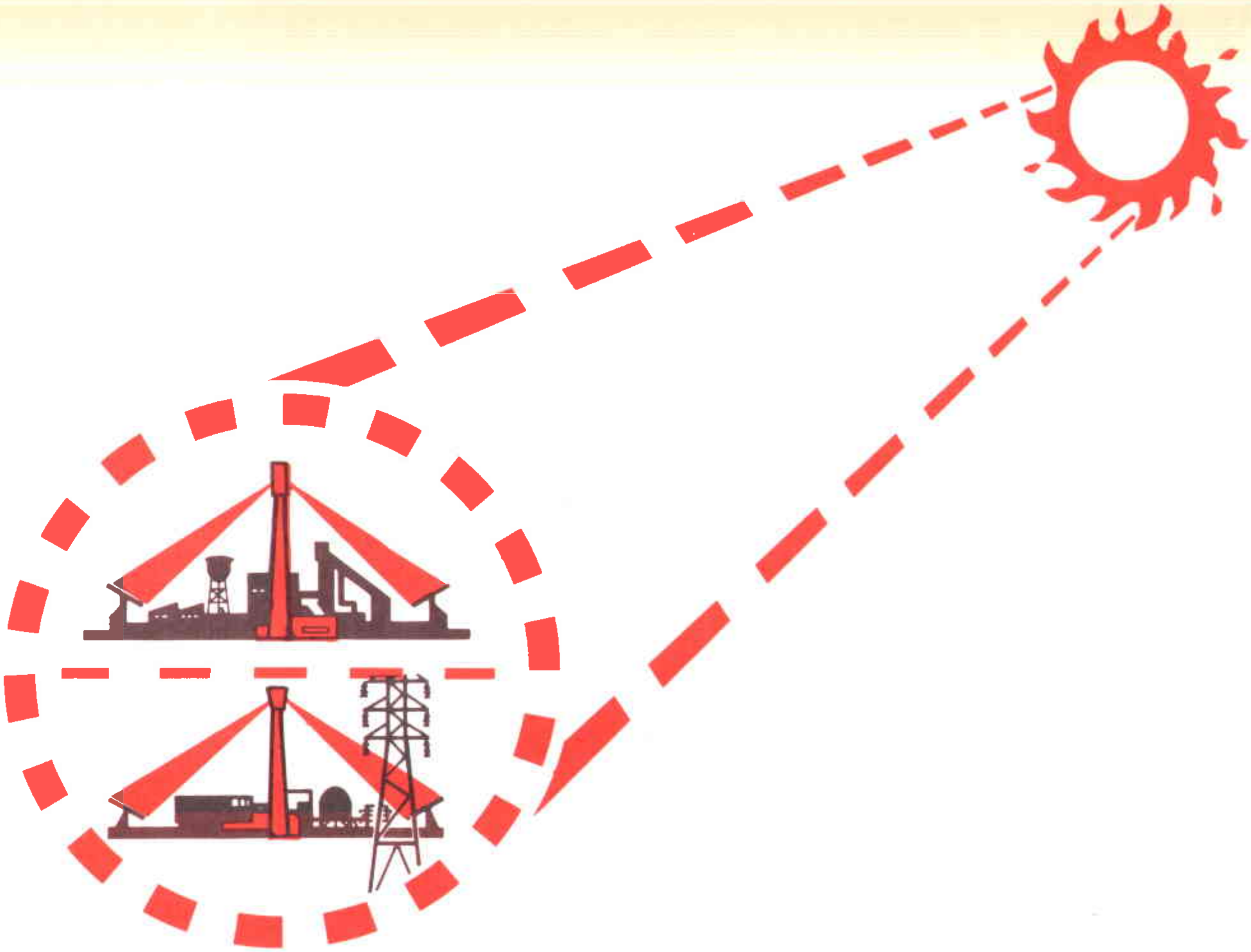
SOLAR FUELS AND CHEMICALS

Annual Operating Plan
Fiscal Year 1983



U.S. DEPARTMENT OF ENERGY

San Francisco
Operations
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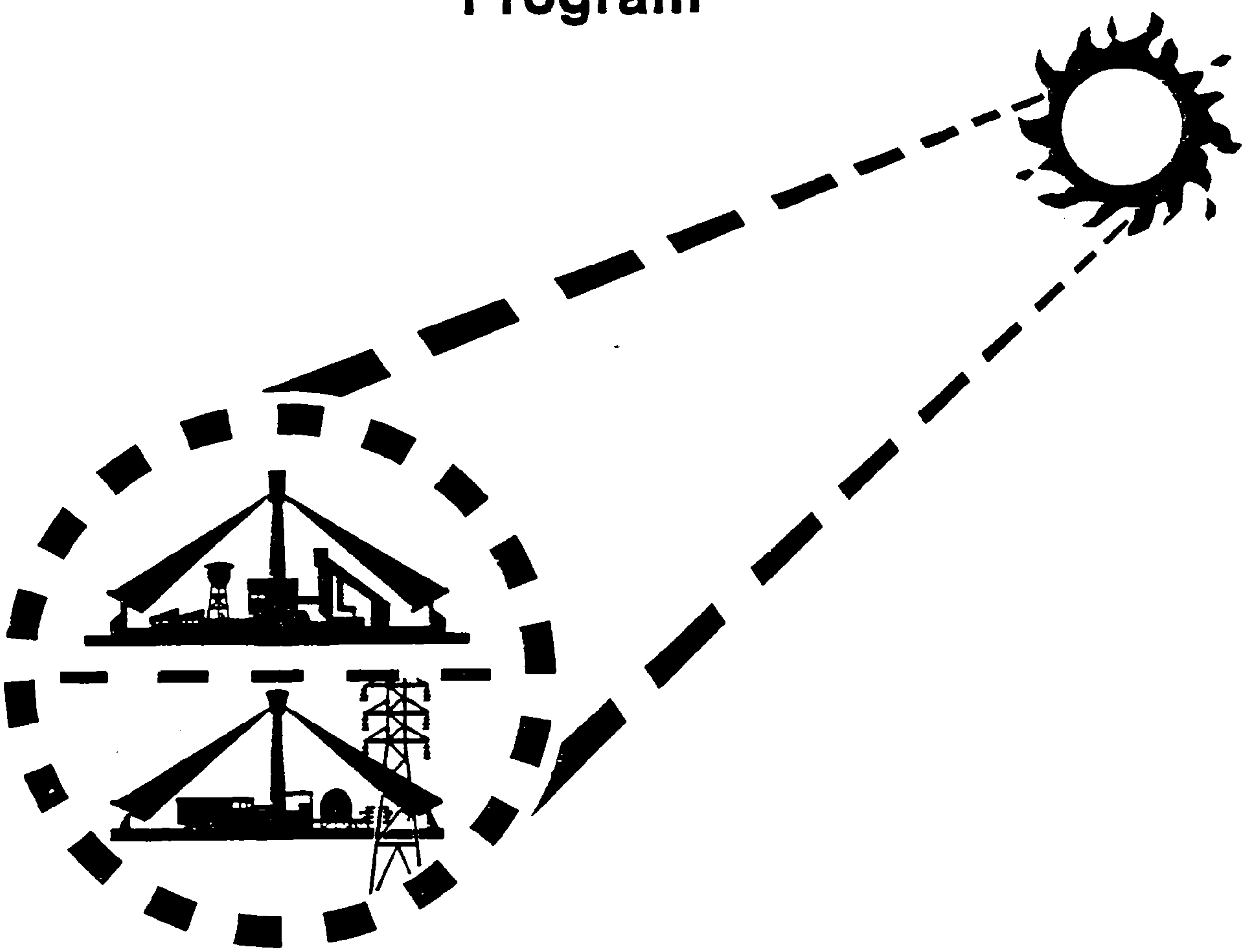
Annual Operating Plan
Fiscal Year 1983
Solar Fuels and Chemicals Program



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EXECUTIVE SUMMARY

This AOP presents the goals, objectives, justification and technical plan for a Solar Thermal Fuels and Chemical Program. This new major thrust is complementary to, and synergistic with, the other Solar Thermal programmatic elements of electric production and industrial process heat.

This program has two major elements. The first is a Solar Hydrogen Project. Following technical and economic analysis, this project was selected to focus and force the development of the technical base toward production of hydrogen via solar water splitting technology. The strategy is to use the project 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. A ten-year developmental plan is described. The effort will culminate in a large scale System Research Experiment (SRE) that will produce solar hydrogen at a rate of 2500-3000 liters/minute.

The second program element is Technology Development. A strategy is described that provides a management structure to evaluate, prioritize and develop those critical elements of the underlying technology that will be required to carry out the Solar Hydrogen Project within a solar field. Additionally, solar unique qualities such as high temperature, high flux and heating rates, and photolytic properties will be investigated as part of this effort. Where technically feasible, solar unique subsystems will be substituted into the Solar Hydrogen Project. Special attention will be paid to expanding the technology base to optimise interim industrial applications.

SECTION I

GOALS, OBJECTIVES, AND STRATEGY

A. INTRODUCTION

This document presents the FY83 Annual Operating Plan (AOP) for the Solar Fuels and Chemicals Program. In structuring the program, advantage was taken of the results of previous program activities, feedback from industry and research organizations, direct study contracts, and a thorough review of technical issues and market data on hydrogen and other fuels and chemicals. These results were incorporated into the present plan.

The plan provides an accelerated thrust aimed at proving the applicability of solar thermal technology to the production fuels and chemicals. The effort moves through a series of bench level and subsystem tests, ending in a technologically significant System Research Experiment (SRE) at the Central Receiver Test Facility (CRTF) in 1992.

The plan institutes a project to produce hydrogen using solar heat at temperatures from 700-900°C (1300-1640°F). A multistep chemical process is used to decompose water to produce hydrogen and oxygen. The baseline cycle, is a water-splitting process based on the decomposition of sulfuric acid as the major energy input. This process was chosen as the baseline for the chemical operations because it is well-defined, contains considerable flexibility to incorporate process improvements, is thermodynamically attractive, and interfaces efficiently with a solar heat source capable of multiple thermal inputs. A description of the process is given in Section I-D.

The Solar Hydrogen Project is structured to capitalize on the capability of the CRTF to supply solar radiation to multiple receivers and reactors. Under this concept, a high-temperature catalytic reactor decomposes sulfuric acid while an intermediate receiver continuously supplies vapor to the decomposer. All other chemical steps are driven from molten salt thermal storage supplied by a third receiver at 540°C (1000°F).

The basic assumption underlying the structure of the Solar Hydrogen Project is that the elements comprising the project are technically feasible and can be successfully engineered into the SRE by 1992. An additional assumption is that development of the SRE will reveal the primary solar engineering and interface problems one would encounter for range of fuels and chemical processes. The program is structured in such a way that improved or solar unique developments, emanating from the technology base or other Solar Thermal Program elements, can be incorporated into the project prior to final SRE design.

Development of the underlying technology base is the other programmatic thrust contained in this AOP. The strategy for the Technology Development is contained in Section IE. In essence, it focuses on developing the critical elements that will be required to carry out a range of chemical processes with a solar source. During the course of development, emphasis will be on supporting those technologies essential to achieving Hydrogen Project milestones and schedules. Importance will be placed on developing technology that incorporates solar unique qualities such as high temperature, high flux and heating rates, and photolytic properties. As feasibility is demonstrated, these elements will be moved into the Hydrogen Project mainstream for potential substitution into the baseline cycle.

B. PROGRAM POLICY AND PROGRAM STRATEGY

1. PROGRAM POLICY

Program policy is viewed as those considerations that affect program planning and direction. Other than the normal Solar Thermal policy guidelines and directives, the following statements are considered formative policy for the Fuels and Chemicals Program.

- The program must contain technical elements that will demonstrate advances in solar thermal technologies. These elements should contain significant technological challenge.
- The program must select a justifiable 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.
- Solar central receiver facilities will be used for all Process Research Unit (PRU) subsystems and System Research Experiments (SRE's).
- Research activities critical to achievement of project milestones and schedules will be conducted as part of the project.

2. PROGRAM STRATEGY

The program strategy is derived from the above policy and an evaluation of the state of related solar and chemical process technology. The overall strategy is to implement a significant demonstration of Solar Fuels and Chemical technology at the CRTF in 10 years. Underlying this is that the related technologies are moving quickly, and that the final SRE must prove updated szate-of-the-art technology in the 1990-1992 time frame. The program strategy guides;

- a major project to drive the fundamental solar engineering technology
- a substantial and continuing effort to expand the technical base for Fuels and Chemicals and to seek solar unique subsystems

- an active involvement in related technological developments including energy storage, materials, process control and instrumentation
- flexibility in modifying the project to make use of technical developments from other segments of the Solar Thermal Program elements.

To implement this strategy, the program management will

- Analyze the major technical challenges associated with operating fuel and chemical processes with a solar source.
- Identify the technical characteristics a project should contain to respond to the technical challenges. Analyze fall back options to assure that the project can achieve goals through a brute force technical approach if necessary.
- Select an appropriate baseline project as a target to focus planning activities. Identify major and critical technologies, developmental horizons, technical risks and funding requirements.
- Structure, plan and implement the project. Establish a ten (10) year developmental time frame to force technology development. Reassess technical risk.
- Conduct a sufficient number of small scale laboratory and solar facility tests to resolve technical uncertainties, optimize process steps and validate concepts.
- Identify the underlying technology base and describe the technical interfaces required to assure achievement of project milestones and schedules.
- Develop the technical and management structure required to analyze and prioritize development of the technology base, and implement an orderly systematic development.
- Identify the technological options for developing solar unique components and subsystems (see Figure I-1 as example). Develop management plan.

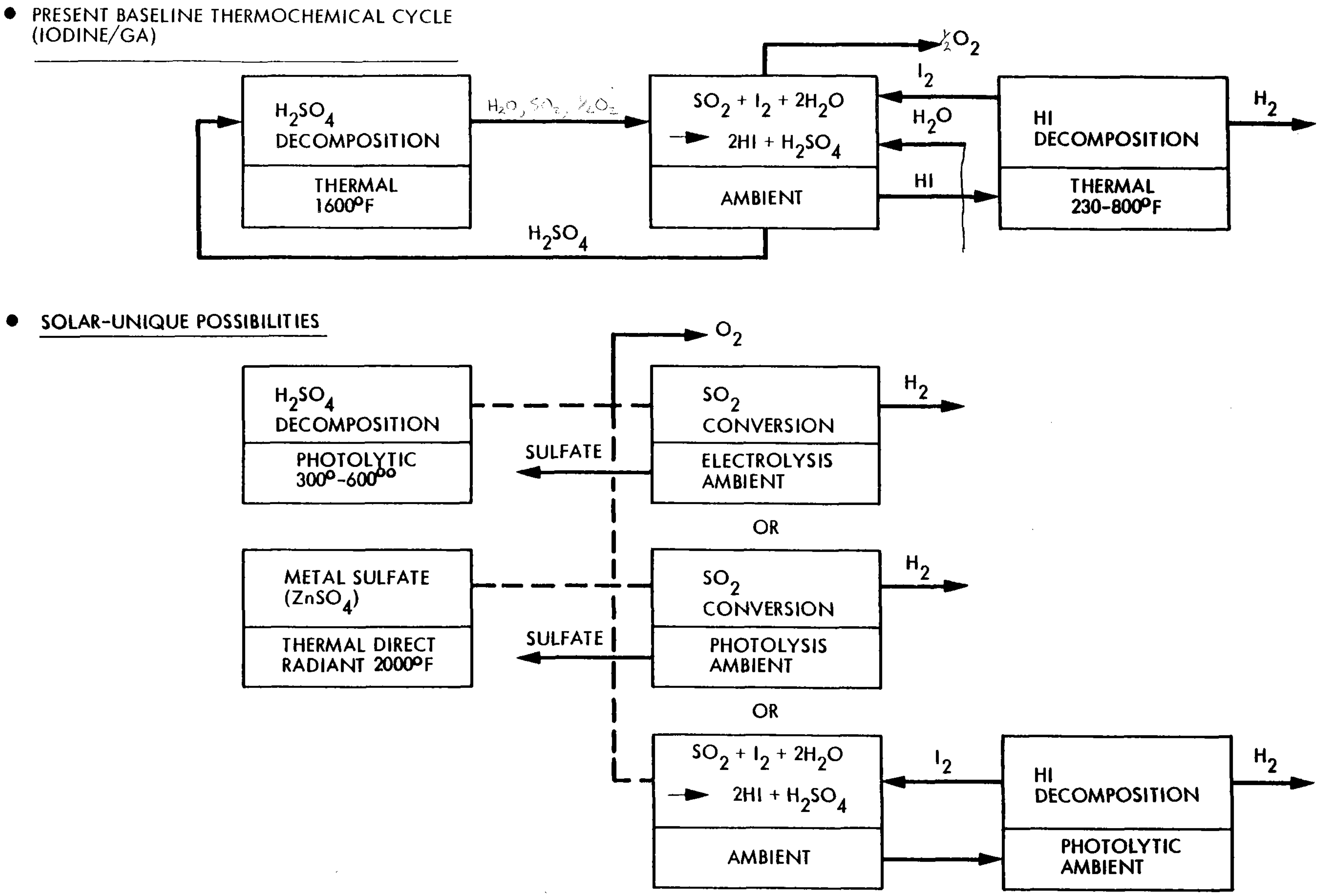

Figure I-1. Theoretical Example of Solar Unique Water-Splitting Cycle

- Conduct periodic technical and economic analyses to provide data to management to update technical and management approach.

C. PROGRAM OBJECTIVES

The primary objective of the Solar Fuels and Chemicals Program is a long term, systematic development of the technology base required for the production of fuels and chemical utilizing solar energy. This development will be focused and accelerated through development of a Solar Hydrogen Project emphasizing hydrogen production by means of thermochemical water splitting. A large scale System Research Experiment will be conducted, at the CRTF in 1992, as proof of concept of the adequacy of the technology base and a validation of efficient and economical solar hydrogen production. To achieve this objective the following major technical objectives need to be accomplished;

- Validation of the baseline thermochemical cycle and identification of promising solar unique unit operations by the end of FY 1983.
- Determination of the temperature/pressure limits of metal reactors in the solar environment.
- Development of ceramic reactors for service with corrosive and erosive materials in a solar environment.
- Completion of the tests at a Solar Test Facility for successful demonstration of the material compatibility for acid vaporization and decomposition by the end of FY 1987.
- Operation of integrated chemical reactors within the solar environment.
- Utilization of multiple receiver operations at varying temperatures and flux levels. Development of the multiple receiver interface.
- Establishment of process control theories, methods and procedures for operations with solar heat and from thermal storage.
- Completed development of the underlying technology base required to conduct an integrated chemical process within the solar environment.

- Completion of the process integration and a large scale System Research Experiment at the CRTF by the end of FY 1992. The goal of the SRE is the production of 2500-3000 liters/minute of hydrogen.

D. TECHNICAL STATUS AND PRIORITIES

1. TECHNICAL STATUS

The baseline thermochemical cycle selected as the basis for planning is the sulfuric acid-iodine cycle. The cycle consists of three major reactions together with a variety of concentration separation and purification operations. The reactions include; (1) decomposition of sulfuric acid at high temperature,

$$H_2SO_4(\ell) \xrightarrow{1300° - 1650°F} SO_2 + H_2O + \frac{1}{2} O_2,$$

(2) the reaction of the resulting sulfur dioxide with iodine and water to reform sulfuric acid and to make hydrogen iodide,

$$SO_2 + I_2 + 2H_2O \xrightarrow{250°F} H_2SO_4 + 2HI,$$

and (3) the decomposition of hydrogen iodide to reform the iodine and to produce hydrogen

$$2HI \xrightarrow{400°F} I_2 + H_2.$$

The sum of these three reactions results in the decomposition of water

$$H_2O \longrightarrow H_2 + \frac{1}{2} O_2$$

with an optimal temperature of about 1500°F.

This process has been demonstrated on a bench scale and is considered the most technically advanced and theoretically the most easily scaleable of the thermochemical cycles. The high-temperature part of the process is common to several other promising cycles, and as such, has great transferability and broadens the technical base for the program. Since the cycle circulates only gases and liquids, it can be operated at elevated pressure, an engineering advantage.

The major factors involved in selecting the baseline process are described in Tables I-1 and I-2. While the technical feasibility is established, major technical challenges remain, primarily in the interfacing with the solar source. These include:

- Optimization of the acid decomposition cycle to establish subsystem specifications, equipment sizing, and containment materials.
- The effects of high temperature cycling on engineering materials of interest in a solar-hydrogen facility including metallic and ceramic materials.
- Transient heat and mass transfer effects typical of a solar hydrogen plant.
- Controls and instrumentation necessary for measurement, data acquisition, and safe operation at the subscale plant level.
- Mechanical and material design including thermal stresses, stress relief, and stability at elevated temperature cycling, corrosion, and protection.
- Complete solarization of the thermochemical cycle and subsystems interfacing. Technical, economic, and environmental aspects of direct process operation versus operation from a thermal energy storage such as molten salt or metal.
- Design data for heat transfer rates.
- Catalyst stability under thermal cycling.
- Solar reactor designs, window materials, thermal inertia requirements, operating strategies and economics of manufacturing techniques.
- Startup and shutdown procedures.

2. PRIORITIES

In order to implement and manage a successful effort to accomplish the stated objectives, the following FY'83 priorities have been established.

Table I-1. Thermochemical Cycles/Sulfuric Acid Cycle as Baseline (Key Technical Problems and Interfaces with Solar Energy)

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

Table I-2. Thermochemical Cycles/Sulfuric Acid Cycle as Baseline (Key Technical Problems and Interfaces with Solar Energy) (Continued)

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
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

Brief subelements are presented for information purposes. Details are presented in Section IIC, Task Descriptions. Due to developmental lead times and the interrelationships of specific tasks, the following work is considered the absolute minimum that has to be undertaken this year to stay within the schedule and plan for the SRE in 1992.

- Pressurized Metal Reactor
  - Sulfuric acid (H_2SO_4) decomposition at both atmospheric and high pressure (10 atm) at 700°C and above in metallic and ceramic reactors. Metallic reactors are simple in design and fabrication. If successful, the metallic reactor can mean lower plant cost because of readily available material and fabrication techniques.
  - Validation of catalyst stability and support structure.
  - Experiments to be conducted at Solar Test Facilities.
- Vertical Tube Ceramic Heat Exchanger
  - Boiling of concentrated sulfuric acid requirement to circumvent corrosion, ceramic heat exchanger tubes are to be developed and demonstrated, including cementing.
  - Experiments to be conducted at Solar Test Facilities.
  - Integration with acid decomposer to be validated.
  - Fluid mechanics (stability) and heat transfer data to be developed.
- Solar Thermochemical Process Design
  - Matching of the acid decomposition cycle to CRTF (or an equivalent), sizing of equipment, material flows, energy management, thermal cascading, controls, instrumentation, data acquisition, and system evaluation criteria.
  - Balance of the plant design, integration, and fabrication schedule.

- <u>Hydrogen Cycle Improvements</u>
  - Optimization of the acid decomposition cycle. Establishment of reliable process techniques to handle wet, acidic hydrogen iodide fluids, separation, and containment, catalyst stability, pumping equipment, and operation of the cycle integrated with energy storage.
  - Improved separation techniques for iodine from HI.
- <u>Cycle/Storage Interface Analysis</u>
  - Design of an acid concentration process to utilize thermal energy storage (molten salt) assumed to be available at CRTF.
  - Interfacing and control strategies for constant load operation.
  - Early CRTF program interaction required.
- <u>Solids Decomposition Experiment</u>
  - Technical and economic characteristics of $ZnSO_4$ decomposition with concentrated insolation. Study of a window reactor instrumented to yield performance data. Absorption kinetics, effect of additives, product separation, and transport.
  - Development of appropriate window materials for direct decomposition reactors operating at high temperatures and pressures.
- <u>Solar Process Control</u>
  - Examine effects of large energy transients on process stability.
  - Examine effect of transient flow of process streams relative to effect on separation efficiencies.

E. TECHNICAL STRATEGY

This section discusses the underlying technical strategy used to direct the interrelated activities of the two major program components, the Solar Hydrogen Project and Technology Development.

1. SOLAR HYDROGEN PROJECT

The following highlights the technical strategy for the project. There is an emphasis to advance and project in two major steps, each a scaleup of a factor of approximately fifty (50). Each scaleup represents a major technological challenge. The process, based on the decomposition of sulfuric acid with subsequent decomposition of hydrogen iodide, has been demonstrated at the laboratory bench scale at 1.0 liter per minute (12.8 kj/minute).

Semi-integrated tests of the solar process will be conducted at various facilities at the 50 liter/minute (640 kj/minute) level. Acid vaporizer/decomposer tests will be conducted at the CRTF with non-solar chemical steps being conducted at contractor facilities. An exception is the acid concentration step which will be conducted at the 2500-3000 liter/minute level in early tests at the CRTF to establish interfacing techniques with thermal storage.

SRE level tests will be conducted at the CRTF at the 2500-3000 liter/minute (32 mj/min) level, first with subsystem tests, and later as a fully integrated system process.

A ten-year time-frame is taken for development. This establishes the requirement for only one intermediate scaling test. The pacing technology is the high-temperature reactor and its operations under solar conditions. Another critical item is the ceramic acid boiler, needed primarily to increase process efficiency and adaptability to the solar source.

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 in the solar-process interfaces, particularly the acid vaporizer/decomposer units and operations from thermal storage. This work will draw on experience from operations at Solar I and extend to complex heat and mass transfer operations.

Technical flexibility is maintained until commitment to a final design in FY87. Areas of particular interest include solar unique subsystems and other technologies that can increase process efficiency, decrease materials problems, or reduce development risk. New or improved methods of utilizing solar facilities will be considered, especially regarding close coupling of energy supply with usage. This work is conducted within an overall effort to strengthen the technology base for solar-driven chemical processes.

2. TECHNOLOGY DEVELOPMENT

The technical strategy for the Technology Development program component evolved over a period of several months, having as its beginning a review of the previous fuels and chemicals program tasks. While valuable scientific contributions were obtained, the lack of focus did not permit optimization of the results nor steady progression in the development of the technology base. The new programmatic approach utilizes much of the previous work in an aggressive and efficient manner.

With a focus provided, an analytical and management structure was developed to assure that the critical underlying solar technology required to operate fuel and chemical processes was developed in parallel with the major chemical subsystems. In working toward an acceptable structure, program goals and objectives were initially characterized as sets of major technological hurdles that had to be overcome. Since "quantum jump" technical developments rarely occur on a cost effective basis, these technical hurdles were characterized and separated into technology stages or targets. The stages were ordered sequentially and chronologically, increasing in technical complexity over time. Each new stage built on the accomplishments of the previous stage.* Figures I-2 and I-3 visually describe the staged technology concept.

*This structure will be expanded and used as an entry mechanism to initiate interactions with industry to define sets of generic technology for classes of industrial fuels and chemicals applications.

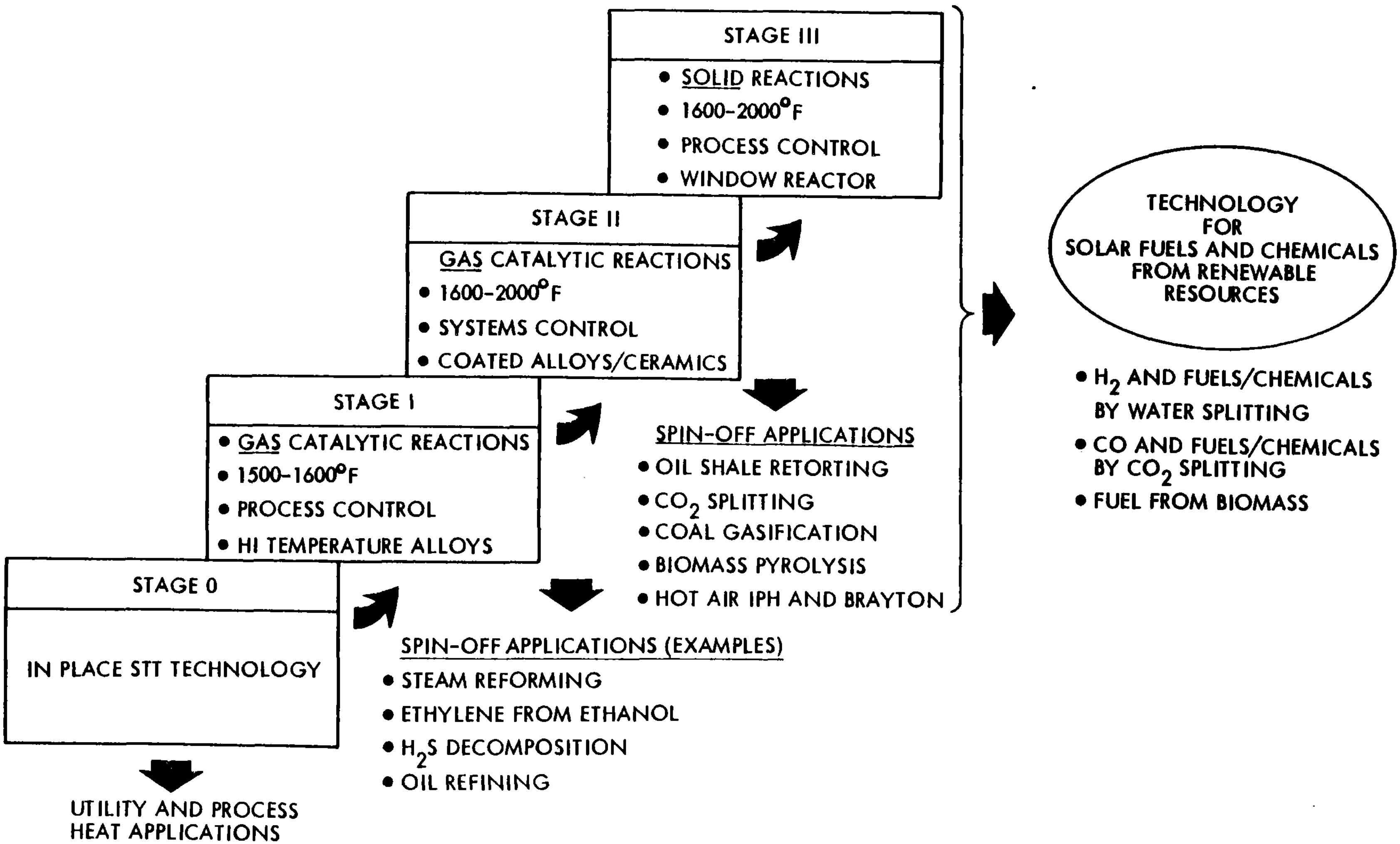

Figure I-2. Staged Technology Concept

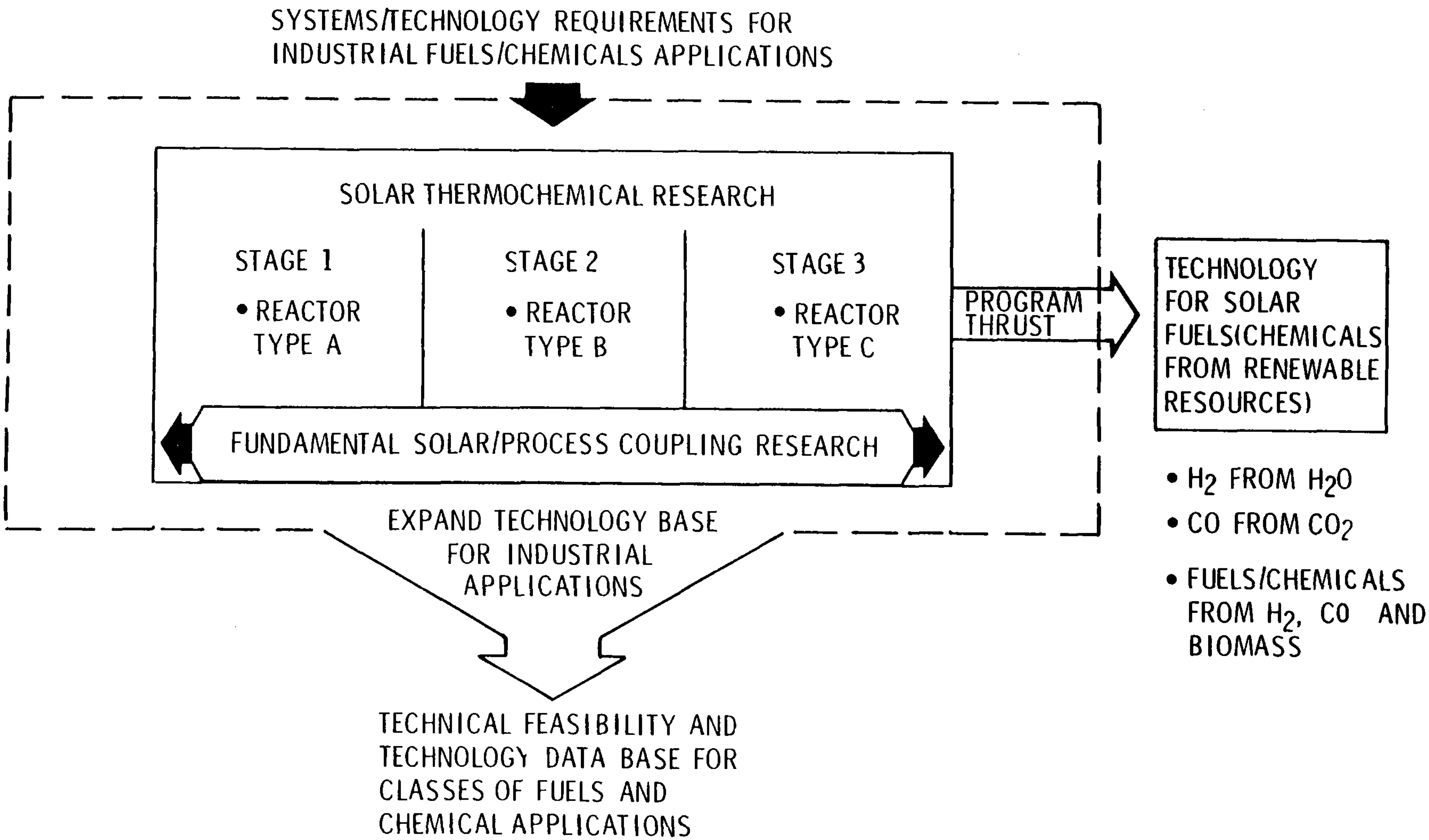

Figure I-3. Simplified Concept of Staged Technology

Further evaluation of ongoing Solar Thermal research relating to Fuels and Chemicals indicated that the Research and Advanced Development work was proceeding at several different levels. For example, commercial feasibility and overall system studies were performed without basic design information on the solar interface and other basic process features.

The levels of technology for various types of work in the Fuels and Chemicals program is illustrated in Figure I-4 relative to research needs, status and priorities. The program can be structured largely in terms of the type of reactors which are used with solar energy. For example, metal catalytic reactors are well characterized while photolytic reactors are not. Technology can be separated into an engineering base and a research base. The engineering base represents the top level technology and the targets that the research should be responding to. Previous research work related to Fuels and Chemicals is included in the matrix.

The strategic value of the structure becomes clear in that several things become obvious from it. For example, it can be seen that the technology base is more complete and advanced in the metallic gaseous catalytic reactor category. This information had a bearing on the selection of the process for the Hydrogen Project. Another observation is that several significant voids exist in both the engineering and research base for the more advanced reactor concepts. This was a contributory input into the selection of FY82 tasks. This structure is now being expanded and reviewed for completeness, but some form of it will serve as the management tool to direct Technology Development.

PROGRAM RESEARCH AND TECHNOLOGY BASE		CATALYTIC GAS/FLUID REACTOR	SOLID REACTION REACTOR	SOLID/FLUIDIZED REACTOR	PHOTON DRIVEN REACTOR
		MAJOR REACTOR CATEGORIES			
TECHNOLOGY BASE	SYSTEM COMMERCIAL SCALE FEASIBILITY	• PFR/DOE STEAM REFORMING SITE SPECIFIC DESIGN • BOEING, SANDERS CONCEPT SITE SPECIFIC DESIGN	OPEN CAVITY / WINDOW	• FY 82-83 DIRECT FLUX SOLAR CHEMICAL REACTOR ASSESSMENT	• FY 82-83 PHOTON DRIVEN CONCEPT STUDY AND ENGINEERING EVALUATION
	RECEIVER/REACTOR FEASIBILITY	• BOEING HOT AIR RECEIVER (1500°F TEST AT CRTF) • (EPRI)	• SANDERS 1/4 Mwt ON CERAMIC MATRIX ACTF ← REACTOR CONCEPTS/CONFIGURATIONS UNDEFINED →	SPECIFIC REACTOR TESTS BASED ON OUTCOME OF FY 82-83 STUDIES	
RESEARCH BASE	SOLAR-PROCESS COUPLING RESEARCH	• FY 82-83 SOLAR COUPLING STUDY AND EXPERIMENT, "GASEOUS CATALYTIC DECOMPOSITION" • FY 82-83 SOLAR COUPLING EXPT "HIGH TEMPERATURE HEAT TRANSFER"	• FY 82-83 SOLAR COUPLING STUDY AND EXPERIMENT "$ZnSO_4$ DECOMPOSITION"	• FY 82-83 DIRECT RADIANT BIOMASS PYROLYSIS EXPERIMENT	GENERIC PROCESS NOT KNOWN
	PROCESS RESEARCH	• THERMOCHEMICAL REACTION STUDIES - GA, WESTINGHOUSE • FY 82-83 CHEMICAL STORAGE STUDY AND TEST	• THERMOCHEMICAL LLNL • OIL SHALE RETORTING • COAL GASIFICATION	• BIOMASS TESTS, PRINCETON • LASL COAL GASIFICATION	
		←	• FY 82-83 THERMOCHEMICAL PROCESS ASSESSMENT SPECIFIC PROCESS RESEARCH AS R&T DEVELOPMENT MECHANISM SUBSEQUENT TO FY 83 PROCESS SELECTION, APPLICATION DEFINITION		→

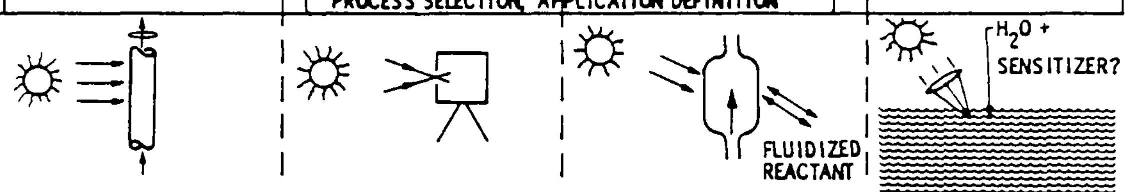

Figure I-4. Technology Development Strategy

F. COST AND PERFORMANCE GOALS

Preliminary analyses have indicated that, in the long term, solar hydrogen in general and high efficiency solar thermochemical hydrogen specifically has the potential to be competitive with other energy production options. Due to the developmental nature of this program however, definition of cost and performance goals will require additional work. This effort will be initiated in fiscal year 1983 and will be conducted in parallel with a conceptual evaluation of the baseline solar hydrogen production system and subsystems. The goals will be updated periodically as design and cost details become available.

In the interim, the program has established certain performance guidelines and targets. The baseline conceptual system has been estimated as having a potential cycle efficiency of 46%. The program efforts will strive to achieve higher cycle efficiency, reducing system complexity and lowering costs through process optimization and solar unique substitute reactions.

SECTION II

PROGRAM DESCRIPTION AND JUSTIFICATION

A. PROGRAM OVERVIEW

The FY83 tas… primarily direct… technologically … acing items of this pl… osi- tion of sulfuric … he major FY83 tasks … ide technology, solar …

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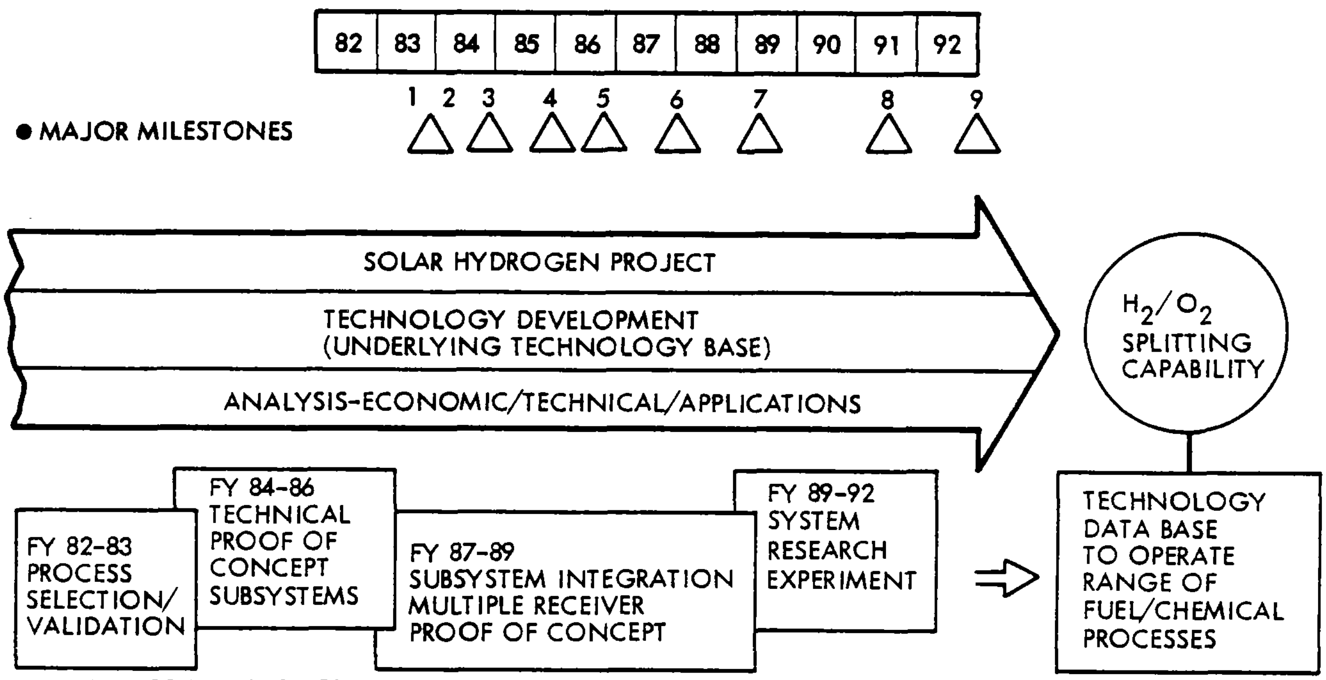
1. 10-YEAR …

Figure II-1 shows the flow of technology development, indicating the major 10-year milestones culminating in an experiment producing 2500-3000 liters/minute of hydrogen. Figure II-2 shows a detailed 10-year development plan which includes tests at the ACTF, CRTF and contractor facilities. Development proceeds from bench-scale tests, to 50 liter/minute process research unit (PRU) tests, to SRE-level tests.

The project contains several technically advanced subsystems. For the critical subsystems, backup strategies have been developed to ensure completion of the project.

The main element is the acid decomposer. It must operate under conditions of cyclic flux and temperature, and at pressures of 10 atmospheres. The initial thrust is to construct and test Incoloy 800H welded reactors. The first tests, a continuation of FY82 work, will be conducted at the ACTF at atmospheric pressure to test stress relief, catalyst behavior, and other design points. Following these, a pressurized reactor will be built and tested at the ACTF. Successful conclusion of these tests will lead to a PRU-level test at the CRTF. If



MAJOR MILESTONES

1. VALIDATION OF SELECTED H_2 CYCLE
2. CATALYTIC METAL REACTOR TEST
3. PRESSURIZED METAL REACTOR
4. SiC VAPORIZATION FEASIBILITY
5. COMPLETION PROCESS CHEMISTRY TESTS
6. MULTIPLE FIELD INTEGRATED TESTS
7. COMPLETE SRE FINAL DESIGN
8. SRE START UP
9. SYSTEM VALIDATION, TECHNICAL PACKAGE FOR INCDUSTRY

Figure II-1. Technical Program Overview - 10 Year Plan

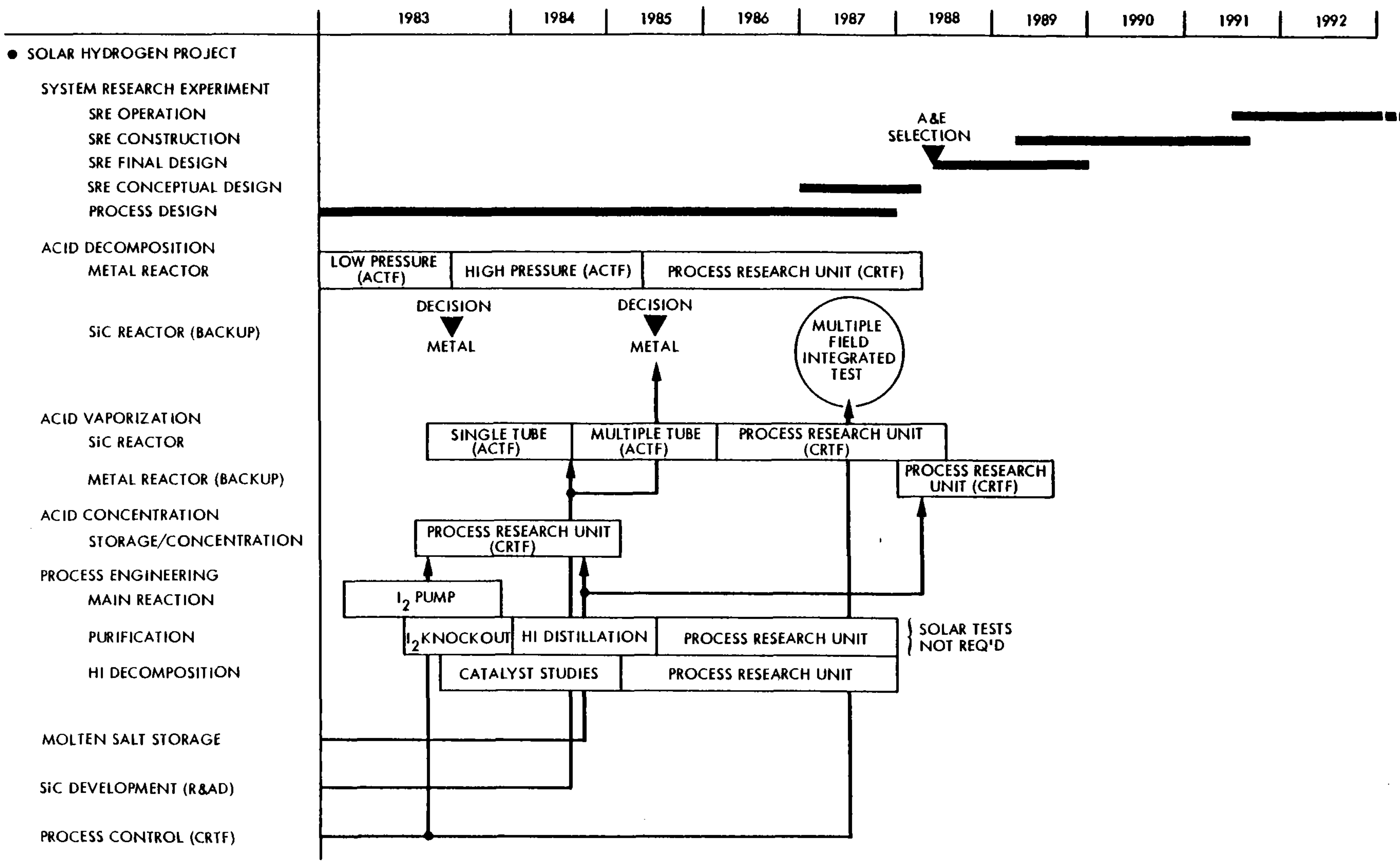


Figure II-2. Solar Hydrogen Project Ten Year Development Plan metal reactors prove inadequate it will impact the program and will require development decisions on the applicability of silicon carbide reactors, or, possibly, windowed reactors for sulfuric acid or metal sulfates.

The next major element is the acid vaporizer. Preliminary analysis has indicated the desirability of supplying sulfuric acid vapor directly to the decomposer from a second, lower-temperature receiver. Silicon carbide receivers are considered the only choice for this service. The major developmental question is whether vertical-tube heat exchangers can be fabricated that will operate at the required pressure under cycling conditions. This will be resolved in stages of development from single-tube and multiple-tube tests at the ACTF, and with PRU and SRE-level tests at the CRTF. The outcome of the tests could lead to design changes in which conventional acid boilers are operated from thermal storage.

Certain parts of the process such as the concentration of sulfuric acid are considered commercial, and will not be subject to development. Acid concentration in particular will be used to test the utilization and control of thermal storage in early, SRE-level tests at the CRTF.

Process control techniques for solar-driven chemical processes will be developed over several years, starting with basic control theory for operating processes with large energy transients. Of particular concern is the operation of mass transfer processes involving separations and purifications on materials leaving the solar reactor. Because these processes are characterized by long residence times, sophisticated control methods may be required to match the reactor with post-reactor processing.

Table II-1 illustrates some aspects of process control technology that must be developed. As process complexity increases, process control strategies must be developed to allow rapid startup, shutdown and non-isothermal operations from storage.

2. FY83 PLAN

Section II.B shows the Work Breakdown Structure for FY83 activities. These activities will tap the expertise of a variety of laboratories in the fields of heat transfer, chemistry, materials and process engineering.

Table II-1. Fuels and Chemicals Process Control Research Requirements

INCREASING TECHNICAL SOPHISTICATION ↓

EXPERIMENT (EXAMPLE)	PROCESS CONTROL REQUIREMENTS	CRTF CAPABILITY
DECOMPOSITION REACTOR	COUPLE FLUX TO FLOW OF PRODUCTS AND REACTANTS TO CONTROL TEMPERATURE AND PRODUCT COMPOSITION.	ON-LINE CONTROL OF MIRRORS FOR FOCUSING/DE-FOCUSING AND REMOVAL. 1600^{0}F, >1000 kw/m^2 (D).
DECOMPOSITION REACTOR WITH FEEDSTOCK RECYCLE	ABOVE, BUT ADDITIONAL REQUIREMENT TO COUPLE FLUX WITH SEPARATION PROCESS. REQUIRES UNDERSTANDING OF DYNAMICS OF SEPARATION PROCESS. MUST ADJUST FLOWS IMMEDIATELY UPON SENSING VARIATIONS IN FLUX. ALSO, PROVIDES FOR RAPID STARTUP.	REQUIRES OPERATION FROM STORAGE, ON-LINE FLOW CONTROL, COMPUTER CONTROL OF COMPLETE SOLAR INTERFACE (N).
OPERATION OF MULTIPLE REACTORS IN SEMI-INTEGRATED PROCESS	REQUIRES DYNAMIC MATCHING OF FLUX, FLOW, AND STREAM COMPOSITION.	REQUIRES INDEPENDENT OPERATION OF MULTIPLE MIRROR FIELDS, ON-LINE FLUX CONTROL (U).
OPERATION OF INTEGRATED PROCESS WITH STORAGE	REQUIRES ALLOCATION STRATEGY FOR MIRROR FIELDS (STORAGE VS. REACTOR). REQUIRES CLOSE COUPLING OF LINEAR AND NON-LINEAR PROCESSES. WILL REQUIRE ON-LINE ADAPTATION AND OPTIMIZATION OF FLUX FOR ALL RECEIVERS. REQUIRES PREDICTIVE CONTROL OF PROCESS.	REQUIRES COUPLING OF FLUX MEASUREMENTS TO MANY PROCESS STREAMS (N). REQUIRES COUPLING OF MIRROR CONTROL COMPUTER TO PROCESS CONTROL COMPUTER (U).

(D) DEVELOPED
(U) CAPABILITY AVAILABLE BUT UNTESTED
(N) CAPABILITY NEEDED

B. WORK BREAKDOWN STRUCTURE

The following tasks and subtasks are required to implement the Solar Fuels and Chemicals Program for FY83.

Task 1: Program Management of Solar Fuels and Chemicals

Task 2: Solar Fuels and Chemicals Program

- Subtask 2.1 Solar Hydrogen Project
  - 2.1.1 High Temperature Catalytic Reactor (FY82 Follow-on)
  - 2.1.2 Pressurized Metal Reactor
  - 2.1.3 Vertical Tube Ceramic Heat Exchanger
  - 2.1.4 Solar Thermochemical Process Design
  - 2.1.5 Thermochemical Cycle Engineering
  - 2.1.6 Hydrogen Cycle Improvements
  - 2.1.7 Cycle/Storage Interface Analysis
- Subtask 2.2 Technology Development
  - 2.2.1 Direct Flux Solar Reactor Analysis
  - 2.2.2 Solids Decomposition Experiment
  - 2.2.3 Direct Radiant Decomposition Experiment
  - 2.2.4 Chemical Storage Kinetics
  - 2.2.5 Solar Process Control
- Subtask 2.3 Technical Support and Analysis
  - 2.3.1 Technical Support
    - 2.3.1.1 System Process Analysis
    - 2.3.1.2 Photochemical Process Engineering
    - 2.3.1.3 Photolytic Acid Decomposition
  - 2.3.2 Analysis

2.3.2.1 Central Receiver/Solar Process Interface Requirements

2.3.2.2 Fuels and Chemicals Mission Analysis

2.3.2.3 NASA/Hydrogen Systems Assessment

2.3.2.4 Solar Hydrogen Cost/Performance Goals

Subtask 2.4 Technical Management

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 major interrelated technical programmatic components. The first acts as the driving force to move the technology toward the programmatic goal, the second provides the supporting technology essential to conduct fuels and chemical processes at a solar facility.

SUBTASK 2.1 SOLAR HYDROGEN PROJECT

This element is based on the programmatic philosophy of selecting and implementing a project that will focus and force the development of the technical base to the production of hydrogen via water splitting technology. By focusing the program in this manner, the project will be 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.

2.1.1 High Temperature Catalytic Reactor

- Task Description

  This task provides incremental support for completion of FY82 tests on the decomposition of sulfuric acid at the ACTF. Funds are to be applied to disassembly and analysis of the heavily cycled metal reactor.

- Critical Technical Issues

  Detailed in FY82 AOP.

- Benefits to Solar Thermal Program

  Detailed in FY82 AOP.

2.1.2 Pressurized Metal Reactor

- Task Description

  Sulfuric acid will be decomposed in a pressurized Incoloy 800H catalytic reactor above 700°C (1300°F). Tests will be conducted in the solar field at the Advanced Components Test Facility. The acid will be decomposed at a total pressure of 10 atm at a rate of about 1 kg/min using an iron oxide catalyst. The primary purpose of the test is to predict design and cycle life of metal catalytic reactors under pressure and solar operating conditions.

- Critical Technical Issues

  This test is a major step towards establishing the feasibility of metal chemical reactors operating at pressure above 700° (1300°F) in a solar field. 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 required for commercial operation. It will provide data for the design life of metal reactors and the maximum allowable temperature for operation of metal reactors. It will establish safety techniques for operation of chemical steps on a solar tower, start up and shutdown procedures and heat transfer rates.

- Benefits to Solar Thermal Program

  This test establishes technical feasibility of metal reactors operating above 700°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.

2.1.3 Vertical Tube Ceramic Heat Exchanger

- Task Description

This task begins studies on the subsystem to vaporize sulfuric acid in a solar field. Tests of heat exchangers made of silicon carbide (SiC) will be made with emphasis on the sealing/joining techniques required to boil sulfuric acid at 400°C and at 10 atm pressure. Tests will be run in the ACTF solar field with a test rig for studying tube-manifold joints under conditions of solar cycling. Single tube tests will be run in which the joints will accept the full solar flux while under pressure. These tests are expected to establish fabrication methods for multiple-tube SiC heat exchangers to be tested in FY85 at the ACTF.

- Critical Technical Issues

Direct vaporization of sulfuric acid in a solar field is an efficient method of utilizing the solar heat, but requires vertical-tube heat exchangers which are resistant to the very corrosive acid. The vaporization must be conducted at about 10 atm pressure to supply the acid decomposer (see Task 2.1.2). The major technical point to be tested is whether the pressure can be contained satisfactorily. Various sealing methods will be tested including mechanical and chemical joining. This task will be followed by multi-tube tests which 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 Program

  This work begins studies on heat exchangers which operate directly in the solar field with the capability of long service life and unparalleled corrosion resistance. Silicon carbide is a ceramic with a high thermal conductivity. Current fabrication techniques require ground, fitted joints. Design studies (Westinghouse, 1981) have shown the usefulness of silicon carbide in solar thermochemical cycles provided that effective sealing techniques can be developed.

2.1.4 Solar Thermochemical Process Design

- Task Description

  This task scopes the design of a thermochemical water-splitting process using solar energy. The task includes basic design of the plant as well as options in utilizing solar energy effectively. Basic heat and mass balances will be made. Rough sizing of reactors and storage vessels will be made based on estimates of day/night energy requirements, heat transfer properties of the major reactors, etc. Tradeoff studies will be made on the use of multiple receivers at different temperature levels, the impact of using large amounts of thermal storage, optimum pressure level of the major reaction steps, and other pertinent data. The purpose of the first year studies is to provide process information required for development of a System Research Experiment.

- Critical Technical Issues

  This task determines the technical path required for development of a large research experiment by scoping the technical requirements of the important process steps. Matching of the solar flux to the heat transfer properties of the reactors will, for example, 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 Program

  This effort will provide design for the optimal utilization of the CRTF for this type of process, by tailoring the process to accept multiple thermal inputs. The heat flux will match the process heat requirements closely. This will maximize process efficiency and minimize costs by reducing the need to cascade thermal energy.

2.1.5 Thermochemical Cycle Engineering

- Task Description

  This task provides basic engineering studies for design and operation of low-temperature process steps in thermochemical water splitting. Handling methods for wet, acidic iodine/hydrogen iodide fluids will be developed to assure reliable process operation. Efficient separation of iodine from this mixture will be examined. Pressure distillation of hydrogen iodine will be studied as a method of improving cycle efficiency. The continuous operation of these and other process steps from thermal storage will be examined to determine the effect of storage on separation efficiencies.

- Critical Technological Issues

  This work examines process operations in which reliability, process szability, variability in stream composition, and similar aspects are examined with respect to operation of a subsystem research experiment. The work provides an engineering demonstrations of pump performance, corrosion properties, thermal cycling, and other effects that could prevent reliable operation of the process. Additional work is directed towards pressurized operation of established process steps to support process design.

- Benefits to Solar Thermal Program

  This task ensures smooth transition of process development for solar thermochemical hydrogen production from the present bench-scale process to the level of System Research Experiment.

2.1.6 Hydrogen Cycle Improvements

- Task Description

  This task supports research on the chemistry of hydrogen production. The work concentrates on improvements in the processing of hydrogen iodide to make hydrogen by increasing solution concentrations, increasing system pressures, and improving decomposition catalysts. Specific tasks include improved separation of iodine from hydrogen iodide solutions, catalytic decomposition and catalyst recovery in the hydrogen iodide unit, and improved separation of HI-water mixtures.

- Critical Technical Issues

  This task addresses process improvements that have been previously identified but have not been tested on a bench-scale apparatus. It is specifically directed at improving process efficiency. The major economic uncertainty of the process chemistry is the efficiency of separation of hydrogen iodide and water. Reduction of energy for this step is a key area available for significant improvement.

- Benefit to Solar Thermal Program

  This work assures the implementation of a mature, technically advanced hydrogen production process at the CRTF.

2.1.7 Cycle/Storage Interface Analysis

- Task Description

  This task provides design of acid concentrators for test at the CRTF using molten salt thermal storage. The task covers equipment design, interfacing with thermal storage and control strategy to provide production of acid of constant specifications.

- Critical Technical Issues

  This task provides specifications for continuous operation of a mass transfer operation from thermal storage. It will provide the basis for optimizing the characteristics of thermal storage to a specific process step. It will later be coupled with the decomposition step to advance the integration and process control technical base.

- Benefits to Solar Thermal Program

  This task identifies design of System Research Experiment level equipment for early test at the CRTF. Information gathered from this task and CRTF experiments will establish design requirements both for thermal storage and for process operations driven from thermal storage.

SUBTASK 2.2 TECHNOLOGY DEVELOPMENT

The purpose of this subtasks is to develop the critical underlying technologies that will be required to conduct range of solar driven fuel and chemical processes. This element focuses on those technologies associated with the solar interface and processing of materials leaving the solar reactor. It also contains those tasks that assure programmatic flexibility through cycle substitution of those elements or subsystems that can be enhanced by unique solar qualities such as high temperatures, high flux and heating rates, controllable exposure and other qualities such as photolytic properties. These enhancements will be assessed in terms of process operational flexibility, performance, product quality, reaction rates and product yield.

2.2.1 Direct Flux Solar Reactor Analyses

- Task Description

  This task supports characterization of chemical reactors which utilize the solar flux without indirect heat transfer. Estimates of overall reactor efficiency will be made by studies of the optical properties of the windows, conceptual designs for large window structures, and the optical and heat transfer properties of reacting materials. The overall goal is to determine the potential of direct flux reactors for use with thermochemical processes in a solar field.

- Critical Technical Issues

  While windowed or unwindowed direct flux reactors may eliminate the need for heat transfer at high temperature, the capability of such reactors to operate at acceptable efficiencies, at process pressures, and at commercial scales remains undetermined. Of particular concern is reflectivity of windows, solid absorption characteristics, additives to solids to improve absorption, cooling of window surfaces and minimization of erosion by solids moving past windows.

- Benefits to Solar Thermal Program

  This task provides information on the desirability and type of work required on windowed chemical reactors. It will scope the capacity, temperature, flux capability, and efficiency of the reactors.

2.2.2 Solids Decomposition Experiment ($ZnSO_4$)

- Task Description

  The characteristics of the decomposition of zinc sulfate with concentrated solar radiation are determined. The kinetics and temperature of decomposition are measured as a function of solar properties, particularly the flux. The purpose is to determine the effects of high solar flux on the decomposition rate of metal sulfates. Additional work studies the effects of pressure and optical properties on the decomposition.

- Critical Technical Issues

  The high solar fluxes available from solar equipment may allow pyrolysis rates substantially higher than that available from current industrial processes. These tests investigate the effect of the high flux on solids decomposing in the range of temperatures from 1700-2000°F. Of particular interest is the potential of the high flux to substantially reduce the decomposition temperature.

- Benefit to Solar Program

  These studies provide the basis for advanced processes utilizing some of the solar unique capabilities. The work scopes the utility of operating at high temperatures and fluxes, provides input relative to window reactor feasibility, identifies solid handling complexities, and provides input data for the potential substitution of this subsystem for the high temperature acid decomposition step.

2.2.3 Direct Radiant Decomposition Experiment (Biomass)

- Task Description

  This task studies the properties of direct flux reactors, primarily in the high-rate reactions of carbonaceous feedstocks. The efficiency of spouted bed reactors will be determined relative to the optical properties of the reactor, the optical properties of the feedstock, and the heat transfer properties of the system. The overall goal of the studies is to characterize the utilization of high solar flux in chemical reactors absorbing solar energy directly.

- Critical Technical Issues

  This task extends previous work that demonstrated benefits of high-flux pyrolysis to control the distribution of products in solid-gas reactors. The work is specifically directed at quantitative descriptions of these phenomena which include fluidization velocity, additives to improve absorption characteristics and residence times for reactions.

- Benefits to Solar Thermal Programs

  This work provides input for advanced processes utilizing solar unique capabilities. It uses concentrated solar heat to conduct rapid pyrolysis of organic feedstocks to maximize the yield of liquid products. The work fills important voids in the technology base required to conduct a range of fuels and chemical processes in a solar field.

2.2.4 Chemical Storage Kinetics

- Task Description

  This task examines the reaction of water and sulfur dioxide to form sulfur and sulfuric acid as the basis of an energy storage system. The work studies the kinetics of the water/SO_2 reaction, the SO_2 being formed by the decomposition of sulfuric acid.

- Critical Technical Issues

  The key issues are the kinetics and extent of this relatively simple reaction which occurs in aqueous solution. Sulfuric acid must be formed in high concentration to give an efficient storage method. If the kinetics appear favorable this task will be transferred to the Advanced Development Program. Economic issues should be reviewed at that time.

- Benefit to Solar Thermal Program

  Success of this work could provide a basis for efficient diurnal and seasonal storage method which uses technology common to that of the thermochemical water splitting processes. Its use is perceived partly as a method to optimize the utilization of the mirror field.

2.2.5 Solar Process Control

- Task Description

  This task examines theoretical aspects of solar process control. The principal concern is the effect of large energy transients on process stability. The effect of transient flow of process streams will be examined relative to its effects on separation efficiencies. A workshop on solar process control will be held to incorporate experience gained at the Barstow facility and to highlight major developmental issues.

- Critical Technological Issues

  Process stability is uncertain in processes with varying energy and material fluxes. Mass transfer processes in particular are characterized by long residence times and non-linear effects. This task will outline the critical areas of process control required to conduct chemical processes in a solar field. To date, no one has post reactor or product handling experience for chemical processes initiated in a solar field.

- Benefits to Solar Thermal Program

  Operation of a chemical process with solar energy provides new opportunities for using solar heat but adds considerable complexity of control. This task will provide design criteria required to give stable and safe process operation.

2.3 TECHNICAL SUPPORT AND ANALYSIS

2.3.1 Technical Support

This element contains two tasks. The output of the work will keep the technical manager current and informed on future programmatic options in the process and photochemical areas.

2.3.1.1 Process Analysis.

- Task Description

  This task provides conceptual process design and scoping for thermochemical process technology. It examines process development and options for improved utilization or interfacing of solar energy. It provides background for anticipating problems arising from scaling up of process steps. It requires staging current with direct and indirect methods of providing fuel and chemical elements.

- Critical Technical Issues

  This task complements contracted design studies by providing management tools for evaluating processes, process options, new technology, and process difficulties.

- Benefits to Solar Thermal Program

  This effort provides flexibility to continuously examine progress in the technical development of hydrogen processes. It maintains management capability to review the current state of development, and to evaluate problems and needs and future directions.

2.3.1.2 Photochemical Process Engineering.

- Task Description

  This task scopes piping and reactor costs for photochemical processes. The goal is to characterize thermal performance with heat rejection costs, chemical transport costs, and other costs not related to specific process chemistry. Characteristics of flat-plate reactors will be examined first.

- Critical Technical Issues

Most photochemical processes operate at ambient temperature. This task examines the engineering and the economic factors involved in solar-driven photochemical processes which could hinder larger scale implementation. Understanding of the critical underlying engineering issues will help formulate a realistic photochemical research plan.

- Benefits to Solar Thermal Program

This work provides formative guidance for research on photochemical processes to assure practical implementation. It will give an indication of the matching of particular types of photochemical processes to solar concentrating equipment.

2.3.1.3 Photolytic Acid Decomposition.

- Task Description

This task examines the liquid-phase, photolytic decomposition of sulfuric acid and other inorganic materials to increase the efficiency of solar hydrogen processes. Theoretical evaluation of charge transfer catalysts for use in concentrated sulfuric acid will be made. Experiments will be conducted on the photolysis of sulfuric acid, hydrogen iodide and other acids and mixtures of acids. The goal is to establish the technical basis for the introduction of photolytic steps into solar hydrogen processes.

- Critical Technical Issues

Photolytic decomposition of the halogen acids are known to occur in dilute aqueous solutions, but not in concentrated solutions at elevated temperature. The photolysis of sulfuric acid has not been studied. The critical issue is whether energetic charge transfer species can be found for sulfuric acid, especially at high temperature.

- Benefit to Solar Thermal Technology

  Energetic photolytic processes, particularly those at high temperature, offer the greatest theoretical benefits for the production of fuels and chemicals from solar energy. They can increase efficiency, decrease materials degradation, and simplify handling of corrosive chemicals.

2.3.2 Analysis

This program element contains the studies and analyses required to substantiate technical directions and directions. In general, these efforts will be contracted to appropriate organizations however, the nature of the work is such that the technical manager must remain cognizant of the on-going efforts in order to assure technical progress in the major technical areas of the Solar Hydrogen Project and Technology Development.

2.3.2.1 Central Receiver/Solar Process Interface Requirements.

- Task Description

  This task identifies interface requirements between a solar hydrogen process and the CRTF. Major interfaces will include:

  - mirror field/reactors
  - thermal storage/chemical process
  - mirror field control/process control
  - CRTF management/hydrogen project management

  The effort involves interface definition, integration of test schedules, and project planning. As a major interface area, close interaction and participation will be required from the central receiver program.

- Critical Technological Issues

  Design and operation of a solar chemical plant is determined partly by the characteristics of the solar heat source. The ability of the solar source to match the thermal characteristics of the process represents a major interface problem that must be identified early in the program prior to subsystem testing.

- Benefit to Solar Thermal Program

  As testing on the Solar Hydrogen Project intensifies, success and schedule achievement will be dependent on smooth interfaces with the central receiver. This is particularly true as the program investigates the use of multiple receivers and integration of process subsystems.

2.3.2.2 Fuels and Chemicals Mission Analysis.

- Task Description

  This task will serve as an independent source of verification regarding the Fuels and Chemicals Program direction. The task will consider markets, state of development of technology, location, and prospects for improved or new technology. Recommendations will be given on project direction.

- Critical Technical Issues

  Processes are continually being proposed for solar process development but little is understood regarding the solar interface. Comparisons are difficult due to the various developmental stages processes are moving through. Questions continue regarding the basis for selection of a specific process over others or indirect versus direct solar applications. This task will provide a framework for consideration of current and emerging technology.

- Benefit to Solar Thermal Program

  This effort will provide additional input into the technical, economic and industrial considerations used to structure the present program. The results will either independently validate program direction or provide input for appropriate redirection.

2.3.2.3 NASA/Hydrogen Systems Assessment

- Task Description

  This task will explore the potential to make a future application of the on-going Solar Hydrogen Project to meeting the hydrogen needs of NASA. NASA centers will take a lead role in performing a systems assessment of NASA's future hydrogen needs and means of meeting the need. In exploring the solar option, close coordination will be required from central receiver personnel.

- Critical Technical Issues

  The critical issues evolve around the technical credibility of the on-going Solar Hydrogen Project and the ability to demonstrate progress with the plan. Strong technical arguments followed by performance and hardware subsystem testing will substantiate that solar is a viable technical option for production of hydrogen.

- Benefit to Solar Thermal Program

  Consideration of solar as an option contributes to the premise of the program's ability to respond to national needs. The assessment will provide the kind of vigorous examination required to place solar within the options and to identify the major programmatic and developmental hurdles required to move solar hydrogen into the competitive arena.

2.3.2.4 Solar Hydrogen Cost/Performance Goals.

- Task Description

  This task examines the costs of hydrogen production by solar-driven water splitting processes. Emphasis is on thermochemical processes and their competitors including electrolysis and photolytic methods. Economic analyses will be made based on the costs of the processes, near-term process improvements, mirror field costs, and energy storage costs.

- Critical Technological Issues

  The costs of solar hydrogen processes are dependent both on the cost of the mirror field and the cost of the chemical equipment. This task will examine this and related aspects of process costs relative to the tradeoffs of cost and efficiency. Competition from other solar processes, particularly lower temperature processes, will be examined.

- Benefits to Solar Thermal Program

  This task will help direct program developmental priorities by assessing tradeoffs and competing processes.

SUBTASK 2.4 TECHNICAL MANAGEMENT

This subtask will provide direct technical support to DOE/SAN management. It will encompass development of research needs, recommendations on research priorities and preparation of research plans. This will require coordination and understanding of all STT program elements. It will include the preparation of technical statements of work for SAN review and approval, and technical management and monitoring of contracted efforts. The Technical Manager will be responsible for assuring timely and aggressive pursuit of program goals, and of notifying SAN of potential schedule slippage in either the Solar Hydrogen Project or Technology Development. At the request of SAN, specific supporting research or studies will be conducted to support major technical decisions. The Technical Manager shall also recommend the "technology readiness" status of solar hydrogen subsystems prior to field experiments at solar facilities. Lastly, the technical manager shall be responsible for task completion, assurance of contractor report completion, and support of SAN in program documentation and reporting.

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

The success of a Solar Hydrogen Project within 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 DOW/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 Hydrogen Project. The balance between work on the project and on the technical base is determined by agreement between HQ and SAN, but allocations are suggested at 60% project, 40% technology base.

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 a full 10-year period, beginning with tests utilizing thermal storage, continuing with PRU 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

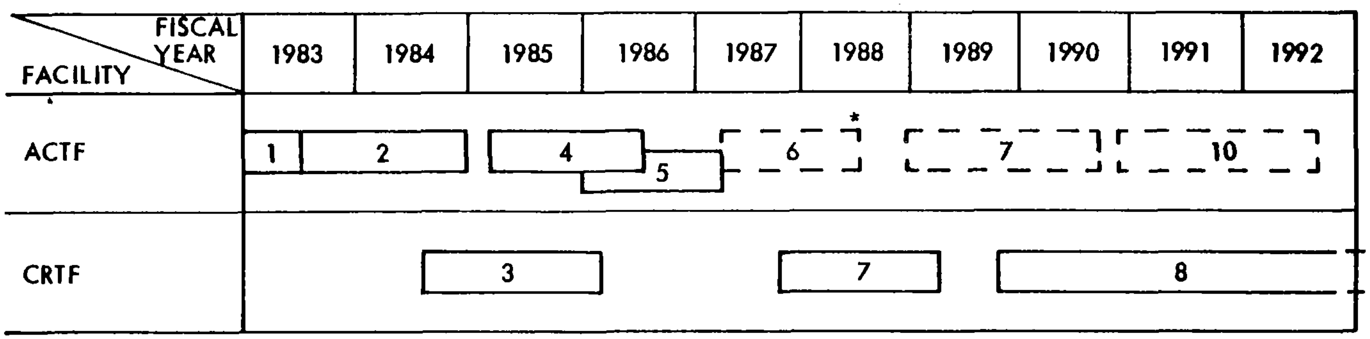
This interface addresses operations from thermal storage, process control, energy management, materials, and new storage and solar capabilities. Interactions will begin immediately relative to tests on utilizing thermal storage for acid concentration, a basic mass transfer process. Design, materials,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

Figure II-3 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-4 shows the projected use of solar facilities during the lifetime of the Solar Hydrogen 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.

	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-3. 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-4. Test Bed Requirements for Solar Hydrogen Project Subsystems at Solar Thermal Facilities

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°C (1300°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 efficiently integrate 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 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°C (1300 to 1650°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 on the usefulness, the growing market, and the versatility of hydrogen. The technology of producing hydrogen from water follows basic thermodynamic 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-5 illustrates many uses in the chemical industry, in the utilities, and in transportation. The projected market for hydrogen in the year 2000 is from 5 to 20 Q 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

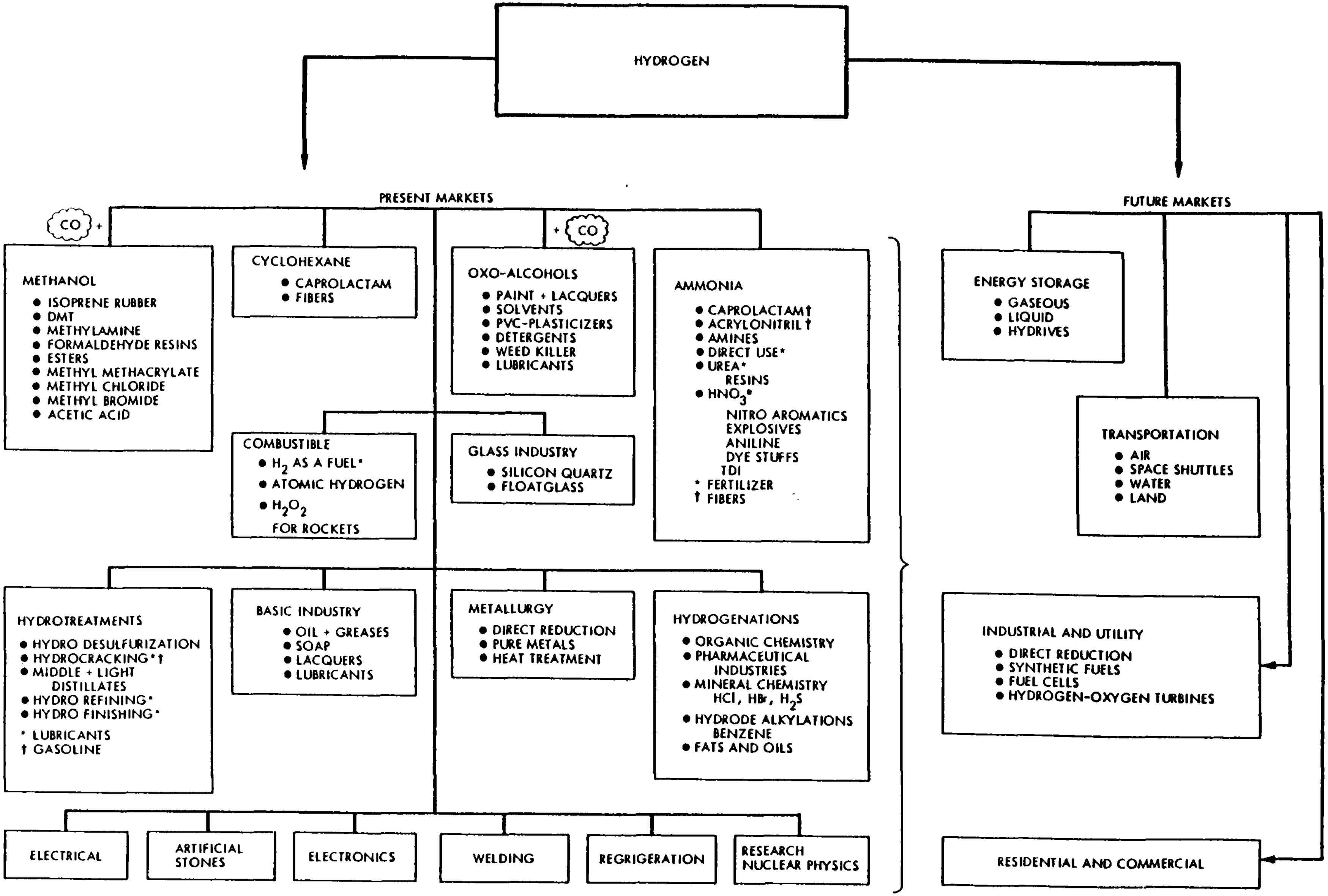


Figure II-5. Near Term and Long Term Hydrogen Applications in many ways. For example, very high temperature capability can be used to simplify process steps. Improved thermal storage or development of chemical storage can be used directly to smooth processing and assure constant plant output. Thermochemical processes inherit economies of scale as the size of the plant increases.

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 included:

- 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, and have not explored solar as an option. In that there is a great deal of cooperation 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 JPL.

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.

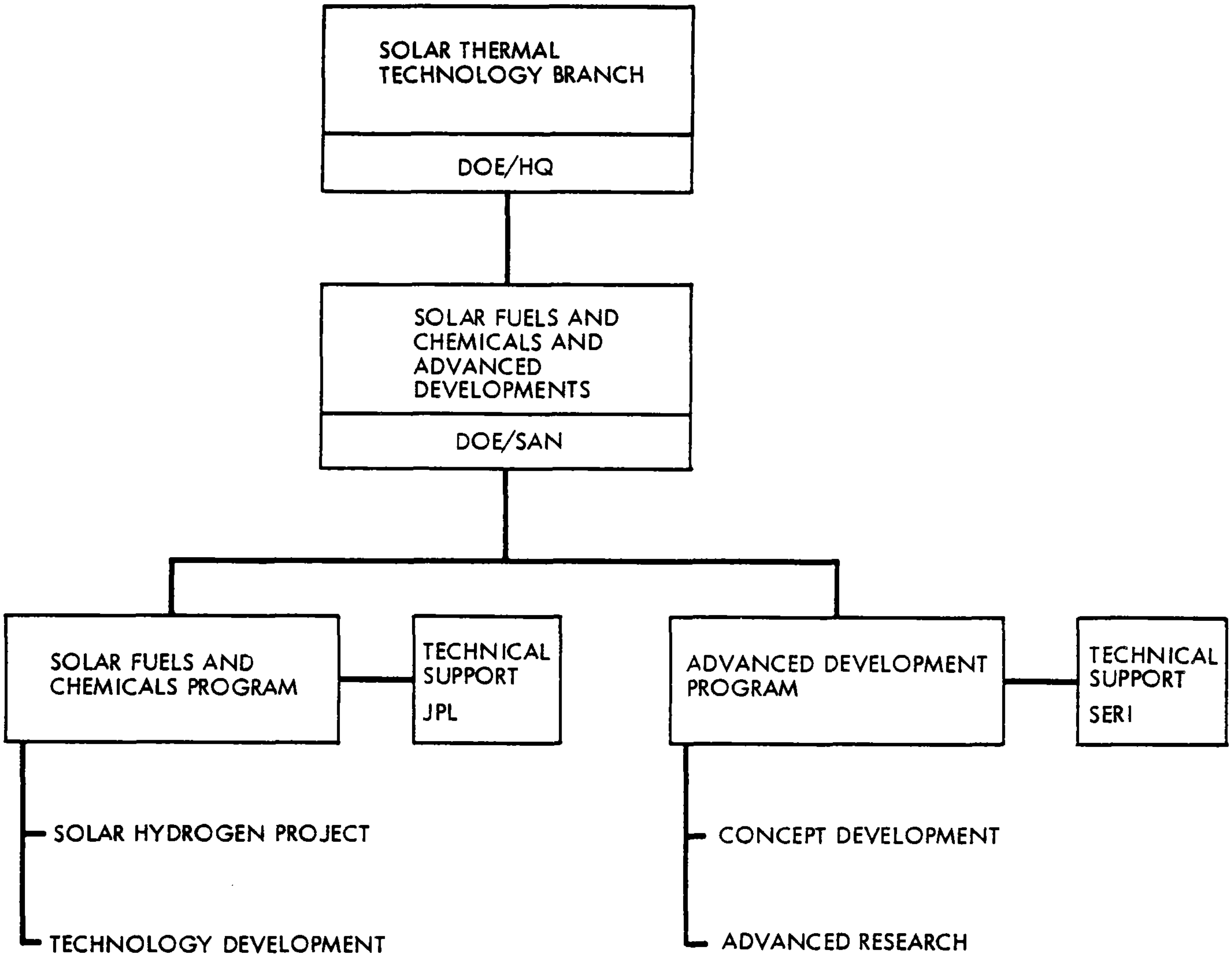


Figure III-1. DOE/SAN Field Management Program Structure

C. 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
- Semi-Annual Reviews
- 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 Hydrogen Project, moving the technology from bench level toward subsystem test and development of the underlying 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 to be 2.5 FTEs or less.

C. FY 82-83 FUNDING BREAKDOWN

Table IV-2 presents the breakdown of budget for FY83 based on the program plan.

Table IV-1. Solar Fuels and Chemicals Program Resources

FY82	FY83	FY84	FY85	FY86
1.48	3.65	4.0	5.0	5.8

TABLE IV - 2

SOLAR FUELS AND CHEMICALS FY'83

BUDGET REQUIREMENTS

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

o SOLAR HYDROGEN PROJECT	Task Costs ($K)	Additive Costs($K)
- High Temperature Catalytic Reactor	150	150
- Pressurized Metal Reactor Test	350	500
- Vertical Tube Ceramic HX	250	750
- Solar Thermochemical Process Design	200	950
- Thermochemical Cycle Engineering	150	1100
- Hydrogen Cycle Improvement	250	1350
- Cycle Storage Interface Tests	150	1500
o PROJECT TECHNICAL MANAGEMENT	200	1700
o TECHNOLOGY DEVELOPMENT		
- Direct Solar Flux Reactor Analysis	150	1850
- Solid Decomposition Experiment	150	2000

DOLLAR SUBTOTAL $\$2.0 \times 10^6$

II. The tasks in this category are deemed critical, as above, and the funds listed will permit the tasks to proceed without incremental funding.

	Task Costs	Additive
- Pressurized Metal Reactor Test (increment)	200	2200
- Thermochemical Cycle Engineering (increment)	150	2350
- Direct Solar Flux Reactor Analysis (increment)	150	2500

DOLLAR SUBTOTAL $\$2.5 \times 10^6$

TABLE IV - 2 (cont)

III. The tasks in this category are deemed essential to supporting the Solar Hydrogen Project Milestones, particularly the solar process control which must be performed at the CRTF.

	Task Costs	Additive Costs
o CR/Solar Process Interface Analysis	50	2550
o Solar Process Control-Technical Development	100	2650
o Chemical Storage Kinetics Experiment	150	2800

DOLLAR SUBTOTAL $\$2.8 \times 10^6$

IV. The tasks in this category are important to the development of solar unique subsystem substitution options. Delay may preclude their use in the SRE.

	Task Costs	Additive Costs
o Advanced Reactor Concepts	180	2980
o System Process Analysis	50	3030
o Photon Process/Cycle Substitution	100	3130
o NASA Hydrogen System Assessment	125	3255
o Solar Hydrogen Cost Performance Goals	70	3325
o Program Management (SAN)	200	3525

PROGRAM DOLLAR TOTAL $\$3.525 \times 10^6$

SECTION V

FY83 OBJECTIVES AND SCHEDULES

The major FY83 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. FY83 MILESTONES

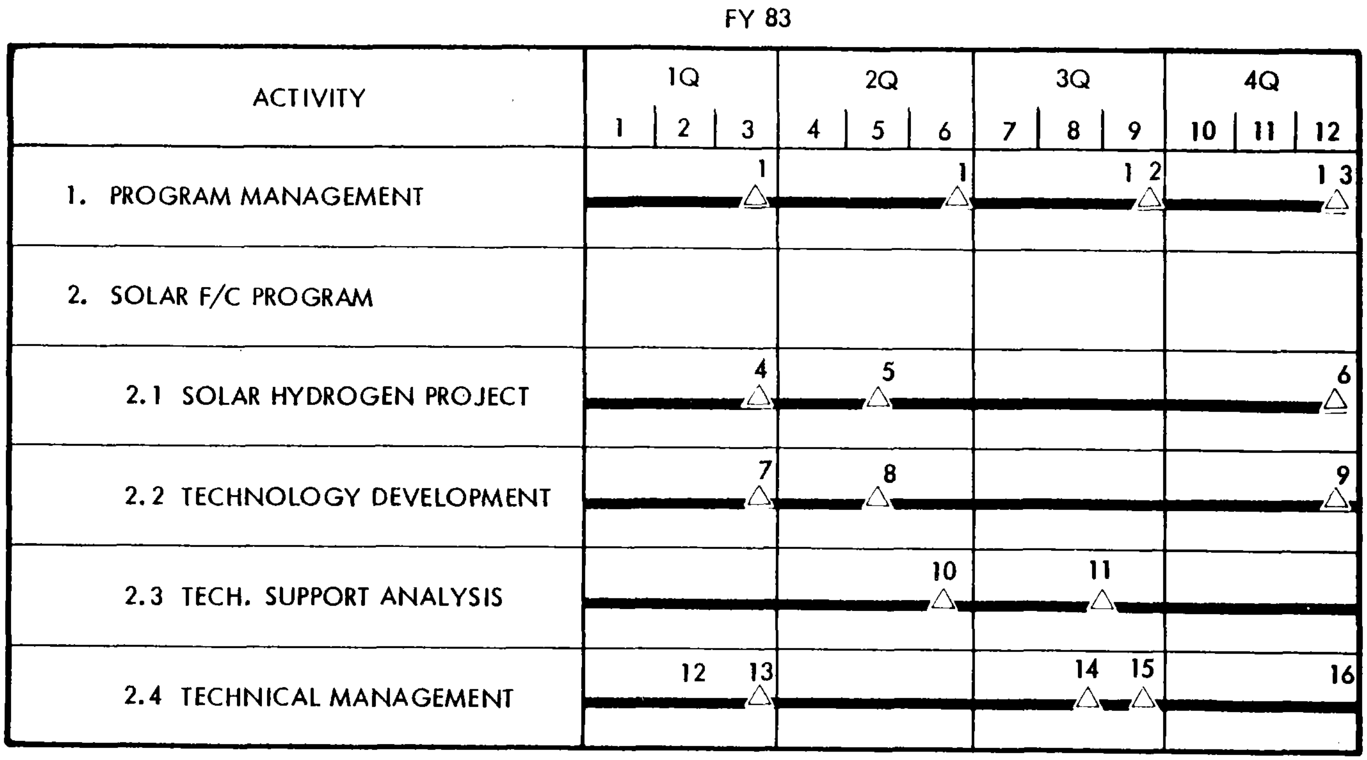
- Validation of Baseline H_2 Process June 83
- Catalytic Gas Reactor Test Complete Feb 83
- Complete Initial Test of $ZnSO_4$ Decomposition Dec 82
- Direct Flux Reactor Study Complete Sept 83
- Photon Research Plan Complete March 83
- NASA H_2-Mission Analysis May 83
- Post Test Analysis of Solar Gas Reactor Apr 83

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
- Annual Reports



1. SAN AND HQ QUARTERLY REVIEWS
2. VALIDATION OF BASELINE T/C PROCESS
3. AOPs, PROGRAM ANNUAL REPORTS, PLANS
4. DESIGN REVIEW OF PRESSURIZED REACTOR
5. CATALYTICAL GAS REACTOR TEST COMPLETE
6. VERTICAL SiC TUBE EXPERIMENT AT ACTF
7. COMPLETE INITIAL TESTS OF $ZnSO_4$ DECOMPOSITION
8. H_2 SYSTEM ANALYSIS REPORT
9. DIRECT FLUX REACTOR STUDY COMPLETE
10. COMPLETE PHOTON RESEARCH PLAN
11. NASA H_2-MISSION ANALYSIS REPORT
12. COMPLETE FY 83 CONTRACT SOWs
13. PRE SOLAR TEST REVIEW
14. POST TEST ANALYSIS REVIEW
15. PROCESS DESIGN REVIEWS

Figure V-1. Solar Fuels and Chemicals Program FY 83 Milestones

- 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 with JPL, for technical management of research and technology activities for 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, or JPL as requested by SAN.

The proposed procurements are presented in Table VI-I.

FY83 PROCUREMENT SUMMARY

TABLE VI-1

TASK	CONTRACTOR
SOLAR HYDROGEN PROJECT RESEARCH	
HIGH-TEMPERATURE CATALYTIC REACTOR	GA (CONTINUATION)
PRESSURIZED METAL REACTOR TEST	COMPETITIVE
VERTICAL TUBE CERAMIC HEAT EXCHANGER	COMPETITIVE
SOLAR THERMOCHEMICAL PROCESS DESIGN	COMPETITIVE
THERMOCHEMICAL CYCLE ENGINEERING	TBD
HYDROGEN CYCLE IMPROVEMENT	GA
CYCLE/STORAGE INTERFACE TESTS	COMPETITIVE
TECHNOLOGY DEVELOPMENT	
DIRECT SOLAR FLUX REACTOR ANALYSIS	(FOLLOW-ON, IGT)
SOLID DECOMPOSITION EXPERIMENT	LLNL
ADVANCED REACTOR CONCEPTS	LBL, U HAWAII
CHEMICAL STORAGE KINETICS EXPERIMENT	GA(UNSOLICITED PROPOSAL)
SOLAR PROCESS CONTROL	(UNIVERSITY CONTRACTS, TBD)

FY83 PROCUREMENT SUMMARY (CONT'D)

TABLE VI-1

TASK	CONTRACTOR
TECHNICAL SUPPORT AND ANALYSIS	
SYSTEM PROCESS ANLAYSIS	TBD
PHOTON PROCESS ENGINEERING/ CYCLE SUBSTITUTION REACTIONS	JPL/TBD
CR/SOLAR PROCESS INTERFACE	SNLL
FUELS AND CHEMICALS MISSION ANALYSIS	SERI
NASA HYDROGEN SYSTEM ASSESSMENT	NASA/KSC
SOLAR HYDROGEN COST/PERFORMANCE GOALS	TBD
TECHNICAL MANAGEMENT	JPL