stability.

B. PROGRAM GOALS AND OBJECTIVES

The goal of the Fuels and Chemicals program is to establish the potential of solar thermal technology in the fuels and chemical industries. This includes the production of materials that may have a significant impact on the nation's energy usage, or, possibly, the use of solar technology to manufacture materials in a particularly advantageous manner. This is accomplished by simultaneous efforts of evaluating the use of advanced solar technology in particular applications by means of experiment and analysis, and of establishing the base of technology that allows an engineering assessment of promising applications. The former effort concentrates on experiments which relate to the effects of temperature, solar flux and heating rate on the reaction rate of materials. The latter concentrates on experiments which relate to the control of stress, heat and mass transfer in reactors accepting high but unsteady solar radiative fluxes.

In summary, the program goal is to determine the technical and economic feasibility for production of fuel and chemicals from renewable resources using solar thermal energy.

The objectives are, 1) to perform appropriate analytical and experimental work to identify solar unique unit options, 2) to identify and develop key technologies required to evaluate fuel and chemical production potential and 3) conduct supporting mission/system and economic analyses to maintain industrial perspective and establish cost and performance goals.

Specific objectives for FY 1984 include:

(1) Assessment of high-rate pyrolysis of inorganic reactants.

(2) Comparative assessment of high rate pyrolysis of coal to produce liquids.

(3) Determination of stress behavior of pressurized metal catalytic reactors at 870 deg C in a solar environment.

(4) Determination of criteria for chemical process stability and control.

(5) Determination of flux limits in photoelectrochemical processes.

(6) Determination of temperature effects on photoelectrochemical processes.

C. PROGRAM LOGIC AND RATIONALE

The program logic is presented in Figure I-1. The logic is based on a melding of program planning, analyses and research and technology development that will provide the data required to determine future programmatic direction, emphasis and resource allocations.

Past year's efforts have been devoted to determining the utility and applicability of solar thermal energy to primary fuel and chemical processes. Results of exploratory studies demonstrated that this energy resource could be used to drive all major fuel and chemical conversion processes, including reduction, gasification, pyrolysis and liquefaction. In addition, it was clear that intermittent, high-flux, high-temperature inputs could be accommodated within a broad range of processes. Other work with windowed reactors and moving beds demonstrated ease of control over heat and mass transfer using direct radiant heat transfer to solids.

Building upon this exploratory research base, activities will focus on analytical and experimental tasks that will provide:

(1) Insight and understanding into whether the solar thermal resource contains unique or advantageous elements that could be beneficial to the fuel and chemical industry

(2) Identification and definition of the technical barriers that would limit or prevent utilization of the resource.

(3) Development of a program and management structure that would result in assessing the technical and economic feasibility for production of fuels and chemicals from renewable resources.

In developing the program structure the logic network revealed that several critical issues must be addressed. These are catagorized somewhat simplistically by the following interrogatives; "Is there anything worth doing?" and "Can it be done?"

In terms of the first issue, the fact that solar thermal technologies can perform specific conversion processes is an inadequate basis upon which to conduct a major program. Investigations are being focused to closely examine the unique or beneficial aspects of the potential that has been identified through preliminary feasibility experiments. Table I-1 presents a partial listing of these promising attributes.

The second issue is equally critical to the decision process. It will provide the data that deal with the solar/process interface and provides management insight into the likelihood of operating fuel and chemical processes with the solar thermal resource. These are the fundamental engineering research issues which could prevent utilization of any identified potential. These experiments are deemed critical to developing industrial interest and involvement in the program.

Table I-1. Examples of Solar Unique or Beneficial Aspects of the Solar Thermal Resource

- High Thermodynamic Efficiency
  - High Carnot Efficiency At High Temperature
  - Wide Choice of Chemical Systems Available to Utilize Efficiency
- Excellent Matching of Solar Receiver Technology
  - Heat Can Be Supplied By Solar Technology at Temperatures and Amounts Dictated by Process
    - Reduced Internal Heat Transfer
    - Efficient Use of Materials and Heat
  - Chemical Reactions Can Absorb Much Larger Amounts of Energy Per Unit Weight and Volume Than IPH or Electrical Generation Systems
- Can Produce Fuels from Variety of Feedstocks
- Solar Amplification
- High Temperature Reactions
  - Two-Step Cycles Become Feasible
  - Direct Metal Reduction
- Photochemical Reactions
  - Quantum-Thermal Hybrids
- Direct Flux Reactions
- High Flux Reactions
  - Unique Chemical and Surface Properties

D. PROGRAM STRATEGY AND STRUCTURE

The program strategy is focused on developing a research and technology management structure which will;

(1) Identify the most promising concepts

(2) Identify the major technical barriers

(3) Be success oriented

- Hold the program within technical risk limits
- Have definable stages and deliverables
- Show measurable progress toward end point
- Provide a structure to evaluate decisions and outcomes

(4) Make realistic appraisals of existing technology

(5) Deal with industry's perception of technical feasibility

(6) Optimize technical developments for application to near-midterm chemical processes.

In providing this structure, it can be seen from Figure I-1, that a great deal of analytical and planning effort was conducted in order to identify the key issues that should be addressed early in the program. This effort should not be construed as one that limits or eliminates options, but as one that optimizes program resources while investigating program merit. Where analysis supported the decision, a key process that was representative of a category of reactions was selected for extensive study in order to focus on the primary science and engineering research issues.

The program structure is presented in Figure I-2. It illustrates the plan to pursue the solar unique options and introduces the concept of "core technologies and staged technology" and presents a long term programmatic goal, the production of basic fuel elements CO and H_2.

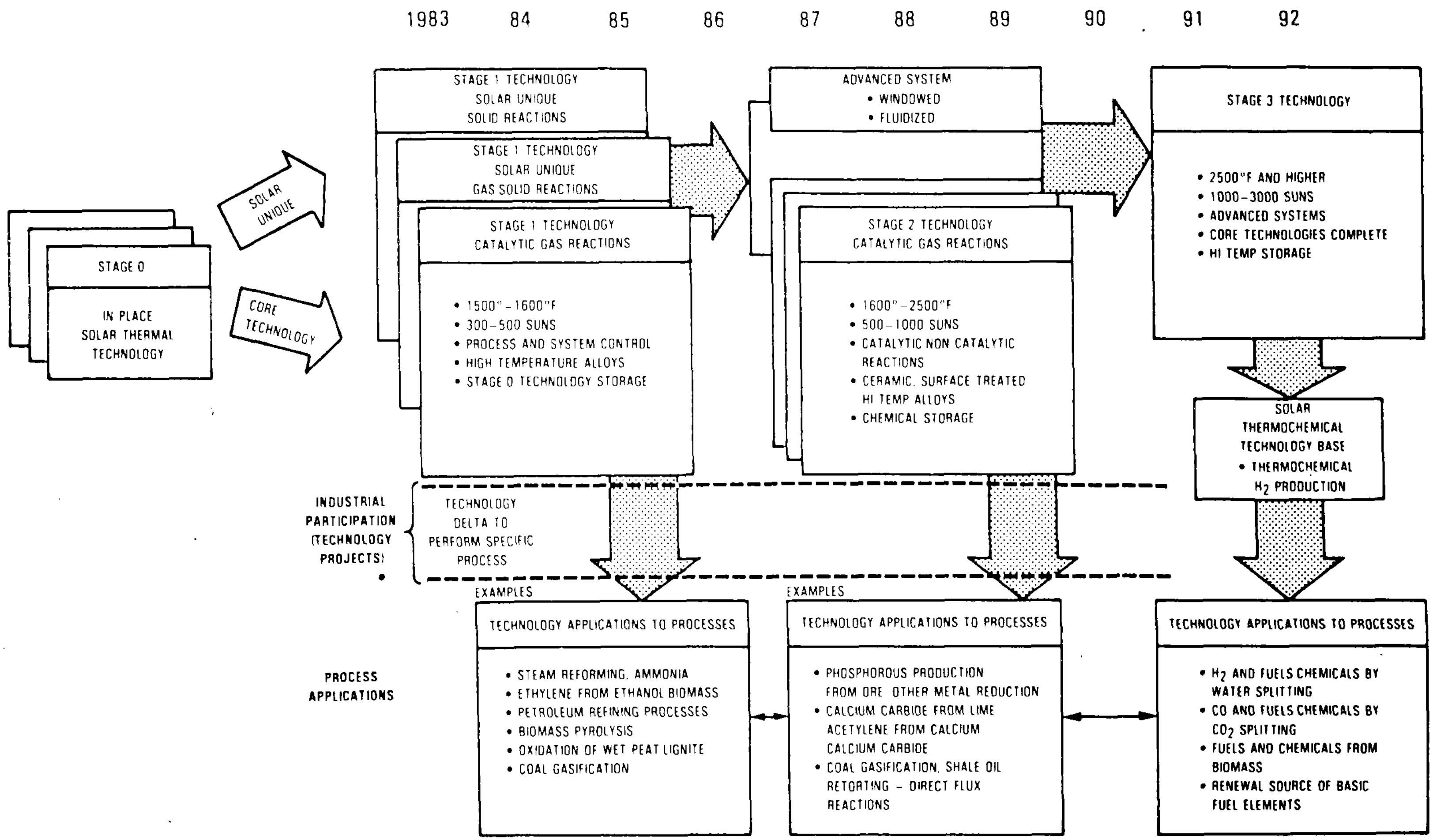


Figure I-2. Solar Fuels and Chemicals Program Structure

Selection of a long-term goal was necessary in order to provide the appropriate planning and management mechanism for the process/solar interface research effort. The analytical work resulted in formation of a "Solar Technology Project." which focuses the solar engineering research, and in formation of the Advanced Concepts effort which examines novel and innovative uses of the concentrating solar technologies.

The program structure also suggests the utility of the technology to industry and the mechanism by which involvement can be encouraged. These program concepts are explained below;

(a) Core Technologies

An assessment was performed to identify the technical barriers that would prevent industry from capitalizing on the potential for fuels and chemicals production. It was learned that, while specific solar thermal capability exists (e.g. high temperature capability), the technical base to make use of it has not been developed. In performing the assessment, several major fuel and chemical processes were examined in great detail. What was learned is that there is a great deal of commonality in terms of missing technologies among the processes. These are all related to the process/solar interface and have been identified as "core technologies." The program structure has been developed to focus on these technologies since an appraisal of the technical feasibility of the core technologies will validate solar engineering merit and will permit application to a range of fuel and chemical processes.

(b) Staged Technology

Preliminary understanding of promising unique and benefical processes indicated the requirement for a broad range of advanced solar thermal technologies. For example, this program requires a new understanding of materials, reactor design and catalyst behavior under conditions of multiple, deep thermal cycles. It also requires new methods to control reaction time under conditions of variable heat input. Additionally, process control and stability are unknown for integrated solar plants; this will require knowledge of how to adapt chemical operations to large thermal transients and understanding the dynamics of processes with variable heat and product stream flows.

The program stresses progressive systematic developments, it is results oriented. In summary, this concept indicates that in order to achieve the program goals several major technological hurdles must be overcome in progressive stages. These stages have been characterized as technology stages or technical targets. Each stage independently represents generic technical developments for a class of industrial fuels and chemicals applications. The stages are sequential in nature increasing in complexity of the technical tasks and targets. Each stage builds on the accomplishments of the previous stage. Our example assumes sequential development of basic thermochemical processes consisting of high temperature catalytic gas reactions and unique reactions involving direct high flux solar interaction. Potential industrial applications of this technology are numerous and are illustrated. These technology stages will be redefined and updated during FY84, as further conceptual and experimental data are developed.

(c) Solar Technology Project

To identify the technical isues and proceed with their resolution, it is convenient to focus on a single project which encompasses most of the features of solar chemical processes. A result of the analysis of the major issues of driving chemical processes with concentrated solar heat was the selection of such a process, one that produces hydrogen from water using only thermal energy. This process, currently in a stage of advanced research, contains most of the features of high-temperature solar chemical processes including operation in an excellent temperature range, good adaptablity to central receiver technology, and well-established and simple chemistry, thermodynamics and kinetics.

The selection of a specific process on which to target the development of the interfacing technology provides both risks and opportunities to the Fuels and Chemicals program. The primary risk is that process development will be seen as the program goal rather than the development of the solar interfacing technology. This may be perceived by both existing and potential contractors and users, and by levels of DOE management less familiar with the program strategies. This risk can be minimized by selection of the process which is well characterized except for the unique problems of heat and mass transfer, materials performance and process control associated with the transient energy source.

The opportunities arise from the selection of a process which has broad academic, industrial, and international interest which can be used to leverage the implemenetation of solar chemical technology. Public interest is also a valuable asset in technologies undergoing a critical phase of evaluation and development.

These considerations as well as a large amount of technical input led to the selection of a water-splitting process operating at a peak temperature of about 870°C (1660°F) as the focus of the Solar Technology Project. This sulfuric acid/iodine process is the best understood of the so-called thermochemical processes, and, unique among similar processes, uses only processing methods familiar to the chemical industry. The production of hydrogen from only heat and water is also seen as an attractive programmatic target and even as a primary technology when fossil fuels become limited in supply.

There are many other potential methods to produce hydrogen from solar energy, but the sulfuric acid/iodine method serves best at establishing the potential for development of solar chemical technology, the goal of the Solar Technology Project. Table I-2 presents some additional rationale for selection of this process, and Table I-3 illustrates the excellent matching of current and future solar central receiver technology with sulfuric acid-based water splitting processes. The sulfuric acid/iodine process will continue to be used as an engineering management mechanism until (1) sufficient data exists to determine that solar thermal cannot provide unique or beneficial features to warrant additional program support, (2) it is determined that the key process/solar interface research issues cannot be resolved (either technically or economically), or (3) additional conceptual studies indicate that some other process or combination of processes are better suited to identifying, managing and resolving the critical process/solar interface issues.

E. PROGRAM POLICY

The method of achieving program goals and objectives has been influenced by program policy which partially dictates the strategy developed to advance

Table I-2. Examples of Technical Basis for Selection of Solar Thermochemical Hydrogen as Solar Technology Project

- Process Represents Essential Solar Fuels/Chemical Core Technologies Needed for F/C Process Industry
  - Best Vehicle for Solar F/C Technology Development
  - Requires Development of Critical Technology
- Potential Higher Efficiency (45 - 50%) Than Other Approaches Such as Electrolysis (25 - 30%). Hence Smaller Solar Field/Lower Cost
- Multiple Reactions Involved Permit Substitution of Several Potential Solar Unique High Temperature Subprocess Options to Enhance Peformance:
  - Solid Decomposition (LLNL)
  - Pyrolytic Decomposition (Los Alamos)
  - Photolytic Decomposition (SERI)
- Utilizes Solar in Ideal Temperature Range (1600°F - 1800°F)
  - Fits Heat and Thermodynamic Characteristics or CR and Dish Systems
- Provides Potential for Chemical Storage and High Capacity Production
- Utilizes Renewable Feedstock (Water)
- Helps Identify Key Issues of Process Control and Stability

Table I-3. Key Technical Problems and Interfaces with Solar Energy

Issues	GA Cycle as Baseline
1. Reactor Must Operate in Achievable Temperature and Flux Range	• Operates in Excellent Range of Temperature (1500 - 1600°F) and Flux (400 - 2000 Kw/m^2)
2. Control Over Reactant Flow, Flux, and Reactor Temperature Must be Established	• Simple Control of Reactant Using a Single Liquid. Allows Control of Temperature Without Affecting Decomposition Chemistry
3. Kinetics of High-Temperature Reaction Must be Known	• Kinetics of Sulfuric Acid Well Established Over Range of Temperatures and Pressures. No Side Reactions
4. Reactor and Peripheral Apparatus Must be Compatible with Experimental Solar Facilities	• Reactor can be Operated in Any Orientation
5. Solar Experiments Must Lead to Full Characterization of Heat and Mass Transfer Characteristics of the Reaction	• Kinetics Well-Established. Heat Transfer to be Studied
6. Low-Temperature Processes Completing the Cycle Must be Known	• Iodine Chemistry Established but Needs Improvement
7. Reactions Forming Gases Must be Operated at Elevated Pressure	• Catalytic Metal Reactor Capable of Pressure Operation
8. Windows Must be Capable of Operating at 1000-2000 Kw/m^2 if Used on Solar Tower	• No Windows Required
9. Reactor/Process Should Provide General Information on Engineering of High-Temperature Reactors Including Heat and Mass Transfer	• Results of Tests Widely Applicable to Catalytic, Endothermic Reactions
10. Immediate Process Interface Must be Simple	• Unreacted Acid Separated as a Liquid. Gases go for Downstream Processing

Table I-3. Key Technical Problems and Intefaces with Solar Energy (Cont'd)

Issues	GA Cycle as Baseline
11. Thermodynamic Considerations	• Operates Near-Equilibrium for High-Efficiency. Overall Heat Match may Require 2 Receivers
12. Materials	• Potentially Critical Materials for Acid Boiler. Westinghouse Work on SiC Vaporizer Applicable

solar chemical technology. The Fuels and Chemicals program includes the following as desirable in the accomplishing of program objectives:

1. The program should assess the advantageous use of concentrated solar heat in chemical technology, and should develop the program to advance the technical areas of greatest impact.

2. The program should utilize the most advanced solar technologies, and should contain significant technical challenge.

3. The program should be structured such that measurable technical milestones are achieved each year by which the potential for applications of solar heat in the chemical industry can be judged.

4. The program should select a focal point or project that will act as a mechanism for the identification and resolution of key design, technical, and engineering problems likely to be encountered in a full-scale solar fuel production system.

5. Research should be conducted on the most cost effective basis; central receiver facilities should be used when scale/size and experimental requirements negate solar simulation experiments.

F. TECHNICAL STRATEGY

This section discusses the underlying technical strategy used to direct the interrelated activities of the program components. These components address a variety of research areas which, together, acquire information on critical technical issues which will determine if concentrated solar energy can be used effectively for driving chemical processes.

1. Solar Technology Project

The need for a project to focus program activities was evident from an analysis of the diverse nature of previous work in solar fuels and chemicals. This work consisted largely of "proof of concept" experiments, but did not address the technical issues related to the engineering of chemical plants in a solar environment. These issues are the first to be questioned by the fuel and chemical industries, and include largely the lifetime and integrity of chemical systems operating with an unsteady energy source. The Solar Technology Project focuses on these issues by studying the chemical engineering of the central receiver-chemical process interface. This includes, primarily, experimental and analytical studies on material stress, heat and mass transfer, and process control, at the high temperature reactor and in processing equipment immediately downstream of the reactor.

To nail down the exact problems that would occur, a plan was developed to establish a complete solar-driven chemical process over a ten-year period, to be operated at the Central Receiver Test Facility, CRTF (Albuquerque). This established a timescale for solving the appropriate problems, and set the specific solar performance characteristics to those of the CRTF.

The chemical process selected for study was a thermochemical water-splitting process based on the decomposition of sulfuric acid. This process operates in an ideal temperature range for central receiver chemical systems (about 870 deg C, 1600 deg F), and allows for a great amount of flexibility in adapting the solar heat source to the chemical process. In particular, the process gives the option of supplying much of the energy from lower temperature receivers, thus reducing the technical risk (and cost) of the initial high temperature receiver. As the central receiver performance improves and as reactor technology is advanced, a greater proportion of the heat can be supplied at high temperature, leading to a more efficient process. Additional reasons for process selection have been presented in Table I-3.

The ten-year timeframe establishes the requirement for only one intermediate scaling test. The pacing technology is the high-temperature reactor and its operations under solar conditions. To prove the technology in a commercial sense, the process must be operated stably, reliably and safely. The technical strategy includes characterization of process control, both in the interface with the high temperature reactor, and in operations from thermal storage. The effect of temperature fluctuations in thermal storage on process operations and costs must be uncovered.

2. Advanced Concepts

The technical strategy for this fiscal year effort centers on the technology related to the decomposition of solids with solar radiation. Perhaps the most important feature of concentrated solar energy is that it is supplied in radiative form, a form that is difficult and expensive to obtain from fossil or nuclear sources. Radiant energy is capable of heating solids at a high rate, producing a variety of beneficial effects including high yields of liquids from organic and fossil feedstocks, and efficient absorption of energy for decomposing inorganic materials. For carbon-containing materials such as coal and biomass, there is a large body of information on the effects of high heating rates on the production of liquids. Such high heating rates are difficult and expensive to achieve in non-solar technologies. In situ combustion of hydrogen with oxygen is commonly used.

Inorganic solids such as limestone and metal sulfates can be decomposed with concentrated solar heat to form decomposition products of unique physical properties, and, possibly, unusual chemical properties. The high heating rates available from advanced solar technologies such as central receivers and parabolic dishes allow decomposition of inorganic materials under non-equilibrium conditions. This occurs because the heating occurs faster than the solid can undergo phase changes and compound formation. For example, it is speculated that zinc sulfate can be decomposed into its oxide before it forms stable oxysulfates.

Part of the Advanced Concepts effort in FY 1984 will center on the fundamentals of reactor design to achieve and utilize the high heating rates efficiently. This will be accomplished by combined experimental and analytical efforts to establish the critical parameters including the changing optical and thermal properties of the material, as well as its decomposition rate.

Additional efforts will center on innovative engineering concepts for the utilization of solar energy and research on specific chemical or photochemical systems. Activities in photochemical systems are influenced by previous assessments which demonstrated that systems with overall efficiencies greater than 15% are essential for commercial success. These assessments showed that flat-plate and cooled trough systems would have unacceptable costs. As a result, work will concentrate on uncooled troughs and central receiver systems.

FY 1984 work will center on the limiting flux and temperature characteristics of photochemical systems, particularly photoelectrochemical water decomposing systems that have shown some promise in a variety of tests. The work will establish the limits of flux that the photosystem can accept, and will establish the effect of temperature (generally thought to be highly deleterious) on candidate systems. The research aspect will be conducted at SERI.

The Advanced Systems effort takes a top-down look at solar chemical technology to determine critical issues associated with the solar-chemical process interface. This may include limiting behavior in the reactor, optimization of field layout, and field and feedstock logistics. The strategy is to conduct a series of design studies to uncover these issues as well as other concerns of the chemical and process design establishment. It is assumed that this effort will be monitored by this program but will be managed as part of the Sandia Livermore effort. Its interaction with the other program elements is shown in Figure I-1.

G. COST AND PERFORMANCE GOALS

The cost of solar heat is largely dependent on the scale of production of mirrors, and projections made outside of the Fuels and Chemicals program show excellent competitive costs of delivered heat given reasonable production scales. The value of this heat is generally improved if it can be delivered, and used, at higher fluxes and temperatures, both from the theoretical and practical point of view. Familiar Carnot limitations apply to the input of energy into chemical systems with high temperatures producing theoretically more efficient processes. In addition, the availability of high temperatures often allows the process designer to increase the rate of heat transfer, consequently reducing the physical size of process equipment.

The near-term performance goal for Fuels and Chemicals includes operating at about 870°C (1600°F) with an efficiency in excess of 50%. The far-term performance goal includes operating at 1100°C (2000°F) at the same efficiency. Both performance goals are chosen to assure efficient use of the solar field. This is required to insure that the costs of solar heat to the chemical process will be acceptable.

Detailed cost goals are not possible to formulate without knowledge of the applicable process, the process efficiency, or the solar field costs. Under the 1978 DOE cost goals, solar heat would be priced at about $5.80/gj, delivered. This is comparable with the current prices of oil and gas.

SECTION II

PROGRAM DESCRIPTION AND JUSTIFICATION

A. PROGRAM OVERVIEW

The FY 1984 tasks for the Solar Fuels and Chemicals program are designed to address primary technical issues associated both with the chemical engineering of solar-driven chemical processes, and with the improved and unique utilizaton of the radiant flux available in the concentrating solar technologies. The adaptation of high temperature solar heat to chemical processes is an unresolved issue. The current program emphasis is on determining the survivability of metal reactors at about 870°C (1600°F) under actual solar operating conditions. Tests conducted in FY 1983 showed excellent performance under low-load conditions, leading to FY 1983-1984 tests of a small pressurized reactor featuring design principles and conditions of larger reactors. In FY 1984, work will begin on process control aspects of solar chemical engineering, perhaps the technical feature of most concern to the chemical industry after reactor integrity. Related work continuing from FY 1983 includes solar process design work which will examine options of interfacing advanced solar towers with capabilities for independent mirror focusing with chemical processes. This study will examine implications related to multiple receiver operation, thermal storage, and utilization of the mirror field. Also carried from FY 1983 are tests to establish enabling technology of ceramic reactors. This work is primarily in the technology for fabricating ceramic heat exchangers, a field which can ultimately lead to unique chemical applications at very high temperature.

Efforts for improved utilization of solar technology include work on the technology of the decomposition of solids. Previous work in many fields has shown the advantages, sometimes dramatic, of rapidly heating solids of all kinds to produce valuable and unusual products. Perhaps the best characterized of these is coal where the yield of liquids from pyrolysis is greatly increased at high heating rates. Such rates are easily obtained with solar radiation, but are achieved only with difficulty in conventional fossil systems.

The decomposition of inorganic solids can be an efficient method of utilizing solar heat, both because of the excellent thermodynamic properties of solids, and because the high heating rates possible can lower the temperature requirements for decomposition. Such solids include the carbonates and sulfates which decompose at temperature ranging from 870 to 1300^{o}C (1600 to 2400^{o}F). The technology for decomposition of solids with a radiative heat source, however, is largely unknown. Reactor design requires a good characterization of the interaction of the optical and thermal properties of the solid with the solar flux. The heating rate is largely dependent on the solar flux as is the decomposition rate and temperature. In addition, the optical properties of the solid may change dramatically as it decomposes. The FY 1984 program will establish the priorities for examining these factors, and will conduct experiments aimed at determining the methodology for reactor design using solids.

Additional work focuses on research topics related to the engineering of processes or operations that are uniquely suited to concentrating solar technologies. These include investigations on the limiting features of photo-conversion methods, improved methods of heat and mass transfer, and improved methods of energy and mirror field utilization.

Extensive review and analysis of the technology of photoconverters has shown limited promise for flat-plate or cooled trough systems because of the substantial costs of the field layout coupled with only modest theoretical efficiencies for the photo-systems. The FY 1984 program examines potentially more efficient and low-cost systems including decoupled quantum-thermal systems which utilize the visible and infrared portions of the solar spectrum separately. Work will be conducted on bounding the flux and temperature limits of photo-converters, particularly photo-electrochemical systems which have shown the greatest performance among the photo systems.

The use of sulfur as a basis for energy storage will be examined analytically and experimentally. The oxidation and reduction of sulfur compounds can form the basis for efficient use of solar heat at 870°C (1600°F), and can produce heat by subsequent combustion at 1650°C (3000°F) for use in energy storage.

B. WORK BREAKDOWN STRUCTURE

The following tasks and subtasks are required to implement the Solar Fuels and Chemicals program for FY 1984. They reflect a balance of the needs for technology for adapting solar technology to conventional chemical processes, and for establishing processes which take advantage of the unique capabilities of concentrating solar technologies.

Task 1: Program Management of Solar Fuels and Chemicals

Task 2: Solar Fuels and Chemicals Program

Subtask 2.1 Solar Technology Project

2.1.1 High-Pressure Catalytic Reactor (FY 1984 Increment)

2.1.2 Solar Thermochemical Process Design (FY 1984 Increment)

2.1.3 Ceramic Heat Exchangers (FY 1984 Increment)

2.1.4 Process Control Fundamentals

2.1.5 Advanced Components Test Facility Support

2.1.6 Interface Options for Chemical Processes

Subtask 2.2 Advanced Concepts

2.2.1 Radiant Decomposition of Inorganic Solids

2.2.2 Principles of Solar Reactor Design for Solids

2.2.3 Photochemical System Analysis

2.2.4 Sulfur-Based Chemical Energy Storage

2.2.5 High Temperature Measurements of Decomposing Solids

2.2.6 Multistep Fixation of Nitrogen from Air

Subtask 2.3 Advanced Systems

2.3.1 Solar Central Receiver Chemical Process Design (Not Part of This AOP)

C. TASK DESCRIPTIONS

TASK 1. PROGRAM MANAGEMENT, SOLAR FUELS AND CHEMICALS

DOE/SAN, as the field manager for the overall program will provide program direction, control of program plans, budget expenditures, major procurements, schedule and other appropriate top-level management functions. Technical management support to SAN will be procured to recommend technical status, provide assessments, manage and monitor technical progress, prepare technical plans, and prepare documentation for review and presentation.

TASK 2. SOLAR FUELS AND CHEMICALS PROGRAM

This element comprises the core of the program and contains two key components. The first, the Solar Technology Project, act to focus the needs of the program to establish the technical feasibility of driving chemical processes with central receiver technology. The second, Advanced Concepts, seeks to establish chemical processes that are uniquely suited to concentrating solar technology and investigates speculative processes and operations that could dramatically improve the utilization and economics of solar technology. Finally, the Advanced Systems effort establishes the larger-scale issues of solar chemical technology, and looks for barriers related to larger chemical operations. This component will be conducted outside of this AOP.

SUBTASK 2.1 SOLAR TECHNOLOGY PROJECT

This element is based on the programmatic philosophy of selecting and implementing a project that will force the development of solar chemical technology. By focusing part of the program, the project is used as a mechanism for the identification and resolution of key design, technical and engineering problems likely to be encountered in a full-scale solar fuel production system. The decomposition of sulfuric acid was selected as the central technology to be examined. This operation is typical of many reactions working in an excellent temperature range for central receiver technology (about 870°C, 1600°F) which absorb heat very efficiently. It is also the central reaction in the most promising thermal methods of producing hydrogen from water, termed "thermochemical" processes.

2.1.1 High-Pressure Catalytic Reactor

Task Description

Sulfuric acid will be decomposed catalytically in an Incoloy 800H reactor at 0.5 to 1 MPa (75 to 150 psi) at 870°C (1600°F). Tests will be conducted at the Advanced Components Test Facility (see Subtask 2.1.5). The acid will be decomposed at the rate of about 3 kg/min. The net heat flux at the reactor surface will be from 30 to 100 kw/m^2. The primary purpose of the test is to obtain experimental data to verify design methods and to determine the cycle life of metal reactors operating with gases under pressure and under solar operating conditions.

Critical Technical Issues

This test is a major step towards establishing the feasibility of metal chemical reactors operating at elevated pressure above 870°C. The major technical points relate to the structural integrity of a reactor operating near its design limits. The test will demonstrate local control of flux, stress relief, heat transfer, and kinetics at temperatures and pressures typical of high-temperature chemical processes. It will provide data for the design life of metal reactors. It will establish safety techniques for operation of chemical steps on a solar tower, startup and shutdown procedures, and heat transfer characteristics.

Benefits to Solar Thermal Technology and Other Applications

This test establishes the technical feasibility of metal reactors operating above 870°C in a solar field. Successful conclusion of the tests will lead directly to the design and construction of larger catalytic reactors capable of operation on a commercial scale. Failure of the tests could lead to abandonment of this technology in favor of ceramic, windowed or open reactors.

Thermal cycling is a major factor in determining the lifetime of commercial reactors of this type in the chemical industry. Success in this effort may establish improved design principles for reactors that could be transferred into conventionally-fueled systems.

2.1.2 Solar Thermochemical Process Design (FY 1983 Start - FY 84 Increment)

Task Description

This subtask scopes the design of a thermochemical process using solar energy. The task, begun in FY 1983, will be completed in FY 1984. The task includes basic design of the plant as well as an evaluation of options in improved utilizaton of the solar field. Basic heat and mass balances will be made. Rough sizing of reactors and storage vessels will be made based on estimates of the day/night energy requirements, heat transfer properties of the major reactors, and so forth. Tradeoff studies will be made on the placement and temperature of operation of multiple receivers based on Subtask 2.1.7 results.

Critical Technical Issues

This task determines the technical path required for developing solar-driven chemical plants of significant scale by scoping the technical requirements of the important process steps. Matching of the solar flux to the heat transfer properties of reactors, for example, will partly determine material flow rates, system pressure and similar characteristics which affect the design and operation of the process. Estimates of overall process efficiency will be made to size the large-scale experiments.

Benefits to Solar Thermal Technology and Other Applications

The effort will provide design for the optimal utilization of advanced solar technology, specifically the Central Receiver Test Facility, for this type of process, by tailoring the process to accept multiple thermal inputs. Since the heat flux can be matched closely to the process needs, process costs can be minimized, especially relative to fossil-driven processes. This study is largely specific to advantages of solar energy usage, and has little application outside the program.

2.1.3 Ceramic Heat Exchangers (FY 1983 Start - FY 1984 Increment)

Task Description

This subtask studies the joining of silicon carbide parts as a precurser to the fabrication of multitube chemical reactors and heat exchangers. The work looks specifically at joining silicon carbide tubes to a manifold of similar material, the area of greatest stress encountered in solar-fired reactors and heat transfer equipment. A single-tube test article will be constructed which will be used to vaporize sulfuric acid at about $400^{o}C$. This effort will serve two purposes at once including (1) establishing the thermal and corrosion performance of silicon carbide heat exchangers, and (2) establishing a technical framework for fabrication of silicon carbide reactors for use at higher temperature.

Critical Technical Issues

Ceramic heat exchangers have the potential of greatly expanding the utilization of high-temperature solar heat. Critical questions remain unanswered however, primarily on methods of fabrication of ceramics in large arrays, and in methods of sealing against system pressures which are required in chemical processes. This task examines these questions, using the vaporization of sulfuric acid as the technical focus. The major technical point to be tested is whether the pressure can be contained satisfactorily, and various sealing methods will be tested including mechanical and chemical joining. Later tests on multi-tube heat exchangers will provide data for manifold design and cycle life. Both fluid mechanics and heat transfer characteristics of single-tube boilers will be investigated as applied to acid vaporization.

Benefits to Solar Thermal Technology and Other Applications

This effort will establish design and fabrication criteria for ceramic heat exchangers operating in a solar environment. It will provide a base of technology to advance ceramic technology into the high-temperature regimes which are beyond the strength limits of metals.

Industrial use of ceramic heat exchangers, particularly in corrosive service, could be advanced by this effort provided that fabrication techniques and lifetime assessments can be established.

2.1.4 Process Control Fundamentals

Task Description

This subtask examines the process stability and process control of chemical operations coupled directly to the solar reactor. Analyses are conducted on the effects of the transient solar flux on the temperature and composition of principal product streams. Of particular interest are the effects of transient streams on separation processes with long characteristic response times. The task will also study modes of process instability to assure safe and stable operations at elevated pressure.

Critical Technical Issues

Instabilities in chemical processes are complex phenomena which can "roll through" an integrated chemical plant and cause damage and unknown hazards. These instabilities can be amplified by exaggerated transient behavior which will be experienced in solar operations. This task begins examining the critical issues associated with potential instabilities. It will examine aspects of process control dealing with the mismatch of characteristic response times among various chemical operations to the varying solar flux.

Benefits to the Solar Thermal Program and Other Applications

This task will assure stable operation of solar chemical plants, thus providing industry with the basis for designing safe, efficient plants. The results will be included in the design base to establish costs related to process control such as mass and heat storage and additional control equipment.

The concept of tight process control to handle transients can be generalized to improve process control in conventional plants, particularly during startup and shutdown.

2.1.5 Advanced Components Test Facility Support

Task Description

This subtask provides for operational support for research tests at the ACTF, primarily for subtask 2.1.1. Work includes support for instrumentaton, maintenance, and improvements to the monitoring and measuring capabilities of the facility.

Critical Technical Issues

Previous work related to subtask 2.1.1 has demonstrated the capabilities and flexibility of the ACTF for experiments in the 25 to 200 kw range.

Benefits to Solar Thermal Technology and Other Applications

Experience gained under this work adds to the capability of all solar facilities to conduct unfamiliar chemical operations. Efficient procedures are developed to assess and address potential safety-related issues, to measure experiment performance start up and shut down of chemical operation, and otherwise conduct cost-effective research level experiments.

2.1.6 Interface Options for Chemical Processes

This subtask examines different techniques of using central receiver systems in chemical processes. It studies the concentration and decomposition of sulfuric acid as a means to establish the optimum configuration of mirror and receiver usage. Options include multi- and single receivers to tailor the solar heat supply to the needs of the chemical process.

Critical Technical Issues

Solar heat is collected more efficiently and cheaply at lower temperatures, but can be utilized more efficiently at higher temperatures. Advanced central receivers have the capability to focus mirrors independently on several receivers, thus tailoring the delivered heat to the process needs. This study examines these options, specifically to determine the extent of advantages (if any) to running multiple receiver chemical processes.

Benefits to Solar Thermal Technology and Other Applications

This effort is the first to examine the unique capability of central receiver systems to match the heat needs of a chemical process. It has the potential of guiding the development of low-cost processes by reducing the needs for internal heat transfer and associated equipment.

SUBTASK 2.2 ADVANCED CONCEPTS

This element develops underlying technologies that use concentrating solar technology uniquely and efficiently. This includes the direct use of the high radiative fluxes available to rapidly and efficiently heat reactive solids. This may allow both the more efficient use of the energy source and also the production of new products with unique physical and chemical properties. This subtask centers on what are considered near-term techniques in that, once the fundamentals of the technology are understood, processes can be implemented in a relatively straightforward manner. These fundamentals include heat transfer, reaction kinetics, and reactor design based on the optical and thermal properties of the solids.

In addition, this element studies concepts related to the particularly advantageous use of solar radiation including photochemical and very high temperature reactions. It also includes unique ways of improving the utilization of solar energy through novel means of energy storage or use. Emphasis in photochemical systems is on engineering design, performance, and limits of photochemical systems, and complements DOE research division's work on basic research. Analysis of photochemical systems proposed to date has shown limited application to concentrating solar technologies because of low efficiencies or high installed costs of non-concentrating systems. Work in Advanced Concepts centers on concepts which circumvent these limitations, possibly by operating in concentrating systems, operating at elevated temperature, or by new photochemical concepts which promise acceptably high efficiencies. Other work studies chemical energy storage concepts which may allow dramatically improved utilization of the solar field by allowing for diurnal and seasonal energy storage.

2.2.1 Radiant Decomposition of Inorganic Solids

Task Description

This work studies the decomposition of inorganic solids in an arc-image furnace that simulates solar radiative heat transfer. The effort centers on the decomposition of inorganic solids, with zinc sulfate as the model. The work will evaluate the importance of heating rate and the changing emissivity and reflectivity of reacting materials. Initial work will be on examining the effects of heating rate on the phase transition temperature of zinc oxide, the major solid product of zinc sulfate decomposition.

Critical Technical Issues

The technology of the decomposition of refractory solids by radiant heat transfer is largely unknown. This is because the high heating rates lower the decomposition temperature and can change the decomposition products. If the heating rates can exceed the rate of recrystallization of components, for example, the temperature and energy requirements for the decomposition will be changed. These features must be understood before a reactor can be designed which can decompose solids efficiently.

Benefits to Solar Thermal Technology and Other Applications

Decomposition of inorganic solids offers an excellent near-term opportunity for unique solar processes and products. This task will, combined with related tasks, help provide the basis for reactor design and control of product properties.

2.2.2 Principles of Reactor Design for Solids

Task Description

This task begins detailed analysis of reactor design techniques including the inter-relationships among heating rate, optical and thermal properties, reaction temperature and reactor configuration. It will establish the data requirements for particular types of reactants based on analysis and results from Subtask 2.2.1. Because of the many variables affecting these systems, this work will look at minimizing the design data requirements for solids reactors.

Critical Technical Issues

This work addresses the issues in Subtask 2.2.1, primarily by analysis of the chemical and thermal characteristics of reactors containing reactive solids. In addition, the task will address the technology required to handle solids in the presence of a transient heat flux.

Benefits to Solar Thermal Technology and Other Applications

This work will lead to a finer understanding of radiant heat transfer and reaction kinetics. This should allow a broader and more efficient use of radiant heat transfer in both solar and conventional chemical systems.

2.2.3 Photochemical System Analysis

Task Description

This effort studies the costs of implementing photochemical technologies, including the costs of land preparation, distribution of chemicals and so forth. The effort has previously calculated parametric costs of flat-plate chemical systems and of cooled line-focus systems. New work will establish cost and efficiency requirements for dish and central receiver systems.

Critical Technical Issues

Many of the proposed photochemical processes are fundamentally low in efficiency, requiring large amounts of reactor area. The cost of establishing these reactors can be estimated, and is often quite large, even without including actual reactor and reactant costs. This effort scopes the requirements for the performance of photochemical systems to guide the research effort.

Benefits to Solar Thermal Technology and Other Applications

This work complements and guides the research plan for advanced photochemical processes. It will identify opportunities for reducing overall costs, and provide sensitivity analyses for efficiency improvements.

2.2.4 Sulfur-Based Chemical Energy Storage

Task Description

This work will study the cycling of sulfur/sulfuric acid systems for the chemical storage of high-quality solar energy. The work is designed to prove the concept of decomposing sulfuric acid to obtain sulfur dioxide, reacting this gas with water to form sulfur and some sulfuric acid, and, finally, burning the sulfur to produce high-temperature energy and reform the sulfuric acid. The task work is directed at determining the critical characteristics of the formation of sulfur from sulfur dioxide and water, the only unproven step in the proposed method.

Critical Technical Issues

Chemical energy storage offers the potential of low-cost diurnal energy storage as well as the capability of storing energy to level seasonal energy requirements. The sulfur storage method in this task has the potential of producing an inexpensive, storable chemical which, while produced using heat at 870^{o}C, is capable of supplying heat in excess of 1500^{o}C when burned in air. This task will study the major technical problem of the kinetics and thermodynamics of sulfur formation from sulfur dioxide and water.

2.2.5 High Temperature Measurements of Decomposing Solids

Task Description

This work develops measurement methods for determining the rate and temperature of decomposing solids in a high solar flux. The work will establish optical techniques to measure the concentraton of zinc oxide, zinc oxysulfate and zinc sulfate in a radiative furnace.

Critical Technical Issues

The radiant decomposition of solids involves the interaction of the optical, thermal, chemical and physical properties of the reactants and products, and, apparently, is very complex. Global measurements of decomposition rates are not sufficient in characterizing the decomposition rates, partly because extensive recombination of products is expected. In addition, the variation in solar flux requires an excellent understanding of the decomposition behavior since, when reactors are designed and built, they will have to have unusually large turn-down ratios. This task should provide unique and valuable tools to understand the fundamentals of solids decomposition.

Benefits to Solar Thermal Technology and Other Applications

This work will provide new tools for understanding how best to utilize solar thermal technology. It may draw extensively from the technology of furnace diagnostics, bringing this expertise into the Solar Thermal program.

2.2.6 Multistep Fixation of Nitrogen from Air

Task Description

This work examines the production of nitric oxide from air by means other than direct thermal reaction of atmospheric nitrogen and oxygen. The task provides for the analysis of multistep chemical processes which will enable the production of nitric oxide at temperatures below $2000^{o}F$.

Critical Technical Issues

The fixation of nitrogen from air by oxidation is an attractive concept to produce fertilizers since it can, theoretically, use much less energy than conventional processes. These processes fix nitrogen by reducing molecular nitrogen, primarily through the reaction of nitrogen with hydrogen to produce ammonia. The theoretical energy requirements to fix nitrogen by producing nitric oxide from air are only about 25% of the route through ammonia. This cannot be accomplished economically, however, because of the unusually poor thermodynamic and kinetic properties of the oxygen-nitrogen reaction. The basic problem is that temperatures in excess of $5000^{o}F$ are required, and, even at that temperature, the reaction yields are very small.

This task studies multistep reactions which lead to the production of nitric oxide from air through indirect reactions. The task will select a reaction scheme operating at temperatures achievable with the concentrating solar technologies, probably under $2000^{o}F$.

Benefits to Solar Thermal Technology and Other Applications

Fixation of nitrogen with solar energy by oxidation could provide a low-energy route to fertilizers using a feedstock readily available at the solar site. The technology for multistep oxidative methods is speculative at present, possibly requiring fluorine-based chemicals which are difficult to contain. This study will investigate the properties of concentrating solar technology including direct flux and high temperature to drive multistep processses containing very reactive chemicals.

TASK 2.3 ADVANCED SYSTEMS (NOT PART OF THIS AOP)

This element studies the broader issues of interfacing solar technologies with chemical plants at the commercial scale. These issues include site-specific issues such as logistics, field layout, global reactor design, and diurnal and seasonal effects. The goal of the task is to assure that the technical tasks fit into a framework consistent with the capabilities of solar central receiver technology.

2.3.1 Solar Central Receiver Process Design

Task Description

This task provides for the conceptual design of a chemical plant at the 100 MW_{th} scale. The purpose of the study is to identify technical issues associated with reactor design, reactor configuration, energy storage, and process control in large chemical systems.

Critical Technical Issues

This effort assures that solar-driven chemical plants can utilize central receiver technology effectively. The study identifies criteria such as heat flux capabilities of reactors, concentration capabilities of central receivers, and similar items which ultimately determine the efficiency with which the chemical process can use the solar heat.

Benfits to Solar Thermal Technology and Other Applications

The work will guide the selection of chemical equipment and chemical processes which are compatible with central receiver technology. It will also identify features of central receiver technology which might be changed to better fit chemical systems. The overall result will be to assure an efficient matching of solar and chemical process technologies.

TASK 2.4 RESEARCH FACILITY OPERATIONS

2.4.1 Advanced Components Test Facility

Task Description

This task provides for operations and maintenance of the Advanced Components Test Facility (ACTF) at the Georgia Institute of Technology. Work includes support for instrumentation, maintenance, and improvements to the monitoring and measuring capabilities of the facility. Much of this work will support subtask 2.1.1

Critical Technical Issues

Previous work related to subtask 2.1.1 has demonstrated the performance, flexibility and capability of the ACTF for experiments in the 25 to 200 kw range.

Benefits to Solar Thermal Technology and Other Applications

Experience gained under this task adds to the capablity of all solar facilities to conduct unfamiliar chemical operations. Efficient procedures are developed to assess and address potential safety-related issues, to measure experiment performance, to conduct routine and timely startup and shutdown of chemical operations, and to otherwise conduct cost-effective research-level experiments.

D. PROGRAMMATIC INTERFACES (R & AD AND SOLAR FACILITIES)

The success of the Fuels and Chemicals Program requires close cooperation and interfacing among the major centers of solar technology. The major programmatic interfaces include:

(1) DOE/HQ-DOE/SAN

Program policy, priorities and funding are determined by DOE/HQ based on information supplied by DOE/SAN and its technical support. Policy and available funding determine the technical priorities, technical sophistication and schedule for the Solar Technology Project. The balance between work on the experiment and on the technical base is determined by agreement between HQ and SAN, but allocations are suggested at approximately 50% experiment, and 50% technology base-advanced concepts.

(2) FUELS AND CHEMICALS PROGRAM - SOLAR FACILITIES

Extensive technical interfacing is required between the Fuels and Chemicals Program and the CRTF to establish design requirements, facility capability, process capability, scheduling and other factors. Interactions are required over the full developmental period, beginning with tests utilizing thermal storage, continuing with multiple receiver tests, and concluding with a fully integrated System Research Experiment. Experiments at the CRTF will be used partly as the basis for the design of equipment, specification of materials, process control, and sizing of reactors.

Interfaces between the Fuels and Chemicals Program and the ACTF will require extensive planning and scheduling to assure timely operation of experiments using new materials technology with corrosive chemicals at elevated pressure. A smooth interface is critical since these experiments pace the project schedule.

(3) FUELS AND CHEMICALS PROGRAM - ADVANCED DEVELOPMENT PROGRAM

This interface is concerned primarily with reactor materials, chemical energy storage and, potentially, window materials and photolytic processes. A critical issue is the availability of ceramic reactors should metal reactors prove unsuitable for the high temperature process steps. The state of readiness of windowed and photolytic reactions will be continually reviewed.

(4) FUELS AND CHEMICALS PROGRAM - RESEARCH AND ADVANCED DEVELOPMENT PROGRAM

This interface addresses operations from thermal storage, process control, energy management, materials, and new storage and solar capabilities. Interactions will begin immediately relative to tests on utilizing thermal storage for acid concentration, a basic mass transfer process. Design, materials, heat transfer, and other technical features will be established by continuing interfaces between the two programs.

Figure II-1 illustrates examples of the types of interchange of technology required between the Solar Fuels and Chemicals Program and other STT program elements. For example, requirements for thermal storage will depend on evolving storage technology, evolving process technology, reactor design and materials, and a variety of other considerations, many of which are yet to be defined. The design of the chemical plant will be closely integrated with the CRTF. Final design will require tradeoffs of process and solar operating considerations.

Figure II-2 shows the projected use of solar facilities during the lifetime of the Solar Technology Project. The ACTF is utilized for basic high-flux tests involving proof of materials and heat transfer. Testing at the ACTF after 1986 is primarily for advanced concepts, particularly if metal reactors prove unsuitable for large tests. The CRTF is utilized heavily from 1987 on, and for control and integration and acid concentration tests in 1984-1985. These tests will establish operating and control procedures, and verify materials and system efficiency.

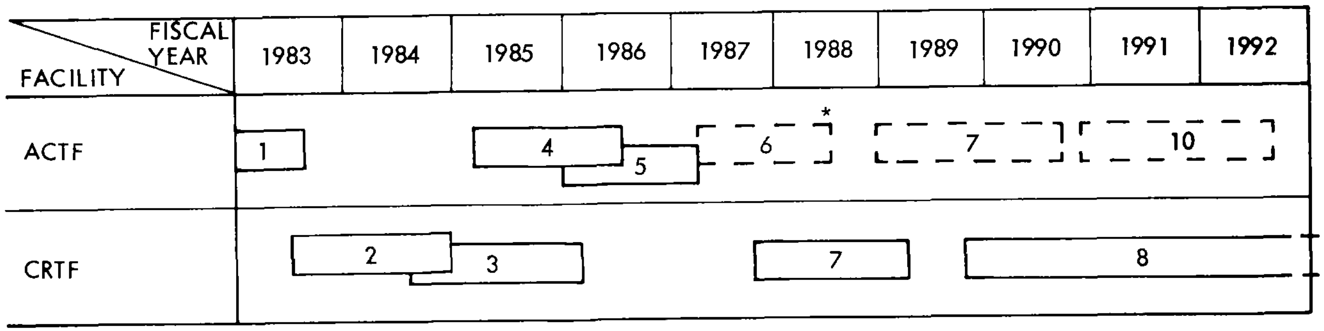
E. PROGRAM JUSTIFICATION

1. PROGRAM THRUST

The Fuels and Chemicals program is a thrust of the Solar Thermal Technology program which expands the uses of solar heat to the chemical process industry. The major technical features which separate this effort from the Solar Electric and Industrial Process Heat include the need to operate at temperatures above $700^{o}C$ ($1300^{o}F$) with chemically active or corrosive materials and at elevated pressure. These features require advanced technology to operate high-temperature chemical reactors in the solar field, to couple the solar-driven reactors with a complex chemical process, to

	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992
FROM STT PROGRAM ELEMENTS TO SOLAR FUELS AND CHEMICALS	• CRTF CHARACTERISTICS • THERMAL STORAGE CHARACTERISTICS	• THERMAL STORAGE SYSTEM DEFINITION • ACTF ACID DECOMPOSER REQUIREMENTS • CORROSION OF MATERIALS	• SiC TECHNOLOGY • WINDOW TECHNOLOGY • ENERGY MANAGEMENT STRATEGY • PROCESS CONTROL STRATEGY • ACID CONC. FROM THERMAL STORAGE	• CHEMICAL ENERGY STORAGE? • HIGH-TEMP THERMAL STORAGE? • SiC REACTOR? • PHOTOLYTIC PROCESSES	• CRTF 5 YEAR COSTS & SCHEDULE • DUAL FIELD OPS AT CRTF • MATERIALS EVALUATION	• ENERGY STORAGE SYSTEM REQUIREMENTS • MIRROR FIELD/PROCESS INTEGRATED ENERGY BALANCE	• CONTRACTING FOR SRE • PROCESS/CRTF CONTROL SPECIFICATIONS	• CONTROL SYSTEM ANALYSIS • REACTOR TESTS • FLUX MAPPING		
SOLAR THERMAL FUELS AND CHEMICALS PROGRAM	• PROCESS DEFINITION • METAL REACTORS • CYCLE ENGINEERING • PROCESS CONTROL THEORY	• SINGLE-TUBE SiC TESTS • PRESSURIZED METAL REACTOR TEST	• PROCESS DESIGN • PRU REACTOR DESIGN • MULTITUBE SiC ACID VAPORIZER • CYCLE ENGINEERING	• PRU VAPORIZER DESIGN	• LOW-TEMPERATURE PROCESSING PRU TESTS	• OPERATE PRU DECOMPOSER/VAP AT CRTF		SRE CONSTRUCTION	SRE INTEGRATION	SRE TEST
TO STT PROGRAM ELEMENTS FROM SOLAR FUELS AND CHEMICALS	• THERMAL STORAGE REQUIREMENTS • SOLIDS DECOMPOSITION TECHNOLOGY	• MATERIALS DEFINITION • SiC JOINING TECHNOLOGY	• LOW-TEMP SiC TECHNOLOGY • PRELIMINARY PROCESS DESIGN • METAL REACTOR VERIFICATION	• CERAMIC VAPORIZER VERIFICATION • RPU DECOMPOSER/VAPORIZER DESIGN (SiC?) • MATERIALS DESIGN • ENERGY STORAGE REQUIREMENTS	• PROCESS EFFICIENCY ESTIMATE • MIRROR FIELD PATTERN DEFINITION • PROCESS REVISIONS	• FINAL DESIGN SRE • CONSTRUCTION SCHEDULE • SYSTEM ANALYSIS	• INTEGRATION SCHEDULE • FINAL PROCESS MODIFICATIONS	• TEST SCHEDULE • VERY HIGH TEMP. PROCESS DEFINITION		

Figure II-1. Examples of Interchange of Technology Between Fuels/Chemicals and Other Solar Thermal Program Elements



1. LOW PRESSURE ACID DECOMPOSER TESTS
2. SINGLE TUBE SiC VAPORIZER TESTS
3. ACID CONCENTRATION WITH THERMAL STORAGE
4. HIGH PRESSURE AND DECOMPOSER TESTS
5. MULTIPLE TUBE SiC VAPORIZER TESTS
6. SOLIDS DECOMPOSITION TEST
7. DUAL FIELD ACID VAPORIZATION/DECOMPOSER PRU TESTS
8. SRE CONSTRUCTION, INTEGRATION, TEST
9. SiC REACTORS
10. PHOTOLYTIC REACTORS

* ADVANCED CONCEPTS

Figure II-2. Test Bed Requirements for Solar Technology Project Subsystems at Solar Thermal Facilities efficiently ingegrate central receiver technology with chemical processes, and generally, to establish the technical foundation for operating chemical plants with the unsteady, radiant heat source.

The program focuses on moving through the technical stages toward the production of hydrogen from water by means of multistep chemical processes. This forces the development of several technologies and forces a more intimate characterization of others. The need for high-pressure reactors for decomposing sulfuric acid drives the technology of catalytic reactors operating from 700° to $900^{\circ}C$ (1300 to $1650^{\circ}F$) in the solar environment. This will require tests to determine the suitability of metal reactors, and, possibly, the need for windowed or ceramic reactors in that temperature range.

The need to vaporize extremely corrosive sulfuric acid drives the technology for lower-temperature ceramic heat exchangers. This takes advantage of Solar I technology in design for boiler efficiency and stability, and extends the usefulness of the technology to a range of corrosive and erosive chemicals.

Thermochemical hydrogen processes are typical of most chemical processes in their complexity and their need for careful process integration. The ability of central receiver technology to supply heat at different levels will allow simplification of the chemical process, reduce the costs of internal heat recovery, and reduce the thermal load at the high-temperature reactor. The need for large amount of heat at lower temperature levels allows extensive and efficient use of thermal storage in the range of current molten salt technology.

The technology for utilization of thermal storage will be extended by coupling storage with non-linear process operations such as distillation and evaporation. This will require extensive characterization of the thermal and control aspects of operations from storage.

The justification for focusing the program by means of a hydrogen project is based in part on the usefulness, the growing market, and the versatility of hydrogen. The technology of producing hydrogen from water follows basic thermo-dynamic laws similar to those of producing electricity. The efficiency of such a process is controlled largely by second law effects, and large improvements in process efficiency which might make the high-temperature technology obsolete are unlikely.

2. HYDROGEN MARKETS AND USES

Hydrogen is a basic element of many fuels and chemicals. Figure II-3 illustrates many uses in the chemical industry, in the utilities, and in transportation. The projected market for hyrogen in the year 2000 is from 5 to 20 Quads based on various projections. Large amounts of hydrogen will be required in the conversion of heavy oils, coal and oil shale to distillate fuels. The production of hydrogen from water and solar energy would, of course, not contribute to the atmospheric buildup of CO_2.

3. SOLAR HYDROGEN PROCESSES

Preliminary analysis, based on DOE cost goals for solar technology, indicate that solar-driven hydrogen processes have more favorable economic perspective in the long run than other processes using fossil fuels as the energy source. This is because of higher escalation rates for fossil fuels than for material and equipment. This trend is expected to follow over the next 50 years because of decreasing supply of natural gas and oil.

Thermochemical processes for the production of hydrogen from water may be particularly effective means for utilizing solar technology. They produce hydrogen efficiently, they use solar heat at an attractive temperature range, and they match the heat load of central receiver systems. Improvements in central receiver technology can be incorporated into thermochemical processes in many ways. For example, very high temperature capability can be used to simplify process steps. Improved thermal storage or development of chemical storage can be used directly to smooth processing and assure constant plant output. Thermochemical processes inherit economies of scale as the size of the plant increases.

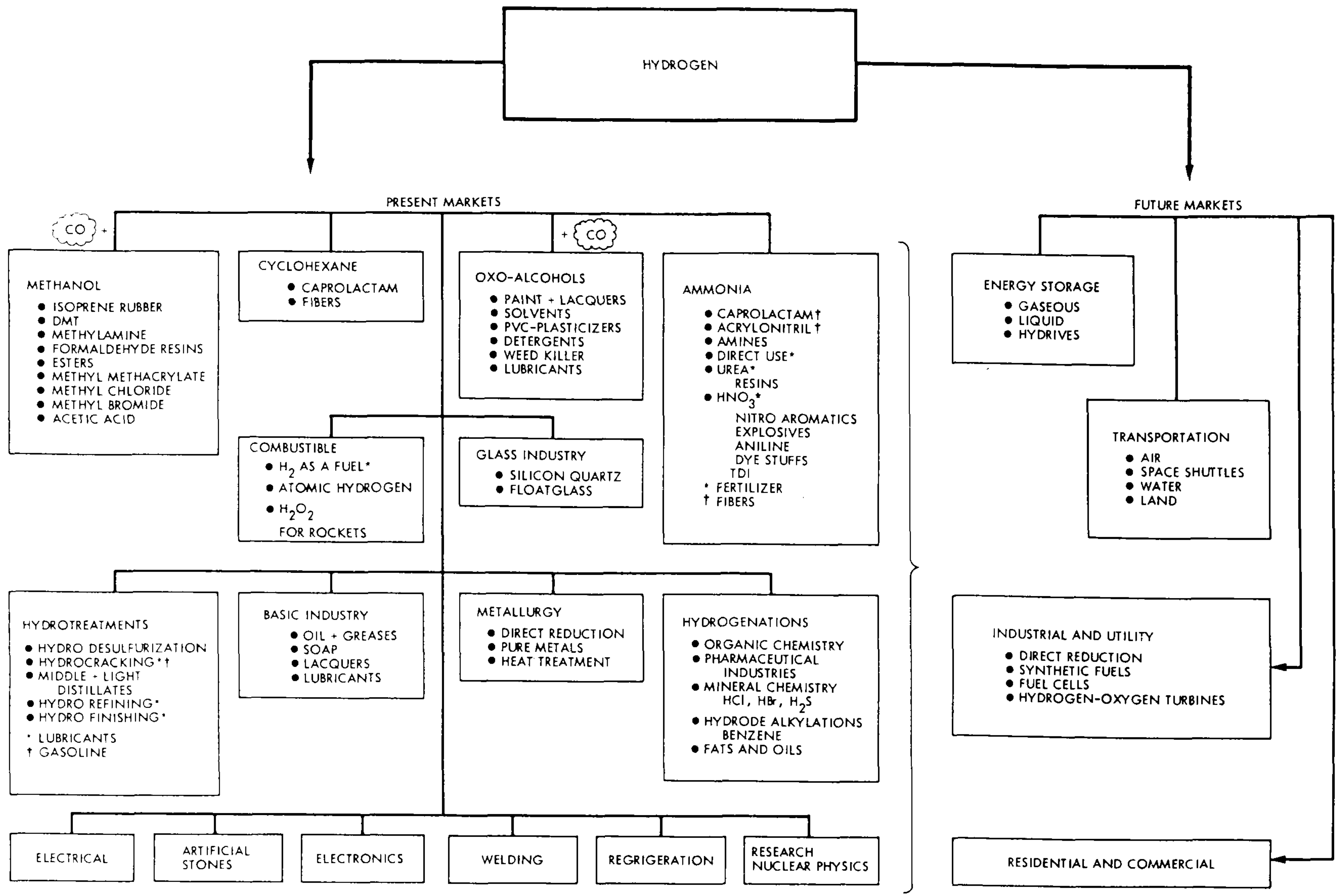


Figure II-3. Examples of Interchange of Technology Between Fuels/Chemicals and Other Solar Thermal Program Elements

F. PROGRAM IN RELATION TO NON-PROGRAM GROUPS

The overall STT program has been reviewed by several groups including the Solar Energy Industry Association (SEIA) and a review panel of the American Solar Energy Society (ASES). The Fuels and Chemicals program is consistent with the recommendations of the SEIA which include:

- Production of liquid and gaseous fuels
- Production of chemicals with special emphasis on reduction of costs

In addition, the (ASES) recommended:

- continued exploration of water splitting cycles to improve cycle efficiency and lower temperature requirements
- that the solar energy supply be integrated into the process rather than just used to substitute for conventional sources
- increased consideration should be given to capitalizing on unique characteristics of solar thermal energy, in particular,
  - non-contaminating energy
  - high thermodynamic quality
  - high flux
  - capability to drive quantum processes

From an international viewpoint, the production of hydrogen by thermochemical cycles has been under study for several years by organizations including Euratom (Ispra, Italy), the Nuclear Research Center (Juelich, West Germany), the University of Tokyo, and private companies in the U.S. A general consensus of these organizations is that the technology based on sulfuric acid is attractive, and that the iodine cycle chemistry is the most advanced of the various closure options. Major work independent of D.O.E.-sponsored work is at Euratom where a pilot-scale acid decomposition apparatus will be tested in 1983, and at the Nuclear Research Center where studies are being conducted on electrolysis of sulfur dioxide for cycle closure. These activities are directed at potential applications for nuclear heat mainly. Only recently, IEA has begun a feasibility study to identify fuels and chemical production research at CRS plant, Almeria, Spain, via steam reforming of methane in a solar receiver. In that there is a great deal of coorperation among the international and U.S. laboratories (through the International Energy Agency), a great deal of technical data can be obtained to support development of the Solar Fuels and Chemicals technology base.

SECTION III

MANAGEMENT APPROACH

A. PROGRAM MANAGEMENT STRUCTURE

The activities of the Department of Energy Solar Thermal Technology (STT) Division are divided into branches for (1) Technology, (2) Systems Test, and Evaluation. The Technology branch activities, in turn, are subdivided into Applied Technology and Advanced Research and Development Programs. Figure III-1 shows the management structure and the organizational responsibilities and the relationship of Solar Fuels and Chemicals Program in relation to other DOE/SAN program elements. DOE/HQ management will be responsible for the policy formation, overall management including establishment of guidelines and priorities for research and program budget allocations. The San Francisco Operations Office, DOE/SAN, has the field management responsibility for the Solar Fuels and Chemicals and the Advanced Development Program elements.

DOE/SAN, as field manager, will provide the overall program management, and control of these elements including control of the major interfaces with other related DOE activities. Technical management and analysis support on the Solar Fuels and Chemicals program will be provided by Sandia-Livermore (Solar Technology Experiment Advanced Systems), and SERI (Advanced Concepts, Research Facility Operations). DOE/SAN will provide for the transition of technical management responsibilities from JPL, now phasing out of the program.

B. PROGRAM CONTROL

Overall program control involving formation of policy, budgets, and research priorities will be provided by DOE/HQ management to ensure program activities are consistent with department directives and overall STT program goals and objectives. DOE/SAN will coordinate with DOE/HQ Technology branch on program plans, budget allocations, procurements, interfaces, and progress of program activities. SAN will obtain necessary concurrence and approvals as required through verbal and written communications and through reporting mechanisms outlined below.

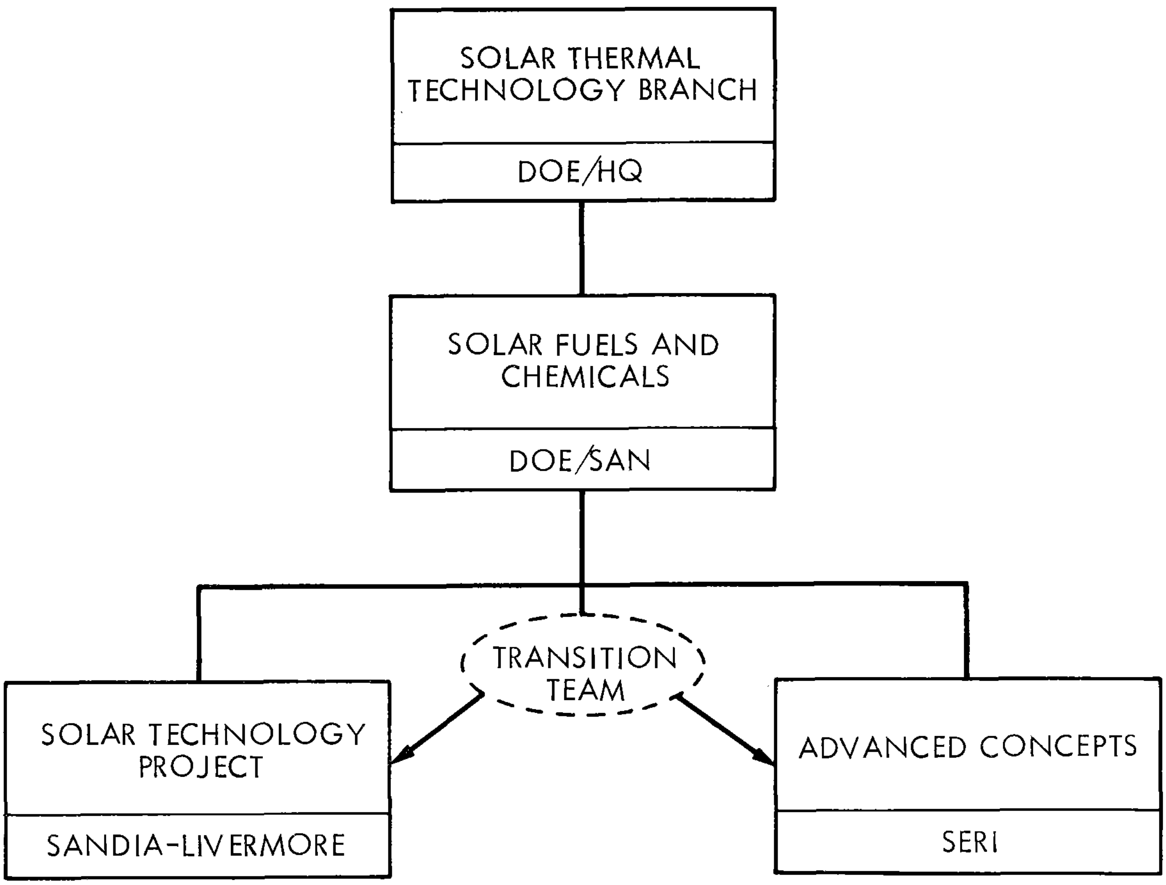


Figure III-1. DOE/SAN Field Management Program Structure

C. PROGRAM COORDINATION

DOE/SAN will hold regularly-scheduled meetings to coordinate Fuels and Chemicals activities with the Materials program (primarily at SERI and its contractors), and with the Central Receiver program (primarily at Sandia-Livermore and its contractors. Meetings will be held quarterly to ensure timely interfacing of the programs. In addition, technical seminars will be held from time to time to discuss developments, technical prospects, or newly-perceived problems or needs.

D. REPORTING

The progress, accomplishments, and plans for various subtasks and program activities will be reported and reviewed through the following activities and reporting mechanisms:

REVIEWS AND PROGRESS

- Weekly Highlights of Accomplishments and Plans
- Monthly Progress Reports
- Quarterly and Special Reviews for SAN and HQ
- Special Workshops and Meetings

PROGRAM DOCUMENTS

- Program Plans and Updates
- Topical Reports and Papers
- Annual Reports
  - Technical Progress Summary
  - Annual Operating Plan

SECTION IV

RESOURCES

This section presents the resources required to implement the Solar Fuels and Chemicals program. The development path, the level of impact on industry, and the rate of program progress will be dependent upon the level and timing of the program budget. The resource estimates are based on accelerating the Solar Technology Project, moving the process technology from bench level toward subsystem test and development of the mainstream technology base.

A. BUDGET SUMMARY

The five-year budget projections for the Solar Fuels and Chemicals program are presented in Table IV-1.

B. MANPOWER

SAN manpower requirements are not funded through this AOP. Technical management manpower is estimated to be 2.5 FTEs or less.

C. FY 83-84 FUNDING BREAKDOWN

Table IV-2 presents the breakdown of budget for FY84 based on the program plan.

Table IV-1. Solar Fuels and Chemicals Program Resources

(millions of dollars)

FY83	FY84	FY85	FY86
1.7	1.7	3.6	5.0

Table IV-2. Solar Fuels and Chemicals FY'84 Budget Requirements

I. The tasks in this category are deemed critical to the development of a Fuels and Chemical Program

	Task Costs ($K)	Summary Costs ($K)
• SOLAR TECHNOLOGY PROJECT		
- High Pressure Catalytic Reactor	400	400
- Solar Thermochemical Process Design	FY83	-
- Ceramic Heat Exchangers	FY83	-
- Process Control Fundamentals	110	550
- Interface Options for Chemical Processes	100	650
• R&T/ADVANCED CONCEPTS		
- Radiant Decomposition of Inorganic Solids	75	725
- Principles of Solar Reactor Design for Solids	100	825
* - Photochemical System Analysis	35	860
- Sulfur Based Chemical Energy Storage	100	960
- High Temperature Measurements of Decomposing Solids	175	1135
- Multistep Fixation of Nitrogen from Air	50	1185
* * • ADVANCED SYSTEMS		
- Solar Central Receiver Chemical Process Design	-	
• RESEARCH FACILITY OPERATIONS		
- Advanced Components Test Facility	250	1435
• PROJECT TECHNICAL SUPPORT	265	1700

PROGRAM TOTAL $\$1.7 \times 10^6$

* Extensive Photochemical Research Conducted at SERI, Not in this AOP
* * RFP Out of Sandia Livermore, Not in this AOP

SECTION V

FY84 OBJECTIVES AND SCHEDULES

The major FY84 objectives, milestones, schedule of activities, and deliverables for the Solar Fuels and Chemicals program are given in Figure V-1 based on current plans and timely resource allocations.

A. *FY84 MILESTONES

- Solar Thermochemical Process Design Complete Nov 83
- Direct Flux Reactor Study Complete Nov 83
- Final Design, Pressurized Reactor Jan 84
- Feasibility Report, Metallic Reactors Feb 84
- Feasibility Reports, Advanced Concepts July / Aug 84
- Pretest Review Pressurized Reactor Aug 84
- Solar Reactor Design Criteria Review Sept 84

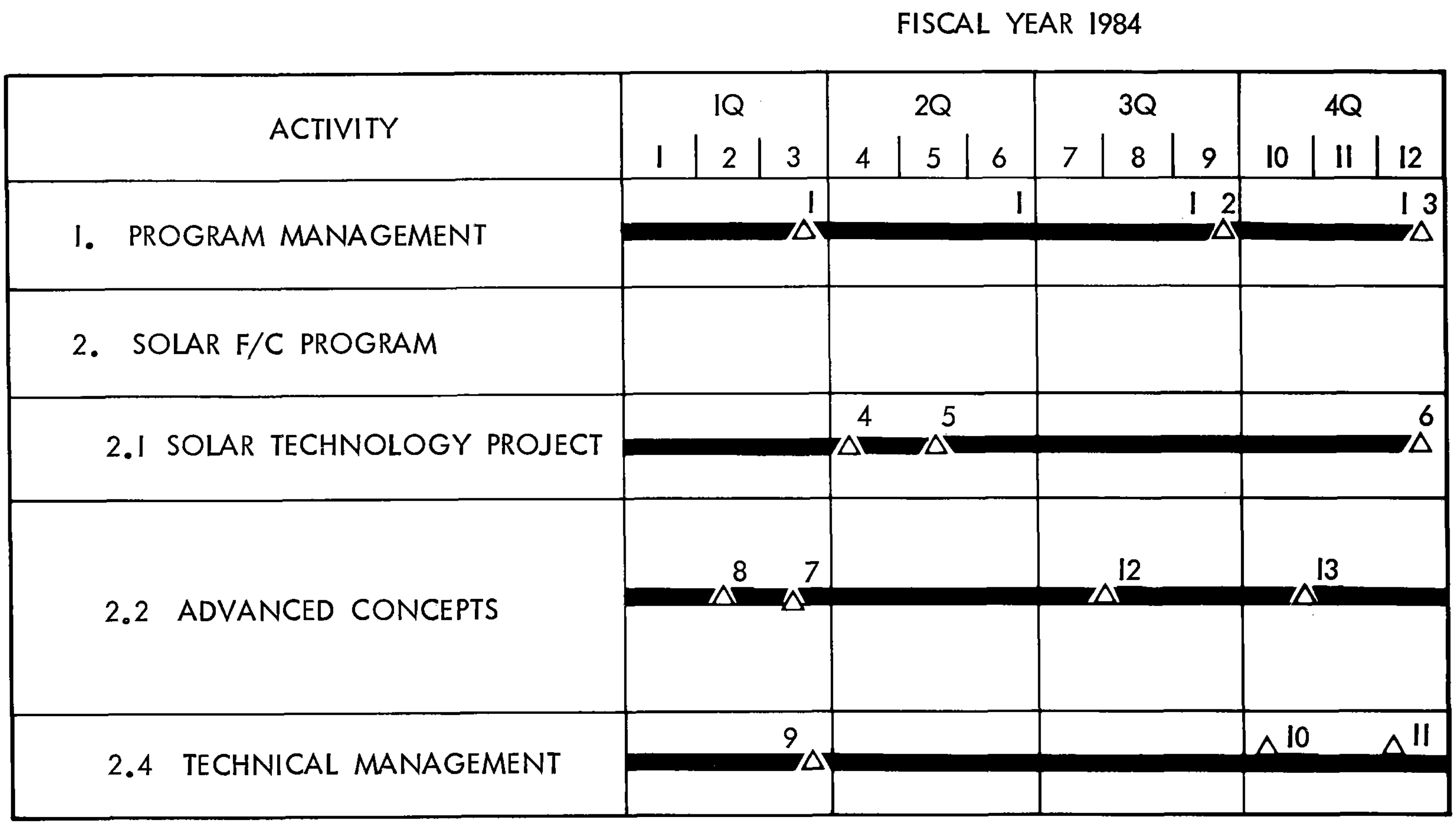
B. MILESTONE SCHEDULE CHART

The schedule of important program activities and major milestones for the Solar Fuels and Chemicals program element are shown in Figure V-1.

C. DOCUMENTATION DELIVERABLES

- Monthly Progress Reports
- Quarterly Review Briefing Charts

All Dates Read as Fiscal Year



1. SAN AND HQ QUARTERLY REVIEWS
2. VALIDATION OF BASELINE TECHNOLOGY PROJECT
3. AOPs, PROGRAM ANNUAL REPORTS, PLANS
4. DESIGN REVIEW OF PRESSURIZED REACTOR
5. SOLAR PROCESS DESIGN REVIEW
6. VERTICAL SiC TUBE EXPERIMENT AT CRTF
7. INITIATE PHOTOCHEMICAL PLAN
8. DIRECT FLUX REACTOR STUDY COMPLETE
9. COMPLETE FY 84 CONTRACT SOWs
10. PRE SOLAR TEST REVIEW
11. SOLAR REACTOR DESIGN CRITERIA REVIEW
12. FEASIBILITY REPORT, SOLIDS DECOMPOSITION
13. FEASIBILITY REPORT, PHOTOCHEMICAL SYSTEMS

Figure V-1. Solar Fuels and Chemicals Program FY 84 Milestones

- Annual Reports
  - Annual Technical Progress Summary
  - Program Plan Update
  - FY83 and FY84 Annual Operating Plans

- Topical and Study Reports
  - Candidate T/C Process Study Report
  - Photon Driven Process Study Plan
  - Chemical Energy Storage Report
  - Solids Decomposition Experiment Report
  - Catalytic Reactor Experiment Report
  - Direct Flux Study Report
  - Systems Application Analysis Report
  - Other Topical Reports

SECTION VI

PROCUREMENT PLAN

A. PROCUREMENT STRATEGY

Because of the highly advanced nature of research in this program procurement will emphasize procurement of specialized expertise and talent. Wherever possible the procurements will be competitive.

B. PROCUREMENT PLAN

DOE/SAN will contract, for technical program support as needed. It is anticipated that SAN will procure major contracts on subtasks through directed, competitive solicitation, and sole source procurements. Small subcontracts for research experiments, and other systems and technology analysis and evaluation tasks will be let through SAN, SERI or SNLL as requested by SAN.

The proposed procurements are presented in Table VI-I.

Table VI-1. FY'84 Procurement Summary

Task	Contractor
o SOLAR TECHNOLOGY PROJECT	
- High Pressure Catalytic Reactor	GA Technologies
- Solar Thermochemical Process Design	Foster Wheeler
- Ceramic Heat Exchangers	Garret Corporation
- Process Control Fundamentals	University, TBD
- Solar Test ACTF	Georgia Inst Technology
- Interface Options for Chemical Processes	Westinghouse
o R&T/ADVANCED CONCEPTS	
- Radiant Decomposition of Inorganic Solids	University Hawaii
- Principles of Solar Reactor Design for Solids	University, Houston
* - Photochemical System Analysis	University, TBD
- Sulfur Based Chemical Energy Storage	GA Technologies
- High Temperature Measurements of Decomposing Solids	National Laboratory
- Multistep Fixation of Nitrogen from Air	University, TBD
* * o ADVANCED SYSTEMS	
- Solar Central Receiver Chemical Process Design	Sandia Livermore RFP Competitive
o RESEARCH FACILITY OPERATIONS	
- Advanced Components Test Facility	ACTF
o Project Technical Support	TBD