AD-A133 803 USAF ADVANCED TERRESTRIAL ENERGY STUDY VOLUME 1 PROJECT 1/1
SUMMARY..(U) INSTITUTE OF GAS TECHNOLOGY CHICAGO ILL
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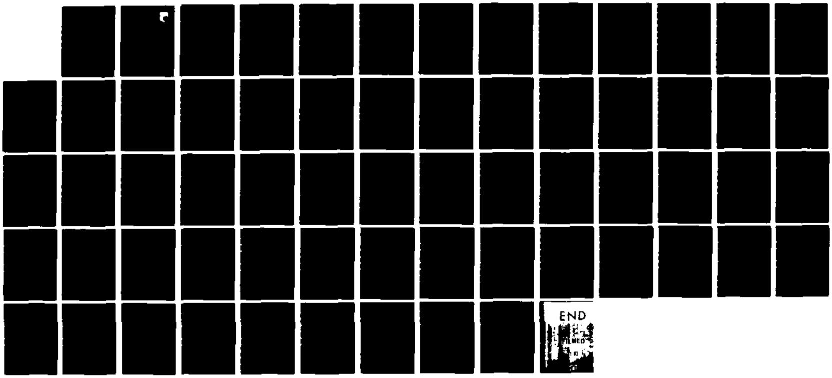
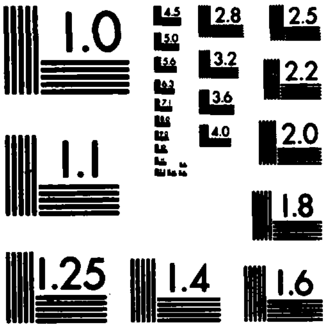
UNCLASSIFIED AFWAL-TR-82-2019-VOL-1 F33615-80-C-2041 F/G 10/1 NL





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AFWAL-TR-82-2019
VOLUME I

USAF ADVANCED TERRESTRIAL ENERGY STUDY

VOLUME I: PROJECT SUMMARY

Institute of Gas Technology
3424 S. State Street
Chicago, Illinois 60616

April 1983

FINAL REPORT SEPTEMBER 1980-FEBRUARY 1982

Approved for public release; distribution unlimited

AERO PROPULSION LABORATORY
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This technical report has been reviewed and is approved for publication.

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFWAL-TR-82-2019, Vol I	2. GOVT ACCESSION NO. AD-A133 803	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (*and Subtitle*) USAF ADVANCED TERRESTRIAL ENERGY STUDY Volume I — Project Summary		5. TYPE OF REPORT & PERIOD COVERED Final Report for Period Sep 80 – Feb 82
		6. PERFORMING ORG. REPORT NUMBER 61045
7. AUTHOR(s) E. J. Daniels B. D. Yudow T. D. Donakowski		8. CONTRACT OR GRANT NUMBER(s) F33615-80-C-2041
9. PERFORMING ORGANIZATION NAME AND ADDRESS Institute of Gas Technology 3424 S. State St., Chicago, IL 60616		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 3145 24 12
11. CONTROLLING OFFICE NAME AND ADDRESS Aero Propulsion Laboratory (AFWAL/POOC) AF Wright Aeronautical Laboratories Air Force Systems Command Wright-Patterson AFB, Ohio 45433		12. REPORT DATE April 1983
		13. NUMBER OF PAGES 59
14. MONITORING AGENCY NAME & ADDRESS (*if different from Controlling Office*)		15. SECURITY CLASS. (*of this report*) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (*of this Report*)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (*of the abstract entered in Block 20, if different from Report*)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (*Continue on reverse side if necessary and identify by block number*)

Diesels	Wind Turbines	Photovoltaics
Fuel Cells	Organic Rankine Cycles	Batteries
Gas Turbines	Stirling Engines	Thermal Energy Storage

20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

This report presents the results of the USAF Advanced Terrestrial Energy Study. The objective of that study was to develop a data base of key parameters of selected energy conversion and energy storage technologies. The data base includes present and expected (through 2000) performance goals of the systems. The data base was established through an extensive literature search, surveys of manufacturers and researchers, and statistical and qualitative analyses of the available input data. The results of the study are reported in four documents:

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Technical Report: Final Report, Volume I, Project Summary

Technical Report: Final Report. Volume II, Technology Handbook

Technical Report: Final Report, Volume III, Parameter Survey

Technical Report: Final Report, Volume IV, Analysis, Data, Bibliography

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Objectives and Scope

The objective of this project was to develop a data base of technical and economic performance parameters of selected energy conversion and energy storage devices. The data base includes not only the state-of-the-art (1980) values of ~~the~~ performance parameters, but also the expected values of ~~the~~ performance parameters in 1985, 1990, and 2000. For energy conversion technologies, performance parameters were developed over a power output from 1.5 to 5000.0 kW. For energy storage technologies, performance parameters were developed over an energy output range equivalent to the power output at continuous annual operation.

The following energy conversion technologies were characterized in this data base:

- Gas Turbines
  - ~~Open cycle,~~ nonrecuperative (nonregenerative)
  - Closed cycle and
  - Open cycle, recuperative ~~(rege~~nerative)
- Diesels
  - Turbocompounded,
  - Turbocharged and
  - Adiabatic;
- Stirlings
  - Free piston and
  - Kinematic;
- Organic Rankine Cycles;
- Fuel Cells
  - Phosphoric acid,
  - Solid polymer electrolyte ~~(SPE)~~
  - and Molten carbonate.

- Photovoltaics
  - Flat plate
  - Actively cooled
  - Photochemical
- Wind Turbines
  - Vertical ~~axis~~
  - Horizontal ~~axis~~.

The following energy storage technologies were characterized in this data base:

- Batteries
  - Zn/Cl_2
  - Zn/Br_2
  - Ni/Fe
  - Li-Al/FeS_2
  - Na/S
  - Advanced sealed lead/acids and
  - Redox Cr-Fe and
- Thermal Energy Storage Devices
  - $CaCl_2 \cdot 6H_2O$, calcium chloride hexahydrate
  - $Na_2SO_4 \cdot 10H_2O$, sodium sulfate decahydrate (Glauber's salt)
  - $Na_2S_2O_3 \cdot 5H_2O$, sodium thiosulfate pentahydrate
  - Olivine ~~ceramic~~ brick and
  - Magnesite ceramic brick and
  - Form-stable polyethylene.

The complete set of parameters and their definitions follow.

- Type. This parameter value is either mobile, transportable, or fixed; it refers to the complete energy system, not just the component technology.

A system is mobile if it 1) is transportable by truck or aircraft and 2) can be assembled or dismantled within 8 hours with no prior site preparation. A system is transportable by truck if the system itself or the largest component of the system can be broken down and does not exceed the dimensions of 10-feet wide by 13-feet high by 60-feet long. For air transportability, the system or largest component of the system cannot exceed 16-feet wide by 9-feet high by 100-feet long, nor can it exceed a weight limit of 350 lb/ft^2 floor loading.

A system is transportable if it 1) is transportable by truck or aircraft subject to the same limitations as mobile and 2) can be set up or removed within 1 week with only minor site preparation.

A system that is neither mobile nor transportable is fixed.

- **Fuel Capability.** Fuel capability indicates the fuels that can provide the primary energy source for each system. Primary fuels for the purpose of this study include —
  - JP-4
  - Diesel (DF-1 or DF-2)
  - Electricity
  - Natural gas
  - Solar
  - Wind
  - Thermal (heat)
  - Methanol

Systems that have multifuel capabilities are denoted "multi."

- **System Acquisition Cost.** The estimated total installed cost in 1980 dollars of the energy system excluding land procurement.

- **Acquisition Cost (except BOP).** The estimated off-the-shelf cost of the component technology excluding the balance-of-plant components for the complete system. The cost is in 1980 dollars.

- **Annual Operating and Maintenance Cost.** The estimated annual cost of operating the energy system. The cost is in 1980 dollars and includes all operating and maintenance expenses except for fuel costs.

- **System Efficiency.** A system's efficiency is the primary energy output divided by the primary fuel energy input. It does not include the energy content of by-product energy recovery unless specifically noted. Efficiency is measured in percent.

- Efficiency (except BOP). This is the efficiency of the component technology and is the direct energy output from the component technology (for example, shaft power for the engine) divided by the energy content of the fuel for the technology. This efficiency is based on the energy balance around the component technology and excludes all balance-of-plant components and by-product energy. Efficiency is measured in percent.

- Lifetime. This is the estimated number of years the energy system is expected to produce its designated output during continuous operation. Continuous operation is as previously defined under "General Requirements."

- Annual Fuel Consumption. This is the calculated annual energy content of designated fuel consumed by the energy system at its designated output during continuous operation. It is measured in Btu's unless otherwise specified.

- Annual Fuel Cost. This is the calculated annual cost of primary fuel. It is the product of the primary fuel price in 1980 dollars times the annual fuel consumption for the energy system. Fuel prices are discussed in the section of this report headed "Fuels and Fuel Prices." Selection of one fuel type for systems with multifuel capability is discussed in the section of this report headed "General Requirements."

- Annual Fuel Cost (5%). This is the calculated annual cost of primary fuel assuming a real price increase of 5% per year. It is measured in 1980 dollars.

- Annual Fuel Cost (10%). This is the calculated annual cost of primary fuel assuming a real price increase of 10% per year. It is measured in 1980 dollars.

- Life-Cycle Cost. Life-cycle cost is the calculated cost of acquiring, operating (including fuel use), and maintaining the energy system at continuous operation at its output level for a period of 20 years. For systems with lifetimes of less than 20 years, the cost of rebuilding or reacquiring a system to extend the life to 20 years is included. The life-cycle cost is measured in 1980 dollars per unit of energy output. The procedure for calculating life-cycle costs is discussed in the section of this report headed "Life-Cycle Costing Analysis."

- Life-Cycle Cost (5%). This is the life-cycle cost of the energy system as previously defined except that fuel costs are assumed to be based on a 5% per year real price increase. It is measured in 1980 dollars per unit of energy output.

- Life-Cycle Cost (10%). This is the life-cycle cost of the energy system as previously defined except that fuel costs are assumed to be based on a 10% per year real price increase. It is measured in 1980 dollars per unit of energy output.

- Start-up Time. The start-up time is the elapsed time in minutes for the system to achieve full output from a "ready to start" or "cold start" condition.

- Shutdown Time. The shutdown time is the elapsed time in minutes to bring a system from a full output condition to an off or standby mode.

- Volume (System). This is the volume in cubic feet of the envelope of the installed energy system.

- Volume (except BOP). This is the volume in cubic feet of the component technology excluding all balance-of-plant components.

- Area (System). This is the land or surface area in square feet required for the installed energy system.

- Area (except BOP). This is the land or surface area in square feet required for the energy technology excluding all balance-of-plant components.

- Weight. This is the total weight of the complete energy system measured in pounds.

- Weight (except BOP). This is the weight in pounds for the energy technology excluding all balance-of-plant components.

- Raw Materials. This is a qualitative parameter to indicate whether each system requires any materials that may not be readily available in sufficient quantity to allow the system to be produced in large quantities. This parameter is measured on an ordinal scale:

  1 — definite raw materials limitations

  3 — potential raw materials limitations

  5 — no apparent raw materials limitation

- Reliability. This is a qualitative parameter that indicates the potential for unanticipated outages of the energy system. Reliability is evaluated in terms of moving parts, operating temperature, modularity (redundancy), stress levels, corrosion, etc. Reliability is measured on ordinal scale:

  1 — high potential unreliability

  2 — moderate potential unreliability

  3 — average

  4 — moderate reliability

  5 — high reliability

  See the section of this report headed "Qualitative" under "Analytical Procedures" for the methods used to determine the relative measures for the technologies.

- Environmental Constraints. This is a qualitative parameter that indicates the potential for environmental insult from the energy system. This parameter is evaluated in terms of thermal discharge; air pollution, including CO, NO_x, SO_x, HC, particulates, and others; noise; odor; solid waste; and chemical waste. Environmental constraint is measured on an ordinal scale:

1 — extreme potential environmental constraint

2 — high potential environmental constraint

3 — average potential environmental constraint

4 — moderate potential environmental constraint

5 — minimum potential environmental constraint

- Locational Constraints. This is a qualitative parameter to indicate the potential for locational constraints that could limit the applicability of the energy systems. This parameter is evaluated in terms of water requirements, personnel requirements, fuel availability, fuel storage, and others (solar, wind). Locational constraints are measured on an ordinal scale:

1 — extreme potential locational constraints

2 — high potential locational constraints

3 — average locational constraints

4 — moderate locational constraints

5 — minimum locational constraints

- Operational Constraints. This is a qualitative parameter that indicates the turn-down and load-following capabilities of the system relative to operating efficiency. This parameter is evaluated in terms of part-load capability, overload capability, and load-following capability. Operational constraints are measured on an ordinal scale:

1 — no turn-down capability

2 — turn-down capability with high efficiency penalty

3 — average turn-down capability

4 — moderate turn-down capability; moderate efficiency penalty

5 — excellent turn-down capability; minor efficiency penalty

- Thermal Energy Available. The thermal energy recoverable from any energy system is a function of the quality and quantity of thermal energy produced by the system. It would be beyond the scope of this study to estimate the thermal energy available from each technology at the 11 different output levels. Consequently, this parameter will be qualitative and measured on an ordinal scale:

1 — no potential for heat recovery

2 — minor potential for heat recovery, extreme use limitation

3 — potential for heat recovery, moderate use limitation

4 — moderate potential for heat recovery, minor use limitations

5 — very high potential for usable heat recovery

Approach to the Study

The general approach to the study included two major functions: data collection and data reduction.

Date Collection

Two techniques of data collection were used, literature search and survey questionnaires.

Two literature searches were conducted. The Department of Energy (DOE) Energy Information Data Bank was accessed to obtain the available literature concerning the energy technologies. The DOE Research in Progress Data Bank was accessed to obtain information and abstracts of research programs being conducted in the relevant technology areas.

The number of abstracts initially identified and reviewed for each technology is presented in Table 1. Because the DOE Energy Information Data Bank does not include the most recent articles available on technologies (within 9 months to 1 year), recent articles were obtained from the library of the Institute of Gas Technology (IGT). IGT staff references provided additional literature. All of the abstracts from the Energy Information Data Bank were reviewed for applicability to this study. Of those, a total of 860 articles were subsequently retrieved and reviewed (Table 2) to obtain input data on performance parameters. The articles that were reviewed and the input data are included in Volume IV of this report.

All the Research in Progress abstracts were reviewed to obtain input data and to identify personnel and organizations who could be surveyed to obtain additional data.

To supplement the input data from the literature searches, we prepared three mail survey questionnaires. The first two questionnaires solicited the full range of information from vendors, manufacturers, and developers of the technologies. Because such a range of information was requested, we conducted a two-stage (the first two questionnaires) survey of manufacturers, vendors, and developers. In the first stage, 115 different manufacturers and vendors were surveyed. Of those, 44 responded. Although this exceeded the response rate normally expected, gaps still existed in the input data required. To supplement the input data, we conducted a second-stage survey of manufacturers and vendors in which a total of 137 questionnaires were mailed out. Of those, 15 responded (Table 3). We also conducted telephone follow-up of nonrespondents.

Table 1. ABSTRACTS AVAILABLE FROM LITERATURE SEARCHES

Energy Technology	No. of Articles From Energy Information Data Bank*		No. of Articles From Research in Progress Data Bank
Gas Turbines	297	(28)	27
Diesels	247	(6)	125
Stirlings	105	(3)	8
Rankine Cycles	47	(7)	18
Fuel Cells	312	(12)	42
Photovoltaics	369	(97)	414
Wind Turbines	299	(3)	51
Batteries	562	(33)	42
Thermal Storage Devices	51	(12)	44

* Numbers in parenthesis are additional, more recent articles retrieved through IGT's library or staff references.

Table 2. ARTICLES REVIEWED FOR DATA

Energy Technology	No. of Articles Reviewed	Articles Reviewed as a Percent of Articles Available From Energy Information Data Bank
Gas Turbines	202	68%
Diesels	96	39%
Stirlings	26	25%
Rankine Cycles	42	89%
Fuel Cells	89	29%
Photovoltaics	196	53%
Wind Turbines	58	19%
Batteries	114	20%
Thermal Storage Devices	37	74%

Table 3. SURVEY OF MANUFACTURERS, VENDORS, AND DEVELOPERS

Energy Technology	Number of Questionnaires Mailed 1st Stage	2nd Stage	Number of Responses 1st Stage	2nd Stage	Total Response Rate, %
Gas Turbines	9	8	2	1	18
Diesels	20	20	14	3	43
Stirlings	3	8	3	1	36
Rankine Cycles	9	11	5	3	40
Fuel Cells	6	2	4	1	63
Photovoltaics	20	22	3	1	10
Wind Turbines	28	24	9	2	21
Batteries	20	30	4	1	10
Thermal Storage Devices*	0	12	0	2	17
TOTALS	115	137	44	15	23

* Thermal storage devices were not part of the orignal work scope and were included after the 1st stage survey.

The third questionnaire sought information from researchers (identified in the DOE Research in Progress Data Bank) concerning the expected development of the technology as a result of their research. Because the information requested from the researchers was not as comprehensive as that requested from the vendors and manufacturers, this survey was followed up with telephone interviews rather than with a second-stage questionnaire. The responses are presented in Table 4.

A limited number of questionnaires were required for two reasons. First, the two-stage questionnaires that were sent to manufacturers and vendors included sections to obtain projected as well as state-of-the-art performance values for the technologies. Therefore, the questionnaires to researchers were to supplement data obtained from the previous questionnaire. Second, the DOE Research in Progress Data Base identifies the agency funding the research and that agency's program monitor. A review of many of the programs contained in data base resulted in relatively few program monitors who apparently are responsible for a complete program area. Consequently, we surveyed these program monitors rather than all the individual researchers. A representative questionnaire is included as an appendix to this volume.

Table 4. SURVEY OF RESEARCHERS

Energy Technology	No. of Questionnaires Mailed	No. of Responses	Total Response Rate,%
Gas Turbines	2	1	50
Diesels	3	1	33
Stirlings	2	1	50
Rankine Cycles	3	1	33
Fuel Cells	2	1	50
Photovoltaics	4	1	25
Wind Turbines	1	1	100
Batteries	2	1	50
Thermal Storage Devices	7	2	29%
TOTALS	26	10	38%

Data Reduction

The input data gathered were subsequently analyzed to determine the expected single value of the parameters at the discrete power output levels of 1.5, 5.0, 20.0, 30.0, 60.0, 100.0, 250.0, 500.0, 750.0, 1000.0, and 5000.0 kW for the years 1980, 1985, 1990, and 2000. The procedures and assumptions made in analyzing the data are discussed in detail in the section of this report headed "Analytical Procedures." In general, the input data were statistically analyzed to determine a mathematical function of the specific parameters as a function of power output level. These functions were then used to determine the expected value of a parameter at the discrete power output level. We then compared the expected values across the technologies for apparent inconsistencies, and modified them if necessary.

DEFINITIONS AND ASSUMPTIONS

General Requirements

To clarify the estimated parameter values included in the data base, definitions and assumptions were adopted regarding the general requirements and applications of each energy technology.

For the energy conversion technologies (that is, all of the technologies except batteries and thermal energy storage devices) each system was defined to include the technology and necessary balance-of-plant components (BOP) for the production of utility-quality power on a continuous, stand-alone basis from a designated primary energy (operating 90% of each year at the required power ouput level). Certain energy conversion technologies can use different energy forms. For example, fuel cell systems can be fueled by almost any hydrocarbon. Therefore, the following criteria were used to specify the designated fuel for cost analysis of the systems for which there are choices:

- A nonlogistic fuel was selected in preference to a logistic fuel only if utilization of the logistic fuel requires system components that are not yet commercially available.

- If there were still alternatives after the above selection was made, then the fuel that imposes the minimum total cost on the life-cycle cost of the system was preferred. Consequently, fuel selection based on cost considered not only the fuel price, but also the efficiency of the technology and fuel storage requirements.

- A logistic fuel was not designated if it incurred unnecessary system efficiency losses through additional conversion to the "traditional" energy input to the technology. For example, diesel fuel was not selected over purchased electricity for charging batteries.

For the energy storage technologies, the following requirements were assumed:

- Batteries. Batteries will supply dc power as output; a complete charge/discharge cycle was assumed to occur twice per day with a total discharge time of 16 hours; the batteries will operate 365 days per year.

- Thermal Energy Storage. Thermal energy storage devices were assumed for space-heating applications with a continuous diurnal cycle (365 days per year operation).

System Definitions

Given the general requirement and the parameters that had to be determined, conceptual systems for each energy technology were developed.

Engines

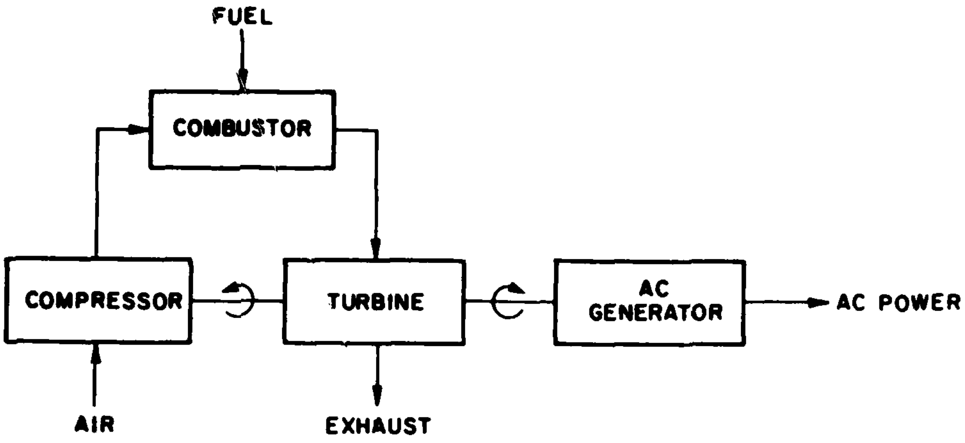
All of the engines produce shaft power, which is then converted to ac power by an ac generator.

Gas Turbines. Figure 1 shows the three turbine systems of interest in this study: open cycle, nonrecuperative; open cycle, recuperative; and closed cycle. Both of the open-cycle systems are commercially available at power output levels greater than 10 kW. The efficiency of the open-cycle recuperative system is greater than that of the simple open cycle because of the use of the turbine exhaust gas for combustion air preheat. The closed-cycle turbine is expected to be commercially available in 1985 and to be more efficient than the open-cycle recuperative system. Because the closed-cycle system uses a working fluid rather than combustion products, it can be operated on alternative primary fuels, including DF-1 and DF-2.

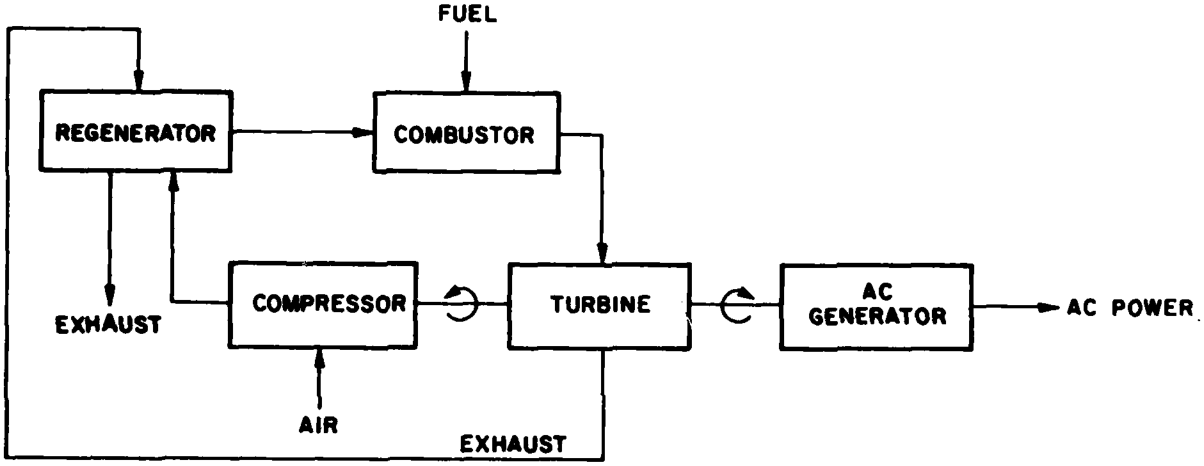
Diesels. Figure 2 shows the three diesel systems of interest: turbocharged, turbocompounded, and adiabatic. Turbocharged diesels are commercially available. Turbocompounded diesels are expected to be commercially available in 1985 and should be more efficient than turbocharged diesels because of the additional shaft power derived from the exhaust-gas-driven turbine. Adiabatic diesels, which are expected to be commercially available in 1990, operate at higher pressures and temperatures than the turbocompounded and turbocharged systems. (The adiabatic is not cooled.) Because of the higher pressure and temperature operation, overall system efficiency is expected to be greater for the adiabatic diesel than for the turbocompounded.

Typically, diesels are fueled with DF-1 or DF-2, but some manufacturers in Europe (for example, Stal Laval) are developing diesels for residual fuel. Because of the price differential this would tend to decrease the life-cycle cost of diesel systems. (Residual is about $5.85/million Btu; DF-1 and DF-2 are about $8.62/million Btu.)

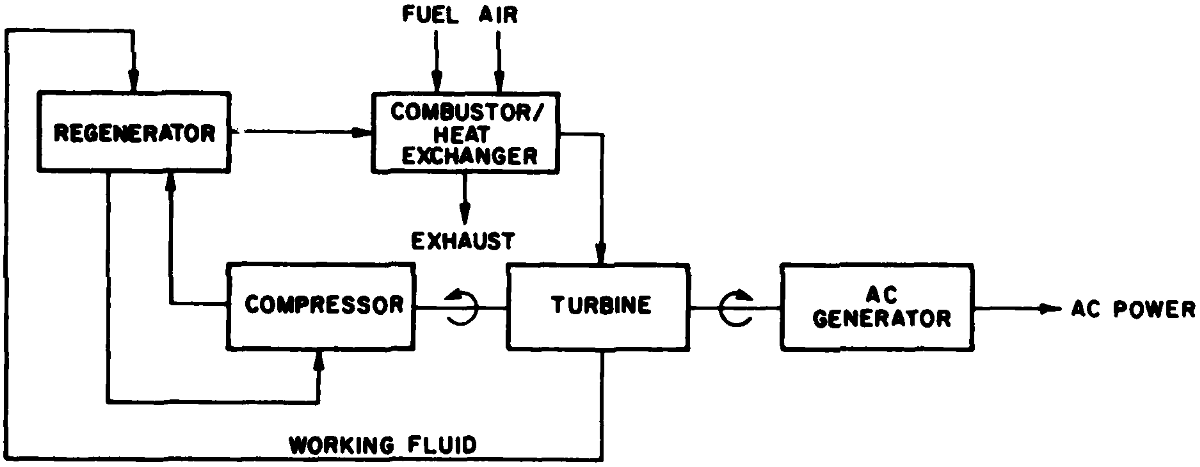
Stirlings. Figure 3 shows the two types of Stirling engines of interest in the study: free-piston and kinematic. The differences in the two technologies do not affect the system configuration. Neither of the Stirlings are commercially available, although Sunpower Corp. did produce a small production run of about 50 1-kW free-piston engines in 1979 at $1000 each. The primary difference between the free-piston Stirling and the kinematic Stirling is that



OPEN CYCLE, NONREGENERATIVE



OPEN CYCLE, REGENERATIVE



CLOSED CYCLE

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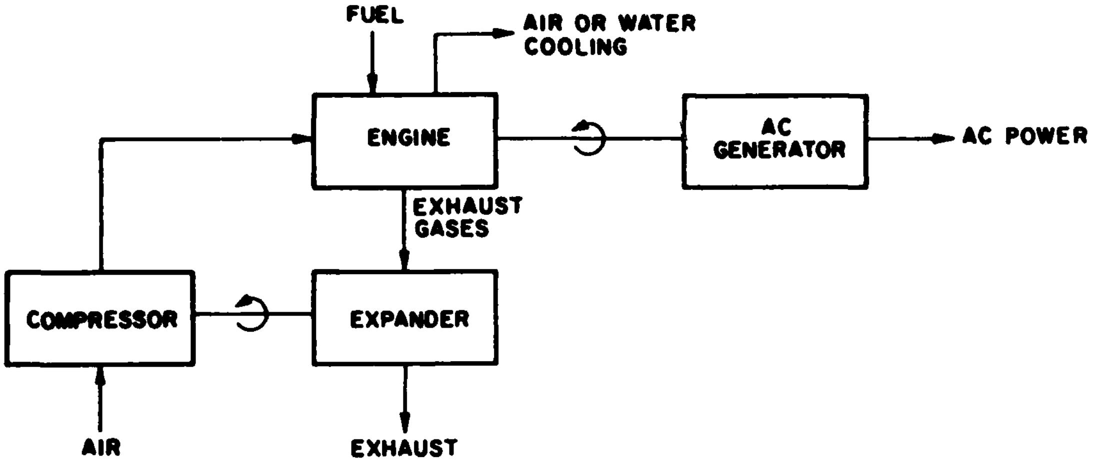
Figure 1. GAS TURBINE SYSTEMS



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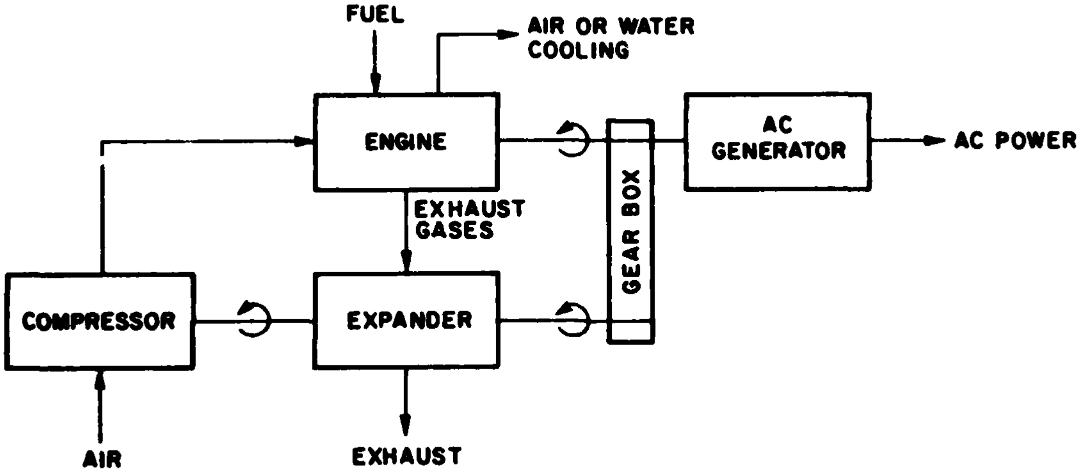

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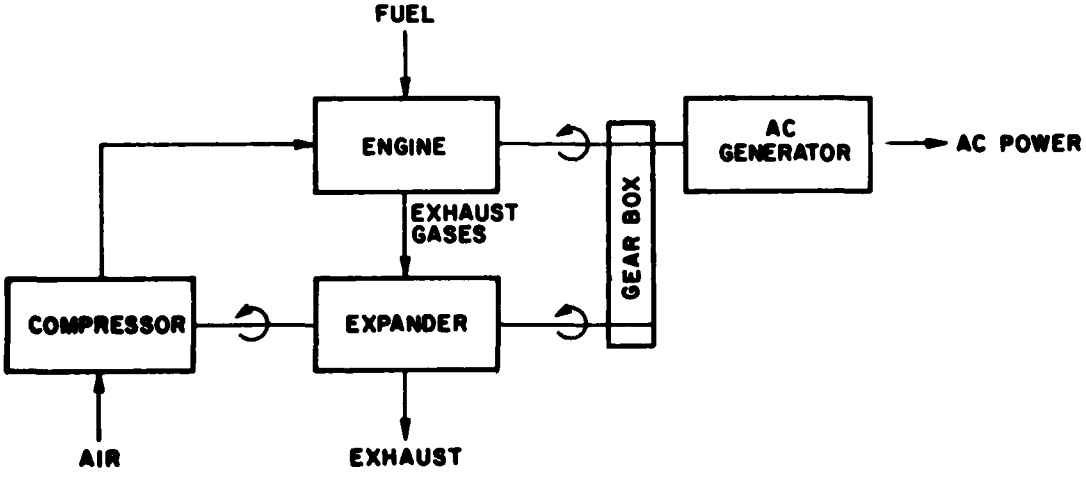

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Figure 2. DIESEL SYSTEMS

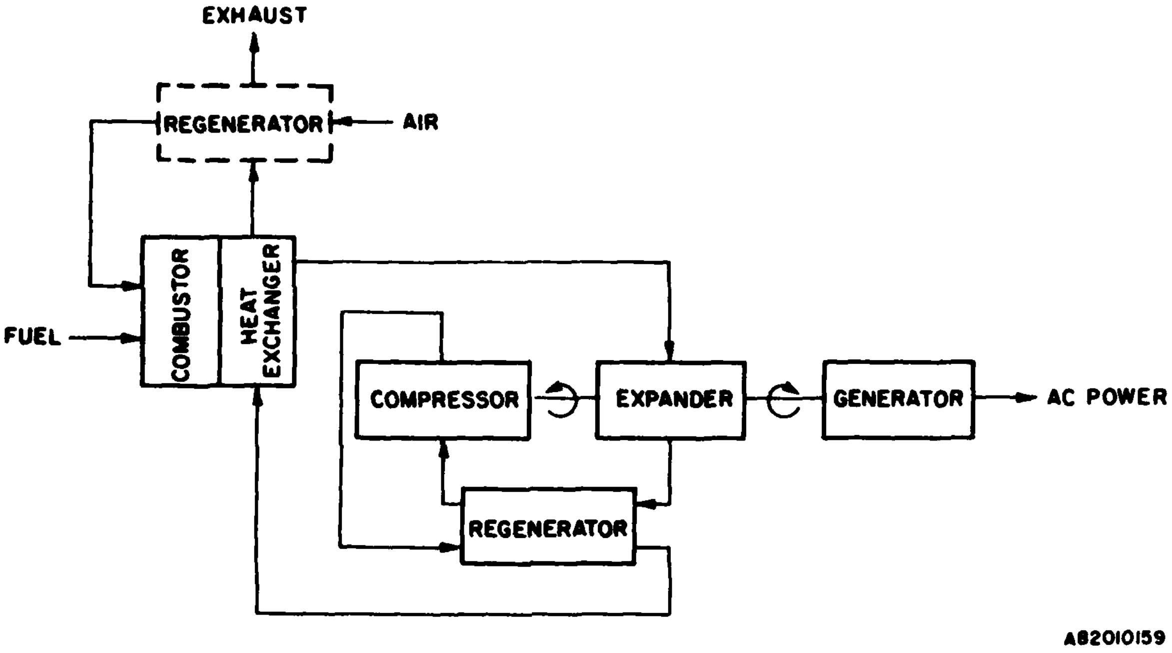

Figure 3. STIRLING SYSTEMS

the stroke of the pistons in the kinematic design is controlled through a mechanical linkage whereas the stroke in the free-piston is controlled by the working fluid in the cylinder. Consequently, the free-piston Stirling should be more efficient by eliminating mechanical losses. Both of the Stirling designs are expected to be commercially available in 1985 to 1990.

Because Stirlings are external combustion engines, they provide a multi-fuel capability relative to diesels and gas turbines.

Organic Rankine Cycle. The organic Rankine cycle (ORC) system shown in Figure 4 is commercially available. ORC's are also external combustion systems and have been designed for a variety of fuel sources, including solar thermal and waste heat. The cost and efficiency of the ORC system can vary greatly depending upon the heat source (which affects heat exchanger requirements) and the quality and quantity of the heat (which affects the operating temperature of the cycle). For the purposes of this study, the designated fuel has been specified as DF-1 or DF-2 to decrease the uncertainty in ORC cost and performance parameters that could otherwise be expected. To the extent that thermal energy is available at less than fuel value for specific ORC applications, the life-cycle costs could be lower than those estimated in this study. The trade-off becomes one of capital cost vs. fuel cost.

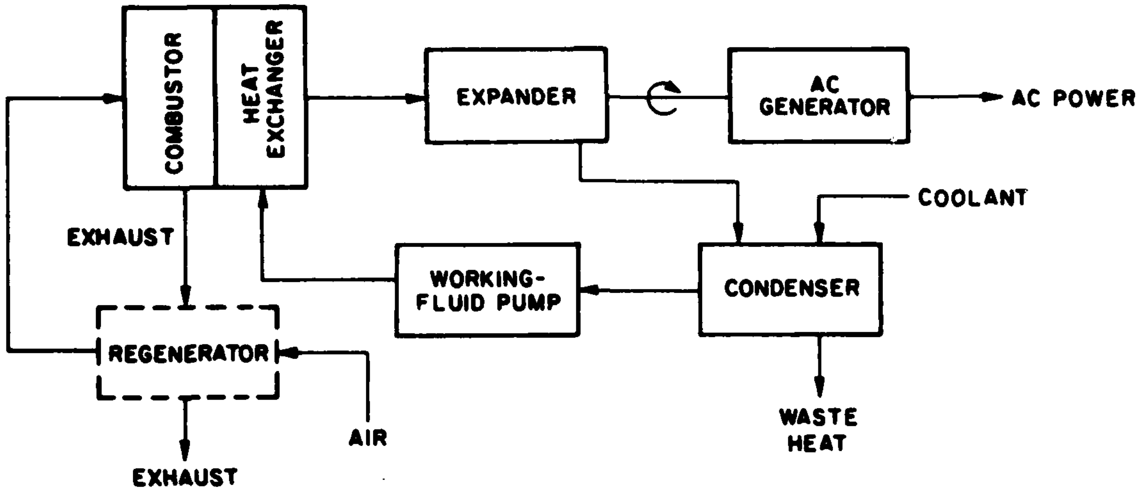

Figure 4. ORGANIC RANKINE CYCLE SYSTEMS

Fuel Cells

There are three types of fuel cells of interest in this study: solid polymer electrolyte (SPE), phosphoric acid, and molten carbonate. The conceptual system configuration in Figure 5 is not affected by the type of fuel cell if the fuel produced by the fuel reformer is assumed to be free of impurities that can affect the operation of the fuel cell. Fuel cells are affected to various degrees by impurities such as CO, H_2S, SO, Cl_2, NO_x, and NH_3. Molten carbonate cells are expected to require sulfur removal down to 1 ppm. Phosphoric acid fuel cells require CO concentrations of less than 4% and usually require a shift reactor to convert CO from the fuel processor to CO_2 and H_2. The conceptual configuration includes a fuel processor (such as a

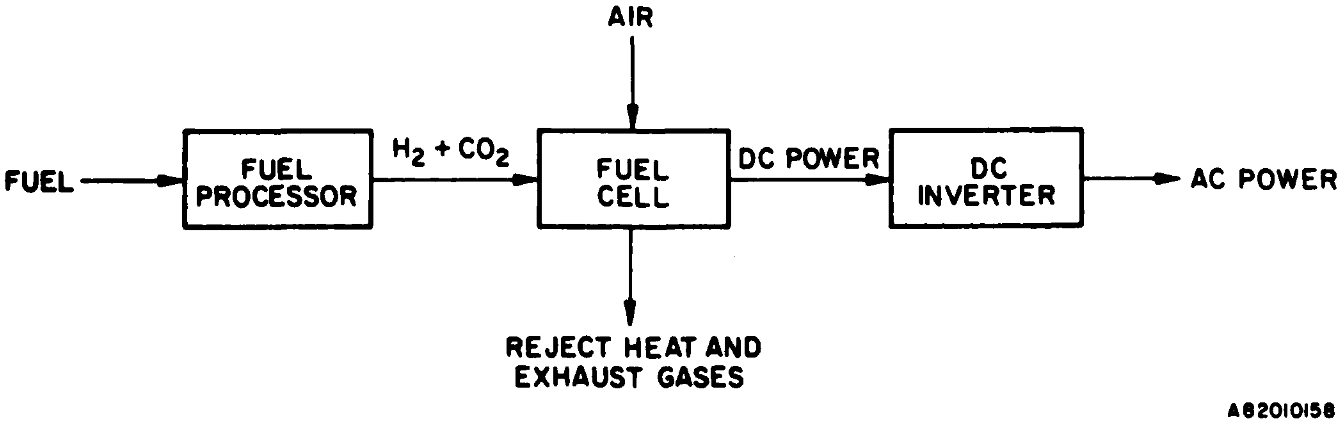

Figure 5. FUEL CELL SYSTEMS

methane-steam reformer, an oil gasifier, a coal gasifier) to convert a hydrocarbon fuel to a hydrogen-rich gas. The fuel cell efficiency at constant hydrogen utilization will increase as the hydrogen concentration in the fuel increases. The hydrogen and oxygen (from the air input) react electrochemically to produce dc power and waste heat. The dc power is transformed to ac with a power conditioner (inverter).

The overall efficiency (thermal and electrical) of each fuel cell type can be affected by the capability to use waste heat from the system. Molten carbonate cells operate at temperatures greater than the phosphoric acid cells (about 900° to 1400°F compared with 150° to 400°F). This permits the potential use of a bottoming cycle for further electrical production. The SPE cell operates at lower temperatures than the phosphoric acid fuel cell and thus permits faster startups.

Wind Turbines

There are two types of wind turbines of interest in this study: horizontal axis and vertical axis. The only real difference between the two is the orientation of the turbine shaft: vertical-axis wind turbines do not have to track the wind direction. The system configuration is presented in Figure 6. Because of the general requirement for continuous ac power output, wind systems include battery storage.

Because wind systems depend upon a number of locational factors (for example, the distribution of wind speed) and machine design factors (such as cut-in speed and rated wind speed), a continuous ac power output system of

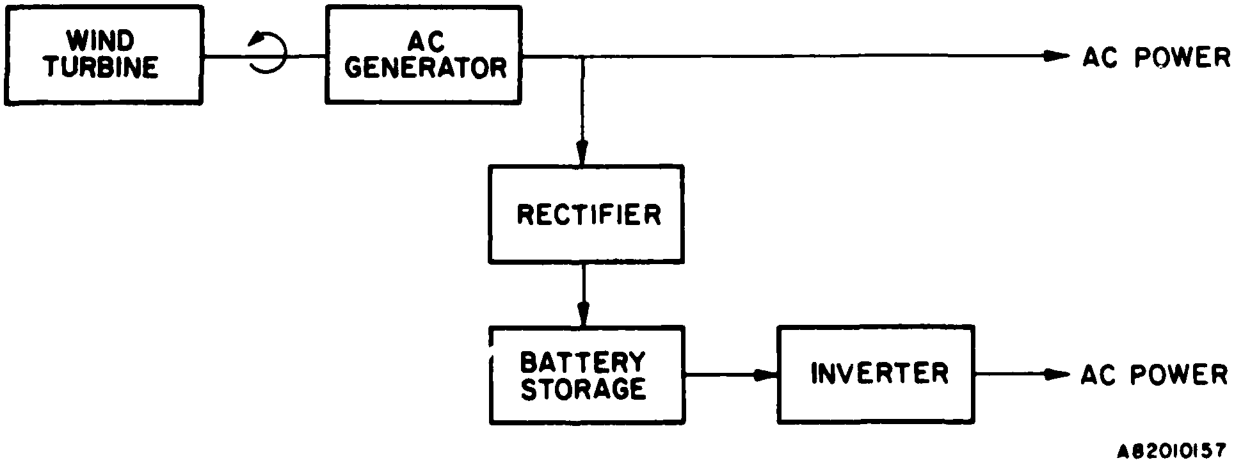

Figure 6. WIND TURBINE SYSTEMS

10 kW requires a wind turbine with a rated capacity of greater than 10 kW. To appropriately identify the required wind turbine rated capacity for the system output requirements, capacity factors were calculated using an approach developed by Powell[1] unless the information on specific machines included the capacity factors (or monthly energy output at design conditions such that the capacity factor could be directly calculated).

The general equation is —

$$R_{WT} = \frac{E_o}{(CF)[X + (1-X)\ \eta_B]} \qquad (1)$$

where —

R_{WT} ≡ rated capacity of the wind turbine in kW

E_o ≡ continuous ouput in kW

CF ≡ capacity factor of the wind turbine

X ≡ fraction of wind machine output directly to load

(1-X) ≡ fraction of wind machine output into batteries

η_B ≡ battery and power conversion system efficiency

$$\eta_B = (\eta_b)(\eta_I) \qquad (2)$$

where —

η_b ≡ battery efficiency

η_I ≡ inverter efficiency

The capacity factor (CF) of the wind turbine is the ratio of the average wind turbine energy output in a specific wind speed regime to the rated energy output as if wind speed is always at the speed at which the wind turbine is rated. The general equation for CF is —

$$CF = e^{-[(\frac{SI}{SA})(0.8862)]^2} - e^{-[(\frac{SR}{SA})(0.8862)]^2} \div$$

$$[(\frac{SR}{SA})(0.8862)]^2 - [(\frac{SI}{SA})(0.8862)]^2 \qquad (3)$$

where —

CF ≡ capacity factor

SI ≡ cut-in speed of the wind machine defined as the wind speed at which the wind machine begins to produce useful power

SR ≡ rated wind speed defined as the wind speed at which the wind machine produces its rated power output

SA ≡ the time-weighted average of the wind speed during a month at the site. This procedure assumes that wind follows a Rayleigh distribution with parameters "g" = 1 and "c" = 2. The mean wind speed for system design should be for the worst month of the year at the site under consideration to ensure that the system will meet the general requirements of continuous power output.

To determine the derating factors for wind turbines, the cut-in speed (SI) and the rated wind speed (SR) were obtained from the literature search and the surveys on the wind systems. The mean wind speed (SA) is assumed to be 8.1 mph, which is the mean (standard deviation of 1.7 mph) of monthly mean wind speeds for 70 nationwide sites for the month of August. August generally has the lowest mean wind speeds.

Given the capacity factor of the wind machine, the rated capacity of the wind machine (R_{WT}) at continuous power output levels (E_o) can be calculated using Equations 1 and 2 with the following assumptions:

1. η_b is assumed at 79%.
2. η_I is assumed at 90%.
3. One day's electrical energy storage is assumed for 80% depth of discharge of batteries regardless of mean wind speed. Thus, a 10-kW continuous system requires 240 kWh of storage or 300 kWh of batteries.
4. X = 0.5; 50% of the wind machine output goes directly to load, and 50% goes to storage and then to load.

Thus the generic equation becomes —

$$R_{WT} = \frac{E_o}{0.86 \times CF} \quad (4)$$

where R_{WT}, E_o, and CF are as previously defined. For the value of SA of 8.1 mph, CF equals 7.48×10^{-2} and the generic equation becomes —

$$R_{WT} = 15.54\ E_o \quad (5)$$

Note that the capacity factor (CF) is quite sensitive to the mean wind speed. For example, we calculated cases assuming a cut-in wind speed of 7.5 mph and a rated wind speed of 23.0 mph and four mean wind speeds of 8.1, 10, 12, and 15 mph (Table 5). Consequently the parameter values for the wind system are likely to be overestimated if the mean wind speed were greater than 8.1 mph and underestimated if the mean wind speed were less than 8.1 mph. The sensitivity of each of the parameter values to mean wind speed was not estimated as it was beyond the scope of this study. However, mean wind speed is a critical parameter in the characterization of wind turbines. Future development of the data base should consider a number of alternative cases (mean wind speeds) for these systems.

Table 5. SENSITIVITY OF WIND MACHINE CAPACITY FACTOR TO MEAN WIND SPEED

Mean Wind Speed, mph	Capacity Factor	Rated Capacity of Wind Machine Required for 10-kW Continuous Power, kW
8.1	0.07	155
10	0.17	69
12	0.26	44
15	0.40	29

We compared the procedure developed for estimating capacity factor using Equation 3 with the information available from those manufacturers who provided direct information as to the capacity factors for their wind machines. Assuming a cut-in speed to a rated wind speed ratio of 1:3 (based on the average of available information), a capacity factor curve can be predicted using Equation 3 as a function of the ratio of rated wind speed to average monthly wind speed as shown in Figure 7. The input data on actual capacity factors from those information sources that provided such data were plotted relative to the predictive curve. As shown, the actual data are reasonably consistent with the predicted data. Therefore this procedure was selected to estimate capacity factors in those cases where the information source did not provide sufficient information to more directly calculated capacity factors.

Photovoltaic Energy Conversion Systems

Three types of photovoltaic energy conversion systems were considered: 1) passively cooled flat plate, 2) photoelectrochemical, and 3) actively cooled. Figure 8 is a schematic diagram of the three systems. Actively cooled photovoltaic systems are interpreted as defining concentrating collectors that require active cooling of photovoltaic cells to maintain efficient photovoltaic solar energy conversion performance.

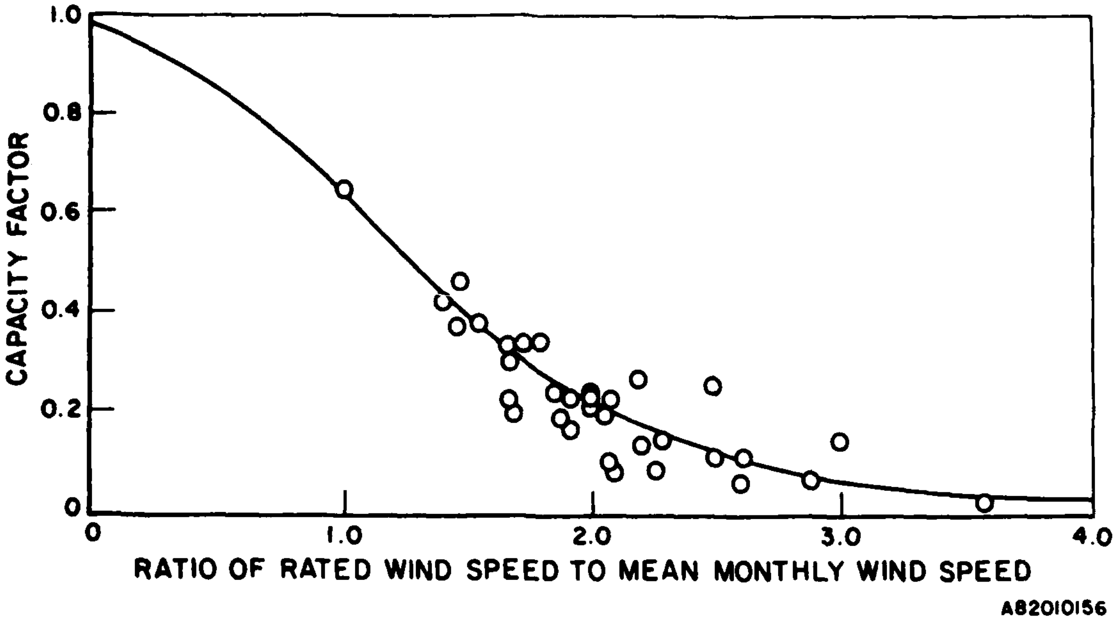

Figure 7. CORRELATION OF PREDICTED CAPACITY FACTORS TO ACTUAL CAPACITY FACTORS FOR WIND MACHINES

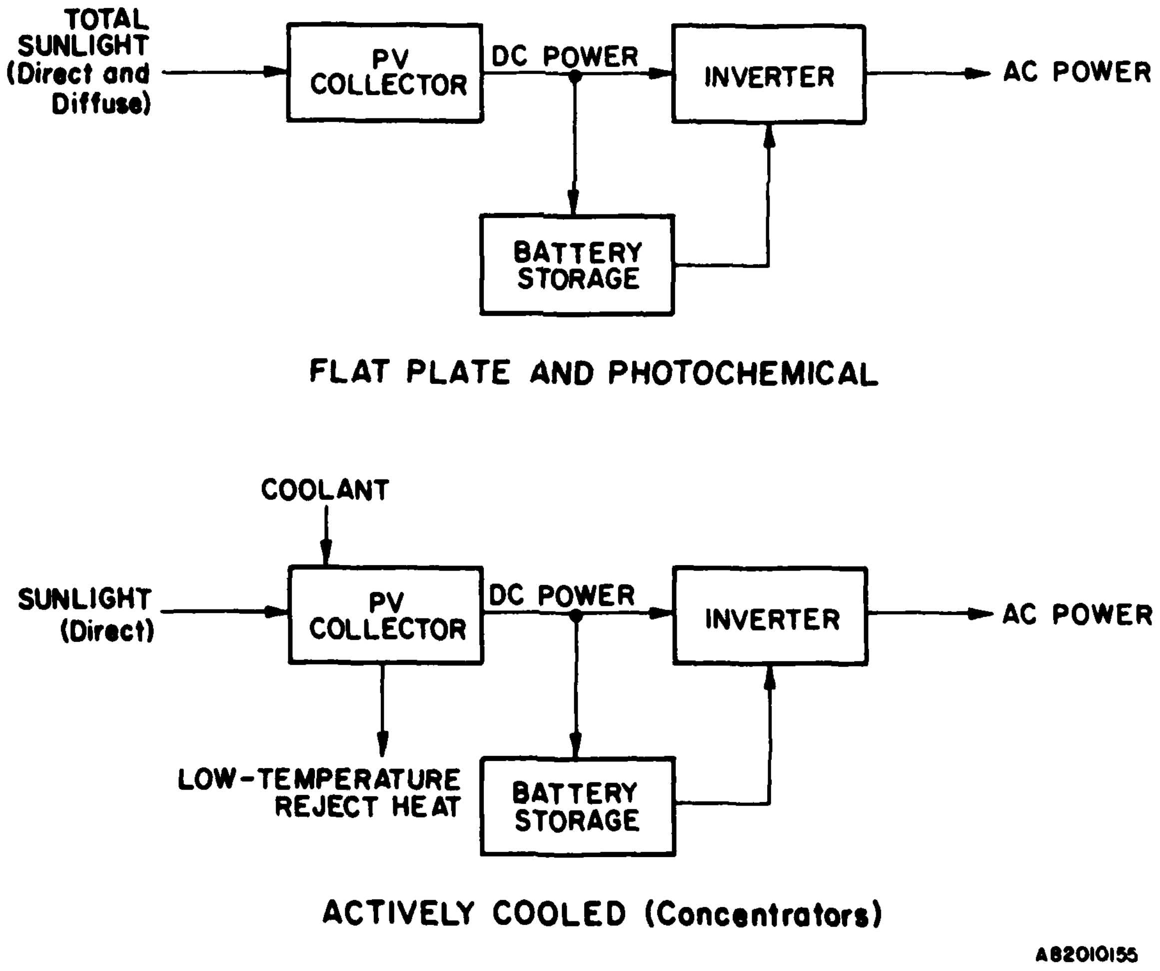

Figure 8. PHOTOVOLTAIC SYSTEMS

Flat-plate and photoelectrochemical photovoltaic systems differ from actively cooled, concentrating photovoltaic systems in two ways. The first difference is that flat-plate and photoelectrochemical systems use the total insolation;* that is, the direct or specular component of sunlight plus the indirect or diffuse sunlight component. Concentrating photovoltaic systems accept only the direct component of sunlight. In addition, because of the use of concentrating optics they must track the sun in at least one axis to keep the sun's image properly focused upon the photovoltaic cells. Flat-plate and photoelectrochemical systems are generally fixed and do not need to track the sun, although sun-tracking systems may be used. Because the energy production of photovoltaic systems depends on the amount of solar energy falling on the collector, actively cooled systems have somewhat lower performance than fixed flat-plate photovoltaic systems. The direct component of insolation is always less than the total insolation. This deficiency, however, is substantially overcome by tracking the sun so that insolation availability is substantially similar for both fixed and tracking systems.

The second difference is that flat-plate and photoelectrochemical systems operate at near-ambient temperatures, while concentrating photovoltaics are actively cooled to maintain cell temperature at efficient operating conditions. Concentrating systems are therefore able to provide low-temperature thermal energy (<180°F) for other uses such as domestic hot water or space heating.

Photovoltaic energy systems require batteries to store electrical energy because of the day/night cycle and the transient nature of daytime solar availability from the movement of the sun in the sky and the presence of clouds. Inverters are necessary to convert the dc output of photovoltaic systems and batteries to utility-quality ac power.

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* In the most general case, photoelectrochemical systems may be used with sunlight concentration.

Sizing photovoltaic arrays — that is, determining array area and battery capacity to produce continuous power output — is complicated by the fact that photovoltaic systems are quite sensitive to site. In a high-insolation site such as the Southwest, a considerably smaller array is required than that required in a Midwest or Northeast location. The design method used to size flat-plate photovoltaic arrays was from Siegal.[2] This design method is not directly applicable to concentrating systems, but was modified as necessary to size these systems with reasonable accuracy. The design method predicted the required array size to produce a continuous 1-kW output. Because photovoltaic systems are modular, system size for larger outputs is a linear function of the desired power requirement. (For example, a 5000-kW_e system is 5000 times the size of a 1-kW_e system.) Designs were prepared for continuous power systems for Albuquerque and Madison insolation to bracket insolation regimes. A linear interpolation was performed on the resulting photovoltaic array area and battery capacity to an average site because the data base developed in this study can only accept parameters of one representative case.

Photovoltaic system designs excluded photoelectrochemical systems because they are currently in the developmental stage and are not expected to be commercial until about 1990. Designs were based on performance characteristics as reported in the data base for single-crystal silicon photovoltaic cells applied to flat-plate and concentrating arrays. They are the primary commercially available photovoltaic technology.

Battery storage capacity was sized such that no energy was wasted during the design month. All array output may thus be applied to the load. Lead-acid battery technology with characteristic parameters as reported in the data base was used as the means of electrical energy storage.

The results of the sizing analysis of photovoltaic array has some implications that should be recognized. Photovoltaic systems for continuous duty are designed to produce power outputs of the desired value. The data-base user must realize, however, that even with energy storage in the system, inherent stochastic variations in insolation availability may lead to occasional power outages. Outages are most likely to occur (albeit infrequently) during the low-insolation winter months. Because the photovoltaic system is considerably oversized to guarantee continuous power output under worst-month insolation conditions, significantly greater annual power output (> 8760 kWH_e/year) is possible if a load or energy storage exists to make use of the system output.

Flat-Plate Photovoltaic System Design. Assumptions and data input values for this design are summarized below:

- Sites considered: Albuquerque, New Mexico, and Madison, Wisconsin
- Photovoltaic system sized for worst-month insolation on a tilted collector surface
- Collector tilted at local latitude and facing due south
- National average daily December insolation on south-facing collector at 45° tilt angle: 1204 Btu/ft^2-day
- Reported photovoltaic array efficiency at 82.4°F for single-crystal, flat-plate collector: 10.6%
- Assumed array absorptivity: 0.85
- Array transmissivity with no cover plate: 1.0
- Assumed array temperature dependent coefficiency of efficiency: 0.222%/°F
- Assumed power conditioning system efficiency: 90%
- Assumed ground reflectivity: 0.2
- Reported battery efficiency (lead-acid technology): 79%
- Reported allowable battery depth of discharge: 80%
- Average daily horizontal total insolation
  - a) Madison: 555.7 Btu/ft^2-day (November)
  - b) Albuquerque: 1051.6 Btu/ft^2-day (December)
- Average daily total insolation on tilted collector
  - a) Madison: 987.7 Btu/ft^2-day
  - b) Albuquerque: 1906.4 Btu/ft^2-day
- Flat-plate collector tilt angle
  - a) Madison: 45°
  - b) Albuquerque: 35°
- Average daytime ambient temperature

a) Madison: 37.8°F

b) Albuquerque: 33.8°F

The results of the analyses are as follows:

- Madison flat-plate photovoltaic array area: 888 ft^2/kW
- Madison required battery storage capacity: 25.4 kWh_e/kW
- Albuquerque flat-plate photovoltaic array area: 444 ft^2/kW
- Albuquerque required battery storage capacity: 22.9 kWh_e/kW.

Actively Cooled (Concentrating) Photovoltaic System Design. Assumptions and data input values are summarized below:

- Siegel's method is not strictly applicable to concentrating photovoltaic systems.
- Photovoltaic systems are sized to worst-month insolation in plane of collector.
- Photovoltaic collector is assumed to be oriented east-west and tracking about a horizontal axis.
- National average winter insolation in plane of collector: 1109 Btu/ft^2-day.
- Reported concentrating photovoltaic array efficiency: 9.1%.
- Monthly average product of cell efficiency and net transmittance of concentrator optics and cell cover is represented adequately by reported concentrating photovoltaic array efficiency.
- Array efficiency is not sensitive to ambient or cell temperatures except as represented by reported data.
- Assumed power conversion system efficiency: 90%.
- Characteristic equation:

$$\bar{E}_d = \eta_c \bar{E} - \bar{D}_o + \eta_B (\bar{D}_o) \qquad (6)$$

where —

$\bar{E}_d$ ≡ desired daily energy production

η_c ≡ power conversion system efficiency

$\bar{E}$ ≡ photovoltaic array daily output = (array arpa) X (array efficiency) X (insolation in plant of collector)

$\eta_B \equiv$ battery efficiency

$D_o \equiv$ photovoltaic array energy diverted through battery storage. In the calculation of $\bar{D}_o$, it is assumed that useful output of the array occurs in a time period of 2 hours less than the actual sunrise to sunset time. During this time period, the array must produce the electrical energy output required in addition to sufficient energy to meet the load during the night, including accounted for battery efficiency.

$\bar{D}_o$ — [photovoltaic array daily energy output — load (kWh) during time period two hours less than day length] $\div\ \eta$

- Average daily insolation in plane of collector
  - a) Madison: 1078.3 Btu/ft^2-day (November)
  - b) Albuquerque: 1842.8 Btu/ft^2-day (February)
- Day length
  - a) Madison: 9.5 hours
  - b) Albuquerque: 10.8 hours

The results of the analysis are as follows:

- Madison concentrating photovoltaic array area: 1097 ft^2/kW
- Madison required battery storage capacity: 25.4 kWh/kW
- Albuquerque concentrating photovoltaic array area: 634.1 ft^2/kW
- Albuquerque required battery storage capacity: 24.1 kWh/kW

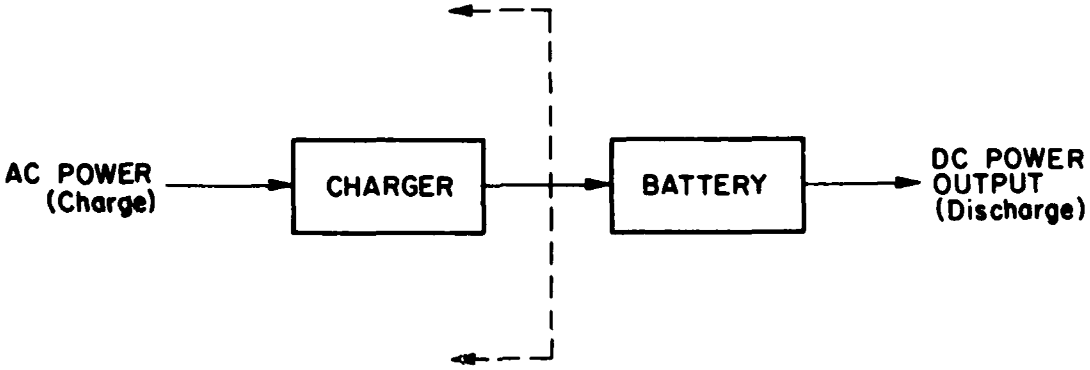
The generic design of flat-plate and concentrating photovoltaic energy conversion system was determined by linear interpolation on the primary independent variable characterizing such systems — the average insolation in the worst month. The results are as follows:

- Generic flat-plate photovoltaic array area: 783.5 ft^2/kW
- Generic required battery storage capacity for flat-plate photovoltaic systems: 24.8 kWh$_e$/kW
- Generic concentrating photovoltaic array area: 1078 ft^2/kW
- Generic required battery storage capacity for concentrating photovoltaic systems: 26.0 kWh/kW

Because the photovoltaic systems are modular, the parameters reported in the data base are based on the above array and storage requirements for a 1-kW continuous system.

Batteries

There are seven types of batteries of interest in this study, although none affect the conceptual system configuration. As shown in Figure 9, the system consists of charger and the battery. However, the charger is shown only because the cost of ac power into the battery (as dc power) must be adjusted for the efficiency of the charger, which has been assumed at 90%.



NOTE: CHARGER INCLUDED ONLY TO ADJUST AC POWER COSTS FOR CHARGER EFFICIENCY

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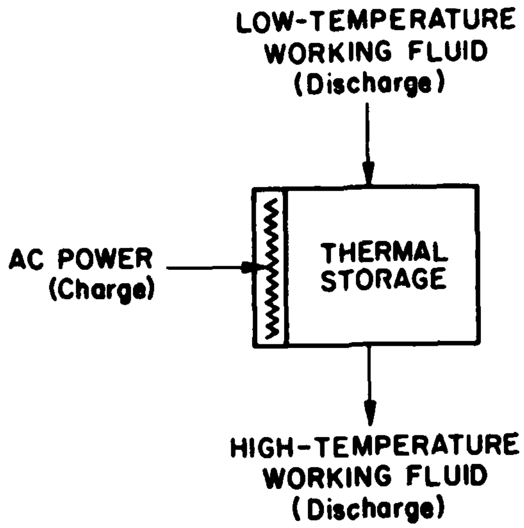
Figure 9. BATTERY SYSTEMS

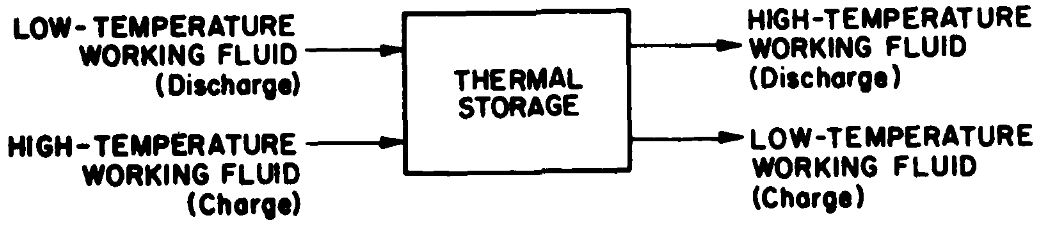
Of the various batteries characterized, only the lead-acid is commercially available. The Ni/Fe and $Li\text{-}Al/FeS_2$ are expected to be commercially available in 1985. The Zn/Cl_2, Zn/Br_2, Na/S, and Redox (Fe/Cr) are expected to be commercially available in 1990.

Thermal Storage Devices

There are six thermal storage materials under consideration: olivine ceramic brick, magnesite ceramic brick, calcium chloride hexahydrate, Glauber's salt, sodium thiosulfate pentahydrate, and form-stable polyethylene. The two brick materials are charged with electric resistance heating, as shown in Figure 10, and operate at temperature around 1200°F. The latter four materials are phase-change materials and are charged with a working fluid



BRICK MEDIA



OTHER MEDIA

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Figure 10. THERMAL ENERGY STORAGE SYSTEMS

(Figure 10). These materials have the following operation temperature: Glauber's Salt, about 73°F; calcium chloride hexahydrate, about 81°F; sodium thiosulfate pentahydrate, about 117°F; and form-stable polyethylene, about 225°F. Although all of the media can be used for space heating, the form-stable polyethylene is typically considered for use with absorption chillers. All of the media are commercially available except for the sodium thiosulfate pentahydrate, which is expected to be commercial in 1985, and the form-stable polyethylene, which is expected to be commercial in 1990.

Fuels and Fuel Prices

Two parameters in this study depend upon the fuel selected for the energy system and the expected cost of the fuel over the 20-year period of this study. Recognizing the uncertainty of fuel price predictions over a 20-year period, a parametric approach was preferred to point predictions. Consequently, the single parameter of annual fuel cost was extended to three parameters: one for constant fuel prices in 1980 dollars, one for fuel prices escalating in real terms of 5%/yr in 1980 dollars, and one for fuel prices escalating in real terms of 10%/yr in 1980 dollars. Because life-cycle cost is a function of annual fuel cost, life-cycle cost was also expanded to three parameters consistent with the price increases assumed for the fuel costs. Note that only the fuel cost component of the life-cycle cost is assumed to escalate in real terms.

Third-quarter 1980 fuel prices for logistics fuels were obtained from the Defense Fuel Supply Center (DFSC). The fuels and prices are presented in Table 6. The prices are defined as the worldwide, standard price of fuel from the DFSC stock fund. The quoted prices are based on the average contract prices of fuels in stock plus the average transportation cost to users. Comparison of the costs of the fuel oils, except for the residuals and Navy special, on an energy basis showed that for the purposes of this study there is no need to differentiate among the fuel oils because all are equivalent in terms of cost per unit of energy. Although the residual fuel oils are least costly in terms of energy, they typically have high sulfur content and are generally used at power generation stations of greater capacities than the 5000-kW upper limit considered in this study. Consequently, two logistic fuels were considered as options for designated fuels: JP-4 because of the ongoing development of a JP-4 reformer, which could provide fuel cell fuel, and diesel because it is the lowest cost-acceptable logistics fuel available regardless of military specifications. Multifuel capabilities of certain technologies (for example, Stirlings and organic Rankine cycles) are accounted for in the Fuel Capability parameter. Multifuel capabilities are also discussed in Volume II: Technology Handbook.

Metered fuels and fuels that are not included in the DFSC stock fund are subject to regional variations in price. For example, natural gas prices at selected USAF installations range from $1.30/million Btu at Hill Air Force Base in Ogden, Utah, to $3.91/million Btu at McClellen in Sacramento, California (Table 7). Electricity prices show a similar dispersion. The averages for electricity and gas supplied to the surveyed bases are reasonably consistent with the U.S. Industrial Price Average for February 1980. For this study we have taken the natural gas and electricity prices as the Air Force base averages for the base case 1980 prices.

Methanol also represents a primary fuel cell system fuel. Methanol prices at selected markets are in Table 8. For this study the average price of methanol has been assumed as the base-case 1980 price.

Other primary energy that must be considered include solar at a zero cost, wind at a zero cost, and thermal energy. As previously discussed in the definition of the parameters, for all energy conversion systems the life-cycle cost and efficiencies do not include any credit for heat recovery. Consequently, for internal consistency the cost of that heat is assumed to be zero for those thermal energy storage devices where heat is the primary energy. This is because the cost is implicitly included in the cost of energy from the energy conversion system (if such a system in fact provided the energy to charge the thermal storage device).

Because of their uncertainty, energy costs are included in the data base under three scenarios: constant prices, 5%/yr real price increases, and 10%/yr real price increases. For the 1980 time period, all three scenarios would be the same. Therefore, to exhibit the sensitivity of the energy system's life-cycle cost to energy prices with all other parameters constant, there were three 1980 scenarios for natural gas, electricity, methanol, JP-4, and diesel:

Scenario 1: minimum cost

Scenario 2: average cost (base case)

Scenario 3: maximum cost

Table 6. STANDARD DFSC FUEL PRICES (3rd Quarter 1980)

Aviation Fuels	Price, $/U.S. gal	Energy Content, Btu/U.S. gal	Price, $/million Btu		
			Maximum	Minimum	Average
Aviation Gasoline (130 Grade)	1.41	120,190 — 123,810	11.73	11.39	11.56
JP-4	1.16	127,500 — 135,714	9.10	8.55	8.83
JP-5	1.27	135,000 — 140,476	9.41	9.04	9.23
Ground Fuels (Gasolines)					
Regular Unleaded	1.29	125,071 — 126,190	10.31	10.22	10.27
Premium	1.29	125,071 — 126,190	10.31	10.22	10.27
Combat Grade (Types 1 and 2)	1.26	125,071 — 126.190	10.07	9.98	10.03
Gasohol	1.29	121,183 — 122.190	10.65	10.56	10.61
Fuel Oils					
Arctic Grade (DF-A)	1.22	138,095 — 145,238	8.83	8.40	8.62
Diesel (DF-1)	1.22	138,095 — 145,238	8.83	8.40	8.62
Diesel (DF-2)	1.22	138,095 — 145,238	8.83	8.40	8.62
Diesel (Marine)	1.22	138,095 — 145,238	8.83	8.40	8.62
Burner Distillate (FS-1)	1.22	138,095 — 145,238	8.83	8.40	8.62
Burner Distillate (FS-2)	1.22	138,095 — 145,238	8.83	8.40	8.62
Residual (FS-4)	0.87	147,619 — 150,000	5.89	5.80	5.85
Residual (FS-5)	0.87	147,619 — 150,000	5.89	5.80	5.85
Residual (FS-6)	0.87	147,619 — 150,000	5.89	5.80	5.85
Navy Special (Bunkering Oil, NSF)	0.87	147,619 — 150,000	5.89	5.80	5.85

Table 7. NATURAL GAS AND ELECTRICITY PRICES AT SELECTED AIR FORCE BASES, 1980

Base	Location	Natural Gas Price, $/million Btu	Electricity Price, $/MWh	Electricity Price, $/million Btu*
Hill	Ogden, UT	1.30	27.24	7.98
Kelly	San Antonio, TX	2.37	33.25	9.75
McClellan	Sacramento, CA	3.91	15.83	4.64
Robins	Warner-Robins, GA	2.44	31.60	9.26
Tinker	Oklahoma City, OK	2.08	27.28	8.00
Wright-Patterson	Dayton, OH	2.72	32.34	9.48
Base Average		2.47	27.92	8.18
U.S. Industrial Prices		2.39	33.10	9.70

* 3412 Btu/kWh

Source: Mr. Clyde McWhirter, Command Engineering: Wright-Patterson AFB (513-257-4103)

Table 8. 1980 METHANOL PRICES

	Gulf Coast		Los Angeles	
	$/U.S. Gallon	$/million Btu*	$/U.S. Gallon	$/million Btu*
1st Quarter	0.75 - 0.78	11.57 - 12.04	0.90 - 0.94	13.89 - 14.50
2nd Quarter	0.75 - 0.77	11.57 - 11.88	0.90 - 0.94	13.89 - 14.50
3rd Quarter	0.75 - 0.77	11.57 - 11.88	0.90 - 0.94	13.89 - 14.50

(Average 1980: $12.97/million Btu)

* 64,810 Btu/U.S. Gallon

Source: Chemical Marketing Reporter

Scenario 2 costs were escalated at 0%/yr (constant), 5%/yr, and 10%/yr to obtain the price estimates for 1985, 1990, and 2000 (Table 9).

For thermal, the 1980 scenarios are as shown in Table 9. These were assumed only to exhibit the sensitivity of the life-cycle cost to energy cost. As shown, the zero cost is maintained as Scenario 1 in 1985, 1990, and 2000. The $3.00/million Btu cost was escalated at 5%/yr for Scenario 2 costs in 1985, 1990, and 2000. The $3.00/million Btu cost was escalated at 10%/yr for Scenario 3 costs in subsequent years. The costs of solar and wind energy were maintained at zero throughout.

Table 9. ESTIMATED FUEL PRICES, 1980-2000 (1980 Dollars)
($/million Btu)

Fuel		1980	Escalation, %/yr	1985	1990	2000
Natural Gas	(1)	1.30	0	2.47	2.47	2.47
	(2)	2.47	5	3.15	4.02	6.55
	(3)	3.91	10	3.98	6.41	16.63
Electricity	(1)	4.64	0	8.18	8.18	8.18
	(2)	8.18	5	10.44	13.32	21.70
	(3)	9.75	10	13.17	21.22	55.04
Methanol	(1)	11.57	0	12.97	12.97	12.97
	(2)	12.97	5	16.55	21.13	34.42
	(3)	14.50	10	20.89	33.64	87.25
JP-4	(1)	8.55	0	8.82	8.82	8.82
	(2)	8.82	5	11.25	14.36	23.40
	(3)	9.10	10	14.20	22.88	59.34
Diesel	(1)	8.40	0	8.62	8.62	8.62
	(2)	8.62	5	11.00	14.04	22.86
	(3)	8.83	10	13.88	22.36	58.00
Thermal	(1)	0		0	0	0
	(2)	3.00	5	3.83	4.89	7.97
	(3)	6.00	10	4.83	7.78	20.18
Solar	(1)	0		0	0	0
	(2)	0		0	0	0
	(3)	0		0	0	0
Wind	(1)	0		0	0	0
	(2)	0		0	0	0
	(3)	0		0	0	0

Note: These prices are the cost of fuel into an energy system, not the cost of energy delivered from the system.

ANALYTICAL PROCEDURES

Quantitative

Statistical Analysis

Input data for the quantitative parameters were gathered over the 1.5 to 5000-kW power output range for the conversion technologies and over the equivalent energy output range at continuous operation for the storage technologies. Using these input data, the parameter value at selected discrete output levels was estimated using statistical analyses.

The approach to the statistical analysis is summarized in Figure 11. The data are analyzed using the least squares method to determine the functional dependence of the parameter to output level. The functional dependence is established by the estimated curve that minimizes the squared error of the input data relative to the curve. The fits that were tested for the different data sets are linear and quadratic polynomials ($P = a + bx + cx^2$), a logarithmic function of the form $P = a + b \log x + c (\log x)^2$, and a power function of the form $P = ax^b$, where P is the parameter value, a, b, and c are constants, and x is the output level.

The resulting mathematical functions, which describe the dependence of the different parameters to output, were used to calculated the expected value of the parameter at 1.5, 5, 20, 30, 60, 100, 250, 500, 750, 1000, and 5000 kW for the conversion technologies and at the equivalent energy output for the storage technologies. The standard error of the data relative to the curve was also calculated to estimate the expected error in the calculated parameter values.

In a strict statistical procedure, the least square analysis should only be conducted when there are a reasonable number of data points relatively evenly dispersed throughout the full range of the estimates to be calculated (1.5 to 5000.0 kW). In certain cases the data were insufficient to determine any functional dependence of the parameter with the output level. In these cases the arithmetic average of the input data was calculated and serves as the estimate of the parameter value at the selected discrete output levels. In other cases, the input data did not cover the full range of output, but were sufficient to determine the functional dependence of the parameter with output over a limited range (for example 100 to 1000 kW instead of 1.5 through

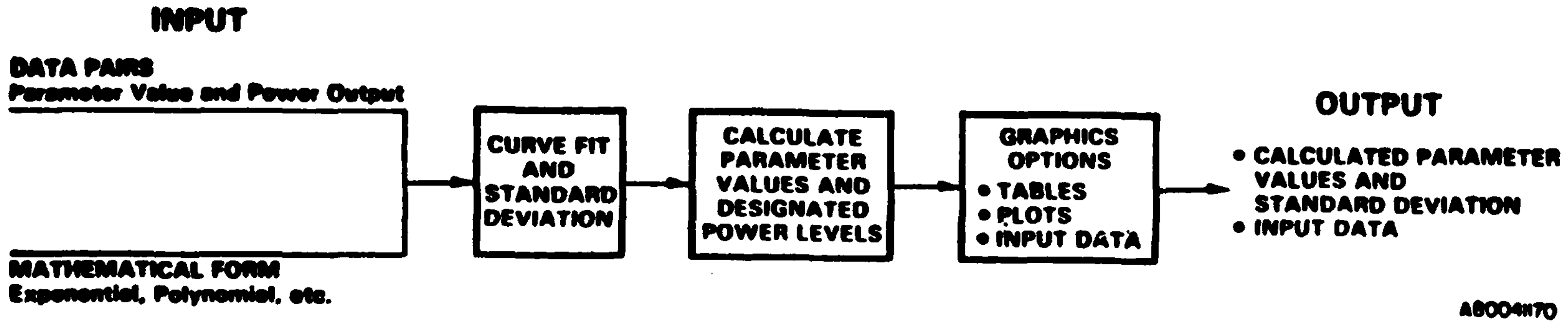

Figure 11. COMPUTER PROGRAM FOR STATISTICAL ANALYSIS

5000 kW). In these cases the mathematical function was determined using the available input data. The range of the input data was extrapolated based upon IGT expert opinion. The analyses and results are documented in Volume IV of this report. In those cases where data were extrapolated beyond the range, the calculated values are so designated.

Technology Projections

As previously discussed, parameter values were to be estimated for the 1980, 1985, 1990, and 2000 time frames. The same procedures as those discussed above were used for all of these time frames where sufficient data were available. That is, the data were analyzed on a cross-sectional basis rather than on a time-series basis. For example, for a parameter such as efficiency, a mathematical function of efficiency vs. output level was estimated for 1980, 1985, 1990, and 2000 based upon the input data. If efficiency were continuously improving over time for the specific technology, each mathematical function was calculated independent of the other function. If, however, there were no input data to indicate a continuous efficiency improvement (for example, efficiency increased by 10% from 1980 to 1985 and no data were available to indicate subsequent improvements) then the mathematical function calculated for the latest time frame (for example, 1985) was also used as the function for all subsequent time frames (such as 1990 and 2000.) In other words, unless input data were available to indicate otherwise, we assumed that the parameter value had achieved its minimum or maximum in the latest year for which data were available and future changes could not be expected.

The key to the technology projections is sufficient data. Obviously one expects less input data for 1990 to 2000 than for 1980 to 1985. But even with the input data for the earliest time frame, there is an error band around the predicted values. In determining whether there were sufficient data in the parameter values in subsequent time frames, a χ^2 (chi square) statistical test was used to determine whether the expected values in time frame i were significantly different (95% confidence level) from the observed values in time frame $i + 1$. The procedure was selected for the following reasons:

1. It is consistent.
2. It ensures that limited information about parameters in future time periods does not arbitrarily result in the inference of improvement in the technology.

3. It provides a methodological procedure for updating the data base as more information becomes available.

4. It ensures that the expected errors in the estimate of the parameter value of time period i are recognized when evaluating data projections.

5. At the 95% confidence level, the procedure is relatively conservative in terms of inferring technology improvements. Technology projections typically tend to be positively biased. That is, if the input data about improvements in a technology are solicited from persons who have an interest in the technology,* the tendency is to be optimistic about the future for the technology. This procedure reduces the effect of the expected bias — that is, inferring an improvement too early in the development of the technology or inferring an improvement that is relatively insignificant compared to the state-of-the-art of the technology.

Formally, the procedure consisted of the following steps:

1. The 95% confidence limits (error band) were calculated for the predicted values of the parameter in time period i.** The 95% confidence limits are given by the predicted value ±1.96 times the standard error of the predicted value (in the case of arithmetic averages, the 95% confidence limits are given by the average ±1.96 times the standard deviation of the average.

2. The input data for time period i + 1 are plotted on a graph of the predicted values and error bands of the parameter value of time period i. This is done to ensure that the subsequent statistical analysis does not result in spurious conclusions. For example, referring to Figure 12, a hypothetical predicted curve and its associated error bands are shown. If the input data for time period i + 1 (denoted by 0) were statistically analyzed it would probably result in a new curve that would intersect the curve of time period i. This type of transition would imply that at certain output levels, the performance of the technology is expected to improve over time, but that at other output levels the performance of the technology is expected to get worse in the future. Of the parameters of interest in this study, there are none that can be expected to get worse over limited output ranges and improve in another range. It is, of course, possible for certain parameters to improve over certain ranges and remain the same over other ranges.

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* This cannot be avoided in technology projections. If the data are solicited from persons who don't have any interest (and probably don't know enough about the technology to provide estimates), there is no indication of the expected direction of the bias.

** There are four time periods of interest: 1980, 1985, 1990, and 2000. Time period i is used to generalize the procedure and doe not specifically refer to any one of these time periods, but to the first of the two time periods that are being evaluated relative to each other.

3. Where the data from time period i + 1 show a change relative to the predicted curve of time period i, that indicates an improvement in the parameter value over a portion of the output or over the total output range a new curve is estimated.

4. The predicted values from the curve for time period i are compared with the predicted values of the curve from time period i + 1 using the χ^2 test at the 95% confidence level. The χ^2 value is a function of the degrees of freedom. The degrees of freedom are determined by the number of discrete output levels that fall within the range of the output of the curve from time period i + 1. For example, the maximum degrees of freedom is limited to 10 (eleven discrete output levels — 1).

5. If the calculated χ^2 exceeds the χ^2 critical value at the appropriate degrees of freedom, then the new curve for time period i + 1 is taken to represent a signficant change in the parameter value relative to the curve of time period i. In this case, the procedure would continue; in the next sequence data for time period i + 2 would be compared with the curve for time period i + 1.

6. If the calculated χ^2 does not exceed the χ^2 critical value at the appropriate degrees of freedom, then the original curve for time period i is taken as representative of the parameter in time period i + 1, and the procedure would then continue comparing the data for time period i + 2 with the curve for time period i + 1.

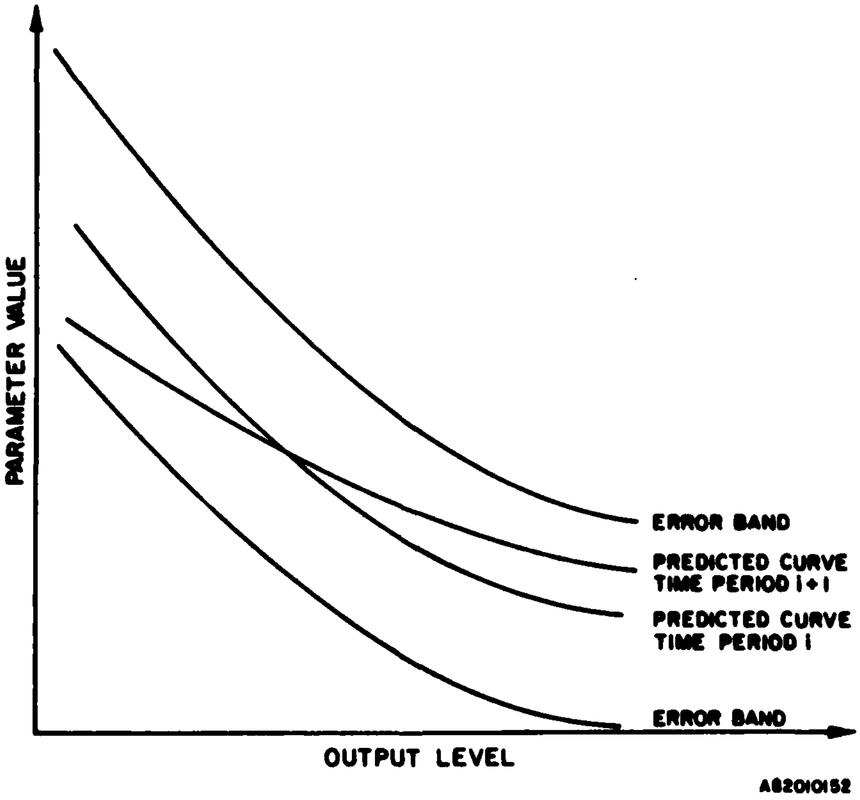

Figure 12. HYPOTHETICAL CURVE AND ERROR BANDS

Life-Cycle Cost Analysis

The life-cycle cost (LCC) of each system was calculated using the following equation:

$$LLC = PV(TIC) + PV(AOC) + PV(AFC) + PV(EMC) + PV(FRC) \quad (7)$$

where —

PV = the present value operator

TIC = the total installed cost of the energy conversion system including the acquisition cost, the cost of balance of system components, and installation, excluding the cost of land

AOC = the annual operating and maintenance costs, exclusive of fuel, over the 20-year evaluation period

AFC = the annual fuel costs (annual energy costs for the storage technologies) over the 20-year evaluation period

EMC = any extraordinary (above the normal AOC) maintenance cost which may occur over the 20-year evaluation period (for example, major overhauls of the system to extend expected system life to 20 years)

FRC = the future replacement cost of the energy conversion system, if required during the 20-year evaluation period.

The equations derived from the raw survey data were used as the basis for the required cost and operating data for the calculations in Volume IV of this report. Annual fuel costs were based on the appropriate choice of fuel as previously discussed. The life-cycle cost is the present value (as of the first year of system operation) of the sum of all system-resultant costs incurred over a 20-year evaluation period. A 20-year, common evaluation period is required to facilitate a direct and valid comparison of the large number of energy conversion systems being considered in this study given their varying service lives, maintenance intervals, and other factors that will affect the amount and timing of system costs. The term "present value" refers to a cash flow that has been adjusted to reflect the interest that could be earned or that must be paid between the time the flow actually occurs and a specified "present" time. A 10% discount rate was used for the calculations to reflect the opportunity cost of diverting financial resources from the private to the public sector. This rate is the standard discount rate to be used in evaluating time-distributed costs and benefits for Federal investments, as established in the Office of Management and Budget (OMB) Circular No. A-94.

Taxes and depreciation (a non-cash expense for offsetting taxes) are, of course, not applicable to Department of Defense cost analyses.

Three separate life-cycle costs were calculated for each energy system consistent with the estimated fuel prices of the three scenarios discussed in the section "Fuels and Fuel Prices" of this report.

The life-cycle costs are in terms of 1980 dollars. The U.S. GNP Implicit Price Deflator, Table 10, was used to adjust input cost data to a 1980 basis.

Table 10. U.S. GNP IMPLICIT PRICE DEFLATORS
(1972 = 100)

Year	Gross National Product
1970	89.26
1971	96.02
1972	100.00
1973	105.80
1974	116.02
1975	127.15
1976	133.71
1977	141.70
1978	152.05
1979 (preliminary)	165.50
1980 (author's estimate)	180.00

Qualitative

The qualitative parameters of reliability, environmental constraints, locational constraints, and operational constraints were evaluated in terms of factors that affect the parameters. The factors considered in the evaluation of these parameters are presented in Table 11.

The following procedure was used to evaluate the ordinal scale used to provide an overall measure of the value of each parameter:

First, all factors of each parameter were rated using the following notation:

— Factor has no impact on parameter for this technology

0 Factor has a minor negative impact on parameter for this technology

- ◐ Factor has a moderate negative impact on parameter for this technology
- ● Factor has a major negative impact on parameter for this technology.

The ratings for each technology are in Volume II of this report.

Second, each notation was assigned an ordinal value as follows:

— => 3
○ => 2
◐ => 1
● => 0

Each factor was assumed to be equally important to the overall measure of the parameter. Therefore a parameter with six factors, such as reliability, could have a minimum score of 0 and a maximum score of 18 (six factors times the ordinal value of no negative impact). This 0 to 18 scale was reduced to a 1 to 5 scale as follows:

Table 11. FACTORS IMPACTING QUALITATIVE PARAMETERS

Parameter:	Reliability	**Parameter:**	Environmental Constraints
Factors:	Moving Parts	**Factors:**	Thermal Discharge
	Operating Temperature		Air Pollution
	Modularity		CO
	Stress Levels		NO_x
	Corrosion		SO_x
	Other		HC
			Particulates
			Other
			Noise
			Odor
			Solid Waste
			Chemical waste
Parameter:	Locational Constraints	**Parameter:**	Operational Constraints
Factors:	Water Requirements	**Factors:**	Part-Load Capability
	Manning Requirements		Overload Capability
	Fuel Availability		Load-Following Capability
	Fuel Storage		
	Other		

0 — 3 => 1
4 — 7 => 2
8 — 11 => 3
12 — 15 => 4
16 — 18 => 5

In cases where the maximum score is not divisible by 5, the order for decreasing the range (number of score values) until the range of the 1 to 5 ordinal ranks are integers was 5, 1, 4, 2, and 3. For example, the score for the reliability parameter includes 19 values (0 through 18). The score was rescaled such that the ordinal ranks of 1, 2, 3, and 4 each contain 4 values from the original score and the rank of 5 contains only 3 values (16, 17, and 18) from the original score. This procedure is based on the premise that the chances for an extremely good score or an extremely bad score are decreasingly less than the chances for an average score of 3.

The parameter of environmental constraints has six major factors and therefore has a maximum score of 18. However, this parameter was evaluated at three levels: Amount of Uncontrolled Emissions, Amount of Emissions With Controls, and Degree of Difficulty in Meeting More Stringent Regulations. Because all three levels are equally important, the score at each level is multiplied by 1/3 and summed to attain an overall score on a scale from 0 to 18 for environmental constraints. Similary, the factor "air pollution" includes six subfactors. Consequently, the score for the factor "air pollution" was multiplied by 1/6 to attain a measure of the impact of air pollution on the parameter environmental constraints.

All of the qualitative parameters were thus reduced to an ordinal scale of 1 (worst) to 5 (best).

CONCLUSIONS AND RECOMMENDATIONS

The development of the data base for the technologies in this study clearly resulted in some problems that could not have been anticipated at the onset of the project. Nonetheless, the conclusion is that the data base as it now stands represents the best information available, and that it is consistent in terms of the treatment of the data.

Obviously, any broad data base has limitations, and this one is no exception. Primarily, the limitations result from the fact that the data represent a wide range of conditions and applications and as such could result in error if the data are taken at value for any unique, specific application. Recognizing this limitation, the expected errors of the predicted data were calculated and are included in Volume IV of this report. The expected errors represent the range of parameter values that can be expected at each output level and to a great extent the ranges are the result of the need for a broad-based data base rather than a need for specific information for a single, unique application. Consequently, this data base should provide the capability to screen technologies on a preliminary basis to identify the most appropriate technologies for selected applications.

The procedures that were used to develop the predicted parameter values provide a basis for updating the data base as new information becomes available. We recommend that as new information becomes available, it should be examined using the procedure that is described for the technology projections to determine whether changes are warranted in the data base.

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APPENDIX. Survey Questions

The questionnaire sent to researchers of diesels is presented to indicate the structure of the questions asked and the format of the questionnaires. Questionnaires sent to manufacturers of the technology included an additional question soliciting parameter values of commercially available technologies.

DIESELS

The objective of this questionnaire is to obtain input data on selected parameters to develop expected performance profiles of diesel engines and diesel generators between 1980 and 2000 over an electric power output range from 1.5 kW to 5000.0 kW.

The questionnaire consists of three sections; a section for each of the three broad categories of diesel engines. The sections are:

- Turbocharged engines
- Turbocompounded engines
- Adiabatic engines.

Each section of the questionnaire is similar in terms of the information requested. Information is requested for the following parameters:

- Efficiency — energy produced ÷ energy consumed as fuel at rated power output and design conditions
- Weight — weight without fuel, coolants, or lubricants
- Dimensions — the length, width, and height of the envelope of the technology
- Start-up time — the elapsed time to rated power output at design conditions from a cold start
- Shut-down time — elapsed time from rated power output to zero power output at design conditions
- Lifetime — the expected life of the technology at continuous operation (including scheduled maintenance) at rated capacity
- Mean time between overhauls (MTBO) — the recommended elapsed operating time at rated capacity between overhauls
- Acquisition cost — the purchase price excluding freight and installation costs
- Installed cost — the estimated total installed cost (for field erected units)
- O&M costs — the estimated annual operating and maintenance costs excluding fuel costs.

To simplify compiling this data, tables have been prepared for your use. You will see that discrete power output levels from 1.5 kW up to 5000.0 kW are indicated. It is not necessary that the data you provide correspond precisely to the discrete power output levels indicated. Please indicate the actual power output level for the data you are providing in the column titled "Power Output Level, Actual."

The power output is defined as the rated output of an engine/generator system producing utility quality electricity.

If you are involved only with prime movers, power output is defined as the rated mechanical shaftpower output.

Because the application for the diesel has not been precisely defined. please feel free to indicate a range in the values of the parameters at each power output level.

Section I. Turbocharged Diesel Engines

1. Please use

- Table 1a to indicate projected parameter values you expect in the 1980-1985 time frame
- Table 1b to indicate projected parameter values you expect in the 1985-1990 time frame
- Table 1c to indicate projected parameter values you expect in the 1990-2000 time frame

Please specify the measurement units you are using in the parentheses below the column headings.

Table 1a.

POWER OUTPUT LEVEL (kW)	ACTUAL POWER OUTPUT LEVEL ( )	EFFICIENCY		WEIGHT		DIMENSIONS		START-UP TIME		SHUT-DOWN TIME	
		SYSTEM ( )	ENGINE ONLY ( )	SYSTEM ( )	ENGINE ONLY ( )	SYSTEM ( )	ENGINE ONLY ( )	SYSTEM ( )	ENGINE ONLY ( )	SYSTEM ( )	ENGINE ONLY ( )
1.5											
5.0											
20.0											
30.0											
60.0											
100.0											
250.0											
750.0											
1000.0											
5000.0											

Table 1a., Continued

LIFETIME		MTBO		ACQUISITION COST		INSTALLED COST		O&M COST	
SYSTEM ( )	ENGINE ONLY ( )	SYSTEM ( )	ENGINE ONLY ( )	SYSTEM ( )	ENGINE ONLY ( )	SYSTEM ( )	ENGINE ONLY ( )	SYSTEM ( )	ENGINE ONLY ( )

Table 1b.

POWER OUTPUT LEVEL (KW)	ACTUAL POWER OUTPUT LEVEL ( )	EFFICIENCY		WEIGHT		DIMENSIONS		START-UP TIME		SHUT-DOWN TIME	
		SYSTEM ( )	ENGINE ONLY ( )	SYSTEM ( )	ENGINE ONLY ( )	SYSTEM ( )	ENGINE ONLY ( )	SYSTEM ( )	ENGINE ONLY ( )	SYSTEM ( )	ENGINE ONLY ( )
1.5											
5.0											
20.0											
30.0											
60.0											
100.0											
250.0											
750.0											
1000.0											
5000.0											

Table 1b. Continued

LIFETIME		MTBO		ACQUISITION COST		INSTALLED COST		O&M COST	
SYSTEM ( )	ENGINE ONLY ( )	SYSTEM ( )	ENGINE ONLY ( )	SYSTEM ( )	ENGINE ONLY ( )	SYSTEM ( )	ENGINE ONLY ( )	SYSTEM ( )	ENGINE ONLY ( )

Table 1c.

POWER OUTPUT LEVEL (kW)	ACTUAL POWER OUTPUT LEVEL ( )	EFFICIENCY		WEIGHT		DIMENSIONS		START-UP TIME		SHUT-DOWN TIME	
		SYSTEM ( )	ENGINE ONLY ( )	SYSTEM ( )	ENGINE ONLY ( )	SYSTEM ( )	ENGINE ONLY ( )	SYSTEM ( )	ENGINE ONLY ( )	SYSTEM ( )	ENGINE ONLY ( )
1.5											
5.0											
20.0											
30.0											
60.0											
100.0											
250.0											
750.0											
1000.0											
5000.0											

Table 1c., Continued

LIFETIME		MTBO		ACQUISITION COST		INSTALLED COST		O&M COST	
SYSTEM ( )	ENGINE ONLY ( )	SYSTEM ( )	ENGINE ONLY ( )	SYSTEM ( )	ENGINE ONLY ( )	SYSTEM ( )	ENGINE ONLY ( )	SYSTEM ( )	ENGINE ONLY ( )

2. In your opinion, are there any locational (e.g. water requirements, manning requirements), operational (e.g. load following capability, turn-down capacity), environmental (e.g. noise, air, thermal, odors) or reliability (e.g. corrosion effects, high operating temperatures) factors that would limit the capability of this technology to be applicable to a range of conditions and applications? If so, please indicate below.

LOCATIONAL FACTORS:

OPERATIONAL FACTORS:

ENVIRONMENTAL FACTORS:

RELIABILITY FACTORS:

*U.S. GOVERNMENT PRINTING OFFICE: 1983 - 659-062/1118


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