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# The Goldstone Energy Project Final Report


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National Aeronautics and Space Administration

**Jet Propulsion Laboratory**
California Institute of Technology
Pasadena, California 91103

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February 15, 1978

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Space Administration

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# PREFACE

The work described in this report was performed by the Applied Mechanics Division and Telecommunications Science and Engineering Division of the Jet Propulsion Laboratory.

The Goldstone Energy Project was initiated shortly after the 1973 oil embargo and it appeared that the development of solar collector technology would move ahead very rapidly. In particular, it was felt that the open market would develop and promote the commercialization of the technology with resulting benefits of higher performance and lower costs.

Large-scale development activities over the last three years have been directed toward other areas. To forecast long-term growth in a new technology area is at best a high-risk proposition; but at this time, it appears that the present funding efforts will continue and that the commercial market will expand in the low-temperature area for hot water and heating, ventilating, and air conditioning (HVAC) applications. At the completion of the project in 1976, there were indications that the Energy Research and Development Administration (ERDA) would sponsor development of solar-electric conversion techniques which are modular in nature and applicable to power systems similar to Goldstone. At the time of this report, the ERDA small power system programs are just beginning.

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## ABSTRACT

The Goldstone Energy Project was established in 1974 to investigate ways in which the Goldstone Deep Space Communications Complex in California could be made partly or completely energy-sufficient, especially through the use of solar- and wind-derived energy resources. Ways in which energy could be conserved at the Complex were also studied. Findings include the following. Wind energy: (1) Theoretical developments are required to generate a simulation process that represents both wind distributions and correlations, point to point, and (2) Winds at Goldstone are insufficient in strength and duration to generate electric power economically. Solar energy: (1) Solar measurements should be correlated with meteorological data at the same site to identify which parameters are probabilistic and which are deterministic, (2) Circumsolar radiation measurements are required to determine the tracking accuracies required for the various types of concentrating collectors, (3) Solar collector technology has not developed to the point at which an energy-on-demand system can be built economically, (4) Heat transport piping costs dictate that solar collectors must be located near the point where heat energy is to be converted or used, and (5) Solar energy systems that produce energy-as-available show promise of becoming economically viable. Energy storage: Hydrogen is not an economic energy storage medium because efficiencies are too low. Energy Conservation: (1) Improved computer programs are needed to analyze existing buildings to identify potential load reductions and evaluate proposed energy conservation measures and (2) Economic energy-conserving practices and processes can be substituted for energy-intensive ones to save operating capital. Obstacles to demonstrating energy self-sufficiency: (1) Operation and maintenance costs of solar energy systems are estimated to be much higher than conventional energy systems, (2) Initial capital costs of present-day technology solar collectors are high and are compounded by low collector efficiency, and (3) No significant market force exists to create the necessary industry to reduce costs through mass production and broad open-market competition.

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## SECTION I

## INTRODUCTION

### A. BACKGROUND AND RATIONALE

As part of a broad program to conserve energy at government installations, the National Aeronautics and Space Administration (NASA) requested its field centers to submit energy-conserving ideas. In response to the NASA request, the Jet Propulsion Laboratory (JPL) examined the concept of operating one or more of the installations that it manages for NASA on clean, renewable synthetic fuels such as hydrogen or methane. Chemical energy stored in the fuels would be converted to useful forms in very-low-pollution, on-site total energy or other highly efficient energy conversion plants. The sun would be the primary source of energy, with solar energy broadly interpreted to include energy in the wind, municipal waste, land-fill gas, farm chaff, etc.

On January 7, 1974, the Laboratory Director established a JPL Energy Program which has as its principal objective the design and implementation of energy systems at JPL and its field installations to attain a high degree of energy self-sufficiency. It was hoped that such systems would not only supply JPL's needs during an extended period of energy shortages but could also serve as an operating model for energy suppliers throughout the Nation. The Goldstone Energy Project was a part of the JPL Energy Program.

One of the NASA installations under investigation was the Goldstone Deep Space Communications Complex (GDSCC), located approximately 70 km (44 miles) north of Barstow, California. Six separate tracking stations and a Microwave Test Facility (MTF) are included in this complex. The concept formulated by the Goldstone Energy Project was to operate the complex largely on hydrogen derived from solar energy and recirculated water.

The installation at Goldstone has unique characteristics which make it appropriate for consideration as a solar-hydrogen demonstration project. One of these characteristics is an installed generating capacity of 12,350 kW which not only meets the power demand of the mission-critical facilities but also provides for on-line and maintenance spares at each of four separate power plants. The engine-generators are now operated only during critical phases of space flight missions or upon failure of commercial electricity service, and they burn fuel oil. The feasibility of converting the existing power plants to operate on hydrogen in addition to fuel oil, and of operating them continuously, was to be determined.

Another characteristic contributing to Goldstone's uniqueness is its geographic location. To minimize radio frequency (RF) noise, the tracking stations were located remote from civilization. Fortunately, the geographic location is also relatively free from the effects of urban smoke and haze that could attenuate the direct rays of the sun. Goldstone is located in the Mojave Desert, which enjoys an abundance of sunshine and a not insignificant amount of wind. In addition, a large land area, currently about 80 km$^2$ (31 square miles), must be retained to protect the tracking stations from encroachment in future years. If a portion of this land area were used for collecting solar energy, a function which does not interfere with space communications, then a valuable secondary use of the land could be demonstrated.

## B. GOAL AND OBJECTIVES

The goal of the Goldstone Energy Project was to contribute to the achievement of the national goal of energy independence by demonstrating a high degree of energy self-sufficiency at a NASA installation which has unique characteristics with respect to exploiting solar energy. The goal was approached simultaneously from two directions: (1) a vigorous campaign to conserve energy was conducted, which included the cost-effective application of advanced technology as appropriate, and (2) conventional, nonrenewable sources of energy were to be replaced by renewable sources to the extent that replacement was demonstrated to be economically justifiable and in the national interest.

The objectives of the Goldstone Energy Project were to reduce the consumption of energy delivered to the Goldstone Complex by 30 to 40% over a 5-year period starting in 1974 and to reduce the consumption of nonrenewable fossil fuels by 70 to 90% over a 5-year period starting in 1976. These objectives were to be met while preserving operational integrity, and while protecting and enhancing environmental quality.

## C. SCOPE OF THE GOLDSTONE ENERGY PROJECT

As authorized by the NASA Office of Tracking and Data Acquisition (OTDA), the Project considered systems which were broadly applicable to all NASA tracking complexes and individual, isolated stations. However, the Project did not include the engineering of specific systems for complexes or stations other than Goldstone.

Although the Project supported the national goal of energy independence as broadly as possible, it did not include energy sources or systems which are inconsistent with the needs of NASA tracking stations.

The scope of the Project did not extend to research and development of energy system components nor to component technology, although an awareness of the progress of component development and its probable availability for use in this Project was mandatory.

Although implementation of the Goldstone Energy Project would reduce the risk of mission interruption due to possible shortages of fossil fuels, this was not a primary consideration of the Project. Moreover, the Project did not include provision for fuel storage or other facilities which could provide survival capability in the event of a major crisis.

Since conservation of energy was to be conducted vigorously, cost-effective application of advanced technology was explored as a secondary effort in some of the contracted studies. The energy conservation investigations were directed toward the ultimate reduction of Goldstone loads. This report includes only those tasks and findings that resulted from the studies relating to the Goldstone Energy Project.

## D. PURPOSE OF THE REPORT

Although this report identifies and summarizes the work conducted in support of the Goldstone Energy Project over a three-year period from July, 1973, to October, 1976, the primary purpose of the assessment report is to provide information for management decision-making. Specifically, the report includes information to aid TDA and OTDA managements to answer questions relating to the Project goals for lowering consumption of non-renewable energy at DSN stations and complexes.

In addition, the report describes the characteristics of the Goldstone Energy Project and explains why the Goldstone installations are uniquely suited to support a demonstration of the concept of energy self-sufficiency using solar energy. The report identifies many configurations that have the potential for energy self-sufficiency, including a configuration which the Project developed and which appears to be the most promising.

# SECTION II

# HISTORY AND GENERAL INFORMATION

## A. HISTORY

### 1. NSF/NASA Solar Energy Study

During the last few years, there has developed a rapidly growing and widely diversified interest in energy demand, dwindling fossil fuel supplies, increasing fuel costs, and possible new energy sources for the short- and long-range future. A very large number of published papers, speeches, and advertisements have addressed the nation's energy problems from technical, environmental, and social viewpoints. One of the early authoritative documents was issued by the National Science Foundation/ National Aeronautics and Space Administration panel titled An Assessment of Solar Energy as a National Energy Resource (Reference 1). This report clearly presents the significant contribution that the use of solar energy can make in meeting the nation's energy requirements. Recognizing that a substantial development program will be required to utilize the solar energy effectively, the NSF/NASA report recommended:

(1) That the Federal government take a leading role in developing a research and development program for the practical application of solar energy to the heat and power needs of the United States.

(2) That the solar energy R&D program provide for simultaneous effort on three main objectives: (a) economical systems for heating and cooling of buildings, (b) economical systems for producing and converting organic materials to liquid, solid, and gaseous fuels or to energy directly, and (c) economical systems for generating electricity.

(3) That research and development proceed on various methods for accomplishing the objectives above and that programs for phased decision points be established for concept appraisal and choice of options at the appropriate times.

(4) That for those developments which show good technical and economic promise, the Federal government and industry continue development, pilot plant, and demonstration programs.

(5) That environmental, social, and political consequences of solar energy utilization be continually appraised and the results employed in development program planning.

### 2. AEC Energy Study

In December 1972, the Atomic Energy Commission submitted a report to President Nixon titled The Nation's Energy Future (Reference 2), which clearly described energy consumption trends in recent years, anticipated energy needs, available fossil and nuclear fuel resources, and the expected depletion rate of the nonrenewable fuel sources. Although the report placed heavy emphasis on the development of the nuclear energy technology, it also stated the need for developing renewable energy sources (hydro, geothermal, and solar). Five energy task areas were recommended for implementation if the nation is to regain and sustain a condition of energy self-sufficiency. These tasks are as follows:

Task 1. Conserve energy by reducing consumption and conserve energy resources by increasing the technical efficiency of conversion processes.

Task 2. Increase domestic production of oil and natural gas as rapidly as possible.

Task 3. Increase the use of coal, first to supplement and later to replace oil and natural gas.

Task 4. Expand the production of nuclear energy as rapidly as possible, first to supplement and later to replace fossil energy.

Task 5. Promote, to the maximum extent feasible, the use of renewable energy sources (hydro, geothermal, solar) and pursue the promise of fusion and central station solar power.

The Goldstone Energy Project was directly involved with achieving the stated objectives of Tasks 1 and 5, namely, energy conservation and the development of renewable energy sources.

3. Project Independence

The nation became acutely aware of the marginal and changing nature of our fuel supplies and needs in the second half of 1973 when the flow of oil to the United States was stopped by the oil-producing nations. As a direct result of the fuel crisis that developed, President Nixon, in a nationwide speech, November 8, 1973, stated that a long range plan for energy self-sufficiency was essential to maintaining the well-being and security of the United States. Hence, Project Independence became established when the President stated:

"Because of the critical role which energy research and development will play in meeting our future energy needs, I am requesting the Congress to give priority attention to the creation of an Energy Research and Development Administration separate from my Proposal to create a Department of Energy and Natural Resources. This new administration would direct the $10 billion program aimed at achieving a national capacity for energy self-sufficiency by 1980. This new effort to achieve self-sufficiency in energy, to be known as Project Independence, is absolutely critical to the maintenance of our ability to play our independent role in international affairs. In addition, we must recognize that a substantial part of our success in building a strong and vigorous economy in this century is attributable to the fact that we have always had access to almost unlimited amounts of cheap energy. If this growth is to continue, we must develop our capacity to provide enormous amounts of clean energy at the lowest possible cost. Thus, irrespective of the implications for our foreign policy and with the implicit understanding that our intentions are not remotely isolationist, the increasing costs of foreign energy further contribute to the necessity of our achieving self-sufficiency in energy."

The President further established the Federal Energy Office as the focal point for energy matters within the Executive Branch in the President's budget speech to Congress on February 4, 1974. The Federal Energy Administration developed the "Project Independence Blueprint" which covers conservation, research and development, energy resource development, quantitative analysis, policy evaluation, and international assessment.

4. Energy Conservation at Federal Installations

In response to an Executive Order from the President of the United States dated June 29, 1973, NASA issued a series of memoranda to its field centers, including JPL. On July 13, 1973, the NASA Associate Administrator for Space Science issued a memorandum which stated the requirement for the designation of an Energy Reduction Coordinator for JPL. On December 10, 1973, the NASA Deputy Administrator issued a memorandum which appointed a special task force on energy conservation and requested "that NASA apply its technical and management ingenuity to seek out new and imaginative ways in which NASA and others can conserve energy that is in short supply."

On January 17, 1974, the NASA Deputy Administrator distributed copies of the NASA Energy Conservation and Management Plan which among other statements included the following:

> "While other agencies will be charged with primary responsibility for energy research and development, NASA certainly can and should play a key role in research, development, and technological application for the longer term solution of projected energy requirements and efficiencies."

B. GENERAL INFORMATION

1. National Requirements

In order to provide for a continuing growth in national productivity it is necessary that an assured supply of energy in the desired form be continuously available in the quantities and at the locations that match the nation's productivity needs. The increasing difficulty of locating and recovering fossil fuels, coupled with the apparent uncertainties resulting from importing a major portion of the petroleum required by the nation, has greatly intensified the problem of domestic energy scarcity. The nation's ability to continue its progress and maintain its international position and security depends upon achieving a significantly greater capability for energy self-sufficiency.

2. Institutional Qualifiers

The California Institute of Technology and the Jet Propulsion Laboratory have a record of participating in and contributing to the achievement of many of the nation's scientific and technical goals. The principal requirements for NASA-Caltech-JPL involvement in a major energy system development such as the Goldstone Energy Project are:

(1) Significant contribution to the National Energy Independence Program. When the question is asked, "Why do it?" the justification should be positive, convincing, and indisputable. The Project should demonstrate that this nation has a supply of clean energy sufficient to meet its needs forever.

(2) JPL-Caltech-NASA Technological role. The Project should be a good example of applying space technology to national needs and should require the services of advanced technological institutions. The Project should be an outstanding accomplishment that could eventually lead to a solar-hydrogen economy; otherwise, it would be a highly visible example of dead-end technology which would discredit the organizations involved.

(3) Proper balance between difficult challenge and risk of failure. Project success should not depend on major breakthroughs to achieve the required performance at a competitive cost. Also, the fact that technology with a social conscience must be competitive in the public marketplace is noted to present a considerable challenge and a high risk.

3. Requirements Upon the Project

In general, the requirements on the project are listed below as they were perceived at the time; that is, the statements are expressed in the present tense rather than in the past tense, which would be appropriate from the vantage of our present knowledge of the project's history. This approach has been taken in order that the way in which the constraints were originally set forth may serve more easily as a guide of experience in the formulation of projects with similar constraints.

a. Justification. The justification for undertaking the Goldstone energy project included at least five important and interrelated factors:

(1) Economic. On the basis of the life-cycle cost analysis, the proposed energy system is expected to result in a positive cost benefit to JPL and NASA.

(2) Conservation of natural resources. The use of renewable fuels to operate the NASA facilities would result in some reduction in the use of increasingly scarce fossil fuels.

(3) Environmental enhancement. The proposed system is expected to enhance environmental quality.

(4) Industry participation. The Project would benefit United States industry by utilizing government resources to strengthen industry through technological advancement.

(5) Unique system demonstration. The Project would demonstrate a unique end-to-end solar-hydrogen energy-on-demand system that could lead the way and contribute to the inevitable transition to the use of renewable fuels as finite supplies of fossil fuels are exhausted in the next century.

The primary emphasis throughout the conduct of the Goldstone Energy Project was to provide information with sufficient validity to enable JPL and NASA to conclude whether building a solar-hydrogen, energy-on-demand system anywhere in the United States on an economically sound basis within the 1970 decade could be justified.

b. Guidelines. An energy system exists at Goldstone. It was designed and built to help in meeting the need of NASA to track spacecraft. Its chief characteristics are adequacy, reliability, and minimum first cost. The evolution of the system over more than a decade has been primarily in the direction of increasing capability to meet demands. With increases in the cost of energy and the desire to move toward national energy self-sufficiency, evolution in a different direction is being considered.

The energy system must generally remain in operation continuously and with high reliability. Downtime to make modifications is permitted only for short periods and only for portions of the system. Thus, while it is appropriate to think in terms of a final system configuration, it is necessary to keep in mind that the modifications will be made in stages, each stage associated with a particular objective, or possibly a single tracking station. Each stage will have to be justified, although not necessarily each tracking station, if the combination of modifications at all tracking stations can be justified.

Therefore, each stage in the evolution of the energy system must be well defined as well as the final configuration, and the analyses must be made stage by stage so that each stage may be understood and justified. In general, the energy system resulting from any one stage should be fully operational and reliable, and better, in terms of the goal and objectives of the Project, than the preceding stage.

Implementation of two stages together, however, is acceptable when the superiority of this concept is clearly demonstrated by detailed analysis.

Modularity and functional or physical redundancy must be retained through any modifications or additions to the energy system. For example, engine-generator capability is both modular and redundant to provide standby units in case of failure, to allow for maintenance while continuing to support operations, and to make it easy to add capability by adding modules.

Those portions of the energy system, such as buildings, electrical transmission lines, and pipelines for fuel distribution, which do not lend themselves to being entirely modular, should be sized for growth. If this Project were not undertaken, the energy system would be expected to grow at 3-1/2% per year. If the Project is undertaken, the amount of growth is expected to be less than 3-1/2%. These growth projections are to be used, however, only to size those elements to be added to the system that cannot readily be modularized to permit easy expansion.

The modularized portions of the system are assumed to experience no growth beyond July 1, 1974. The purpose of this guideline is to simplify the study.

c. <u>Constraints</u>. The constraints on the Project pertain to the conceptual design of the energy system. The chief constraint was that systems to be implemented must be economically viable or have economic potential. The following is a list of those constraints:

(1) The Project must not interfere with GDSCC's primary mission of tracking spacecraft. If possible, it should improve the capability of executing that mission.

(2) The energy system shall be safe to operate and maintain. The proposed system shall be at least as safe to operate and maintain at each stage of implementation as it was at the previous stage, and shall, as a minimum, meet Occupational Safety and Health Administration (OSHA) standards. This requirement does not impose any obligation with respect to the existing energy system.

(3) The Project must not adversely impact the environment at Goldstone. If possible, the system should improve air and water quality.

(4) The Project is constrained to use technology which will be aesthetically pleasing and acceptable to the general public, and which will support the national goal of self-sufficiency as broadly as possible. Techniques for achieving self-ficiency which are narrowly restricted to federal installations or to a small region of the country, such as Southern California, are not acceptable.

(5) The energy system must be capable of being designed and built by means of fixed-price contracts to an established budget and schedule and according to NASA Construction of Facilities practices. That is, it is not to be implemented as research and development.

(6) The Project must have economic viability or economic potential, or both.

(7) The number of maintenance and operations (M&O) personnel required for the proposed energy system shall be minimized and shall not, in any case, exceed the number of personnel required for the present system. The mix of personnel skills may be changed as necessary.

(8) The siting of the various elements of the proposed energy system must be entirely contained within the Goldstone property and shall not interfere with, or otherwise degradethe performance of, the tracking stations either during construction or operation. No element shall alter the radio frequency horizon mask as seen by an antenna nor generate radio frequency interference. The elements shall be sited so as to minimize the amount of land used exclusively the energy system.

(9) Electrical energy shall not be fed back to the public utility, nor shall operation be in parallel with Southern California Edison Company (SCE).

(10) Gaseous synthetic fuels shall not be released to the atmosphere as a method of discarding excess energy when the fuel storage device is filled.

(11) The operational integrity of the Complex and of each tracking station and facility must be maintained throughout the implementation and operation. This means that the energy system must remain at least as reliable, maintainable, flexible, and redundant as it now is, and the completed system must have an assessed reliability at least as high as the present system.

(12) Environmental quality must be protected and enhanced by the implementation and operation of the proposed energy system.

(13) Component performance must be analyzable so that optimization is possible and system performance can be predicted with only a small margin of uncertainty.

(14) Modular construction is required because it shall be the means for providing the flexibility needed to permit (a) off-line maintenance and repair and (b) incremental increases in capacity without service interruption. System elements which cannot be modular, such as buildings and pipelines, shall be sized for projected growth.

(15) Component technology must either exist or be in an advanced state of development.

(16) A clean, renewable synthetic fuel must be used as the primary fuel for the operation of the engine-generators. (Small injections of diesel fuel oil for ignition purposes may be used if necessary.)

d. Consideration of Goldstone Uniqueness. The Goldstone Deep Space Communications Complex, located north of Barstow, California, consists of six separate tracking stations that are used for communicating with earth-orbital, lunar, and planetary spacecraft, and a Microwave Test facility. Figure 2-1, a site plan of the Complex, identifies each of the seven major facilities and shows their relative locations. The Apollo and Mojave Stations are part of the Spaceflight Tracking Data Network (STDN) managed by the Goddard Space Flight Center (GSFC), and DSS's 11, 12, 13, and 14 and the MTF are part of the Deep Space Network managed by JPL, which is also the general manager for the Complex.

Collectively, the Complex consumed 30,000 MWh/yr of electrical energy in 1973, of which 90% was supplied by the Southern California Edison Company (SCE) and 10% by four on-site diesel and turbine power plants. The plants have sufficient capacity to meet the total peak power demand of the Complex, including on-line and maintenance spares, except for one R&D station (DSS 13), to which none of the on-site generator power is connected. Table 2-1 shows the total installed generating capacity by power plant, location, and engine-generator rating.

Goldstone appeared to have several characteristics which made it unique for demonstrating energy self-sufficiency:

(1) A significant amount of installed generating capacity, which is fully operational and has a long-term tracking and data acquisition mission in support of the nation's space program.

(2) A near-ideal location in the southwestern region of the United States, with an average annual insolation among the highest in the world. In addition, the local terrain has broad valleys for solar collectors, high plateaus and hills on which to locate wind turbines, and even isolated canyons for safe fuel storage if necessary. Located in the desert at an altitude of 900 m (3000 ft), it has low humidity and cool nights, with typical wet-bulb nighttime temperatures of 10-15°C (50-59°F).

(3) A large amount of land area, which, although essential for alleviating the threat of radio frequency interference, could nevertheless be made available for other useful purposes provided they did not adversely affect GDSCC's primary mission.

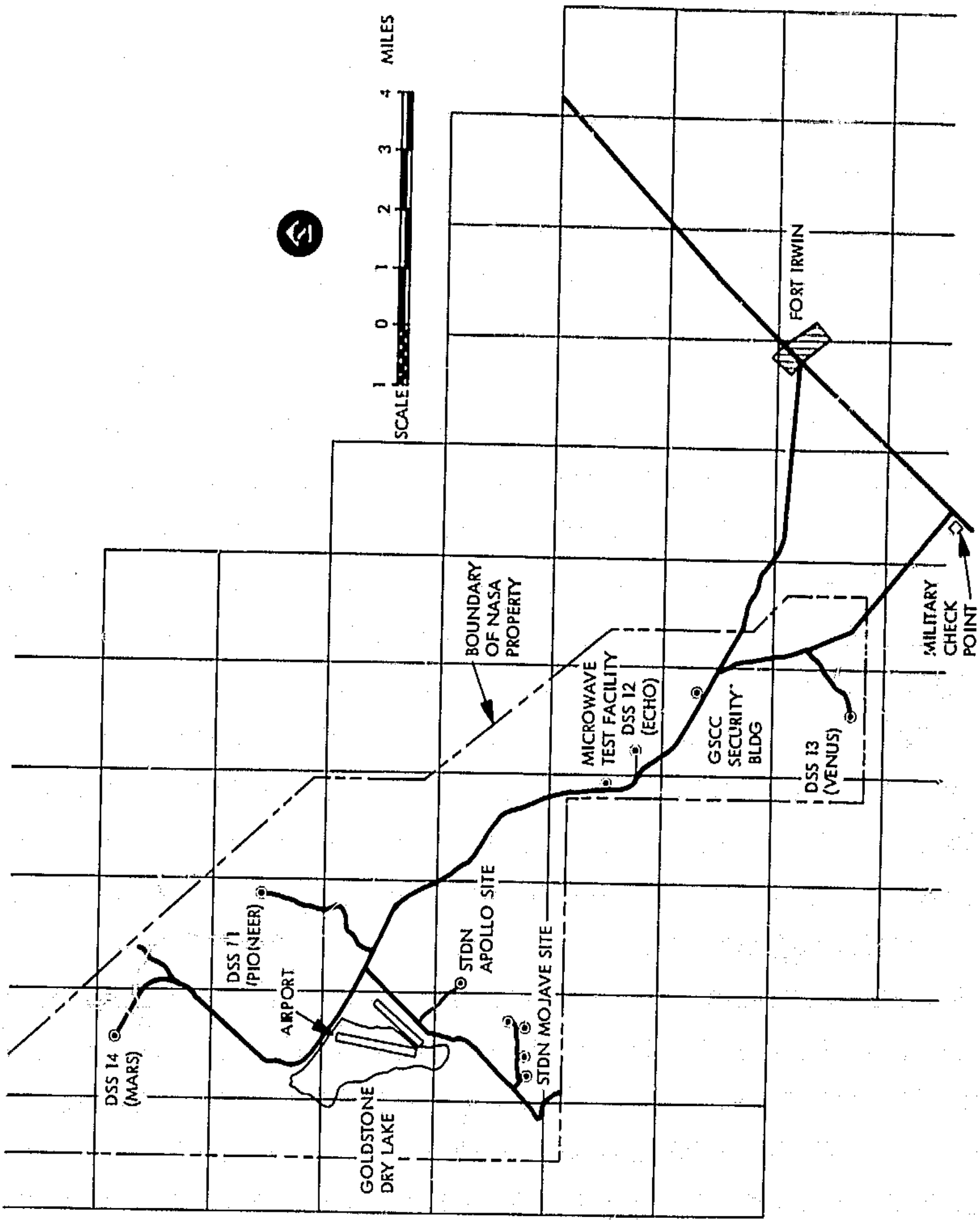


Figure 2-1. GDSCC Site Plan, General Layout

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Table 2-1. GDSCC Power Plant Capabilities

| Facility | Generator Capabilities | | | |
|---|---|---|---|---|
| | Engine Type | Capacity, kW | | Number |
| | | Generator | Plant | |
| DSS 11 | Diesel | 150 | 1,300 | 2 |
| | | 500 | | 2 |
| DSS 12 | Diesel | 350 | 1,850 | 1 |
| | | 500 | | 3 |
| DSS 14 | Diesel | 500 | 5,000 | 4 |
| | | 750 | | 4 |
| STDN | Diesel | 250 | 4,200 | 2 |
| | | 350 | | 2 |
| | Gas Turbine | 750 | | 4 |
| Total | | | 12,350 | 24 |

(4) A complete, fully operational, self-contained Energy System of significant size (equivalent to a small community of 3000 homes in energy consumed), under a single general administrator (NASA-OTDA) and free of zoning or other land-use restrictions--all of which afford an unusual opportunity for the application of systems technology.

(5) A very strong technological base, starting with a large cadre of technical personnel at the Complex who operate and maintain the tracking stations and extending to the JPL scientific and engineering personnel who designed the Complex, managed its construction, and supervise its operation. In addition, JPL is a part of the California Institute of Technology and NASA.

(6) Modularized power plant construction with sufficient capacity at each of four separate plants for maintenance spares. This configuration makes possible a structured, evolutionary approach to implementation without jeopardizing the operational integrity of the overall energy system.

e. <u>Life-Cycle Cost Specifications</u>. A life-cycle cost approach was specified that involves comparing the cost of a new or alternative system against the cost of the present system. The cost of an alternative system is defined as the cost required to implement, maintain, replace as necessary, and operate the new system for the first 10 years of its useful life. The cost of the existing system is defined as the cost to maintain, replace as necessary, and operate the existing system for the same 10-year period. The break-even point is defined as the time when the costs of the two systems are equal.

For purposes of determining the life-cycle cost of the alternative system, the implementation or construction cost is considered to be a one-time cost incurred at the beginning of useful life of the system, although the actual costs may be incurred over a period of time. A graphical presentation of this cost accumulation is shown in Figure 2-2. It should be noted that the construction cost does not include special one-time development, production engineering, tooling, or other similar costs that would not be required for the installation and construction of a similar system.

The accumulation of the life-cycle cost for the existing system is developed in the same manner, except that no initial costs are included; i.e., the cost of the existing system is zero at the beginning of the 10-year cost comparison period. The graphical representation of the cost accumulation for the existing system and the alternative system is provided in Figure 2-3. This illustration shows a break-even cost at about 8-1/2 years, with the proposed system having a lower total cost after that date. Thus Figure 2-3 indicates that the alternative system is economically viable because the break-even point is within the 10-year base period. When the break-even point is beyond the 10-year period, the proposed system would normally not receive any further consideration unless the break-even point was close to the 10-year time period and other factors warranted its implementation. It is noted that break-even times do not exist for cases where the life-cycle costs do not converge.

f. <u>Energy Cost Projections</u>. A fundamental question associated with the computation of life-cycle costs is how to accommodate the effect of inflation. In the studies done in support of this report, life-cycle costs were determined in fixed 1975 or 1976 dollars, depending upon the time period in which the study was conducted. The value of energy was projected (as far as 1990 in terms of 1976 dollars for the solar heating and cooling study). The value of energy, hence the relative cost, can be expected to escalate relative to other commodities in the marketplace. The following factors are still as true as when they were postulated at the beginning of the Goldstone Energy Project:

(1) The world demand for energy is growing and will force the price of energy upward in accordance with the supply-demand relationship.

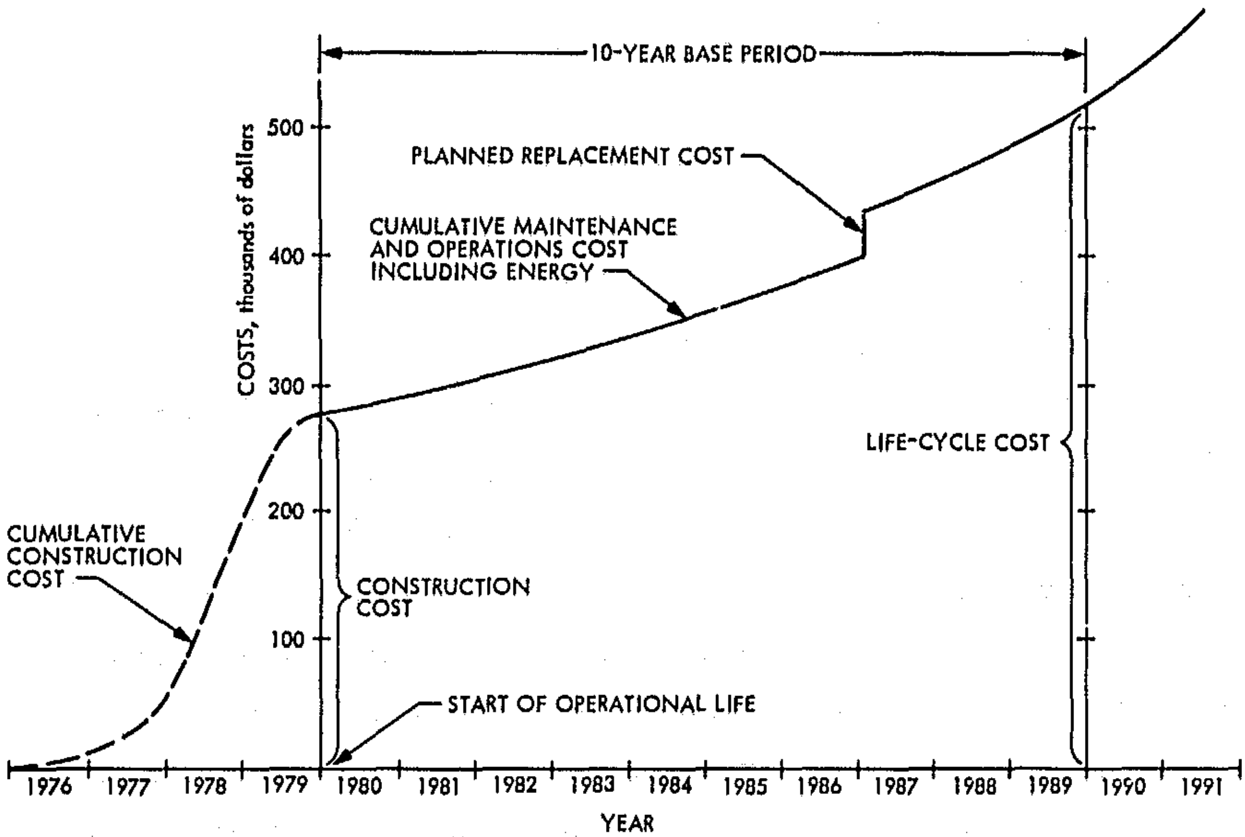


Figure 2-2. Illustration of Cost Accumulation to Obtain the Life-Cycle Cost of an Alternative Configuration

(2) A favorable United States balance of trade in the world market and other factors will require a greater dependence on domestic fuel sources, even at higher prices.

(3) Exploitation of domestic fuel resources such as the Alaskan North Shore Oil, offshore oil, and coal or oil shale mining will lead to higher prices because the resources will become harder to extract.

(4) Public concern about atomic power will lead to added safety and security for power plants, fuel handling, and radioactive waste disposal.

(5) If the national goal of energy independence is aggressively pursued and achieved, it will result in higher energy costs to the United States consumer.

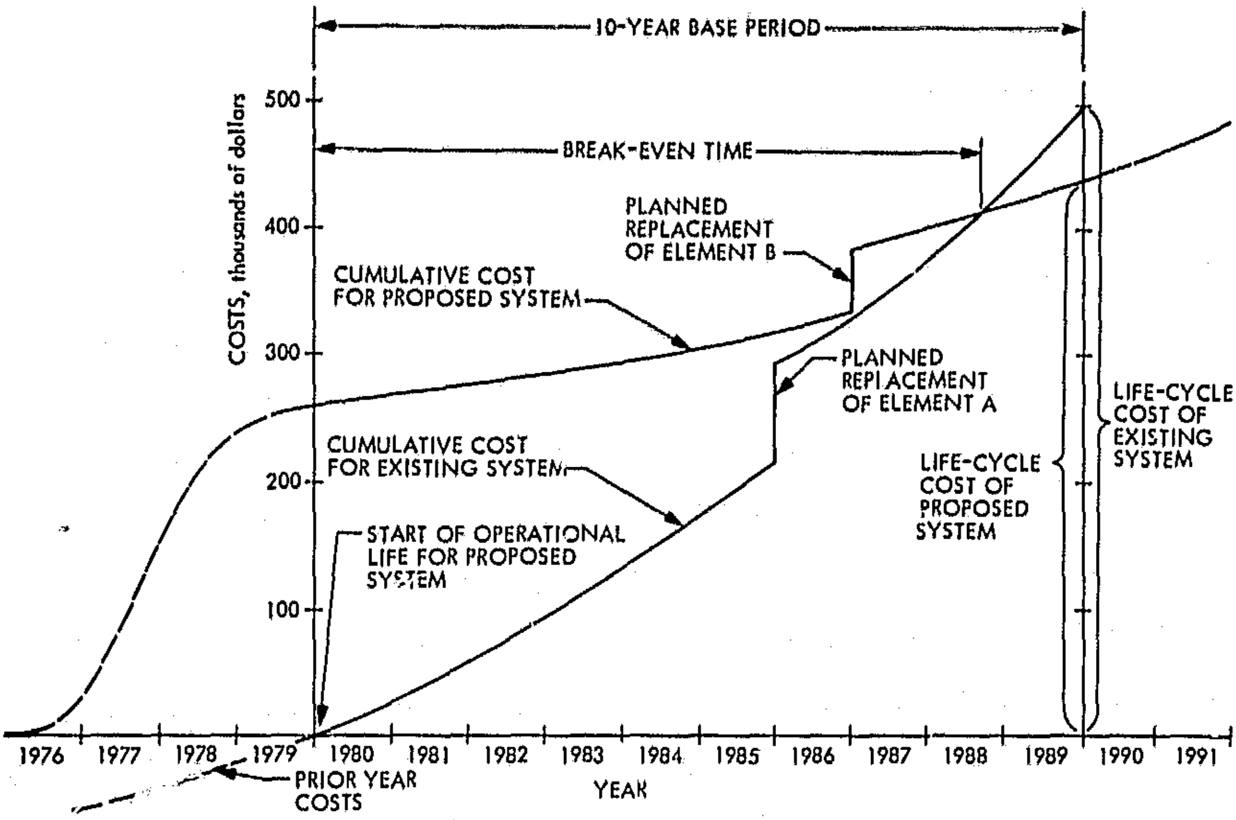


Figure 2-3. Illustrative Comparison Between the Life-Cycle Costs of Two Alternatives

(6) National progress requires more energy per capita to increase productivity even as energy waste is being eliminated.

(7) Public demand for improved environmental quality will promote the production of clean energy in various useful forms, even at higher prices.

Because of these factors, it was assumed that the increase in the value of all forms of energy from 1973 would be at least double by 1975. After 1975, prices were assumed to increase at a rate of 10% per year until the midpoint of construction of any new project or subproject. After the midpoint date, the value of energy relative to other commodities in the open marketplace was assumed to climb at a rate of 7.5% per year.

In 1974, just after the peak of the fuel crisis, this projection of the value of energy was considered to be conservative. The rationale for this cost guideline was to avoid the use of inflated dollars as much as possible in assessing economic viability. In retrospect, the assumption was not conservative since energy costs have not escalated as rapidly as expected. Table 2-2 shows the costs of energy at Goldstone for the years 1973 through 1977.

g. Intangible Cost Considerations. One of the major objectives of this Project was to reduce the consumption of petroleum fuel and petroleum-fuel-derived commercial electricity by a minimum of 70%. At the same time, there would have been an attendant reduction in the air pollutants that would be released by the burning of petroleum fuel. The conservation of an irreplaceable natural resource and the enhancement of environmental quality are respectable accomplishments. However, these accomplishments cannot easily be translated into monetary savings to support Project justification. In addition, the elimination of petroleum fuel consumption for the operation of the Goldstone power plants, or for the generation of commercial power used at Goldstone, would reduce the need to import foreign oil and cause a direct dollar-for-dollar contribution toward a favorable United States balance of payments. While these intangible factors were not included in the life-cycle cost analysis, they should be considered relative to making final conclusions and recommendations.

Table 2-2. Cost of Energy at Goldstone

| FY | Low Pressure Gas | | Diesel | | ¢/kWhe |
|---|---|---|---|---|---|
| | ¢/liter | ¢/gal | ¢/liter | ¢/gal | |
| 73 | 3.2 | 12 | 3.2 | 12 | 1.32 |
| 74 | 6.3 | 24 | 6.3 | 24 | 1.95 |
| 75 | 6.6 | 25 | 8.7 | 33 | 2.59 |
| 76 | 8.2 | 31 | 9.8 | 37 | 2.78 |
| 77 | | | | | 2.83 |

# SECTION III

# PROJECT DESCRIPTION

## A. PURPOSE OF THE GOLDSTONE ENERGY PROJECT

The primary emphasis throughout the conduct of the Goldstone Energy Project was to provide information with sufficient validity to enable JPL and NASA to conclude whether building a solar-hydrogen, energy-on-demand system anywhere in the United States on an economically sound basis within the 1970 decade can be justified.

The following questions are typical of those which were asked about Goldstone and the state of the technology in the various solar energy application areas:

(1) What are the existing loads or energy requirements at Goldstone? What is the character of those loads? How do the loads vary and why? How can the existing loads be modified or reduced?

(2) What energy requirements could be met by on-site resources? What is the character of potential on-site resources? How much solar radiation? How much wind? What useful energy could they provide?

(3) Is technology ready to support the utilization of on-site resources? Are technological breakthroughs required? Can a "design and build" project be carried out?

(4) Is it economically feasible to utilize on-site resources? What capital costs and life cycle costs can be expected?

## B. APPROACH

Decades of dedicated effort by thousands of solar energy enthusiasts have produced few, if any, commercially viable products or systems. With the cost of conventional energy increasing and the public receptive to the need for clean energy, a unique situation existed for the hitherto unused system engineering techniques to attack the problem. The project personnel were mindful of the pitfall of drawing on empirical results of individual experimenters and relied only on fundamental engineering principles based on science and theory.

To achieve the project purpose and to answer the questions raised during the formulation of the Project, an energy system configuration was devised to illustrate the wide range of options available and to provide a point of departure for all studies. Before the studies were initiated, the options were sequentially evaluated according to a set of criteria described below. A number of options were eliminated, reducing the possibilities to a baseline system configuration, to be used as an example for analysis by an architectural and engineering contractor as part of a system feasibility study.

1. Energy System Evaluation Criteria

The criteria developed by JPL for the purpose of evaluating the energy system options and arriving at a baseline configuration were as follows:

Performance:

(1) Conservation of nonrenewable energy resources through the use of solar energy.

(2) Evolution of the energy system, from its present configuration to the final configuration, with no loss of operational integrity.

(3) Preservation or improvement of environmental quality, including ecological considerations.

(4) Elimination of energy waste, resulting in higher efficiency and lower consumption.

(5) Flexibility to meet changing energy requirements.

Cost:

(6) Economic viability as it relates to

(a) Acquisition and the continuing cost of ownership.

(b) Cost break-even within 10 years.

Schedule:

(7) Technological maturity such that the Project

(a) Could be scheduled for implementation within 5 years.

(b) Would not require technical breakthroughs.

Risk and Confidence:

(8) Minimum risk of failure and maximum confidence of success; that is, the system should

(a) Be "design and build" not "research and development."

(b) Provide a noninterruptible source of energy in terms of capacity and reliability.

Other:

(9) Applicability of the techniques and configurations to other federal installation and the civil sector.

## 2. Energy System Options

The basic solar energy system elements (following the nomenclature and using the descriptions contained in Reference 1) are shown in Figure 3-1. Optional solar energy system configurations for supplying primary energy to Goldstone are formed by interconnecting the elements in various ways.

In the left portion of Figure 3-1, the flow of solar radiation from the sun through some collection process (either natural or man-made) to a state or form available at or near the earth's surface is illustrated. The center portion of Figure 3-1 illustrates the various processes which operate on the energy and produce either electrical power or solar-derived fuel. For completeness, the currently existing public utility and fossil fuel sources are also identified. In the right portion of Figure 3-1, utilization of the energy at Goldstone is shown.

## 3. Baseline Configuration

Evaluation of the system options according to the criteria listed above led to an early choice of hydrogen and oxygen as the clean, renewable, synthetic fuel for the baseline configuration. Electricity to produce hydrogen and oxygen would be supplied by wind-electric or solar-thermal-electric arrays, or both.

A key factor in evaluating wind-electric and solar-thermal-electric arrays was the amount of hydrogen-oxygen storage. A solar-thermal-electric plant would require no more than 10 days of fuel storage. However, if 10-20% of the primary energy were supplied by the wind, no additional storage would be required, and the combined wind-solar plant would be slightly less expensive. The combined plant would be less expensive because windmills cost less than solar collectors on a dollar per kilowatt basis even with a 40% load factor for the windmills, and the plant would qualify as a utility system resource.

In addition to the above considerations, it was thought that (1) windmills could be procured for earlier delivery than solar collectors and with less risk of delivery delays, and (2) a small but significant number of windmills would be desirable to provide the necessary test of public acceptance. Therefore, the principal evaluation criteria for selecting a baseline configuration included cost, schedule, qualification as a system resource, minimum land area, and public acceptance. A preliminary evaluation was made to determine which individual elements and system configurations satisfied the evaluation criteria (and hence could attain the program objectives) and should be studied in more detail.

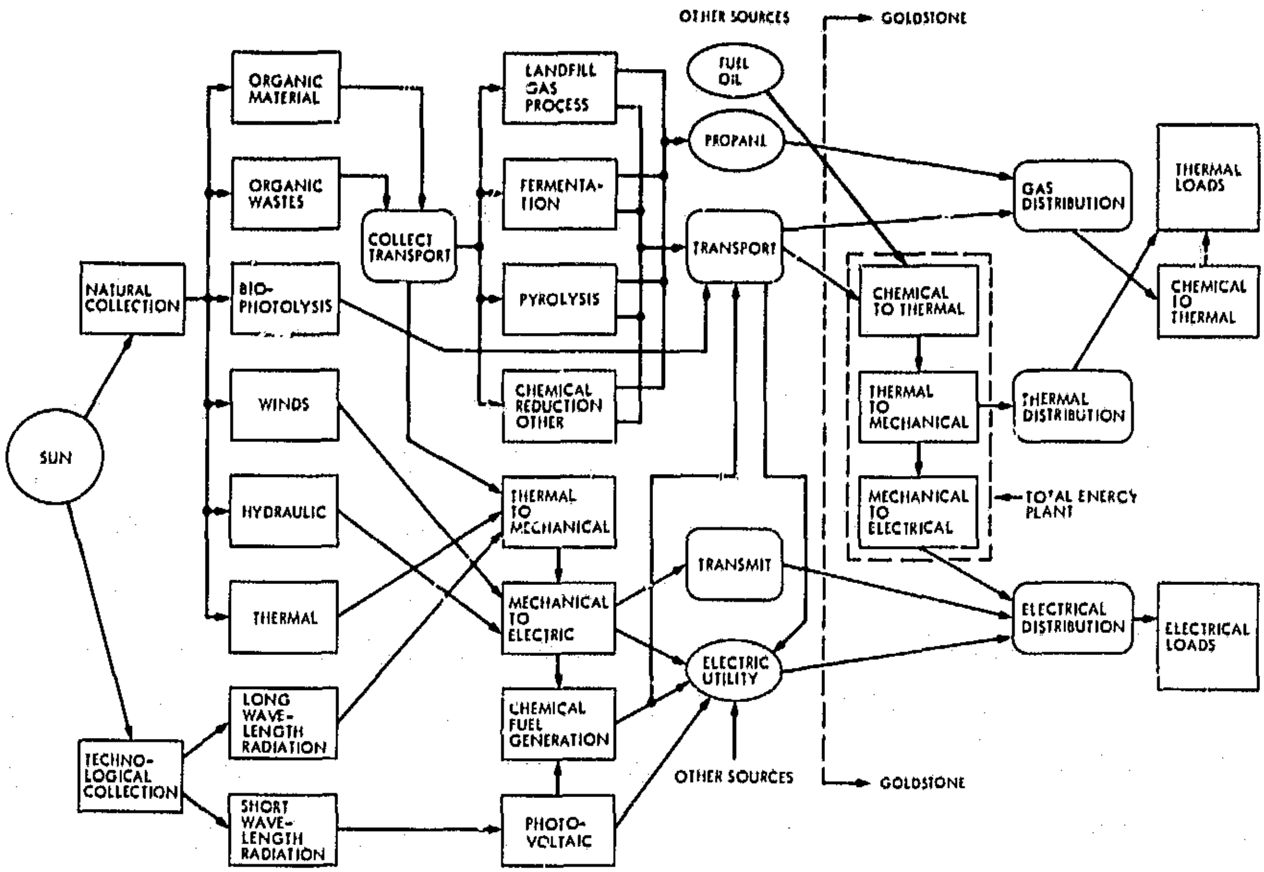


Figure 3-1. Basic Solar Energy System Elements

This evaluation led to the elimination of a number of options. The reduced solar energy system elements are shown in Figure 3-2.

The baseline configuration is shown in Figure 3-3. The existing engine-generators are used to furnish electricity for the electrical loads, with commercial electricity as a backup. The engine-generators are fitted with waste heat recovery devices to provide working fluids, such as steam and chilled water, for heating and cooling. The existing heating and cooling equipment is retained to permit operation on locally generated or commercial electricity, particularly when the demand for electricity is too low to produce enough waste heat for heating and cooling.

The existing engine-generators are converted to burn hydrogen and oxygen as well as fuel oil and air. Hydrogen and oxygen are provided by wind-electric-hydrogen and solar-electric-hydrogen fuel plants. In case of peak loads or low hydrogen fuel production, fuel oil or commercial electricity would be used. The percentages of annual energy to be supplied from each source are indicated in the figure.

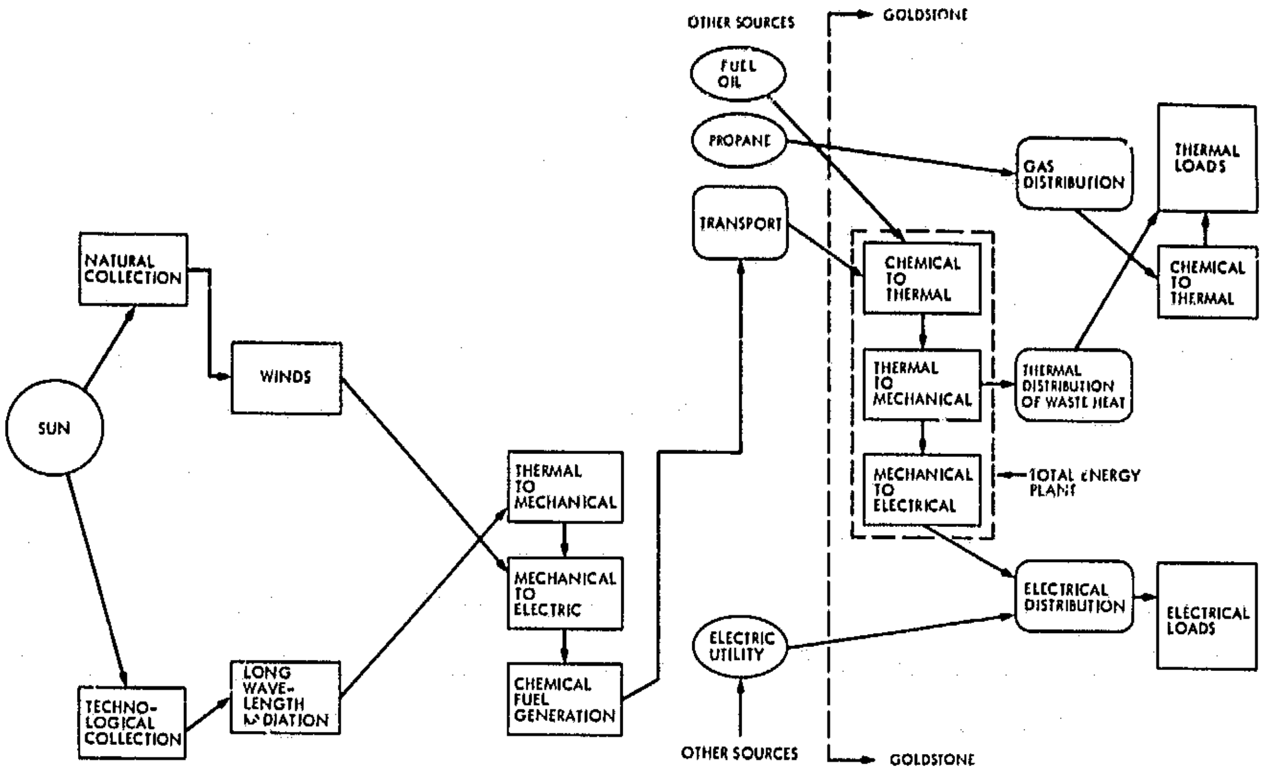


Figure 3-2. Reduced Solar Energy System Elements

Since it is imperative that the reliability and operational integrity of the tracking stations not be impaired, a key feature of this configuration is that the existing engine-generators isolate the new technology from the loads.

Commercial electricity is retained as a backup. Propane is used for some of the heating load and is retained as a backup; however, since it provides less than 1% of the annual energy, the percentage is not shown in Figure 3-3.

## 4. Energy Requirements

Before any analysis of on-site energy utilization could be made, the existing energy system, its loads and energy requirements, needed to be understood and characterized. The architect-engineer company of Keller & Gannon, a subsidiary of Lester B. Knight, San Francisco, California, was contracted to conduct an Energy Audit and Conservation Study at Goldstone. Among the tasks to be accomplished were determination of the magnitude and characteristics of all major energy loads and the preparation of a model capable of predicting the energy requirements when the Goldstone energy systems were operating under the varying

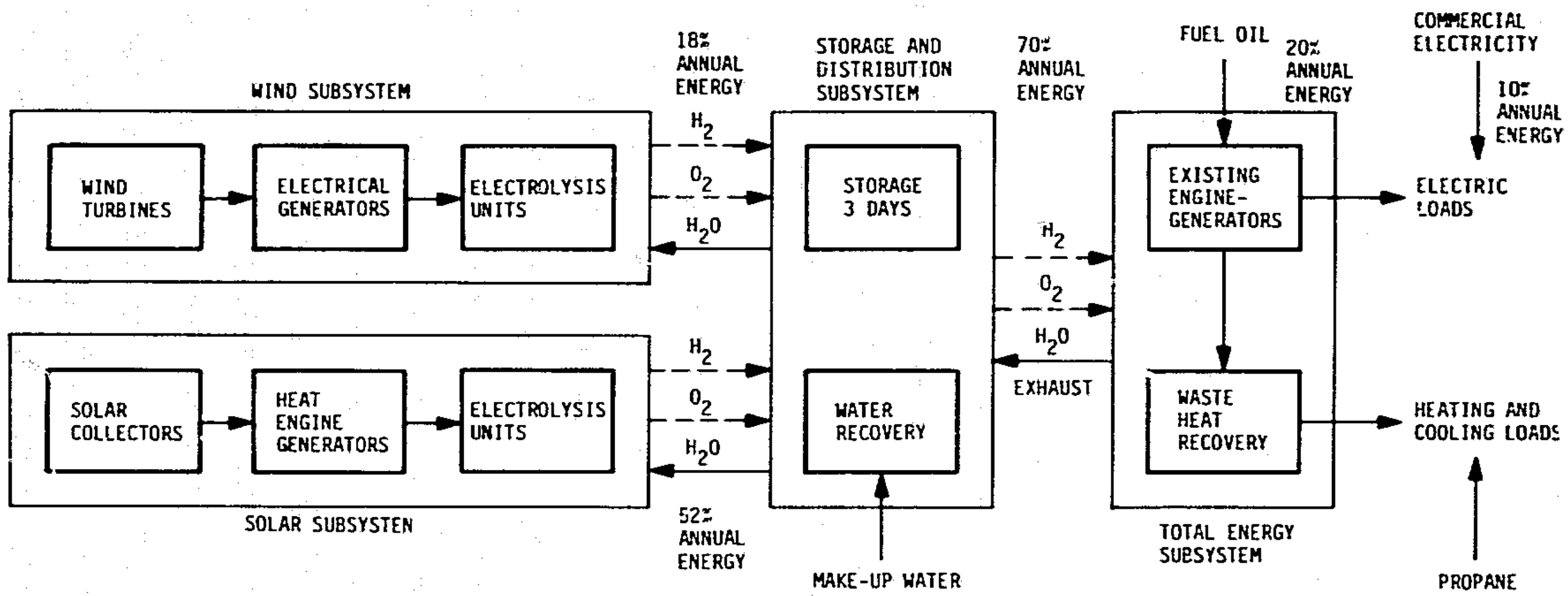


Figure 3-3. Baseline Configuration of the Goldstone Energy System

conditions of weather and tracking operational modes. The results are contained in the study final report (Reference 3).

A major load is defined as a piece of equipment or group of equipments normally operated to perform a function or related set of functions which consumes 5% or more of the energy (in any form) used at a tracking station. All energy was accounted for in the audit, either by usage in a specific major load or grouped in minor loads. The heating, ventilating and air-conditioning systems (HVAC) for any building of more than 36 $m^2$ (400 $ft^2$) of floor area were considered to be a major load since it was felt that these systems also had a great potential for energy savings.

A block diagram showing the major energy loads associated with each tracking station was prepared. This block diagram, together with the characterizations of the several major energy loads, formed the basis for a model capable of predicting the energy consumption for each tracking station under any particular combination of ambient conditions and tracking modes. The several models were combined into an overall model capable of predicting the energy consumption for the Goldstone Complex as a whole. The modeling was done utilizing an existing and recognized computer program, E-CUBE. The Goldstone energy model was verified by inputting data from existing records including ambient conditions and operational modes.

The characterization of the major loads included the effects of such factors as the sun, weather, mission support, building characteristics, equipment characteristics, and operating doctrine. Operating doctrine included both operational procedures and operational standards (e.g., thermostat settings) especially in the area of air conditioning. Cost-effective recommendations were furnished which would reduce energy consumption. These recommendations were accompanied by budgetary cost estimates, operation and maintenance costs, and the number of years for simple pay-out.

The Evaluation of Modifications to Conserve Energy at Goldstone conducted by Burns and Roe, Westbury, N.Y., as part of the Goldstone Energy System Study included a joint JPL--Burns and Roe on-site survey of the Goldstone facilities aimed at identifying potential energy conservation modifications. Tasks included the collection of data necessary to assess the 10-year energy savings of specific recommendations and preparation of budget estimates to implement recommendations. The survey was focused primarily on the 13 buildings at Goldstone which account for the major energy usage. The recommendations for system modifications are described in the Burns and Roe Total Energy Subsystem Report (Reference 4).

Measurements and observations made by Burns and Roe during the field survey were utilized in evaluating the energy conservation recommendations. Information furnished by JPL and utilized in the evaluation included architectural drawings, original design calculations, maintenance and operating manuals, existing lighting loads, equipment loads, and recommended lighting load reductions. The information generated by

Keller & Gannon on energy requirements was reviewed, assessed, and utilized in the evaluation where appropriate.

A not insignificant asset associated with the energy audit conducted by Keller & Gannon and the field survey conducted by Burns and Roe is the volume of valuable facilities parameters that describe all the buildings of the Goldstone Complex. The facilities parameters include any aspect of a building that affects energy consumption: air conditioning equipment, utilities, lighting, architectural material properties, occupancy, electronic equipment, and weather, to name only a few. To reduce the time and cost associated with the acquisition, maintenance, and distribution of energy-related basic design information, a data base was designed and implemented.

The energy data base engineering capability is based upon the following criteria:

(1) A readily available and easily accessible source of valid and up-to-date technical and descriptive data.

(2) A central, standardized reference to augment engineering designs that are energy-efficient.

(3) Information for effective energy management.

(4) A historical record of energy consumption for comparison with energy project objectives.

The data base is a structured data base of raw values and is maintained as a standardized, cross-referenced hierarchical tree of files such that all users will obtain energy data according to a standard format (Reference 5).

5. Resources

Design of an economically viable solar energy conversion system must be done not only on the basis of its intended output but also on the basis of the energy input that can be expected during its lifetime. Simulation of system operation by a dynamic system model can allow evaluation of expected performance within an acceptable uncertainty, if enough knowledge about the primary driving functions, solar radiation and wind, is available. For these reasons, the Project initiated efforts to measure the power in the wind and solar radiation at Goldstone and develop that data into prediction models. The dynamic system analysis was developed as a tool with which performance estimates could be made based upon the prediction models.

a. Statistical Analysis of Insolation. Development of a probabilistic model of insolation for the Mojave Desert area, based on accurate radiation intensity measurements made at Goldstone, was undertaken by JPL (References 6 and 7). The output of the model is a representation of insolation characteristics depicting those aspects of both long-and short-term behavior on which system performance depends, expressed as a year-long time series of radiation intensities that can be extrapolated to match closely all important aspects of insolation integrated over many years. At the time the development work on the model was begun, the only relevant data sets on which the design could be based comprised 19 years of cloud cover data as reported by the National Weather Service (NWS) and six months of measured pyrheliometer data taken at 2-min intervals. Both of these data sets were used in the construction of a "first draft" model. The NWS cloud cover data consists of hourly reports of the percentage of total sky cover as well as other information such as number of layers, height, etc. The measured insolation data consists of direct component pyrheliometer data with known accuracies and calibrations.

Measured insolation data and coincident cloud cover data were merged; the resulting correlation was used to extend the measured data over a year. The probability characteristics of the model's outputs, which include averaged, integrated, and instantaneous point intensities at time intervals chosen by the user, match the probability characteristics of the combined sets of measured insolation data and the 19 years of cloud cover data.

b. Statistical Analysis of Wind. At the start of the wind model studies, there was a limited amount of digitized wind speed data available for the Goldstone site. This data had been collected during the years 1966-1968 at three different anemometer heights on a wind tower near the Mars antenna to determine structure wind loading. The records consist of average wind speeds over 5-min periods at sampling intervals of either 1 or 3 hours.

The Mars tower is situated on flat, desert-like terrain bordered by a few low hills. This area has some similarities to a typical airport. Consequently, to have supplementary regional data for a better description of local wind phenomena, a substantial amount of U.S. Weather Bureau archive wind speed records were digitized for computer examination. These consisted of hourly average wind speed records at three nearby airports: Edwards Air Force Base, George Air Force Base, and the Daggett Marine Center airport. All of these sites are in the Mojave Desert, as is Goldstone, and within a 110-km (70-mile) radius. The instrumentation used to collect the data and the sampling procedure are not known. The data, however, is supposed to represent the hourly average wind speed determined from a sample of duration of a few minutes or else of an instantaneous estimate by on-site operating personnel.

In addition to the older existing data, a new data collection program for the Goldstone site was initiated in October 1974 with 10 anemometers distributed at six sites. For two years, these units have provided continuous strip chart readings of wind speeds. However, only a relatively small part of this data has currently been reduced to a form suitable for processing. This equipment consists of a cup-type anemometer that measures the horizontal component of wind speed and a vane-type wind azimuth direction indicator. Meteorology Research Inc., Pasadena, California, assisted in site reconnaissance for these stations and designed, supplied, and erected the instrumentation (References 8 and 9).

Wind speed ratio (the ratio of short-term mean speed at a proposed windmill site to long-term mean speed at a reference site) was studied as a means of accounting for the effect of local terrain on wind speed. Meteorology Research Inc. used computer programs to generate a family of isotachs (lines of constant wind speed) over the Goldstone region. The Goldstone terrain was approximated by an array of rectangular cells subjected to a uniform horizontal flow field. The programs solved the pertinent equations of fluid motion, indicating the points of maximum wind velocities.

The original purpose of the wind model studies was to examine the suitability of the Goldstone site for the collection of wind energy. The specific objectives were to be able to identify promising candidate windmill sites and estimate the incident wind energy. Subsequently, during the evolution of the comprehensive energy system simulation, an additional requirement arose to derive a wind speed simulation model. Consequently, there are two distinct types of models that were initiated: the original site-evaluation type of model is an attempt to parameterize candidate windmill studies on the basis of relatively long-time periods (months or years) for the collection of wind energy; the more recent simulation model attempts to provide sequences of representative sample wind speeds at relatively short-time intervals (possibly hours). Although both models evolve from the same basis of the available or projected statistical characteristics of the site, their formulation and application, which tend toward being deterministic in the first case and stochastic in the second, are greatly different. Aside from developing a limited interim model for wind speed simulation and discussion of a proposed extended simulation model, most of the effort to date has been on the original parameter type site evaluation model. The models are described in Reference 9.

c. Dynamic Analysis. One of the constraints leveled on the project was that system performance be predictable within a small margin of uncertainty. In contrast to conventional power systems that operate predominantly as steady-state output devices, solar power systems must be designed to utilize a variant energy input in the form of insolation and wind. Solar radiation intensity is location-dependent, and fluctuation with time is only partly deterministic, with largely probabilistic effects occurring on time scales from minutes to seasons or longer. Wind speed and direction have similar characteristics. One consequence of these characteristics is that solar-driven systems spend a significant portion of their operating time responding to transients, and it is expected that their performance would differ from that predicted on a steady-state basis.

The dynamic model analysis was undertaken to construct a computer-based analytical tool that would simulate the dynamic nature of prospective solar energy systems, taking into account the time dependencies inherent in their operation. The model is described, together with the computer program, in References 10, 11, 12, and 13.

A primary requirement placed on the program that embodies the desired dynamic model was that it be convenient and easy to use. Since it is intended to analyze the performance of many alternative energy systems, the program is modular, allowing quick and simple substitution of components in the system under study. Modules of the dynamic analysis were developed for all components of the baseline configuration.

6. Technical and Economic Feasibility Studies

a. Goldstone Energy System Study. The system study considered the feasibility of operating the Goldstone complex where a major portion of the power was derived from solar energy (the essence of the Goldstone Energy Project). The study was conducted in accordance with Statement of Work No. 1420-1 (Reference 14) by the architectural and engineering firm of Burns and Roe, Inc., of Woodbury, New York.

Burns and Roe evaluated the cost and performance of the baseline configuration and several alternatives to establish the economic viability or economic potential of solar energy utilization by 1980. The results of the Study are contained in three reports (References 4, 15, and 16).

1) Solar Position Paper. The project envisioned that the conclusions and recommendations of the study would depend heavily on the assumptions pertaining to the performance and cost of solar collectors. The results contained in the position paper are projections of future collector performance and estimated minimum production costs to fabricate collectors based on optimizing current collector designs.

2) Hydrogen Fuel Generation Report. During the preparation of the Solar Position Paper, it became evident that the original objective of the study could not be achieved; that is, a system could not be designed which would economically convert the existing Goldstone facilities to use solar energy in accordance with the constraints of the Statement of Work. It was suggested by Burns and Roe, and agreed by JPL, that (a) a greater effort be directed toward the position paper in order to ensure that no viable alternative was overlooked, and (b) those constraints not affecting the safe operation of Goldstone be removed in order to provide a greater flexibility in selecting fuel-saving solar energy facilities for analysis. The report presents the analysis of expected performance and cost of recommended wind and solar subsystems, together with recommendations for the most promising applications of these energy sources.

3) Total Energy Subsystem Report. The Total Energy Subsystem Report contains the results of six substudies: (a) evaluation of energy conservation modifications to the Goldstone facilities, (b) evaluation of solar heating and cooling for four major buildings, (c) evaluation of diesel engine waste heat recovery to conserve energy, (d) evaluation of dual-fuel operation of the standby diesel-engine generator sets at

Goldstone using hydrogen, (e) evaluation of remote monitor and control of Goldstone power plants, and (f) analysis of interconnection of the Goldstone electric transmission network.

A solar heating and cooling system suitable for supplying a significant fraction of the heating and cooling requirements of the four major buildings of the Echo Station was analyzed. The four buildings which were considered are:

| Building Number | Function |
|---|---|
| G-21 | Administration and Cafeteria Building |
| G-26 | Control Building |
| G-33 | Engineering and Communications Building |
| G-38 | Network Laboratory and Maintenance Building |

The solar heating and cooling system proposed and evaluated is a centralized system in which hot water for heating and chilled water for cooling are produced locally and distributed by means of a piping system to the buildings. The major system components are the solar collector field, the absorption refrigeration units, the thermal storage tank and auxiliary hot water heaters, the chilled water storage tank, and the cooling towers.

At the present time, these buildings are heated and cooled by conventional systems utilizing low-pressure gas (LPG) fired boilers and electric motor driven expansion, vapor compression, refrigeration systems.

In addition to evaluating the solar heating and cooling system, a comparison between the 10-year life-cycle cost of the solar system and the existing system was performed. This study does not include an overall system optimization; however, the results of this study are sufficiently detailed to determine the economic viability of installing a solar heating and cooling system at Echo Station.

From the start of this study it was realized that a retrofitted solar heating and cooling system would be capital-intensive and that energy conservation measures which reduce heating and cooling requirements at small capital costs should also be considered. Therefore, in addition to the use of a solar heating and cooling system, various energy conservation measures were assumed to reduce the annual heating and cooling requirements of the facilities. These measures include the use of individual fan coil units instead of multi-zoned air-handling units, reduced lighting loads, reduced outside air supply, etc.

b. Component Analyses. Many basic and applied research tasks have been conducted elsewhere to develop techniques for generating electric power using direct and indirect solar energy. Throughout the study, it became increasingly clear that many evolutionary steps are required before solar energy power systems can be moved from the research laboratory phase to the field applications area. Several components concerned with the required technology have been studied and are discussed below.

1) Performance of a Solar-Thermal Collector. Toward meeting the need for low-cost solar collectors, a parabolic trough solar-thermal collector with axis oriented parallel to the N-S earth axis was studied to develop simplified measurement techniques to provide rapid evaluation of a collector system. Simple methods for determining the thermal losses in a receiver pipe, analytical formulation for the direct component of insolation on a clear day, and determination of the collector performance are discussed in the study report (Reference 17).

2) Total Energy Systems. An evaluation was made by Burns and Roe to determine the feasibility of converting the existing diesel-generator power plants at Goldstone to total energy systems using waste heat recovery and diesel-generated electric power to heat, cool, and power the Goldstone facilities. Four stations were considered: Mars, Pioneer, Echo and Mojave. Waste heat from the diesel engine water jackets and exhaust gas is used to heat and, via absorption refrigeration, to cool the major buildings at these sites. Electric power supplied by the diesels was used to heat and cool minor buildings at the sites and to power all lights, fans, and instrumentation.

3) Hydrogen-Fueled Diesel Engine Tests. A test program was undertaken at Cornell University under JPL contract to provide a feasibility demonstration of a hydrogen-fueled diesel engine. This fueling system was proposed as a means of operating the diesel engine power plants at Goldstone on a fuel derived from solar energy. The program and the results are described in References 18 and 19.

Cornell University was contracted by the Department of Transportation for the investigation of emissions from a hydrogen-fueled, spark ignition engine. The investigation was performed by Howard S. Homan, under the direction of Professor P. C. T. de Boer.

The test facility is a 606-$cm^3$ (37-$in.^3$) displacement, Waukesha Cetane Cooperative Fuel Research (CFR) engine, equipped with a hydrogen-fuel injection valve that is unique to Cornell. The valve was designed to allow adjustment of injection duration and timing and to investigate emissions with respect to the independent variables of compression ratio, fuel/air ratio, and injection schedule parameters. The design of the valve is such that injection can be achieved during a combustion event, so that Diesel operation can be simulated. Ignition was by a spark plug, energized by a conventional ignition system. The facility is equipped with instrumentation to allow measurement of efficiency, power output, engine operating pressures, fuel flows, and exhaust emissions. Additional equipment is used to safely supply, monitor, and control high-pressure hydrogen.

The test program was devised to explore compression ignition over a range of compression ratios, equivalence ratios 0 (0 = (fuel/air ratio actual)/fuel/air ratio stoichiometric), and injection timing to represent projected operation of a hydrogen-fueled Caterpillar Model D3999 diesel engine. Pertinent conditions or events associated with a test were noted, including ignition parameters, and subjective engine operation "quality". Alternative ignition aids, a continuous spark system, a timed spark system, and a glow plug were supplied to aid operation where compression ignition was unsuccessful.

4) <u>Dual Fuel Diesel Engine Study</u>. If a hydrogen economy is instituted at Goldstone, hydrogen-fueled diesels may be attractive prime movers.

Burns and Roe evaluated the possibility of converting the existing D-398 and D-399 Caterpillar diesel engines at Goldstone to dual-fuel operation, hydrogen, or diesel oil.

# SECTION IV

# PROJECT FINDINGS

In the course of conducting the Goldstone Energy Project and preparing this final report, much valuable data was developed from the performance of the numerous studies described in Section III of this report. The backbone of the Project was the study conducted by Burns and Roe; however, the supporting studies, derivation of analytic techniques and the development of instrumentation also lead the way to many significant technical conclusions concerning solar energy utilization, solar collector design, and system applications. These findings are summarized here in brief. (The reader is referred to the list of references for detailed discussions.)

## A. ENERGY REQUIREMENTS

### 1. Energy Model

The Keller and Gannon work of developing and verifying an energy model of Goldstone energy consumption provided a categorization of the major loads by site. The major categories are space heating equipment, air conditioning equipment, lighting and electronic racks at all stations, and electromechanical equipment at the Mars Station. The computed consumption was found to be approximately 14% higher than the site records show for the same period.

The computed energy exceeds the recorded energy in every case when comparing the totals of stations against metered data for the year 1973. This seems to indicate that the energy model could be improved by a better representation of one or more of the categories of major loads or more accurate driving functions such as weather. The following points can be made regarding the accuracy of the energy model:

(1) There are six categories of loads, each with an associated level of confidence:

(a) Space Heating has a high confidence level. There are some inaccuracies in the calculation of heating requirements, but these seem to be self-compensating-the computed consumption of LPG is only 2% higher than the recorded consumption.

(b) Exterior Lighting has a high confidence level. The associated demand is easily determined by a count of lighting fixtures, and the demand utilized in the model has been verified by operations personnel. The hours of operation are somewhat less easily determined, but the values utilized have also been verified by operating personnel.

(c) Electronic Loads have a high confidence level because they are well enough isolated to permit reliable field measurement, and the electronic demand does not vary significantly throughout the year.

(d) The Air Conditioning (cooling) load has a lower confidence level because the energy model is based upon the air volumes shown on the construction drawings. Changes during installation or adjustments during the years since startup would change the air volumes.

(e) The Weather Load as a statistical average has a high confidence level; however, for the specific study of 1973, the average weather may not be representative.

(f) The Miscellaneous Electric loads have a much lower confidence level. Station tracking and transmitting loads, the preponderant loads in this category, were measured during the field survey, but operations personnel indicated that the measured values were not representative of the various operating modes. These load figures were subsequently adjusted on the basis of very limited records of short-term measurements of power levels which had been accumulated over several years by operating personnel.

(2) The air conditioning and miscellaneous electric loads account for 57 percent of the total computed energy consumption, and because these two load categories have the lowest confidence levels, it is suggested that a load metering program for these two categories would produce the data most likely to reduce the excessive energy consumption now simulated by the energy model.

(3) The E-CUBE series of computer programs are design tools and are oriented to the evaluation of HVAC systems on the basis of energy consumption and cost. The programs are designed to handle individual zones of HVAC systems, but for this study it was necessary to handle individual building rather than zones. These programs as design tools may not be suitable for analysis of existing buildings.

## 2. Potential Load Reductions

Both Keller & Gannon and Burns and Roe concluded that the Goldstone loads could be reduced. The two efforts had the same objective but different approaches.

Keller & Gannon used the energy model to analyze building and equipment characteristics and operating doctrine. Cost-effective recommendations for reducing energy consumption were developed, compatible with a total energy system which utilizes waste heat. (Some of the recommendations are no longer economic because the Burns and Roe study determined that waste heat utilization at Goldstone is not economic. See Subsection IV. C.2.)

Burns and Roe relied on a field survey to suggest and evaluate energy conservation recommendations. The survey was focused on the 13 buildings at Goldstone which account for the major portion of energy usage as determined by Keller & Gannon.

Each company estimated the energy savings to be obtained from the implementation of the recommendations. The combined recommendations have been generalized and are listed here as areas where energy conservation can be effected:

(1) Reduce lighting levels.

(2) Reduce intake of outside air when not using economizer cycle and adjust mixing dampers.

(3) Reduce amounts of reheat and eliminate humidification.

(4) Upgrade automatic control systems.

(5) Restrict building HVAC system operating during unoccupied periods.

(6) Add outside air economizer cycle.

(7) Insulate certain walls and reduce window area exposed to sun.

(8) Separate systems serving both occupied and unoccupied areas.

(9) Adopt electronic equipment and general operating procedures and HVAC equipment set points that are energy efficient.

The final reports (References 3 and 4) should be consulted for the detailed recommendations.

## B. RESOURCES

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### 1. Wind

The project examined many annual records of hourly wind speeds recorded at Goldstone, Edwards Air Force Base, Daggett Marine Center, and George Air Force Base. From these data, the project established empirical probability distributions of wind speeds and closed-form functions and the associated parameters that provide good approximation to the empirical distributions. Examinations of these data records have led to a convenient method for comparing candidate windmill sites on the basis of expected annual average power in the wind. This method has been shown to provide estimates for a candidate site for which only the average wind speed is known or can be estimated. A monthly wind power model was developed for a specific Goldstone site via correlation analysis with 14 years of Edwards Air Force Base data. This model is designed to give more accurate estimates of the expected monthly power in the wind than would be given by the 2 years of recorded data for the Goldstone site.

Meteorology Research Inc. was unable to extrapolate wind behavior from a reference site to other sites on the basis of their computer models and the data collected from 6 potential wind turbine sites. Causes may be that the spatial resolution used to characterize the Goldstone terrain was too coarse or that the reference data set was not sufficiently complete. An examination of the data from the potential wind turbine sites showed that certain sites average considerably more wind than others. It is not surprising that the better sites are hilltops.

Burns and Roe were given existing wind data (originally collected to support antenna design) to determine the power that wind turbines could extract from the wind at Goldstone. It was found that the annual average wind speed is too low to be exploited as major energy source to meet Goldstone energy requirements.

The work described previously has emphasized examinations of wind speed distributions and average power expected over relatively long periods of time. To extend this work to generate representative hourly wind speed samples as the input to an energy system simulation, it would also be necessary to preserve the statistical characteristics of the hour-to-hour correlation of wind speeds. Much has already been done to establish the nature of the wind speed distribution. On the other hand, relatively little has been performed to establish the correlation functions. Beyond this, new theoretical developments will be required to generate a simulation process that represents both distributions and correlations. As a useful by-product, the simulation process might be adaptable in telemetry noise degradation studies of water vapor in the radar beam path.

## 2. Insolation

The ability to collect solar radiation measurements and determine the quantity and character of total, direct, and diffuse radiation is necessary before any solar energy device can be designed by solar-system engineers. Commercial devices for measuring total or global radiation (pyrheliometers) have existed for a long time. However, at the time the Project set out to measure radiation levels (References 20 and 21), no suitable field instrument existed to measure the direct component. The first task was then to develop a direct component-measuring instrument with high-precision field-worthiness and that could operate unattended.

Prior NASA-supported work under a different program at JPL (References 22 and 23) had resulted in the development of a primary absolute cavity radiometer (PACRAD) which was recently accepted as an international standard of irradiance (Reference 24). Using this instrument as a point of departure, the Project developed an instrument capable of withstanding the stringent Goldstone field conditions (Reference 25). The self-contained unit is called the Kendall Radiometer System Mark 3.

The Mark 3 units have maintained calibration against the international standard over the initial 2 years of field use.

Three years of direct and global insolation data have been collected using the Mark 3 and pyrheliometers. From 6 months of reduced data, the project has shown that the diffuse component can be calculated for use by the solar power system designers. The accuracy of these calculations has been substantiated by direct measurement of the diffuse component. Without formal statistical comparison, preliminary analysis of the data has lead to development of several findings relative to solar radiation intensity:

(1) When clouds are present, the instantaneous level of solar radiation varies from a cloudless level to near zero in a very short time interval.

(2) The Goldstone atmosphere is sometimes subject to turbidity which appears to be related to smog levels. There appears to be a correlation between wind direction and turbidity at Goldstone which probably can be extended to the whole Mojave Desert.

(3) On visibly cloudless days and near noon when the rate of change of solar intensity is small, the level of insolation varies a significant amount from the ASHRAE* model expectation due to turbidity, commonly ±15%.

(4) A clearness number as a function and measure of turbidity can be computed from the accurate instrumentation measurements.

(5) The above concepts may be a function of specific geographical location and seasonal variations.

Any system design will have to take into account these causes and effects upon the insolation available to drive the system.

An extension of the above analysis has lead to the development of a preliminary mathematical model of solar radiation for the Goldstone area. The probabilistic model is a function of measured clear-day insolation levels, clouds, and changing weather conditions season to season. To make the model more useful to the solar-system designers, additional data analysis is required to permit extension of the model to reflect expected, but undefined correlations:

(1) All measured data needs to be reduced and analyzed. The preliminary model is based on only 6 months of reduced data.

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*American Society of Heating, Refrigeration and Air-Conditioning Engineers.

(2) Solar measurements should be correlated with meteorological data at the same site to identify which parameters are probabilistic and which are deterministic. The better statistical model could reflect ground level temperature, humidity, rainfall, barometric pressure, windspeed and wind direction.

Discussions with design engineers indicate some additional field measurements are required to support the predicted performance of various solar systems. Circumsolar radiation (insolation originating from an annular area 2-4° around the sun) is vitally important to the determination of the tracking accuracies required for the various types of concentrating collectors and should be included in future measurements. Night-sky temperatures should be measured to understand the potential for using collectors to radiate heat at night or to determine how cold collectors become and how much morning solar insolation will be required to bring the collectors up to operating temperature.

## C. TECHNICAL AND ECONOMIC FEASIBILITY STUDIES

### 1. Hydrogen Utilization

The study efforts conducted by Burns and Roe in the preparation of the Solar Position Paper (Reference 16) were limited to the analysis of solar collector performance and costs for use in solar thermal-to-electric power generation. From the results presented in the Solar Position Paper, it was concluded that "no collector presently available or in an advanced state of development can support the building of an energy-on-demand system anywhere in the U.S. on an economically sound basis within the 1970 decade." Burns and Roe and JPL agreed that the results of the analyses performed during the preparation of that paper were sufficient to preclude performing a complete system analysis. The analytic results presented in the Solar Position Paper and final report on Hydrogen Fuel Generation (Reference 15) are considered to be representative of the performance and costs associated with the various components of advanced power systems.

The candidate wind-hydrogen subsystem best suited to being dismantled and relocated to an alternate site was found to be the isolated wind-hydrogen configuration sized to generate 300 $kW_t$ of hydrogen and oxygen. The life-cycle cost of this system is estimated to be \$1,670,000 or \$5,320/$kW_t$. It should be noted that this cost is based on operating the wind-hydrogen subsystem only during those hours when sufficient wind is available. The wind data for the Goldstone site indicates that sufficient wind is available for an average of 6 hours per day. If these costs were based on a 24-hour per day usage factor, the cost would be \$21,280/$kW_t$. If a 15% conversion factor from thermal energy (in the form of hydrogen) to electric energy (through the existing diesel generators at Goldstone) were applied, the resulting costs would be \$142,000/$kW_e$ not including the costs of hydrogen storage and distribution.

The recommended solar-hydrogen subsystem was estimated to have a total capital cost of $8,069,000. The annual operation and maintenance costs of $30,000 brings the 10-year life-cycle costs to $8,369,000. Since this subsystem will generate 300 $kW_t$ of hydrogen and oxygen for 24 hours each day, the cost would be $27,900/$kW_t$. If a 15% conversion factor from thermal energy (in the form of hydrogen) to electric energy (through the existing diesel generators at Goldstone) were applied, the resulting costs would be $186,000/$kW_e$, not including the costs of hydrogen generation and distribution.

The hydrogen-fueled diesel engine tests performed by Cornell University demonstrated that diesel engines of the type installed at Goldstone could be operated on hydrogen providing an ignition source is supplied and that the fuel is injected directly into the combustion chamber. Successful operation can be expected over a range of compression ratios of 15:1 to 30:1, equivalence ratios of 0.1 to 0.8, and mean effective pressures up to 80 psi. Converted engine efficiencies can be expected to equal or exceed diesel engine efficiencies by 5 to 10 percent. Exhaust emissions are lower.

Several development tasks were identified that would enhance the operational aspects of a hydrogen-air, dual-fueled diesel engine, namely:

(1) Develop a reliable injection valve.

(2) Design a glow plug igniter capable of long-term operation under load.

(3) Develop the parameters that relate mixing and combustion chamber configuration to combustion efficiency.

(4) Extend the range of tests to higher mean effective pressures.

An evaluation was made of converting the existing D-398 and D-399 Caterpillar diesel engines at Goldstone to dual-fuel operation, hydrogen or diesel oil. Based on work performed in Europe and the United States over a period of 50 years and encouraging results of tests performed at Cornell University, dual-fuel operation of the diesels appears feasible using diesel oil or hydrogen with naturally aspirated turbocharging. However, because of turbocharging and fuel changeover requirements, it is not expected to be feasible to run the existing diesel engines on hydrogen and oxygen as well as on fuel oil and air. The estimated cost of converting one D-399 engine to dual-fuel operation on hydrogen and fuel oil using air aspiration is about $30,550.

Burns and Roe concluded from this study that neither a wind-hydrogen nor a solar-hydrogen system will be economical in the near future. Due to the scarcity of wind at the Goldstone site that could be utilized for power generation, Burns and Roe recommended that wind turbines no longer be considered an economic means of generating electricity at Goldstone. The compounded costs and inefficiencies of the hydrogen subsystem (including electrolytic units, hydrogen storage, hydrogen distribution, and hydrogen diesel generators) results in more than a 10-fold increase in the total cost of the system. Future studies should consider a solar energy-as-available system which uses only moderate thermal storage as a buffer to level the insolation.

The severe operating constraints specified for the energy system at Goldstone were among the causes of high system cost. For either a wind or solar system to be economically viable, it is necessary for the system to be designed to accept the energy as available. To burden either system with the high cost of converting valuable electric energy into thermal energy (in the form of hydrogen) and then reconverting it into electric energy (through diesel generators) is an unreasonable demand. The compounding of these high costs and low efficiencies would preclude the economic viability of even the most promising advanced power systems.

## 2. A Solar-Augmented Conventional System

One of the cost deterrents of a solar-thermal-electric system is the following dilemma: If the system is designed to generate electricity 24 hours a day, it must incur the expense of a large thermal storage system; if the system is designed to generate electricity only during sunshine hours, the power generating equipment stands idle for most of the day.

An approach to overcome this situation would be to augment a conventional fossil-fuel-fired system with a solar system. During sunshine hours the solar system would supply the thermal requirements of the plant, while during nighttime hours the plant would burn fuel in the conventional manner. The solar system would be economically justified if its costs were less than the resulting fuel savings resulting from such a hybrid plant.

## 3. Total Energy

The results of the evaluations contained in the Total Energy Subsystem Report (Reference 4) generally indicate that economical, energy conserving, and reliable operation of the Goldstone facilities is feasible without extensive replacement of equipment or redesign of systems. The study results can be summarized with recommendations as follows:

(1) Evaluation of the existing buildings at Goldstone showed that approximately $1,400,000 of operating expenses could be saved over a 10-year period by implementing conservation modifications. These recommendations generally are:

- (a) Adopt operating procedures and HVAC equipment set points that are energy-efficient.
- (b) Reduce lighting loads.
- (c) Reduce thermal losses.

(d) Reduce ventilating air flows.

(e) Eliminate humidification supplied by boilers.

(f) Balance and eliminate leakage in existing HVAC systems.

(g) Relocate some equipment and segregate selected HVAC zones.

(h) Add economizers to some HVAC systems.

(2) An economic evaluation of a conceptual solar heating and cooling system design serving Buildings G-21, G-26, G-33, and G-38 at Echo Station was performed. The results of the evaluation indicated that a central solar heating and cooling system serving the four major buildings at Echo is not an economically viable alternative to the existing system. This conclusion is further justified when it is realized that energy conservation measures were assumed for the solar HVAC system, but not for the existing HVAC system when the comparison between the two was made. The following recommendations resulted from this evaluation:

(a) Solar collector system costs are dominated by the cost of piping and valves. Therefore, solar heating and cooling system designs will be more attractive when collectors can be located near, or on top of, the buildings they serve.

(b) Solar heating and cooling is more attractive for new buildings or old buildings requiring complete replacement of HVAC equipment. In this way, the cost of the solar heating and cooling system is offset by the cost of a new, conventional heating and cooling system.

(c) Solar heating and cooling should be considered for existing buildings at Goldstone which have predominantly daytime loads and do not have winter cooling requirements.

(d) Although the study does not recommend the implementation of a solar heating/cooling facility as of the time it was conducted, increased fuel costs and further solar component development may change the economic analysis to justify such a facility in the near future.

(3) The evaluation to determine the feasibility of converting the existing diesel-generator power plants at Goldstone to total energy systems using waste heat recovery and diesel generated electric power to heat showed that the 10-year life-cycle cost of the power stations considered increases

between 26% and 73% when converted to total energy systems. The conversion was not recommended.

(4) The cost of a central, remote monitor and control system for the Goldstone power plants was estimated. Such a system would reduce operating labor requirements and improve monitoring and power dispatching capabilities at Goldstone. The concept system utilized digital bipolar pulse signals (similar to teletype communications) with a central console at Echo Station with dedicated buried lines to each of the power plants: Mars, Pioneer, Echo and Mojave. The estimated cost of the system is $600,000 or roughly equivalent to the 10-year cost of three diesel engine operating personnel. A study should be performed to determine if diesel operating staff could be reduced without affecting diesel generator reliability with remote start and control capability.

(5) The feasibility of interconnecting the Goldstone complex using existing transmission lines within Goldstone was confirmed. It appeared at that time that such a grid would limit flexibility since diesel power could not parallel SCE power in the same grid. For reliability and flexibility it was recommended that the 34.5-kV SCE-connected grid be extended to enable each station to select either purchased power or diesel power at any time.

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