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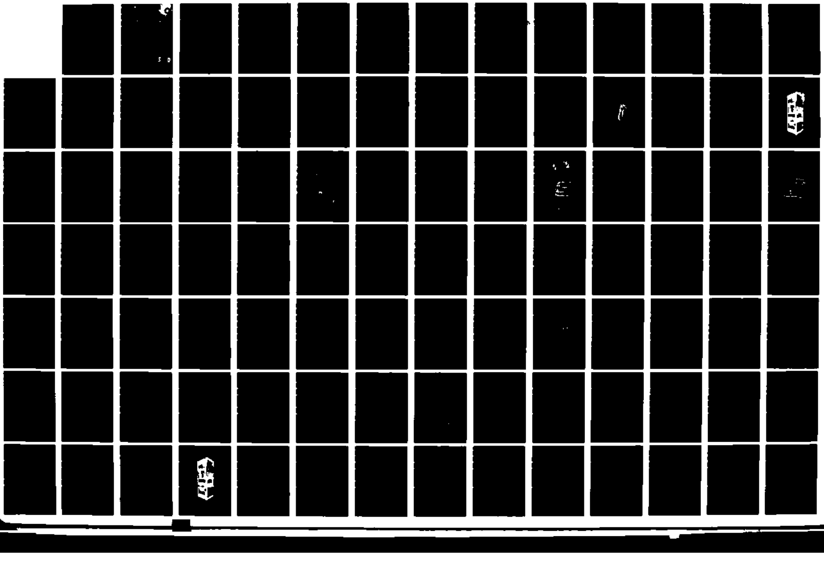

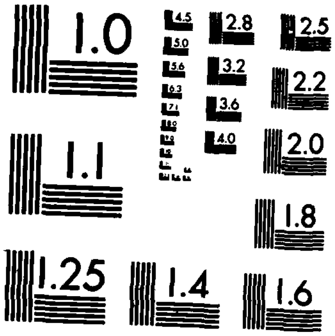

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U. S. AIR FORCE FUEL CELL APPLICATION ANALYSIS

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JANUARY , 1982

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AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
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This technical report has been reviewed and is approved for publication.

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Fuel Cell Power Unit conceptual designs and cost/benefit analyses were accomplished for six U.S. Air Force applications. The applications included two attended remote sites, two unattended remote sites; and two tactical/mobile requirements. The electrical power ratings of these designs ranged from 23kW to 100kW. Fuels considered included diesel, Jet Fuel (JP-4) and methanol. Life cycle cost and benefit analyses showed that significant savings and operational improvements could be realized with the introduction of fuel cells into the USAF power generation inventory.

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1.0 EXECUTIVE SUMMARY

The general objective of the work done under United States Air Force (USAF) Contract No. F 33615-80-C-2038 has been to investigate and analyze the application of phosphoric acid fuel cell (PAFC) technology to several of the USAF generic requirements for ground electric power and heat. Specific objectives of this program included: (a) performing fuel cell application analyses for six USAF specified applications, (b) providing preliminary conceptual designs and technical risk assessments of fuel cell power units (FCPU) for each application and, (c) providing final conceptual designs for each application. The USAF specified the applications to be examined in both generic terms and by specific example.

The technical approach to the work was: (1) construct a generic FCPU design specification for each application, (2) perform a preliminary conceptual design of a FCPU for each generic application, (3) apply the FCPU design, iteratively, to the specific example applications, and (4) revise and complete the design specifications and FCPU's conceptual designs.

1.1 APPLICATIONS

The generic and example applications are illustrated in Table 1-1. There are five generic applications, including three prime power applications and two tactical mobile applications. The specific example for the small unattended remote units is that of providing shelter power for the proposed MX missile system (based on the concept of 4600 shelters and 200 mobile MX missiles). Two Fuel Cell Power Unit (FCPU) designs were developed for this application, one utilizing methanol (wood alcohol) fuel and one utilizing ethanol (grain alcohol) fuel. The difference between the two alcohol fuels is not trivial since the overall FCPU design is highly sensitive to the type of fuel selected and the method of fuel processing. This provides another way of looking at the example applications - there are two alcohol fuel applications and four USAF

TABLE 1-1

APPLICATIONS

Generic Application	Description	FCPU Electric Power Rating kW	FCPU Heat Rating Btu/Hr	Prime Fuel	Secondary Fuel
Unattended Remote Site; 5-20 kW Electric Power	Individual MX Missile Shelter Power	23	None	Methanol	None
Unattended Remote Site; 5-20 kW Electric Power	Individual MX Missile Shelter Power	23	None	Ethanol	Methanol
Attended Remote Site; 30-60 kW Electric Power	DEWLine, PIN-1 Site	60	238,000	DF-A	JP-4
Attended Remote Site; 120-250 kW Electric Power	Communications Site - Menorca, Spain	100	None	DF-2	JP-4
Tactical Mobile System; 30-60 kW Electric Power	Foreward Air Controller Radar	60	None	JP-4	DF-2
Tactical Mobile System; 120-250 kW Electric Power	Tactical Aircraft Ground Support	60*	145,000	JP-4	DF-2

* Power for maintenance and air conditioning only. (See text.)

logistic fuel applications. The logistic fuels (jet fuels and diesel fuels) are more difficult to process into an acceptable fuel processing system than the alcohol fuels.

In practice, the logistic fuel FCPU's must be capable of utilizing any of the several logistic fuels available. This requires designing these systems for the most refractory of the prime and secondary fuels, which is grade DF-2 diesel fuel. The effect of using jet fuel instead of diesel fuel is small in FCPU terms. The heat to electrical conversion efficiency increases a couple of tenths of a percentage point using jet fuel, and because jet fuel (on the average) contains less sulfur than diesel fuels, FCPU maintenance will be reduced. Fuel consumption using jet fuel will be higher by about ten percent because the energy content of jet fuel per gallon is less than that of diesel fuels.

Conversion of the application information into generic specifications and application models was, relatively, straightforward for the first five applications of Table 1-1. Such was not the case for the second tactical mobile application. As may be noted, the specific application is tactical aircraft ground support. There are three power requirements under this category. They are:

Requirement	Approximate Power
Provide Aircraft Engine Starting Air	190-210 kW
Provide Cooling Air During Aircraft Maintenance	7-8 kW
Provide Electrical Power During Aircraft Maintenance	50-60 kW

Currently, all of the power requirements are covered by the use of the A/M32A-60/60A gas turbine. No doubt it is operationally desirable to use a single power unit for all three power needs. It is, however, less fuel efficient. Most of the operating time is spent providing power for maintenance. Very little of the time is spent providing aircraft engine starting power. The A/M 32A-60/60A has poor part load performance so that a straight FCPU substitution for the A/M 32A-60/60A would save substantial amounts of fuel and fuel expense. However, overall life cycle cost savings would be marginal, at best. The most cost effective approach is to retain the gas turbine for engine starting duty only and then use a FCPU to provide the cooling and maintenance power. This latter approach is used herein.

1.2 PHOSPHORIC ACID FUEL CELL TECHNOLOGY

The generic system for FCPU's using PAFC technology is well established. A block diagram illustrating the major subsystem of which a PAFC power system is composed is given in Figure 1-1.

As indicated in Figure 1-1, steam (and sometimes air) and fuel are heated, mixed and converted in the fuel processing subsystem to a hydrogen rich gas. This gas, along with air, is introduced into the fuel cells where the hydrogen is electrochemically oxidized to water, producing DC electric power and heat. This power is controlled and conditioned into a form suitable for using apparatus consumption. In this study, the unattended remote site units produce 120V DC power. The attended remote site units produce 60 Hz AC power and the tactical mobile units produce 400 Hz AC power. Standard voltages in the 110V-416V range are available from the AC units.

If the application has a requirement for heat as well as electric power, the waste heat from the FCPU can be recovered for futher use. This heat can be recovered as hot air, hot water or steam. The maximum temperature at which meaningful quantities of waste heat are available from PAFC systems is about 350°F.

All of the designs of this study use steam to reform the fuels into a hydrogen rich gas suitable for PAFC's consumption. To make the FCPU's water self-sufficient, a portion of the water vapor in the FCPU's exhausts is condensed for reuse in the fuel processing step. No additional make-up is required.

The major non-commercial items in the FCPU's are the fuel processing subsystem and the fuel cells and power conditioner of the power generation subsystem.

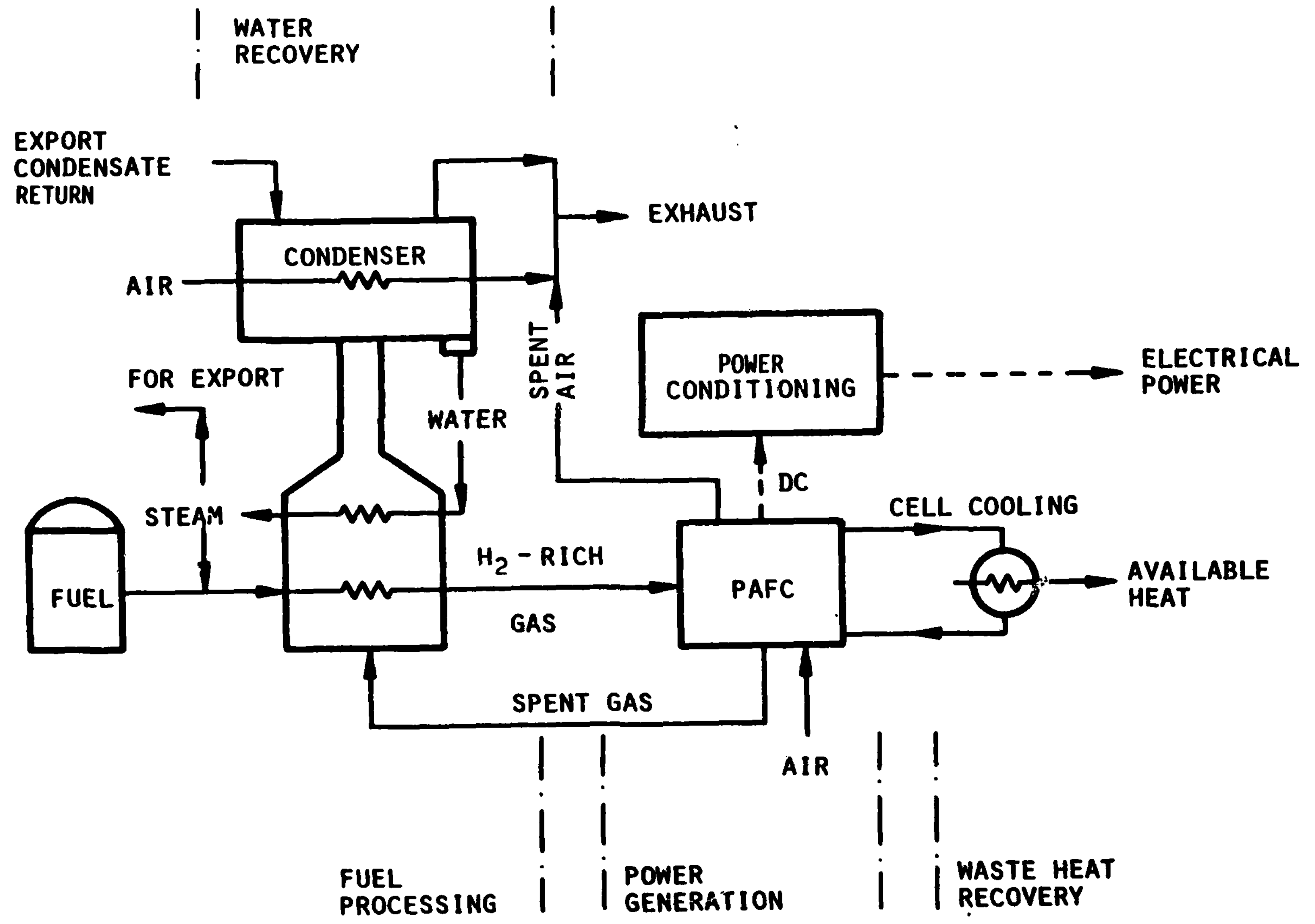

Figure 1-1. FCPU Major Subsystems

1.2.1 FUEL CELL CONCEPT

The basic phosphoric acid (PAFC) fuel cell concept used throughout this study is that of the air cooled cell. This is a concept developed by the Energy Research Corporation (ERC) for use in small (1.5 kW-5 kW) units for U. S. Army Mobile Electric Power. This ERC concept has been adopted and adapted by Westinghouse for its on-site integrated energy and utility fuel cell programs.

Other cooling schemes that could have been used include water cooling and liquid cooling using a dielectric fluid. The liquid-cooled designs require the use of numerous tubes to convey and contain the liquid. As a result, there are a large number of tube connections that present potential leakage problems. Since reliability is a most important design requirement for all the FCPU's conceived under this program, the air-cooled design appears preferable. It is felt that overall study results will not be affected significantly by the choice of fuel cell cooling method.

Two detail fuel cell design configurations were used. The first of these is the original ERC developed DIGAS* MARK I cell. This first configuration was used in the 23 kW unattended remote site FCPU's (MX individual shelter power example). The unattended remote site units are direct derivatives of the previously mentioned 1.5 kW-5 kW units which incorporate the MARK I cells. The other four FCPU designs utilize a MARK II cell design. The MARK II fuel cell configuration was developed under a DOE/NASA sponsored on-site integrated energy system program, Contract DEN3-161.

The details of a MARK II configuration are illustrated in Figure 1-2. The individual fuel cell is comprised of bipolar plates, two gas diffusion electrodes and an acid matrix. The "Z" patterned channels in the bipolar plates direct the flow of the reactant hydrogen rich gas and air in a counterflow mode and in channels of equal length.

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*U. S. Patent 4192906

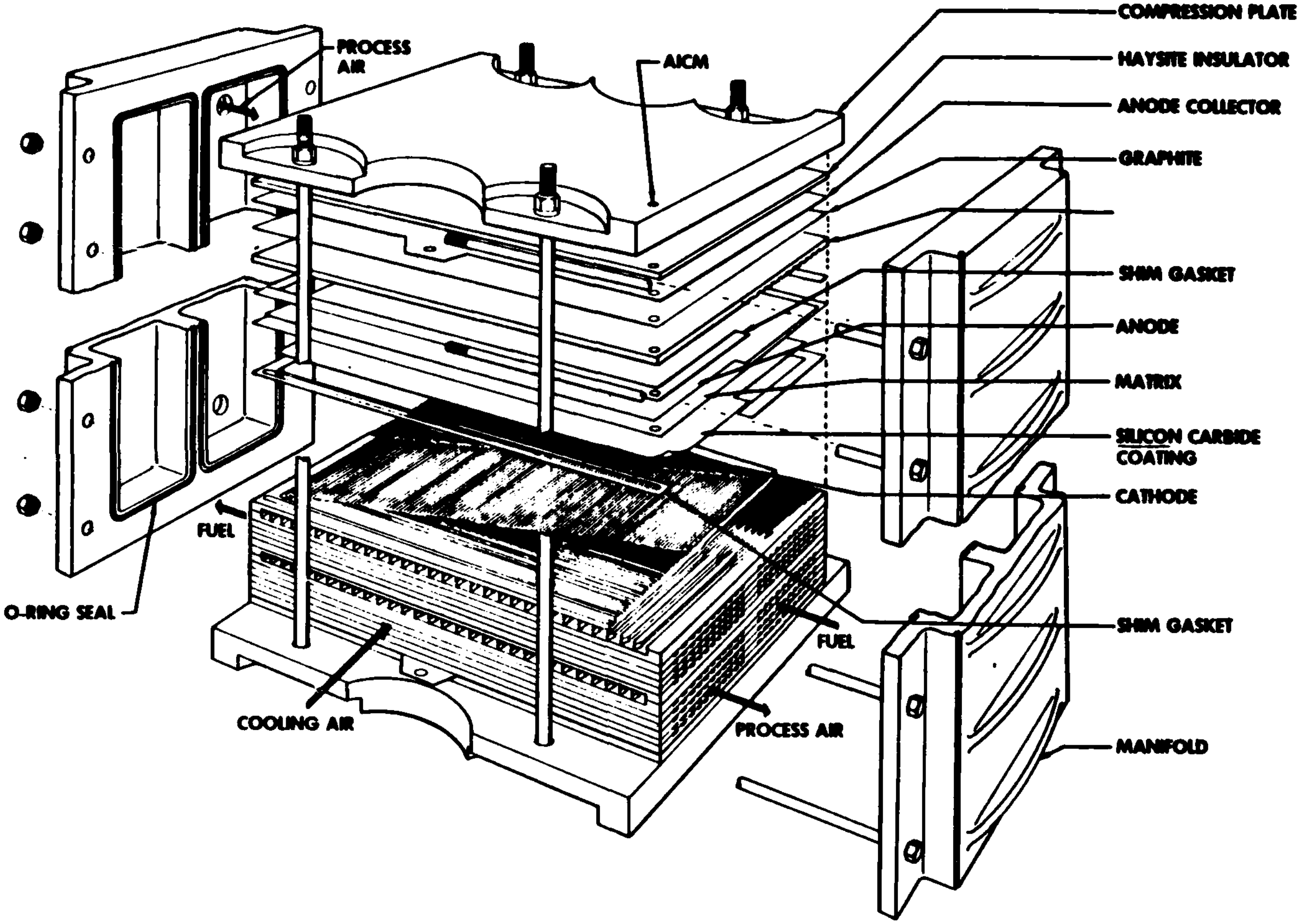

Figure 1-2. MARK II PAFC Air Cooled Fuel Cells

Heat is removed from the cell stacks by air which is directed through cooling plates located at approximately every fifth cell. The cooling channels are configured in a "tree" shape to achieve a flat temperature profile across the stack, and to keep the peak to average temperature ratio as low as possible.

In the predecessor MARK I configuration the reactant flows are directed in a crossflow pattern. The hydrogen rich gas flows lengthwise of the cell and the air crosswise in the same direction as the cooling air flow. The cooling air and reactant air are mixed together in the MARK I cell configuration rather than separated as in the MARK II configuration. The MARK I arrangement is simpler than the MARK II, but suffers from some dilution of the oxygen content of the reactant air.

1.2.2 POWER CONDITIONING CONCEPTS

The 23 kW methanol/ethanol FCPU's deliver 120V ± 5 percent DC power. As these units operate at atmospheric pressure, there is a wide swing in cell voltage output with load. DC to DC power conditioning is required to maintain output voltage within acceptable limits. The power conditioners conceived for the DC to DC units of this study are scaled up versions of those of the ERC 3kW 5 kW portable units.

The four logistic fuel units of the study deliver AC power. Obviously, since the fuel cells deliver DC power, considerable power conditioning is required. Westinghouse is in the process of developing a family of multikilowatt DC to AC converters to be used with solar photovoltaic arrays. These solar photovoltaic DC to AC converters have the basic characteristics required for logistic fuel FCPU use, such as;

- They produce high quality (less than five percent harmonic distortion) three-phase AC efficiently;
- They are self-starting, self-controlling and self-protecting.
- They can be used either "stand-alone" or in multiunit paralleling.

Unfortunately, these units cannot be used "off-the-shelf" with the logistic fuel FCPU's. This is partly because the control logic for use with a solar array is different from that required for fuel cells and partly because the power conditioning units are designed to meet commercial environmental standards and size and weight. Hence, development effort will be required to modify the solar array units to logistic FCPU's needs; but the solar array units represent an advanced starting point.

An example of the Westinghouse power conditioning unit for photovoltaic applications is the AV1 503-A. A picture of the unit with control cabinet covering stripped away is shown in Figure 1-3. Some of the parameters of the AV1 503-A are as follows:

• KVA	50 Continuous, 100 for 5 Seconds
• Output	60 Hz, 3-Phase, 4-Wire, 120/208 Volts
• Harmonic Distortion	Less than 5 Percent
• Efficiency	At 0.9 Power Factor and 100% Load, 91%
• Input	200-300 Volts DC (up to 350 volts DC with slight deviations to specifications)
• Environment	Ambient Temperature: -10° to +45° Celsius Relative Humidity: 96% (non-condensing) Barometric Pressure: 790-520mm Hg

1.2.3 FUEL PROCESSING CONCEPTS

As indicated earlier, the fuel processing subsystem converts the process fuel, in this case liquid hydrocarbons, into a hydrogen-rich fuel gas stream that can be used in the PAFC. In addition, the fuel processing subsystem must remove any fuel contaminants, such as sulfur, to acceptable levels. The choice of fuel processing systems for a particular FCPU is highly dependent on the type of raw fuel and overall FCPU requirements.

Figure 1-3. Westinghouse AV1 503-A Power Conditioner

Renewable Energy Source (Alcohol) Fuels

The unattended remote site units of this study use methanol and ethanol. Substantial development work has been done by the Energy Research Corporation (ERC) on methanol reformers. This work has been done in connection with their development of 1.5 kW-5 kW portable FCPU's.

ERC has been successful in catalytic steam reforming of methanol using a copper catalyst. The reforming temperature is low (400°F to 600°F). At these low temperatures, sufficient CO shift conversion ($CO + H_2O \rightarrow CO_2 + H_2$) occurs to eliminate the need for the separate shift converter required with most other fuels.

Less work has been done on ethanol, by ERC, than methanol. However, laboratory work on ethanol reforming, using a modified methanol reformer, has been most encouraging. Compared to methanol fuel processing, more steam, higher temperatures (600°F-800°F), and a separate shift converter are required. Further, the modified methanol reformer can still process methanol. The reverse is not true. The straight methanol reformer cannot satisfactorily process ethanol.

These foregoing ERC developed RES fuel processing systems were the natural choices for the two unattended remote site FCPU's of this program.

Aviation and Diesel Fuels

The potential applications of the two attended remote site and two tactical mobile unit designs of this study require the use of USAF logistic fuels; aviation fuel, JP-4, and diesel fuels, DF-A and DF-2. Further, there is the requirement that USAF logistic fuel FCPU's be able to operate using either aviation or diesel fuels.

Steam reforming is used extensively in the oil refining and chemical industries to produce hydrogen from natural gas and naphtha. The commercial processes are sulfur sensitive and not suitable for use with diesel fuels. They might be stretched to handle JP-4.

Two developmental processes were identified as being suitable for incorporation into the logistic fuel FCPU's designs of this study. They are:

- High Temperature Steam Reforming (HTSR)
- Autothermal Reforming (ATR)

Both of these processes have undergone successful laboratory type developments on U. S. Government and Electric Power Research Institute (EPRI) sponsored programs. The processes operate at temperatures at which reforming catalysts are less susceptable to sulfur poisoning. Both processes have shown a good potential in the laboratory to handle high sulfur fuels.

HTSR

HTSR differs from commercial steam reforming, primarily in the operating temperature and desulfurization step. The reformer operates at 1600-1800°F where sulfur poisoning is limited and pretreatment fuel desulfurization is not needed. Desulfurization occurs at the reformer outlet in a single bed of ZnO, where removal to <10 ppm H_2S is needed to protect the shift catalyst.

The process operates on similar steam/carbon ratios to the conventional steam reformer, and produces similar gas quantities and concentrations at the fuel cell inlet. Hydrogen yield, however, is lower because more fuel is consumed in the reformer burner to maintain proper temperature for heat transfer into the reactor bed.. Hydrogen yield is about 0.28 lbs H/lb fuel used.

The key component in this process is the high temperature reformer, which may be subject to carbon deposition at these high operating temperatures. The most promising catalysts for high temperature steam reforming have been developed by Toyo Engineering and Tokyo Gas of Japan. Carbon deposition is minimized by using a nickel-free calcium oxide Toyo (T-12) catalyst at the reformer inlet, followed by a nickel Toyo catalyst (T-48) at the outlet. Although high catalyst volumes are needed in this process, this is the only reported HTSR process capable of handling high sulfur fuels without carbon deposition. This process has reportedly been tested in pilot plant runs on No. 2 fuel oil for up to 4,000 hours without catalyst deterioration or pluggage. Shorter term testing was performed by Kinetic Technology International Corporation in California with reported similar carbon free performance. Additional testing is being performed.

If the Toyo catalysts prove durable, the high temperature steam reformer will offer multiple high sulfur fuel capability, with performance efficiency similar to a conventional steam reformer.

ATR

ATR processes operate at temperatures similar to a HTSR (1600-1800°F) with post desulfurization. Reforming heat is provided within the catalyst bed by insitu combustion of fuel and oxygen. Approximately 25-35 percent of the fuel is consumed in providing reaction heat. This results in a hydrogen yield after CO shifting of 0.28 lbs H/lb fuel used. Sufficient energy is available in the product gases and combustion of spent fuel cell gas to heat reactants to incoming temperatures. Therefore, this process does not require additional heat from outside sources and is sometimes called adiabatic reforming.

Developmental work on this process is being carried out by United Technologies Corporation (UTC), Engelhard Industries (EI), and the Jet Propulsion Laboratories (JPL). Based on their work, this process appears capable of operating at steam/carbon ratios of 3.0 and air/carbon ratios of 1.8 using commercial high temperature catalysts. Because of the reactor temperature profile, complete hydrocarbon conversion (methane slip) appears to be a potential problem with this process. However, it is anticipated that proper reactor design and catalyst quantities can reduce this problem.

The key advantages of using an ATR are:

- Good transient response capability
- Low starting times
- Simpler reactor design

Compared to a HTSR, the disadvantage of using an ATR is the dilution of the fuel cell fuel gas feed because of the nitrogen added during the insitu combustion process. Because hydrogen concentrations are lower in the fuel cell feed, cell voltage is lower compared to STR and HTSR systems. In addition, since the ATR does not require external combustion, the heating value of the unreacted hydrogen exiting the fuel cell cannot be effectively utilized. To obtain similar power ratings, a system using an ATR will probably consume 25 percent more fuel than one using an HTSR.

Process Selection

Process selection, as stated previously, depends on general FCPU requirements as well as on the raw fuel to be used. For the attended remote site FCPU's, the primary emphasis is on efficiency and low fuel consumption, as long as minimal requirements for such characteristics as size, weight, starting time and responsiveness can be met. The HTSR fuel processing system, when incorporated into a FCPU, results in lower fuel consumption than an ATR. Other requirements can also be satisfied for attended remote site units. Therefore, the HTSR is the fuel processing system of choice for attended remote site FCPU's.

The preliminary conceptual designs for the attended remote site FCPU's were created before starting on the tactical mobile unit designs. From this prior experience, it was evident that [at the present state-of-art] FCPU's incorporating a HTSR fuel processing subsystem could not be designed to meet certain tactical mobile unit requirements on size, weight, and startup time. Therefore, an ATR fuel processing subsystem was selected for incorporation into the tactical mobile FCPU's.

1.3 FUEL CELL POWER UNITS CONCEPTUAL DESIGNS

Commonalities of all the FCPU's designs are:

- Microprocessor controlled
- Self-contained modular packaging
- Air cooled fuel cells

- Lower fuel consumption than alternate gas turbine or diesel power systems
- Higher calculated reliability than alternate gas turbine or diesel power systems
- Lower maintenance requirements than alternate gas turbine or diesel power systems
- Unattended or virtually unattended operation except for startup and shutdown (and refueling on the tactical mobile units)
- Environmentally benign

The six conceptual designs can be conveniently presented in pairs as: two remote unattended site units, two remote attended site units, and two tactical mobile units. As might be expected, the paired units have identical features and generalities in common. A major design requirement of all the concepts was low fuel consumption compared to alternate power systems.

1.3.1 REMOTE UNATTENDED SITE FCPU'S

The two units designed for remote unattended site application are identical except for the fuel processing system. One fuel processing system is designed to handle methanol fuel only. The other fuel processing system is designed to handle ethanol as the primary fuel with methanol as an alternate fuel.

Aside from high efficiency, the most important design consideration was the need for exceptionally high unattended operational reliability. This need was satisfied by selecting unpressurized (atmospheric operation) systems using air cooled fuel cells.

An artist concept of the 23 kW methanol FCPU is shown in Figure 1-4.

The 23 kW ethanol FCPU appears identical except for a small increase in size. As seen, these units are conceived as a single all weather module for outside installation with minimum effort. In concept it would be installed on a concrete pad alongside of the MX missile shelter resident operational support equipment enclosure.

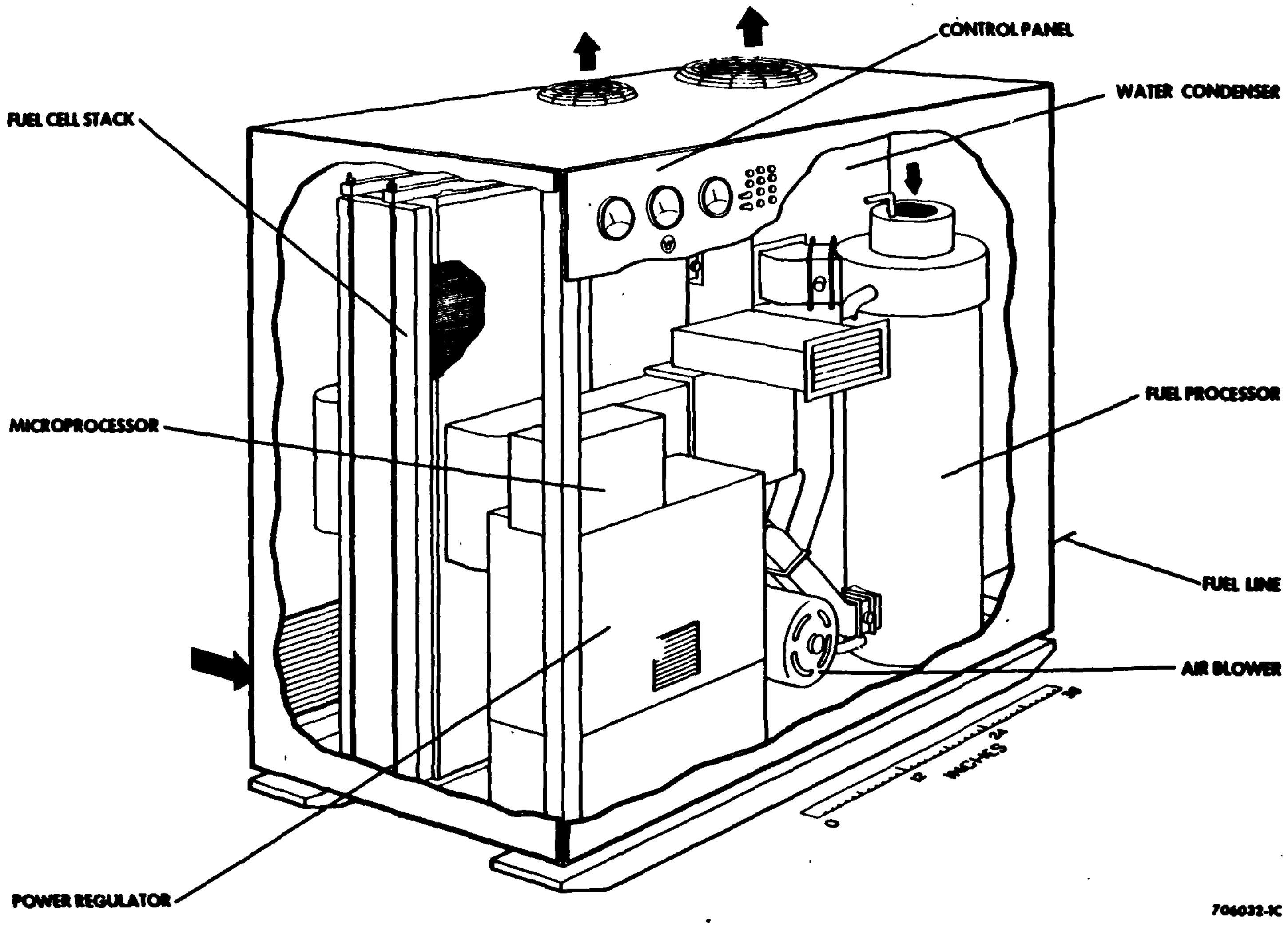

Figure 1-4. 23 kW Remote Unattended Site FCPU

Some of the key parameters of these units are supplied in Table 1-2.

1.3.2 REMOTE ATTENDED SITE UNITS

The two FCPU's designed for remote attended site operation are similar but not identical. One unit has a 60 kW rating. The other unit has a 100 kW rating. The individual fuel cells and the fuel cell assemblies (stacks) are identical. The 60 kW unit has two stacks of 320 cells each. The 100 kW unit has three stacks of 320 cells each.

The primary fuel for both units is a diesel fuel (DF-A and DF-2, respectively). The secondary fuel is aviation turbine fuel (JP-4).

The USAF generic applications for these units are those currently serviced by diesel-electric generators such as DEWline PIN-1 and the Menorca, Spain communications site. The FCPU's would replace the diesel-electrics in such existing installations with minimal disturbance to the existing installation. The FCPU's should be able to use the existing fuel storage and handling facilities and fit within the confines of existing engine rooms.

A major design consideration, then, was to maximize FCPU efficiency* within a size that will fit, reasonably, within existing engine rooms. This size parameter has two aspects: (1) the power required by the site and (2) the availability of power required by the site. For the two sites examined, availability of power of 99.9 percent or better is required.

The availability of power requirement can be met, using less than perfectly reliable units, by the well known practice of installing multiple units with a total rated capacity in excess of maximum power demands. The more reliable the units, the less the excess capacity required. Also, maintenance costs and operating labor costs are reduced with high reliability units.

---

*Minimization of fuel consumption. Fuel cost is a large life cycle cost factor for these units.

TABLE 1-2

REMOTE UNATTENDED FCPU PARAMETERS

	Methanol FCPU	Ethanol FCPU
Operational mode	Continuous	Continuous
Physical Parameters		
Type of Fuel	194 Proof Methanol	192 Proof Ethanol
Rated Power Fuel Consumption, Gal/Hr.	3.3	2.4
Volume, ft^3	97	105
Footprint, ft^2	17	19
Weight, lbs.	1,430	1,500
Performance Parameters		
Mean Time Between Failures, Hr.	3,770	3,690
Availability in Example Application, %	99.9	99.9
Minor Maintenance Period, Mo.	6	6
Major Overhaul Period, Yr.	5	5
Electrical Output Rating		
Power, kW	23	23
Potential, Volts	120	120
Frequency, Hz	DC	DC
Startup Time, Hr	1	1
Cold Shutdown Time, Hr.	2	2
Thermal Energy		
Provided to Application, Btu/Hr.	0	0
Nominal Available above 200°F, Btu/Hr.	54,000	50,000
Electrical Generation Efficiency		
Based on HHV Fuel, %	38.3	40.4
Based on LHV Fuel, %	43.7	45.1

Because reliability is increased by simplicity of design and reduced component loadings, both size and fuel consumption of a given design are increased. The principle "drivers" for these designs, then, were fuel consumption, size and reliability and affecting an acceptable compromise among them.

The major system operating variable affecting all three foregoing "drivers" is pressure level. The projected operating pressure levels of PAFC systems are from one to ten atmospheres. An intermediate operating pressure level of four atmospheres was selected for these remote attended site units as effecting a reasonable compromise among the design "drivers".

An artist's concept of the 100 kW unit is shown in Figure 1-5. With the exception of being smaller, the 60 kW unit appears the same. As shown, the FCPU is packaged as three pieces: a condenser, a power station, and power conditioner. The condenser would be installed outside the engine room, perhaps on the roof. Under hot weather conditions, relatively large amounts of condenser cooling air are required. This would be inconvenient to duct to and from an engine room. Further, it allows for placement of the fuel units in the same space now occupied by existing diesel-electric units.

In the two example applications, use of multiple FCPU's is required to obtain necessary power availability. The FCPU power stations would be spaced throughout the bulk of the engine room. The power conditioner elements would be grouped together in one location for convenient overall power "takeoff" and control.

The number of FCPU's required in both applications is fewer than the number of presently installed diesel-electrics. At PIN-1 four FCPU's will suffice against five diesels. At Menorca the ratio is three FCPU's to four diesel-electrics.

Some of the key parameters of these units are supplied in Table 1-3.

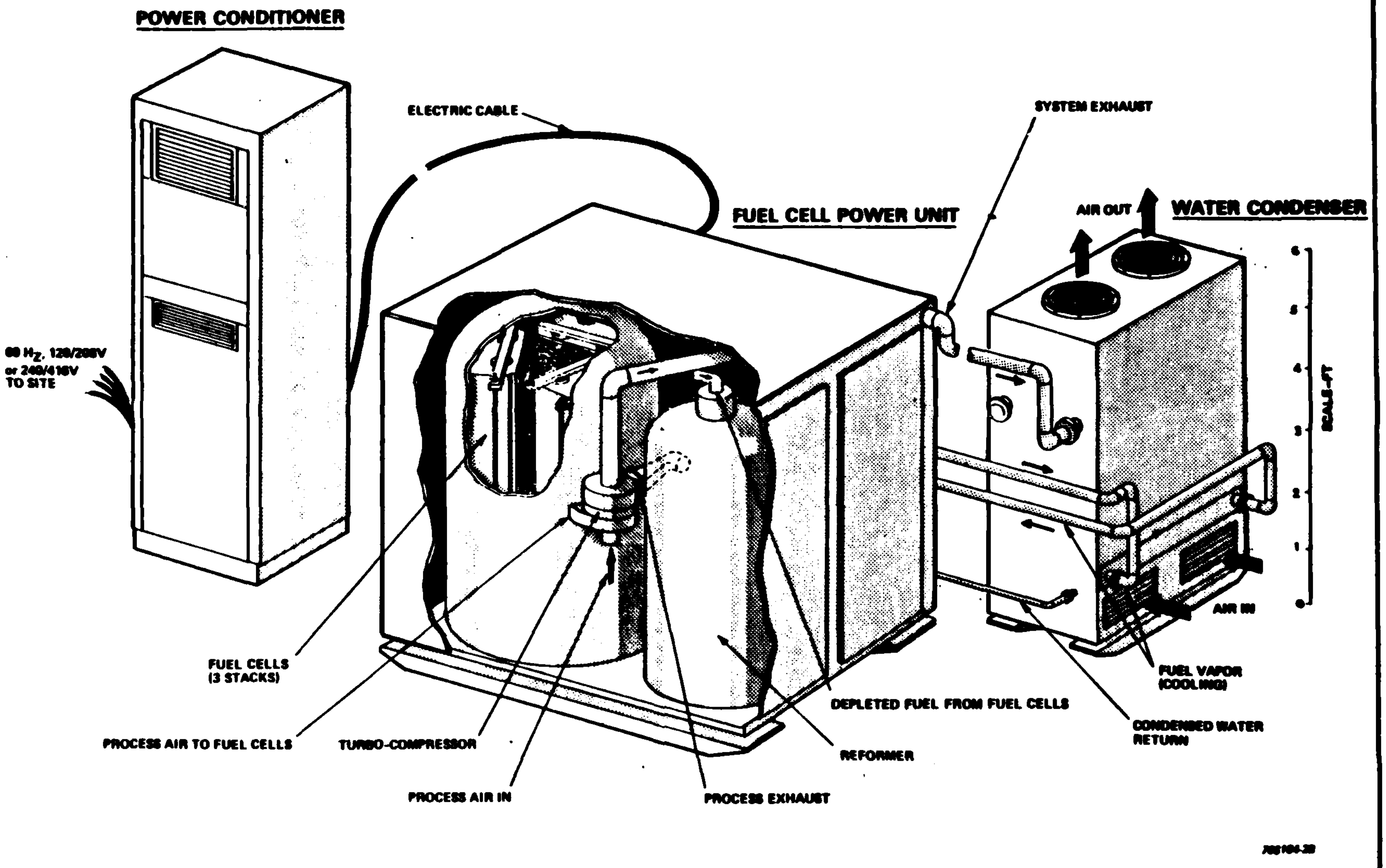

Figure 1-5. Attended Remote Site FCPU

TABLE 1-3
REMOTE ATTENDED FCPU PARAMETERS

	60 kW	100 kW
Operational Mode	Continuous	Continuous
Physical Parameters		
Type of Fuel	DF-A	DF-2
Rated Power Fuel Consumption, Gal/Hr.	5.0	7.1
Volume, Ft^3	273	388
Footprint, ft^2	52	63
Weight, Lbs.	6,200	10,300
Performance Parameters		
Mean Time Between Failures, Hr.	3,000	2,680
Availability in Example Application, %	99.9	99.99
Minor Maintenance Period, Mo.	6	6
Major Overhaul Period, Yr.	2.5	2.5
Electrical Output Rating		
Power, kW	60	100
Potential, Volts	120/208	120/208
Frequency, Hz	60	60
Startup Time, Hr.	1 to 2	1 to 2
Cold Shutdown Time, Hr.	2	2
Thermal Energy		
Provided to Application, Btu/Hr.	238,000	0
Nominal Available above 200°F, Btu/Hr.	208,000	233,000
Electrical Generation Efficiency		
Based on HHV fuel, %	30.5	34.9
Based on LHV fuel, %	32.5	37.1

In the foregoing Table 1-3 it will be noted that the electrical generation efficiency of the 100 kW unit is substantially greater than that of the 60 kW unit. For the PIN-1 application it was cost effective to sacrifice some generation efficiency in the interest of supplying a greater total of electrical plus thermal energy to the site.

1.3.3 TACTICAL MOBILE FCPU'S

The two FCPU's designed for tactical mobile use are nearly identical except for arrangement and packaging of components. Systemwise they are identical except that the ground maintenance power cart has an added steam generator to provide steam to a companion, but undesigned, absorption air conditioner cart.

The primary fuel for both units is JP-4 aviation turbine fuel. The secondary fuel is diesel fuel (DF-2 or DF-A).

The USAF generic applications for these units are those currently serviced by gas turbine electric units. These applications are represented by the examples used here for foreward air controller radar power and power for tactical aircraft ground support. The gas turbines used in these applications are fuel "hoggish" but light-weight and responsive to the demands of intermittant operation because of fast startup and shutdown capabilities. The thermal to electrical efficiencies of the gas turbine units is in the range of 4 to 8 percent, depending upon application.

The design effort was to preserve a substantial amount of the high efficiency and high reliability characteristics of FCPU's but at sizes, weights, and with startup and shutdown times acceptable, if not desirable, for tactical mobile use. The approach used was: (1) to select the system operating pressure at the maximum ten atmospheres currently projected for PAFC systems and (2) incorporate an autothermal reformer to reduce startup times well below those projected for the previously discussed attended remote site units which use the more efficient high temperature steam reformer process.

An artist's conception of the FCPU, as mounted on a self-propelled cart, for tactical aircraft ground support is shown in Figure 1-5. The unit for use as a forward air controller radar power (not shown) appears quite differently. It has been envisioned as a much more compact skid mounted unit. As has been said previously, except for the packaging the FCPU's proper are practically identical.

Some of the key parameters of these units are supplied in Table 1-4.

As was the case with attended remote site units, the unit providing thermal and electrical energy to its specific application has the lower electrical generation efficiency.

1.4 COST ESTIMATES

The elements used in preparing life cycle cost estimates for each of the six FCPU's were: capital costs, operating and maintenance costs, and fuel costs. The costs do not include "cost-of-money".

The capital cost elements were: the research and development (R&D) costs to arrive at a prototype fuel cell power unit of a particular type, the cost of a production unit and initial spares, technical data operating and repair manuals, and special on-site equipment and installation costs where applicable. The capital costs are given in 1980$ without cost escalations. R&D and technical data costs are spread over one thousand units of production except for the tactical aircraft ground support application where 800 units were used.

The operating and maintenance (O&M) cost elements were: (as applicable) operating labor, supplies and overhead, maintenance labor, parts and overhead, and transportation costs. The O&M costs are given in 1980$ without cost escalations.

Alcohol fuels costs were estimated using standard price projections for power plant fuel delivered in Los Angeles, California in the 1990's in 1980$. The projections were made by the Fuels and Fuel Processing Subcommittee of the

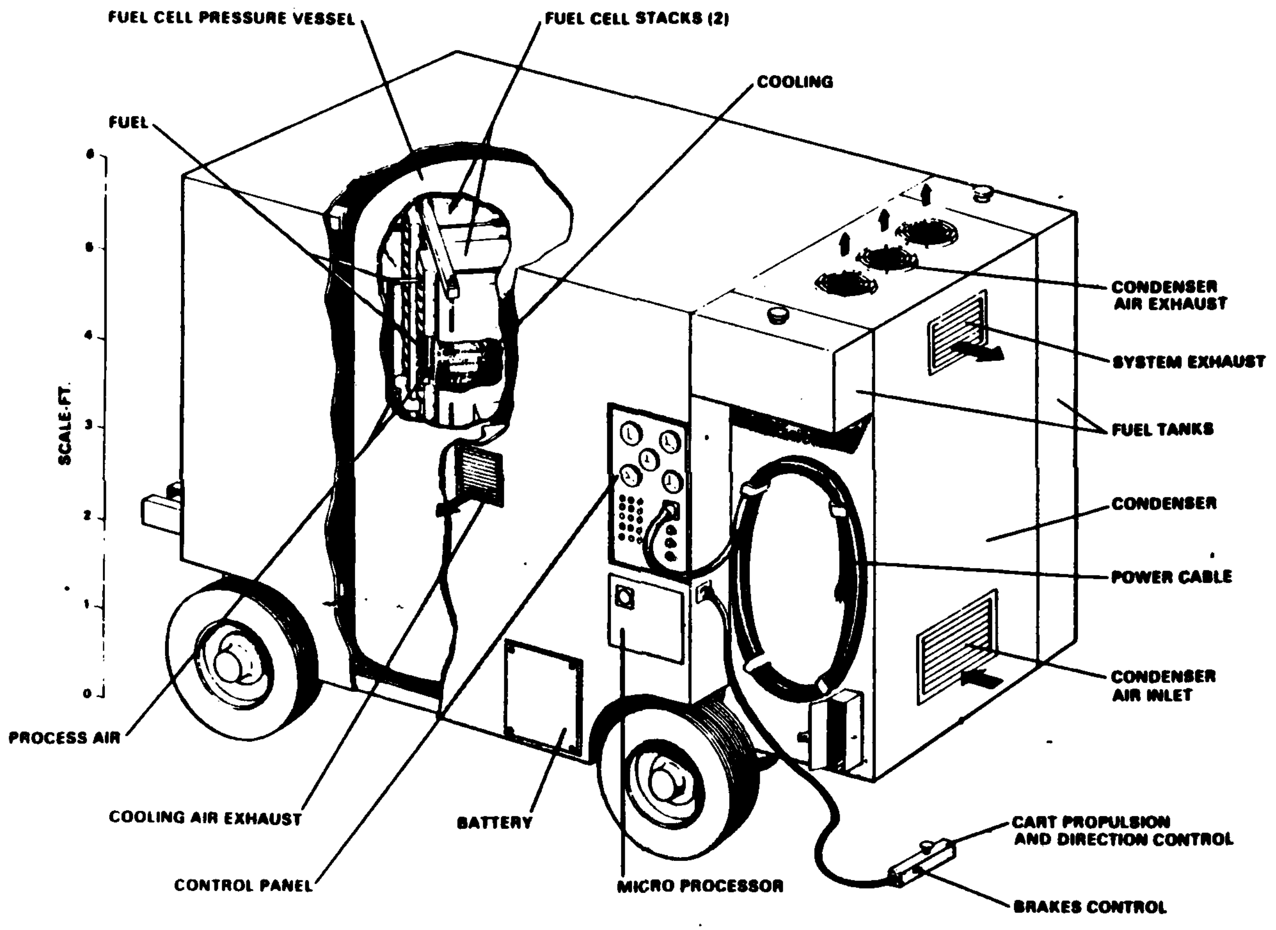

Figure 1-6. Tactical Aircraft Maintenance Power Cart

TABLE 1-4
TACTICAL MOBILE FCPU PARAMETERS

	Radar Power	Maintenance Power
Operational Model	Intermittant	Intermittant
Physical Parameters		
Type of Fuel	JP-4	JP-4
Rated Power Fuel Consumption, Gal/Hr.	5.9	6.7
Volume, ft^3	225	273
Footprint, ft^2	38	45
Weight, Lbs.	4,050	5,030
Performance Parameters		
Mean Time Between Failures, Hr.	2,620	2,000
Availability in Example Application, %	99.3	98.6
Minor Maintenance Period, Mo.	8	12
Major Overhaul Period, Yr.	23	63
Electrical Output rating		
Power, kW	60	60
Potential, Volts	120/208, 240/416	120/208,140/416
Frequency, Hz	400	400
Startup Time, Hr.	0.5	0.5
Cold Shutdown Time, Hr.	1	1
Thermal Energy		
Provided to Application, Btu/Hr.	0	145,000
Nominal Available above 200°F, Btu/Hr.	138,000	105,000
Electrical Generation Efficiency		
Based on HHV fuel, %	27	23.9
Based on LHV fuel, %	28.9	25.5

Electric Utility Fuel Cell Users Group. This is an Ad Hoc group organized by EPRI and U. S. DOE. The pessimistic price projected by the group is $10 per million Btu. The optimistic price projected is $7 per million Btu. The optimistic price is the one used here.

Logistic fuel prices were estimated by taking a current delivered price for the application as an initial price and escalating the prices for future years in 1980$. The price escalation used for three of the four logistic fuel applications was 5 percent per year. For the Menorca site example, a price escalation of 7 percent per year was used. The current price of fuel delivered to the USAF at the Menorca site is considerably below the market price at Menorca. This is because of past contractual arrangements with the Spanish Government. These arrangements will most likely be adjusted in the future.

A summary of labor, transportation, and fuel prices used in cost estimating is given in Table 1-5.

Production unit costs were estimated on the basis of a thousand units of production. This is an extrapolation of existing information.

Westinghouse and Energy Research Corporation have data bases for estimating the costs of prototype FCPU's. This information was extrapolated by the following means:

For the non-commercial components of the FCPU, an experience curve effect was assumed. These components are the fuel processor, the fuel cells, and the power conditioner. No experience curve effects were applied to commercially available components such as pumps, heat exchangers, valves, fans, and sensors. Some cost reductions because of volume purchasing will be experienced for commercial items, but have not been incorporated into the estimates.

Experience curve effects have been observed in many types of production processes. They are a measure of the cost reductions that occur with increases in the cumulative size of a production run. The cost reductions are caused by the

TABLE 1-5
COSTING FACTORS

Factor	MX Missile Shelter Power	DEWLine Station Power	Menorca Communications Site Power	Foreward Air Controller Radar Power	Ground Support Maintenance Power
Life Cycle Cost Time Period	1986-1998	1981-2000	1981-2000	1981-2000	1981-2000
Fuel	Methanol, Ethanol	DF-A	DF-2	JP-4	JP-4
1981 Delivered Fuel Cost	N/A	$1.75/Gal	$1.22/Gal	$1.30/Gal	$1.00/Gal
1990's Delivered Fuel Cost	$7/10^6 Btu	N/A	N/A	N/A	N/A
Fuel Cost Escalation	-0-	5%/Year	5%/Year	5%/Year	5%/Year
Other Costs Escalation	-0-	-0-	-0-	-0-	-0-
Labor Cost	$21/Labor Hr	$46/Labor Hr	$12/Labor Hr	$21/Labor Hr	$21/Labor Hr
Transportation Cost	30¢/Mile/Item	$1.22/Lb	$1.22/Lb	$1.22/Lb	$1.22/Lb
Initial Spares Provisioning	One Year Supply	One Year Supply	One Year Supply	One Year Supply	One Year Supply

combined effects of improved labor efficiencies, technical and manufacturing improvements, economics of scale, and volume purchasing of components and materials.

Based on the analysis of experience on similar types of equipment, an 85 percent experience curve was used resulting in a 15 percent cost reduction when the cumulative number of units are doubled. For a cumulative production of one thousand FCPU's, the experience curve effect reduces non-commercial components costs to 20 percent of the prototype values.

R&D costs have been abstracted from development risk assessments performed on each of the six units. These risk assessments are summarized in Section 1.5. It should be noted here, however, that the development program to a prototype for the unattended remote site units (MX application) was envisioned to require much more reliability testing than the logistic fuel units developments for substitution in existing attended multi-unit installations.

Life cycle cost (LCC) estimates for the two alcohol fueled unattended remote site units for a 12.5 year life cycle are as follows:

LCC Item	Methanol Unit	Ethanol Unit
Capital Costs, $	87,900	91,000
O&M Costs, $	64,600	67,500
Fuel Costs, $	106,300	100,100
Totals, $	258,800	259,200

The current plan for powering the 4,600 shelter MX concept is to use a utility type grid to conduct power to the individual shelters. The grid concept creates problems that may not be solvable in the areas of Electro Magnetic Pulse (EPM) protection and Protection of Location Uncertainty (PLU). These problems are far less severe if individual power units are used at each shelter. In addition, it might be possible to harden individual power sources to a useful level not attainable with a grid system.

The use of an individual FCPU at each shelter will also be cost effective compared to a new utility type grid. The LCC for the FCPU's figures to be a cost of 15.8¢/KWHR. Admittedly this is high compared to present prices of electricity. However, todays electric prices are a result of using equipment installed at yesterdays prices. A new rural electrification system to deliver power to what amounts to 200 scattered villages is quite a different matter. Using todays prices for equipment and installation, there is virtually no possibility of building such a system to deliver electricity for as little as 15.8¢/KWHR. A price of 50¢/KWHR for a new rural grid is more representative.

Twenty year life cycle cost estimates for the logistic fuel FCPU's and a comparison with the life cycle costs of the appropriate corresponding power source are provided in Table 1-6. As shown, the comparison is done using the specific application examples of the program. For the PIN-1 and Menorca sites the O&M cost estimates for diesel engine-generator operation were obtained from cognizant USAF personnel. For the tactical mobile applications the O&M costs for the gas turbine generator were derived from an internal USAF study of alternatives to existing gas turbine usage for tactical aircraft ground support.

By examining Table 1-6, it will be noted that there are capital costs associated with each of the existing systems because some of the existing units will have to be replaced entirely, not just overhauled, over the next twenty years.

There are apparant anomalies in the data presented.* Taking the remote site units first, the fuel savings at PIN-1 are a great deal larger than at Menorca because the PIN-1 FCPU is displacing not only electric generating fuel but heating fuel as well.

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*Real life data rarely plot as a smooth curve

TABLE 1-6

LOGISTIC FUEL APPLICATIONS, LCC COMPARISONS FOR AN INDIVIDUAL FCPU

	Attended Remote Site Units				Tactical Mobile Units			
	DEWLine PIN-1		Menorca Communications Site		Radar Power		Maintenance Power	
LCC Item	FCPU	Diesel-Generator Plus Water Heater	FCPU	Diesel-Generator	FCPU	Gas Turbine	FCPU	Gas Turbine
Capital Costs, $	187,300	60,000	268,500	167,000	164,400	32,400	175,200	40,500
O&M Costs, $	751,500	855,000	1,127,200	1,906,300	566,800	510,700	153,700	246,400
Fuel Costs, $	1,525,900	2,318,800	1,824,000	2,248,300	451,500	1,279,000	100,000	773,600
Totals, $	2,465,500	3,233,800	3,219,700	4,321,600	1,182,700	1,822,200	428,900	1,060,500

The anomalies in the O&M cost comparisons between PIN-1 and Menorca arise from two causes. The less important of these is that the costs of operating and maintaining the heating system at PIN-1 are not included in the dieselgenerator costs given in Table 1-6. The more important reason is that the O&M costs for both FCPU's were done on a consistant staffing basis. In practice, there is heavier engine room staffing at Menorca than PIN-1. Hence, the projected reduction in staff by the improvements from the increased FCPU's reliability over existing units is less at PIN-1 than at Menorca. It is understood that Menorca is experimenting with reduced engine room staffing.

Turning to the tactical mobile units, the LCC estimates are a good bit less than those of the remote site units because the tactical mobile units are used only intermittently, not continuously. The LCC advantages of the FCPU's over the existing gas turbine units is because the FCPU's are four to six times more fuel efficient than the gas turbines as electricity generators.

The anomaly in the O&M costs between the radar power and maintenance power units is because of the usage models employed. The maintenance power units are assumed to be located at a particular airbase. The radar units are presumed to be transported six times a year to and from a permanent base to forward locations. These transport costs for a 2 ton FCPU or a 0.5 ton gas turbine generator are included in the O&M costs for the radar power units. The obvious conclusion is that FCPU's are still cost effective compared to gas turbines even including costs associated with mobility.

1.5 DEVELOPMENT ASPECTS

Some of the general commonalties between the six FCPU's designs were given previously in the introduction to Section 1.3. More specific commonalities will be outlined here.

1.5.1 COMMONALITY BETWEEN UNITS

Fuel Cells

For the two unattended remote site and two attended remote site units the individual fuel cells can be identical without sacrifice in performance. The individual cells can be the 12 in x 17 in MARK II air cooled cells being developed by Westinghouse for FCPU's for utility use.

The cell stack for each of the two unattended remote site units can be identical. The cell stacks for each of the two attended remote site units can also be identical. However, the stacks for the attended remote site units will be taller and will be designed for higher pressure operation than those for the unattended remote site units.

The individual cells and stacks used in the tactical mobile units designs are identical. The technology is basically the MARK II cell design that could be used in the other designs. However, the cells are somewhat smaller (10 in x 14 in), thus reducing the units size. This is an important consideration for tactical mobile units. More importantly, the pressure level in the cooling air passages is maintained at a level less than that in the rest of the cell. Current cell technology uses equal pressures throughout.

Fuel Processing

For fuel processing, the FCPU's designs may be grouped in pairs regarding the use of common technology. The two unattended remote units using alcohol fuels use a common copper catalyst technology. The two attended remote units for USAF logistic fuels use high temperature steam reformer technology. The two tactical mobile units use autothermal reformer technology.

In the alcohol fuels grouping, a common ethanol reformer can be used for both methanol and ethanol. This would be profitable only if the application really needs an ethanol as well as methanol fuel use capability. Otherwise, a single fuel methanol fuel processor offers greater efficiency and a lower cost.

All four logistic fuel units could use a common reformer technology but only at the sacrifice of either performance or cost effectiveness for some of the units.

Power Conditioning

The DC to DC unattended remote FCPU's power conditioners are identical.

Within the other two groupings the DC to AC power conditioners are either identical (tactical mobile application) or similar, but of different size and input/output (attended remote site application).

1.5.2 DEVELOPMENT WORK AREAS

While no major breakthroughs are required to achieve the projected performance and design characteristics of the six FCPU's, work to develop the designs to a prototype level will be required. To evaluate the work required a technical development risk assessment was performed at both the major component level and the overall system level. The major components were taken as: (a) fuel processing, (b) fuel cell, (c) power conditioning and (d) balance of plant.

Each of these major component categories and the overall system was evaluated with respect to the following factors:

- current technology status
- technology status rating
- required technology status to meet design requirements for the proposed application
- proposed development program to achieve the required technology status
- estimated developmental effort expressed in terms of manhours of R&D personnel (engineering plus technicians)
- estimated developmental effort expressed in terms of development dollars (labor and materials)
- probability of success of the proposed developmental program
- ongoing programs or potential design alternatives.

The technology status rating criteria used are illustrated in Table 1-7.

A summary of the assessment for the six designs is given in Table 1-8. Referring to the technology ratings exhibited in Table 1-8, the least developed area of major component technology is that of fuel processing. Fuel processors for five out of six of the units must be rated as category (C) or developmental technology. While there is encouraging laboratory work on which to base these fuel processor designs, actual use in FCPU's has not been demonstrated. The other area of (C) or developmental technology exhibited is that for the fuel cells for the tactical mobile power units because the cells are conceived as having the cooling air passage pressure at a much lower level than the pressure in the balance of the cell. On the basis of stress analysis, this looks promising but has yet to be demonstrated physically.

Turning to the cost aspects of the assessment of Table 1-8, the overall system development costs for the unattended remote units are projected to be much higher than for the balance of the units. As stated in Section 1.4, this is because of application differences for the units. The unattended remote units were applied as single unbacked power sources for MX shelters. The other units can be tried out as part of a multiunit power complex. While all the units must be reliable in use, the MX units must have demonstrated that reliability experimentally before application. Such reliability demonstrations require much operating time and corresponding expense.

It will be noted that in some of the major component areas zero dollars (or no development program) are stated even though the components are not off-the-shelf as of today. In these areas there are development programs for other FCPU's that are anticipated to provide the missing knowledge and hardware.

1.6 SUMMARY OF RESULTS

This USAF fuel cell application analysis program has examined three generic groups of applications and in terms of two specific examples per group. The three generic groups are: (1) unattended remote sites, (2) attended remote sites and (3) tactical mobile. The specific examples are:

TABLE 1-7

TECHNOLOGY STATUS RATING CRITERIA

TECHNOLOGY RATING	TECHNOLOGY STATUS	PERFORMANCE DATA BASE	EXTRAPOLATION FROM PERFORMANCE DATA BASE	APPLICATION OR DEVELOPMENT PROGRAMS REQUIREMENTS	R&D PROGRAM CHARACTERISTICS	
					RATIONALE	PROBABILITY
Established (A)	Firm selections can be made. Equipment is commercialy available in form required.	Sufficient	None	Minimal, routine applications engineering.	Not Applicable	Not Applicable
Near Term (B)	A number of equipment candidates are identified. Candidates are commercial or near commercial.	Incomplete	Short extrapolations from existing data base are involved.	Confirmatory testing and minimal R&D.	Straight-forward	Virtually Certain
Developmental (C)	Equipment not previously designed, but engineering data base exists for design.	Incomplete; important gaps exist.	Large extrapolations from existing data required.	Considerable R&D is required.	A credible rationale exists. Alternative avenues are evident.	Good to excellent
Speculative (D)	Equipment not previously designed with major materials, design or manufacturing uncertainties.	Sparse or absent.	Highly speculative or not possible.	Extensive R&D is required.	Rationale is not clear, or requires a break-through or serendipity.	Fair to poor.

TABLE 1-8

DEVELOPMENT WORK AREAS ASSESSMENT

Work Area	23 kW Unattended Remote Technology Development Program Rating		Effort Estimate $ Millions		60 kW and 100 kW Attended Remote Technology Development Program Rating		Effort Estimate $ Millions		Tactical Mobile Technology Development Program Rating		Effort Estimate $ Millions	
	CH_3OH	C_2H_5OH	CH_3OH	C_2H_5OH	60kW	100 kW	60 kW	100 kW	Radar Power	Main. Power	Radar Power	Main. Power
Fuel Processing	B	C	*0.83*	*2.08*	C	C	2.08	2.08	C	C	2.40	2.80
Fuel Cell	B	B	0.35	0.50	B	B	0.00	0.00	C	C	3.00	3.00
Power Conditioning	A	A	0.05	0.05	A	A	0.00	0.00	A	A	0.10	0.10
Balance of Plant	A	A	0.10	0.10	A	A	0.00	0.20	A	A	0.00	0.00
Overall System	B	B	14.30	14.60	B	B	4.50	5.25	B	B	4.00	4.70
Totals			15.63	17.33			6.58	7.53			9.50	10.60

Group 1	23 kW, MX shelter power, Methanol fuel
	23 kW, MX shelter power, Ethanol fuel
Group 2	60 kW, DEWline PIN-1 Site, Diesel fuel
	100 kW, Menorca, Sp. Communications Site, Diesel fuel
Group 3	60 kW, Foreward Air Controller Radar, Aviation turbine fuel
	60 kW, Tactical Aircraft Maintenance, Aviation turbine fuel

A distilled summary of the results of this analysis are presented in Table 1-9. As shown, the substitution of fuel cell power units as the electric power source for these existing or projected applications will result in major fuel and cost savings to the USAF with no major offsetting disadvantages evident for two of the three generic groups.

It is suggested that the USAF expedite its program to develop and substitute FCPU's in the applications analyzed. Simple interest return on the investment (ROI) in development and production costs will average 20 percent for Group 2 and 3 FCPU's. The ROI value is probably conservative as it assumes the fuel costs only escalate at 5 percent per year.

TABLE 1-9

UNITED STATES AIR FORCE FUEL CELL APPLICATION ANALYSIS SUMMARY

General Application	Specific Application	FCPU Replacement For:	Major Advantages		Major Dissdvantages
			Technical	Costs	
Unattended Remote Site	MX Shelter Power, Methanol Fuel	New Rural Type Utility Grid	Low EMP or PLU Problem	Substantial but Undetermined Cost Savings	None
Unattended Remote Site	MX Shelter Power, Ethanol Fuel	Ditto	Ditto	Ditto	Ditto
Attended Remote Site	DEWLine PIN-1 Site	Diesel Electric Generators	34% Fuel Savings	LCC Savings = $770,000/FCPU	None
Attended Remote Site	Menorca, Spain Communications Site	Ditto	19% Fuel Savings	LCC Savings = $1,100,000/FCPU	Ditto
Tactical Mobile	Foreward Air Controller Radar	Gas Turbine Electric Generators	65% Fuel Savings	LCC Savings = $640,000/FCPU	FCPU Weight and Volume Substantially Larger than Gas Turbines
Tactical Mobile	Tactical Aircraft Maintenance	Ditto	87% Fuel Savings	LCC Savings = $630,000/FCPU	

2.0 INTRODUCTION

The general objective of this program has been to investigate and analyze the application of phosphoric acid fuel cell technology to several of the United States Air Force (USAF) needs for ground electric power and heat. The purpose is to provide guidance to possible USAF fuel cell development and application efforts in the future.

The specific objectives of the program were to: (a) perform fuel cell application analyses for six USAF specified applications, (b) provide preliminary conceptual designs and technical risk assessments [of Fuel Cell Power Units (FCPU) for each application] and (c) provide final conceptual [FCPU] designs for the applications.

2.1 APPLICATIONS

The generic applications considered were as follows:

Application No.	Description	Electric Power Level
1 & 6	Unattended Remote Site	5-20
2	Attended Remote Site	30-60
3	Attended Remote Site	100-250
4	Tactical Mobile System	30-60
5	Tactical Mobile System	120-250

Specific sites/systems examples of the generic applications analyzed as a basis for development of FCPU design specifications and costing studies were as follows:

Application No.	Description
1/6	Individual MX Missile Shelter Power Site, Two RES* Fuels
2	DEWLine, PIN-1 Site
3	European Communications, Menorca, Spain Site
4	Foreward Air Controller Radar Power Supply
5	Tactical Aircraft Ground Maintenance Power Supply

The two RES fuels considered were methanol (wood alcohol) and ethanol (grain alcohol). This is not a trivial distinction. Use of methanol in Phosphoric Acid Fuel Cells (PAFC) is current practice. Little work has been done towards use of ethanol in PAFC systems.

Ethanol is a more refractory fuel to use than methanol; but ethanol will be a less difficult fuel to use than the USAF logistics fuels of Applications 2-5. Substantially successful laboratory scale work has been done on fuels similar to USAF logistic fuels on U. S. Government sponsored programs.

The applications examined can be characterized as FCPU substitutions for other type power supplies, as:

Application No.	FCPU Substitution For:
1/6	Utility Grid Power Supply
2/3	Diesel-Electric Power Supply
4/5	Gas Turbine - Electric Power Supply

2.2 PROGRAM METHODOLOGY

The broad course of the program followed the outline of specific objectives given previously. Namely: (1) gather information and organize, analyze and determine priority of the information to yield FCPU design requirements and

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*Renewable Energy Source

constraints; (2) create and cost a preliminary conceptual design for each application at the process design level; and (3) convert the process design into conceptual physical embodiments as layout drawings and artist's conceptions, along with refinement of the preliminary process design and costing. A part of the final cost refinement effort was preparation of projected life cycle costs of a FCPU for each application and, for Applications No. 2 through 5, a comparison with the life cycle costs of the existing electric power systems being used to satisfy these applications.

A primary purpose of the applications analysis was to create a set of generic, yet realistic, design specifications of FCPU for each application. It was the purpose of the design specification to assure that the FCPU design would satisfy not only the physical requirements of the particular applications, but of many other similar applications as well.

An additional purpose of the application analysis was to establish operational modes and operational and maintenance costing rates and factors for each application. These, taken along with the physical needs specifications, were then used to direct the design effort towards lowest life cycle costs while satisfying the physical needs. It is worth noting that the lowest life cycle cost unit always was the most fuel efficient unit that was conceived to satisfy the physical requirements.

The design specifications and costing factors were derived for each application by iterative interaction with USAF designated commands as follows:

Application No.	Principal Contact Points	
1/6	BMO, MNNBL, Norton AFB, CA	Major T. Hughes
2	ASD, Peterson AFB, CO	Mr. D. Cain; FIS, Mr. C. Martin
3	AFCS, Torrejon AFB, Spain	Mr. John Siska
4	TAGIF, Langley AFB, VA	Capt. J. Shields
5	ENEG, WPAFB, OH	Lt. Col. R. Poplowski

The various design specifications created with the help of the foregoing commands may be found in Appendices C1-C5.

The design process involved three major steps. All steps involved a considerable amount of iteration to arrive at conceptually ideal components and systems.

The preliminary conceptual design steps involved three elements. The initial effort was to develop a broad range of characteristics and choices for the three most important FCPU subsystems. These subsystems are: (1) the fuel processing subsystem, (2) the fuel cell subsystem and (3) the electric power conditioning subsystem. The results of this effort are covered in Section 3.0.

Using the subsystem characteristics and choices developed previously, process (schematic) designs were created and modified to satisfy design requirements and minimize anticipated life cycle costs in terms of production unit costs and fuel costs. The development risks associated with the design were then assessed and the costing analysis extended to site specific operating, maintenance and installation costs; all in an interative manner.

The third design step involved taking the schematics and tabular descriptions of the preliminary conceptual design step and creating conceptual physical embodiments for each design. These physical embodiments are in the form of layout drawings and artist's renditions.

The application and design characteristics, development risk assessment, life cycle costing and cost comparisons for each of the conceptual FCPU's created are reported in self-contained sections of this report.

Report section numbers covering the various FCPU's are as follows:

Application No.	FCPU Electrical kW	Heat Btu/Hr	Generic Application	Example of Use	Report Section
1/6	23	NA	Unattended Remote	MX Shelter, Methanol Ethanol	4.0
2	60	238,000	Attended Remote	DEWLine, PIN-1	5.0
3	100	NA	Attended Remote	Menorca, Spain	6.0
4	60	NA	Tactical Mobile	Foreward Air Controller Radar	7.0
5	60	145,000	Tactical Mobile	Tactical Aircraft Maintenance	8.0

3.0 SUBSYSTEM CHARACTERISTICS

The principle non-commercial items in a FCPU are the fuel processing subsystem and the phosphoric acid fuel cells (PAFC) and power conditioner of the power generation subsystem. These items are identified in the generic type block diagram of Figure 3-1 and are discussed in detail in Sections 3.1, 3.2 and 3.3.

As indicated in Figure 3-1, steam (and sometimes air) and fuel are heated, mixed and converted in the fuel processing subsystem to a hydrogen rich gas. This gas, along with fresh air, is introduced into the fuel cells where the hydrogen is electrochemically oxidized to water, producing heat and DC electric power. This power is controlled and conditioned into a form suitable for using apparatus consumption. In this study the unattended remote site units produce conditioned 120 volts DC power. The attended remote site units produce 60 Hz AC power and the tactical mobile units produce 400 Hz AC power. Standard voltages in the 110 V to 416 V range are available, depending on the requirements.

The fuel to electric power conversion efficiency of PAFC systems is higher than that of most competitive power systems. In addition, if the application has a requirement for heat and electric power the waste heat from the FCPU can be recovered for further use. This might be in the form of hot air, hot water, or steam. The maximum temperature at which meaningful fuel quantities of (truly) waste heat are available from PAFC systems is about 350°F. Combined electricity plus process heat thermal effiencies of over 80% are obtainable.

All the designs of this study use steam to reform the fuels into a hydrogen rich gas suitable for PAFC's consumption. The tactical mobile units also introduce air directly into the fuel processor, making the system thermally self-sufficient. To make the FCPU's water self-sufficient, a portion of the water vapor in the FCPU's exhausts is condensed for reuse in the fuel processing step. This water for fuel processing could have been provided without the

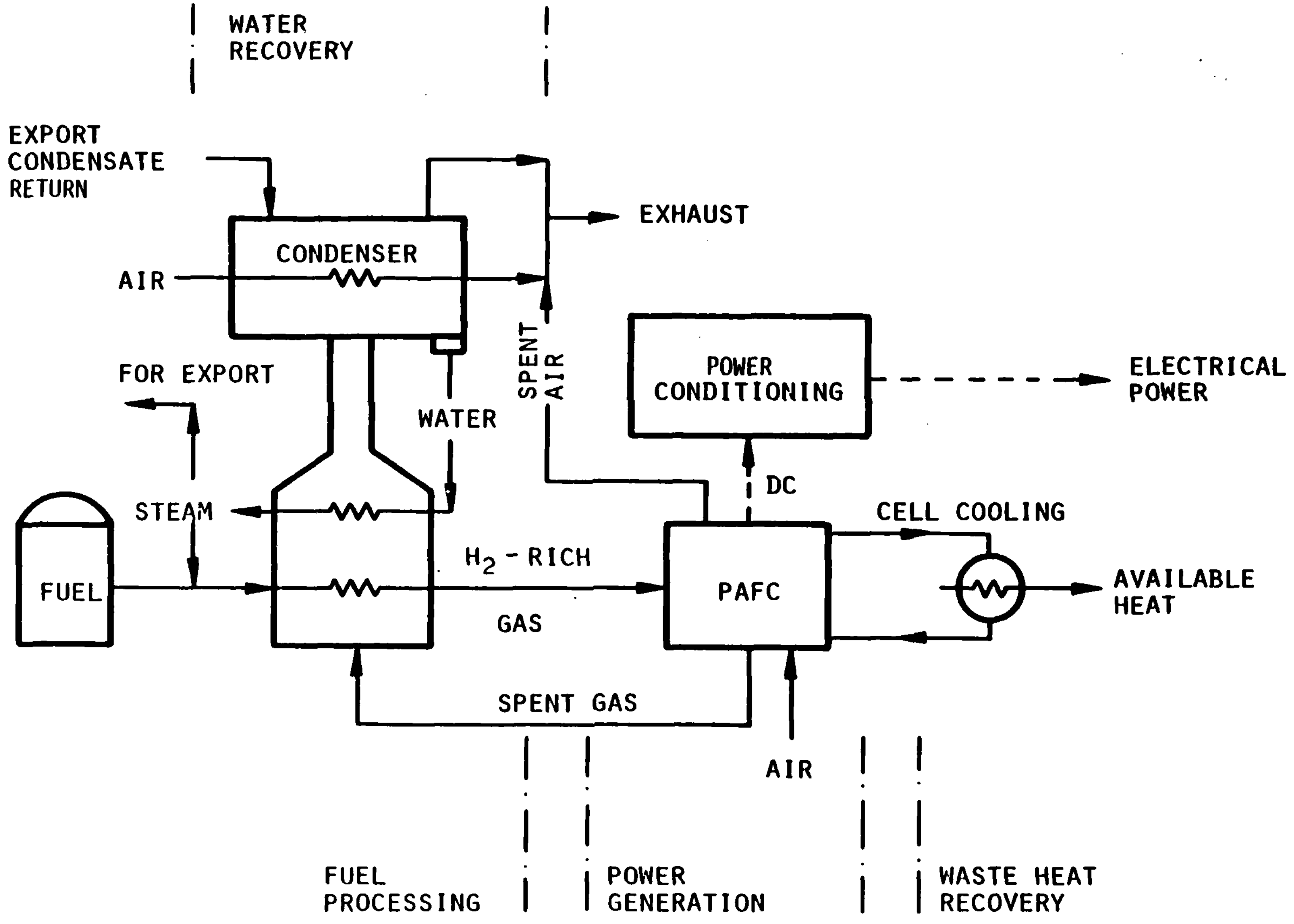

Figure 3-1. FCPU Major Subsystems

condensing step by recirculating a portion of the FCPU exhaust through the fuel processor and fuel cells. However, this seriously dilutes the hydrogen concentration in the fuel cell. This in turn leads to a 10 percent to 15 percent increase in fuel consumption for a given power output. Also, it probably will result in a net increase in system size because of the increased gas volume throughput even through the [large] condenser element is eliminated*.

3.1 FUEL CELL CONCEPT

The basic phosphoric acid fuel cell concept used throughout this study is that of the air cooled cell. This is a concept developed by the Energy Research Corporation (ERC) for use in small (1.5 kW-5 kW) units for U. S. Army Mobile Electric Power. This ERC concept has been adopted by Westinghouse for its use on-site integrated energy and utility fuel cell programs.

Other cooling schemes that could have been used include water cooling and liquid cooling using a dielectric fluid. The liquid-cooled designs require the use of numerous tubes to convey and contain the liquid. As a result, there are a large number of tube connections that present potential leakage problems. Since reliability is a most important design requirement for all the FCPU's conceived under this program, air-cooled design appears preferable. It is felt that overall study results will not be significantly affected by the choice of a fuel cell cooling method.

Two detail fuel cell design configurations were used. The first of these is the original ERC developed DIGAS** MARK I cell. This first configuration was used in the 23 kW unattended remote site FCPU's (MX individual shelter power example). The unattended remote site units are direct derivatives of the previously mentioned 1.5 kW-5 kW units which incorporate the MARK I cells.

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*There is some expert opinion that holds that the recycle water to the fuel processor will have to be cleaned before reuse. If required, this can be done by standard procedures with a liquid return. Procedures for cleaning a water vapor return have not been developed to our knowledge.

**U. S. Patent 4192906

The balance of the FCPU's are designed around the MARK II derivative of the original ERC MARK I cell. The MARK II fuel cell configuration was developed under a NASA sponsored on-site integrated energy system program, contract DEN3-161.

The details of a MARK II configuration are illustrated in Figure 3-2. The individual fuel cell is comprised of bipolar plates, two gas diffusion electrodes and an acid matrix. The "Z" patterned channels in the bipolar plates direct the flow of the reactant hydrogen-rich gas and air in a counter flow mode and in channels of equal length.

Heat is removed from the cell stacks by air directed through cooling plates located at approximately every fifth cell. The cooling channels are configured in a "tree" shape to achieve a flat temperature profile across the stack, and to keep the peak to average temperature ratio as low as possible.

In the predecessor MARK I configuration the reactant flows are directed in a crossflow pattern. The hydrogen rich gas flows lengthwise of the cell and the air crosswise in the same direction as the cooling air flow. The cooling air and reactant air are mixed together in the MARK I cell configuration rather than separated as in the MARK II configuration. This MARK I arrangement is simplier than the MARK II but suffers from some dilution of the oxygen content of the reactant air.

For performance and structual reasons it is desirable for the incoming cooling air to be close to cell temperature. This is usually accomplished by recirculating the cooling air through a waste heat exchanger where the air temperature of the cooling air to be returned is carefully controlled. Because in the MARK I cell the reactant air and cooling air are mixed together, there is a reduction in the oxygen content of the mixture exiting the fuel cell. This oxygen reduction is carried back to the cell air inlet by the recirculating cooling air. Some, but not all, of the reduction in oxygen content, below standard air value, can be made-up by introduction of fresh air at cell inlet.

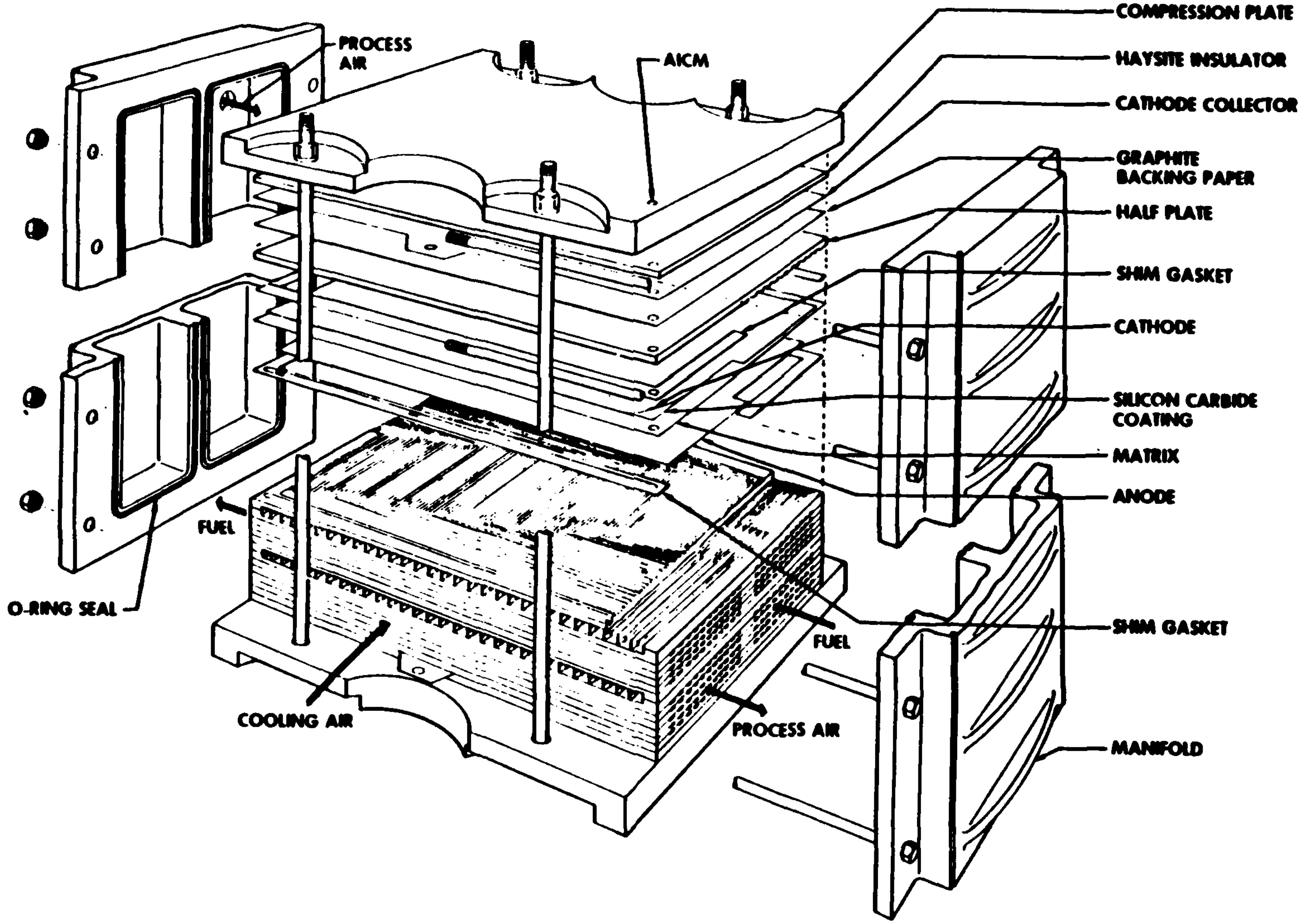

Figure 3-2. MARK II PAFC Air Cooled Fuel Cells

Another advantage of the MARK II cell separation of the reactant air and coolin air streams is that the two streams can be supplied at different pressure levels. This can be used, sometimes, to obtain a better overall FCPU system optimization.

The performance level demonstrated in a MARK I DIGAS stack of six intermediate size cells is 620 mV/cell at 50 psia, 374°F and 300 MA/cm^2. At atmospheric pressure, a MARK II separated gas stack of 23 full size cells has demonstrated performance of 600 mV/cell at 150 MA/cm^2 and 347°F. These results are not directly comparable since cell voltage varies with operating temperature, pressure, and current density. The demonstrated lifetime of the baseline components is greater than 25,000 hours for the electrodes and matrices, and 10,000 hours for the bipolar plates. Full size (1200 cm^2) versions of all baseline components have been manufactured and tested in 23 cell stacks with both MARK I DIGAS and MARK II separated air cooling.

The MARK II bipolar and cooling plate designs are recent innovations. Accordingly, the accumulated operating time is 10,000 hours in a small cell. A number of stacks of intermediate size cells (three 3-cell and one 10-cell) and one 5-cell stack of full size components have operated for over 7,000 hours. Two 23-cell stacks, including cooling plates, were recently built and have operated stably for hundreds of hours.

A MARK I DIGAS stack of six intermediate size (340 cm^2) cells has been operated stably for hundreds of hours at an elevated pressure. The measured performance of this stack at 15 psia (atmospheric pressure) and at 65 psia is plotted in Figure 3-3. Several stacks of 80 intermediate size cells have been built and tested at ERC and tested at other organizations (MERADCOM, LASL, and Westinghouse Research and Development Center).

The cell performance values used in the conceptual designs of this study were derived from MARK I DIGAS data. Design conditions did not correspond exactly to test data conditions. Corrections to design conditions were made to the

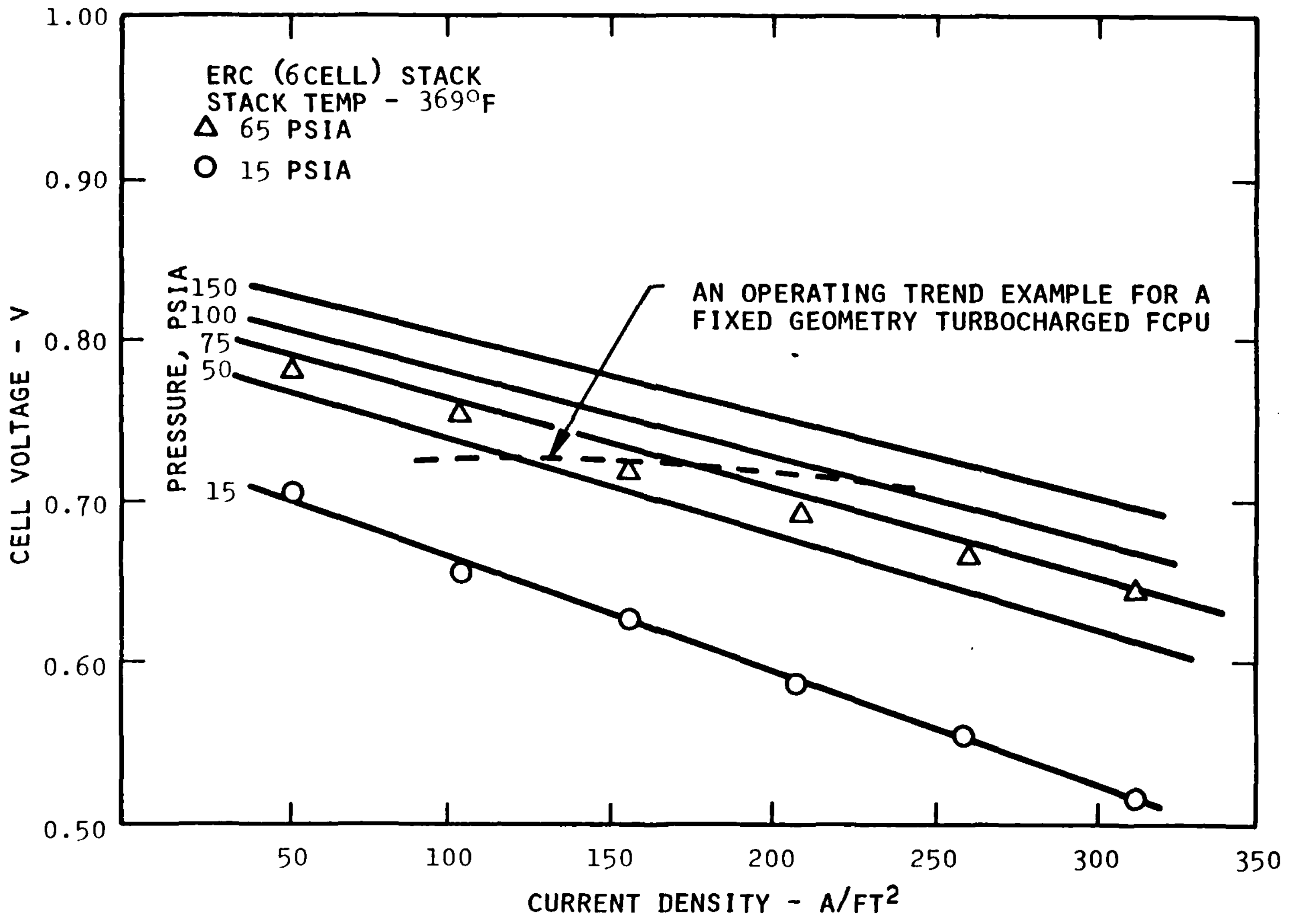

Figure 3-3. MARK I DIGAS Cell Performance

test data base using empirical factors. An important parameter in this respect is cell operating pressure, which is represented by:

$$Vp = V_{15} + A \ln Pr$$

where Vp is the cell voltage at a given current density at a particular pressure and

V_{15} is the cell voltage at the same current density at 15 psia
Pr is the ratio of the particular pressure to 15 psia
A is a constant derived empirically from the test data.

This rationalization expression is illustrated by the pressure parameter lines of Figure 3-3. In the design process other empiric corrections for cell temperature and reactants concentrations were made to the MARK I data base.

As observed in Figure 3-3, as the load (current) drawn from a cell is reduced, at constant pressure, the cell voltage goes up. This is the same phenomenon that occurs with other electrochemical devices such as a battery. The increase in cell voltage represents an increase in cell electrical generation efficiency. As can be observed, also, an increase in cell operating pressure at constant current density increases cell voltage and electrical generation efficiency.

The increase in cell voltage with reduced current density, at constant pressure, is the reason for the oft quoted remark that fuel cells have good part load efficiency. This is particularly so for systems operated at atmospheric pressure, such as the two unattended remote site units of this study. Atmospheric pressure is essentially constant at a given site.

Operating PAFC at above atmospheric pressures yields substantial dividends in electrical generation efficiency and power density. This characteristic was used in the design of the attended remote site and tactical mobile units of this study. This was primarily to increase efficiency in the remote site units and to reduce size in the tactical mobile units while maintaining good efficiency.

Pressurization is accomplished by a system exhaust motivated turbocharger. This approach markedly increases electrical generation efficiency and power density relative to atmospheric operation. An example operating line for such a system is indicated by the dashed line of Figure 3-3. For these more complex pressurized systems, the voltage-current characteristic can either rise, fall or remain nearly constant with electrical demand, since the operating pressure varies with load.

3.2 FUEL PROCESSING CONCEPTS

The unattended remote site units of this study use methanol and ethanol. Substantial development work has been done on methanol reformers by ERC in connection with their development of 1.5 kW-5 kW portable FCPU's.

ERC has been successful in catalytic steam reforming of methanol using a copper catalyst. The reforming temperature is low (400°F to 600°F). At these temperatures, sufficient CO shift conversion ($CO + H_2O \rightarrow CO_2 + H_2$) occurs to eliminate the need for the separate shift converter required with most other fuels.

Less work has been done on ethanol by ERC (or anybody else) than methanol. However, laboratory work using a modified methanol reformer has been most encouraging. More steam, higher temperatures (600°F-800°F), and a separate shift converter are required compared to methanol fuel processing.

The potential applications of the two attended remote site and two tactical mobile unit designs of this study require the use of USAF logistic fuels, JP-4 and diesel fuel.

Commercial and developmental processes were reviewed for their potential use with logistic aviation and diesel fuels (see Table 3-1). Of these many reforming processes, three were identified as potentially suitable for Phosphoric Acid Fuel Cell (PAFC) system integration. These are:

- Conventional Steam Reforming (STR)
- Autothermal Reforming (ATR)
- High Temperature Steam Reforming (HTSR)

Conventional steam reforming is used commercially to produce hydrogen from methane and naphtha and can be potentially extended to handle aviation jet fuel (JP-4). Fuel feeds are limited normally to low sulfur grades because of practical problems caused by the removal of large amounts of sulfur. High Temperature Steam Reforming and Autothermal reforming processes operate at temperatures at which catalysts are less succeptable to sulfur poisioning. Both processes show good potential for handling high sulfur fuels because they minimize the problems associated with sulfur removal.

Both ATR and HTSR are considered development processes because they operate at temperatures where carbon deposition is a potential problem. Other processes, identified in Table 3-1, are not considered advantageous in PAFC systems either because of severe operating conditions, low thermal efficiencies or operational problems of soot formation, catalyst regeneration, and process control.

3.2.1 CONVENTIONAL STEAM REFORMING

A conventional steam reforming process modified for PAFC application is depicted in Figure 3-4, a and b. In this process, desulfurized fuel vapor is mixed with steam and endothermally reformed into a hydrogen-rich gas. The sulfur content of the desulfurized fuel gas must be less than 1 ppm. Reforming takes place in a nickel catalyst bed, operating at outlet temperatures of 1200-1400°F, for logistic fuels (Ref. 3-1, 3-2)*. Heat is supplied to the reformer by combustion of unused fuel cell hydrogen, supplemented by additional liquid fuel depending upon overall system design. The reformer operates with a steam/carbon ratio of approximately 4.0 to avoid carbon formation and blockage of the catalyst bed. Product gases leave the reformer at 1400°F, and are

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*References for Section 3.0 may be found in Appendix A-1

TABLE 3-1

FUEL REFORMING PROCESSES

Process	Parameters	Key Characteristics
Thermal Cracker (Texaco, Shell)	2400-2700°F 85 ATM.	Low thermal efficiency Produces soot, NH_3 Process control difficult
Steam Cracker (Segas)	2000-2600°F 59-90 ATM.	Low thermal efficiency High water rates Produces soot Process control difficult
Catalytic Cracker (Siemems, Germany)	1800-2200°F Moderate Pressures	Produces soot Requires catalyst regeneration
Fluidized Bed Steam Ref. (Grand Paroisse/Heurty)	1600-1800°F Moderate Pressures	High thermal efficiency Difficult operation Carbon formation
Autothermal Reforming (BASF, LURGI, Haldor Topsoe)	1500-1800°F 1-10 ATM	Moderate thermal efficiency High O_2/C rates Good response
HTSR (Toyo Catalysts)	1600-1800°F 1-10 ATM	Moderate thermal efficiency High S/C rates Moderate response
Conventional Steam Reforming	1200-1400°F 1-10 ATM	High thermal efficiency Moderate response No sulfur tolerance

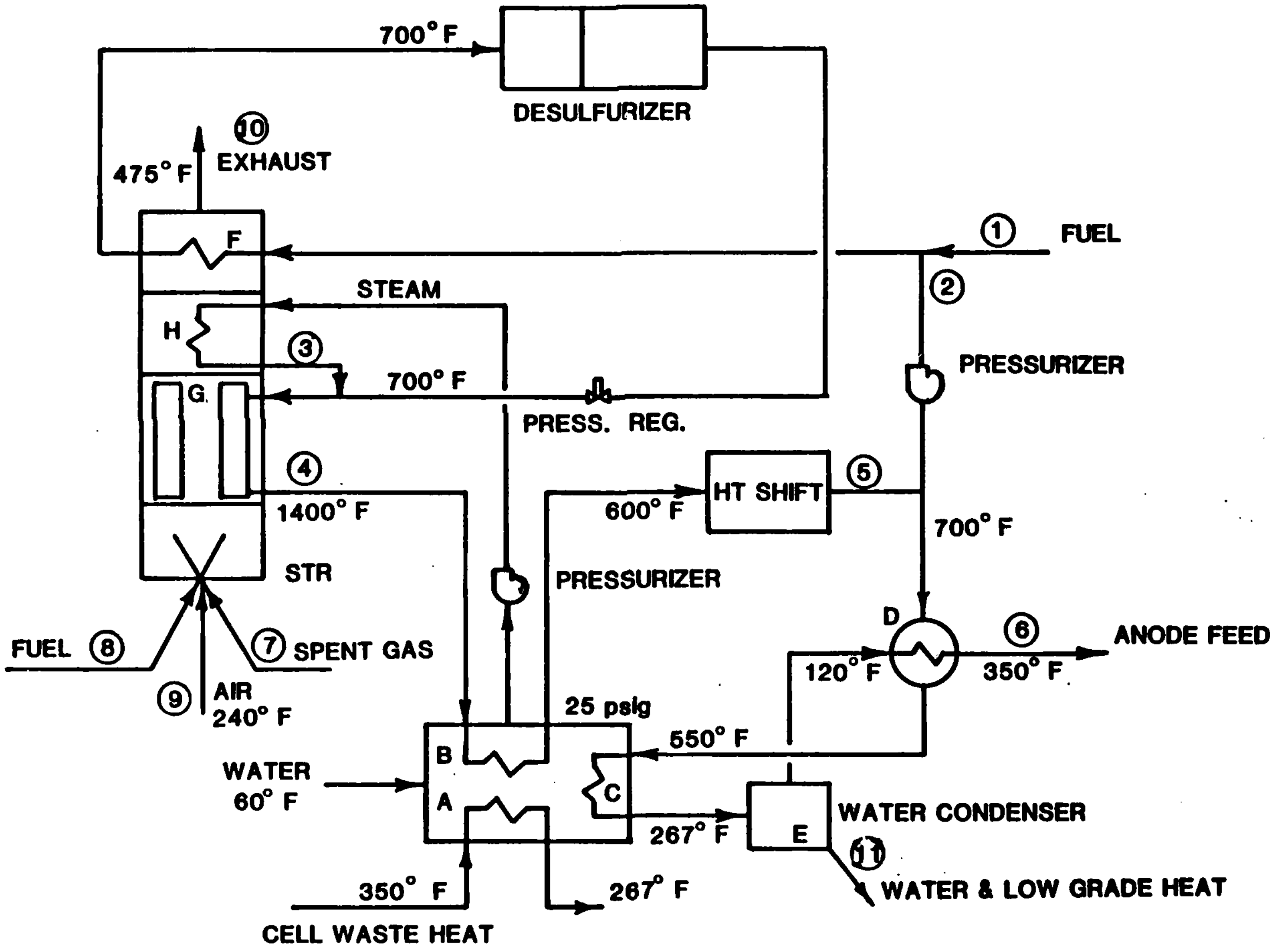

Figure 3-4a. Conventional Steam Reforming System (STR)

STREAM NO.	STR FUEL 1	RECIRC GAS 2	STR STEAM 3	STR EXIT 4	SHIFT EXIT 5	ANODE FEED 6	ANODE EXIT 7	BURNER FUEL 8	COMB. AIR 9	COMB. EXH. 10	WATER REC. 11
Lb Moles											
H_2		0.134		2.500	2.804	2.76	0.40				
CO		0.004		0.376	0.074	0.07	0.07				
CO_2		0.044		0.620	0.924	0.88	0.88			1.31	
CH_4		0.002		0.053	0.053	0.05	0.05				
H_2O		0.109	4.0	2.583	2.279	0.21	0.21			0.933	1.96
N_2									2.846	2.846	
O_2									.663	0.085	
CH1.88	1.0							.131			
Total, Lbs	13.88	4.29	72.0	90.17	90.17	50.60	46.06	1.82	100.9	148.9	35.28
Temp, °F	60	700	1000	1400	700	350	350	190	240	475	120

Design Bases

85% cell H_2Use

18600 btu/lb fuel (NHV)

52018 btu/lb H_2

4348 btu/lb CO

21758 btu/lb CH_4

95% fuel conversion

No thermal Losses

Heat Exchanger Loads (btu/lb reformer fuel)	Sensible	Latent
A - Cell Waste Heat Input	3736	
B - Product Gas Cooler	3035	
C - Conderner Prg Cooler	1150	
D - Product Gas Reheater	494	
E - Water Condenser	800	2373
F - Fuel Vaporizer	283	207
G - Reformer Bed	6014	
H - Steam Supht'r	0	

Figure 3-4b. State Conditions for Conventional Steam Reformer

cooled to 600°F, before entering a shift converter. The purpose of the shift converter is to reduce carbon dioxide (CO) content in the gas to <2 percent while increasing hydrogen content via water gas shift reaction. Product gases are then dehumidified to remove moisture and effectively improve cell performance by reducing diluents. CO shifting is necessary to protect the fuel cell catalyst from poisoning as this reduces cell voltage.

The key step in this process is the desulfurization of fuel vapor which takes place in a dual catalyst reactor. Vaporized fuel is mixed with recycled hydrogen gas and passed through a nickel or cobalt molybdenum catalyst to hydrogenate fuel sulfur and olefins. Fuel sulfur is converted to hydrogen sulfide (H_2S) and removed in a zinc oxide (ZnO) absorbent bed. The reactor is operated at 700-750°F to obtain maximum H_2S removal (30 lbs S/200 lbs ZnO).

To achieve low outlet H_2S concentrations, the hydrodesulfurizer unit must operate at high hydrogen partial pressure (Ref. 3-3). Both empirical studies and bench-scale tests have demonstrated that desulfurization of high sulfur fuels (No. 2 oil at 8500 wppm S*) is feasible. However, a two stage process operating at pressures in excess of 300 psig is required. Desulfurization of naphtha (<500 wppm S) is achieved commercially at 300 psig. Operation at these high pressures is not considered practical for USAF fuel cell applications. However, desulfurization of JP-4 (<350 wppm S) (Ref. 3-4) is potentially feasible using a single reactor operating at lower pressures. The actual operating conditions need to be verified by experimentation. To accommodate variations in fuel sulfur levels, considerable design margin in recycle hydrogen rates, operating pressures, and zinc oxide capacity, may be needed to adequately protect the reformer catalyst.

The thermal performance of the STR option is dependent upon system design and integration with the fuel cell. Based on the conditions specified in Figure 3-4, a and b, and assuming no thermal losses, a conventional steam reformer can

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*Weight Parts per Million Sulfur

produce approximately 0.34 lbs H_2 per pound of JP-4 consumed. As shown in Table 3-2, endothermic reforming and preheating of reactants requires 14308 Btu per lb of fuel entering the reformer. Energy available in product gases and combustion of unused fuel cell anode gases provides about 60 percent of this needed energy. The remaining 40 percent can be obtained by utilizing fuel cell waste heat and burning additional fuel. Approximately 13 percent additional liquid fuel is needed. If fuel cell waste heat is not used, additional fuel requirements are approximately 20 percent, yielding a hydrogen production of 0.285 lbs/per lb of fuel consumed.

This option offers the following advantages over HTSR and ATR options as applied to PAFC systems:

- Lower thermal losses due to lower temperature operations
- Lower equipment sizes and weights
- Lower cost materials of construction
- and, lower overall cost of design.

The key disadvantage to conventional steam reforming is its limitation on fuel sulfur content. This process is not considered applicable to diesel grade logistic fuels because of sulfur content (Ref. 3-5) and may be marginal when applied to JP-4 type fuels.

3.2.2 HIGH TEMPERATURE STEAM REFORMING (Ref. 3-6, 3-7)

A high temperature steam reforming process, modified for PAFC application is depicted in Figure 3-5, a and b. The primary difference between a HTSR and a STR is the operating temperature and desulfurization step. The reformer operates at 1600-1800°F where sulfur poisoning is limited and pretreatment fuel desulfurization is not needed. Desulfurization occurs at the reformer outlet in a single bed of ZnO, where removal to <10 ppm H_2S is needed to protect the shift catalyst.

TABLE 3-2

THERMAL PERFORMANCE OF REFORMING OPTIONS

	STR	HTSR	ATR
Steam/Carbon Ratio	4	4	3
Air/Carbon Ratio	0	0	1.8
Product Gas Temp, °F	1,400	1,800	1,800
Heat Requirements, btu/lb fuel reformed			
Endothermic Reforming	6,014	6,048	0
Reactants to Inlet Conditions	8,294 (1)	9,978 (2)	8,450 (3)
Total Heat Required	14,308	16,026	8,450
Heat Available, btu/lb fuel reformed			
Product Gas Cooling	4,185 (4)	5,588 (4)	4,995 (5)
Spent Anode Gas Combustion (6)	4,252	4,252	3,455
Additional Fuel Combustion	2,252 (7)	6,186 (8)	0
Usable Cell Waste Heat	3,619	0	0
Total Heat Input	14,308	16,026	8,450
Low Grade Waste Heat, (10) btu/lb Fuel	3,173	3,173	3,146
Hydrogen Production, (11) lb/lb Fuel Consumed			
With cell waste heat	.34	.284	.276
Without cell waste heat	.285	.284	.276

(1) Steam @ 1,000°F, Fuel @ 700°F

(2) Steam @ 1,600°F, Fuel @ 600°F

(3) Steam @ 1,400°F, Air @ 1,400°F, Fuel @ 700°F

(4) Product Gases Cooled to 267°F before H_2O Condenser

(5) Product Gases Cooled to 475°F before H_2O Condenser

(6) Anode Gas Combustion to 475°F before H_2O Condenser, 85% cell H_2 utilization.

(7) Additional Fuel Combustion to 475°F Exhaust (13.1% Fuel Match)

(8) Additional Fuel Combustion to 475°F Exhaust (36% Fuel Match) Combustion of Gas & Fuel @ 1.15% Stoair

(9) Cell Waste Heat Boiler @ 25 psig, 267°F Saturated Steam Temp.

(10) Condenser Sensible & Latent Heat

(11) Assumes Shift Conversation to <2% vol. CO

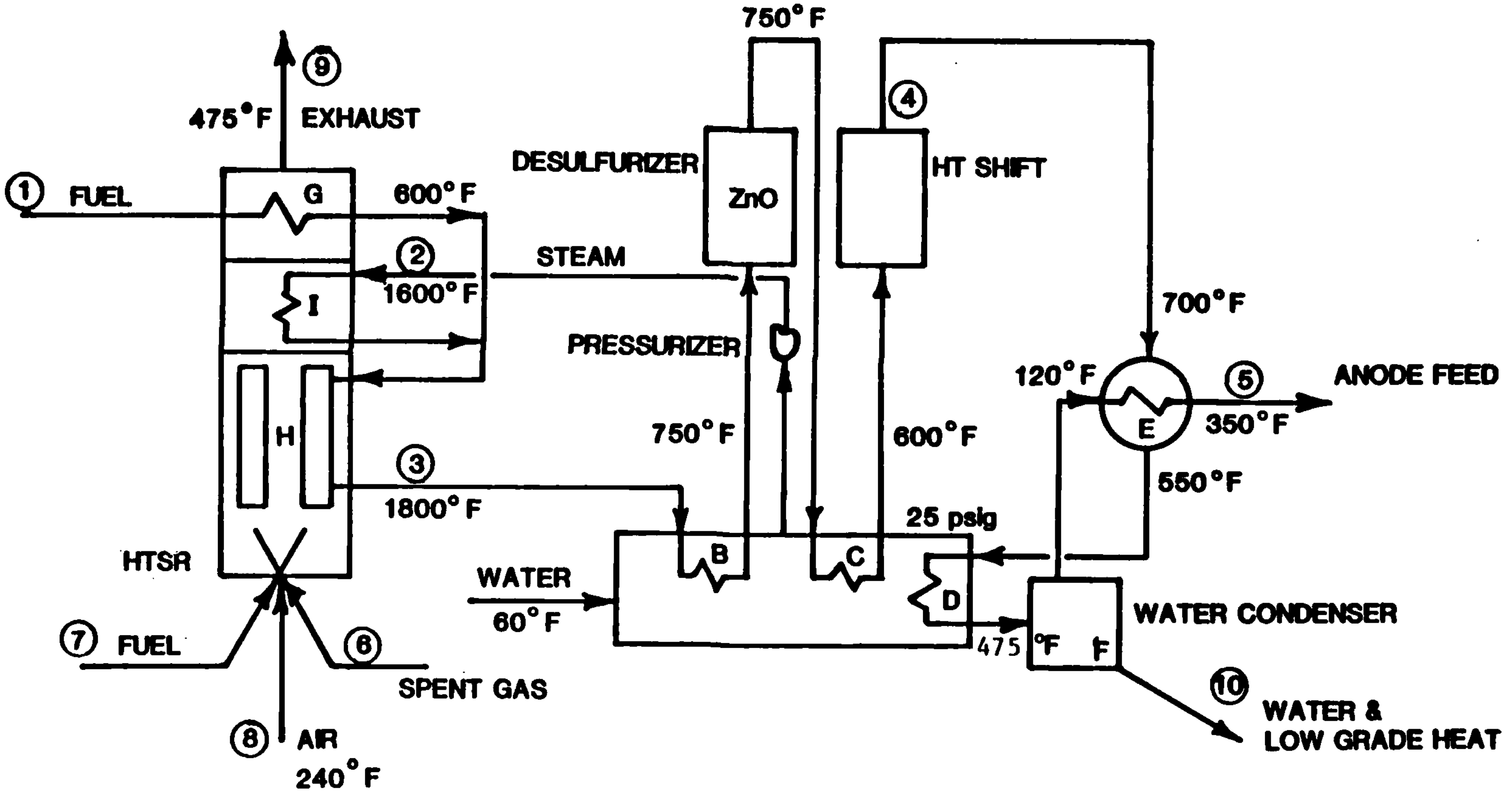

Figure 3-5a. High Temperature Steam Reforming System (HTSR)

Stream No. Lb moles	HTSR Fuel 1	HTSR Steam 2	HTSR Exit 3	Shift Exit 4	Anode Feed 5	Anode Exit 6	Burner Fuel 7	Comb. Air 8	Comb. Exh. 9	Water Rec. 10
H_2			2.20	2.67	2.67	0.40				
CO			0.54	0.07	0.07	0.07				
CO_2			0.41	0.88	0.88	0.88			1.760	
CH_4			0.05	0.05	0.05	0.05				
H_2O		4.0	2.64	2.17	0.21	0.21			0.648	1.96
N_2								4.30	4.30	
O_2								1.00	0.136	
CH 1.88	1.0						.360			
Total, Lbs	13.88	72.0	85.88	85.88	50.60	46.06	5.00	152.4	203.5	35.28
Temp., °F	600	1600	1800	700	350	350	190	240	475	120

Design Basis

85% Cell H_2 Use
18600 btu/lb fuel (NHV)
52018 btu/lb H
4348 btu/lb CO
21758 btu/lb CH
95% fuel conversion
No thermal losses

Heat Exchanger Loads (btu/lb Reformed Fuel)	Sensible	Latent
A - Cell Waste Heat Input	-0-	
B - Product Gas Cooler	3930	
C - Product Gas Cooler	560	
D - Condenser Precooler	1150	
E - Product Gas Reheater	494	
F - Water Condenser	1535	2372
G - Fuel Vaporizer	283	207
H - Reformer Bed	6048	
I - Steam Supht'r	4585	

Figure 3-5b. State Point Conditions High Temperature Steam Reformer

The process operates on similar steam/carbon ratios to the conventional steam reformer, and produces similar gas quantities and concentrations at the fuel cell inlet. Hydrogen yield, however, is lower because more fuel is consumed in the reformer burner to maintain proper temperature for heat transfer into the reactor bed (see previous Table 3-2). Because of the higher operating temperatures, fuel cell waste heat cannot be utilized.

The key component in this process is the high temperature reformer, which may be subject to carbon deposition at these high operating temperatures. The most promising catalysts for high temperature steam reforming have been developed by Toyo Engineering and Tokyo Gas of Japan. Carbon deposition is minimized by using a nickel-free calcium oxide Toyo (T-12) catalyst at the reformer inlet, followed by a nickel Toyo catalyst (T-48) at the outlet. Although high catalyst volumes are needed in this process, this is the only reported commercial process capable of handling high sulfur fuels without carbon deposition. Maintaining acceptable levels of unreacted carbon (dry methane slip) leaving the reactor while utilizing reasonable catalyst volumes is a performance goal. This process has reportedly been tested in pilot plant runs on No. 2 fuel oil for up to 4000 hours without catalyst deterioration or pluggage. Shorter term testing was performed by Kinetic Technology International Corp., California, with reported similar carbon free performance. Additional testing is being performed.

If the Toyo catalysts prove durable and performance goals can be achieved, the high temperature steam reformer will offer multiple fuel capability, and overall plant performance efficiency similar to a conventional steam reformer. The disadvantages of using a HTSR for PAFC service compared to other options are:

- Higher Catalyst Volumes (and perhaps lower fuel conversion)
- Higher Cost Design for Reformer Tube Materials
- Longer Starting Times because of Higher Mass and Higher Operating Temperatures

3.2.3 AUTOTHERMAL REFORMING (Ref. 3-6, 3-7, 3-8)

Autothermal process conditions are depicted in Figure 3-6, a and b. This process operates at temperatures similar to a HTSR (1600-1800°F) with post desulfurization. Reforming heat is provided within the catalyst bed by insitu combustion of fuel and oxygen. Approximately 25-35 percent of the fuel is consumed in providing reaction heat. This results in a hydrogen yield after CO shifting of 0.28 lbs H/lb fuel used*. Sufficient energy is available in the product gases and combustion of spent fuel cell gas to heat reactants to incoming temperatures. Therefore, this proces does not require any additional fuel combustion, nor can it utilize fuel cell waste heat. Overall fuel cell plant efficiency with an ATR is projected to be lower than with an HTSR or a conventional steam reformer. This is a result of the less effective utilization of the heat of combustion of the unreacted hydrogen in the fuel cell exhaust.

Developmental work on this process is being carried out by United Technologies Corp. (UTC), Engelhard Industries (EI), and the Jet Propulsion Laboratories (JPL). Based on their work, this process appears capable of operating at steam/carbon ratios of 3.0, and air/carbon ratios of 1.8, and using commercial high temperature catalysts. Complete hydrocarbon conversion (methane slip) appears to be a potential problem with this process because of the reactor temperature profile. However, it is anticipated that proper reactor design and catalyst quantities can reduce this problem.

The key advantages of using an ATR are:

- Good Transient Response Capability
- Low Starting times

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*Note that the ATR and HTSR produce approximately the same amount of hydrogen per pound of fuel used. The difference is that all of the fuel is fed to the ATR reactor, while only 74% of the total fuel is sent to the HTSR, the remainder being burned in the reformer furnace.

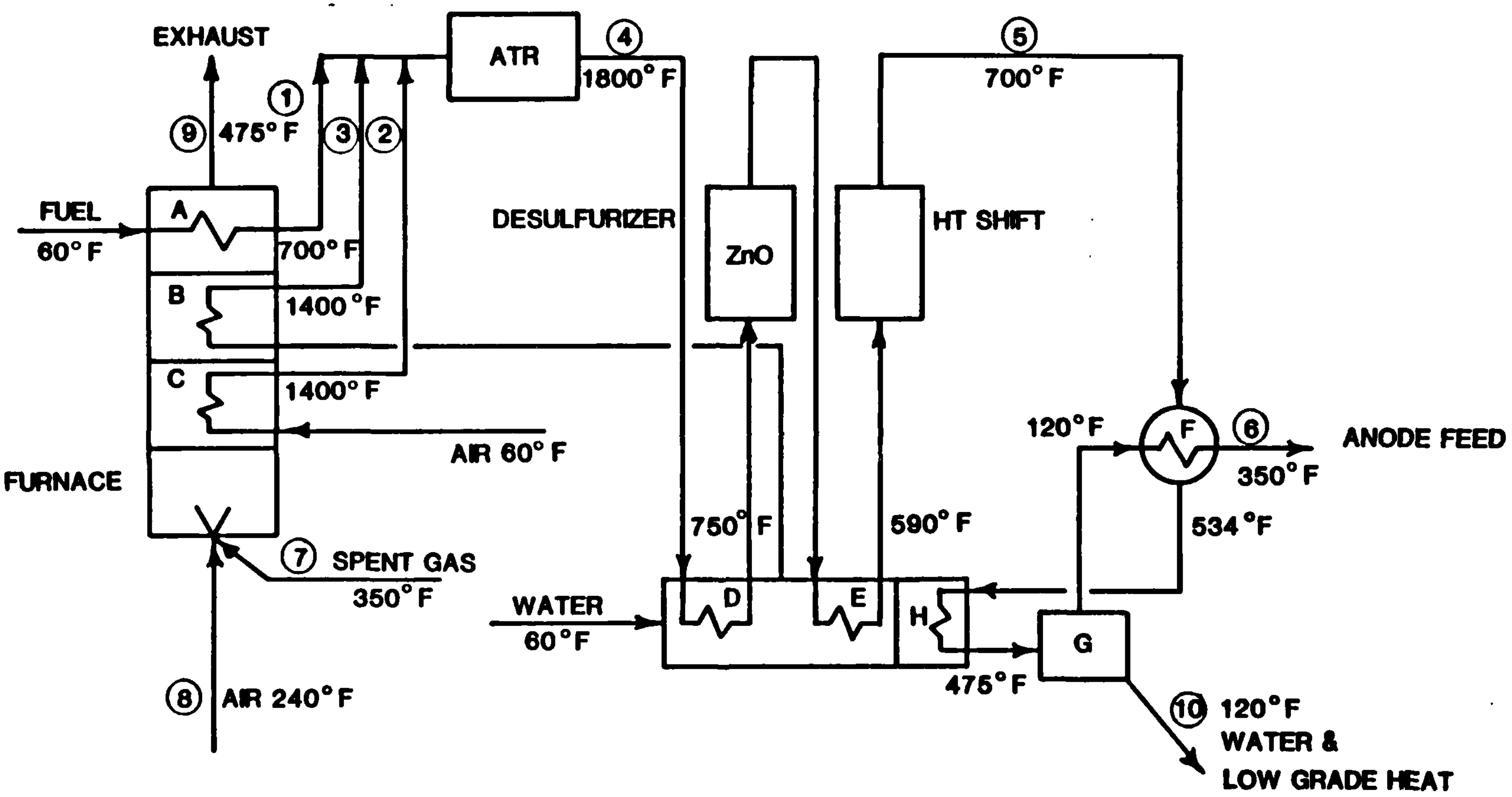

Figure 3-6a. Autothermal Reforming System (ATR)

Stream No. Lb moles	ATR Fuel 1	ATR Steam 2	ATR Exit 3	ATR Exit 4	Shift Exit 5	Anode Feed 6	Anode Exit 7	Comb. Air 8	Comb. Exh. 9	Water Rec. 10
H_2				1.560	1.92	1.92	0.288			
CO				.420	0.06	0.06	0.06			
CO_2				.530	0.89	0.89	0.89		1.00	
CH_4				.050	0.05	0.05	0.05			
H_2O			3.00	2.280	1.92	0.38	0.38		0.768	1.54
N_2		1.43		1.430	1.430	1.430	1.430	1.354	2.784	
O_2		0.38						.315	0.410	
CH 1.88	1.0									
Total, Lbs	13.88	52.20	54.00	120.08	120.08	92.36	89.09	48.00	137.09	27.72
Temp., °F	700	1400	1400	1800	700	350	350	240	475	120

Design Basis

85% Cell H Use
18600 btu/lb fuel (NHV)
52018 btu/lb H_2
4348 btu/lb CO
21758 btu/lb CH_4
95% fuel conversion
No thermal losses

Heat Exchanger Loads (btu/lb reformer fuel)	Sensible	Latent
A - Fuel Vaporizer	283	207
B - Steam Superheater	1685	
C - Air Heater	1280	
D - Gas Cooler	4198	
E - Gas Cooler	589	
F - Gas Reheater	597	
G - Water Condenser	1281	1865
H - Condenser Precooler	208	

Figure 3-6b. State Point Conditions Autothermal Reforming

- Simplier Reactor Design
- Multi-Fuel Capability

The disadvantage of using an ATR compared to other options is its somewhat lower hydrogen yield (see previous Table 3-2), potentially lower fuel cell voltage, and overall plant efficiency. Because hydrogen concentrations are lower in the fuel cell feed, cell voltage is lowered in comparison to STR and HTSR systems. To obtain similar power ratings a system using an ATR will probably consume 25 percent more fuel than a HTSR.

3.2.4 STR, HTSR, ATR QUALITATIVE COMPARISONS

The three reforming options can be compared qualitatively as follows:

TABLE 3-3
QUALITATIVE COMPARISON OF REFORMING OPTIONS

	STR	HTSR	ATR
Fuel Capability	LF	F	F
Fuel Consumption	MF	F	LF
Effective Cell Voltage	F	F	LF
Thermal Response	F	LF	MF
Subsystem Starting	M	LF	MF
Subsystem Size & Weight	MF	F	LF
Subsystem Cost	MF	LF	F
Maintenance Cost	MF	F	F
Life Cycle Cost	MF	F	LF
MF - Most Favored (10 points each)	50	0	20
F - Favorable (5 points each)	15	30	15
LF - Least Favored (1 point each)	1	3	4
Total Points	66	33	39

Clearly a STR system is preferable to either a HTSR or ATR fuel system if these comparisons are made without regard to application. However, if a constraint is added that the systems must be able to use either diesel fuel or both jet and diesel fuel, then the STR system must be eliminated from consideration for small power plants. The STR system cannot handle a diesel fuel without a very complex and high pressure desulfurization subsystem. The comparison then has to be between HTSR and ATR fuel systems. The strong points of the HTSR system relative to an ATR system are: fuel consumption, effective cell voltage, subsystem size and weight, maintenance costs and life cycle costs. The strong points of the ATR system are thermal response, starting time and lower subsystem cost.

The qualitative comparison then becomes:

TABLE 3-4

HTSR, ATR QUALITATIVE COMPARISON

	HTSR	ATR
Fuel Capacity	F	F
Fuel Consumption	MF	LF
Effective Cell Voltage	MF	LF
Thermal Response	LF	MF
Subsystem Starting	LF	MF
Subsystem Size and Weight	MF	LF
Subsystem Cost	LF	MF
Maintenance Cost	F	F
Life Cycle Cost	MF	LF
MF - Most Favored (10 points each)	40	30
F - Favorable (5 points each)	10	10
LF - Least Favored (1 point each)	3	4
Total Points	53	44

On the basis of this Table 3-4 comparison, a HTSR fuel system will be favored over an ATR system for the most applications required in diesel fuel or multi-fuel capability. Exceptions might be where the importance of starting or thermal response outweigh the importance of fuel consumption or life cycle cost. In these cases, "weighting factors" would have to be added to arrive at a semi-quantitative comparison. For certain applications (e.g. tactical mobile), the HTSR might be ruled out solely based on its inability to meet certain mandatory application requirements, such as size, weight, or transient response.

3.3 POWER CONDITIONING

The 23 kW methanol/ethanol FCPU's deliver 120V ± 5 percent DC power. As these units operate at atmospheric pressure there is a wide swing in cell voltage output with load (see preceeding Figure 3-3). DC to DC power conditioning is required to maintain output voltage within acceptable limits. The power conditioners conceived for the 23 kW DC units of this study are scaled-up versions of those of the ERC 3 kW-5 kW portable units.

The four logistic fuel units of the study deliver AC power. Obviously, since the fuel cells produce DC power, considerable power conditioning is required. Westinghouse is in the process of developing a family of multi-kilowatt DC to AC converters to be used with solar photovoltaic arrays. These solar photovoltaic DC to AC converters have the basic characteristics required for logistic FCPU use such as:

- they produce high quality (less than 5 percent harmonic distortion) 3-phase AC efficiently;
- they are self-starting, self controlling and self protecting.
- they can be used either "stand-alone" or in multiunit paralleling.

However, the units cannot be used "off-the-shelf" with the logistic FCPU's. This is partly because the control logic for use with a solar array is different from that required for fuel cells and partly because the power conditioning units are designed to meet commercial environmental standards and size and weight (which are less stringent than miulitary requirements). Hence, development effort will be required to modify the solar array units to logistic FCPU's needs. However, the solar array units represent an advanced starting point.

An example of the Westinghouse power conditioning units for photovoltaic applications is the AVI 503-A. A picture of this unit with control cabinet covering stripped away is shown in Figure 3-7. Some of the parameters of the AVI 503-A are as follows:

• KVA	50 Continuous, 100 for 5 Seconds
• Output	60 Hz, 3-Phase, 4-Wire, 120/208 Volts
• Harmonic Distortion	Less than 5 Percent
• Efficiency	At 0.9 Power Factor: Under 5% Load, 64% Under 25% Load, 86% Under 100% Load, 91%
• Output Protection	Over Voltage Under Voltage Over Current Abnormal Frequency
• Input	200-300 Volts DC (Up to 350 volts DC with slight deviations to specifications)
• Environment	Ambient Temperature: -10 to +45 Celsius Relative Humidity: 96% (non-condensing) Barometric Pressure: 790-520mm Hg
• Weight (lbs)	1,830
• Size	24 Inch Standard Rack on 4 Inch Casters 28.3 Inches Wide, 30.3 Inches Deep 91.0 Inches High Including Casters
• Additional Information	Solar Photovoltaic Array Peak Power Tracking Load Shed Signal on Overload Battery Charger Control Signal Automatic Startup and Utility Grid Paralleling

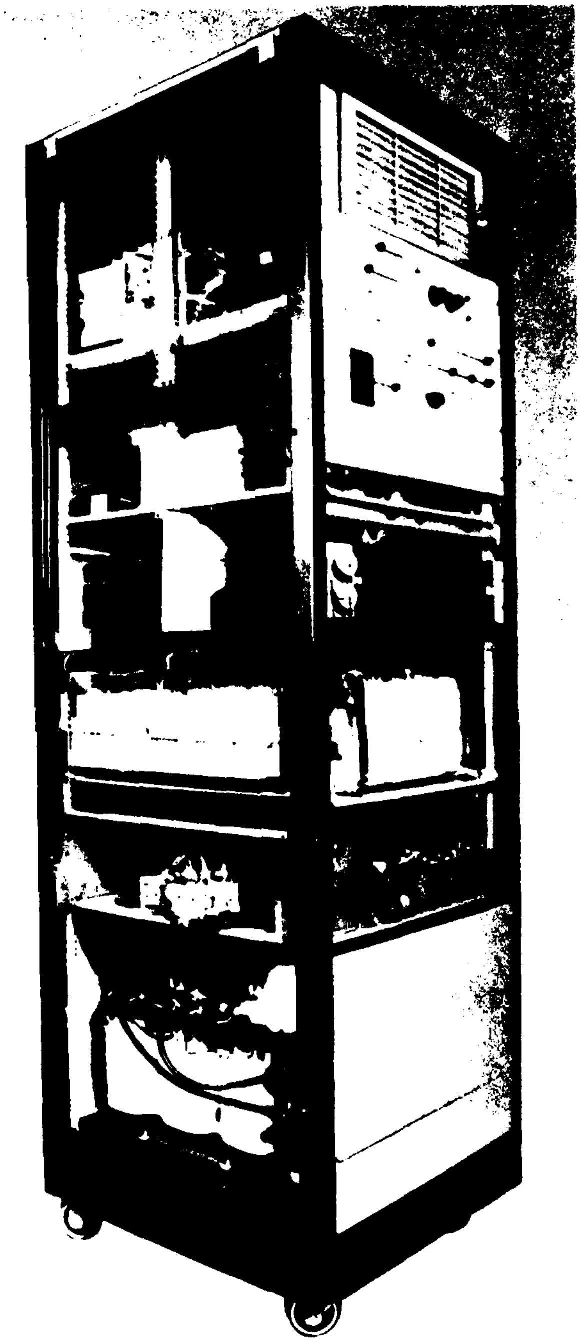

Figure 3-7. Westinghouse AVI 503-A Power Conditioner

4.0 SMALL RES* UNATTENDED REMOTE POWER SYSTEMS

4.1 INTRODUCTION

An application analysis, preliminary conceptual design, development risk assessment and Life Cycle Cost (LCC) analysis has been carried out. The applications studied are two of the six generic applications specified for analysis under the U. S. Air Force Fuel Cell Application Analysis program, Contract F 33615-80-C-2038.

The specific application selected by the Air Force was that of providing the base load electrical power required by a MX missile shelter using either methanol (wood alcohol) or ethanol (grain alcohol) as the power plant fuel. Both fuels are classed as RES* fuels. This application requires a nominal electric power output of 15 kWe, with a peak power of 23 kWe, at 120V dc. There is no requirement for use of the waste heat from the electrical generation power plant. A preliminary conceptual design of phosphoric acid fuel cell (PAFC) systems that fulfills the operational requirements of an electrical power plant to service such as a MX missile shelter has been created. Some of the major features of the design are as follows:

- Fully automated operation and control for remote, unattended operation
- Current state-of-art component technology
- Single integrated skid-mounted all-weather package to minimize installation costs
- Heat rate less than 9,000 Btu/kW-hr

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*Renewable Energy Source

- Uses RES fuels (methanol, ethanol)
- Operates at ambient air pressure and is air cooled. This minimizes system complexity and increases reliability.

A more complete summary of the two 15 kWe nominal output power fuel cell system characteristics is given in Table 4-1 and Table 4-2.

A technical development risk analysis of the preliminary conceptual designs was carried out. Because the designs use current state-of-art component technology, no technology breakthroughs are required to achieve operational hardware. However, a program to develop the fuel reformers and to provide fully qualified power plants for such as the MX shelter power application will be required.

The last items in Tables 4-1 and 4-2 are dollar values for Life Cycle Costs (LCC) for individual Fuel Cell Power Units (FCPU). The largest uncertainty in these values is the cost of the fuel.

Methanol is now generally made from natural gas but can be made from coal. This is a cheaper resource than natural gas.

Ethanol is now made by the centuries old process of fermenting food and distilling the result. It can be made from much less expensive feed stocks, such as cellulose waste, and more efficiently. There is reason to believe that if there were sufficient emphasis placed on using 190 proof alcohols as fuel, their price would be similar to that of other combustible fuels. This is not true at present.

In this study it is assumed that the future price of 190 proof alcohol will be competitive with that of other fuels. Future generic fuel price projections of the EPRI Utility Fuel Cell Users Group have been used. The 1990 fuel price range of the Fuel Cell Users Group is \$7 to \$10 per million Btu's. Table 4-1 and 4-2 cost values were calculated using $\$7/10^6$ Btu. If a value of $\$10/10^6$ Btu is used, the LCC's increase about 17 percent.

TABLE 4-1

FUEL CELL POWER UNIT PARAMETERS FOR UNATTENDED REMOTE UNIT - ETHANOL FUELED

1. PHYSICAL PARAMETERS

   a) Type of Fuel: Ethanol

   Composition - C_2H_5OH - 95.6% (by volume)
   Higher Alcohols - Trace
   Water - 4.4%

   b) Fuel Consumption: 13,470 gallons per year

   c) Volume/Size: Volume: 105 ft^3
   Size: 19 ft^2

   d) Weight: 1,500 lbs

   e) Environmental Constraint:

   Thermal Discharge - 80,000 Btu/hr

   Air Pollution - NO_x <0.24 lbs/MWh generated
   Others: SO_2, CO, etc. - nil.

   Noise - <70 db @ 25 ft. (Specified)

   Solid Waste - None

   Chemical Discharge - Trace H_3PO_4

   Radioactive Wastes - None

2. PERFORMANCE PARAMETERS

   a) Reliability:

   Mean Time Between Failures - 3,690 hours (calculated)

   Availability - >99.9% required

   b) Lifetime: 12.5 years required (20-30 years capability)

   c) Operation and Maintenance:

   Ease of Operation: Unattended

   Ease of Maintenance: Trouble shooting, component replacement and checkout.

   Maintenance Skills Required: E-4 or civilian equivalent.

TABLE 4-1 (Continued)

d) Growth Potential: Major elements are of modular construction. Growth potential without size increase is low. Growth potential with size increase is large.

e) Start-up/Shutdown Time:

Start-up - One hour
Shutdown to Hot Standby - <15 minutes
Cold Shutdown - Two hours

f) Thermal Energy Available: No thermal energy requirement identified. Could provide about 50,000 Btu/hr above 200°F.

g) Electrical Output: 15 kW average, 23 kW maximum, four to five maximums per year for up to eight hours per each.

Voltage - 120V DC
Voltage Regulation - 3%
Voltage Ripple - <5.5%

3. COST PARAMETERS (1980 $)

a) Capital Costs:

Fuel Cell Power Unit - $56,100 (1000 unit production run)

Fuel Tanks and Lines - $11,600

Site Preparation - $500

Installation and Other Costs - $1,200

TOTAL - $69,400

b) Maintenance Cost:

Transportation for Repair - $60/yr

Personnel Cost - $580/yr civilian personnel @ $42,000 per year

Special Equipment Cost - $26/yr

Replacement Hardware Costs - $4,700/yr

TOTAL - ∿$5,400/yr

c) Operation Costs:

Fuel and Fuel Transportation Costs - $8,000/yr (@ $7/10^6 Btu)

Supplies - $6/yr

Operating Personnel Costs - None

d) Life Cycle Cost: $258,700, 12.5 years, $7/10^6 Btu Fuel Cost

TABLE 4-2

FUEL CELL POWER UNIT PARAMETERS
FOR UNATTENDED REMOTE UNIT - METHANOL FUELED

1. PHYSICAL PARAMETERS

   a) Type of Fuel: Methanol

   Composition - CH_3OH - 96% (by volume)
   Higher Alcohols - 1.5%
   Water - 2.5%

   b) Fuel Consumption: 18,800 gallons per year

   c) Volume/Size: Volume: 97 ft^3
   Size: 17 ft^2

   d) Weight: 1,430 lbs

   e) Environmental Constraint:

   Thermal Discharge - 126,500 Btu/hr max, 78,800 Btu/hr aver.

   Air Pollution - NO_x <0.24 lbs/MWh generated
   Others: SO_2, CO, etc. - nil.

   Noise - <70 db @ 25 ft.

   Solid Waste - None

   Chemical Discharge - Trace H_3PO_4

   Radioactive Wastes - None

2. PERFORMANCE PARAMETERS

   a) Reliability:

   Mean Time Between Failures - 3,770 hours (calculated)

   Availability - >99.9% required

   b) Lifetime: 12.5 years required (20-30 years capability)

   c) Operation and Maintenance:

   Ease of Operation: Unattended

   Ease of Maintenance: Trouble shooting, component replacement and checkout.

   Maintenance Skills Required: E-4 or civilian equivalent.

TABLE 4-2 (Continued)

d) Growth Potential: Major elements are of modular construction. Growth potential without size increase is low. Growth potential with size increase is large.

e) Start-up/Shutdown Time:

Start-up - One hour

Shutdown to Hot Standby - <15 minutes

Cold Shutdown - Two hours

f) Thermal Energy Available: Application does not require thermal energy. Could provide about 54,000 Btu/hr above 200°F.

g) Electrical Output: 15 kW average, 23 kW maximum, four to five maximums per year for up to eight hours per each.

Voltage - 120V DC

Voltage Regulation - 3%

Voltage Ripple - <5.5%

3. COST PARAMETERS

a) Capital Costs:

Fuel Cell Power Unit - $53,400 (1,000 unit production run)

Fuel Tanks and Lines - $12,500

Site Preparation - $500

Installation and Other Costs - $1,200

TOTAL - $67,600

b) Maintenance Cost:

Transportation for Repair - $60/yr

Personnel Cost - $580/yr civilian personnel @ $42,000 per year

Special Equipment Cost - $26/yr

Replacement Hardware Costs - $4,500/yr

TOTAL - ∿$5,000/yr

c) Operation Costs:

Fuel and Fuel Transportation Costs - $8,000/yr (@ $7/$10^6$ Btu)

Supplies - $6/yr

Operating Personnel Costs - None

d) Life Cycle Cost: $258,800, 12.5 years, Fuel at $7/$10^6$ Btu

An artist's concept of a small stationary unattended 23 kW RES fueled unit is shown in Figure 4-1. The ethanol fueled unit will be about five percent larger and heavier than the methanol unit. The ethanol fueled unit will be about five percent more fuel efficient than the methanol unit. The LCC's of the two units are the same within the accuracy of the estimates. The ethanol unit will probably be able to utilize methanol without major performance impact. The methanol unit, however, will probably not be able to utilize ethanol.

The results of the MX application analysis, the preliminary conceptual design descriptions, the development risk assessments of the designs, as applied, and the Life Cycle Costing are covered in the following sections:

Section 4.2 - MX Application Fuel Cell System Requirements and Constraints
Section 4.3 - Power Plant Designs
Section 4.4 - Development Risk Assessments
Section 4.5 - Life Cycle Costs

4.2 MX APPLICATION FUEL CELL SYSTEM REQUIREMENTS AND CONSTRAINTS

The nature of this application is to provide on-site electric power to the Resident Operational Support Equipment (ROSE) of each individual MX missile system shelter. Currently, the baseline system for providing the ROSE shelter power is a utility power grid with back-up on-site diesel engine generators at each cluster of shelters. With a utility grid power supply, all 4600 shelters of the MX system are electrically interconnected. The electro-magnetic pulse (EMP) from a single nuclear bomb can travel over the entire grid because of the electrical interconnection. Such an EMP could, potentially, critically damage the electrical equipment in many shelters; thus defeating the purpose of having many disperse shelters.

Studies of a solution to the EMP problem have included on-site power generation using diesel engine generators. This diesel solution has been ruled out

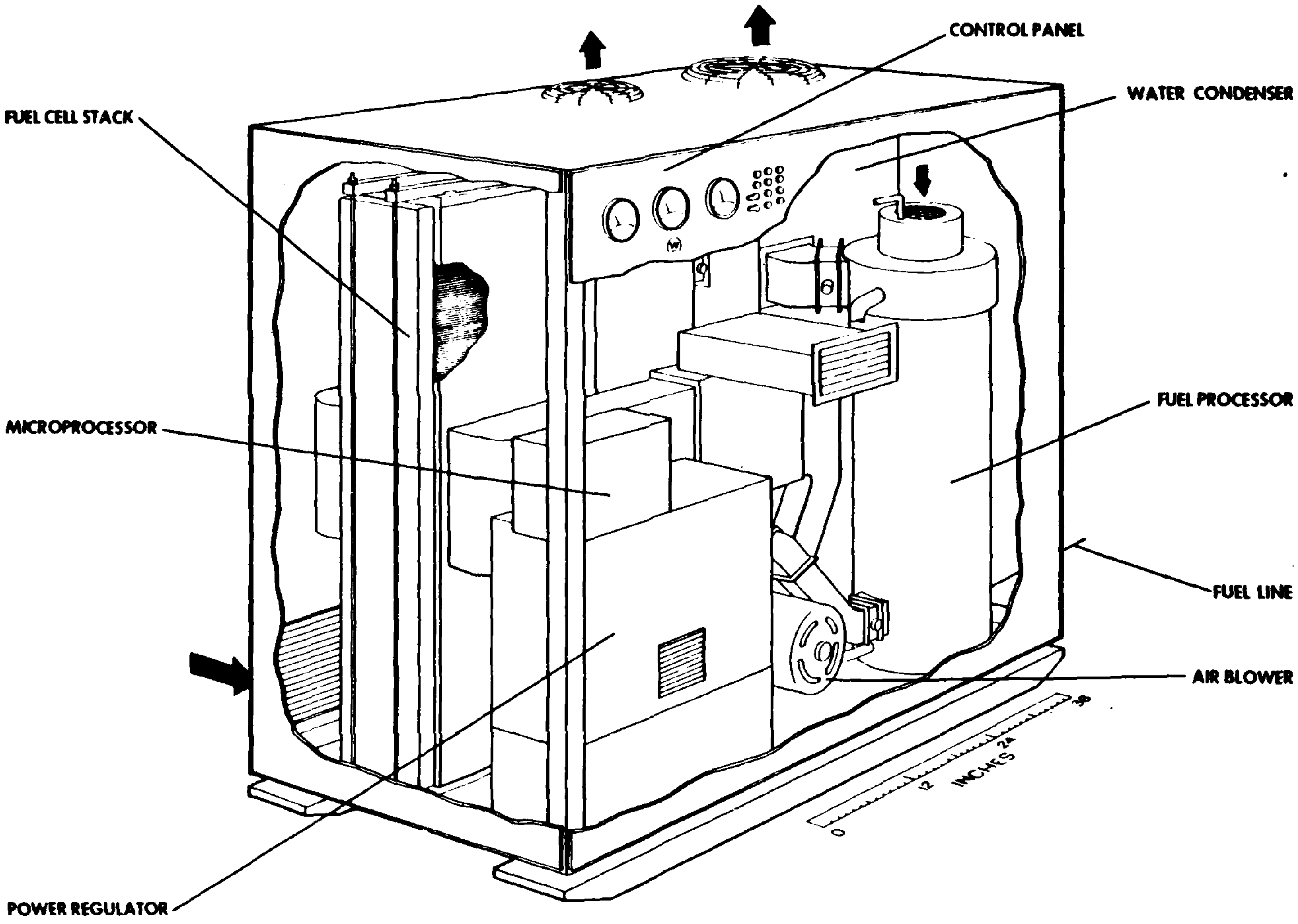

Figure 4-1. 23 kW Remote Unattended FCPU - RES Fuels

because of its high life cycle costs (primarily fuel costs) and high maintenance requirements (Ref. 4-1*).

The use of phosphoric acid fuel cell (PAFC) power systems to generate on-site MX shelter power through the use of fuel cell power units (FCPU) will result in both lower fuel costs and maintenance requirements compared to diesel engine generators.

4.2.1 GENERAL DESCRIPTION OF MX APPLICATION

4.2.1.1 MX SYSTEM DESCRIPTION (Ref. 4-2)

General

The 200 missiles are the heart of the MX System, with each missile located in a linear cluster of 23 shelters. The system survivability is assured by dispersal and a secure basing mode. Dispersal is achieved by deploying the system throughout a large number of valleys over a wide geographic area.

Secure basing is achieved by the ability to rapidly relocate the missile at anytime between the 23 shelters in the cluster and the uncertainty of which shelter houses the missile. The shelters and clusters are supported by a number of support facilities. Two hundred clusters are planned, each containing 23 shelters, for a total of 4600 individual shelters. A conceptual sketch of the shelters and conceptual layout of the clusters is shown in Figure 4-2.

Shelters

Shelters will be constructed of reinforced concrete and covered by a soil overburden. Any one of 23 shelters in a cluster may contain the missile. To preserve missile location uncertainty, each shelter will be powered to the same degree, with dummy loads imposed in "empty" shelters. Each shelter site will cover approximately two and one-half acres enclosed by a stock fence. A

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*References may be found in Appendix A-2

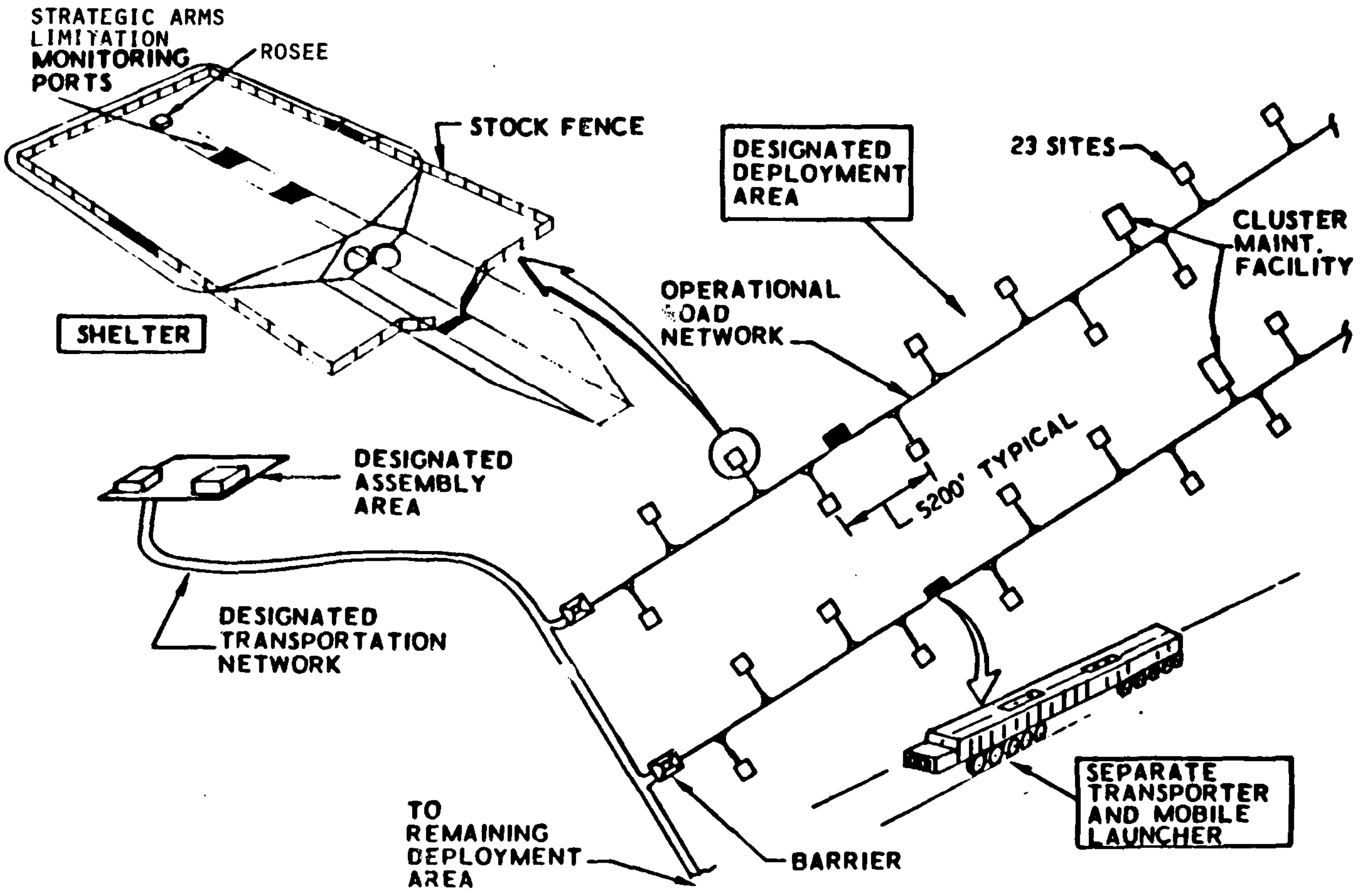
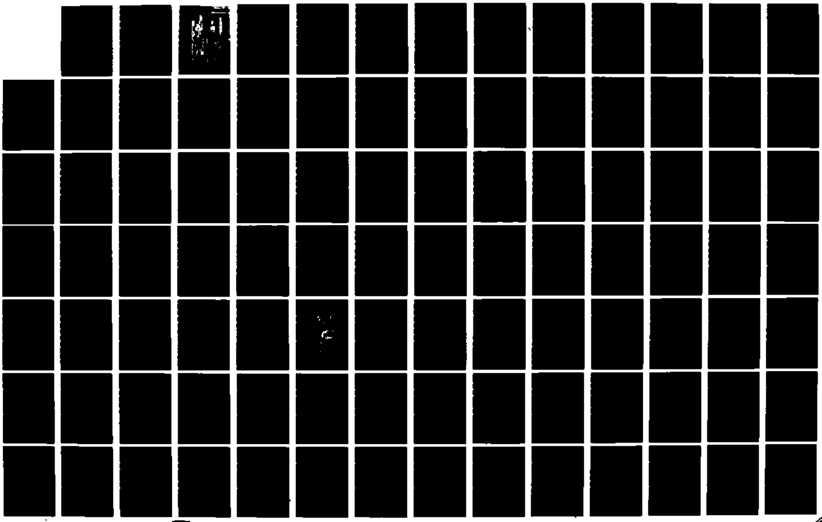
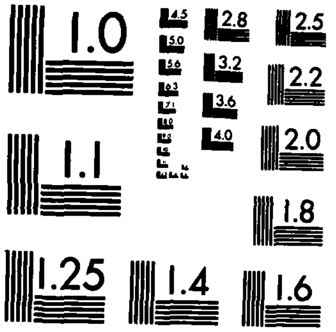


Figure 4-2. Shelter/Cluster Conceptual Layout

AD-A126 121 U S (UNITED STATES) AIR FORCE FUEL CELL APPLICATION 2/5
ANALYSIS..(U) WESTINGHOUSE ELECTRIC CORP PITTSBURGH PA
ADVANCED ENERGY SYST.. W D POUCHOT ET AL. JAN 82
UNCLASSIFIED WAESD-TIME-3134 AFWAL-TR-82-2004 F/G 10/2 NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Resident Operational Support Equipment Enclosure (ROSEE) will be situated at each shelter site.

Clusters

Clusters will be geographically dispersed in valleys throughout the deployment area. Each of the 200 clusters will consist of 23 shelters, interconnected by a roadway. Clusters will also be interconnected by a road network, providing access to the Designated Assembly Area (DAA).

The shelters and clusters are supported by a number of operating bases and surveillance, security, maintenance and assembly facilities.

4.2.1.2 MX BASELINE POWER SYSTEM CONCEPT

The MX Baseline Power System (BPS) is being designed as a conventional grid system, served from commercial power sources.

General

The BPS concept layout shown in Figure 4-3 is being designed as a conventional transmission grid which distributes power from the source to all MX system elements. For reliability, the BPS will obtain power at two or more utility switching stations, located at geographically dispersed points. Definition of the acronym's used in Figure 4-3 may be found in Appendix D-1.

BPS reliability will be further enhanced by standby diesel generators at each distribution center. These standby diesel generators, which will have at least 30 days operational capability, will be activated by the Supervisory Control and Data Acquistion (SCADA) system. A shelter emergency internal power system will be capable of providing uninterrupted power for two hours at a reduced survival level.

Availability Estimate

On the basis of at least two commercial utility interfaces and the generators at the distribution centers, power availability at the shelters and clusters

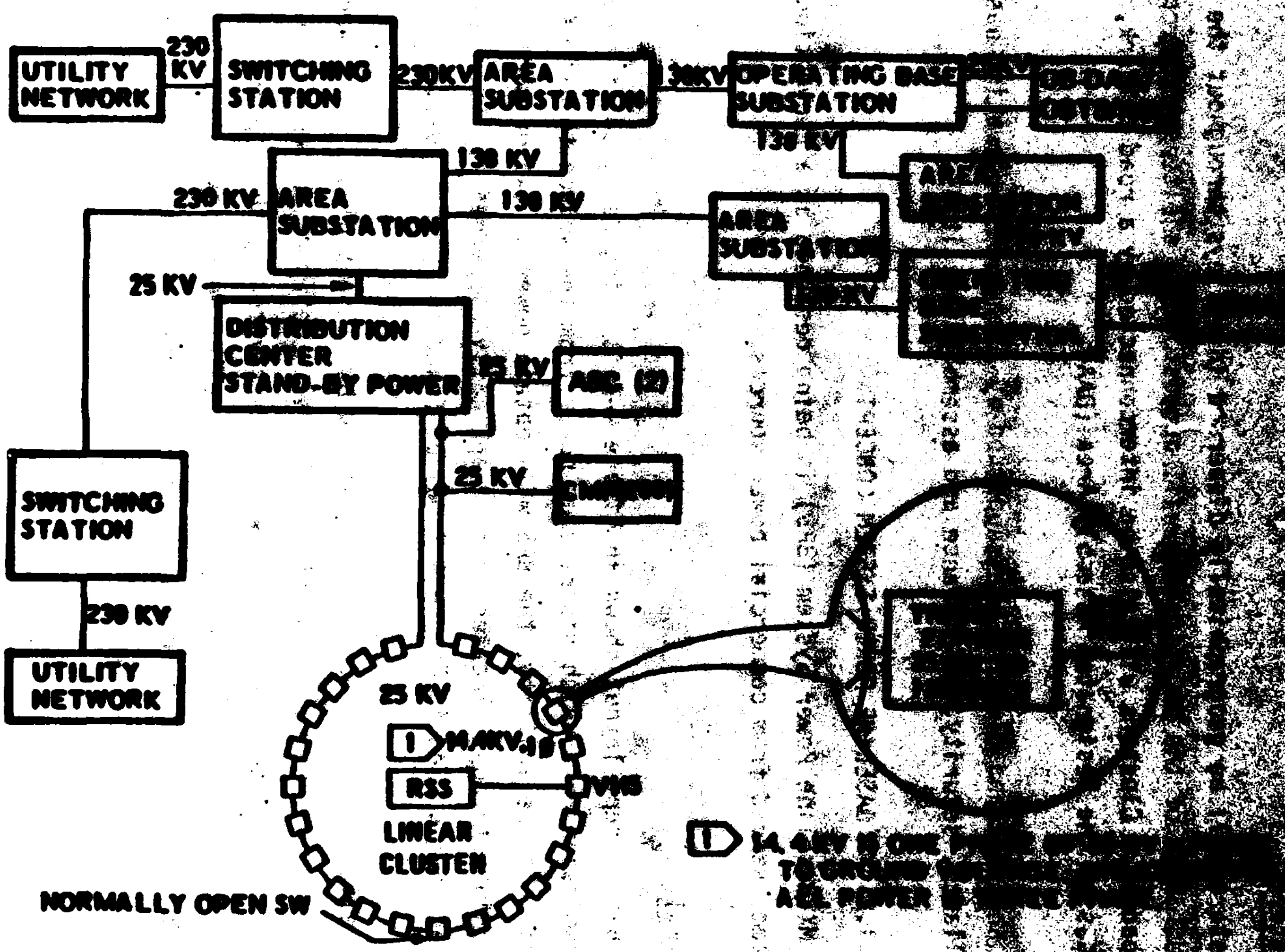


Figure 4-3. Baseline Power System (BPS) Concept

(including RSS's, but excluding the Cluster Maintenance Facilities (CMFS)), is estimated at 0.999. Availability is defined as the ratio of the time power of acceptable quality is available to the time it is required, which in the case of MX is continuous.

The BPS will furnish normal commercial and standby diesel power for MX pre-attack modes. MX post-attack power to critical mission loads will be furnished by a separate survival power source carried on the Launcher.

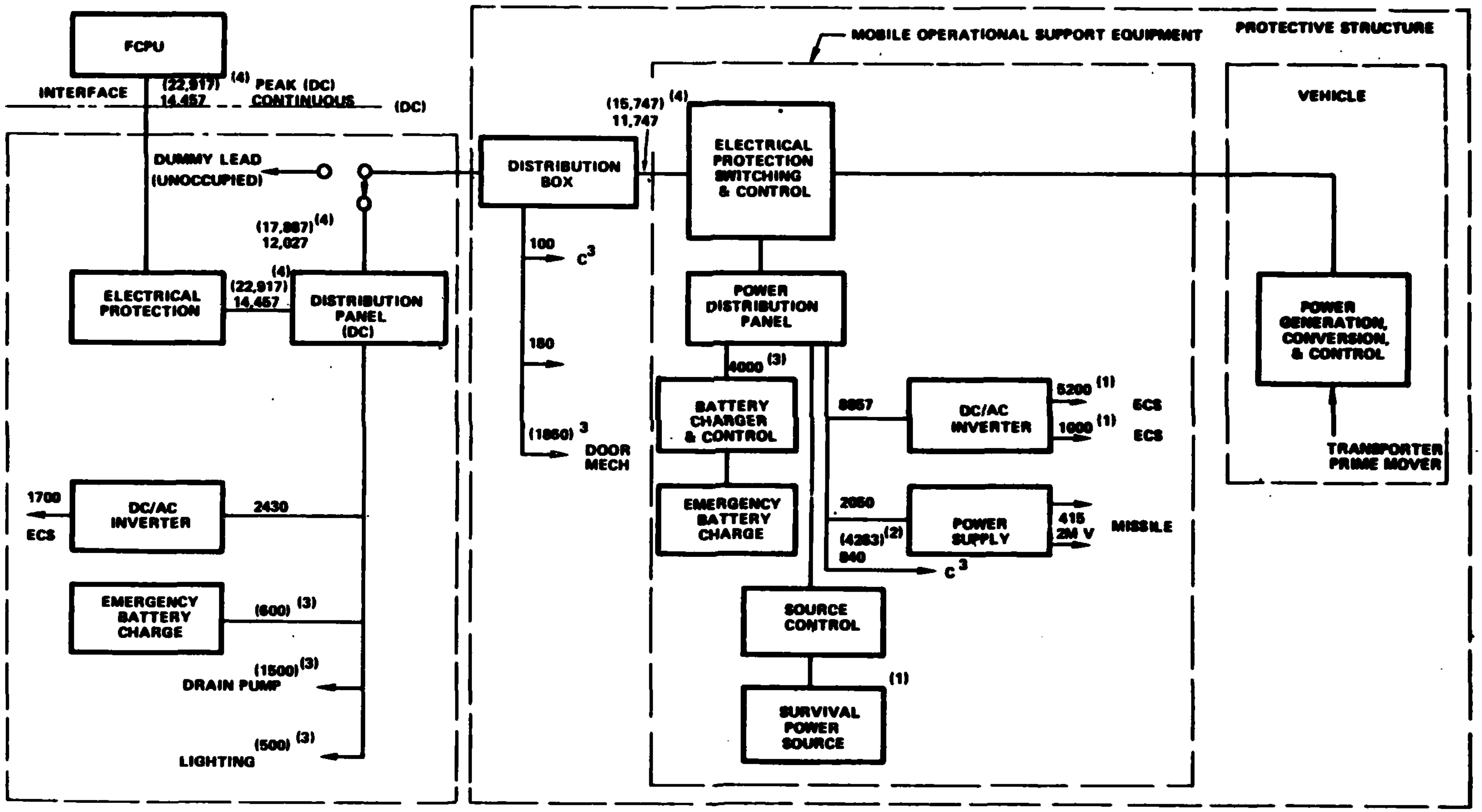
4.2.1.3 INDIVIDUAL MX SHELTER DC POWER REQUIREMENTS

For all systems described hereafter, the loads given do not include losses associated with systems control and maintenance, as well as transmission, distribution and conditioning losses from the power plant(s) to the user interfaces. These losses must be accounted for in the power plant design.

The projected shelter power loads and power levels associated with DC supply are shown schematically in Figure 4-4. The fuel cell power unit (FCPU) needs to provide regulated 120 ±5 percent VDC electrical power of 14.5 kW (23.0 kW peak) to each shelter interface. The distribution of the FCPU power to various shelter functions is shown as steady and/or noncontinuous quantities as indicated.

Throughout most of the year the shelter load demand has a steady state value of 14.5 kW dc with an additional peak of 1.0 kW for 10 seconds every five minutes. The most severe shelter load transient has a peak power of 23.0 kW and a duration of 48 hours before reverting to the steady state load. This transient is expected to occur randomly, but only once a year per shelter, and its primary feature is an eight hour charge of the Mobile Operational Support Equipment (MOSE) emergency battery at the 4.0 kW level and a 0.6 kW charge of the Resident Operational Support Equipment (ROSE) emergency battery for four hours.

Random but possibly simultaneous functions including operation of the ROSE sump pump (48 hours) and lighting (12 hours). These pump and lighting variations may cause two kW swings in power demand for time periods as low as ten



(1) POWER FOR EMERGENCY AND SURVIVAL PERIODS NOT SHOWN.
(2) C^3 PEAK POWER SUPPLIED BY BATTERY.
(3) INDIVIDUAL NONCONTINUOUS LOADS SHOWN IN ( ), OTHERWISE LOADS ARE AVERAGE VALUES.
(4) NONCONTINUOUS AND STEADY (AVERAGE) LOADS COMBINED.
(5) ALL LOADS EXPRESSED IN WATTS.

Figure 4-4. MX-FCPU Shelter Power Block Diagram seconds. Four additional transients to peak loads of 23.0 kW are expected to occur randomly throughout the year for durations of one hour or less.

4.2.2 MX SHELTER POWER APPLICATIONS AND REQUIREMENTS DATA SHEETS

To summarize investigations into the requirements for individual units to provide MX shelter prime power, two documents have been prepared. They are:

- Applications Data Sheet - W - ADS - 1/6
- Requirements Data Sheet - W - RDS - 1/6

The two documents set forth the primary requirements and design considerations for the MX shelter prime power application. The Applications Data Sheet (ADS) is specifically directed at the MX application. The requirements data sheet is broader in scope and sets forth operating and performance characteristics and performance requirements for 23 kW fuel cell power units. The Applications Data Sheet is given in Appendix C-1A. The Requirements Data Sheet is given in Appendix C-1B.

The reasons for this duality of documents is the result of circumstances. The primary source of information on the MX shelter power system requirements was the U. S. Air Force Ballistic Missile Office (BMO). However, BMO has been concerned, primarily, with the utility grid baseline system. As such, BMO was thoroughly familiar with detail requirements for the utility grid system, but was not in a position to provide, readily, detail requirements for a small independent power source for MX service. BMO could provide information on the magnitude and nature of the various MX shelter loads. This information was obtained from BMO documents supplemented by private communications with BMO personnel.

For design purposes, the BMO information needed to be translated into a detail set of FCPU requirements. The translation method selected was to first create a generic spec (W-RDS-1/6) for a 23 kW FCPU based on military specifications for small diesel and gas turbine electric power units to service loads similar to that of a MX shelter. Specification W-RDS-1/6 was then modified to provide a fit to the specific MX application as W-ADS-1/6.

4.3 POWER PLANT DESIGN

4.3.1 INTRODUCTION

General requirements of a Fuel Cell Power Unit (FCPU) to provide MX shelter power are:

- FCPU sized and configured to satisfy the electric power requirements of an individual MX shelter
- Remote unattended operation of the unit
- A minimum of 99.9 percent electric power availability to the individual shelter without electrical interconnections between individual power units. This is to minimize nuclear bomb electro-magnetic pulse (EMP) effects.
- A design of FCPU that can be developed for quantity (4600 units) and quality delivery in a 1986-1989 time frame
- Minimization of FCPU capital, operation and maintenance costs while satisfying the other requirements

These characteristics can best be met by a simple design that employs proven fuel cell design concepts.

The designs chosen were based on a thorough evaluation of various fuel cell options. Tradeoff studies were conducted to arrive at preferred design arrangements. The major subsystems and overall process options are described in Section 4.3.2. System aspects, such as operation and control, size and weight, etc., are discussed in Section 4.3.3. Power plant usage concepts and considerations, such as the logistics of fuel supply and maintenance, and overall power system availability, are presented in Section 4.3.4.

4.3.2 PROCESS OPTIONS AND MAJOR SUBSYSTEM DESCRIPTIONS

Several options were considered for each of the following FCPU major subsystems:

- Fuel Processing
- Fuel Cells
- Power Conditioning
- Balance-of-Plant

The options that were selected and the proposed FCPU designs are described hereafter, along with a FCPU performance and major subsystem design parameters.

4.3.2.1 SYSTEM OPTIONS AND COMPONENTS

The key desired characteristics for an application such as a MX Shelter Power Plant are high reliability, low fuel consumption, and low capital cost balanced against other needs. The PAFC concept most favored for meeting these characteristics is an unpressurized, air cooled PAFC design, similar to designs under development for U. S. Army portable electric power.

The RES fuels selected are methanol and ethanol. Fuel processing of ethanol into a form suitable for fuel cell subsystem use is more difficult than with methanol. Ethanol reforming is done at higher temperatures and requires more steam than methanol. The process designs of the two units are nearly identical except for the fuel reforming operations. It is informed opinion than an ethanol fuel processing system will process methanol, satisfactorily. The reverse situation is not promising.

Atmospheric air cooled design is recommended for a MX shelter power type unit. Neither pressurized operation or water cooling is expected to offer a design advantage and would result in a power unit with higher initial cost and lower system reliability. Pressurized cell operation could be used to reduce stack size or improve cell voltage and system efficiency. Since power unit size is not a major constraint and the proposed designs are capable of heat rates below 9000 Btu/kW, there is little incentive for proposing pressurized operation. Pressurized design will increase stack cost and add additional components to the system. More importantly, these components will decrease the ability to meet the high reliability goals established for the application.

A water-cooled fuel cell design offers some advantages to the MX power unit, but has not been recommended for this application. In the MX power unit, the size of system heat exchangers, air ducting, and blower size and auxiliary power requirements could be decreased. However, it is doubtful that the marginal capital and operating dollars savings that would result would be enough to offset the increased stack cost for water-cooled design. To provide adequate cell cooling and avoid hot spots, a large number of small diameter tubes must be uniformly distributed throughout the stack and connected to a common supply and return manifold. To prevent localized chilling, the system is normally pressurized to maintain water temperature below the boiling point but close to cell operating temperature. Each of these tubes are therefore operating under pressure, in an environment where stack acid leakage may occur. The cost and reliability of this design is considered less favorable than an air cooled design.

4.3.2.2 POWER PLANT PROCESS DESIGN DESCRIPTION

A conceptual schematic identifying the major process components in the methanol unit is shown in Figure 4-5. Mass flow rates, temperatures, and heat exchanger loads at 23 kW peak output are listed in Table 4-3.

The system operates on a proportioned mixture of fuel and water (58 percent wt. methanol, 42 percent wt. water). To minimize overall system fuel consumption, the amount of water used in the reforming process should be minimized commensurate with satisfactory operation of the reformer. Energy Research Corporation experience with methanol reformers is that the minimum ratio of methanol to water that can be used satisfactorily is the 58 percent wt. to 42 percent wt. selected.

Vaporization of the mixture takes place in a liquid/air heat exchanger situated in the fuel cell air cooling loop. The vaporized fuel is superheated to approximately 600°F and steam reformed into a 70 percent vol. hydrogen gas within a single unit. Endothermic reforming heat is provided by combustion of unused hydrogen exiting the fuel cell anode. With fuel vaporization located outside the reformer, there is sufficient energy in the anode waste gas to

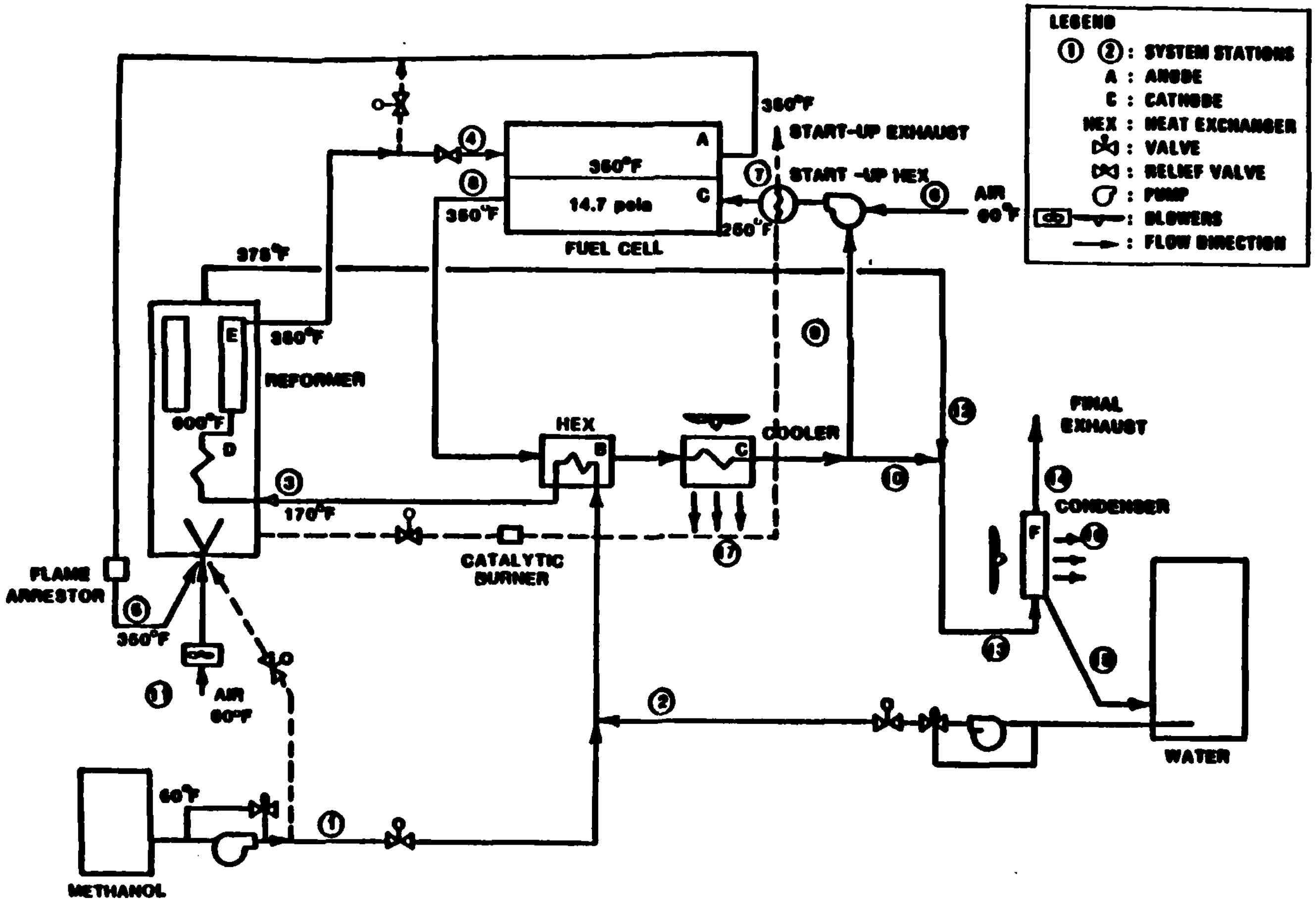


Figure 4-5. Schematic Arrangement of Methanol Fuel Cell Power Unit

TABLE 4-3

STATE POINTS - 23 kW METHANOL - FUELED FCPU
Flow Rate - (lbs - moles/hr)

Stream No.	Description	H_2	CO	CO_2	H_2O	N_2	O_2	C_3HOH	Total (Lbs/Hr)	Temp. ^oF
1	Fuel Supply							0.659	21.00	60
2	Water Supply				0.857				15.43	60
3	Reformer Feed				0.857			0.659	36.43	170
4	Reformer Exit/Anode Feed	1.965	0.013	0.646	0.211				36.43	350
5	Anode Exit	0.295	0.013	0.646	0.211				33.09	350
6	PAFC Make-Up Air					6.320	1.680		230.72	60
7	Stack Air Supply				21.890	89.160	12.690		3296.00	250
8	Stack Exit Air				23.560	89.160	11.350		3300.00	350
9	Recirculation Air				21.890	82.840	11.010		3066.00	268
10	PAFC Exhaust				1.670	6.320	0.840		233.9	268
11	Furnace Air					0.941	0.250		34.3	60
12	Furnace Exhaust			0.659	0.857	0.941	0.084		66.7	375
13	Combined Exhaust			0.659	2.175	7.261	0.924		301.0	300
14	System Exhaust			0.659	1.318	7.261	0.924		285.6	120
15	Recovered Water				0.857				15.4	120
16	Cooling Air					100.000	26.580		3650.0	100
17	Cooling Air					48.200	12.800		1760.0	160

Design Basis

60^oF, 0% RH
2.0 Cell Stoair
1.5 Combustion Stoair
85% Cell H_2 Utilization
9078 Btu/Lb Methanol (NHV)
4348 Btu/Lb CO
52,018 Btu/Lb H_2

Heat Exchanger Loads (Btu/Hr)

		Sensible	Latent	Area, Ft^2
A.	Fuel Cell	85,000	-	-
B.	Fuel Vaporizer	1,575	24,950	12.0
C.	Recirculation Heat Exchanger	42,900	-	30.0
D.	Fuel Superheater	7,070	-	1.5
E.	Reformer Bed	12,800	-	8.0
F.	Water Condenser	20,300	14,975	60.0

provide for all superheat and reforming heat requirements, based on a fuel cell operating at 85 percent hydrogen utilization.

The catalyst used in the reformer is a commercial copper - zinc oxide grade. It promotes both reforming and water-gas shift reactions, thereby limiting the amount of carbon monoxide in the product gas. Typical reformed gas concentration of 70 percent vol H_2, 23 percent vol CO_2, 6.5 percent vol H_2O, and less than 0.5 percent vol CO is obtained at equilibrium outlet temperatures near 350°F. No additional fuel conditioning is needed before entering the fuel cell.

Oxygen consumed in the fuel cell reaction with hydrogen is provided [illegible] makeup air supply. To enhance recovery of water from the cell exhaust air [illegible] makeup air should be limited to less than two times cell oxygen needs. Makeup [illegible] is combined with recycled air to provide a sufficient total air mass for [illegible] cooling while maintaining high inlet air temperatures necessary for good cell performance. Waste heat is removed from the cooling air loop via the fuel/steam vaporizer and an air/air heat exchanger.

Water is recovered from the process by combining both cell exhaust air and reformer combustion products and utilizing an air to air heat exchanger. Approximately 40 percent of the water in the system exhaust is recovered by cooling to 120°F. This provides all of the water required within the process (i.e. no fresh makeup water is required) up to an ambient temperature of about 110°F. For operation above 110°F excess condensate collected during the cooler portions of a day is stored in the condenser sump. This water is used to supplement the water supply during the hotter hours of a hot day.

A conceptual schematic identifying the major process components in the ethanol unit are shown in Figure 4-6. Mass flow rates, temperatures, and heat exchanger loads at 23 kW peak output are listed in Table 4-4.

The system operates on a proportioned mixture of ethanol and water which is steam reformed into a hydrogen rich gas. Although there is little ethanol reforming experience upon which to base the design, a steam/carbon molar ratio

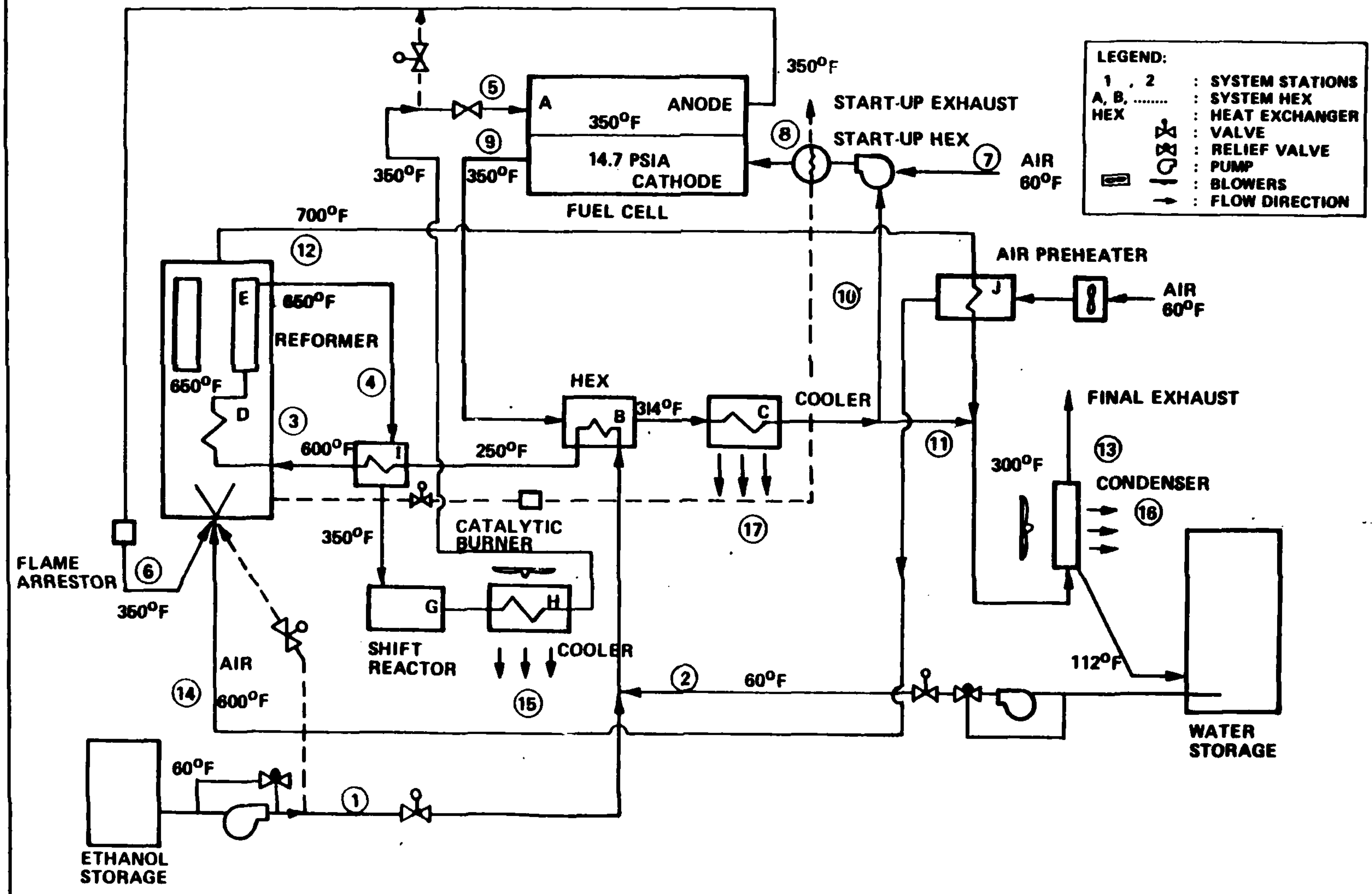


Figure 4-6. Schematic Arrangement of Ethanol Fuel Cell Power Unit

TABLE 4-4

STATE POINTS - 23 kW ETHANOL-FUELED FCPU

Stream No.	Description	Flowrate (lb-moles/hr)							Total (lbs/hr)	Temp. (°F)
		H_2	CO	CO_2	H_2O	N_2	O_2	C_2H_5OH		
1	Fuel Supply							0.33	15.2	60
2	Water Supply				1.16				20.8	60
3	Reformer Feed				1.16			0.33	36.0	600
4	Reformer Exit	1.84	0.14	0.52	0.31				36.0	650
5	Anode Feed	1.94	0.04	0.62	0.21				36.0	350
6	Anode Exit	0.27	0.04	0.62	0.21				32.7	350
7	PAFC Make-Up Air					6.32	1.68		231.0	60
8	Stack Air Supply				21.89	89.16	12.69		3296.0	250
9	Stack Exit Air				23.56	89.16	11.85		3300.0	350
10	Recirculation Air				21.89	82.84	11.01		3066.0	263
11	PAFC Exhaust				1.67	6.32	0.84		234.0	263
12	Furnace Exhaust			0.66	0.48	1.03	0.09		70.3	700
13	System Exhaust			0.66	0.89	7.35	0.93		283.0	112
14	Burner Supply Air					1.03	0.27		37.6	600
15	Cooling Air					2.22	0.59		81.0	150
16	Cooling Air					103.40	27.50		3780.0	100
17	Cooling Air					53.20	14.20		1950.0	150

DESIGN BASIS

60°F, 0% R.H.
2.0 Cell Stoair
1.5 Combustions Stoair
85% Cell H_2 Utilization
12,780 Btu/Lb Ethanol (HAV)
No Thermal Losses

HEAT EXCHANGER LOADS (Btu/hr)

		Sensible	Latent	HEX Area, Ft^2
A	Fuel Cell Stock	85,000	-	-
B	Fuel Vaporizer	5,130	25,690	14.0
C	Recirculation Cooler	42,100	-	30.0
D	Superheater	880	-	1.0
E	Reformer Bed	27,270	-	8.0
F	Water Condenser	15,100	21,200	85.0
G	Shift Reactor	1,760	-	-
H	Shift Cooler	1,760	-	3.0
I	Fuel Preheater	6,200	-	12.0
J	Air Preheater	4,870	-	3.0

of 1.75 (steam/ethanol ratio of 3 ¯) and a reforming temperature of 650°F (min.) was selected for this analysis. Ethanol reforming tests recently conducted at Energy Research Corporation indicate that these values appear reasonable. Developmental tests will be needed to verify the ideal operating temperature and fuel mix.

As with the methanol unit, vaporization of the mixture takes place in a liquid/air heat exchanger situated in the fuel cell air cooling loop. The vaporized fuel is superheated to approximately 650°F and steam reformed into raw gas containing 69 percent hydrogen using a series chain of three elements, a reformer, cooler, and shift converter. Endothermic reforming heat is provided by combustion of unused hydrogen exiting the fuel cell anode. With fuel vaporization located outside the reformer, there is sufficient energy in the anode waste gas to provide for all superheat and reforming heat requirements, based on a fuel cell operating at 85 percent hydrogen utilization. No additional furnace fuel is required under normal operating conditions.

The reformed gas is cooled to 350°F in the fuel superheater and passed through a low temperature shift converter. The gas composition exiting the shift converter, and entering the fuel cell, consists of 69 percent H_2, 22 percent CO_2, 7.3 percent H_2O, and 1.5 percent CO.

Oxygen consumed in the fuel cell reaction with hydrogen is provided by a makeup air supply. To enhance recovery of water from the cell exhaust air, makeup air is limited to less than two times cell oxygen needs. Makeup air is combined with recycled air to provide a sufficient total air mass for cell cooling while maintaining high inlet air temperatures necessary for good cell performance. Waste heat is removed from the cooling air loop via the fuel/steam vaporizer and an air/air heat exchanger.

Water is recovered from the process by combining both cell exhaust air and reformer combustion products and utilizing an air to air heat exchanger. Approximately 54 percent of the water in the system exhaust is recovered by cooling to 112°F. This provides all of the water required within the process (i.e., no fresh makeup water is required) up to ambient temperatures of about 100°F. For operation above 100°F excess condensate collected during cooler portion of the day is stored in the condenser sump. This water is used to supplement the water supply during the hotter hours of a hot day.

4.3.2.3 POWER PLANT DESIGN PERFORMANCE

A cell current density of 150 amps/ft^2 (ASF) was selected as the design basis for both power units during 23 kW peak output. Based on reformer product gas compositions and existing state-of-the-art PAFC cell performance, the projected system operating points for fuel cell voltage and current characteristics are shown in Figure 4-7.

The fuel cell stack design for the units was chosen primarily to obtain high cell voltage and electrical efficiency at normal output, while limiting waste heat removal, fuel requirements, and associated equipment sizes at peak output. It was determined during the design of the methanol-fueled FCPU that the chosen current density (150 ASF) results in the lowest life cycle costs. A summary of the cost analysis results are given in Table 4-5.

Higher current density designs offer considerable reduction in stack size for a given power requirement. Changing the proposed fuel cell design from 150 ASF to 225 ASF at peak output offers a 30 percent reduction in stack size. However, it also results in a 16 percent loss in cell efficiency and 16 percent increase in fuel use and waste heat removal requirements. This increase affects the majority of components in the power unit (air, fuel, water, electrical). The capital costs of these components exceed those of the fuel cell stack. The largest impact, however, may be in the increased cost of fuel over the power plant life. Assuming a stack life of five years, a variable cell cost of \$50/ft^2, and methanol at 80¢/gal, changing the cell operating point from 150 ASF to 255 ASF will result in an additional annual outlay of \$1,540. This does not include the increased costs of designing all auxiliary components to support 255 ASF operation. To obtain output voltage, higher current density design also leads to smaller cell sizes which result in a higher cell cost per square foot.

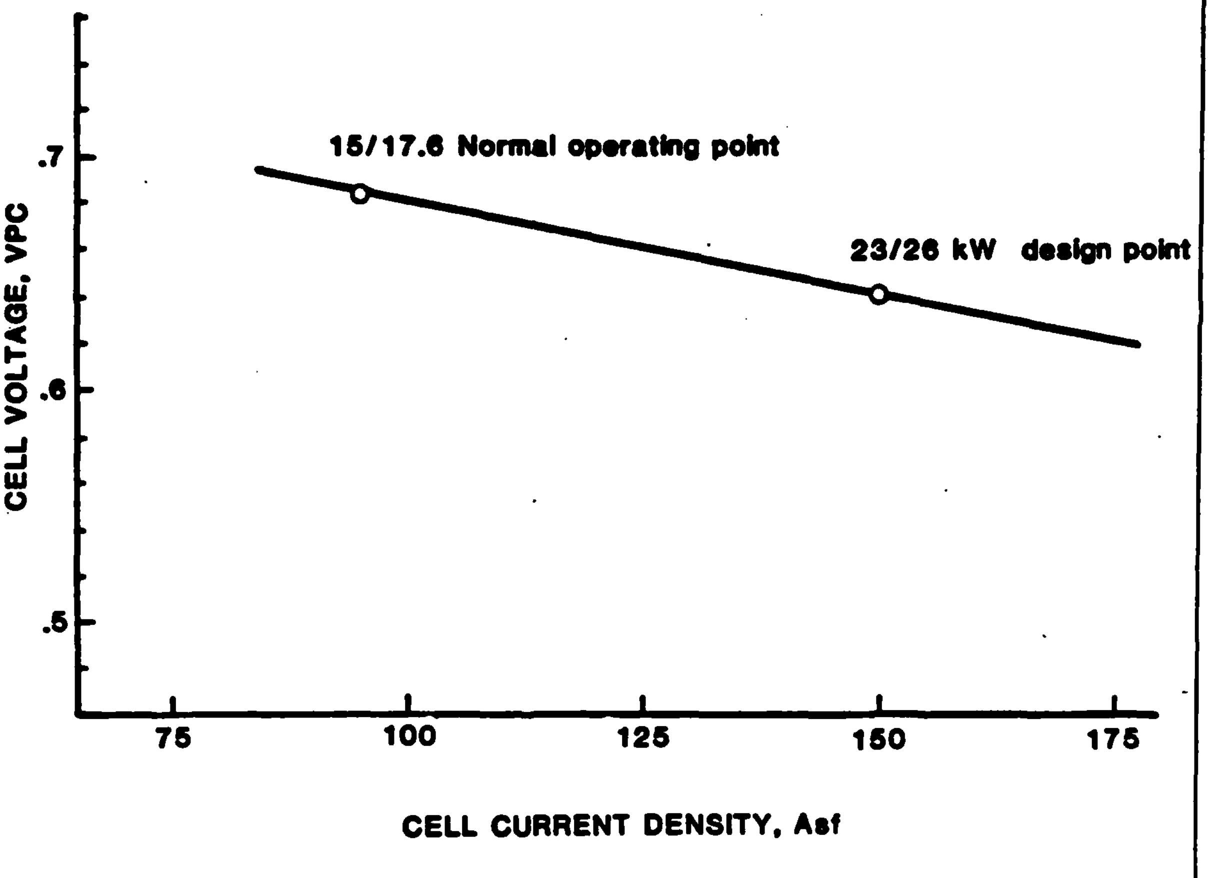


Figure 4-7. Fuel Cell Voltage Versus Current Density

TABLE 4-5

COMPARATIVE ANALYSIS
MX POWER UNIT - DESIGN POINT SELECTION

	CELL DESIGN POINT OPTIONS				
	I	II		III	
Gross Power, kW (Peak/Normal)	26.0/17.5	26.1/17.7		26.3/17.9	
Cell Design Point, vpc @ ASF					
23 kW Peak Output	.64 @ 150	.60 @ 200		.55 @ 255	
15 kW Normal Output	.68 @ 95	.66 @125		.64 @ 150	
Total Cell Area, ft^2	270	215		.69	
Relative Stack Size	1.0	.80		.69	
	1.0	1.07		1.16	
Relative Aux. Comp. Sizes	2.1	2.25		2.44	
System Fuel Use, gph					
Incremental Costs	Base	$5250 (1a)	$2953 (1b)	$11,900 (1a)	$4725 (1b)
Fuel Use, 5 Years	Base	560	560	1,280	1280
Reformer/Fuel System (2)	Base	250	250	500	500
Heat Exchangers (3)	-0-	$6060	$3763	$13,680	$6505
Total Added Cost	Base	$2750	$2750	$ 4,200	4200
Savings in Stack Cost (4)	-0-	$3310	$1013	$ 9,480	$2305
Net Cost Outlay					

(1a) 8,750 hrs/yr operation, 45¢/gal. Methanol.

(1b) 8,750 hrs/yr operation, 80¢/gal. Methanol.

(2) Reformer and Fuel System Cost assumed 30% fixed and 70% variable, \$2,000/lb H_2 variable cost.

(3) Heat Exchanger variable cost taken as \$30/ft^2.

(4) Stack Cost assumed 30% fixed and 70% variable, \$50/ft^2 variable cost.

The methanol FCPU performance is shown in Table 4-6. The major component design parameters and predicted performance are given in Table 4-7. A conservative reformer thermal loss of 9,000 Btu per hour (2.6 kW_t) was assumed. This heat loss could most likely be reduced, resulting in a higher reformed furnace exhaust gas temperature. However, it is not clear that this would result in lower FCPU heat rates. If the hotter exhaust gas was utilized to preheat combustion air, the furnace fuel requirements could be reduced. Since unreacted hydrogen in the anode exhaust is the sole source of reformer furnace fuel, reduced fuel requirements necessitate operating the fuel cell with a higher hydrogen utilization. High hydrogen utilization has further implications including reduced cell voltage and lower furnace flame temperatures. Therefore, further improvement of plant heat rate by reduction of reformer heat losses requires careful study and overall performance optimization.

The ethanol FCPU performance is shown in Table 4-8. Major component design parameters are given in Table 4-9. System electric generating efficiency, defined as the net dc output divided by the higher heating value of the fuel, is 40.4 percent at peak load (23 kW) and 41.5 percent at normal load (15 kW). These represent plant heat rates of 8,450 and 8,220 Btu per kilowatt-hour, respectively.

4.3.3 FUEL CELL POWER UNIT CHARACTERISTICS

4.3.3.1 SYSTEM OPERATION AND CONTROL

There are six major control functions which must be exercised to provide an operational unit. These functions are outlined in Table 4-10. The nature of the control required is similar to that required of smaller methanol fueled units developed or under development by the Energy Research Corporation for the U. S. Army. For these army units, a microprocessor based control was selected. A similar concept has been selected for operational control of these FCPU's. The two major reasons for using a microprocessor are: (1) flexibility to accommodate the control system to either unanticipated or anticipated system changes, such as a change in system design to allow use of either methanol or ethanol fuel; and (2) minimum development risk on the control system because of prior Energy Research Corporation experience.

TABLE 4-6

DESIGN DATA SUMMARY SHEET
METHANOL FUEL CELL POWER UNIT

DESIGN BASIS

Power Output, kW (Nominal/Peak)	15/23
Regulated DC Output Voltage	120
Fuel Type	Methanol
Ambient Temperature, °F	-25 to 120
Altitude, Ft. Above Sea Level	5000
Make-up Water, gpm	0

PROJECTED PERFORMANCE

	15 kW Normal Output	23 kW Peak Output
Gross Power, kW	17.6	26.0
Parasitic, kW	1.7	1.7
DC/DC Conversion, %	95	95
Net Power, kW	15.0	23.0
Fuel Cell Voltage, VDC per cell	.684	.640
Hydrogen Needs, lbs/hr	2.12	3.34
Methanol Consumption, lbs/hr	13.3	21.0
Fuel Rate, gallons per hour	2.03	3.20
Fuel Heat Input, 10^3 Btu/hr(1)	130.0	205.0
Electric Output, 10^3 Btu/hr	51.2	78.5
System Efficiency, %	39.4	38.3
Heat Rate, Btu/kW-hr	8667	8913
System Starting Time, Minutes		30-40
System Weight (excl. Fuel Storage), lbs.		1500
System Volume, Ft^3		97
System Footprint, Ft^2		17

(1) Liquid methanol - HHV = 9764 Btu/lb; S.G = 0.787

TABLE 4-7
MAJOR COMPONENT DESIGN PARAMETERS - METHANOL FCPU

FUEL CELL	
Design Pressure, PSIA	ATMOSPHERIC
Design Temperature, °F	350
Cell Hydrogen Utilization, %	85
Process Air Stoichiometry	2
Cooling Load, 10^3 Btu/hr	85,000
Output Voltage, DC	150
No. of Cells Required	235
Active Cell Area, ft^2	1.15
Operating Point, vpc* @ ASF	
23 kW Output	.640 (@) 150 ASF
15 kW Output	.684 (@) 95 ASF
Process/Cooling Air Rate, SCFM	700
FUEL CONDITIONER	
Design Pressure, PSIA	ATMOSPHERIC
Catalyst Type	Cu-ZnO
Burner Blower Output, SCFM	5-50
Combustion Stoichiometry	1.5
Startup Firing Rate, GPH	4.5-6.3
, Btu/hr x 10^3	360-480
Shift Catalyst Volume, ft^3	.5
MISCELLANEOUS EQUIPMENT	
Cooler Fan Output, SCFM	400
Water Condenser Fan Output, SCFM	800

*vpc = volts DC per cell

TABLE 4-8

DESIGN DATA SUMMARY SHEET
ETHANOL FUEL CELL POWER UNIT

DESIGN BASIS

Power Output, kW (Nominal/Peak)	15/23
Regulated DC Output Voltage	120
Fuel Type	Ethanol
Ambient Temperature, °F	-25 to 120
Altitude, Ft. Above Sea Level	5000
Make-up Water, gpm	0

PROJECTED PERFORMANCE

	15 kW Normal Output	23 kW Peak Output
Gross Power, kW	17.6	26.0
Parasitic, kW	1.7	1.7
DC/DC Conversion, %	95	95
Net Power, kW	15.0	23.0
Fuel Cell Voltage, VDC per cell	.684	.640
Hydrogen Needs, lbs/hr	2.12	3.34
Ethanol Consumption, lbs/hr	9.65	15.2
Fuel Rate, gallons per hour	1.47	2.31
Fuel Heat Input, 10^3 Btu/hr(1)	123.3	194.3
Electric Output, 10^3 Btu/hr	51.2	78.5
System Efficiency, %	41.5	40.4
Heat Rate, Btu/kW-hr	8220	8450
System Starting Time, Minutes		30-40
System Weight (excl. Fuel Storage), lbs.		1500
System Volume, Ft^3		105
System Footprint, Ft^2		19

(1) Liquid ethanol - HHV = 12,780 Btu/lb; S.G = 0.789

TABLE 4-9

MAJOR COMPONENT DESIGN PARAMETERS - ETHANOL FCPU

FUEL CELL	
Design Pressure, PSIA	ATMOSPHERIC
Design Temperature, °F	375
Cell Hydrogen Utilization, %	85
Process Air Stoichiometry	2
Cooling Load, 10^3 Btu/hr	85,000
Output Voltage, DC	150
No. of Cells Required	235
Active Cell Area, ft^2	1.15
Operating Point, vpc* @ ASF	
23 kW Output	.640 (@) 150 ASF
15 kW Output	.684 (@) 95 ASF
Process/Cooling Air Rate, SCFM	700
FUEL CONDITIONER	
Design Pressure, PSIA	ATMOSPHERIC
Catalyst Type	Cu-ZnO
Space Velocity, hr^{-1}	1,500
Catalyst Volume, ft^3	.35
Burner Blower Output, SCFM	5-50
Combustion Stoichiometry	1.5
Startup Firing Rate, GPH	6-8
, Btu/hr x 10^3	360-480
MISCELLANEOUS EQUIPMENT	
Cooler Fan Output, SCFM	400
Water Condenser Fan Output, SCFM	800

*vpc = volts DC per cell

TABLE 4-10
MAJOR CONTROL REQUIREMENTS

FUNCTION	METHOD
Load Following	Current measurement feedback to fuel valves
Fuel & Water Mixing	Constant Pressure Proportioning valves
Reformer Temperature	Burner Air Control Supplemental Firing
Fuel Cell Temperature	Recirculation Air Temperature Control via Cooler Fan Speed
Exhaust Gas Water Concentration	Load Following damper control to maintain 2.0 Stoair supply
Water Condenser Cooling	Differential Temperature Control

FCPU starting is achieved by heating the reformer catalyst and fuel cell to operating temperature by combusting fuel in the reformer and diverting a portion of the combustion gases for fuel cell heating. Heating of the fuel cell is accomplished by circulating cell air through a startup heat exchanger, situated at the fuel cell air inlet. Thermocouple (RTD) sensors are used to control burner firing rate. For starting, a battery of 0.75 kWh at the one hour rate will provide sufficient power for operation of system components (excluding cooler fan and water condenser fan) for the 30-40 minute starting period. This could be the two hour Ni-Cd battery in the MX ROSE or an auxiliary battery carried by the "startup" crew.

Load following is obtained by measuring fuel cell current output (demand) and adjusting fuel and water proportioning valves. This controls the volume of reactants entering the reformer and hydrogen output to the fuel cell. Rapid transient response capability (two seconds from 15 kW to 23 kW with full voltage recovery) is obtained by supplemental liquid fuel combustion, plus an increase in fuel cell anode flow passages total design volume of 0.5 ft^3 over steady state required volume.

Thermal System Control is obtained by monitoring reformer and fuel cell temperatures and adjusting flow rates, accordingly. Reformer catalyst temperature is controlled by changing combustion temperatures by controlling combustion air fan speed or damper positioning at the reformer exhaust outlet. Fuel cell plate temperature is maintained at 350°F by controlling temperature of the recirculation air. As load decreases on the fuel cell, recirculation air temperature is increased to maintain cell air outlet temperature at 350-375°F. Recirculation air temperature is increased by reducing cooler fan speed or damper opening.

To maintain water concentrations in the cell exhaust at high levels during part load, fresh air supply is reduced. This is accomplished by using an air damper controlled in response to current demand. The damper would be proportioned to maintain desired makeup air to the process air blower during all load conditions. This function is necessary to maintain a high dewpoint for water recovery. At part load conditions the water condenser fan speed would be reduced to conserve power. To insure adequate water recovery, fan speed would be controlled to maintain system exhaust below the design dewpoint temperature; ambient temperatures permitting (see previous Section 4.3.2.2).

4.3.3.2 SYSTEM SIZE AND WEIGHT

The projected volume and weight of the power units is shown in Table 4-11. These projections are based on scaleup of existing designs with allowances for additional components, including water recovery and heat removal equipment. The fuel cell stack is the largest and heaviest component, comprising about 40 percent of the assembled power unit weight and approximately 12 percent of system volume. Electrical control equipment, including the main power conditioner, and parasitic power control equipment comprises about 25 percent of power unit weight and 10 percent of system volume. Water recovery equipment is the largest component by volume, comprising approximately 13 percent of projected power plant volume.

4.3.3.3 SYSTEM FIRST COST

An estimate of the production cost of uninstalled 23 kW FCPU's is shown in Table 4-12. The basis of the cost estimate is an internal cost study by the Energy Research Corporation (ERC) of the costs of ERC's conceptually similar 1-1/2 kW U. S. Army unit as produced in 1000 unit production lots. The costs for the smaller unit were updated, adjusted for equipment size differences, and addition of water recovery apparatus to arrive at the 23 kW FCPU valves. As can be seen, the units are estimated to cost \$2,440/kW for ethanol and \$2,320/kW for methanol.

Westinghouse carried out an independent analysis of the cost of the 23 kW ethanol FCPU. This analysis of the cost was derived from costing studies in support of the Westinghose programs on FCPU's for electric utilities and much smaller on-site integrated energy systems. Westinghouse estimates the cost of the ethanol FCPU at \$2,490/kW. Because of the preliminary conceptual nature of the design, the difference of \$50/kW between the ERC and Westinghouse estimates is not significant.

TABLE 4-11
SYSTEMS COMPONENT SIZES

	Methanol Unit		Ethanol Unit	
	Weight, lbs	Volume, ft^3	Weight, lbs	Volume, Ft^3
Fuel Cell Stack w/Manifolds	630	12.5	630	12.5
Fuel Vaporizer	10	1.0	10	1.0
Recirculation Heat Exchanger	30	6.0	30	6.0
Gas Cooler	-	-	3	0.2
Reformer/Burner Assembly	120	10.0	120	8.0
Shift Reactor	-	-	30	0.5
Water Recovery Condenser	60	10.0	80	13.3
Pumps, Fans & Blowers, Valving	80	-	80	-
Housekeeping Power Supplies and Control Components	120	4.0	120	4.0
Output Power Conditioner	250	7.0	250	7.0
Misc. Ducting, Piping Insulation, Skid Base	130	-	150	-
Packaging Factor (50%)	-	48.5	-	52.5
	1430	97.0	1503	105.0

TABLE 4-12
PROJECTED COST(1)
23 kW POWER UNITS

	Ethanol	Methanol
Fuel Cell Assembly	17,400	17,400
Reformer/Burner Assembly	8,500	8,000
Fuel Delivery	3,000	3,000
Air Delivery	5,500	5,500
Water Delivery	2,500	2,500
Heat Exchangers	10,000	8,000
Automatic Control Unit	1,200	1,200
Sensors and Drivers	3,000	2,800
"Housekeeping" Power Supply	2,000	2,000
Structural	3,000	3,000
	$56,100	$53,400
	$ 2,440/kW	$ 2,322/kW

(1) The above represents cost projection for 1,000 units of production, 1980$.

4.3.3.4 SYSTEM RELIABILITY

The Mean Time Between Failures (MTBF) of the FCPU's are estimated to be 3,770 hours for the methanol unit and 3,690 hours for the ethanol unit. The anticipated failure rates of FCPU components are given in Table 4-13. Most of the values come from typical failure rate data associated with USAF fixed ground support systems as reported by Rome Air Development Center (NPRD-1). For the fuel cell and reformer, it was assumed that failures will be of the "wearout" type, with the "wearout" caused by catalyst degradation over a lifetime of 40,000 hours. At the present time, this is the PAFC industry lifetime goal before cell replacement.

The MTBF of the FCPU's can be increased by adding redundant components, and increasing ducting and tubing wall thickness and support to improve the ducting and tubing mechanical integrity. For example, if the housekeeping power supply, automatic control unit circuits, flow valves, temperature sensors and reforming catalyst were "doubled-up" and reinforced ducting and tubing used, the FCPU's MTBF is estimated to increase to approximately 5,500 hours and 5,400 hours for the methanol and ethanol units, respectively. These changes will increase the estimated capital cost of the units about 23 percent.

4.3.3.5 DESIGN LIFE AND MAINTENANCE CHARACTERISTICS

The major design and maintenance characteristics for the MX Shelter power unit are shown in Table 4-14. Maintenance of the PAFC system is expected to be minimal in comparison to alternative systems. The fuel cell stack represents the primary maintenance cost, with replacement anticipated within 4.5 years. Life testing of fuel cell stacks have demonstrated performance of 40,000 hrs and above without major voltage losses. Typical voltage loss projected by the PAFC industry over 40,000 hours is 10 percent. This is largely due to deactivation of the fuel cell platinum catalyst. A voltage loss in excess of 10 percent from the MX shelter FCPU fuel cell stacks could limit output power to less than 23 kWe peak.

Reformer catalyst deactivation can be expected to occur within a similar time frame. Deactivation would be caused by poisoning or catalyst sintering. Life

TABLE 4-13

RELIABILITY ESTIMATE(1)
MAJOR COMPONENT FAILURES
23 kW POWER UNITS

	Methanol Failure Rate No./10^6 Hours	Ethanol Failure Rate No./10^6 Hours
Fuel Cell	25.0(2)	25.0(2)
Reformer	25.0(2)	25.0(2)
Burner	15.0	15.0
Heat Exchangers	6.0	7.0
Fuel Pump	7.5	7.5
Water Pump	2.8	2.8
Air Blowers	22.5	18.5
Microprocessor	20.0(3)	20.0(3)
"Housekeeping" Power Supply	20.0(3)	20.0(3)
Valves		
Flow	24.9	24.9
Pressure Regulating	7.2	7.2
Solenoid	8.0	11.2
Relief	4.8	4.8
Check	12.0	12.0
Sensors		
Pressure	2.7	2.7
Level	4.8	7.2
Temperature	29.0	34.8
Current, Power	3.2	3.2
Ducting	15.0	15.0
Tubing	10.0	10.0
	265.4 MTBF = 3,770 Hours	270.9 MTBF = 3,690 Hours

(1) Based on average data from non-electric parts reliability data NPRD-1, Rome Air Development Center, 1978.

(2) Assumes fuel cell and reformer catalyst life of 40,000 hours.

(3) Assumed values for high reliability designs.

TABLE 4-14

SYSTEM DESIGN LIFE AND MAINTENANCE CHARACTERISTICS

SYSTEM DESIGN LIFE GOAL	20 yrs min.
MAJOR REPLACEMENT	
Fuel Cell Stack	4.5 yrs
Reformer Catalyst	5 yrs
Power Conditioning	12.5 yrs
FORCED OUTAGE MAINTENANCE	
General Inspection & Cleaning	yearly
Component Failures (MTBF)	3,770/3,690 (5 months)
ON LINE MAINTENANCE	
Fuel and Air Filter Replacement	6 months
Acid Replacement	yearly
Calibration & Adjustment	yearly

test data on methanol reforming catalysts have demonstrated 10,000 hrs without loss of catalyst activity or integrity. Similar catalyst lifetimes are anticipated when reforming ethanol. It is anticipated that proper reactor thermal design and catalyst tube design can support a five year or higher catalyst replacement life.

Under "Forced Outage Maintenance" and "On-Line Maintenance" of Table 4-14; there are five items. The characteristics designated as yearly are derived from Energy Resesrch Corporation's experience on other PAFC programs.

Because the expected MTBF for a unit is five months,the yearly maintenance for a majority of the units can be taken care of during a shutdown for repair. Those units which do not fail can get a yearly service call.

4.3.4 POWER PLANT USAGE CONCEPT/CONSIDERATIONS FOR MX SHELTER POWER

The proposed concept consists of individual Fuel Cell Power Units (FCPU's) located adjacent to each MX shelter. Each FCPU consists of a single phosphoric acid fuel cell power generator rated at 15 KWe (nominal), 23 KWe (peak) capacity. System availability is maintained at or above the desired 0.999 level by a combination of FCPU reliability and maintenance procedures. All FCPU's for a 23 shelter cluster share common fuel facilities but are not electrically interconnected. A more thorough discussion of concept logistics considerations and proposed solutions follows.

4.3.4.1 FUEL SUPPLY

The FCPU's are designed for use with commercial fuel-grade alcohols. Since the fuel processing portion of the FCPU requires the intimate mixing and reaction of alcohol and steam, the use of neat alcohol (moisture-free) is not required. However, the FCPU is sensitive to a variety of fuel contaminants, most notably sulfur, nitrogen, heavy metals, olefins, and heavy hydrocarbons. Therefore, the content of these impurities should be limited to a few parts per million. Traces of higher alcohols may be present in the fuel and should present no problem. The choice of water content in the fuel is one of logistics and cost. Lower proof (more water content) alcohol may be less expensive, but would require larger storage and distribution systems. For usage considerations it is assumed that the FCPU uses fuel-grade alcohol with a minimum C_2H_5OH content of 95.6 percent (ethanol fuel) or a minimum of 96 percent CH_3OH (methanol fuel) as the case may be.

A central fuel receiving and storage facility is planned for each MX cluster of 23 shelters. Two months fuel storage of ethanol (approximately 60,000 gallons) would require a tank 24 ft diameter by 20 ft high, while 80,000 gallons of methanol would require a tank 30 ft dia x 15 ft high. Fuel would be delivered from the central storage facility to the FCPU's located at each shelter by piping. Each FCPU would have a 100 gallon (two/three day) storage tank. Repairs to gas or water utility lines do not usually take more than 48 hours.

A cluster consists of a linear array of 23 shelters on an average of 5,200 foot centers. This is a distance of approximately 115,000 feet from the first shelter in an array to the last. It will be assumed that the central fuel storage will be placed near the first shelter of a cluster just behind the road barrier. Fuel at a rate required by a total cluster is initially introduced into a single fuel pipeline extending the length of the cluster. The size of pipe required is very small. The entrance (fuel tank) end fuel velocity would be only 3 inches/second in a 1-inch internal diameter pipe at the nominal total cluster fuel flow rate of 48 gallons/hour of methanol.

For cost estimation purposes, it is assumed that the central fuel tank would be elevated above the levels of the shelters. The fuel would be fed by gravity to shelters. The tank would be surrounded by a fence to prevent casual intrusion. The pipe would be buried to prevent casual damage by live-stock or other intruders.

The costs are estimated as follows:

	Ethanol		Methanol	
	Cluster	Per Shelter	Cluster	Per Shelter
Piping, Installed	$172,500	$ 7,500	$172,500	$ 7,500
Main Tank, Installed	60,000	2,610	80,000	3,480
23 Individual Shelter Tanks, Installed	11,500	1,500	11,500	1,500
TOTALS	$244,000	$11,610	$264,000	$12,480

4.3.4.2 MAINTENANCE AND SPARE PARTS

To establish the maintenance and spare parts requirements for application of an FCPU to the MX application, preliminary study from an overall system level perspective was conducted. Five general areas were assessed in this preliminary study:

1. The definition and selection of generic options.
2. General features and considerations for the comparison matrix tradeoff study of these options.
3. Availability scenarios, servicing considerations and uncertainty conclusions for reference option selected.
4. Annual cost of maintenance and spare parts.
5. The impact of change in the design reliability for the fuel cell power unit.

Options for system design were defined as variations on the following basic approaches to obtain enhanced availability with the FCPU:

- Power units interconnected electrically
  - all units interconnected as net
  - groups of units (partially interconnected)

- Completely independent units with availability of on call recovery service

    - without use of on-site batteries
    - with use of on-site batteries
    - with use of on-site batteries and transportable Auxiliary Power Unit (APU)

- No special system availability enhancement - provide scheduled service and move missile if in faulted shelter until recovery of the power unit in planned servicing operation.

The optional system concepts selected for assessment included three that had the potential of meeting all of the basic requirements and criteria and a fourth which was included for comparison purposes, but which would impose a departure from the general requirement of individual shelter availability. These four generic system concepts were: 1) utilization of electrical interconnection between power units to provide the required availability and flexibility, 2) complete separate units with stand-alone capabilities relying upon on-site battery storage for two hours during which a repair crew could be provided to repair the unit (the two hour period of use of the on-site batteries would be at reduced power. The on-site batteries do not have the capability of providing 15 kWe continuously for two hours), 3) the same as the second option, but providing the repair crew with an auxiliary power unit, probably diesel, and that would permit them to extend the service time and minimize the use of on-site batteries, and 4) no enhancement of availability but the option to move a missile and reroute it to areas that had power. This latter option is not acceptable since it imposes additional requirements on the SAC operation.

These four options were compared on the basis of a number of parameters to establish which concept provided the greatest potential for a successful system utilizing the fuel cell. Qualitative relative ratings were established on a subjective scale to provide an initial comparative assessment. This comparison is shown in Table 4-15. Of the parameters that were assessed, a heavier weighting was considered for availability and cost. These were looked into in more detail once the preferred system (System 3) was made visible.

TABLE 4-15
FCPU MX TRADEOFF COMPARISON MATRIX[5]

OPTIONS / Parameters	GROUPED SYS. INTERCONNECT SITES	INDEPENDENT SYS.		MISSILE REROUTING
		ON SITE BATTERY FOR SERVICE TIME	APU FOR SERVICE TIME	
	1	2	3	4
Req'ts Met ● Safety ● Performance ● System Interface	Yes (OK on all)	Yes (Conditional)	Yes (OK on all)	No
Availability/[1] Confidence Level-Shelter Power	1	3	2	5
Vulnerability -Sabotage, etc	5	2	2	2
EMP Survival	5[2]	1	1	1
Service Skills	3	2	2	2
Level of Service Required	2	3	3	2
Cost - Capital[3] - Operating	5 3	2 3	2 4	1 5
Overall Complexity	4	2	3	1
Technology Status	1	2[4]	2[4]	1

NOTES:

[1] $ tradeoffs for reliability needed vs. crew/equipment requirements.
[2] Partial groupings are still high risk and costly.
[3] $ tradeoffs needed to better compare these systems.
[4] Some fuel cell modules development for quick component replacement.
[5] Rating System: 1-Excellent, 2-Very Good, 3-Good, 4-Fair, 5-Poor.

Hardware Costs

Looking at Table 4-15, the subjective assessment was that interconnection of the FCPU's would give the best shelter power availability of the four schemes considered (System 1). However, it would also make the solution of the EMP problem a technically difficult design requirement on an overall system basis. In addition, there is the added cost of the interconnections which are not required by any of the other three approaches. An estimate of these interconnection costs was made. The results are summarized in following Table 4-16.

TABLE 4-16

SHELTER/INTERCONNECTION-DC-DC

Distance Between Shelter Units	5,200 Ft
Power Level	15 kW dc
Voltage	120 Vdc ±5%
Loss Accepted (voltage)	5%
Cable Cross-Section Needed	2.8 in^2
Cost of Cable/Shelter Unit	$400,000/unit
Other Equipment/Shelter Unit	$25,000/unit
Cost per Year - (12-1/2 years)	$30,000/unit

It will be noted that the estimated cost of $30,000/unit/year is more than half the cost of an FCPU proper (see previous Table 4-12.).

The spare parts needed to restore a FCPU to operating status after a failure, on the average, is not changed much, if at all, by the particular usage/servicing scenarios examined. The spare parts' costs are determined by what needs to be replaced because of FCPU random and wearout failures.

In assessing replacement parts' cost, four scenarios were considered. The first was to assume that replacement of the FCPU would take place at the end of nominal five year service life of the fuel cell program. At the five year point, the FCPU would start on time zero again and would operate potentially, for another five years. The second scenario was to assume a reasonable salvage value (40 percent) for the items replaced under the first option approach. The third scenaro was to permit the longer life items to be replaced on a 12.5 year or failure initiated basis with only the major five year wearout items replaced at five years. The fourth scenario was the third option assuming a 40 percent salvage value for replaced parts.

The cost results from considering the four replacement options is given in Table 4-17. The replacement parts' costs were assumed to be the same as the initial parts' costs given previously in Table 4-12. The meantime between failures was taken as 3,700 hours against the previously estimated 3,690 hours and 3,770 hours for ethanol and methanol, respectively.

TABLE 4-17

REPLACEMENT PARTS COSTS

Options	Ethanol Cost $/Year	Methanol Cost $/Year
1. Replace complete FCPU at five year intervals	$11,100	$10,600
2. Replace only five year wearout items at five years	$ 7,900	$ 7,500
3. Same as Option 1, with 40 percent used parts salvage value	$ 6,700	$ 6,300
4. Same as Option 2, with 40 percent used parts salvage value	$ 4,700	$ 4,500

It is an engineering judgment that Option 4, which results in the lowest replacements parts costs, is a viable option for the MX application. Therefore, it is assumed that hardware costs can be held to an average of $4,500-$4,700/year/FCPU.

Servicing Costs

To arrive at an estimate of the maintenance-repair servicing costs associated with a FCPU, the maintenance repair characteristics given in Table 4-18 were assumed.

TABLE 4-18

MAINTENANCE REPAIR CHARACTERISTICS

Major Components - Replacement Time	6 Hours
Other Components - Replacement Time	4 Hours
Events per Day	30
Nominal Variance of Events per Day - (4,600 units)	±50%
Crew Size	2 Men
Working Shift	8 Hours
Labor Cost with Benefits/Man	$42,000/Year
Auxiliary Power Unit Cost	$500/kW
Service Equipment Life (all)	5 Years
Trucks and Equipment (each)	$20,000
Number Trucks and Equipment	1 Ea. Crew*
Variable Costs - Transportation	30¢/Mile

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*NOTE: Provided for all crews to permit spares and maximum service capacity for unusual outage rates.

The "events per day" estimate in Table 4-18 assumes a FCPU with a MTBF of 3,700 hours averaged over a total of 4,600 units.

The crew requirements for service and maintenance are estimated with a 1.5 factor to cover the Table 4-18 normal variance of events per day of ±50 percent. Using the FCPU components reliability "breakout" given in Table 4-13 as a guide to the type of failures to be expected, a total of 26 crews would be needed on an eight hour shift, three shifts per day operation to cover a design value of 45 events per day. The nature of the type of maintenance expected is illustrated in Table 4-19. To assess the adequacy of 26 crews to provide 99.9 percent availability of power to an individual MX shelter, additional scenario factors were assumed as follows:

Assume as a worse case that all 30 units normally expected to be out sometime during any 24 hours period were out at the same time, and only the on-site batteries were available as a backup. Under these conditions and utilizing the time schedule of Table 4-20 for repair, plus assuming that 18 of 26 crews can be called to work to the schedule of Table 4-20 (all 18 would be at work within four hours). It is nearly, but not quite, possible to maintain 99.9 percent shelter power availability. However, if each crew had an APU available, the total average power unavailability of individual shelter power would drop to just over one hour. This average one hour outage when averaged with the other outages expected during a year yields well above 99.9 percent power availability.

The average servicing costs per year for an individual FCPU for System 3 are estimated to be as follows:

Labor Plus Overhead, G&A, etc.	$475
Special Equipment	$ 31
Transportation	$ 45
TOTALS	$551

TABLE 4-19

SKILL LEVELS
(Modularization Dependent)

OPTIONS / SKILLS	SYSTEM CONCEPTS			
	1	2	3	4
a) F.C. System trained Mechanical	Trained E4 Level Skills Trouble-Shoot Modular System Replace Modules Operate Unit	Same as (1)	Same as (1)	Same as (1) (Plus Need Use of SAC Crews for Transport)
b) Electrical	Add Power Transmission and Distrib. Skills	(As Included in Above)	(As included in Above)	
c) Fuel Systems	Trained E4 Level Skills Methane Handling	Same as (1)	Same as (1)	Same as (1)
d) Diesel/Elec/Mech	None	None	Diesel Elect. APU Skills (E4 Level)	None
e) Emergency & Safety	H. Voltage Transmission System Skills in Addition to Those of (a) Above	Same as Imposed by (a) Above	Diesel Fueled APU Operation Skills in Addition Those of (a) Above	Same as Imposed by (a) Above

<u>Fuel Cell System Skills</u> - Level depends on modularizing

1. Electrical circuits and switching operations/repair
2. Fluid systems and flow/compressor operations/repair
3. Instrumentation and troubleshooting
4. Fuel handling/reformer-combustor operations

TABLE 4-20

ADDED ASSUMPTIONS FOR SERVICE AND REPAIR ESTIMATES

• Total Number of Crews	26
• Crews Available for Call	18
• Standby Crews	2 on 2 hours call
• Crews Available on 2 hour notice	4
• Crews Available on 4 hour Notice	6
• Travel Times	
- 8 Crews	0 hours
- 4 Crews	2 hours
- 6 Crews	4 hours
• Fuel Cell Units - Standard MTBF	3,700 hours
• On Site Batteries Availability	2 hours (at reduced power)

It will be noted that the $551 maintenance-repair servicing cost is much less than the estimated maintenance repair hardware cost previously given as $4,500-$4,700.

Impact of MTBF on FCPU Maintenance Cost

In Section 4.3.3.4, System First Cost and Reliability, two levels of ethanol FCPU MTBF and costs associated with each were given as follows:

MTBF (Hours)	FIRST COST ($/kWe)	$/FCPU
3,690	2,440	56,100
5,400	3,000	69,000

The higher MTBF FCPU is obtained, largely, by doubling up on some of the more failure prone components of the lower MTBF FCPU. With the higher MTBF unit only 20 service calls per day would be expected as against 30 with the lower

MTBF unit. This will result in a reduction of the servicing costs from $551 per unit per year to say $367 per unit per year, but will not result in any decrease in hardware replacement costs. This is because both the high and low MTBF units will require, on an average basis, replacement of the same components. In the case of the low MTBF unit all the spares are carried in some central inventory. In the case of the high MTBF unit some of the spares are carried in place on the unit. This drives the first cost of the high MTBF unit, based on a 12.5 year usage time span to $925 per year per unit above the low MTBF unit, or the net cost of the high MTBF unit is at least $741 per year per unit higher than the lower MTBF unit. A similar assessment for the methanol unit yielded a value of $696.

Fuel and Air Filter Servicing Costs

As discussed in Section 4.3.3.5, it is expected that the fuel and air filters associated with an FCPU should be changed two times a year.

To estimate the costs of air and fuel filter replacement, the nature of the crew and equipment was assumed to be the same as given in Table 4-18 on maintenance, except that the trucks and equipment per crew were assumed to cost $10,000 each. It was further assumed that because of the "spread-out" nature of a cluster that it would take one two man crew two days to change all the filters of the FCPU's in a cluster. For the total MX complex of 200 clusters, with filter replacement every six months, a total of four crews on a single shift 200 working days per year basis will be required.

With the foregoing assumptions, the filter servicing cost is $80 per year per FCPU plus the cost of the filters, or a total of $100 per year per FCPU.

4.3.4.3 OPERATING COSTS

Since the FCPU is designed for unattended operation, the only strictly operating cost is that of the fuel for the unit. This is a major cost element.

In estimating the cost of fuel there is only minor uncertainty in the amount of fuel required per year, but there is a major uncertainty in what this fuel will cost per gallon. Standard price projections for power plant fuel delivered in Los Angeles, California, in 1990 in 1980 dollars are (Ref. 4-3):

	Ethanol	Methanol
High - \$8.16/10^6 Btu - or approx.	69¢ per gallon,	52¢ gallon
Low - \$7.04/10^6 Btu - or approx.	59¢ per gallon,	45¢ gallon

Recent prices are more like 110¢/gallon for ethanol (Ref. 4-4) and 80¢/gallon for methanol (Ref 4-5). To illustrate the importance of this parameter, calculations have been done using both, projected prices and recent prices. The results are as follows for an individual FCPU:

	Ethanol	Methanol
Fuel Used (gal/yr) (fuel alcohol) -	13,470	18,846
Fuel Cost (\$/yr) Projected Price -	7,947	8,481
Fuel Cost (\$/yr) Recent Price -	14,817	15,077

For summary purposes, the more optimistic projected fuel costs have been used hereafter.

The reasons behind the optimism are that FCFU's can use 190 proof alcohol, rather than the anhydrous (200 proof) alcohol ordinarily bought for laboratory or chemical use. One hundred ninety proof alcohol is considerably cheaper and less energy intensive to make than 200 proof alcohol. If alcohol were in demand for fuel use, its price would have to be similar on a dollars per million Btu's to the price of other fuels. This can be done using less expensive feedstocks, such as cellulose wastes, rather than food stock, such as corn or sugar, for ethanol, and coal rather than natural gas for methanol.

4.3.4.4 INSTALLATION COSTS

The FCPUs are skid mounted and can be designed to operate when tilted up to 15° without problems. In principle then, there would be no need for any site preparation for installation next to the ROSEE adjunct to the shelter. A unit could be skidded up to the side of the ROSEE, the full line and electrical connections made and the unit started up. In practice, however, because of the 12.5 years or more that a FCPU may be installed, and the desirability of a smooth, relatively clean surface from which to work when performing maintenance, installation of a concrete pad with walkway clearance around the unit is recommended. Cost of this pad, installed, is estimated at $500.

There are two elements that will be considered in the actual installation costs, as distinguished from site preparation cost. These are: the cost of transportation from the factory to the installation site and the cost of installation, checkout, and initial operation at the site. According to the Westinghouse Shipping Department, the common carrier rate, Pittsburgh, Pennsylvania to Las Vegas, Nevada, is $15 per 100 pounds. This is $225 for a 1,500 pound FCPU.

The actual installation is considered to be split into two operations: (1) the actual physical installation and hookup and (2) checkout and initial operation. For the first operation, it is assumed that a three man crew equipped with truck and portable crane can install two units per day at a cost of $560 per FCPU. For the second operation it is assumed that a two man crew, with truck, will take one day to thoroughly check out the unit and place it in operation at a cost of $400 per FCPU. Therefore, the total installation cost is estimated to be $1,185.

4.4 DEVELOPMENT RISK ASSESSMENT

Technical development risk assessments were performed at both the subsystem/major component level and the overall system level. The technology status rating criteria is presented in Table 4-21. Each subsystem or major component was evaluated with respect to the following factors:

- Current technology status
- Technology rating (Table 4-21 criteria)
- Required technology status to meet design requirements for the proposed application

TABLE 4-21

REQUIREMENTS FOR APPLICATION AT (A) TECHNOLOGY RATING LEVEL

TECHNOLOGY RATING	TECHNOLOGY STATUS	PERFORMANCE DATA BASE	EXTRAPOLATION FROM PERFORMANCE DATA BASE	APPLICATION OR DEVELOPMENT PROGRAMS REQUIREMENTS	R&D PROGRAM CHARACTERISTICS	
					RATIONALE	SUCCESS PROBABILITY
Established (A)	Firm selections can be made. Equipment is commercially available in form required.	Sufficient	None	Minimal, routine applications engineering.	Not Applicable	Not Applicable
Near Term (B)	A number of equipment candidates are identified. Candidates are commercial or near commercial.	Incomplete	Short extrapolations from existing data base are involved.	Confirmatory testing and minimal R&D.	Straight-forward	Virtually Certain
Developmental (C)	Equipment not previously designed, but engineering data base exists for design.	Incomplete; important gaps exist	Large extrapolations from existing data required.	Considerable R&D is required	A credible rationale exists. Alternative avenues are evident.	Good to excellent
Speculative (D)	Equipment not previously designed with major materials, design or manufacturing uncertainties.	Sparse or Absent	Highly speculative or not possible.	Extensive R&D is required.	Rationale is not clear, or requires a break-through or serendipity.	Fair to poor.

- Proposed developmental program to achieve the required technology status
- Estimated developmental effort expressed in terms of manhours of R&D personnel (engineering plus technicians)
- Estimated developmental effort expressed in terms of development dollars (labor and materials)
- Probability of success of the proposed developmental program
- Ongoing programs or potential design alternatives.

A summary of the development risk assessments is given in Tables 4-22 and 4-23 for methanol and ethanol, respectively. All development items were given a technology rating of Established (A) or Near Term (B). No major breakthroughs are required to achieve the proposed performance and design characteristics (e.g., reliability, lifetime, cost) of the phosphoric acid fuel cell power unit for the MX Shelter power application. The characteristics of the power unit for this or any comparable application that minimize the development risk are:

- Relatively low power rating (23 kW)
- Medium temperature ethanol or low temperature methanol fuel processing
- Atmospheric pressure operation
- Minimal packaging (i.e., size and weight) and transportability restrictions
- Relatively minor power conditioning requirements (DC-DC voltage regulation)
- Minimal startup/shutdown requirements.

The total estimated development efforts are 156,600 man hours for the methanol unit and 169,500 manhours for the ethanol unit (engineering, technicians, administration) over a four-year period. The majority of this effort is associated with design and testing of fuel cell power units to qualify this technology for military service and to verify performance and reliability estimates. The estimated total development costs of $15.6 million or $17.3

TABLE 4-22

DEVELOPMENT RISK ASSESSMENT
USAF FUEL CELL APPLICATION ANALYSIS, F33615-80-C-2038
METHANOL FUELED MX SHELTER POWER SYSTEM

SUBSYSTEM/MAJOR COMPONENT	CURRENT TECHNOLOGY STATUS	TECHNOLOGY RATING	REQUIRED TECHNOLOGY STATUS	REQUIRED DEVELOPMENTAL PROGRAM	ESTIMATED MANHOURS (Thousands)	ESTIMATED DEV. COST (000$)	PROBABILITY OF SUCCESS	ONGOING PROGRAMS & POTENTIAL ALTERNATIVES
1.0 FUEL PROCESSING								
1.1 Fuel Handling and storage	Extensive commercial experience with large stationary systems.	A	Simple, lightweight, semi-portable system. High reliability with MTBF $\geq$ 8000 hours.	1. Fuel pump selection and testing to establish reliability characteristics.	0.6	30	Excellent	U.S. Army studies.
1.2 Fuel Vaporizer/ Steam Generator	Extensive experience and data on separate methanol and water vaporizers.	B	Single vaporizer/steam generator for methanol/ water mixture.	1. Theoretical evaluation. 2. Lab scale testing to determine heat transfer characteristics and temperature requirements.	1.0	50	Excellent	None.
1.3 Methanol Reformer/ Furnace	Laboratory and small-scale (<5 KWe) experience. Related commercial experience with high temperature reformer for natural gas and methanol synthesis reactors. Extensive commercial experience with catalyst in low temperature shift converters. Small, mobile units (<5 KWe) under development for U. S. Army.	C	Lost cost, high reliability design. MTBF $\geq$ 5,000 hours. High conversion (>99.9%) at moderate steam-to-carbon ratios.	1. Full-scale design evaluation and verification 2. Cost Improvements	10.0	750	Very good	Extensive development programs for U.S. Army (small mobile units) and D.O.E (large stationary units).

TABLE 4-22 (Continued)

SUBSYSTEM/MAJOR COMPONENT	CURRENT TECHNOLOGY STATUS	TECHNOLOGY RATING	REQUIRED TECHNOLOGY STATUS	REQUIRED DEVELOPMENTAL PROGRAM	ESTIMATED MANHOURS (Thousands)	ESTIMATED DEV. COST (000$)	PROBABILITY OF SUCCESS	ONGOING PROGRAMS & POTENTIAL ALTERNATIVES
2.0 FUEL CELL								
2.1 Fuel Cell Stack	Laboratory and prototype experience. Life tests up to 80,000 hrs with H_2 fuel. Electrical performance (0.64 vDC at 150 amps/ft^2) exceeded in small test cells, but not full-size stacks. Large, multi-cell stacks being tested for utility applications. 4.8 MW demonstration plant under construction.	8	Cell life 40,000 hours. Cell voltage = 0.64 VDC at current density of 150 amps per ft^2. Minimal acid loss. Low cost design with high reliability.	1. Stack (multi-cell) testing to determine issues of thermal expansion, current collection, electrical isolation, manifold seals, flow distribution, acid management, startup/shutdown, and cooling improvement. 2. Cost improvement studies (lower catalyst loadings, manufacturing improvement, etc.)	7.0	350	Very good	Several development programs sponsored by D.O.E., U.S. Army, E.P.R.I., and various electric utilities. In house development by potential suppliers.
2.2 Cooling Systems and Fuel Cell Auxiliaries	Existing designs have water, air, and dielectric cooling. Laboratory and prototype experience with both atmospheric and pressurized systems.	8	High reliability and low cost. Atmospheric pressure operation.	No development program recommended.	0	0	N.A.	N.A.

TABLE 4-22 (Continued)

SUBSYSTEM/MAJOR COMPONENT	CURRENT TECHNOLOGY STATUS	TECHNOLOGY RATING	REQUIRED TECHNOLOGY STATUS	REQUIRED DEVELOPMENTAL PROGRAM	ESTIMATED MANHOURS (Thousands)	ESTIMATED DEV. COST (000$)	PROBABILITY OF SUCCESS	ONGOING PROGRAMS & POTENTIAL ALTERNATIVES
3.0 POWER CONDITIONING								
3.1 DC-DC Voltage Regulator	Existing technology Requires inversion to AC for voltage control, followed by rectification. Efficiencies 85-90%.	A	High efficiency (90-95%) Low cost.	1. Review of existing technology. 2. Investigation of direct DC power control.	1.0	50	Good	U.S. Army mobile units.
4.0 BALANCE OF PLANT								
4.1 Instrumentation and Control	Developed for small mobile systems and large (5 MWe)stationary plants. Assumes manned operaton.	A	High reliability and safety. Unmanned operation with automatic back-up.	1. Development of unmanned totally automatic control system.	2.0	100	Very Good	None for this particular requirement.
4.2 Air Cooler and Water Condenser.	Conventional technology.	A	Automatic operation. High reliability.	None	0	0	N.A.	N.A.
5.0 OVERALL SYSTEM	Complete, small (< 5kWe) units delivered to U.S. Army for premixed methanol/water fuel. Large (5MWe)stationary system under construction using natural gas fuel.	B	High reliability operation/with automatic control. Proper interfacing with load demand. Long life (12.5 years). Low performance degradation during operating lifetime. Capability to handle real methanol fuels.	Qualification program and field testing including: 1. Breadboard modules unit. 2. House development units (3). 3. Life test units (3). 4. Field test qualification units (3).	135	14,300	Very Good	None to verify this particular design and application requirements.
				TOTAL DEVELOPMENT PROGRAM	156.6	15,630		

TABLE 4-23

DEVELOPMENT RISK ASSESSMENT
USAF FUEL CELL APPLICATION ANALYSIS, F33615-80-C-2038
ETHANOL FUELED MX SHELTER POWER SYSTEM

SUBSYSTEM/MAJOR COMPONENT	CURRENT TECHNOLOGY STATUS	TECHNOLOGY RATING	REQUIRED TECHNOLOGY STATUS	REQUIRED DEVELOPMENTAL PROGRAM	ESTIMATED MANHOURS (Thousands)	ESTIMATED DEV. COST (000$)	PROBABILITY OF SUCCESS	ONGOING PROGRAMS & POTENTIAL ALTERNATIVES
1.0 FUEL PROCESSING								
1.1 Fuel Handling and storage	Extensive commercial experience with large stationary systems.	A	Simple, lightweight, semi-portable system. High reliability with MTBF 8000 hours.	1. Fuel pump selection and testing to establish reliability characteristics.	0.6	30	Excellent	U.S. Army studies.
1.2 Fuel Vaporizer/ Steam Generator	Extensive experience and data on separate ethanol and water vaporizers.	B	Single vaporizer/steam generator for ethanol/ water mixture.	1. Theoretical evaluation. 2. Lab scale testing to determine heat transfer characteristics and temperature requirements.	1.0	50	Excellent	None.
1.3 Ethanol Reformer/ Furnace	No directly applicable experience. Related small scale experience on methanol reformer. Related commercial experience with H_2 generator from natural gas or naptha fuels. Extensive commercial experience with catalyst in low temperature shift converters.	C	Lost cost, high reliability design. MTBF 40,000 hours. High conversion (99.9%) at moderate steam-to-carbon ratios.	1. Catalyst verification and life testing, including effect of impurities. 2. Multi-tube reformer design and testing. 3. Full-scale design evaluation and verification 4. Cost Improvements	20.0	2,000	Very good	Small "in house" Program at ERC

TABLE 4-23 (Continued)

SUBSYSTEM/MAJOR COMPONENT	CURRENT TECHNOLOGY STATUS	TECHNOLOGY RATING	REQUIRED TECHNOLOGY STATUS	REQUIRED DEVELOPMENTAL PROGRAM	ESTIMATED MANHOURS (Thousands)	ESTIMATED DEV. COST (000$)	PROBABILITY OF SUCCESS	ONGOING PROGRAMS & POTENTIAL ALTERNATIVES
2.0 FUEL CELL								
2.1 Fuel Cell Stack	Laboratory and prototype experience. Life tests up to 80,000 hrs with H_2 fuel. Electrical performance (0.64 VDC at 150 amps/ft^2) exceeded in small test cells, but not full-size stacks. Large, multi-cell stacks being tested for utility applications. 4.8 MW demonstration plant under construction.	B	Cell life 40,000 hours. Cell voltage = 0.64 VDC at current density of 150 amps per ft^2. Minimal acid loss. Low cost design with high reliability.	1. Stack (multi-cell) testing to determine issues of thermal expansion, current collection, electrical isolation, manifold seals, flow distribution, acid management, startup/shut-down, and cooling improvement. 2. Basic bipolar plate and cooling plate development and performance improvement. 3. Cost improvement studies (lower catalyst loadings, manufacturing improvement, etc.).	10.0	500	Very good	Several development programs sponsored by D.O.E., U.S. Army, E.P.R.I., and various electric utilities. In house development by potential suppliers.
2.2 Cooling Systems and Fuel Cell Auxiliaries	Existing designs have water, air, and dielectric cooled designs. Laboratory and prototype experience with both atmospheric and pressurized systems.	B	High reliability and low cost. Atmospheric pressure operation.	No specific development program recommended. "Taken care of" in item 5.0.	0	0	N.A.	N.A.

TABLE 4-23 (Continued)

SUBSYSTEM/MAJOR COMPONENT	CURRENT TECHNOLOGY STATUS	TECHNOLOGY RATING	REQUIRED TECHNOLOGY STATUS	REQUIRED DEVELOPMENTAL PROGRAM	ESTIMATED MANHOURS (Thousands)	ESTIMATED DEV. COST (000$)	PROBABILITY OF SUCCESS	ONGOING PROGRAMS & POTENTIAL ALTERNATIVES
3.0 POWER CONDITIONING								
3.1 DC-DC Voltage Regulator	Existing technology Requires inversion to AC for voltage control, followed by rectification. Efficiencies 85-90%.	A	High efficiency (90-95%) Low cost.	1. Review of existing technology. 2. Investigation of direct DC power control.	1.0	50	Good	U.S. Army mobile units
4.0 BALANCE OF PLANT								
4.1 Instrumentation and Control	Developed for small mobile systems and large (5 MWe)stationary plants. Assumes manned operaton.	A	High reliability and safety. Unmanned operation with automatic back-up.	1. Development of unmanned totally automatic control system.	2.0	100	Very Good	None for this particular requirement.
4.2 Air Cooler and Water Condenser.	Conventional technology.	A	Automatic operation. High reliability.	None	0	0	N.A.	N.A.
5.0 OVERALL SYSTEM	Complete, small (5 kWe) units delivered to U.S. Army for premixed methanol/water fuel. Large (5MWe)stationary system under construction using natural gas fuel. Forty-five 40 kW units are scheduled to be operating in 1984	B	High reliability operation/with automatic control. Proper interfacing with load demand. Long life (12.5 years). Low performance degradation during operating lifetime. Capability to handle fuel grad e ethanol fuels.	Qualification program and field testing including: 1. Breadboard modules. 2. House development units (3). 3. Life test units (3). 4. Field test qualification units (3).	135	14,600	Very Good	None to verify this particular design and application requirements
				TOTAL DEVELOPMENT PROGRAM	169.6	17,330		

million, respectively, includes all labor and materials, including the various test and demonstration FCPU's.

The total development cost estimated for the MX ethanol unit is $1.7 million more than the development cost estimate for the MX methanol unit. The major reason for the increase is a large amplification of the reformer development program for ethanol versus methanol. There is no demonstrated ethanol reformer practice upon which to base a design. The reformer art must be created in specific ethanol terms even though there is much related art to draw upon. On-the-other-hand, except for size and detail changes for MX unit use, methanol reformers are demonstrated state-of-art.

In carrying out the Development Risk Assessment, it has been assumed that the FCPU's would be the primary power supplies for the MX system and that the first production units would be required in 1986. Further, since the FCPU's are the primary power supplies for the MX, FCPU reliability and performance must be demonstrated to a high confidence level.

To demonstrate confidence in a statistical sense requires a large number of operating hours. For example: (1) using standard statistical techniques (Ref. 4-6) (2) assuming that the units produced have an actual MTBF of 3,000 hours, and (3) that the failures experienced during testing reflect the 3,000 hour MTBF, a total of 36,000 test hours is required to demonstrate that the units have at least a 2,000 hour MTBF to a 95 percent confidence level.

Most of these hours should be accumulated prior to delivery of field test qualification units to the Air Force. Assuming that at least six months of field trials are desirable and that the design and the minor, but necessary, component development portions of the four year program occupy the first two years, there are 18 months available during which major test hours may be accumulated. If the three house FCPU's and the three endurance FCPU's are available on the average of 50 percent of the time on a round-the-clock basis, just over 39,000 operating hours can be accumulated during the 18 month period.

In summary, it is felt that the proposed fuel cell power unit design involves relatively minor development risk with regard to component performance and reliability. The minimal development risk is a direct result of the proposed design concept, which utilizes the most proven and simplest phosphoric acid fuel cell features (e.g., alcohol fuel, atmospheric pressure operation, dc power conditioning, etc.). Despite the low development risk related to subsystem/component performance, significant development expenses are required to test and verify full-scale units for military use.

4.5 LIFE CYCLE COST

The following assumptions were made in computing the cost of the various Life Cycle Cost (LCC) elements for an individual FCPU:

- No cost escalation over period of service
- Life cycle period - 12.5 years
- R&D and Technical Data costs spread over 1000 production units
- No complete FCPU replacements will be required during 12.5 years service use because of units 20 year design life
- Capital, operation, and maintenance average yearly costs from Section 4.3
- 1980 $ rounded off
- Fuel Price $7 per 10^6 Btu

The results of the LCC calculations are as follows:

Cost Elements	Ethanol	Methanol
R&D	$ 17,300	$ 15,600
Technical Data	200	200
Initial Spares	4,700	4,500
FCPU Maintenance	67,500	64,600
FCPU Operation Costs	100,100	106,300
FCPU Capital Costs	69,400	67,600
TOTAL (12.5 years)	$259,200	$258,800

The cost of 190 proof alcohol in the future is the largest uncertainty in these LCC's. For example, currently ethanol is made, as it has been for thousands of years, from food. This is easy to do. It also uses an expensive feedstock and is relatively energy inefficient. Ethanol can be made from considerably cheaper feedstocks, such as cellulose wastes, and with greater energy efficiency. Similarly, methanol is, at present, generally made from natural gas. It could be made from coal, which is a cheaper feedstock. This is a developing technology.

If alcohols were made in large volumes using more advanced processing methods, there is reason to believe that alcohol fuel would be price competitive with other fuels on a dollar per heat unit basis. This is the position taken in this study. The price used is the most optimistic projected by the EPRI Fuel Cell Users Group for fuels generally in the 1990's. The pessimistic price projected by the EPRI group is \$10 per 10^6 Btu, rather than \$7 per 10^6 Btu. Using the \$10 per 10^6 Btu price, the LCC of the individual FCPU would increase about 17 percent.

5.0 60 KW DIESEL FUELED ATTENDED REMOTE POWER SYSTEM

5.1 INTRODUCTION AND SUMMARY

An application analysis, preliminary conceptual design development risk assessment, and Life Cycle Cost (LCC) estimate of a Fuel Cell Power Unit (FCPU) has been carried out. The application studied is the second of the six generic applications specified for analysis under the U. S. Air Force Fuel Cell Application Analysis program, Contract F 33615-80-C-2038. The generic application as specified in Section 4.1.1.1.2 of the Contract Statement of Work is an attended remote site with a power requirement between 30 kW and 60 kW.

The specific example selected for this application is that of providing electrical power and hot water space heating to a Distant Early Warning Line (DEWLine) radar site. The example site is designated PIN-1 and is located some five miles northwest of Clinton Point, Canada, beside the Arctic Ocean.

The electrical power requirements of the PIN-1 site are of utility 60 Hz AC type at voltages of 120/208V, 3-phase, 4-wire and 240/416V, 3-phase, 4-wire. Average daily peak power requirement is 190 kW and the average electric demand is 145 kW. Availability of power must be 99.5 percent or higher.

Electrical power to the PIN-1 site is currently supplied by 60 kW diesel-electric generators*. A portion of the space heating load of the station is provided by utilizing the waste heat from the diesel engines. Total space heating requirements are approximately 550,000 But/hr and are nearly constant year round. Diesel waste heat supplies the main Module Train Building only, and represents approximately 41 percent of the total space heating load.

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*In all, there are five diesel-electric units at the PIN-1 site. The normal situation is three operating, one on standby, and one off-line for maintenance.

The proposed FCPU design satisfies both the electrical demand and 100 percent (550,000 Btu/hr) of the space heating requirements. Since the FCPU's are more efficient producers of electricity than diesels, and a greater percentage of the reject heat is recovered, total site fuel consumption would be substantially reduced if fuel cells were substituted for the diesel generators.

It is proposed to satisfy the power and availability requirements of the PIN-1 site by using four 60 kW rating FCPU's. Although the unit rating is the same as that of the present diesel units, only four FCPU's are required versus five diesel-generators. The installation situation using FCPU's is somewhat more favorable because the higher reliability of FCPU's eliminates the need for a fifth backup unit required of the diesel installation. Estimated power availability using FCPU's is 0.9993.

A preliminary conceptual design of a 60 kW phosphoric acid FCPU that fulfills the operational requirements for use at the PIN-1 site (for example) has been created. Some of the major features of the design are as follows:

- Uses Air Force logistic diesel fuel (DF-A). Can also use JP-4 as a substitute fuel.
- Produces 12.0 kW-hrs per gallon of fuel used. (Current site average fuel usage is equivalent to an electricity production of 10.4 kW-hr per gallon of fuel.)
- No liquid waste disposal necessary (no oil changes).
- Current state-of-the-art component technology, except for the fuel reformer which is emerging laboratory technology.

A more complete summary of the 60 kW FCPU's characteristics is given in Table 5-1.

An artist's conception of the 60 kW FCPU is shown in Figure 5-1. The fuel cell unit proper and the power conditioning elements of the FCPU fit within the module train building of the PIN-1 site. The water condenser would be mounted external to the building. Its purpose is to recover water from the system exhaust to be reused in the fuel processing step of the FCPU cycle.

TABLE 5-1

60 kW FCPU CHARACTERISTICS SUMMARY

1. PHYSICAL PARAMETERS

   a) Type of Fuel: DF-A, alternate JP-4

   b) Fuel Consumption: 26,400 gallons per year (per unit)
   105,600 gallons per year (total, 4 units)

   c) Volume/Size: Volume - 282 ft^3; Footprint - 33.6 ft^2 (Power Station)
   - 7.5 ft^2 (Power Conditioner)
   - 10 ft^2 (Water Condenser)

   d) Weight: 6,200 lbs

   e) Environmental Constraint:

   Thermal Discharge: 230,000 Btu/hr MAX
   136,000 Btu/hr AVER

   Air Pollution: NO_x <0.24 lbs/MWH generated
   SO_2 - 5 to 10 ppm
   Others - Nil

   Noise: <75 db at 1 ft

   Solid Waste: 300 lbs per year of ZnO/ZnS

   Chemical Discharge: Trace H_3PO_4

   Radioactive Waste: None

2. PERFORMANCE PARAMETERS

   a) Reliability:

   Mean Time Between Failures: 3,000 hours
   Availability: 99.5% required; 99.93% calculated

   b) Lifetime: 20 years

   c) Operation and Maintenance:

   Ease of Operation: Record data; make minor adjustments once per day. Fifteen percent operator attention assumed.

   Ease of Maintenance: Trouble shooting, component replacement and checkout.

   Maintenance Skills Required: E-4 or civilian equivalent.

TABLE 5-1 (Continued)

d) Growth Potential:

Fuel cell stacks are of modular construction; growth potential of individual 60 kW FCPU's is limited by reformer and auxillary equipment capacities. Growth potential by parallelling more FCPU's appears infinite.

e) Start-up/Shutdown Time:

Start-up: 1-2 hours
Shutdown to Hot Standby: ∿15 minutes
Cold Shutdown: Two hours

f) Thermal Energy Available: 238,000 Btu/hr at 60 kW power output

g) Electrical Output:

Rating: 60 kW, 60 Hz, 120/208V or 240/416V
Class: 2 (Utility)
Operating Range: 20 kW to 66 kW

3. COST PARAMETERS

a) Capital Costs:

Fuel Cell Power Unit - $162,600; $2,710/kW
Fuel Tanks and Lines - Not applicable; existing installation.
Site Preparation - Not applicable; existing installation.
Initial Installation and Other Costs - $5,900

b) Maintenance Cost:

Transportation for Repair - $1,695/year
Personnel Cost - $8,830/year
Special Equipment Cost - None
Replacement Hardware Costs - $11,950/year

c) Operation Costs:

Fuel and Fuel Transportation Costs - $40,700/year (first year)
Supplies - $200/year
Operating Personnel Costs - $15,100/year

d) Life Cycle Costs:

20-year Life Cycle Cost - $2,466,000

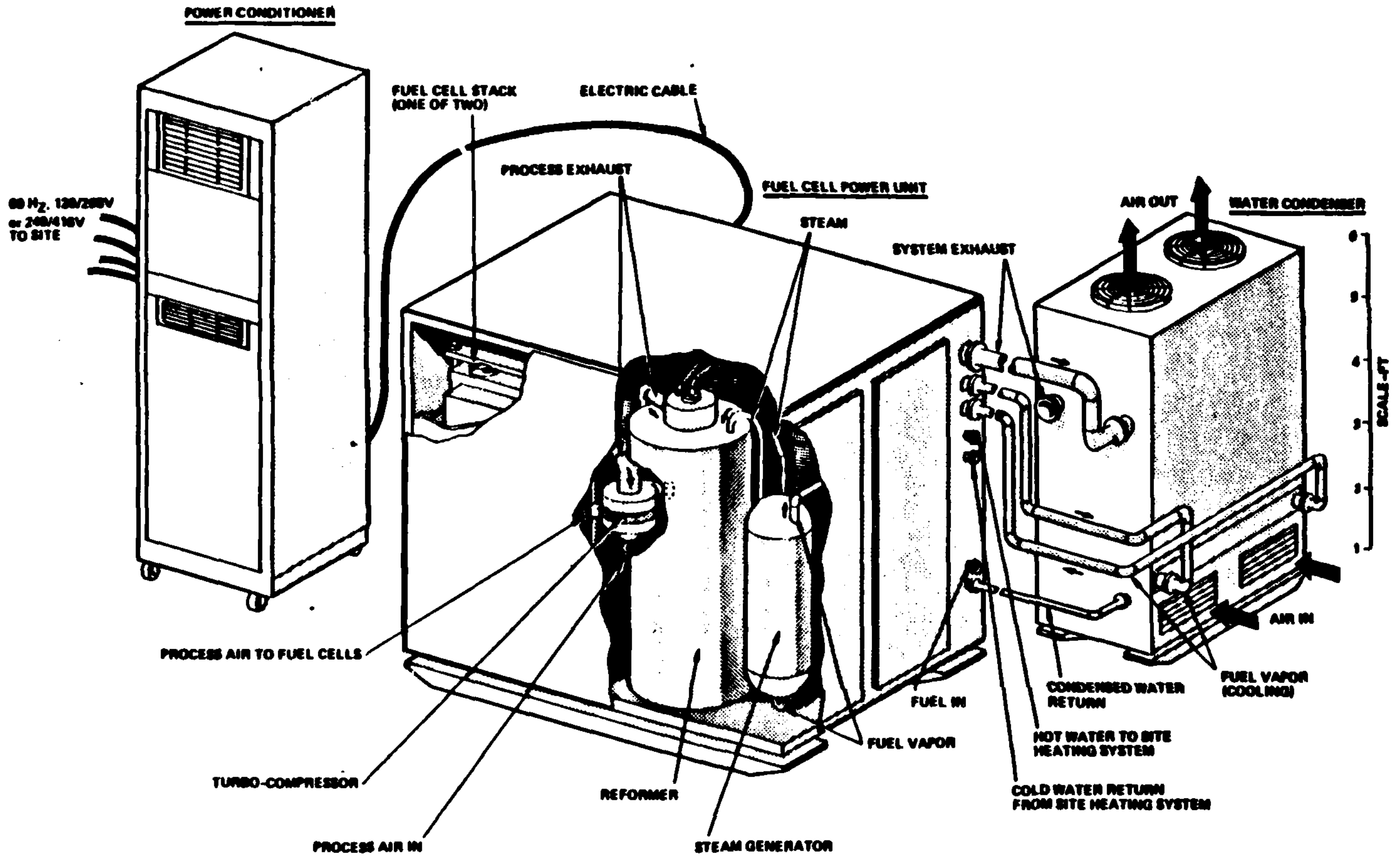

Figure 5-1. 60 kW, Diesel Fuel-Artic, Fuel Cell Power Unit

A technical development risk analysis of the foregoing preliminary conceptual design was carried out. No technology breakthroughs are required to achieve operational hardware. The design uses current state-of-the-art components except for the fuel reformer. Fuel cell stack technology being developed for utility and on-site integrated energy system applications is compatible with DEWLine fuel cell requirements. There is sound experimental, but laboratory based, knowledge on which to base the reformer design.

A program to develop the 60 kW DEWLine FCPU should have the following recommended major elements:

- A development effort to fully qualify the fuel reformer for FCPU service.
- A detail design and system analysis, integration, and optimization effort.
- A FCPU experimental verification and qualification effort.

It is estimated that the cost of such a development program will be approximately $6,580,000.

Preliminary life cycle cost estimates have been performed and indicate substantial savings when using FCPU's in place of diesel-electric generators. Total life cycle costs for a single 60 kW FCPU are $2.47 million over 20 years. Total life cycle cost savings for the PIN-1 application, as a whole, are over $2.8 million, and projected savings for the entire DEWLine System are $115 million. These estimates were made using a base year fuel cost delivered to PIN-1 of $1.75 per gallon, escalated at 5 percent per year.

An analysis of the DEWLine application, the preliminary conceptual design of a 60 kW FCPU, the development risk assessment of the FCPU and Life Cycle Cost estimates are given hereafter:

Section 5.2 - DEWLINE APPLICATION DESCRIPTION
Section 5.3 - POWER PLANT DESIGN

Section 5.4 - DEVELOPMENT RISK ASSESSMENT
Section 5.5 - LIFE CYCLE COST ESTIMATES
Section 5.6 - CONCLUSIONS

5.2 DEWLINE APPLICATION DESCRIPTION

A potential application of this Fuel Cell Power Unit (FCPU) is to provide prime electric power and power plant waste heat to remote radar stations of the Distant Early Warning Line (DEWLine) System. Currently, DEWLine sites are powered by diesel-electric generator sets. A major effort is underway to upgrade the radar stations with newer and more efficient electric generators.

The remote location of the DEWLine sites increases the cost and logistic considerations of supplying power generation fuel. Operation and maintenance of the electric generators is considerably more expensive due to the remote location. In addition, the disposal of lube oil from the existing diesel generators presents environmental problems. Fuel Cell Power Units (FCPU's) have the potential of reducing fuel, maintenance, and operation costs, while providing highly reliable electric power in a clean, quiet, and environmentally benign manner.

5.2.1 GENERAL APPLICATION DESCRIPTION (*)

5.2.1.1 DEWLINE RADAR SYSTEM

History

The DEWLine, located along an arc-shaped line closely approximating that of the Arctic Ocean coast and currently extending some 3,600 miles from Point Lay, Alaska (200 miles north of the Arctic Circle) eastward through Alaska, Canada, and Greenland to Kulusuk Island off the east coast of Greenland (at a point

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*Note: Much of the following descriptive information has been taken directly from the DEWLine Civil Engineering Information Brochure, Distant Early Warning (DEW) System Office, Aerospace Defense Command, January 1976. Updated information and additional comments were obtained directly from ADS personnel (primarily Mr. Don Cain) and FSI personnel (primarily C. Martin).

intersected by the Arctic Circle), was officially turned over to a civilian contractor as a system in 1957, following a five-year conception, development, and construction period.

The primary mission of the DEWLine was to provide an early warning of airborne attack from the North in sufficient time to enable the United States and Canada to take meaningful offensive and defensive action. The secondary mission, but extremely important, is the management, operation and maintenance of a modern wide-band communication system.

As originally constructed, the DEWLine extended only to the East coast of Canada at Cape Dyer, Canada and contained six Main Radar Stations, twenty-four Auxiliary Radar Stations, twenty-seven Intermediate Radar Stations, and three communications oriented rearward sites. Upgraded equipment and operational techniques have eliminated the need for the original intermediate stations. Today the DEWLine consists of the original Main and 21 Auxiliary Stations, and four additional Auxiliary Stations in Greenland.

Assigned Units

Military Units and Organization: The Aerospace Defense Command via its Distant Early Warning (DEW) System Office, exercises functional control of the DEW System. Overall operational control is exercised through NORAD. Militarily, the DEWLine is subdivided into three systems: (1) The DEW East Radar System consisting of four DEWLine Auxiliary Radar Stations beginning with DYE-4 on Kulusuk Island on the east coast of Greenland and running westward to DYE-1 on the west coast at Quaqatoqaq; (2) the DEW Canadian System consisting of four DEWLine Main Radar Stations and seventeen Auxiliary Radar Stations beginning with DYE-M (main station) on the east coast of Baffin Island at Cape Dyer and running westward to and including BAR-1 (auxiliary station) located at Komakuk Beach on the coast of the Arctic Ocean (Beaufort Sea) close to the Canadian/Alaskan border; and (3) the DEW Alaskan System consisting of two Main Radar Stations and four Auxiliary Radar Stations beginning with BAR-M (main station) on Barter Island, Alaska, and running westward to and including LIZ-2 (auxiliary station) located on the Arctic coast at Point Lay, Alaska. As indicated in the DEW System Organization Guide, Figure 5-2, military personnel are stationed at each of the six Main Radar Stations. Only contractor personnel are stationed at the remaining stations listed.

Organization

As originally conceived, the DEWLine consisted of six sectors each organized with a headquarters, including a military Data Center. For military functional and operational purposes, this arrangement is still in effect today. However, the Contractor has been permitted to restructure the DEWLine into four civilian geographical areas for administrative and logistic purposes, as shown in the Operation and Administrative Organization Chart, Figure 5-3. Civil Engineering management is provided on the DEWLine from four sector headquarters located at BAR-Main, CAM-Main, FOX-Main, and Sondrestrom AB (Greenland). The BAR-Main sector will manage sites LIZ-2 through BAR-Main; CAM Sector will manage sites BAR-1 through CAM-2; FOX sector will manage sites CAM-3 through DYE-Main; and Sondrestrom sector will manage all sites in Greenland (DYE-1 through DYE-4).

Support is rendered by the USAF at Sondrestrom, AB, Greenland; U. S. Navy at Point Barrow, Alaska, and Canadian Ministry of Transportation (MOT) at Cambridge Bay, Tuktoyaktuk, and Hall Beach, Canada. Details of support rendered at these locations are contained in the respective Host-Tenant, Cross-Service and other Agreements. The Danish Civil Aviation Administration is responsible for the operation and maintenance of the airstrip at DYE-4 and the maintenance of the road from the airstrip to the NEW site.

Layout

The DEWLine is laid out as indicated in the DEWLine Layout Map, Figure 5-4.

5.2.1.2 PIN-1 AUXILIARY RADAR STATION

The generic category for this Fuel Cell application is "an attended remote site with a power requirement between 30 kW and 60 kW". After interaction with personnel at the DEW System Office, Peterson AFB, Colorado, the PIN-1 Auxiliary Radar Station was chosen as a representative DEWLine site that meets the

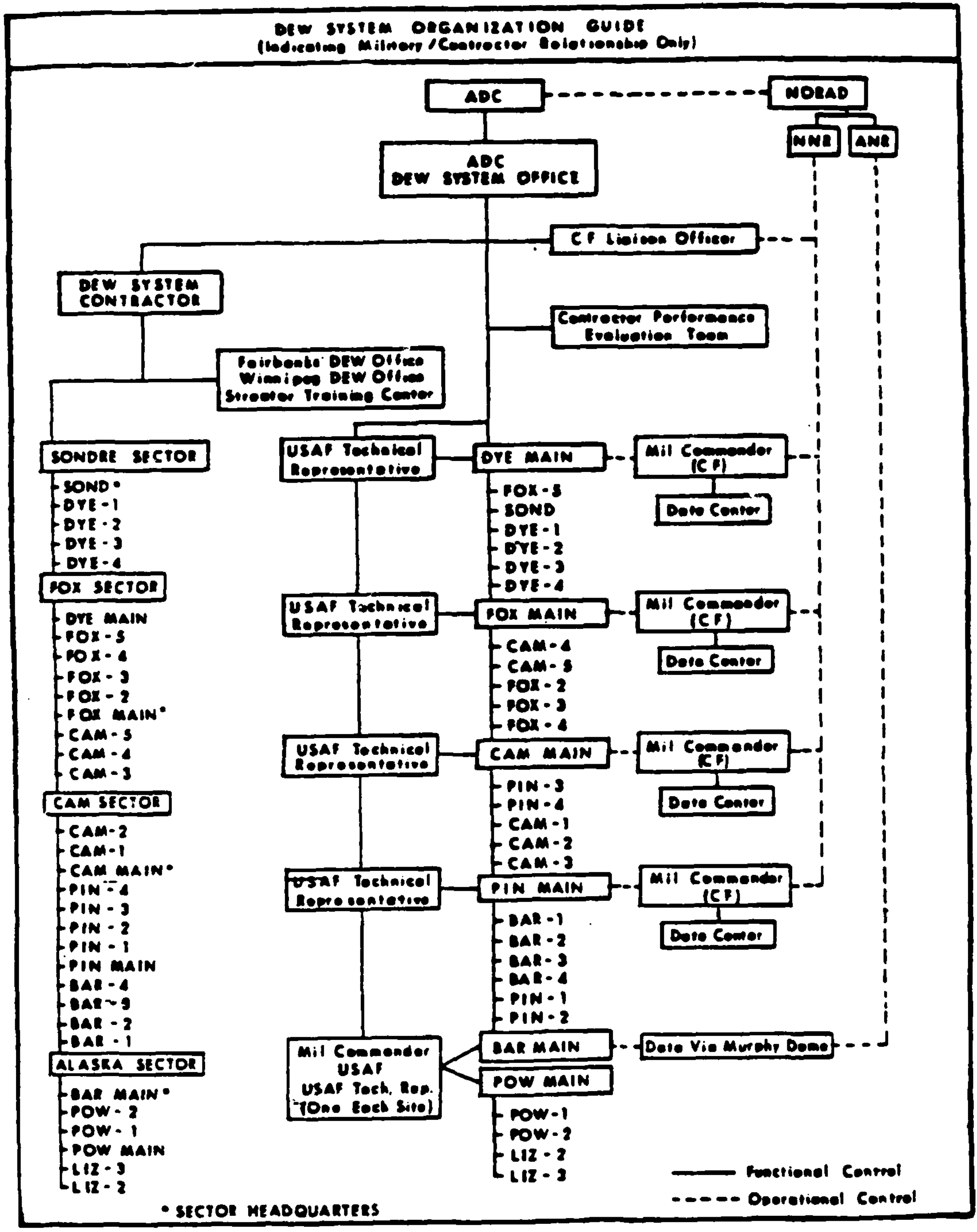

Figure 5-2. Dew System Organization Guide

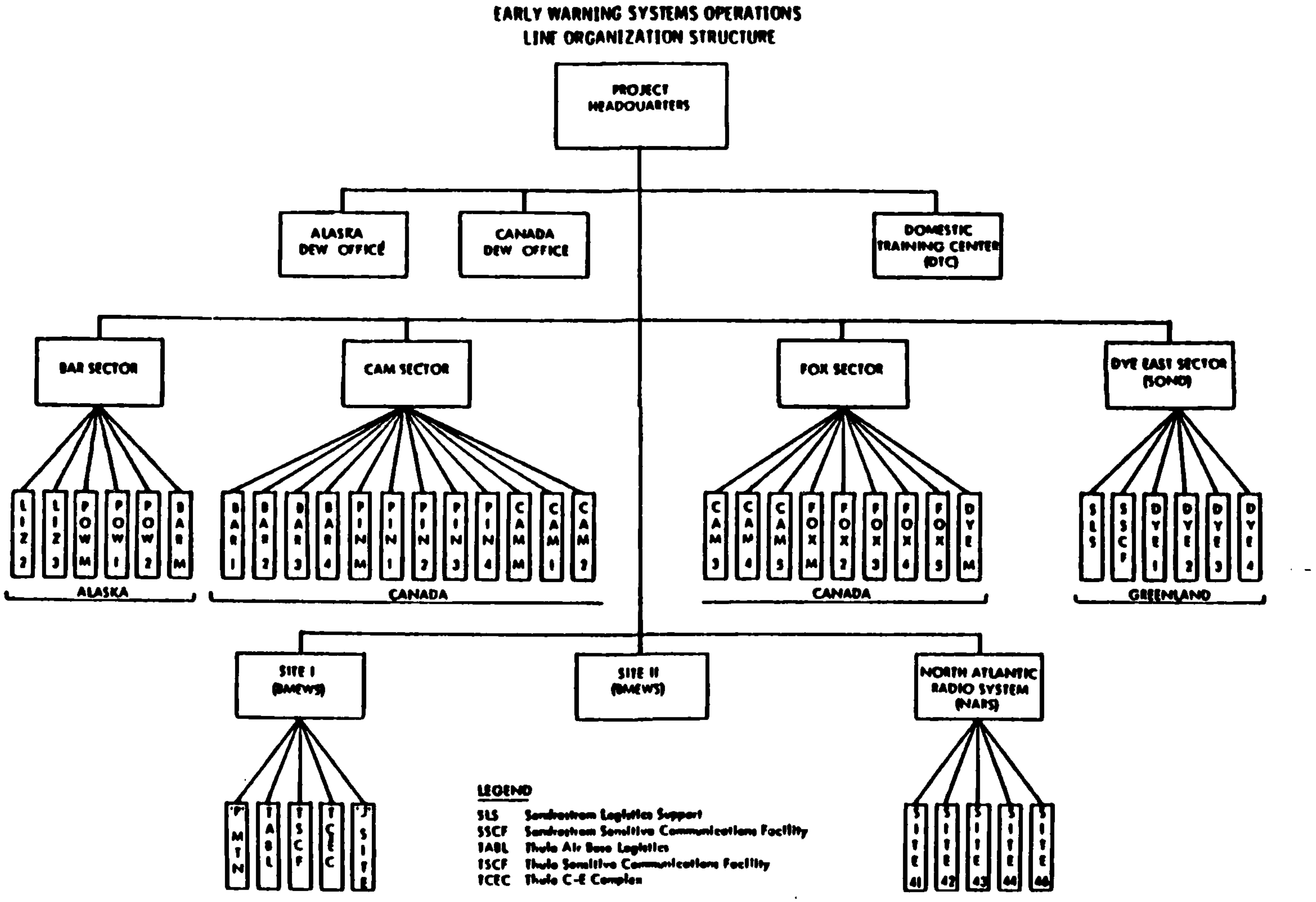

Figure 5-3. Dew System Operation and Administrative Organization Chart

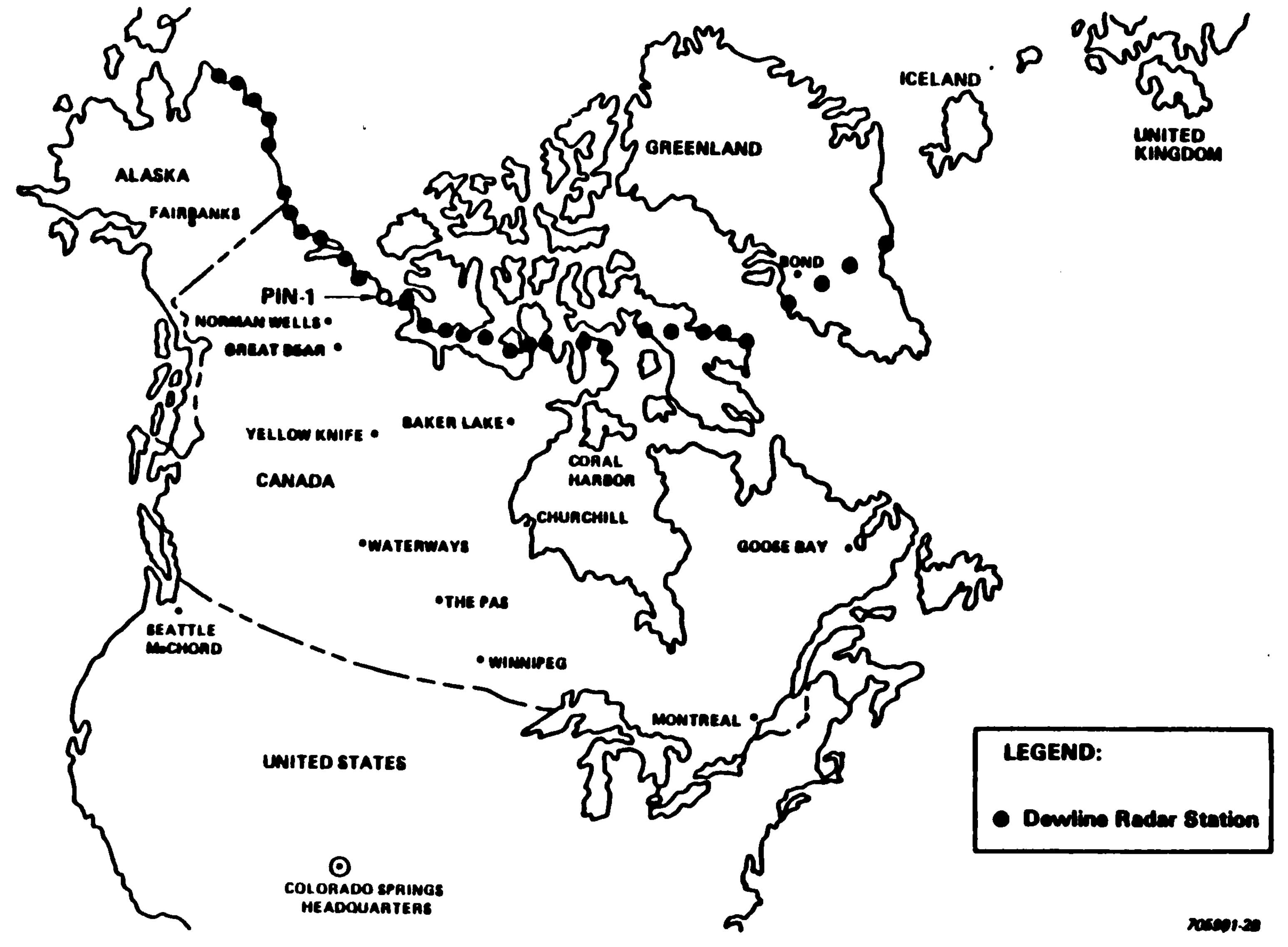

Figure 5-4. Dewline Layout Map

category requirements. Although PIN-1 has a peak electrical demand of 190 kW, it is powered by multiple 60 kW units.

General

PIN-1 is an auxiliary radar station of the DEW Canadian System. The civil engineering management is conducted through the CAM Sector headquarters located at the CAM-Main radar station. A complete site description and facilities details are given in Appendix D-2. A summary of the most pertinent site characteristics is given in the following paragraphs.

Location and Climate

Location: Clinton Point, Canada, on the Arctic Ocean shore of Amundsen Gulf. PIN-1 is located some five miles northwest of Clinton Point and ten miles east of Mount Rennel.

Precipitation: Annual (including 32-inch snowfall) = 8 inches

Temperature: Absolute minimum and maximum = -43°F, +83°F

Altitude: 300 feet above sea level

Facilities

Grounds: Total acres = 2,939

Buildings:		
	Semipermanent	= 4 (19,700 ft^2)
	Temporary	= 3 (1,600 ft^2)
	DIAND Eskimo Housing Units	= 2
	Total Number	= 9

Aircraft Facilities: Total surface (gravel) = 95,018 square yards

Water Distribution

External - Accomplished by water-haul from fresh water lake

Internal - Consists of steel receiving tank, filter plant, softener, chlorinator, primary and secondary potable water storage tanks, electric hot water heater, pumps, valves, lines, etc.

Electric Power

Generation: Diesel-Electric Units

Number: Five.

Make: GMC Model 60275.

Rating: 60 kW, 1200 rpm, 120/208V, 3 ph, 60 cy at 80% PF.

Internal Distribution - System consists of switchboard, single bus system (servicing both technical and utility loads) and assorted branch circuits in Module Train, with single bus service provided to the technical and utility load.

External Distribution - System consists of ground and drum supported cable runs, in general (with short buried runs under manmade obstructions), servicing buildings and areas requiring electric power and such transformers associated therewith.

Number of primary power transformers	4
a. Power plant to Garage (one, 120/208/2,400V)	75 KVA
b. Garage (one, 2,400/120/208V)	75 KVA
c. Powerplant to Airstrip Area (one, 120/208/2,400V)	30 KVA
d. Airstrip area (one, 2,400/120/208V)	30 KVA

Pol Storage/Distribution

Product is delivered by sealift to receiving tanks for redistribution via pipeline to Building Site and other secondary tanks and transferred via pumphouse to various fill stands and building day tanks. The day tanks of isolated buildings are serviced by tank vehicle. Drum stocks transferred via portable pump units or tank vehicle, as required.

Total Storage Capacity, External Tanks (U. S. Gallons)	282,550 GAL
1. Avgas: (5 drums, emergency stock)	225 GAL
2. Diesel Oil: (4 tanks, steel)	260,000 GAL
3. Mogas: (1 tank)	20,525 GAL
4. Athey Wagon:	1,800 GAL
Total length of pipelines (including building feeder lines)	2 inch x 8560 ft

Heating

Module Train:

1. Primary System: Circulating hot water servicing single-tube, finned convectors. Heat recovered from powerplant engine coolant and exhaust gases is transferred to heating system via heat exchangers.
2. Supplementary System: Electric unit heaters in areas not fully serviced by convectors.
3. Emergency System: During periods when an insufficient number of engine-alternator units are operating to fulfill heating requirements, an oil-fired boiler (450,000 BTU/hr output) is available to supply hot water for the heating system.
4. C&E Mission Modules: Heat recovered from electronic equipment is distributed and recirculated via fans and ductwork.

Other Buildings:

1. Garage: Hot air, oil-fired furnace (4500 cfm, 400,000 Btu/hr)
2. Warehouse: Hot air, oil-fired furnace (3400 cfm, 240,000 Btu/hr)

5.2.1.3 ELECTRIC POWER REQUIREMENTS

Engineering Information Brochure

According to ADS personnel, (Ref 5-1)*, the electric power requirements at the PIN-1 radar station have changed from those listed in the 1976 DEWLine Civil.

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*References given in Appendix A-3.

Whereas the Brochure lists an average electric demand of 192 kW and a daily peak demand of 208 kW, the revised demands are 145 kW and 180-190 kW, respectively. Assuming average monthly power consumption and average monthly fuel oil consumption have been reduced in accordance with the reduced electric demand, the revised consumption figures for PIN-1 are as follows:

TABLE 5-2

PIN-1 POWER AND FUEL CONSUMPTION

Average Electric Demand	145 kW
Average Daily Peak	180-190 kW
Minimum Electric Demand (after load shedding)	120 kW
Average Power Consumption	
- Monthly	104,400 kW-hr.
- Annual	1,252,800 kW-hr
Fuel Oil Consumption (all purposes)	
- Monthly	10,500 gal

Normal operation of the existing diesel-electric generators consists of three operating units, one standby unit, and one off-line maintenance unit. In the case of a unit failure, the remaining two operating units are able to maintain minimum station load by load shedding (shutting down of non-essential power consumers such as lights, dishwashers, etc.) The standby unit is able to come up to load in approximately one minute. The minimum load condition (after load shedding) is a transient mode and the electric power system must be able to return the station to full power in a short time (several minutes maximum).

Overall electric power availability is maintained at 99.5 percent or higher. The design operating life of the electric power generators is 20 years. Existing engine room dimensions at PIN-1 are 24'L X 12'W X 10'H.

5.2.2 FCPU DESIGN REQUIREMENTS

The PIN-1 radar station electric power requirements and operational requirements establish the overall design basis for a fuel cell electric power system. However, the design requirements for individual FCPU's must be more specific and include such things as physical dimensions and weight limitations, voltage connection, reliability, electrical performance, environmental requirements, cost goals, etc. These items have been established from a variety of sources, including:

- DEWLine Civil Engineering Information Brochure (January, 1976)
- Personal conservations with Mr. Don Cain, 4700th Air Defense Squadron (Support), TAC, Peterson AFB
- Written comments from TAC Civil Engineering (Major S. Gray to W. A. Summers, February 6, 1981)
- Personal conversations with Mr. Craig Martin, FSI Civil Engineering, Colorado Springs, Colorado
- Mobile Electric Power Characteristic Data Sheets (MIL-STD-633E)
- Other military and federal specifications and standards
- Westinghouse and Energy Research Corp. experience related to PAFC design and capabilities

The FCPU design requirements have been summarized in a document entitled, "Requirements Data Sheet, Fuel Cell Power Unit, Attended Remote, 60 kW, 60 Hz, No. W-RDS-2". A copy is included in Appendix C-2. Some of the important requirements are:

Power Classification = Type II (prime)
Class 2 (utility)
Mode I (50/60 Hz)
Fuel Type: DF-A, Fed. Spec. VV-F-800B
Voltage Connection, 120/208V, 3 phase, 4 wire
240/416V, 3 phase, 4 wire
Reliability: MTBF (specified) = 1,500 hours
Fuel Consumption: 5.0 gph (max)
Cold Start-up: 1 hour at -20°F
Design Life: 20 years

5.3 POWER PLANT DESIGN

Since such sites as those of DEWLine require prime power, without a utility grid back-up, high power system reliability is the most important design criteria. The specified availability of electric power is 99.5 percent, with actual availability (using diesel generators) even higher. This high availability is maintained by the use of multiple power generators. At PIN-1 (145 kW average electric demand), five 60 kW diesel-electric generators are employed. Using a similar philosophy, four 60 fuel cell power units (FCPU's) are proposed. Fewer FCPU's are required than diesels due to their higher individual availabilities. The FCPU concept is shown schematically in Figure 5-5.

In addition to high reliability, the remote DEWLine application requires high system efficiency and minimal operating and maintenance requirements. These characteristics not only have a major impact on life cycle costs, but are important from a logistics standpoint as well. Other power plant requirements, such as weight and volume, mobility, noise level, start-up time, etc., are of lesser importance for this application.

Each individual FCPU can be subdivided into four major subsystems as shown on Figure 5-6. These subsystems are:

- Fuel Processing
- Power Generation (PAFC)
- Power Conditioning (DC/AC Conversion)
- Waste Heat Recovery

In order to establish the preferred system design and arrangement, a thorough evaluation was made of the various subsystem and major component options, and tradeoff studies were conducted to determine their effect on overall system performance, etc. These studies are discussed in Section 5.3.1. The chosen Fuel Cell Power Unit (FCPU) design concept is described in Section 5.3.2, along with subsystem design summaries and projected FCPU performance. Power plant usage considerations, such as design life and maintenance requirements, fuel

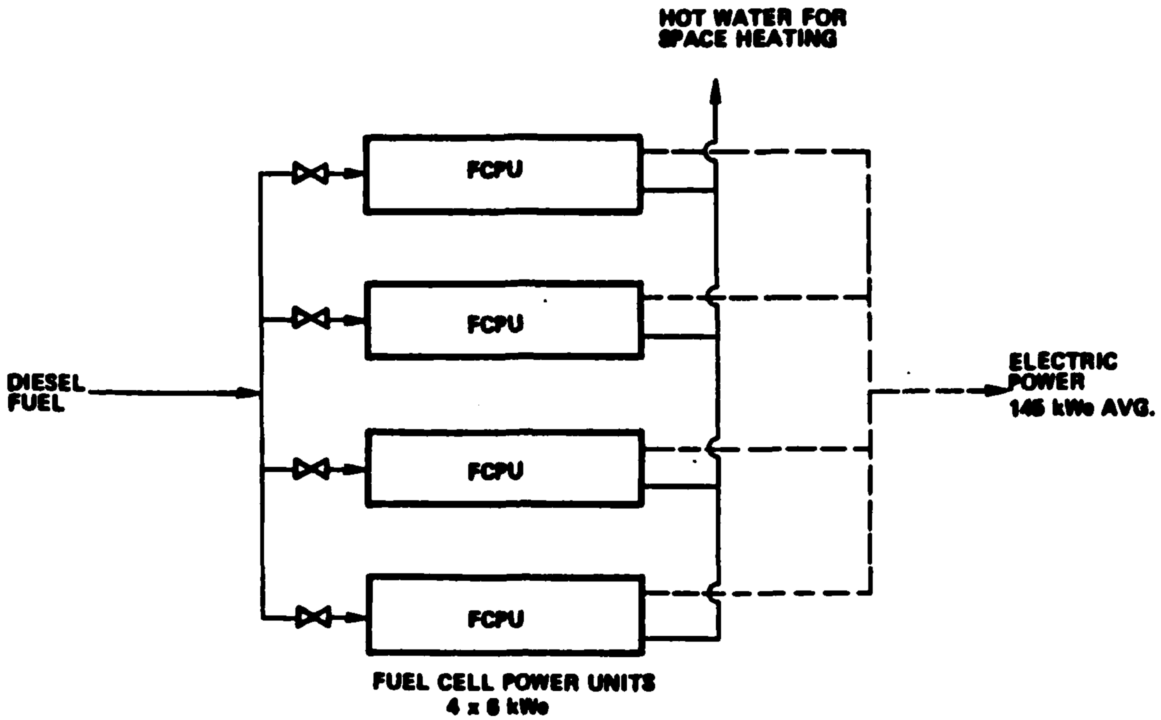


Figure 5-5. FCPU Concept for PIN-1

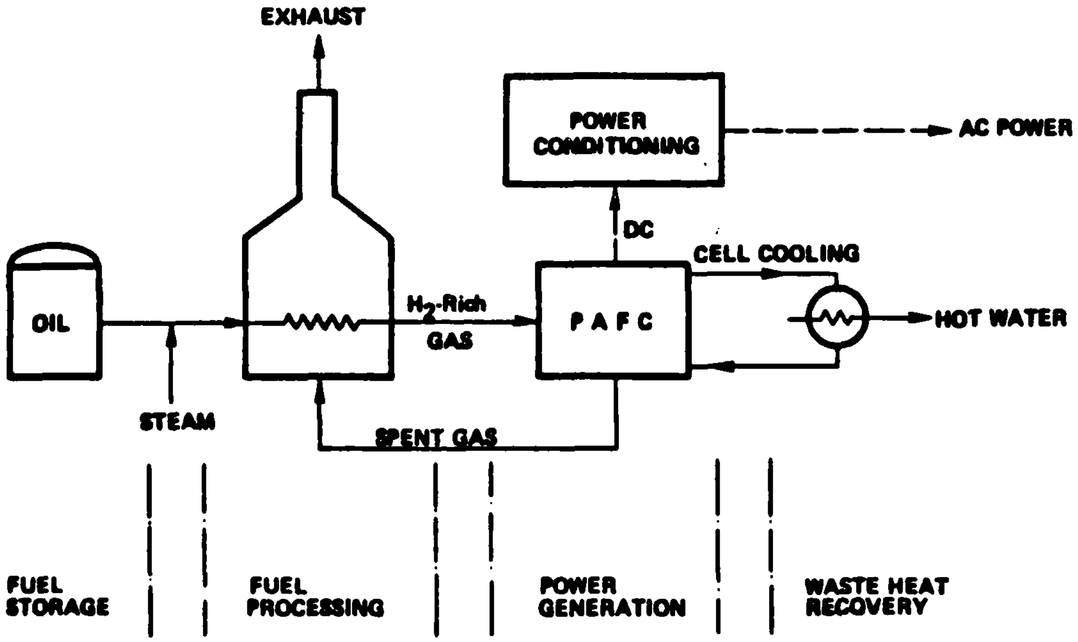


Figure 5-6. FCPU Major Subsystems

supply, system operation, and availability of power are presented in Section 5.3.3. A preliminary cost analysis is given in Section 5.3.4.

5.3.1 MAJOR SUBSYSTEM OPTIONS AND TRADEOFFS

The major tradeoffs studied for this application concerned the method and type of fuel processing system, the design (e.g. cell size, cooling method, etc.) and operating point for the phosphoric acid fuel cell stack, and overall system options concerning water recovery, waste heat utilization, and system operating pressure.

5.3.1.1 FUEL PROCESSING SUBSYSTEM

The Fuel Processing Subsystem (FPS) converts the process fuel, normally a gaseous or liquid hydrocarbon, into a hydrogen-rich fuel gas stream that can be utilized in the anode of the phosphoric acid fuel cell. In addition, the FPS must remove any fuel contaminants, such as sulfur, to acceptable levels. A number of FPS designs have been tested or proposed, and the choice of a particular design is highly dependent on the type of raw fuel and the fuel cell requirements.

The DEWLine radar stations are presently powered by diesel-electric generators fueled with a light Arctic-grade diesel fuel, DF-A. Most sites also have jet fuel, JP-4, available. However, due to present storage and logistic considerations, it is preferred to continue to utilize DF-A as a powerplant fuel. A summary of DF-A Fuel properties is given in Table 5-3.

Diesel fuel is a heavier feedstock than those presently employed in conventional hydrogen production plants. Due to its greater tendency to crack and form carbon deposits, and its relatively high sulfur content (compared to natural gas or naphtha), it requires an advanced FPS design. A study of fuel processing systems for jet and diesel fuels reached the following major conclusions (Ref 5-2):

- Of the various fuel reforming processes available, only the following three were deemed desirable for PAFC powerplants:

  1) Conventional Steam Reforming (STR)
  2) High Temperature Steam Reforming (HTSR)
  3) Autothermal Reforming (ATR)

- For light fuels, perhaps including JP-4, conventional steam reforming is preferred.

- STR is not practical for heavy feedstocks due to the complexity and potential operational problems associated with high pressure desulfurization.

- HTSR is preferred over ATR on the basis of higher process efficiency and lower life cycle costs.

- ATR may be preferable for applications requiring rapid startup or reduced system cubage and weight.

Based on specification W-RDS-2 requirements a high temperature steam reformer was selected. The HTSR has a slightly higher hydrogen yield per pound of fuel and a higher hydrogen concentration in the reformed gas than an autothermal reformer, resulting in reduced gas flowrates and greater system fuel economy. Although the ATR has advantages in transient response, startup time, and lower system weight, these characteristics were not considered major requirements for this application. A summary of the candidate fuel reforming processes is given in Table 5-4.

5.3.1.2 PHOSPHORIC ACID FUEL CELL

The processed fuel gas is electrochemically reacted in a phosphoric acid fuel cell (PAFC) module to produce DC electricity and process heat. The PAFC module consists of individual fuel cells arranged in a vertical stack, associated structural components, anode and cathode gas feed and distribution system, and a fuel cell cooling system. The major design options include fuel cell size (active cross sectional area per cell), stack arrangement, the type and design of the cooling system, and selection of the design current density.

TABLE 5-3
FUEL PROPERTIES

Type	DF-A, Arctic Diesel
H/C Molar Ratio	1.8
Arg. Molecular Wt.	175
Representative Formula	$C_{12.7}H_{22.8}$
Distillation End Point, °F	572
Sulfur (max), ppm	1,500
API Gravity	41.0
Higher Heating Value	
Btu per pound	19,780
Btu per gallon	133,500
Delivered Cost, $/gal.	1.75

TABLE 5-4
FUEL REFORMING PROCESSES

PROCESS	OPERATING CONDITIONS	CHARACTERISTICS
● Conventional Steam Reforming	1,400-1,600°F 20-40 atm	- Low S Tolerance - Limited to Heavy Naphtha or Lighter Feedstocks
● High Temperature Steam Reforming	1,600-1,800°F 1-10 atm	- Good S Tolerance - Can Handle Heavy Fuels - Large Catalyst Volume
● Autothermal Reforming	1,600-2,200°F 1-10 atm	- Adiabatic Operation - Simpler System Design - Cannot Use Fuel Cell Waste Heat - Higher Plant Heat Rate

Cell Sizing

The basic building blocks of the PAFC subsystem are the individual fuel cells, composed of bipolar plates, anode and cathode layers, the electrolyte (H_3PO_4) matrix, and associated components. Various overall cell sizes (width and length) have been employed by different designs and for different applications. For a given cell voltage and current density, the active cell area determines power output per cell and therefore the total number of cells required.

For the DEWLine application, a 12" X 17" cell size was chosen. This is the standard PAFC design being developed by Westinghouse Electric Corporation and Energy Research Corporation (ERC). By using a standard cell design that is being developed for other fuel cell applications, the development risk for the fuel cell subsystem is markedly reduced. If a non-standard cell design was chosen, basic cell development and testing would be required.

It is noted that other cell designs and sizes, such as those under development by United Technologies Corp. or Engelhard Industries, could also have been selected. However, the Westinghouse/ERC cell design is compatible with the system requirements and was the design for which the most information was available. No advantage was determined for selecting one of the alternate designs. It is felt that the study results and conclusions are valid for PAFC's on a general basis, although it was necessary to choose a particular design in order to size system components and prepare a complete plant design.

Stack Arrangement

Tradeoffs were evaluated in respect to the number of cells per stack, number of stacks, method of electrical interconnection (i.e., series versus parallel), and output DC voltage. An existing power conditioning system design was employed, requiring an input DC voltage of the range 200-300 volts. Since the voltage per cell under pressurized conditions is approximately 0.7 volts (depending on design conditions of current density, etc.), the required number of cells in series is 285 to 425. At a design current density of 135 amps per square foot and cell voltage of 0.72 volts (see following discussion of current density selection), the total number of 12" X 17" cells required to produce a gross power output of 69 kW is 640. To limit stack height and provide the required output voltage, these are arranged into two stacks of 320 cells each, connected in parallel fashion. Output DC voltage is approximately 230 volts at rated load.

Cooling Method

Various cooling methods are feasible for PAFC stacks. The Westinghouse/ERC concept utilizes recirculating air cooling, and was the design selected for the FCPU. Other cooling schemes include water cooling and liquid cooling employing a dielectric fluid. The liquid-cooled designs require the use of numerous tubes to contain and convey the liquid. As a result, there are a large number of tube connections that present potential leakage problems. Since reliability is the most important design requirement for the application, the air-cooled design appears preferable. However, it is felt that the overall study results, including FCPU performance and cost, will not be significantly affected by the choice of fuel cell cooling method.

Current Density

Due to polarization and internal resistance (ohmic losses), the obtainable cell voltage decreases with increasing current density (amps per square foot of active cell area). The designer is therefore faced with a tradeoff between efficiency (i.e., high cell voltage at low current density) and capital cost (i.e., smaller cell area at higher current densities).

A preliminary tradeoff study comparing various current densities for a 60 kW pressurized FCPU is shown in Table 5-5. It can be seen that higher current densities do result in substantially smaller stack sizes, but they also require larger auxiliary (primiarily heat removal) systems and have higher plant heat rates. A moderately low current density of 135 amps per square foot results in the lowest life cycle cost.

TABLE 5-5

DESIGN POINT SELECTION
60 kW Pressurized FCPU

Design Current Density, ASF	100	135	200	300
Cell Voltage, vpc	0.74	0.72	0.69	0.66
Total Cell Area, Ft^2	930	710	500	350
Relative Stack Size	1.31	1.00	0.70	0.49
Relative Heat Rejection	0.94	1.00	1.11	1.22
System Fuel Use, gph	4.88	5.03	5.25	5.49
Incremental Costs (1980$)				
Fuel Cell Stack	13,600	Base	(13,000)	(22,300)
Fuel Processing	(1,000)	Base	1,300	3,000
Cooling and Aux.	(2,700)	Base	5,000	9,900
Total Cost Differential	9,900	Base	(6,700)	(9,400)
Incremental Fuel Cost (5 years)	(6,100)	Base	9,800	20,500
Net Incremental Cost	3,800	Base	3,100	11,100

($) = Cost credit

5.3.1.3 SYSTEM DESIGN OPTIONS

Both water recovery and waste heat recovery have been incorporated into the 60 kW FCPU system design. Approximately 70 percent of the water contained in the system exhaust is condensed and returned to the process. This makes the FCPU water self-sufficient; no fresh makeup water is required.

Waste heat recovery is utilized to provide 210°F hot water for space heating and also to reduce the heat load on the water condensers. To provide a high waste heat potential, and also simplify reformer thermal design, all the waste heat from the fuel cell cooling loop is used for space heating. This results in a "nonintegrated" fuel processing subsystem, which requires a slightly higher system fuel consumption, but allows for better thermal integration in the reformer subsystem. Approximately 70 percent of the cogeneration heat for heating hot water comes from the fuel cell cooling loop, while the remaining 30 percent is recovered from cooling of the reformed gas and the reformer furnace flue gas.

The choice of system operating pressure was based on a performance and cost comparison between an unpressurized (atmospheric) system design and a pressurized (60 psia) design. Although atmospheric operation is normally assumed for small on-site PAFC systems, pressurization increases system efficiency and reduces the size of most major components. On the other hand, pressurization increases system complexity and control, and requires the addition of a relatively expensive turbocompressor. Since high system efficiency was deemed a major requirement of the 60 kW power system, a tradeoff study of system pressure was conducted. System flowsheets and material balances for atmospheric operation are shown in Figure 5-7 and Table 5-6. Those for pressurized operation are given in later Section 5.3.2.1, Process Description.

The performance of the pressurized and unpressurized systems are shown in Table 5-7. The pressurized system has a 13 percent lower plant heat rate (11,200 versus 12,800 Btu per kW-hr). Both systems provide 100 percent (550,000 Btu/hr) of the station space heating needs, although the atmospheric system has the potential to supply an additional 140,000 Btu/hr. A potential

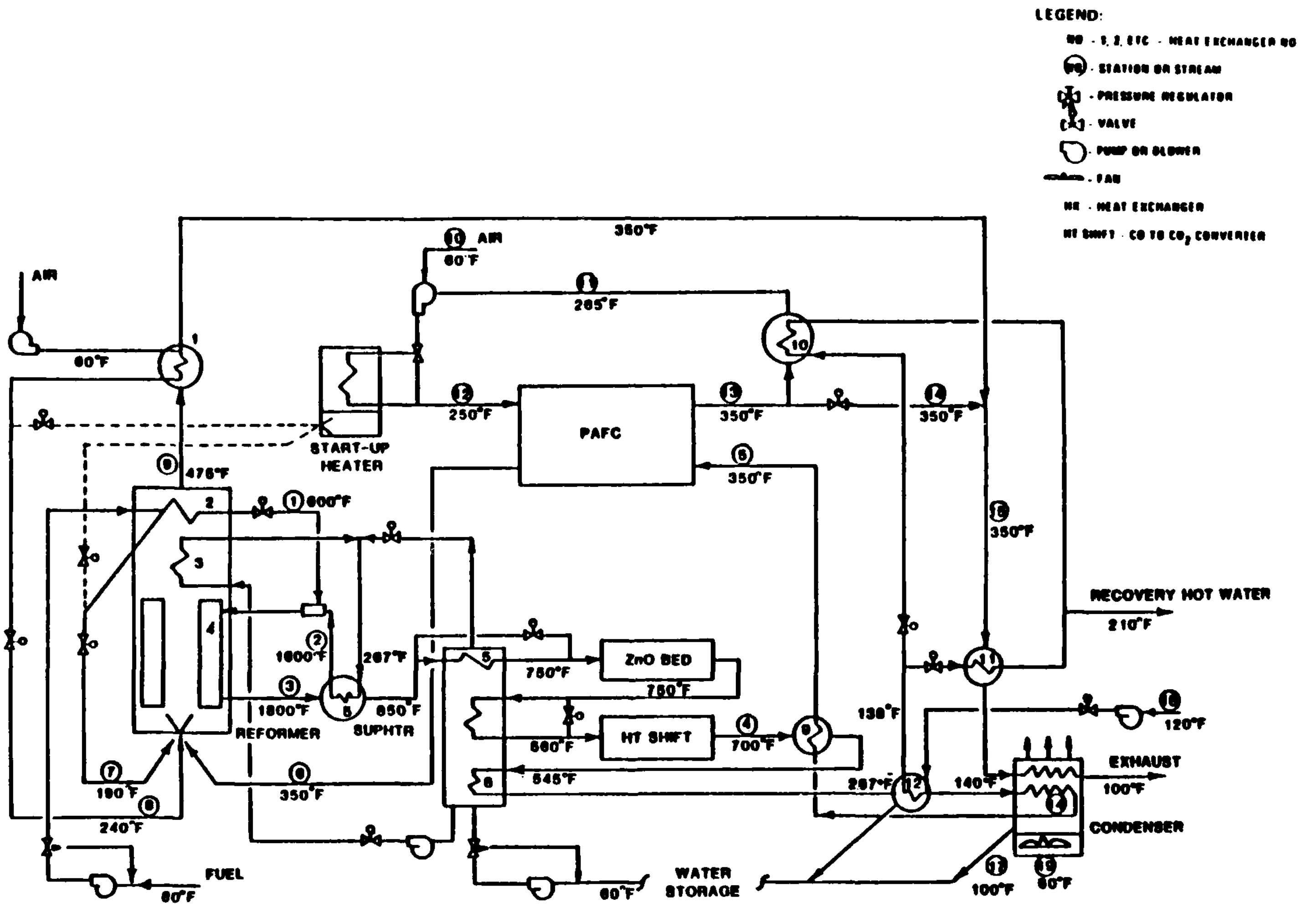


Figure 5-7. 60 kW FCPU System Schematic - Atmospheric Cell Operation

TABLE 5-6

STATE POINTS - ATMOSPHERIC CELL OPERATION

STREAM	MOLAR FLOW, lb-m/hr								FLOW lb/hr	TEMP °F	PRESS PSIA
	H_2	CO	CO_2	CH_4	H_2O	N_2	O_2	HC			
1. Fuel to Reformer								1.946	27.00	600	60
2. Steam to Reformer					7.781				140.06	1600	60
3. Reformer Product	4.279	1.051	0.797	.097	5.136				167.06	1800	60
4. Shift Exit	5.194	.136	1.711	.097	4.221				167.06	700	60
5. PAFC Feed Gas	5.194	.136	1.711	.097	0.203				94.73	350	-
6. PAFC Exit Gas	0.779	.136	1.711	.097	0.203				85.87	350	-
7. Fuel to Burner								0.657	9.11	190	60
8. Burner Air Supply						7.000	1.859		255.5	240	-
9. Reformer Exhaust			2.601		1.792	7.000	0.242		350.4	465	-
10. PAFC Air Supply						16.61	4.414		606.2	60	-
11. Recycle Air					52.36	219.6	29.18		8134.8	265	-
12. PAFC Air In					52.36	236.2	33.59		8741.0	250	-
13. PAFC Air Out					62.78	236.2	31.39		8750.0	350	-
14. PAFC Exhaust					4.414	16.61	2.207		615.2	350	-
15. Total Exhaust			2.601		6.207	23.61	2.450		965.6	350	-
16. Recovery Water					3.665				66.0	130	-
17. Recovery Water					4.116				47.1	100	-
18. Hot Water Supply						98.3	22.8		3485	120	-
19. Condenser Air Flow						236.7	62.9		8640	60	-

DESIGN BASIS

85% Cell H_2 use
95% Fuel Conversion
18550 BTU/LB DF-A (NHV)
52018 btu/Lb CO
21758 btu/Lb CH4
2.0 Cell Stoair
1.15 Burner Stoair
60°F, 0% Rel. Hum.
69 kW Gross Power
60 kW Net Power

HEAT EXCHANGER LOADS (BTU/HR)

	SENSIBLE	LATENT	AREA, ft^2
1. Air Heater	12400		10
2. Fuel Vaporizer	6730	5590	6
3. Primary Stm. Vaporizer	--	106290	15
4. Reformer Bed	163300		17
5. Steam Superheater	96260		33
6. Gas Cooling Coil #1	9833		3
7. " " " #2	17650		6
8. " " " #3	26130		16
9. Gas Reheater	14070		10
10. Heat Recovery Coil #1	176190		190
11. " " " #2	59265		120
12. " " " #3	12050	64000	150
13. Water Cndr Coil #1	11210	65660	360
14. " " " #2	2640	6175	30

TABLE 5-7

ATMOSPHERIC VERSUS PRESSURIZED OPERATION
60 kW FUEL CELL POWER UNIT

	ATMOSPHERIC	PRESSURIZED
Net ac Power, kW	60	60
Gross dc Power, kW	70.5	69.0
Current Density, ASF	135	135
Operating Pressure, PSIA	15	60
Cell Voltage, VPC	0.64	0.72
Total Cell Area, Ft^2	815	710
Total HX Area, Ft^2	950	780
Turbo-Compressor Flow Rate, lb./Min.	0	16
Unit Heat Rate, Btu/kW-Hr	12,800	11,200
Process Heat Available, 10^3 Btu/Hr	690	550
(3 Units; 145 kWe Avg. Load)		
Space Heating Demand, 10^3 Btu/Hr	550	550

economic comparison is shown in Table 5-8. The pressurized units cost $52,000 more than the unpressurized units, but the cost differential is recovered, in less than two years, by reduced fuel costs.

TABLE 5-8

ATMOSPHERIC VERSUS PRESSURIZED OPERATION
ECONOMIC COMPARISON

	ATMOSPHERIC	PRESSURIZED
Annual Power Consumption, 10^6 kW-Hr	1.26	1.26
Annual Fuel Use, 10^3 Gallons	118	103
Percent Space Heating Needs	100	100
Capital Cost Differential (4 Units)	-	$52,000
Annual Fuel Savings at $1.75/Gal.	-	$26,300
Payback Period	2 Years	

5.3.2 FCPU DESCRIPTION

5.3.2.1 PROCESS DESCRIPTION

The Fuel Cell Power Unit consists of a pressurized fuel processor, a pressurized phosphoric acid fuel cell stack, DC-AC power conditioning, and associated pumps, compressors, and heat exchangers. Figure 5-8 and Table 5-9 show the system schematic and associated flow streams and state points (at rated load of 60 kW).

Arctic-grade diesel fuel, DF-A, is steam reformed in a high temperature steam reformer operating at 65 psia, 1800°F outlet temperature, and a steam-to-carbon ratio of 4.0. Fuel conversion to carbon oxides is 95 percent, resulting in a dry methane slip (dry volume percent CH_4 in reformer exit) of 1.6 percent. Reformed gas composition is near equilibrium at the exit temperature and contains 38 percent H_2, 9 percent CO, 7 percent CO_2, 1 percent CH_4, and the remainder water. The product gases exiting the reformer are then cooled to 750°F, passed over a ZnO bed to remove H_2S, further cooled to 560°F, and passed through a shift converter. The shift converter reacts approximately 87 percent

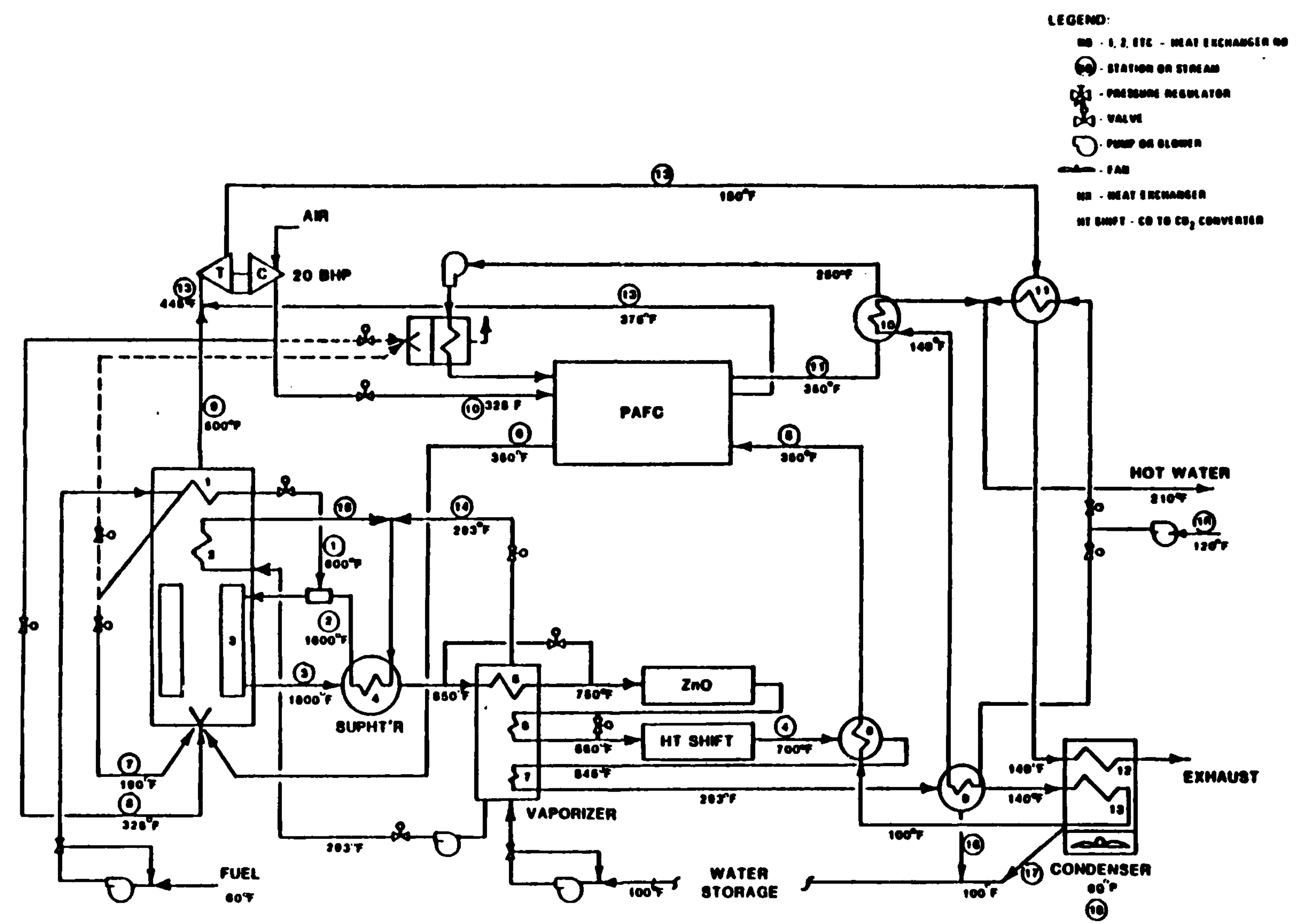


Figure 5-8. 60 kW FCPU System Schematic - Pressurized Operation

TABLE 5-9

STATE POINTS - PRESSURIZED OPERATION - 60 kW FCPU

	STREAM	MOLAR FLOW, LB-m/hr H_2	CO	CO_2	CH_4	H_2O	N_2	O_2	HC	TOTAL lbs/hr	TEMP °F	PRESS PSIA
1.	Reformer Fuel								1.737	24.11	600	60
2.	Steam To Reformer					6.947				125.00	1600	60
3.	Reformer Products	3.821	.938	.712	.087	4.586				149.17	1800	60
4.	Shift Exit	4.637	.122	1.528	.087	3.769				149.17	700	60
5.	Fuel Cell Feed	4.637	.122	1.528	.087	0.180				84.58	350	60
6.	Exit Feed Gas	.695	.122	1.528	.087	0.180				76.67	350	60
7.	Burner Fuel								0.59	8.18	190	60
8.	Burner Air Supply						6.241	1.659		227.84	325	60
9.	Reformer Exhaust			2.323		1.600	6.241	0.216		312.64	500	60
10.	PAFC Air Supply						14.82	3.94		541.10	325	60
11.	Cooling Air						153.5	40.56		5595.0	350	14.7
12.	PAFC Exhaust Air					3.94	14.82	1.97		548.90	375	60
13.	Total Exhaust			2.323		5.54	21.06	2.18		861.66	180	--
14.	Vaporizer Exit					1.17				21.00	293	60
15.	Reformer Vap. Exit					5.78				104.00	293	60
16.	Water Recovery					2.78				50.00	140	--
17.	Water Recovery					4.17				75.00	100	--
18.	Hot Water Supply					175,6				3160.0	120	--
19.	Condenser Air Flow						226.0	60.0		8250.0	60	

DESIGN BASIS

85% Cell H_2 use
95% Fuel Conversion
18550 BTU/LB DF-A (NHV)
52018 btu/Lb CO
21758 btu/Lb CH4
2.0 Cell Stoair
1.15 Burner Stoair
60°F, 0% Rel. Hum.
69 kW Gross
60 kW Net

HEAT EXCHANGER LOADS (BTU/HR)

		SENSIBLE	LATENT	AREA, ft^2
1.	Fuel Vaporizer	6010	4990	10
2.	Prim. Steam Vaporizer	-	94900	13
3.	Reformer Bed	145800	-	16
4.	Steam Superheater	84920	-	30
5.	Gas Cooling Coil	9810	-	2.5
6.	Gas Cooling Coil	15760	-	5.5
7.	Gas Cooling Coil	21150	-	13.0
8.	Gas Reheater	12560	-	5.0
9.	Hot Water Heater	12000	45775	100
10.	Hot Water Heater	201400		250
11.	Hot Water Heater	10080		50
12.	Condenser Coil	10000	58600	300
13.	Condenser Coil	2360	8200	40

of the residual CO with steam to produce additional H_2 and lower the CO concentration to less then 2 percent. The purified gases are then cooled to condense out the moisture and reheated to 350°F before entering the fuel cell anode.

The fuel cell reacts 85 percent of the available hydrogen with oxygen to produce DC power and process heat. The oxygen is supplied by a once-through air flow with an inlet stoichiometry of 2.0 and a pressure of 60 psia. The process heat is removed by a separate cooling air flow that enters at 250°F and leaves at 350°F.

Unreacted H_2 in the anode exhaust, along with residual CO and CH_4, are burned in the reformer furnace to provide heat for the endothermic reforming reaction. Additional liquid fuel, representing 25 percent of the total FCPU fuel requirements, is also burned in the reformer furnace. The fuel reforming takes place in a high temperature steam reformer of the type being developed by Toyo Engineering Corporation. It consists of a fixed bed of two types of catalysts (designated T12 and T48) placed in series. Total gas space velocity (TGSV) is $800V/V/hr^{-1}$ (volumetric flowrate of gas per catalyst bed volume).

The hot reformer exhaust gas is used to vaporize the fuel and generate approximately 83 percent of the process steam. The remaining steam is generated in an external feedwater heater/steam generator. The two steam flows are combined and superheated to 1,600°F by hot product gas leaving the reformer.

Air is supplied for reformer furnace fuel combustion and fuel cell process air via a turbo-charger/compressor operating on reformer combustion gases and cell exhaust air. There is sufficient energy in these streams to develop the 22 BHP needed to compress ambient air to 60 psia. Total air requirements are based on burner combustion at 1.15 stoichiometry and fuel cell stoichiometry of 2.0.

Cell cooling air is recirculated in a pressurized, closed loop system. Separate air manifolding provides flexibility in cell cooling channel design and air requirements. Heat absorbed by the cooling air is used to heat hot water to 210°F for integration with the DEWLine space heating system. Additional waste heat is recovered during the cooling of reformer product and system exhaust gases prior to the water condenser. Total cogeneration heat, supplied by heating recycled water from 120°F to 210°F, is 238,000 Btu per hour, or 36 percent of the total fuel higher heating value. System thermal efficiency, defined as net AC electric power plus cogeneration heat divided by the total fuel heat input (based on the higher heating value), is 66.1 percent. Power plant heat rate is 11,200 Btu per kilowatt-hour.

Design parameters for each of the major subsystems are given in Table 5-10.

5.3.2.2 POWER PLANT PERFORMANCE

The FCPU performance profile for 60 percent, 100 percent, and 110 percent load levels is shown in Table 5-11. A complete design and performance summary at rated load is given in Table 5-12. The electric generating efficiency and thermal utilization are nearly constant over the load range. Four FCPU's, operating at 60 percent load each, provide the required electric load of 145 kW and 100 percent of the station space heating needs. Fuel to electric power conversion rate is 12.0 kilowatt-hours per gallon.

5.3.2.3 FCPU SIZE AND WEIGHT

The projected volumes and weights of major system components and the assembled power unit are shown in Table 5-13. These projections are based on scale up of existing designs with allowances for additional components, including water recovery and heat recovery equipment. Items not included are auxiliary battery power, fuel and water storage, and inert gas vessels used for system starting. The estimated package weight and volume are slightly higher than would be required with a similar 60 kW system used with natural gas or naphtha. These differences are attributed to additional fuel processing components and heat recovery equipment.

The overall volume of the power unit is projected near 282 ft^3 with a system weight of 6200 lbs. To accommodate the existing PIN-1 engine room size requirements, the FCPU is physically divided into the following three sections:

TABLE 5-10
MAJOR FCPU DESIGN PARAMETERS

FUEL CELL SUBSYSTEM	
Design Pressure, psia	60
Design Temperature, F	350
Cell Hydrogen Utilization, %	85
Process Air Stoichiometry,	2.0
Cooling Load, 10^3 Btu/hr	170
Output Voltage, VDC	230
No. of Cells Required	640
No. of Cell Stacks	2
Active Cell Area, ft^2 per cell	1.1
Operating Point, vpc @ ASF	
110% Design	.71 @ 150 ASF
100% Design	.72 @ 135 ASF
60% Design	.74 @ 80 ASF
Cooling Air Required, CFM @ STP	1,530
FUEL CONDITIONING SUBSYSTEM	
Design Pressure, psia	65
Reformer Design Temp, °F	1,800
Space Velocity, $v/v/hr^{-1}$	800
Catalyst Type (Toyo T12/T48)	CaO, NiO
Catalyst Volume, ft^3	5.5
Shift Catalyst Type,	Cu/ZnO
Shift Catalyst Volume, ft^3	3.6
Desulfurization Catalyst	ZnO
Desul. Catalyst Volume, ft^3	2.5
Design Fuel Sulfur, wppm	1,000
Turbo-Charger Output, CFM @ STP	190
Design Combustion Stoichiometry	1.15

TABLE 5-10

MAJOR FCPU DESIGN PARAMETERS (Continued)

POWER CONDITIONING SUBSYSTEM

KVA Rating (continuous)	69
Input, Volts DC	200-300
Output	60 Hz, 3-phase, 4-wire, 120/208 volts
Type	Voltage Fed, Forced commutated
Harmonic Distortion	Less than 5 percent
Efficiency @ 0.9 Power Factor	
50% Load (35 KVA)	91%
100% Load (69 KVA)	92%

HEAT RECOVERY SUBSYSTEM

Total Heat Recovery (4 units), 10^3 Btu/hr	550
Inlet Water Temperature, °F	120
Outlet Water Temperature, °F	210
Heat Exchanger Type	Shell and Tube
Percent Space Heating Demand	100

TABLE 5-11
FCPU PERFORMANCE PROFILE

	Average Load	Rated Load	Peak Load
Percent Rated Load	60	100	110
Net AC Power, kW	36	60	66
Gross DC Power, kW	42.5	69.0	75.8
Current Density, ASF	84	135	150
Nominal System Pressure, psia	40	60	65
Cell Voltage, vpc	.74	.72	.71
Fuel Use, gph	3.0	5.0	5.6
Process Heat, 10^3 Btu/hr.	139	238	271
Heat Rate, Btu/kW-hr.*	11,100	11,200	11,300
Thermal Utilization, %	65.4	66.1	66.4

*HHV = 138,600 Btu/gal.

TABLE 5-12
FCPU DESIGN AND PERFORMANCE SUMMARY

DESIGN BASIS

Power Output, kW (Nominal/Peak)	60/66
Voltage, Regulated AC	120/208
Fuel Type	DF-A
Ambient Temperatures, °F	-65 to +85
Altitude, feet above SL	10,000

PROJECTED PERFORMANCE(1)

Parasitic Power Req., kW	3.5
ac/dc Conversion Eff., %	92
Gross Cell Power, kW	69
Thermal Losses, % Input	5
Power Efficiency, kw-hr/gal	12.0
Heat Rate, Btu/kW-hr @ A 60 kW	11,200
Cogeneration Heat, Btu/hr @ 60 kW	238,000
Water, Gal/hr @ 60 kW	15
Recovered Process Water, % Needs	100
System Thermal Efficiency, %	66.1
System Starting Time, hrs	1-2
System Weight, lbs (exluding storage tks)	6,200
System Footprint, ft^2	51
System Volume, ft^3	282

(1) Based on DF-A, 0.81 Specific Gravity, 133,500 Btu/gal (HHV)

TABLE 5-13
60 KW FCPU COMPONENT SIZES

	Weight, lbs.	Volume, Ft.^{3}
Fuel Cell Stack w/Manifolds	1,500	35
High Temperature Steam Reformer	650	10
Shift Reactor and ZnO Vessel	400	8
Heat Exchangers	500	35
Pumps, Blowers, Turbocharger, etc.	250	6
Controls, Packaging Skid Base, etc.	600	85
Subtotal	3,900	179
Power Conditioner	2,200	52
Water Condenser	100	51
Total	6,200	282

Approximate Dimensions:

Power Generator	6'6"L X 5'2" W X 5'4"H
Power Conditioner	3'L X 2'6"W X 7'H
Water Condenser	4'L X 2'6"W X 5'1"H

- Power Generator - 6'6"L X 5'2"W X 5'4"H; 3,900 lbs
- Power Conditioner - 3'L X 2'6"W X 7'H; 2,200 lbs.
- Water Condenser - 4'L X 2'6"W X 5'1"H; 100 lbs.

All four power conditioners (one per FCPU) could be located side-by-side in one corner of the engine room. The air-cooled water condenser would be located outside of the engine room, presumably on the roof. The power generator units can be spaced in the engine room to allow ready access to each unit.

5.3.2.4 FCPU CONTROL AND OPERATION

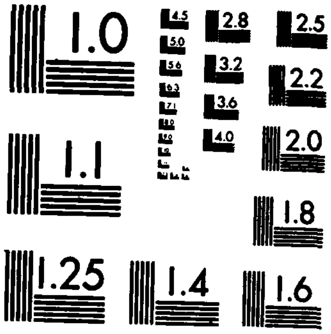
Microprocessor based control is recommended for use with the 60 kW FCPU. Table 5-14 lists the primary control functions which will be needed for minimum control of the power plant. Assessment of all operational requirements is unknown at this level of effort because the system incorporates developmental reformer technology. Two key problems, coking and sulfation, may occur within the reformer subsystem, requiring a means of detection and avoidance. Carbon deposition and pluggage of the reformer catalyst can be detected by an increase in reformer pressure loss; this can be minimized or avoided by proper control of the reformer. Also, sulfur removal rate and absorption capacity of the ZnO desulfurizer bed must be monitored to protect downstream catalysts. This requires the use of two ZnO beds in series, with H_2S detection between beds. These control requirements will need additional study with working models to adequately assess control set points and detection means. In addition to using an automatic control system, operational assistance will be needed during system warm-up and starting. Normal operation will be "hands-off," with operator attention required on a "walk-by" basis.

Power unit starting is achieved by heating the reformer, desulfurizer, and shift catalyst to operating temperatures by firing fuel in the reformer burner. A separator burner/heat exchanger unit is utilized in the cooling air loop for fuel cell heating. Starting time will be governed by the reformer subsystem due to its higher operating temperature and limits imposed by reformer metallurgy and catalyst heating. Heating of reformer subsystem

TABLE 5-14
MAJOR CONTROL FUNCTIONS

Controlled Variable	Control Means
Power Output (load following)	Current Measurement Feedback to Control Valves
Fuel & Steam Flow	Proportioning Control Valves
Reformer Temperatures	RTD Feedback to Burner Firing Rate
Fuel Cell Temperature	RTD Feedback to Recirculation Cooling Air Flow Valve
Shift Outlet Temperature	Thermostatic By-Pass Flow Control on Steam Vaporizer
ZnO Bed Temperature	Thermostatic By-Pass Flow Control on Steam Vaporizer
System Pressure	Turbocharger Output Pressure Regulation
Fuel Cell Pressure	Differential Pressure Regulation on Anode & Cathode
Water Condenser Temperature	Air Cooler Fan Number and Speed or Damper Flow Control
Exhaust Gas Water Concentration	Load Following Damper Control to Maintain 2.0 Cell Air Supply

AD-A126 121 U S (UNITED STATES) AIR FORCE FUEL CELL APPLICATION 3/5
ANALYSIS..(U) WESTINGHOUSE ELECTRIC CORP PITTSBURGH PA
ADVANCED ENERGY SYST.. W D POUCHOT ET AL. JAN 82
UNCLASSIFIED WAESD-TIME-3134 AFWAL-TR-82-2004 F/G 10/2 NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

catalyst may require the use of moisture free or inert gas (e.g. nitrogen) to prevent moisture condensation or oxidation of catalysts. Thermocouple (RTD) sensors would be used to control burner firing rates. A separate air blower is needed to provide combustion air until sufficient thermal energy is available to drive the turbocharger compressor. Power for operating system components during start-up can be provided by adjacent operating power units or by a common battery pack. Although starting time cannot be fully assessed at this time, a minimum of one to two hours is estimated. Starting power for operation of the system, excluding the water condenser fan, for the two hour period is projected near 5 kW.

Load following is obtained by measuring fuel cell current output (demand) and adjusting reformer fuel and steam flow valves, accordingly. This controls the volume of reactants entering the catalyst bed and hydrogen output to the fuel cell. Rapid demand, if required, is tied into the reformer burner control to provide increased combustion and reaction heat. Gas phase flow control valves would be used to modulate steam and vaporized fuel flow. Combustion air and fuel cell process air flow valves control air flow rates in response to demand. Preliminary analysis of transient response rates indicates the capability of applying a simulated 10 kW motor load while operating at 50 kW output.

Thermal system control is obtained by monitoring reformer catalyst, shift catalyst, desulfurizer bed, and fuel cell temperatures and adjusting flow rates, accordingly. Reformer catalyst temperature is maintained by adjusting burner combustion rate during changes in system demand. Desulfurizer and shift catalyst temperatures are maintained by controlling the amount of gas entering or by-passing the external water vaporizer. If necessary, steam superheat and fuel vapor temperature may have to be controlled to avoid carbon deposition in the reformer, or maintain gas outlet temperatures. These control functions may be necessary depending on reformer design.

Fuel cell plate temperatures are controlled by the rate of heat removal from the cooling air loop. This requires adjusting water heating system flow rates between the facilities storage tanks and the heat recovery unit. A near constant space heating load has been assumed. If large variations in space heating demand exist, an air cooler, operating parallel with the space heating system, may be required.

System pressures would be maintained by pressure regulators at the fuel and water pumps and in the process air and anode gas stream entering the fuel cell. To prevent crossleaks in the cell stack, the cooling air loop and stack assembly are encased in a pressure vessel. Loss of system pressure would signal shutdown of the power unit.

Water recovery rate in the system exhaust condenser would be subject to changes in system flows. To ensure adequate recovery for system needs, temperature of gases entering the unit would be controlled by upstream heat exchangers, and air flow would be varied to control the exhaust temperature leaving the system.

5.3.3 POWER PLANT USAGE CONSIDERATIONS

5.3.3.1 DESIGN LIFE AND MAINTENANCE REQUIREMENTS

The Fuel Cell Power Units will require both scheduled and unscheduled maintenance. Major component design life and maintenance requirements are shown in Table 5-15. Based on reliability estimates performed during this study for other FCPU's, the mean time between failure for each 60 kW FCPU is estimated to be 3,000 hours. This assumes that preventative maintenance and routine system inspections (during operator "walk-by") will be performed. The MTBF estimate includes unscheduled outages only, and does not represent scheduled outages for overhauls, catalyst replacement, etc.

In general, the FCPU's are expected to require substantially less maintenance than diesel-electric generators. Therefore, no additional maintenance personnel will be required beyond those used presently. It may be possible to reduce the size of the maintenance crew, but this is unlikely since the same maintenance personnel that service the electric power generators also service other radar station equipment. At present, the power plant is manned approximately 25 percent of the day. It is estimated that this can be reduced to 15 percent for a fuel cell power plant.

TABLE 5-15

SYSTEM MAINTENANCE CHARACTERISTICS

<u>Major Component Replacement</u>	
Fuel Cell Stack	5 Years
Reformer Catalysts	3-5 Years
Shift Catalyst	3-5 Years
Desulfurizer Catalyst	6 Months
<u>Forced Outage Maintenance</u>	
Fuel Vaporizer Cleaning	1-6 Months
Inspection & Cleaning	Yearly
<u>On Line Maintenance</u>	
Acid Replenishment	Yearly
Calibration & Adjustment	Yearly

A six month scheduled outage is assumed for each FCPU, on a rotating basis. This outage is planned to allow replacement of the ZnO desulfurization catalyst, cleaning of the fuel vaporizer, and replacement of any short-life components (e.g., filters, etc.). The replacement of ZnO catalyst is dependent on the actual sulfur content of the fuel. A catalyst bed of 150 pounds has been used, which allows 1,250 hours of full load operation (60 kW) with DF-A containing 1,000 ppm sulfur. The catalyst life would be 4,150 hours with 60 percent load operation and 500 ppm sulfur. Cleaning of the fuel vaporizer is required due to coking at vaporization temperatures. The actual severity of coking with typical DF-A fuel needs to be assessed. If severe coking occurs, it may be necessary to use parallel vaporizers and decoke while the FCPU is operating. The estimated total duration of the six month scheduled outage is 12 hours, which includes time for cool down and restart.

The FCPU's will require overhauls at 2-1/2 year and 5 year intervals. The primary reason for the 2-1/2 years overhaul is to replace the reformer and shift catalysts. These catalysts are anticipated to have a 3-5 years life. Therefore, it is uncertain whether or not they will remain active until the five year major overhaul. Replacement after 2-1/2 years is a conservative approach, and experience may show that 5 year replacement intervals are sufficient. Total outage time for the 2-1/2 years overhaul is estimated to be 60 hours.

The 2-1/2-year overhaul will also be used to replace any short-life components such as pump seals, burner components, etc. Even though the estimated Mean Time Between Failures of the FCPU's is 3,000 hours, preventative maintenance during the six month scheduled outages and 2-1/2 and 5 year overhauls may markedly increase unit reliability.

The purpose of the five year overhaul is the replacement of the fuel cell stack. Fuel cell performance will slowly degrade with time, and 40,000 hours, or roughly five years, is the design life of a stack. Typical voltage loss over this period is expected to be 5-10 percent. The high temperature steam reformer will also be overhauled at five year intervals. If required, reformer tubes will be replaced.

Since the five year overhaul requires replacement of a major component (the fuel cell stack), the logistics of this overhaul need to be studied. The feasibility of on-site replacement of the stack will depend on the final FCPU design arrangement and the availability of on-site maintenance capabilities. The full stack, less manifolds, will weigh approximately 1,000 pounds. An alternative to on-site stack replacement is the shipping of the FCPU to a fuel cell maintenance facility, perhaps at the manufacturer's factory. In this case, a replacement FCPU, or alternately a replacement fuel cell subsystem, would be substituted for the unit to be overhauled. Again, the final unit design must be consistent with the proposed maintenance program. Shipping of the FCPU to remote maintenance facilities will impose additional transportability requirements. Replacement of the fuel cell subsystem for maintenance will require suitable modulization of the design. Life cycle cost estimates have been based on on-site stack replacement with round trips' transportation costs for the replaced elements.

In determining FCPU availability, seven days were allowed for the five year overhaul. It is felt that this is sufficient time for either maintenance approach, on-site stack replacement or replacement with a new unit and remote maintenance.

5.3.3.2 FUEL SUPPLY AND STORAGE

The FCPU's have been designed to utilize the same power plant fuel (DF-A) as the existing diesel-electric generators. The present storage and fuel distribution system can be utilized without modifications. Since the fuel cell units are more efficient than the diesels, they will use less fuel and will be able to operate longer on the same amount of stored fuel. With an average electric demand of 145 kW and an FCPU power rate of 12 kilowatt hours per gallon, the existing 260,000 gallon diesel oil storage would last for approximately 900 days if used exclusively for power production.

Consideration was given to designing the FCPU's for operation with jet fuel, JP-4. Due to its lower boiling point and lower sulfur content, JP-4 is somewhat easier to steam reform than diesel oil. However, the severe arctic conditions require special precautions in handling and storing fuels due to the possibility of freeze-up. Also, the use of JP-4 would require a modification of the existing logistics of fuel delivery. Diesel oil would still be required for other site uses. Therefore, it was decided to design the FCPU's for normal operation on diesel fuel, with the provision to use JP-4 as a back-up fuel.

When JP-4 is used, the fuel rate measured in gallons per hour, will increase about 10 percent. JP-4 has a lower heating value on a volumetric basis than DF-A.

5.3.3.3 SYSTEM OPERATION AND AVAILABILITY OF POWER

Overall electric power system availability at DEWLine sites must be 0.995 or higher. This is accomplished with existing diesel-electric units by a combination of multiple units with backup and load shedding. The present operating procedure calls for three operating units, one standby unit, and a fifth unit which is presumed off-line for maintenance. The three operating units must have sufficient reserve margin such that any two units can maintain minimum station demand should the third unit trip. This is accomplished by load shedding, whereby non-essential power consumers (e.g., lighting, dishwashers, etc.) are shutdown until the backup unit can be started (usually one minute).

The present diesels at PIN-1 have a rated capacity of 60 kW plus 10 percent overload. The average electric load is 145 kW, with an average daily peak of 180-190 kW. In the case of a unit failure, load shedding permits critical station loads to be maintained by two operating 60 kW units.

As part of the upgrading of DEWLine sites, the existing diesel-electric generators will be replaced by 150 kW turbo-charged diesel units. For the PIN-1 site, four 150 kW units would be required (i.e., two operating, one standby, one maintenance). At the normal station electric load (145 kW), the two operating units would operate at 48 percent capacity, substantially reducing their efficiency. The use of 150 kW units also results in 600 kW of installed electric generating capacity, versus 300 kW installed capacity for five 60 kW units.

The proposed FCPU capacity is 60 kW, which is comparable to the existing diesel units. The use of 60 kW units results in lower capital costs than 150 kW due to the lower installed capacity. Since the FCPU's have a slow startup rate (i.e., approximately one hour), it is not possible to use the same load shedding and standby unit procedures as with diesels. The load shedding is a temporary condition and cannot be tolerated for more than a few minutes.

However, fuel cells also have the desirable characteristic of high part load efficiency. Therefore, it is proposed to utilize four operating 60 kW FCPU's. At the average load of 145 kW, each unit would be running at 60 percent of rated capacity. If a single unit failed, the remaining three units could supply all of the station electric power demands, including the 180-190 average daily peak. This would permit sufficient time to repair or replace the failed unit while still maintaining the specified electric power availability.

Mean Time Between Failure (MTBF) for the FCPU's is estimated to be approximately 3,000 hours. This compares to a specified MTBF of 500 hours for MEP-006A 60 kW diesel engine driven generator sets. The higher reliability of the FCPU's allows the specified power system availability (0.995) to be maintained without a fifth backup unit. Table 5-16 shows the projected FCPU availability (including scheduled maintenance and overhauls) to be 98.9 percent. Since at least two units must fail before there is a power outage, the electric power availability is 0.9993 (see Appendix D-2B). This exceeds the specified availability by a safe margin and no back-up FCPU is recommended.

It should also be noted that even in the case of two FCPU failures, the remaining two units have a rated capacity of 120 kW and an overload capacity of 132 kW. Therefore, even in this rare case the radar station would be able to maintain critical functions. The availability of at least two FCPU's is estimated to be 0.999995 (see Appendix D-2B). Therefore, availability of critical electric power for the radar units is nearly 100 percent, with less than three minutes per year average outage.

TABLE 5-16

FCPU AVAILABILITY

Cause of Outage	Hours Unavailable in Year Indicated				
YEAR	1	2	3	4	5
1. Unscheduled (MTBF = 3,000 hrs., MTTR = 12 hrs	35	35	35	35	35
2. Six-Month Scheduled Maintenance	24	24	12	24	12
3. 2-1/2 Year Overhaul (Catalyst Replacement, etc.)	0	0	60	0	0
4. Five Years Overhaul (Stack Replacement, etc.)	0	0	0	0	168
Subtotal	59	59	107	59	215
Five Years Total					499

$$\text{Availability} = \frac{\text{Total Hours - Hours Unavailable}}{\text{Total Hours}} = \frac{5 \times 8{,}760 - 499}{5 \times 8{,}760} = 0.989$$

5.3.4 FCPU COST ANALYSES

5.3.4.1 CAPITAL COSTS

An estimate of FCPU capital costs by account number is given in Table 5-17. A breakdown of equipment included in each account is given in Appendix B. Total FCPU capital cost, based on 1980 dollars, is $162,600. This represents a unit cost of $2,710 per kilowatt.

These estimates are based on a mature FCPU market with a 1,000 units of cumulative production. Except for existing commercial components, such as pumps, fans, etc., an experience curve effect was assumed. Experience curve effects have been observed in many types of production processes and are a measure of the cost reductions that occur with increases in the cumulative size of a production run. These cost reductions are due to the combined effects of improved labor efficiencies (i.e., learning curve effects); technical and manufacturing improvements; economies of scale; and volume purchasing of components and materials. An 80 percent experience curve means the cost per unit will decrease by 20 percent when the cumulative number of units produced is doubled.

Similarly, an 85 percent experience curve will result in a 15 percent cost reduction when the cumulative number of units is doubled. Based on analysis of experience curves for similar types of equipment, an 85 percent experience curve was assumed. For a cumulative production of 1,000 FCPU's, the experience curve reduces initial capital costs of the non-commercial components by 80 percent.

5.3.4.2 OPERATING AND MAINTENANCE COSTS

Normal operation of the FCPU is automatic and does not require constant operator attention. Start-up and shutdown, fault correction, and other abnormal operating conditions do require operator assistance. At present, DEWLine power generators are manned approximately 25 percent of the time. It is conservatively estimated that this can be reduced to 15 percent of the operating time for FCPU power generation. Based on operating labor costs supplied by the DEW

TABLE 5-17

CAPITAL COST ESTIMATE
60 KW DEWLINE FCPU

ACCOUNT	DESCRIPTION	COST (1980$)
1000	Fuel Cell Assembly	45,500
2000	Fuel Processing	33,100
3000	Fuel Delivery	3,300
4000	Water Delivery	4,800
5000	Air Delivery	10,000
6000	Heat Exchangers	30,300
7000	Controls & Instrumentation	6,000
8000	Power Regulation	24,800
9000	Structural	4,800
	Total =	$162,600
	=	$ 2,710/kW

System Office, a labor costing rate of $46 per hour was assumed. The annual power plant operating cost is, therefore, $60,400, or $15,100 per FCPU.

A breakdown by account number leading to an estimated total yearly hardware replacement cost of $11,950 per year is illustrated by Table 5-18. The failure rates per million operating hours are the same as used to estimate a MTBF of 3000 hours. Cleaning of the fuel vaporizer and replacement of the sulfur removal catalyst are assumed to occur at six month intervals. Other scheduled maintenance such as changing fuel and air filters can also be accomplished at the same time.

In constructing Table 5-18, the major subsystems (Account Nos. 1000 through 9000) were assumed to be totally replaced in case of a failure. The failed parts were assumed to have a salvage value that ranged from 40 percent of the initial cost for the fuel cell, to 85 percent of the initial cost for the power conditioner. Replacement part costs of the major subsystems were cumulated without regard to costs of valves, ducting, tubing and sensors associated with these subsystems.

Valves, ducting, start-up battery, etc. were evaluated under the special accounts at the bottom of Table 5-18. The failures were treated as individual valve, sensor, etc., replacements with no salvage value for the failed part.

Table 5-18 indicates that an unscheduled repair because of a unit failure can be expected to occur 2.9 times per year on the average, reflecting the MTBF estimate of 3000 hours. When added to the scheduled maintenance outages, total hours of maintenance and service are 96 hours per year per FCPU. The nature of the maintenance skills required would be trained E4 level skills: (1) trouble shoot modular system, (2) replace modules, and (3) return unit to operating condition. These are the same skills required for servicing and repair of all the FCPU's of this study.

The total operating, servicing, and maintenance costs are estimated as follows:

TABLE 5-18

60 KW FCPU HARDWARE REPLACEMENT COSTS (1980$)

Account No.	Item	Failure Rate Per 10^6 Hrs.	Operating Hrs. Per Year	Failures Per Year	Yearly Average Hardware Replacement Cost - $
1000	Fuel Cell Assembly	25	8,664	0.217	5,330
2000	Fuel Processing	25	8,664	0.217	3,450
3000	Fuel Delivery	7	8,664	0.061	80
4000	Water Delivery	2	8,664	0.017	30
5000	Air Delivery	19	8,664	0.165	700
6000	Heat Exchangers	5	8,664	0.043	550
7000	Controls & Instrumentation	20	8,664	0.173	310
8000	Power Regulators	40	8,664	0.347	1,170
9000	Structure	0	8,664	0.000	0
Special	Valves & Sensors	150	8,664	1.300	260
Special	Startup Battery	1,000	10	0.010	<1
Special	Ducting & Tubing	40	8,664	0.347	70
			Totals	2.897	11,950

Maintenance Crew Size	2 Persons
Costing Rate per Crew	$92/Hour ($92,000/Year Each Person)
Hours of Maintenance & Service	96 Hours/Year
Service & Maintenance Labor Cost	$8,830/Year
Special Equipment	None
Hardware Replacement Costs	$11,950/Year
Supplies (Filters, Sulfur Catalyst, etc.)	$200/Year
Hours of Operator Attention	3,299 Hours/Year
Operator Costing Rate	$46/Hour
Operating Labor Cost	$15,100/Year
Total O&M Cost	$36,080/Year

5.4 DEVELOPMENT RISK ASSESSMENT

A technical development risk assessment was performed at both the subsystem/major component level and the overall system level. The technology status rating criteria are presented in Table 5-19. Each subsystem or major component was evaluated with respect to the following factors:

- Current technology status
- Technology rating (Table 5-19 criteria)
- Required technology status to meet design requirements for the proposed applications
- Proposed developmental program to achieve the required technology status
- Estimated developmental effort expressed in terms of manhours of R&D personnel (engineering plus technicians)
- Estimated developmental effort expressed in terms of development dollars (labor and materials)
- Probability of success of the proposed developmental program
- Ongoing programs or potential design alternatives.

TABLE 5-19

TECHNOLOGY STATUS RATING CRITERIA

TECHNOLOGY RATING	TECHNOLOGY STATUS	PERFORMANCE DATA BASE	EXTRAPOLATION FROM PERFORMANCE DATA BASE	APPLICATION OF DEVELOPMENT PROGRAMS REQUIREMENTS	R&D PROGRAM CHARACTERISTICS	
					RATIONALE	SUCCESS PROBABILITY
Established (A)	Firm selections can be made. Equipment is commercially available in form required.	Sufficient	None	Minimal, routine applications engineering.	Not Applicable	Not Applicable
Near Term (B)	A number of equipment candidates are identified. Candidates are commercial or near commercial.	Incomplete	Short extrapolations from existing data base are involved.	Confirmatory testing and minimal R&D.	Straight-forward	Virtually Certain
Developmental (C)	Equipment not previously designed, but engineering data base exists for design.	Incomplete; important gaps exist	Large extrapolations from existing data required.	Considerable R&D is required	A credible rationale exists. Alternative avenues are evident.	Good to excellent
Speculative (D)	Equipment not previously designed with major materials, design or manufacturing uncertainties.	Sparse or Absent	Highly speculative or not possible.	Extensive R&D is required.	Rationale is not clear, or requires a break-through or serendipity.	Fair to poor.

A summary of the development risk assessment is given in Table 5-20. Those areas presenting the greatest risk (and largest development requirements) are as follows:

Fuel Processor

The production of hydrogen by steam reforming of hydrocarbons is a well established technology, and is used extensively in the petrochemical industry for the production of ammonia, etc. However, the hydrocarbon feedstock is normally a mixture of low molecular weight compounds, such as natural gas or light naphtha. Heavy naphtha, with a distillation end point up to 350°F and containing up to 30 percent aromatics, has also been used in some instances, primarily in India.

The DEWLine application calls for the production of hydrogen from Arctic-grade diesel fuel, DF-A. This fuel has a distillation end point of 572°F, contains up to 2,500 ppm sulfur, and has a high aromatic content. These properties require a non-conventional steam reformer design. The use of heavy fuels, such as DF-A, in conventional steam reformers results in coke formation and sulfur poisoning of the nickel catalyst. Extensive pretreating, to lower the sulfur content to less than 1 ppm and partially crack the larger molecules, is deemed uneconomical and impractical for fuel cell applications.

Based on the results of an EPRI-sponsored study (Ref 5-3), the most promising fuel-processing alternatives are high temperature steam reforming and autothermal reforming. The tradeoffs between these two options are discussed in Section 3.1.1. High temperature steam reforming was chosen as the preferred process for the DEWLine application.

The Department of Energy has sponsored a development program for distillate fuel steam reforming technology. A summary of the status of this program was presented in a recent report by Catalytica Associates, Inc. (Ref 5-4). Autothermal reforming is receiving the largest share of DOE funding, with development programs being carried out by United Technologies Corporation (UTC), Engelhard Industries, and the Jet Propulsion Laboratories. In addition,

TABLE 5-20

DEVELOPMENT RISK ASSESSMENT
60 kW FCPU, DF-A FUEL

SUBSYSTEM/MAJOR COMPONENT	CURRENT TECHNOLOGY STATUS	TECHNOLOGY RATING	REQUIRED TECHNOLOGY STATUS	REQUIRED DEVELOPMENTAL PROGRAM	ESTIMATED MANHOURS (thousands)	ESTIMATED DEVEL. COST (000$)	PROBABILITY OF SUCCESS	ONGOING PROGRAMS & POTENTIAL ALTERNATIVES
1.0 FUEL PROCESSING								
1.1 Fuel Handling and storage	Existing on-site facilities and experience with DF-A diesel fuel.	A	No change required.	No development program is required.	0	0	N.A	N.A
1.2 Fuel Vaporizer	Commercial experience in petrochemical industry primarily with direct-fired heaters.	B	Tubular vaporizer located in convection section of reformer furnace. Continuous operation without coke formation.	1. Experimental testing to determine rate of coke formation.	1.0	80	Very Good.	
1.3 High Temperature Steam Reformer	Extensive commercial experience with conventional steam reforming on fuels from methane to heavy naphtha. Laboratory and pilot plate experience with HTSR of No. 2 fuel oil.	C	Stable performance on DF-A (E.P.= 572°F) without coking on sulfur poisoning steam-to-carbon ratio < 4.0. Fuel conversion to carbon oxides > 95%.	1. Catalyst testing. 2. Multi-tube reformer testing. 3. Full-scale system evaluation and analysis. 4. Cost study.	20.0	2000	Very good	Existing DOE and EPRI sponsored studies on HTSR of No.2 fuel oil. Potential alternative is auto-thermal reforming, which is also under D.O.E. development.

TABLE 5-20 (Continued)

SUBSYSTEM/MAJOR COMPONENT	CURRENT TECHNOLOGY STATUS	TECHNOLOGY RATING	REQUIRED TECHNOLOGY STATUS	REQUIRED DEVELOPMENTAL PROGRAM	ESTIMATED MANHOURS (Thousands)	ESTIMATED DEV. COST (000$)	PROBABILITY OF SUCCESS	ONGOING PROGRAMS & POTENTIAL ALTERNATIVES
2.0 FUEL CELL								
2.1 Fuel Cell Stack	Laboratory and prototype experience. Life tests up to 80,000 hrs with H_2 fuel. Large, multi-cell stacks being tested for utility applications. 4.8 MW demonstration plant under construction. 40 kW on-site program in progress (natural gs fueled)	B	Cell life 40,000 hours. Pressurized (60 psia) cell operation. Cell voltage = 0.72 VDC at current density of 135 amps per ft^2. Minimal acid loss. Low cost design with high reliability.	None. Development under other programs assumed adequate.	0	0	N.A.	Several development programs sponsored by D.O.E., U.S. Army, E.P.R.I., GRI, and various electric utilities. In house development by potential suppliers.
2.2 Cooling Systems and Fuel Cell Auxiliaries	Existing designs have water, air, and dielectric cooled designs. Laboratory and prototype experience with both atmospheric and pressurized systems.	B	High reliability and low cost. Pressurized (60 spia) operation.	Stack pressurization and cooling issues to be resolved as part of fuel cell stack development. No development effort is recommended for the auxillary components (blowers, heat exchangers, etc.).	0	0	N.A.	N.A.

TABLE 5-20 (Continued)

SUBSYSTEM/MAJOR COMPONENT	CURRENT TECHNOLOGY STATUS	TECHNOLOGY RATING	REQUIRED TECHNOLOGY STATUS	REQUIRED DEVELOPMENTAL PROGRAM	ESTIMATED MANHOURS (Thousands)	ESTIMATED DEV. COST (000$)	PROBABILITY OF SUCCESS	ONGOING PROGRAMS & POTENTIAL ALTERNATIVES
3.0 POWER CONDITIONING								
3.1 DC-DC Voltage Regulator	Existing technology. Package units being developed for photovoltaic and Fuel cell applications.	A	High efficiency (90-95%) Low cost.	No developmental program is recommended.	0	0	N.A.	Suppliers developing standard units for various alternate energy systems.
4.0 BALANCE OF PLANT								
4.1 Instrumentation and Control	Developed for small mobile systems and large (5 MWe)stationary plants. Assumes manned operaton.	A	High reliability and safety. Design for attended remote operation.	No developmental program is recommended.	0	0	N.A.	N.A.
4.2 Turbo-compressor, heat recovery.	Conventional technology.	A	Automatic operation. High reliability.	None	0	0	N.A.	N.A.
5.0 OVERALL SYSTEM	Complete, small (5kW) units delivered to U.S. Army for premixed methanol/water fuel. Large (5MWe)stationary system under construction using natural gas fuel. Various levels of experience with intermediate site units. 40 kW units to be tested.	B	High reliability operation/with automatic control. Proper interfacing with load demand. Long life (20 years). Low performance degradation during operating lifetime. Capability to handle diesel fuels.	Qualification program and field testing including: 1. Laboratory units of subsystems 2. House development unit (1). 3. Field test qualification units (1).	45.0	4500	Very Good	None to verify this particular design and application requirements.
TOTAL DEVELOPMENT PROGRAM					66.0	6,500		

analysis-oriented work is being conducted by several other organizations. Research on high temperature steam reforming is included in the Engelhard DOE contract. The Electric Power Research Institute (EPRI) has also sponsored several studies of high temperature steam reforming including contracts with Catalytica, UTC, and Kinetics Technology International Corporation. The most promising HTSR process appears to be the Total Hydrocarbon Reforming (THR) process developed by Toyo Engineering and Tokyo Gas of Japan. This process has reportedly been run in pilot plant runs for up to 4,000 hours with no catalyst deterioration or deactivation.

It is felt that a further developmental effort is required to qualify HTSR for Fuel Cell Power Unit service. The areas of concern are:

- Carbon formation in the feed preheater
- Methane slip (i.e., conversion in reactor)
- Catalyst stability and life
- Thermal response and start-up rate
- Subsystem cost

The proposed developmental program would include lab-scale catalyst testing and evaluation, a multi-tube reformer test, and a design, analysis, and economic study of a full-scale (DEWLine unit capacity) fuel processing system. Total estimated man-hours (engineers plus technicians) required are 20,000. Estimated development cost (including materials) is $2,000,000.

Fuel Cell Stack

The proposed fuel cell operating conditions are:

- Current density at full load = 135 amps per Ft^2
- Cell temperature = 375°F
- Nominal cell pressure = 60 psia
- Cell voltage at 100% output = 0.72 VDC

- Active cell area = 1.1 Ft^2
- Number of cells = 640
- Number of stacks = 2
- Reformed DF-A fuel

Although phosphoric fuel cells have been tested and operated successfully under similar conditions, several areas require further investigation and development. Most existing PAFC stacks are operated under atmospheric pressure at approximately 350°F. In addition, they are usually fueled by pure hydrogen or a clean, reformed gas derived from methanol or natural gas. The reformed DF-A fuel gas will be cleaned prior to entering the fuel cell stack, but the effect of trace impurities, such as heavy metals or nitrogen, and the high carbon oxide content, require further testing.

Several development programs are presently being conducted on phosphoric acid fuel cell technology. The primary sources of funding are DOE, EPRI, GRI, various electric utilities, U. S. Army, and the fuel cell developers. Work is being conducted by Westinghouse/Energy Research Corporation, United Technology Corporation and Engelhard Industries. The various applications that these development programs are directed at include:

- Small, mobile units for the U. S. Army (3-5 kW)
- On-Site Integrated Energy Systems (40-150 kW)
- Dispersed utility power plants (5-10 MW)

The extent of these programs, and the applicability to the DEWLine application requirements, are uncertain at this time. The most closely related work appears to be the Onsite Fuel Cell Field Test Project, which is jointly sponsored by the Gas Research Institute (GRI) and DOE. Up to fifty 40 kW phosphoric acid fuel cell energy systems, built by United Technologies Corporation, will be fabricated and installed at 20-30 industrial sites. This program will supply considerable data and knowledge that can be utilized to refine the DEWLine FCPU design. However, these units are natural gas fueled, unpressurized, and do not have the same thermal integration rquirements as the proposed FCPU's.

Based on the projected development of PAFC cell and stack technology, no additional development effort is deemed necessary at this time. This is a result, primarily, of the decision to use a standard (12" X 17") fuel cell size and design that is already under development and is projected to be commercially available in the time frame required for DEWLine installations.

System Integration and Testing

The packaging and integration of the various subsystems/major components into a Fuel Cell Power Unit is developmental in the sense that previous units with similar requirements (especially fuel type) have not been built and operated. The requirements for a high temperature steam reformer and pressurized cell operation (using a turbo-compressor unit) present unique system considerations. In addition, the FCPU must be designed for water recovery and waste heat utilization. As noted above, the planned 40 kW Field Test Program will help answer many of these concerns. It is suggested that a system verification and qualification program be conducted. The verification program would include construction and testing of the following units:

- Laboratory units of major subsystems
- House development unit (full size)
- Field qualification unit

The estimated cost of materials and test apparatus is approximately $1,250,000. Estimated manpower requirements (engineers and technicians) are 45,000 hours. Total developmental cost for the system verification and qualification program is $4,500,000.

The total recommended developmental program, based on the development risk assessment as discussed above, requires 66,000 man-hours of development labor (engineers plus technicians). The total program cost is approximately

$6,580,000. These estimates are based on the present status of technology development and the assumed future commercial availability of fuel cell modules. Considerable research, development, and testing are presently being conducted or are planned in all areas of appreciable developmental risk. The impact of these programs, most of which are subject to funding review, on the DEWLine application development risk is highly speculative. The estimated development risk assumes moderate input from these parallel programs. Accelerated development in these areas may substantially reduce the development risk, whereas an absence of parallel development will require a larger developmental program.

5.5 LIFE CYCLE COSTS (LCC)

5.5.1 INDIVIDUAL 60 kW FCPU

The basic LCC elements used and assumptions about each are as follows:

R&D - Cost from Section 5.4 spread over 1000 units
Production - Capital Cost from Section 5.3.4.1
Initial Spares - One years supply of spare parts from Section 5.3.4.2
Fuel Cell Power Unit Replacement - none over 20 years
Maintenance - Cost per year from Section 5.3.4.2
Operating Personnel - Cost per year from Section 5.3.4.2
Repair Transportation - $1.28 per pound of spare parts required
Initial Transport and Installation - $0.95 per pound of FCPU
Technical Data - Same as Ref. 5-5 spread over 1000 units
Fuel - Base year cost of $1.75/gallon escalated at 5% per year
LCC Period - 20 years

The 20 year cost for each LCC element and the total for an individual FCPU is given in the following table:

LCC Element	Cost (1980 $)
R&D	6,600
Production	162,600
Initial Spares	12,000
Fuel Cell Power Unit Replacement	0
Maintenance	415,600
Operating Personnel	302,000
Repair Transportation	33,900
Fuel	1,525,900
Technical Data	200
Initial Transport and Installation	5,900
TOTALS	2,465,500

5.5.2 COMPARISON WITH DIESEL ENGINE-GENERATOR SETS

A comparison of FCPU life cycle costs to those using diesel engine-generator sets at the PIN-1 DEWline station was made. The comparison was done on the basis of the replacement 150 kW diesel-electric generators proposed for this site. As for the individual FCPU LCC estimates, the LCC period was taken as 20 years. Fuel costs for both FCPU's and diesels were assumed to be $1.75/gallon in the base year, escalated at 5 percent/year thereafter.

The comparison is given in Table 5-21. As shown, use of FCPU's in preference to the diesel engine-generator sets would result in a total 20 year savings of about $3.1 million. Total LCC savings for all 32 DEWline stations (6 main and 25 auxiliary) would be approximately $115 million.

5.6 CONCLUSIONS

A 60 kW FCPU has been designed that meets U. S. Air Force requirements for remote attended electric power and on-site heating. An example application for the 60 kW FCPU is the PIN-1 Auxiliary Radar Station of the DEWLine System. Four 60 kW FCPU's are proposed to supply the PIN-1 average station loads of 145 kW and 550,000 Btu/hr thermal. The FCPU's have lower fuel consumption, higher cogeneration efficiency, greater reliability, less operating needs, and

TABLE 5-21
FCPU'S VERSUS DIESEL GENERATORS

	Diesel	FCPU
Installed Capacity, kW	4 x 150	4 x 60
Average Heat Rate, Btu/kW-Hr	14,830	11,100
Percent of Space Heating Needs	41	100
Noise Level	High	Low
Mean Time Between Failure	500	3,000
Capital Cost	240,000	749,200
O&M Cost (20 years)	3,420,000	3,006,000
Power Plant Fuel Cost (20 years)	8,061,800	6,103,600
Heating Fuel Cost (20 years)	1,213,500	0
LCC Totals	12,935,300	9,858,800

lower life cycle costs than the 150 kW diesel-electric generators now being installed as DEWLine replacements. Estimated life cycle cost savings over the projected power plant 20 year lifetime are over $3 million for PIN-1. Projected savings for the entire DEWLine System are approximately $115 million.

The proposed FCPU design uses state-of-the-art fuel cell technology, with the exception of the fuel processing system. A development risk assessment was performed, and it is estimated that a development program of 66,000 man-hours and a total cost of $6,580,000 will be required to develop and qualify an FCPU for a DEWLine type application.

6.0 100 KW DIESEL FUELED REMOTE ATTENDED POWER SYSTEM

6.1 INTRODUCTION AND SUMMARY

An application analysis, preliminary conceptual design, development risk assessment and Life Cycle Cost (LCC) estimate of a Fuel Cell Power Unit (FCPU) has been carried out. The application studied is the third of the six generic applications specified for analysis under the U. S. Air Force Fuel Cell Application Analysis program, Contract F 33615-80-C-2038. The generic application as specified in Section 4.1.1.1.3 of the Contract Statement of Work is an attended remote site with a power requirement between 100 kW and 250 kW.

The example application selected by the Air Force was that of providing electrical power to a European communications station. The site analyzed is designated MENORCA and is located off the coast of Spain in the Mediterranean Sea on Islas Baleares.

The electrical power requirements of the example site are of utility 60 Hz AC type at voltages of 120/208V, 3-phase, 4-wire. Average daily peak power requirement is 200 kW and the average electric demand is 180 kW. Availability of power must be 99.99 percent or higher.

Electrical power to the example site is currently supplied by 250 kW diesel-electric generators. In all there are four 250 kW units. One unit is kept on line, one on automatic standby, one on manual standby, and one disconnected for maintenance. No commercial power is available.

It is proposed to satisfy the power and availability requirements of the example site by using three 100 kW rating FCPU's. Although the unit rating is less than that of the present diesel units, only three FCPU's are required versus four diesel-generators. The installation situation using FCPU's is somewhat more favorable because the higher reliability of FCPU's eliminates the need for a fourth backup unit required of the diesel installation. Estimated power availability using FCPU's is 0.9999.

A preliminary conceptual design of a 100 kW phosphoric acid FCPU that fulfills the generic operational requirements for use at attended remote U. S. Air Force sites and is suitable for use at the MENORCA example site has been created. Some of the major features of the design are as follows:

- Uses logistic DF-2 fuel. Can also use JP-4 as a substitute fuel.
- Produces 14.2 kW-hrs per gallon of fuel used. (Current MENORCA site average fuel usage is equivalent to an electricity production of 11.5 kW-hr per gallon of fuel.)
- No liquid waste disposal necessary (no oil changes).
- Current state-of-the-art component technology, except for the fuel reformer which is emerging laboratory technology.

A more complete summary of the 100 kW FCPU's characteristics is given in Table 6-1.

An artist's conception of the 100 kW FCPU is shown in Figure 6-1. The fuel cell power unit and power conditioning elements would be installed within existing engine rooms at sites such as the MENORCA site. The water condenser would be mounted external to the engine room. The purpose of the water condenser is to recover water from the system exhaust for reuse in the unit's fuel processing element.

A technical development risk analysis of the foregoing preliminary conceptual design was carried out. No technology breakthroughs are required to achieve operational hardware. The design uses current state-of-the-art components except for the fuel reformer. Fuel cell stack technology being developed for utility and on-site integrated energy system applications is compatible with the 100 kW FCPU's requirements. There is sound experimental, but laboratory based, knowledge on which to base the reformer design.

TABLE 6-1
100 KW FCPU CHARACTERISTICS SUMMARY

1. PHYSICAL PARAMETERS

   a) Type of Fuel: DF-2, alternate JP-4

   b) Fuel Consumption: 36,500 gallons per year (per unit)
   109,400 gallons per year (total, 3 units)

   c) Volume/Size: Volume - 388 ft^3; Footprint - 40 ft^2 (Power Generator)
   - 12 ft^2 (Power Conditioner)
   - 11 ft^2 (Water Condenser)

   d) Weight: 10,300 lbs

   e) Environmental Constraint:

   Thermal Discharge: 300,000 Btu/hr AVER.

   Air Pollution: NO_x <0.24 lbs/MWH generated
   SO_2 - 5 to 10 ppm
   Others - Nil

   Noise: <75 db at 1 ft.

   Solid Waste: 3 tons. per year of ZnO/ZnS

   Chemical Discharge: Trace H_3PO_4

   Radioactive Waste: None

2. PERFORMANCE PARAMETERS

   a) Reliability:

   Mean Time Between Failures: 2,680 hours

   Availability: 99.99% required; 99.99% calculated (5-year average)

   b) Lifetime: 20 years

   c) Operation and Maintenance:

   Ease of Operation: Record data; make minor adjustments once per day. Fifteen percent operator attention assumed.

   Ease of Maintenance: Trouble shooting, component replacement and checkout.

   Maintenance Skills Required: E-4 or civilian equivalent.

TABLE 6-1 (Continued)

d) Growth Potential:

Fuel cell stacks are of modular construction; growth potential of individual 100 kW FCPU's is limited by reformer and auxillary equipment capacities. Growth potential by parallelling more FCPU's appears infinite.

e) Start-up/Shutdown Time:

Start-up: 1-2 hours

Shutdown to Hot Standby: ∿15 minutes

Cold Shutdown: Two hours

f) Thermal Energy Available:

Not designed for waste heat recovery as example site did not require it. Could provide 233,00 Btu/hr above 200°F at rated load.

g) Electrical Output:

Rating: 100 kW, 60 Hz, 120/208V or 240/416V

Class: 2 (Utility)

Operating Range: 33 kW to 110 kW

3. COST PARAMETERS

a) Capital Costs:

Fuel Cell Power Unit - $231,500; $2,315/kW

Fuel Tanks and Lines - Not applicable; existing installation.

Site Preparation - Not applicable; existing installation.

Initial Installation and Other Costs - $9,800

b) Maintenance Cost:

Transportation for Repair - $2,060/year

Personnel Cost - $1,860/year

Special Equipment Cost - None

Replacement Hardware Costs - $19,540/year

c) Operation Costs:

Fuel and Fuel Transportation Costs - $44,530/year (First year)

Supplies - $200/year

Operating Personnel Costs - $32,700/year

d) Life Cycle Costs:

20-year Life Cycle Cost - $3,219,700

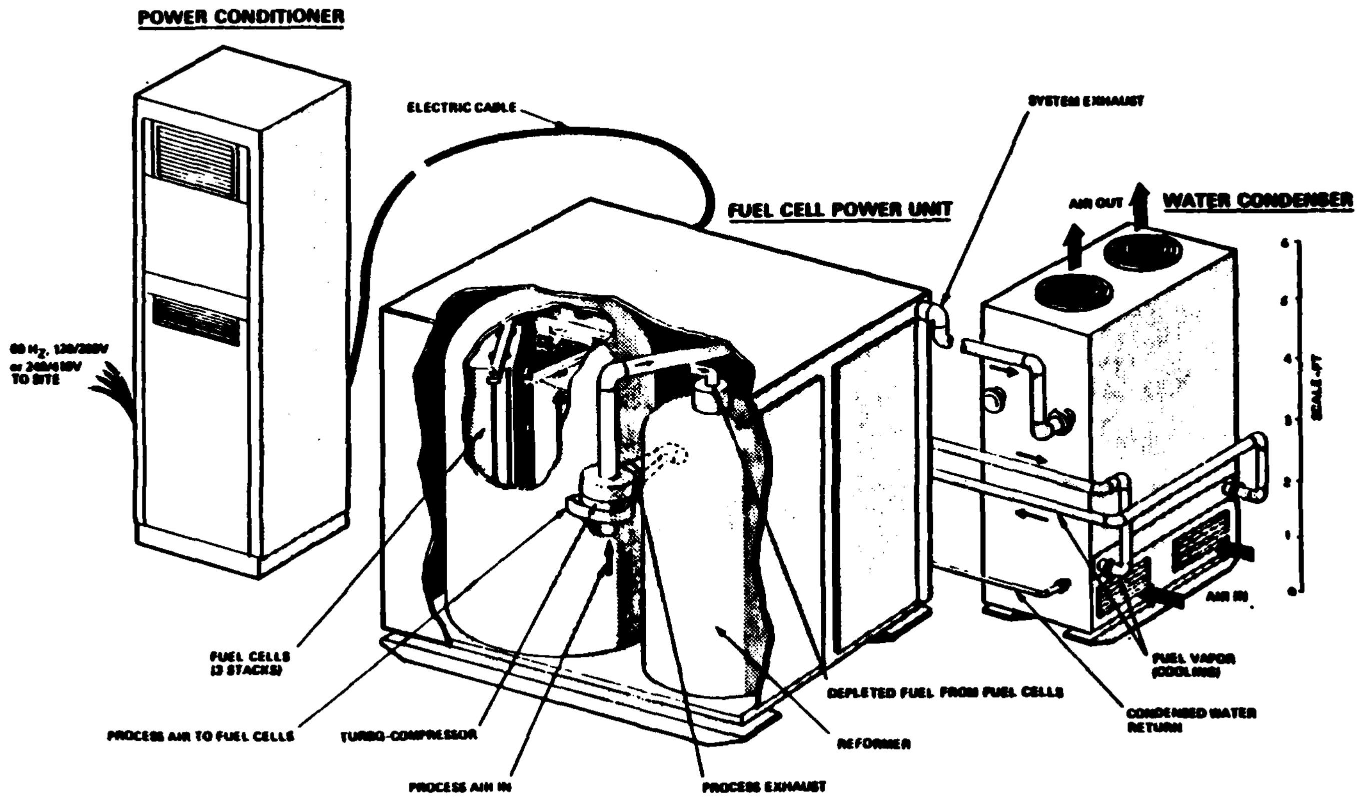


Figure 6-1. 100 kW Diesel Fuel FCPU

A program to develop the 100 kW FCPU should have the following recommended major elements:

- A development effort to fully qualify the fuel reformer for FCPU service.
- A detail design and system analysis, integration, and optimization effort.
- A FCPU experimental verification and qualification effort.

It is estimated that the cost of such a development program will be approximately $7,530,000.

Preliminary life cycle cost estimates have been performed and indicate substantial savings when using FCPU's in place of diesel-electric generators. Total life cycle costs for a single 100 kWe FCPU are $3.2 million over 20 years. Estimated total 20 year life cycle cost savings for fuel cells versus diesels, at the MENORCA site, are in excess of $3.0 million. The LCC savings are calculated on a base year fuel cost of $1.22/gallon escalated thereafter at seven percent/year.

The results of the application analysis, the preliminary conceptual design of a 100 kW FCPU, the development risk assessment of the FCPU, and Life Cycle Cost (LCC) analysis are given in the following sections:

Section 6.2 - Application Description
Section 6.3 - Power Plant Design
Section 6.4 - Development Risk Assessment
Section 6.5 - Life Cycle Costs
Section 6.6 - Conclusions

6.2 APPLICATION DESCRIPTION

6.2.1 GENERAL APPLICATION DESCRIPTION

This is the third of five generic applications specified by the Air Force Wright Aeronautical Laboratories for assessment of phosphoric acid fuel cell systems. The general application category is "an attended remote site with a power requirement between 100 kW and 250 kW". Initially, it was intended to choose a Digital European Background (DEB) site for study. However, most DEB sites with the required electrical generating demand are grid-connected and use diesel generators for backup power only. Since a prime power site was desired, it was decided to use a European communications site which is not part of the DEB system. For information on suitable sites, contact was made with Mr. John Siska, Chief Civil Engineering, Communications Group (AFCS), Torrejon AFB, Madrid, Spain. The following site requirements and description were based on information and discussions with Mr. Siska.

6.2.1.1 MENORCA COMMUNICATIONS SITE

The chosen radar site is located at Menorca, Spain on Islas Baleares. It is a general communications site and is located on an island in the Mediterranean Sea off the coast of Spain.

Menorca, Spain has an elevation of 853 feet above normal sea level and a temperate climate. Ambient temperature ranges from 38°F to 88°F. No space heating is supplied from the power plant system. A requirements sheet for Menorca, completed by Mr. Siska, is given in Appendix D-3A.

6.2.1.2 ELECTRIC POWER REQUIREMENTS

Average electric load at the MENORCA site is 180 kW. Peak electric load is 200 kW. Present plant power supply consists of four 250 kW diesel-electric generators. No commercial power is available, although a feasibility study of commercial power is being conducted.

The 250 kW diesels are somewhat oversized and were actually chosen for site electric loads greater than those at present. Operating procedure calls for one operating generator, one on automatic standby, one on manual standby, and one disconnected for maintenance. The automatic standby unit is capable of providing power in 0-8 seconds, while the manual standby unit requires 2-3 minutes.

Required system availability is 99.99 percent, or 53 minutes per year of power outage. The existing diesel system exceeds this requirement.

Present diesel fuel cost is $1.22 per gallon, which is the result of special considerations given to the USAF by the Spanish government. Open market fuel oil prices are approximately double this cost, or $2.50 per gallon. Jet fuel is available at approximately the same price, but diesel fuel is preferred.

6.2.2 FCPU DESIGN REQUIREMENTS

The MENORCA site electric power requirements and operational requirements are as discussed in previous Section 6.2.1. These requirements establish the overall design basis for a fuel cell electric power system. However, the design requirements for individual FCPU's must be more specific and include such things as physical dimensions and weight limitations, voltage connection, reliability, electrical performance, environmental requirements, cost goals, etc. These items have been established from a variety of sources, including:

- Personal conversations with Mr. John Siska, Chief Civil Engineering, Communications Group (AFCS), Torrejon AFB, Madrid, Spain
- Written comments from Mr. Siska (John Siska to W. A. Summers, March 31, 1981)
- Personal conversations with AFCC personnel, Scott AFB, (primarily J. Hassel and J. Zych)
- Mobile Electric Power Characteristic Data Sheets (MIL-STD-633E)
- Other military and Federal specifications and standards
- Westinghouse and Energy Research Corporation (ERC) experience related to PAFC design and capabilities

The FCPU design requirements have been summarized in a document entitled, "R quirements Data Sheet, Fuel Cell Power Unit Attended Remote, 100 kW, 60 Hz, No. W-RDS-3". A copy is included in Appendix C-3. Some of the important requirements are:

Power Classification = Type II (prime)
Class 2 (utility)
Mode I (50/60 Hz)
Fuel Type: DF-2, Fed. Spec. VV-F-800B
Voltage Connection, 120/208V, 3 phase, 4 wire
240/416V, 3 phase, 4 wire
Reliability: MTBF (specified) = 1,500 hours
Fuel Consumption: 8.0 gph (max)
Cold Start-up: 1 hour at -20°F
Design Life: 20 years

6.3 POWER PLANT DESIGN

Since the example application requires prime power, without a utility grid backup, high power system reliability is the most important design criteria. The specified availability of electric power is 99.99 percent, with actual availability (using diesel generators) even higher. This high availability is maintained by the use of multiple power generators. At MENORCA (180 kW average electric demand), four 250 kW diesel-electric generators are employed. Using a similar philosophy, three 100 kW fuel cell power units (FCPU's) are proposed. Fewer FCPU's are required than diesels due to their higher individual availabilities.

In addition to high reliability, the example application requires high system efficiency and minimal operating and maintenance requirements. These characteristics not only have a major impact on life cycle costs, but are important from a logistics standpoint as well. Other power plant requirements, such as weight and volume, mobility, noise level, start-up time, etc., are of lesser importance for example type applications.

Each individual FCPU can be subdivided into four major subsystems as shown on Figure 6-2. These subsystems are:

- Fuel Processing
- Power Generation (PAFC)

- Power Conditioning (DC/AC Conversion)
- Waste Heat Recovery

In order to establish the preferred system design and arrangement, a thorough evaluation was made of the various subsystem and major component options, and tradeoff studies were conducted to determine their effect on overall system performance, etc. These studies are discussed in Section 6.3.1. The chosen Fuel Cell Power Unit (FCPU) design concept is described in Section 6.3.2, along with subsystem design summaries and projected FCPU performance. Power plant usage considerations, such as design life and maintenance requirements, fuel supply, system operation, and availability of power are presented in Section 6.3.3. A preliminary economic analysis is given in Section 6.3.4.

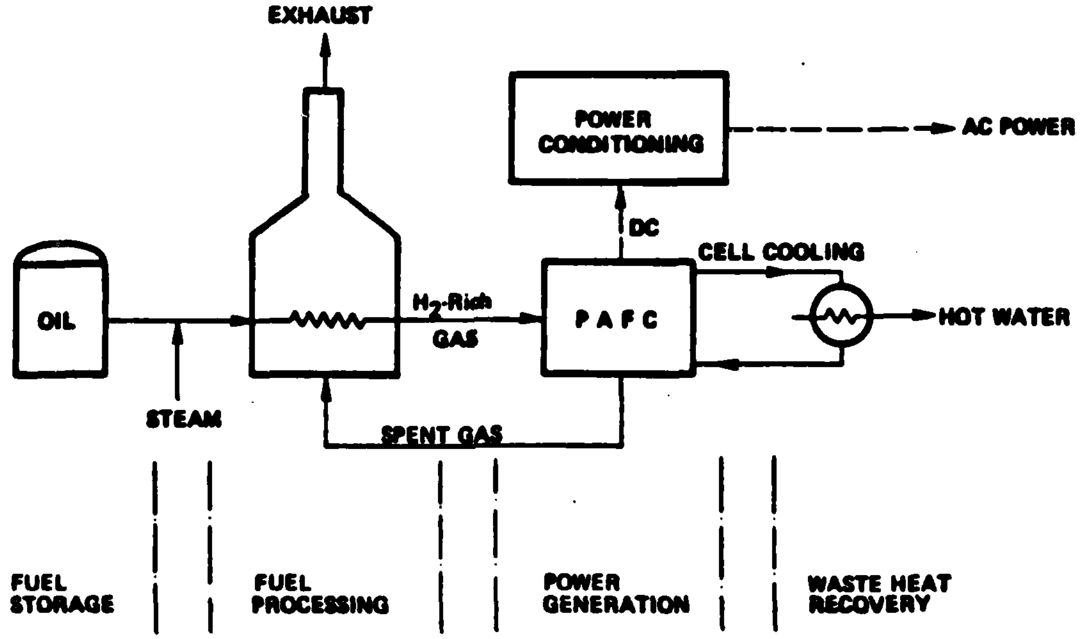


Figure 6-2. FCPU Major Subsystems

6.3.1 MAJOR SUBSYSTEM OPTIONS AND TRADEOFFS

The major tradeoffs studied for this application concerned the method and type of fuel processing system, the design (e.g. cell size, cooling method, etc.) and operating point for the phosphoric acid fuel cell stack, and overall system options concerning water recovery, waste heat utilization, and system operating pressure.

6.3.1.1 FUEL PROCESSING SUBSYSTEM

The Fuel Processing Subsystem (FPS) converts the process fuel, normally a gaseous or liquid hydrocarbon, into a hydrogen-rich fuel gas stream that can be utilized in the anode of the phosphoric acid fuel cell. In addition, the FPS must remove any fuel contaminants, such as sulfur, to acceptable levels. A number of FPS designs have been tested or proposed, and the choice of a particular design is highly dependent on the type of raw fuel and the fuel cell requirements.

The European communications sites are presently powered by diesel-electric generators fueled with No. 2 diesel fuel, DF-2. Most sites also have jet fuel, JP-4, available. However, because of present storage and logistic considerations, it is preferred to continue to utilize DF-2 as a powerplant fuel. A summary of DF-2 fuel properties is given in Table 6-2.

TABLE 6-2
FUEL PROPERTIES

Type	Diesel Fuel, DF-2
H/C Molar Ratio	1.7
Avg. Molecular Wt.	200
Representative Formula	$C_{14.6}H_{24.8}$
Distillation End Point, °F	708
Sulfur (max), ppm	5,000
API Gravity	34.7
Higher Heating Value	
Btu per pound	19,570
Btu per gallon	138,600

Diesel fuel is a heavier feedstock than is presently employed in conventional hydrogen production plants. Due to its greater tendency to crack and form carbon deposits, and its relatively high sulfur content (compared to natural gas or naphtha), it requires an advanced FPS design. A study of fuel processing systems for jet and diesel fuels was performed under this contract and major conclusions included the following (Ref 6-1*):

- Of the various fuel reforming processes available, only the following three were deemed desirable for PAFC powerplants:

  1) Conventional Steam Reforming (STR)
  2) High Temperature Steam Reforming (HTSR)
  3) Autothermal Reforming (ATR)

- For light fuels, perhaps including JP-4, conventional steam reforming is preferred.
- STR is not practical for heavy feedstocks due to the complexity and potential operational problems associated with high pressure desulfurization.
- HTSR is preferred over ATR on the basis of higher process efficiency and lower life cycle costs.
- ATR may be preferable for applications requiring rapid startup or reduced system cubage and weight.

Based on the Westinghouse RDS-3 operational requirements utilizing DF-2 fuel, a high temperature steam reformer was selected. The HTSR has a slightly higher hydrogen yield per pound of fuel and a higher hydrogen concentration in the reformed gas than an autothermal reformer, resulting in reduced gas flow rates and greater system fuel economy. Although the ATR has advantages in transient response, startup time, and lower system weight, these characteristics were not considered major requirements for this application. A summary of the candidate fuel reforming processes is given in Table 6-3.

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*References to this report section may be found in Appendix A-4.

TABLE 6-3
FUEL REFORMING PROCESSES

PROCESS	OPERATING CONDITIONS	CHARACTERISTICS
● Conventional Steam Reforming	1,400-1,600°F 20-40 atm	- Low Sulfur Tolerance - Limited to Heavy Naphtha or Lighter Feedstocks
● High Temperature Steam Reforming	1,600-1,800°F 1-10 atm	- Good Sulfur Tolerance - Can Handle Heavy Fuels - Large Catalyst Volume
● Autothermal Reforming	1,600-2,200°F 1-10 atm	- Adiabatic Operation - Simpler System Design - Cannot Use Fuel Cell Waste Heat - Higher Plant Heat Rate

6.3.1.2 PHOSPHORIC ACID FUEL CELL

The processed fuel gas is electrochemically reacted in a phosphoric acid fuel cell (PAFC) module to produce dc electricity and process heat. The PAFC module consists of individual fuel cells arranged in a vertical stack, associated structural components, anode and cathode gas feed and distribution system, and a fuel cell cooling system. The major design options include fuel cell size (active cross sectional area per cell), stack arrangement, the type and design of the cooling system, and selection of the design current density.

Cell Sizing

The basic building blocks of the PAFC subsystem are the individual fuel cells, composed of bipolar plates, anode and cathode layers, the electrolyte (H_3PO_4) matrix, and associated components. Various overall cell sizes (width and length) have been employed by different designers and for different applications. For a given cell voltage and current density, the active cell area determines power output per cell and therefore the total number of cells required.

For the 100 kW FCPU, a 12" X 17" cell size was chosen. This is the standard PAFC design being developed by Westinghouse Electric Corporation and Energy Research Corporation. By using a standard cell design that is being developed for other fuel cell applications, the development risk for the fuel cell subsystem is markedly reduced. If a non-standard cell design were chosen, basic cell development and testing would be required.

It is noted that other cell designs and sizes, such as those under development by United Technologies Corporation or Engelhard Industries, could also have been selected. However, the Westinghouse/ERC cell design is compatible with the 100 kW system requirements and was the design for which the most information was available. No advantage was determined for selecting one of the alternate designs. It is felt that the study results and conclusions are valid for PAFC's on a general basis, although it was necessary to choose a particular design to size system components and prepare a complete plant design.

Stack Arrangement

Tradeoffs were evaluated in respect to the number of cells per stack, number of stacks, method of electrical interconnection (i.e., series versus parallel), and output dc voltage. An existing power conditioning system design was employed, requiring an input DC voltage of the range 200-300 volts. Since the voltage per cell under pressurized conditions is approximately 0.7 volts (depending on design conditions of current density, etc.), the required number of cells in series is 285 to 425. At a design current density of 150 amps per square foot and cell voltage of 0.72 volts (see following discussion of current density selection), the total number of 12" X 17" cells required to produce a gross power output of 115 kW is 960. To limit stack height and provide the required output voltage, these are arranged into three stacks of 320 cells each, connected in series*. Output dc voltage is approximately 230 volts at rated load.

Cooling Method

Various cooling methods are feasible for PAFC stacks. The Westinghouse/ERC concept utilizes recirculating air cooling, and was the design selected for the 100 kW FCPU. Other cooling schemes include water cooling and liquid cooling employing a dielectric fluid. The liquid-cooled designs require the use of numerous tubes within the stack to contain and convey the liquid. As a result, there are a large number of tube connections that present potential leakage problems. Since reliability is the most important design requirement for the 100 kW FCPU, the air-cooled design appears preferable. However, the overall study results, including FCPU performance and cost, will not be significantly affected by the choice of fuel cell cooling method.

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*The individual stacks are identical to those of the 60 kW FCPU of Section 5.0.

Current Density

Due to polarization and internal resistance (ohmic losses), the obtainable cell voltage decreases with increasing current density (amps per square foot of active cell area). The designer is therefore faced with a tradeoff between efficiency (i.e., high cell voltage at low current density) and capital cost (i.e., smaller cell area at higher current densities).

A preliminary tradeoff study comparing various current densities for a 60 kW pressurized FCPU for attended remote siting was conducted earlier in this study. It was found that higher current densities resulted in substantially smaller stack sizes, but they also required larger auxiliary (primarily heat removal) systems and had higher plant heat rates. A moderately low current density of 135 amps per square foot resulted in the lowest life cycle cost. For the 100 kW FCPU, it was decided to employ the same design conditions and stack arrangements as developed for the earlier 60 kW FCPU. To increase net power output from 60 kW to 100 kW, the number of stacks was increased from two to three (nearest whole number). The resultant design current density is slightly higher (150 amps/ft^2 versus 135 amps/ft^2) than for the 60 kW FCPU. It should be noted that by duplicating the 60 kW stack design, the need to develop two separate stack designs (and the associated development risk) is eliminated.

6.3.1.3 SYSTEM DESIGN OPTIONS

The example application requires electric power only; no requirement for cogeneration of heat for space heating or other station needs was identified. Therefore, the FCPU system design differs from the 60 kW FCPU arrangement which employs heat recovery. In the 100 kW FCPU arrangement, maximum use was made of fuel cell waste heat to lower the overall FCPU heat rate rather than for cogeneration purposes.

Based on the results of a trade-off study performed for the 60 kW FCPU, a pressurized FCPU design was chosen. The 60 kW FCPU study showed that the additional capital cost of pressurization to 60 psia could be recovered in less than two years by fuel cost savings. Since identical stack design conditions were chosen for the 100 kW FCPU, these same conclusions should be valid. Therefore, a 60 psia system design pressure was chosen.

The FCPU produces more water than it consumes. Therefore, water recovery and complete water self-sufficiency is possible. This can be accomplished by the use of a water condenser on the system exhaust. An alternative is to exhaust the warm humid system gases and use fresh water makeup. The use of water makeup would require approximately 27 gallons per hour of treated water. Since the quantity and quality of fresh makeup water at an remote site is uncertain, it was decided to design the FCPU for water recovery. This requires cooling the exhaust gases from 389°F to 100°F in a water condenser with approximately 530 square feet of heat exchanger surface. Approximately 75 percent of the water vapor in the system exhaust is recovered to make the system water self-sufficient.

6.3.2 FCPU DESCRIPTION

6.3.2.1 PROCESS DESCRIPTION

The Fuel Cell Power Unit consists of a pressurized fuel processor, a pressurized phosphoric acid fuel cell stack, dc-ac power conditioning, and associated pumps, compressors, and heat exchangers. Figure 6-3 and Table 6-4 show the system schematic and associated flow streams and state points (at rated load of 100 kW).

Regular-grade diesel fuel, military classification DF-2, is steam reformed in a high temperature steam reformer operating at 65 psia, 1,800°F outlet temperature, and a steam-to-carbon ratio of 4.0. Fuel conversion to carbon oxides is 91 percent, resulting in a dry methane slip (dry volume percent CH_4 in reformer exit) of 3.0 percent. Reformed gas composition is near equilibrium at the exit temperature and contains 35 percent H_2, 9 percent CO, 7 percent CO_2, 1.6 percent CH_4, and the remainder water. The product gases exiting the reformer are cooled to 750°F by passing through a steam superheater and a steam generator. They then pass over through a ZnO bed to remove H_2S, are further cooled by raising steam, and enter a shift converter at 560°F. The shift converter reacts approximately 89 percent of the residual CO with steam to produce

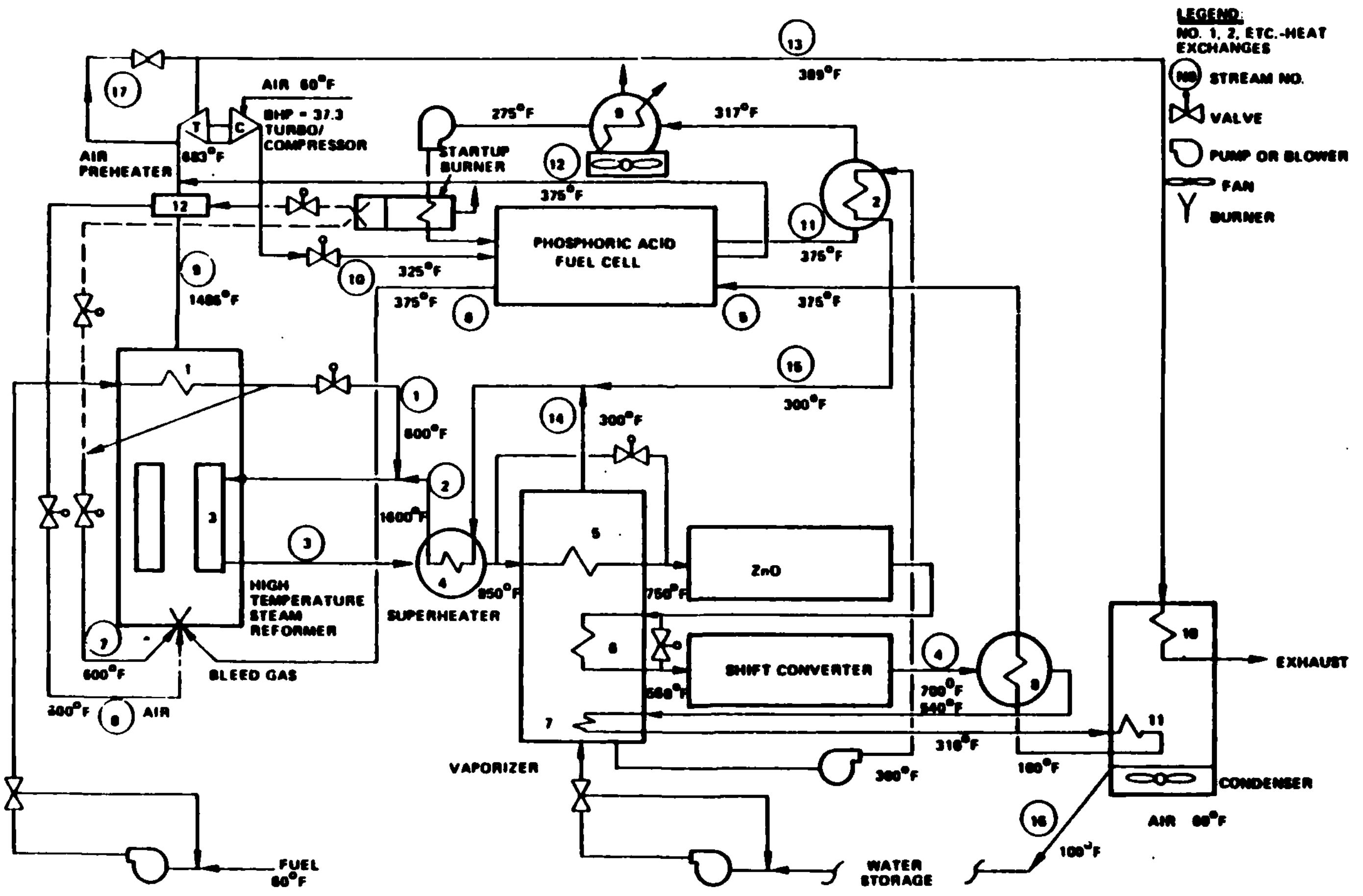

Figure 6-3. 100 kW Fuel Cell Power Unit System Schematic

TABLE 6-4

100 KW FUEL CELL POWER UNIT STATE POINTS

	STREAM	Molar Flow, lb-mole/hr H_2	CO	CO_2	CH_4	H_2O	N_2	O_2	DF-2	Mass Flow lbs/hr.	Temperature °F	Pressure PSIA
1.	Reformer Fuel								0.22	44	600	65
2.	Steam to Reformer					12.69				228	1,600	65
3.	Reformer Products	6.32	1.58	1.32	0.29	8.49				272	1,800	65
4.	Shift Exit	7.72	0.18	2.72	0.29	7.09				272	700	65
5.	Fuel Cell Feed	7.72	0.18	2.72	0.29	0.18				148	375	60
6.	Depleted Fuel Gas	1.16	0.18	2.72	0.29	0.18				135	375	60
7.	Burner Fuel								0.03	6	600	60
8.	Burner Air Supply					0.86	7.74	2.06		298	600	60
9.	Furnace Exhaust			3.61		3.15	7.74	0.27		439	1,486	58
10.	PAFC Air Supply					0.28	24.69	6.56		906	325	60
11.	Cooling Air					3.45	309.20	82.19		11,350	375	60
12.	PAFC Exhaust Air					6.84	24.69	3.28		919	375	58
13.	Total Exhaust			3.61		9.99	32.43	3.55		1360	389	14.5
14.	Boiler Steam Flow					2.63				47	300	65
15.	PAFC Vap. Exit					10.03				181	300	65
16.	Water Recovery					12.66				228	100	1.0
17.	Turbine Bypass			0.51		1.40	4.54	0.50		190	683	58

DESIGN BASIS

85% H_2 Utilization
5% Furnace Thermal Losses
200% Stoich. Cathode Air
115% Stoich. Burner Air
0.72 vpc at 135 ASF
72% Turbo/Comp EFF.

60°F, 50% Rel. Humidity
900 Ft. altitude
115 kW DC Gross
100 kW AC Net

PROCESS HEAT EXCHANGERS

No.	Description	Load (10^3 Btu/hr)	Hx Area, Ft^2
1	Fuel Vaporizer	24.4	2.4
2	PAFC Steam Generator	164.7	281
3	Reformer Bed	220.5	40
4	Superheater	151.2	14
5	Gas Cooling Coil	15.5	2.4
6	Gas Cooling Coil	28.9	6.4
7	Feedwater Heater	34.4	17
8	Gas Reheater	24.0	21
9	Cooling Air HX	119.0	146
10	Condenser Coil	233.2	320
11	Condenser Coil	157.1	207
12	Air Preheater	20.0	7.1

additional H_2 and lower the CO concentration to less than two percent by volume on a dry basis. The processed gases are cooled to 100°F to condense out moisture and reheated to 375°F before entering the fuel cell anode. The anode feed gas contains 70 percent H_2, 25 percent CO_2, and the remainder CO, CH_4 and H_2O.

The fuel cell reacts 85 percent of the available hydrogen with oxygen to produce dc power and process heat. Average fuel cell operating temperature is 375°F. The oxygen is supplied by a once-through air flow with an inlet stoichiometry of 2.0 and a pressure of 60 psia. The process heat is removed by a separate cooling air flow that enters at 275°F and leaves at 375°F.

Unreacted H_2 in the anode exhaust, along with residual CO and CH_4, are burned in the reformer furnace to provide heat for the endothermic reforming reaction. Additional diesel fuel, representing 12 percent of the total FCPU fuel requirements, is also burned in the reformer furnace. The fuel reforming reaction takes place in a high temperature steam reformer of the type being developed by Toyo Engineering Corporation (Ref. 6-2). It consists of a fixed bed of two types of catalysts (designated T12 and T48) placed in series. Total gas space velocity (TGSV) is $800V/V/hr^{-1}$ (volumetric flowrate of gas per catalyst bed volume).

The flue gas from the reformer furnace is used to vaporize the fuel and to preheat burner combustion air. After passing through the air preheater coils, the flue gas is combined with the spent cathode air and exhausted through a turbocompressor. The turbocompressor has an overall efficiency of 72 percent and produces 37.3 BHP to compress fresh ambient air to 60 psia. Total compressed air requirements of 270 SCFM are based on burner combustion with 1.15 stoichiometric air and a fuel cell cathode stoichiometry of 2.0. Fifteen percent of the exhaust gas is bypassed around the turbocompressor under 100 kW design conditions. This permits better controllability of turbocompressor performance and allows the system pressure to be maintained under part load or high ambient temperature conditions.

Two steam generators are employed to produce 228 lb per hour of 65 psia saturated steam. Approximately 20 percent of the steam is raised in the fuel processor steam generator, while the remaining 80 percent is produced by a separate steam generator located in the fuel cell air cooling loop. The steam is superheated to 1,600°F by the hot reformed gas.

Cell cooling air is recirculated in a pressurized, closed loop system. Separate air manifolding provides flexibility in cell cooling channel design and air requirements. Heat is rejected by the cooling air first to the fuel cell steam generator and then to an air cooler. A pressurized blower recirculates the re-cooled air back to the fuel cell stack.

An air-cooled condenser is used to recover process water from both the anode gas feed stream and the turbocompressor exhaust. Approximately 75 percent of the water in these two streams is condensed, supplying 100 percent of the process water needs and eliminating the need for fresh water makeup under normal operating conditions.

Major design parameters for each of the primary subsystems are given in Table 6-5.

6.3.2.2 POWER PLANT PERFORMANCE

The FCPU performance profile for 60 percent, 100 percent, and 110 percent load levels is shown in Table 6-6. A complete design and performance summary at rated load is given in Table 6-7. The electric generating efficiency is nearly constant over the load range. Three FCPU's, operating at 60 percent load each, provide the average electric load of 180 kW. Fuel to electric power conversion rate is 14.2 kilowatt-hours per gallon. Unit heat rate at 60 percent load, based on the higher heating value of the fuel, is 9,770 Btu per kilowatt-hour, representing an electric generating efficieny of 34.9 percent.

6.3.2.3 FCPU SIZE AND WEIGHT

The projected volumes and weights of major system components and the assembled power unit are shown in Table 6-8. These projections are based on scaleup of

TABLE 6-5
MAJOR 100 KW FCPU DESIGN PARAMETERS

FUEL CELL SUBSYSTEM	
Design Pressure, psia	60
Design Temperature, F	375
Cell Hydrogen Utilization, %	85
Process Air Stoichiometry,	2.0
Cooling Load, 10^3 Btu/hr	284
Output Voltage, VDC	230
No. of Cells Required	960
No. of Cell Stacks	3
Active Cell Area, ft^2 per cell	1.1
Operating Point, vpc @ ASF	
110% Design	.71 @ 165 ASF
100% Design	.72 @ 150 ASF
60% Design	.74 @ 92 ASF
Cooling Air Required, CFM @ STP	2,500
FUEL CONDITIONING SUBSYSTEM	
Design Pressure, psia	65
Reformer Design Temp, °F	1,800
Space Velocity, v/v/hr^{-1}	800
Catalyst Type (Toyo T12/T48)	CaO, NiO
Catalyst Volume, ft^3	10.0
Shift Catalyst Type	Cu/ZnO
Shift Catalyst Volume, ft^3	6.6
Desulfurization Catalyst	ZnO
Desul. Catalyst Volume, ft^3	10.0
Design Fuel Sulfur, wppm	2,500
Turbocharger Output, CFM @ STP	270
Design Combustion Stoichiometry	1.15

TABLE 6-5
MAJOR 100 KW FCPU DESIGN PARAMETERS (Continued)

POWER CONDITIONING SUBSYSTEM

KVA Rating (continuous)	115
Input, Volts dc	200-300
Output	60 Hz, 3-phase, 4-wire, 120/208 volts
Type	Voltage Fed, Forced commutated
Harmonic Distortion	Less than 5 percent
Efficiency @ 0.9 Power Factor	
50% Load (35 KVA)	91%
100% Load (69 KVA)	92%

TABLE 6-6
100 KW FCPU PERFORMANCE PROFILE

	Average Load	Rated Load	Peak Load
Percent Rated Load	60	100	110
Net ac Power, kW	60	100	110
Gross dc Power, kW	70.8	115	126.3
Current Density, ASF	92	150	165
Nominal System Pressure, psia	45	60	60
Cell Voltage, vpc	.74	.72	.71
Fuel Use, gph	4.2	7.1	7.9
Heat Rate, Btu/kW-hr.*	9,770	9,780	9,910
Efficiency, %*	34.9	34.9	34.4

*HHV = 138,600 Btu/gal.

TABLE 6-7
100 KW FCPU DESIGN AND PERFORMANCE SUMMARY

DESIGN BASIS	
Power Output, kW (Nominal/Peak)	100/110
Voltage, Regulated AC	120/208
Fuel Type	DF-2
Ambient Temperatures, °F	32 to 100
Altitude, feet above SL	900

PROJECTED PERFORMANCE(1)	
Parasitic Power Req., kW	5.8
DC/AC Conversion Eff., %	92
Gross Cell Power, kW	115
Furnace Thermal Losses, %	5
Turbocompressor Efficiency, %	72
Power Efficiency, kw-hr/gal	14.2
Heat Rate, Btu/kW-hr @ 100 kW	9,780
Water, Gal/hr @ 100 kW	27
Recovered Process Water, % Needs	100
Generating Efficiency, %	34.9
System Starting Time, hrs	1-2
System Weight, lbs (exluding storage tks)	10,300
System Footprint, ft^2	63
System Volume, ft^3	388

(1) Based on DF-2, 0.85 Specific Gravity, 138,600 Btu/gal (HHV)

TABLE 6-8
100 KW FCPU COMPONENT SIZES

	Weight, lbs.	Volume, Ft.^{3}
Fuel Cell Stack w/Manifolds	2,200	50
High Temperature Steam Reformer	1,100	20
Shift Reactor and ZnO Vessel	1,200	20
Heat Exchangers	630	45
Pumps, Blowers, Turbocharger, etc.	420	10
Controls, Packaging, Skid Base, etc.	1,000	94
Subtotal	6,550	239
Power Conditioner	3,600	84
Water Condenser	150	65
Total	10,300	388

Approximate Dimensions:

Power Generator	7'L X 5.7'W X 6'H (without skid base)
Power Conditioner	3'L X 4'W X 7'H
Water Condenser	4.7'L X 2.3'W X 6'H (without skid base)

existing designs and previous FCPU sizing estimates, primarily from the DEWLine 60 kW FCPU study. Items not included are auxiliary battery power, fuel and water storage, and inert gas vessels used for system starting. The estimated package weight and volume are slightly higher than would be required with a similar 100 kW system using natural gas or naphtha. These differences are attributed to additional fuel processing components and heat recovery equipment.

The overall volume of the power unit is projected near 388 ft^3 with a system weight of 10,300 lbs. The FCPU is physically divided into the following three sections:

- Power Generator - 7'L X 5.7'W X 6'H; 5,650 lbs.
- Power Conditioner - 3'L X 4'W X 7'H; 3,600 lbs.
- Water Condenser - 4.7'L X 2.3'W X 6'H; 150 lbs.

All three power conditioners (one per FCPU) could be located side-by-side in one corner of the MENORCA site engine room. The air-cooled water condensers could be located outside of the engine room, presumably on the roof. The power generator units can be spaced in the engine room to allow ready access to each unit.

6.3.2.4 FCPU CONTROL AND OPERATION

Microprocessor based control is recommended for use with the 100 kW FCPU. Table 6-9 lists the primary control functions which will be needed for minimum control of the power plant. Assessment of all operational requirements is unknown at this level of effort because the system incorporates developmental reformer technology. Two key problems, coking and sulfation, may occur within the reformer subsystem, requiring a means of detection and avoidance. Carbon deposition and pluggage of the reformer catalyst can be detected by an increase in reformer pressure loss; this can be minimized or avoided by proper thermal control of the reformer. Also, sulfur removal rate and absorption capacity of the ZnO desulfurizer bed must be monitored to protect downstream catalysts. This requires the use of two ZnO beds in series, with H_2S detection between

TABLE 6-9
100 KW FCPU MAJOR CONTROL FUNCTIONS

Controlled Variable	Control Means
Power Output (load following)	Current Measurement Feedback to Control Valves
Fuel & Steam Flow	Proportioning Control Valves
Reformer Temperatures	RTD Feedback to Burner Firing Rate
Fuel Cell Temperature	RTD Feedback to Recirculation Cooling Air Flow Valve
Shift Outlet Temperature	Thermostatic Bypass Flow Control on Steam Vaporizer
ZnO Bed Temperature	Thermostatic Bypass Flow Control on Steam Vaporizer
System Pressure	Turbocharger Output Pressure Regulation and Bypass Valve Adjustment
Fuel Cell Pressure	Differential Pressure Regulation on Anode & Cathode
Water Condenser Temp.	Air Cooler Fan Number and Speed or Damper Flow Control
Exhaust Gas Water Concentration	Load Following Damper Control to Maintain 2.0 Cell Air Supply

beds. These control requirements will need additional study with working models to adequately assess control set points and detection means. In addition to using an automatic control system, operational assistance will be needed during system warm-up and starting. Normal operation will be "handsoff," with operator attention required on a "walk-by" basis.

Power unit starting is achieved by heating the reformer, desulfurizer, and shift catalyst to operating temperatures by firing fuel in the reformer burner. A separator burner/heat exchanger unit is utilized in the cooling air loop for fuel cell heating. Starting time will be governed by the reformer subsystem due to its higher operating temperature and limits imposed by reformer metallurgy and catalyst heating. Heating of reformer subsystem catalyst may require the use of moisture free or inert gas (e.g. nitrogen) to prevent moisture condensation or oxidation of catalysts. Thermocouple (RTD) sensors would be used to control burner firing rates. A separate air blower is needed to provide combustion air until sufficient thermal energy is available to drive the turbocharger compressor. Power for operating system components during start-up can be provided by adjacent operating power units or by a common battery pack. Although starting time cannot be fully assessed at this time, a minimum of one to two hours is estimated. Starting power for operation of the system, excluding the water condenser fan, for the two hour period is projected near five kW.

Load following is obtained by measuring fuel cell current output (demand) and adjusting reformer fuel and steam flow valves accordingly. This controls the volume of reactants entering the catalyst bed and hydrogen output to the fuel cell. Rapid demand, if required, is tied into the reformer burner control to provide increased combustion and reaction heat. Gas phase flow control valves would be used to modulate steam and vaporized fuel flow. Combustion air and fuel cell process air flow valves control air flow rates in response to demand. Preliminary analysis of transient response rates indicates the capability of applying a simulated 15 kW motor load while operating at 85 kW output.

Thermal system control is obtained by monitoring reformer catalyst, shift catalyst, desulfurizer bed, and fuel cell temperatures and adjusting flow rates accordingly. Reformer catalyst temperature is maintained by adjusting burner combustion rate during changes in system demand. Desulfurizer and shift catalyst temperatures are maintained by controlling the amount of gas entering or bypassing the external water vaporizer. If necessary, steam superheat and fuel vapor temperature may have to be controlled to avoid carbon deposition in the reformer, or maintain gas outlet temperatures. These control functions may be necessary depending on reformer design.

Fuel cell plate temperatures are controlled by the rate of heat removal from the cooling air loop. This requires adjusting the air flow rate in the air-cooled heat exchanger.

System pressures would be maintained by pressure regulators at the fuel and water pumps and in the process air and anode gas stream entering the fuel cell. To prevent crossleaks in the cell stack, the cooling air loop and stack assembly are encased in a pressure vessel. Loss of system pressure would signal shutdown of the power unit. Air pressure and flow rate from the turbocompressor can be controlled by adjusting the throttle valve in the bypass line. The final strategy of system pressure control will depend on a complete system dynamic analysis.

Water recovery rate in the system exhaust condenser is subject to changes in system flows and ambient conditions. To ensure adequate recovery for system needs, a water storage tank is incorporated between the condenser and feedwater heater. Condenser air flow can be varied to maintain a minimum acceptable exhaust temperature leaving the system with a high storage tank level override.

6.3.3 POWER PLANT USAGE CONSIDERATIONS

6.3.3.1 DESIGN LIFE AND MAINTENANCE REQUIREMENTS

The Fuel Cell Power Units are designed for a useful life of twenty years. This assumes that major component replacement and scheduled maintenance are performed as shown in Table 6-10. Major system components have been isolated and

TABLE 6-10
FCPU MAINTENANCE SCHEDULE

Maintenance Function	Six-Month Scheduled Outage	2 1/2-Year Overhaul	5-Year Overhaul
Fuel Vaporizer Cleaning	X	X	X
Desulfurizer Catalyst Replacement	X	X	X
Inspection and Cleaning	X	X	X
Filter Replacement, etc.	As Req'd.	As Req'd.	As Req'd.
Acid Replenishment	As Req'd	X	X
Reformer Catalyst Replacement		As Req'd.	X
Shift Catalyst Replacement		As Req'd.	X
Minor Component Overhaul (pumps, fans, burner, etc.)	As Req'd.	X	X
Reformer Overhaul			X
Fuel Cell Stack Replacement			X
FCPU Downtime	12 hours	48 hours	4 days

modularized to facilitate maintenance. The level of maintenance skill required is estimated to be a military E-4 or the civilian equivalent

A six month scheduled outage is programmed for each FCPU, on a rotating basis. This outage is planned to allow replacement of the ZnO desulfurization catalyst, cleaning of the fuel vaporizer, and replacement of any short-life components (e.g., filters, etc.). The replacement of ZnO catalyst is dependent on the actual sulfur content of the fuel. A catalyst bed of 150 pounds has been used, which allows six months of normal load operation (60 kW) with DF-2 containing 2500 ppm sulfur. If diesel fuel containing the maximum permissible sulfur content (5000 ppm for CONUS areas) were used, the catalyst life would be reduced to 2300 hours at 60 kW or 1500 hours at 100 kW.

Cleaning of the fuel vaporizer is required during the six month scheduled outage due to coking at vaporization temperatures. The actual severity of coking with typical DF-2 fuel needs to be assessed. If severe coking occurs, it may be necessary to clean the vaporizers more frequently or use parallel vaporizers and decoke while the FCPU is operating. The estimated total duration of the six month scheduled outage is 12 hours, which includes time for cool down and restart.

The FCPU's require overhauls at 2-1/2 year and 5 year intervals. The primary reason for the 2-1/2 year overhaul is to replace the reformer and shift catalysts. These catalysts are anticipated to have a 3-5 year life. Therefore, it is uncertain whether or not they will remain active until the five year major overhaul using DF-2 fuel. Replacement after 2-1/2 years is a conservative approach, and experience may show that five year replacement intervals are sufficient. The 2-1/2 year overhaul will also be used to replace any short-life components such as pump seals, burner components, etc. Even though the estimated Mean Time Between Failures of the FCPU's is 2680 hours, preventative maintenance during the six month scheduled outages and 2 1/2 and five year overhauls may markedly increase unit reliability. Total outage time for the 2-1/2 year overhaul is estimated to be 48 hours.

The purpose of the five year overhaul is the replacement of the fuel cell stack. Fuel cell performance will slowly degrade with time, and 40,000 hours, or roughly five years, is the design life of a stack. Typical voltage loss over this period is expected to be 5-10 percent. The high temperature steam reformer will also be overhauled at five year intervals. If required, reformer tubes will be replaced. Total duration of the five year overhaul is estimated to be four days.

Since the five year overhaul requires replacement of a major component (the fuel cell stack), the logistics of this overhaul need to be studied. The feasibility of on-site replacement of the stack will depend on the final FCPU design arrangement and the availability of on-site maintenance capabilities. The three full stacks, less manifolds, will weigh approximately 500 pounds each. An alternative to on-site stack replacement is the shipping of the FCPU to a fuel cell maintenance facility, perhaps at the manufacturer's factory. In this case, a replacement FCPU, or alternately a replacement fuel cell subsystem (2,200 lbs), would be substituted for the unit to be overhauled. Naturally, the final unit design must be consistent with the proposed maintenance program. Shipping of an FCPU to remote maintenance facilities will impose additional transportability requirements. Replacement of the fuel cell subsystem for maintenance will require suitable modulization of the design. Life cycle cost and FCPU availability estimates have been based on on-site stack replacement.

However, the four days allowed for the five year overhaul are considered sufficient for either maintenance approach, on-site stack replacement or replacement with a new unit and remote maintenance.

6.3.3.2 FUEL SUPPLY AND STORAGE

The FCPU's have been designed to utilize the same power plant fuel (DF-2) as existing diesel-electric generators. The present storage and fuel distribution system can be utilized without any modifications. Since the fuel cell units are more efficient than the diesels, they will use less fuel and will be able to operate longer on the same amount of stored fuel. With an average electric demand of 180 kW and an FCPU power efficiency of 14.2 kilowatt hours per gallon, the monthly fuel consumption is approximately 9,400 gallons, or 15 percent to 20 percent less than the existing diesels.

Consideration was given to designing the FCPU's for operation with jet fuel, JP-4. Due to its lower boiling point and lower sulfur content, JP-4 is somewhat easier to steam reform than diesel oil. However, the use of JP-4 would require a modification of the existing logistics of fuel delivery. Diesel oil would probably still be required for other site uses. Therefore, it was decided to design the FCPU's for normal operation on diesel fuel, with the provision to use JP-4 as a back-up fuel. Using JP-4 the FCPU fuel consumption rate will increase about 10 percent because of the lower heat content of JP-4 versus DF-2.

6.3.3.3 SYSTEM OPERATION AND AVAILABILITY OF POWER

The present MENORCA plant arrangement consists of four 250 kW diesel-electric generators. Normal operation consists of one operating unit, one automatic standby, one manual backup, and one off-line for maintenance. In the case of a failure of the operating unit, the automatic standby unit comes on-line in a few seconds. This momentary loss of power causes equipment outages from a few minutes to 30 minutes. If the automatic standby unit fails to start, the manual backup unit can be brought on-line in 2-3 minutes. However, any loss of power for more than 15 seconds causes the whole communication system to shutdown, requiring several hours before normal operation can be resumed.

The specified power reliability for this application is 99.99 percent. This means a permissible cumulative power outage of 53 minutes per year. The existing plant arrangement exceeds these requirements.

A modified unit operating strategy is required in the case of a fuel cell power plant. Since the FCPU's have a slow start-up rate (i.e., approximately 1-2 hours), it is not possible to rely on an automatic standby unit. However, fuel cells also have the desirable characteristic of high part load efficiency. Therefore, it is possible to operate with multiple units, each operating at part load. In the case of the failure of one unit, the remaining units can handle full station load without a power outage. The proposed arrangement consists of three 100 kW FCPU's, each operating at 60 percent load under normal conditions. In the case of a unit trip, the remaining two units can supply all the station electric demand, including the 200 kW peak load.

Each FCPU has an estimated Mean Time Between Failure (MTBF) of 2,680 hours, as shown in Table 6-11. Most of the anticipated failure rates were taken from typical failure rate data associated with USAF fixed ground support systems as reported by the Rome Air Development Center (NPRD-1). Where data was not available (e.g., fuel cell subsystem, fuel processor, power conditioner), estimates for high reliability designs were assumed. The fuel cell assembly and fuel processor were each assumed to have one unscheduled outage during their 40,000 hour design life. This does not include scheduled outages for catalyst replacement, etc.

The individual FCPU availability is estimated to be 99.1 percent, as shown in Table 6-12. This value represents the percentage of calendar time that an individual FCPU is available for power generation over a five year period (i.e., the lifetime of a stack). Since only two of the three installed FCPU's are required to satisfy the station electrical demand, the availability of power, defined as the percentage of time that 200 kW of electric power capacity is availability, is greater than the individual FCPU availability. As shown in Appendix D-3B, power availability varies from 0.9999 in Year 1 of cell life to 0.9998 in Year 5. The average over a five year cell lifetime is 0.9999, which meets the MENORCA station requirements.

6.3.4 FCPU CAPITAL AND O&M COSTS

6.3.4.1 CAPITAL COSTS

An estimate of FCPU capital costs by account number is given in Table 6-13. A breakdown of equipment included in each account is given in Appendix B. Total FCPU capital cost, based on end of year 1980 dollars, is $231,500. This represents a unit cost of $2,315 per kilowatt.

TABLE 6-11

RELIABILITY ESTIMATE
100 KW FUEL CELL POWER UNIT

COMPONENTS	FAILURE RATE, PER 10^6 HRS(1)
Fuel Cell Assembly	25.0(2)
Fuel Processor	25.0(2)
Heat Exchangers	9.0
Fuel Pump	7.5
Water Pump	5.6
Air Blowers	13.5
Turbocharger	10.0
Microprocessor	20(3)
Housekeeping Power Supply	20(3)
Power Conditioner	20(3)
VALVES	
Flow	66.4
Press Reg.	9.6
Solenoid	8.0
Relief	4.8
Check	12.0
SENSORS	
Pressure	5.4
Levels	4.8
Temperature	58.0
Current, Power	3.2
Ducting	15.0
Tubing	30.0
	372.8, MTBF = 2,680 hours

(1) Based on avg. data from non-electric parts reliability data NPRD-1, Rome Air Development Center, 1978

(2) Assumes fuel cell and reformer catalyst life of 40,000 hrs.

(3) Assumed values for high reliability designs

TABLE 6-12
100 KW FCPU AVAILABILITY

Cause of Outage	Hours Unavailable in Year Indicated				
Year	1	2	3	4	5
1. Unscheduled (MTBF = 2,680 hrs., MTTR = 8 hrs.)	26	26	26	26	26
2. Six-Month Scheduled Maintenance	24	24	12	24	12
3. 2 1/2 Year Overhaul (Catalyst Replacement, etc.)	0	0	48	0	0
4. Five Year Overhaul (Stack Replacement, etc.)	0	0	0	0	96
Subtotal	50	50	86	50	144
Five Year Total					380

$$\text{Availability} = \frac{\text{Total Hours - Hours Unavailable}}{\text{Total Hours}} = \frac{5 \times 8{,}760 - 380}{5 \times 8{,}760} = 0.991$$

TABLE 6-13
CAPITAL COST ESTIMATE
100 KW FCPU

Account	Description	Cost (1980$)
1000	Fuel Cell Assembly	67,000
2000	Fuel Processing	54,000
3000	Fuel Delivery	4,000
4000	Water Delivery	6,100
5000	Air Delivery	14,000
6000	Heat Exchangers	27,700
7000	Controls & Instrumentation	8,000
8000	Power Regulation	43,000
9000	Structural	7,700
	Total =	$231,500
	=	$ 2,315/kW

These estimates are based on a mature FCPU market with a 1,000 units of cumulative production. An experience curve effect was assumed for the non-commercial components such as the fuel cells and fuel processing system. No experience curve effects were applied to commercially available components, such as pumps, heat exchangers, etc., even though some cost reduction due to volume production will undoubtedly be experienced. Experience curve effects have been observed in many types of production processes and they are a measure of the cost reductions that occur with increases in the cumulative size of a production run. These cost reductions are due to the combined effects of improved labor efficiencies (i.e., learning curve effects); technical and manufacturing improvements; economies of scale; and volume purchasing of components and materials. An 80 percent experience curve means the cost per unit will decrease by 20 percent when the cumulative number of units produced is doubled. Similarly, an 85 percent experience curve will result in a 15 percent cost reduction when the cumulative number of units is doubled. Based on analysis of experience curves for similar types of equipment, an 85 percent experience curve was assumed. For a cumulative production of 1000 FCPU's, the experience curve reduces initial non-commercial elements capital costs by 80 percent.

6.3.4.2 OPERATING AND MAINTENANCE COSTS

Normal operation of the FCPU is automatic and does not require constant operator attention. Start-up and shutdown, fault correction, and other abnormal operating conditions do require operator assistance. At present, the example MENORCA power plant is operated by a ten man crew, with two men per shift and three shifts per day. The station is experimenting with a six man operating force. It is estimated that a fuel cell power plant could be operated with only four men (one per shift). Based on operating labor costs supplied by Mr. J. Siska (AFCS), a labor costing rate of $24,500 per man-year was assumed. Therefore, the estimated annual power plant operating labor cost (with fuel cells) is $98,000, or $32,700 per FCPU.

A breakdown by account number leading to an estimated total yearly hardware replacement cost of $19,540 per year is illustrated by Table 6-14. The failure rates per million operating hours are the same as used to estimate the MTBF of

TABLE 6-14
100 KW FCPU HARDWARE REPLACEMENT COSTS (1980$)

Account No.	Item	Failure Rate Per Million Hrs	Operating Hrs Per Year	Failures Per Year	Yearly Average Hardware Replacement Cost - $
1000	Fuel Cell Assembly	25	8,681	0.217	8,720
2000	Fuel Processing	25	8,681	0.217	5,630
3000	Fuel Delivery	7	8,681	0.061	100
4000	Water Delivery	6	8,681	0.052	130
5000	Air Delivery	23	8,681	0.200	1,190
6000	Heat Exchangers	9	8,681	0.078	910
7000	Controls & Instrumentation	20	8,681	0.174	410
8000	Power Regulators	40	8,681	0.347	2,030
9000	Structure	0	8,681	0.000	0
Special	Valves & Sensors	172	8,681	1.493	300
Special	Startup Battery	1,000	10	0.010	<1
Special	Ducting & Tubing	45	8,681	0.391	80
			Totals	3.240	19,540

2,680 hours. Cleaning of the fuel vaporizer and replacement of the sulfur removal catalyst are assumed to occur at six month intervals. Other scheduled maintenance such as changing fuel and air filters can be accomplished at the same time.

In constructing Table 6-14, the major subsystems (Account Nos. 1000 through 9000) were assumed to be totally replaced in case of a failure. The failed parts were assumed to have a salvage value that ranged from 40 percent of the initial cost in the case of the fuel cell to 85 percent of the initial cost in the case of the power conditioner. Replacement part costs of the major subsystems were less costs of valves, ducting, tubing and sensors associated with these subsystems.

Valves, ducting, start-up battery, etc. were evaluated under the special accounts at the bottom of Table 6-14. The failures were treated as individual valve, sensor, etc., replacements with no salvage value for the failed part.

Table 6-14 indicates that an unscheduled repair because of a unit failure can be expected on the average to occur 3.2 times per year, reflecting the MTBF estimate of 2,680 hours. When added to the scheduled maintenance outages, total hours of maintenance and service are 76 hours per year per FCPU. The nature of the maintenance skills required would be trained E4 level skills: (1) trouble shoot modular system, (2) replace modules, and (3) return unit to operating condition.

The total operating, servicing, and maintenance costs per FCPU are estimated as follows:

Maintenance Crew Size	2 Persons
Costing Rate per Crew	$24.50/Hour ($24,500/Year Each Person)
Hours of Maintenance & Service	76 Hours/Year
Service & Maintenance Labor Cost	$1,860/Year

Special Equipment	None
Hardware Replacement Costs	$19,540/Year
Transportation for Repair	$2,060
Supplies (Filters, Sulfur Catalyst, etc.)	$330/Year
Operator Costing Rate	$24,500/Man-year
Operating Labor Cost	$32,700/Year
Total O&M Cost (per FCPU)	$54,430/Year

6.4 DEVELOPMENT RISK ASSESSMENT

A technical development risk assessment was performed at both the subsystem/major component level and the overall system level. The technology status rating criteria are presented in Table 6-15. Each subsystem or major component was evaluated with respect to the following factors:

- Current technology status
- Technology rating (Table 6-15 criteria)
- Required technology status to meet design requirements for the proposed applications
- Proposed developmental program to achieve the required technology status
- Estimated developmental effort expressed in terms of manhours of R&D personnel (engineering plus technicians)
- Estimated developmental effort expressed in terms of development dollars (labor and materials)
- Probability of success of the proposed developmental program
- Ongoing programs or potential design alternatives.

A summary of the development risk assessment is given in Table 6-16. Those areas presenting the greatest risk (and largest development requirements) are as follows:

TABLE 6-15

REQUIREMENTS FOR APPLICATION AT (A) TECHNOLOGY RATING LEVEL

TECHNOLOGY RATING	TECHNOLOGY STATUS	PERFORMANCE DATA BASE	EXTRAPOLATION FROM PERFORMANCE DATA BASE	APPLICATION OR DEVELOPMENT PROGRAMS REQUIREMENTS	R&D PROGRAM CHARACTERISTICS	
					RATIONALE	SUCCESS PROBABILITY
Established (A)	Firm selections can be made. Equipment is commercially available in form required.	Sufficient	None	Minimal, routine applications engineering.	Not Applicable	Not Applicable
Near Term (B)	A number of equipment . candidates are identified. Candidates are commercial or near commercial.	Incomplete	Short extrapolations from existing data base are involved.	Confirmatory testing and minimal R&D.	Straight-forward	Virtually Certain
Developmental (C)	Equipment not previously designed, but engineering data base exists for design.	Incomplete; important gaps exist	Large extrapolations from existing data required.	Considerable R&D is required	A credible rationale exists. Alternative avenues are evident.	Good to excellent
Speculative (D)	Equipment not previously designed with major materials, design or manufacturing uncertainties.	Sparse or Absent	Highly speculative or not possible.	Extensive R&D is required.	Rationale is not clear, or requires a break-through or serendipity.	Fair to poor.

TABLE 6-16

DEVELOPMENT RISK ASSESSMENT
100 KW REMOTE ATTENDED FCPU

SUBSYSTEM/MAJOR COMPONENT	CURRENT TECHNOLOGY STATUS	TECHNOLOGY RATING	REQUIRED TECHNOLOGY STATUS	REQUIRED DEVELOPMENTAL PROGRAM	ESTIMATED MANHOURS (thousands)	ESTIMATED DEVEL. COST (000$)	PROBABILITY OF SUCCESS	ONGOING PROGRAMS & POTENTIAL ALTERNATIVES
1.0 FUEL PROCESSING								
1.1 Fuel Handling and storage	Existing on-site facilities and experience with DF-2 diesel fuel.	A	No change required.	No development program is required.	0	0	N.A	N.A
1.2 Fuel Vaporizer	Commercial experience in petrochemical industry primarily with direct-fired heaters.	B	Tubular vaporizer located in convection section of reformer furnace. Continuous operation without coke formation.	1. Experimental testing to determine rate of coke formation.	1.0	80	Very Good.	
1.3 High Temperature Steam Reformer	Extensive commercial experience with conventional steam reforming on fuels from methane to heavy naphtha. Laboratory and pilot plant experience with HTSR of No. 2 fuel oil.	C	Stable performance on DF-2 without coking or sulfur poisoning. Steam-to-carbon ratio < 4.0. Fuel conversion to carbon oxides > 90%.	1. Catalyst testing. 2. Multi-tube reformer testing. 3. Full-scale system evaluation and analysis. 4. Cost study.	20.0	2000	Very good	Existing DOE and EPRI sponsored studies on HTSR of No.2 fuel oil. Potential alternative is auto-thermal reforming, which is also under D.O.E. development.

TABLE 6-16 (Continued)

SUBSYSTEM/MAJOR COMPONENT	CURRENT TECHNOLOGY STATUS	TECHNOLOGY RATING	REQUIRED TECHNOLOGY STATUS	REQUIRED DEVELOPMENTAL PROGRAM	ESTIMATED MANHOURS (Thousands)	ESTIMATED DEV. COST (000$)	PROBABILITY OF SUCCESS	ONGOING PROGRAMS & POTENTIAL ALTERNATIVES
2.0 FUEL CELL								
2.1 Fuel Cell Stack	Laboratory and prototype experience. Life tests up to 80,000 hrs with H_2 fuel. Large, multi-cell stacks being tested for utility applications. 4.8 MW demonstration plant under construction. 40 kW on-site program in progress (natural gas fueled)	B	Cell life 40,000 hours. Pressurized (60 psia) cell operation. Cell voltage = 0.72 VDC at current density of 150 amps per ft^2. Minimal acid loss. Low cost design with high reliability.	None. Development under other programs assumed adequate.	0	0	N.A.	Several development programs sponsored by D.O.E., U.S. Army, E.P.R.I., GRI, and various electric utilities. In house development by potential suppliers.
2.2 Cooling Systems and Fuel Cell Auxiliaries	Existing designs have water, air, and dielectric cooled desins. Laboratory and prototype experience with both atmospheric ans pressurized systems.	B	High reliability and low cost. Pressurized (60 psia) operation.	Stack pressurization and cooling issues to be resolved as part of fuel cell stack development. No development effort is recommended for the auxiliary components (blowers, heat exchangers, etc.).	0	0	N.A.	N.A.

TABLE 6-16 (Continued)

SUBSYSTEM/MAJOR COMPONENT	CURRENT TECHNOLOGY STATUS	TECHNOLOGY RATING	REQUIRED TECHNOLOGY STATUS	REQUIRED DEVELOPMENTAL PROGRAM	ESTIMATED MANHOURS (Thousands)	ESTIMATED DEV. COST (000$)	PROBABILITY OF SUCCESS	ONGOING PROGRAMS & POTENTIAL ALTERNATIVES
3.0 POWER CONDITIONING								
3.1 DC-AC Inverter	Existing technology. Package units being developed for photovoltaic and Fuel cell applications.	A	High efficiency (90-95%) Low cost.	No developmental program is recommended.	0	0	N.A.	Suppliers developing standard units for various alternate energy systems.
4.0 BALANCE OF PLANT								
4.1 Instrumentation and Control	Developed for small mobile systems and large (5 MWe)stationary plants. Assumes manned operaton.	A	High reliability and safety. Pressure control with integrated system using a turbo-compressor.	1. Control system design and analysis. 2. Transient response analysis.	3.0	200	Very Good	System analyses for other PAFC applications.
5.0 OVERALL SYSTEM	Complete, small (< 5kW) units delivered to U.S. Army for premixed methanol/water fuel. Large (5MWe)stationary system under construction using natural gas fuel. Various levels of experience with intermediate site units. 40 kW units to be tested.	B	High reliability operation/with automatic control. Proper interfacing with load demand. Long life (20 years). Low performance degradation during operating lifetime. Capability to handle diesel fuels.	Qualification program and field testing including: 1. Laboratory units of subsystems 2. House development unit (1). 3. Field test qualification units (1).	45.0	5250	Very Good	None to verify this particular design and application requirements.
TOTAL DEVELOPMENT PROGRAM					69.0	7,530		

- Active cell area = 1.1 Ft^2
- Number of cells = 960
- Number of stacks = 3
- Reformed DF-2 fuel

Although phosphoric fuel cells have been tested and operated successfully under similar conditions, several areas require further investigation and development. Most existing PAFC stacks are operated under near atmospheric pressure at approximately 350°F. In addition, they are usually fueled by pure hydrogen or a clean, reformed gas derived from methanol or natural gas. The reformed DF-2 fuel gas will be cleaned prior to entering the fuel cell stack, but the effect of trace impurities, such as heavy metals or nitrogen, and the high carbon oxide content, require further testing.

Several development programs are presently being conducted on phosphoric acid fuel cell technology. The primary sources of funding are DOE, EPRI, GRI, various electric utilities, U. S. Army, and the fuel cell developers. Work is being conducted by Westinghouse/Energy Research Corporation, United Technology Corporation and Engelhard Industries. The various applications that these development programs are directed at include:

- Small, mobile units for the U. S. Army (3-5 kW)
- On-Site Integrated Energy Systems (40-150 kW)
- Dispersed utility power plants (5-10 MW)

The extent of these programs, and the applicability to the 100 kW FCPU requirements, are uncertain at this time. The most closely related work appears to be the On-site Fuel Cell Field Test Project, which is jointly sponsored by the Gas Research Institute (GRI) and DOE. Up to fifty 40 kW phosphoric acid fuel cell energy systems, built by United Technologies Corporation, will be fabricated and installed at 20-30 industrial sites. This program will supply considerable data and knowledge that can be utilized to refine the 100 kW FCPU design. However, these units are natural gas fueled, unpressurized, and do not have the same thermal integration requirements as the proposed FCPU's.

Based on the projected development of PAFC cell and stack technology, no additional development effort is deemed necessary at this time. This is primarily a result of the decision to use a standard (12 in X 17 in) fuel cell size that is already under development. It is assumed that sufficient development on the PAFC stack will be performed under other programs and that this technology will be adaptable to the 100 kW FCPU.

Instrumentation and Control

The MENORCA application requires that three FCPU's be operated in parallel and that they be independent of a utility grid or other source of auxilary power. In addition, the selected FCPU design is pressurized to 60 psia and highly integrated. These conditions require the development of a sophisticated automatic control system capable of maintaining stable operation, responding to load changes, and indicating and taking corrective action in the case of component failures or other upsets.

These requirements can be met by an automatic control system employing a microprocessor. Development effort is required to identify critical control functions and to determine the most appropriate equipment and control logic. In addition, the transient response of the system to a load change needs to be analyzed by a dynamic analysis. Estimated development effort is 3,000 manhours at a cost of $200,000.

System Integration and Testing

The packaging and integration of the various subsystems/major components into a Fuel Cell Power Unit is developmental in the sense that previous units with similar requirements (especially fuel type) have not been built and operated. The requirements for a high temperature steam reformer and pressurized cell operation (using a turbo-compressor unit) present unique system considerations. In addition, the FCPU must be designed for water recovery and waste heat integration. As noted above, the planned 40 kW Field Test Program will help answer many of these concerns. However, it is suggested that a system verification and qualification program be conducted. The verification program would include construction and testing of the following units:

- Laboratory units of major subsystems
- House development unit (Full size)
- Field qualification unit

The estimated cost of materials and test apparatus is approximately $2,000,000. Estimated manpower requirements (engineers and technicians) are 45,000 hours. Total developmental cost for the system verification and qualification program is $5,250,000.

Total Developmental Program

The total recommended developmental program, based on the development risk assessment as discussed above, requires 69,000 man-hours of development labor (engineers plus technicians). The total program cost is approximately $7,530,000. These estimates are based on the present status of technology development and the assumed commercial availability of fuel cell modules. Considerable research, development, and testing are presently being conducted or are planned in all areas of appreciable developmental risk. The impact of these programs, most of which are subject to funding review, on 100 kW FCPU development risk is highly speculative. The estimated development risk assumes moderate input from these parallel programs. Accelerated development in these areas may substantially reduce the development risk whereas an absence of parallel development will require a larger developmental program.

6.5 LIFE CYCLE COSTS (LCC)

6.5.1 100 KW FCPU LCC

The applicable life cycle costing (LCC) elements and the basis of the elements' costs are as follows:

Life Cycle Period - 20 years
R&D - Table 6-16 cost spread over 1,000 units
Technical Data - Value from Ref. 6-5 spread over 1,000 units
Production Cost - Unit capital cost from Section 6.3.4.1
Operating Personnel Cost - From Section 6.3.4.2
Maintenance & Supplier Cost - From Section 6.3.4.2
Transportation for Repair - From Section 6.3.4.2
FCPU Replacements - Move over 20 years
Initial FCPU Transportation & Installation - $0.95 per pound
Initial Spares - One years supply per Table 6-14
Fuel - Base year cost - $1.22/gallon escalated at 7%/year thereafter

The estimated life cycle costs by element and in total are as follows:

Element	Cost (1980 $)
R&D	7,500
Production	231,500
Initial Spares	19,500
FCPU Replacements	0
Maintenance & Supplies	432,000
Operating Personnel	654,000
Repair Transporation	41,200
Fuel	1,824,000
Technical Data	200
Initial Transportation & Installation	9,800
TOTALS	$3,219,700

6.5.2 MENORCA SITE - DIESELS VS. FCPU LCC

The MENORCA Site currently uses 250 kW diesel-electric generators. A comparison of the twenty year life cycle costs for the current diesel installation versus those for a projected FCPU installation is given in Table 6-17. As

TABLE 6-17
FCPU VERSUS DIESEL GENERATORS

	Diesel	FCPU
Installed Capacity, kW	4 x 250	3 x 100
Average Heat Rate, Btu/kW-Hr	12,050	9,770
Noise Level	High	Low
Mean Time Between Failure	500 (Specified)	2,680
	(1980 $)	(1980 $)
Capital Cost (Initial)	0	747,000
Replacement Cost (20 years)	500,000	0
O&M Cost (20 years)	5,719,000	3,381,600
Fuel Cost (20 years)	6,745,000	5,472,000
Total LCC	12,964,000	9,600,600

LCC Saving Using FCPU's 3,363,400

shown, substitution of FCPU's for the diesel-electrics at the MENORCA site gives a projected cost savings of almost $3.4 million.

6.6 CONCLUSIONS

A 100 kW FCPU has been designed that meets the generic requirements for U. S. Air Force remote attended use. As an example of use the MENORCA Communications site of the USAF European communications system was selected. Three 100 kW FCPU's are proposed to supply the average MENORCA station electrical demand of 180 kW. The FCPU's have lower fuel consumption, higher efficiency, greater reliability, less operating needs, and lower life cycle costs than the 250 kW diesel-electric generators presently installed. Estimated life cycle cost savings over a projected power plant twenty year lifetime are about $3.4 million.

The proposed FCPU design uses state-of-the-art fuel cell technology, with the exception of the fuel processing system. A development risk assessment was performed, and it is estimated that a development program of 69,000 man-hours and a total cost of $7,530,000 will be required to develop and qualify an FCPU for MENORCA type applications.

7.0 60 KW TACTICAL MOBILE FCPU
(FOREWARD AIR CONTROLLER RADAR EXAMPLE)

7.1 INTRODUCTION AND SUMMARY

An application analysis, preliminary conceptual design, development risk assessment and Life Cycle Cost (LCC) analysis of a phosphoric acid fuel cell power unit has been carried out. The generic application investigated is a tactical mobile electric power system with a power requirement between 30 kW and 60 kW. An example of a United States Air Force application for the unit is 60 kW mobile electric power for a Foreward Air Controller Radar System.

Currently, the United States Armed Forces have two types of tactical mobile electrical generator systems. Both are rotating units. One is based on use of a diesel engine as the prime mover. The other uses a gas turbine as the prime mover. The diesel units are relatively heavy and fuel efficient as opposed to the gas turbine units which are relatively light but fuel inefficient.

Gas turbine units are used, currently, to provide electric power to Foreward Air Controller Radar Systems. It is the desire of TAFIG, Langley AFB, Virginia, to find replacement power plants for the currently used gas turbine units that will provide substantial improvements in weight, volume, and fuel consumption over these present units.

Two different sets of design requirements have been derived for 60 kW fuel cell tactical mobile electric power generators. The first set of requirements are for a generic 60 kW mobile power generator using diesel units as background. The second set of requirements is based on the gas turbine driven generators providing power to a Foreward Air Controller Radar System.

A 60 kW Fuel Cell Power Unit (FCPU) for tactical mobile use has been designed. The FCPU design involves improvement over state-of-the-art phosphoric acid fuel cell power unit technology as a whole; but individual component characteristics have, at a minimum, a laboratory tested basis. The FCPU design more than meets the requirementes of a generic application based on diesel units as background; including the use of JP-4 and diesel fuels. A summary of the FCPU's characteristics may be found in Table 7-1.

An artist's conception of the 60 kW tactical mobile FCPU is shown in Figure 7-1.

This study has found that even a "stretched" phosphoric acid fuel cell technology results in power units that are much bigger and heavier than current gas turbine power units. The FCPU design is, however, well within air transportability requirements and is much more fuel efficient than current gas turbine power units; 6 gph versus 17.5 gph. More specifically, the FCPU design is approximately four times heavier (4,050 lbs versus 950 lbs) than the gas turbine units used to power Foreward Air Controller Radar Systems. Because of the much lower FCPU fuel consumption, the total weight of power unit plus fuel that must be transported from base to field for a typical two week Foreward Air Controller Radar exercise is actually lower using FCPU's than using gas turbine units. This, of course, assumes that the fuel as well as power units must be transported from the basing point to a distant remote temporary Foreward Air Controller Radar site.

A straight twenty year Life Cycle Cost (LCC) comparison between FCPU's and gas turbine units shows a decided cost advantage in favor of FCPU's. This is because the cost of fuel over any extended period of time is a dominating factor. At a JP-4 fuel cost of $1.30 per gallon*, escalated at 5 percent/year, and a total yearly operating time of 1750 hours, a twenty year LCC advantage for a FCPU over a gas turbine unit of approximately $600,000 is estimated. Such a cost estimate does not consider the intangibles associated with

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*$0.80/gal. base cost plus $0.50/gal cost of delivery to remote site.

TABLE 7-1

POWER PLANT DESIGN SUMMARY

As applicable, the following summary of the 60 kW tactical mobile FCPU parameters is based on an operating time of 1,750 hours per year.

PHYSICAL PARAMETERS

a) Type of Fuel: JP-4 Primary, Diesel Fuels Secondary

b) Fuel Consumption: 10,000 Gallons/Year

c) Volume/Size:

Volume - 225 Ft^3
Size - 37.5 Ft^2

d) Weight: 4,050 lbs.

e) Environment Constraint:

Thermal Discharge	- 445,000 Btu/Hr Average
Air Pollution	- NO <0.24 Lbs/Mwh Generated
Noise	- <84 dbA at 4 Meters
Solid Waste	- 75 Lbs Zinc Sulfide/Zinc Oxide per Year
Chemical Discharge	- Trace H_3PO_4
Radioactive Wastes	- None

PERFORMANCE PARAMETERS

a) Reliability:

Mean Time Between Failures	- 2,600 Hours with Preventive Maintenance
Availability	- 99.3% without On-Site Repair, ∿100% with On-Site Repair

b) Lifetime: 22.5 Years without Major Component Replacement

c) Operation and Maintenance:

Ease of Operation	- Unattended Operation with Refueling Every 8 Hours
Ease of Maintenance	- Failure Maintenance Requires: Trouble shooting, component replacement and check-out. Preventive maintenance requires cleaning of fuel vaporizer and replacement of sulfur removal catalyst, plus other routine cleaning and adjustment.

TABLE 7-1 (Continued)

Maintenance Skills Required - E4 or Civilian Equivalent

d) Growth Potential: Major elements are of modular construction. Power unit growth potential without size increase is low. Growth potential with size increase is large.

e) Start-Up/Shutdown Time:

Startup - One-Half Hour
Shutdown to Hot - <15 Minutes
Standby to Cold Shutdown - One Hour

f) Thermal Energy Available: Example application does not require thermal energy. Could provide about 138,000 Btu/Hr at temperatures above 200°F.

g) Electrical Output: 60 kW Rating at 0.8 Power Factor, 400 Hz, 120/208V or 240/416V; 66 kW Peak

COST PARAMETERS

a) Capital Costs:

Fuel Cell Power Unit - $152,000
Other Capital Costs - $2,600 (initial spare parts provisioning)

b) Maintenance Cost:

Transportation for Repair - $180/Year
Personnel Cost - $1,680/Year
Special Equipment Cost - Not Applicable
Replacement Hardware Costs - $2,600/Year
Total - $4,300/Year

c) Operation Costs:

Fuel and Fuel Transportation Costs - $13,600/Year (First Year Only)
Supplies - $200/Year
Operating Personnel Costs - $14,300/Year
Transportation To And From Operating Sites Costs - $7,200/Year
Special Equipment at Site Cost - $2,000/Year
Total - $37,300/Year

d) Life Cycle Cost: $1,182,700 (20 year total)

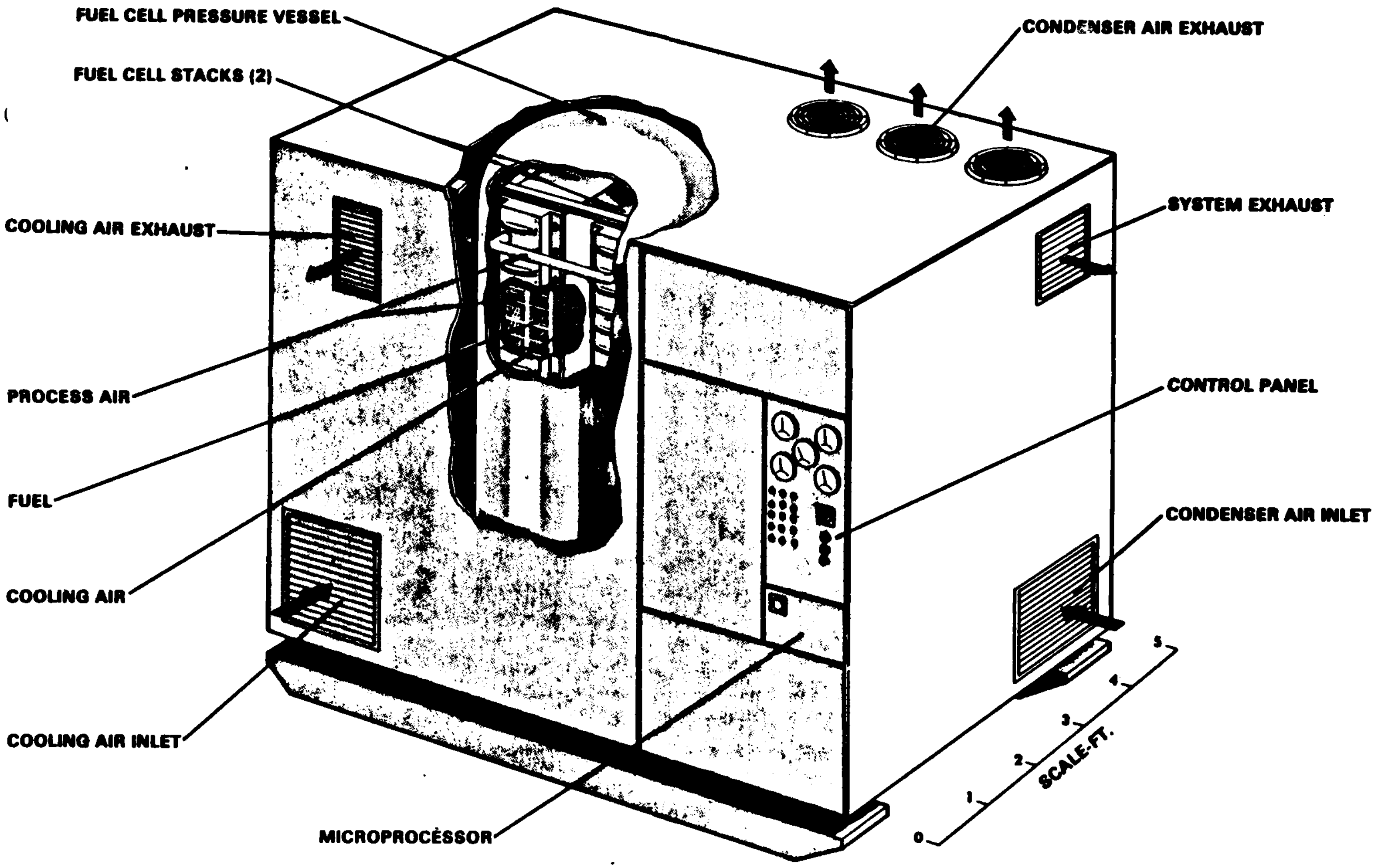

Figure 7-1. 60 kW Tactical Mobile FCPU
(150 psia, ATR/PAFC System)

transporting four tons of FCPU's to accomplish what can be accomplished, currently, with one ton of gas turbine units**.

Because of the laboratory nature of the technology of many of the components used in the FCPU design, the development risk has been assessed to be equivalent to a $10,000,000 development program to produce a single unit for field trials.

7.2 SYSTEM REQUIREMENTS

The generic application considered herein is a tactical mobile electric power system with a power requirement between 30 kW and 60 kW (Ref. 7-1)*. A specific application to be considered (Ref. 7-2) is a 60 kW Mobile Power Generator for a Foreward Air Controller Radar System.

Currently the United States Armed Forces has two types of tactical mobile electrical generator systems. Both are rotating units. One is based on use of a diesel engine as the prime mover The other uses a gas turbine as the prime mover. The diesel units are relatively heavy and fuel efficient. The gas turbine units are relatively light but fuel inefficient.

Two different sets of requirements have been derived under this program for 60 kW fuel cell tactical mobile generators. The first set of requirements is for a generic 60 kW mobile power generator using diesel units as background. The second set of requirements is based on gas turbine driven generators providing power to a Foreward Air Controller Radar System (FACRS).

The generic classification for both units is:

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*References for Section 7.0 given in Appendix A-5.

**Assumes the use of two units, one primary, one backup, for Foreward Air Controller Radar System duty.

Power Rating	60 kW at 0.8 power factor, 400 Hz, 120/208V or 240/416V
Type:	I (tactical)
Class:	1 (precise)
Mode:	II (400 Hz)

7.2.1 FACRS APPLICATION*

As stated previously, the existing electrical power units for the FACRS application are gas turbine driven. The units are mounted on a pallet that holds two 60 kW units. One unit is the operating unit with the other unit functioning as a backup. The overall dimensions of the units are 60 in long x 36 in wide x 30 in high. They weigh 950 pounds each. Fuel to electrical efficiency, using JP-4 fuel, is seven or eight percent (17 gph at 60 kW).

The FACRS application is an "on call" operation. The units are flown from a central base to needed locations as required. Typically, the units are deployed about six times per year for two week periods. When deployed, the demand for power is continuous. During the period of continuous demand, operating time may be split between the two units on the pallet. When the units are at the central base, they are operated for about four hours per week to maintain a ready status. Average operating time per unit per year is about 20 percent (1,750 hours) of the total yearly time available (8,760 hours).

The primary requirements of a power unit for the application are reliability and mobility in a rough handling environment. It was the opinion of TAFIG personnel that any replacement units should be significantly lighter, more reliable, and more efficient than the existing gas turbine units. Another requirement, once in place, is a fast startup to full power. It was the opinion of TAFIG personnel that a one hour startup time for a unit would be acceptable if

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*Principle source of information: Capt. J. Shields, TAFIG, Langley AFB, Virginia.

the unit were brought to hot standby during the transport from base to foreward location.

A detail applications data sheet (W-ADS-4) for the FACRS application has been prepared (see Appendix C-4A). This applications data sheet was reviewed, informally, with TAFIG personnel. Some of the important requirements for a fuel cell power unit for the application are:

Maximum Dimensions: 60 in x 36 in x 30 in

Maximum Volume: 36 Cubic Feet

Maximum Allowable Weight (excluding Fuel): 950 Lbs

The unit shall be inaudible at 100 meters when operating at any load level.

The unit shall be designed to withstand an 18 inch end drop and a 10 mph railroad impact.

Reliability: 1,500 Hours MTBF

Transient Electrical Performance:

	Voltage	Frequency
Application of Rated Load	15% Dip	1.5% Undershot
Recovery	0.1 Sec	1.0 Sec
Rejection of Rated Load	15% Rise	1.5% Overshot
Recovery		
Application of Simulated Load	30% Dip	
Recovery	0.15 Sec	
Total Harmonic Distortion	5.0%	
Individual Harmonic	1.5%	

7.2.2 GENERIC APPLICATION*

As mentioned previously, a set of design requirements for a generic 60 kW fuel cell power unit (FCPU) tactical mobile generator were created. The basic background information used in preparing the generic requirements was that for current diesel powered units; but modified to force lower fuel consumption, higher reliability, and multifuel capability into FCPU design. Admittedly, these modifications were done with the knowledge attained from prior program work that fuel consumption, reliability and multifuel capability, were the chief virtues of FCPU's compared to diesel generators.

The requirements data sheet (W-RDS-4) for the generic application is provided in Appendix C-4B. Some of the important requirements for a FCPU from W-RDS-4 are as follows:

Maximum Dimensions: 90 in x 72 in x 67 in

Maximum Volume: 250 Cubic Feet

Maximum Allowable Weight: 4,000 Lbs

Noise Level shall not exceed 84 db at 4 meters

The unit shall be designed to withstand a 12 inch end drop

Reliability: 1,500 Hours MTBF

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*Primary source of information: U. S. Army Mobile Electric Power, Col. Rowe, et al.

Transient Electrical Performance:

	Voltage	Frequency
Application of Rated Load	12% Dip	1.4% Undershot
Recovery	0.5 Sec	1.0 Sec
Rejection of Rated Load	12% Rise	1.5% Overshot
Recovery	0.5 Sec	1.0 Sec
Application of Simulated Load	25% Dip	
Recovery	0.7 Sec	
Total Harmonic Distortion	5%	
Individual Harmonic	2%	

The primary requirements of a FCPU for the generic application, in qualitative terms, is the same as that for the FACRS application, namely, reliability, mobility, and fast startup and electrical response in a rough handling situation. What these qualitative terms mean as quantitized requirements is quite different between the specifications. No attempt was made to reconcile the two viewpoints represented by the specifications. The generic requirements document was selected to guide the design effort reported hereafter as it reflects, more precisely, the capabilities of a FCPU than does the FACR's requirements document.

7.3 SYSTEM DESIGN

As stated previously, the set of requirements and constraints selected for design were those of the 60 kW generic tactical mobile FCPU (W-RDS-4). The general system arrangement for PAFC power units is well established. Important detail system options available are: system operating pressure level, degree of recovery of water from the system for reuse in the fuel reforming step, and the fuel cell waste heat cooling medium. The most important component options are the selection of the type of fuel reformer and, given a system operating pressure level, the selection of the individual fuel cell current-voltage design point.

7.3.1 SYSTEM/COMPONENT OPTIONS AND PERFORMANCE

7.3.1.1 SYSTEM OPTIONS AND COMPONENTS

There are only two types of reformers capable of successfully handling JP-4 and other USAF logistic fuels (Ref. 7-3). These are an auto-thermal reformer (ATR) and a high temperature steam reformer (HTSR). An ATR was selected for this application. Although the ATR generates a larger volume of product gases for a given hydrogen demand than a HTSR, it operates at higher gas space velocities and offers better response characteristics.

The amount of reformer catalyst needed by the ATR is approximately 50 percent of the catalyst needed in a HTSR. Since an ATR uses insitu combustion to generate reaction heat, transient response and starting time are not limited by surface heat transfer rates as in a HTSR. ATR transient response capabilities are needed in this tactical mobile application.

The size and volume constraints for this tactical mobile application are severe in terms of PAFC FCPU capabilities. The system design pressure was selected as high as practicable, 150 psia. This is the maximum pressure currently being projected for advanced PAFC systems. High system operating pressure allows the use of high fuel cell current density at reasonable electrical efficiency (cell voltage). This reduces the size of the fuel cell module with little or no penalty in system fuel rate and, hence, fuel processor size. Pressurization also reduces gas specific volumes, resulting in size and weight savings in ATR and shift catalyst volumes, and heat exchanger sizes. Pressurized operation increases piping and vessel wall thickness, but results in a net weight savings, as well as volume reduction. To a first approximation, the weight of the boundary components (piping and vessels) does not change with pressure because the decrease in surface area from increase in pressure is balanced out by the required increase in wall thickness to support the increased pressure. However, the weight of the interior components does decrease as system pressure is increased and system volume declines.

An atmospheric pressure air cooled cell design was selected over water or other liquid cooling or pressurized air cooling. In this application, there is no need for cogeneration waste heat; therefore, use of atmospheric pressure air cooling eliminates the need for a waste heat exchanger. This is an important consideration in satisfying weight and volume limits for the design.

Use of atmospheric pressure, air-cooling does introduce a development risk over and above the norm for air-cooled PAFC design. Current hardware is designed to operate with nearly equal cooling and process air pressures and will not sustain a pressure differential of 135 psi between the two. The state-of-art fuel cell stack and module designs will have to be changed to sustain the increased pressure differential, and the design changes substantiated by experiment.

Water recovery from the FCPU exhaust has been incorporated into the unit. Between -65°F and +90°F ambient temperature, the unit can recover sufficient water to meet ATR needs on an instantaneous basis. On days when the maximum ambient temperature exceeds 90°F, excess water is condensed and stored during the cooler hours of the day for makeup during the hotter hours. On a day where the maximum ambient reaches 125°F, the storage of excess condensate, which equals the makeup required, is about 30 gallons. Storage is in the condenser sump.

A design current denstiy of 300 ASF was selected. It is the maximum value currently projected for PAFC design. Fortunately, it also satisfies the design specification weight limit. Back-of-the-envelope analysis indicates that the 300 ASF current density selected results in a FCPU design of near minimum weight. At higher current density design, the savings in fuel cell stack size and weight are only marginally larger than the increase in size and weight of the fuel processing subsystem and air cooling and supply system. At lower current density design, the overall system weight starts to increase markedly. Based on cost-current density parametering for the MX shelter FCPU under this Air Force Fuel Cell Application Analysis program, the minimum current density that satisfies other requirements will result in minimum FCPU life cycle cost.

7.3.1.2 PROCESS DESIGN DESCRIPTION

The PAFC system shown in Figure 7-2 identifies the major components, operating conditions, and flow paths in the proposed 60 kW tactical power unit design. The design is based on reforming JP-4 in an ATR operating at 150 psia, 1,800°F, and steam/carbon ratio of 3.0 and air carbon ratio of 1.8*. The process flow rates shown in Table 7-2 are based on 95 percent fuel conversion and a near equilibrium ATR outlet concentration of 24 percent volume hydrogen. Product gases from the ATR are cooled and treated in successive stages to remove sulfur (H_2S) and increase hydrogen yield (CO shift).

The fuel cell consumes 85 percent of the available hydrogen to produce DC power. The remaining combustibles are used to provide system heat requirements for water vaporization, fuel vaporization, and air heating in a separate furnace. Approximately 12 percent of the heat requirements for vaporization are supplied in the furnace. The remaining water vaporization needs are obtained in an external vaporizer heated by ATR product gases. State point conditions at the design point are given in Table 7-2.

This ATR exhaust loop also contains a superheater for raising the steam temperature to ATR inlet temperature. The split vaporizer arrangement is designed to make use of system waste heat without the need for supplemental fuel firing, and as an aid in system starting and thermal control.

ATR air, furnace combustion air, and fuel cell process air is supplied by a two-stage turbocharger compressor operating at an overall efficiency of 69 percent. Two hundred (200) cfm of air at STP is compressed to 150 psia, requiring 33.8 AHP and a total gas side energy input of 48.4 GHP. This energy is supplied by furnace and fuel cell exhaust air which enters the turbine at 600°F and a pressure somewhat below 150 psia. To reduce turbocharger size and improve efficiency, an interstage air cooler is provided. Interstage cooler

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*Development ATR test data indicate that an air/carbon ratio of 1.6 may be possible with advanced catalyst and reformer design. This would reduce system fuel consumption by about 7 percent below the values given hereafter.

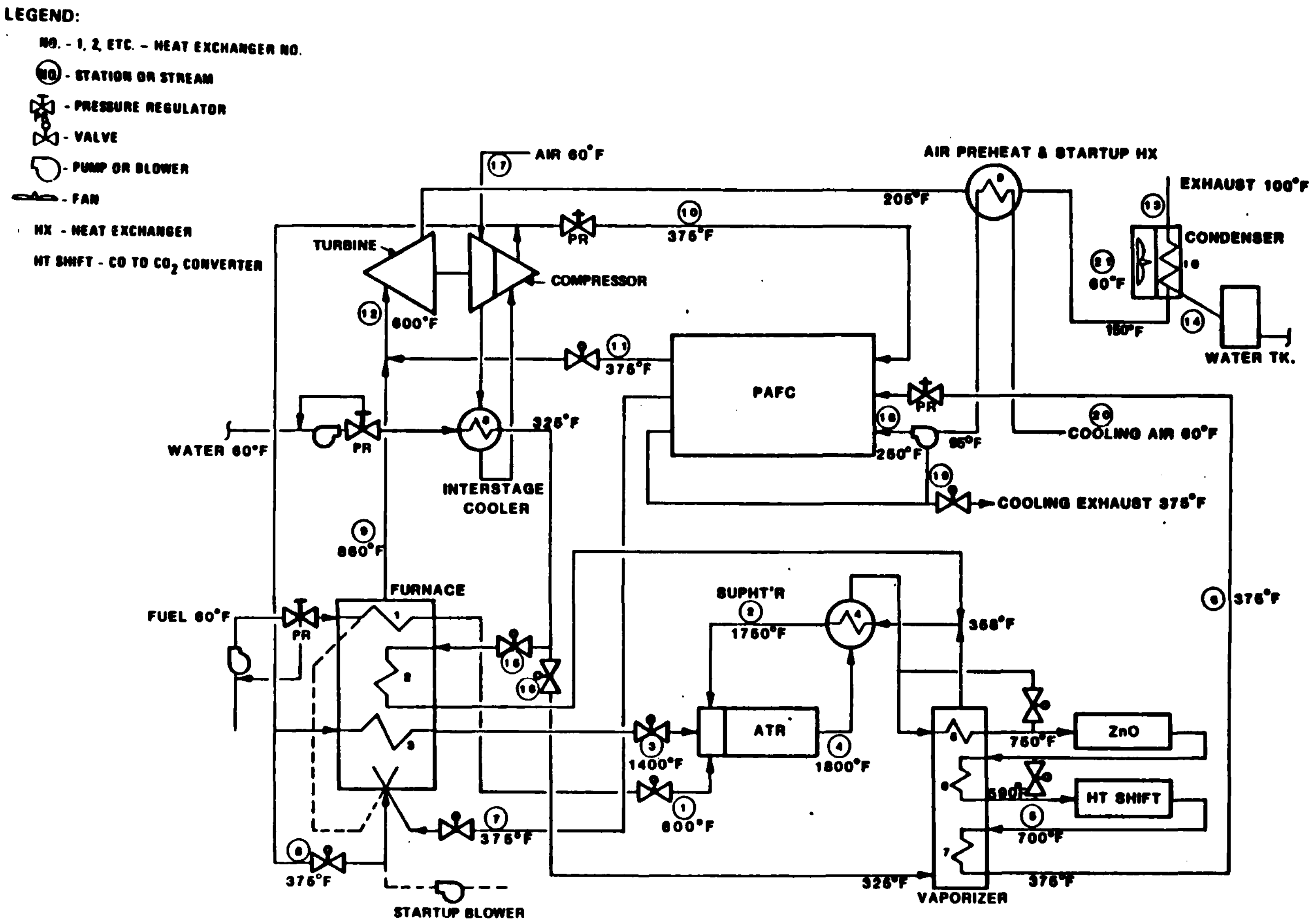

Figure 7-2. 60 kW Tactical Mobile Power Unit Schematic
150 psia - ATR/PAFC System

TABLE 7-2

60 KW TACTICAL MOBILE SYSTEM***

MOLAR FLOW, LB-M/HR

Stream*	H_2	CO	CO_2	CH_4	H_2O	N_2	O_2	HC	Flow Lbs/Hr	Temp. °F	Press. PSIA
1. ATR Fuel								2.595	36.03	600	150
2. ATR Steam					7.786				140.16	1750	150
3. ATR Air						3.709	0.986		135.41	1400	150
4. ATR Products	4.049	1.090	1.376	0.130	5.918	3.709			311.60	1800	150
5. Shift Exit	4.983	0.156	2.310	0.130	4.983	3.709			311.60	700	150
6. Fuel Cell Feed	4.983	0.156	2.310	0.130	4.983	3.709			311.60	375	150
7. Exit Feed Gas	0.747	0.156	2.310	0.130	4.983	3.709			303.13	375	150
8. Burner Air						3.073	0.817		112.20	375	150
9. Furnace Exhaust			2.595		5.990	6.782	0.106		415.34	860	150
10. Cell Process Air						15.935	4.236		581.74	375	150
11. Cell Exhaust Air					4.236	15.935	2.118		590.17	375	150
12. Turbine Exh. Supply			2.595		10.226	22.717	2.224		1005.53	600	150
13. System Exhaust			2.595		2.440	22.717	2.224		865.39	100	15
14. Recovery Water					8.327				149.89	100	15
15. Water to Furn./Vap.					0.960				17.30	325	150
16. Water to Cooler/Vap.					6.826				122.86	325	150
17. Compressor Air Sup.						22.722	6.040		829.49	60	15
18. Cell Cooling Air						193.330	51.400		7058.00	250	15
19. Recycle Air						106.922	28.540		3907.10	375	15
20. Makeup Cooling Air						86.310	22.940		3150.90	60	15
21. Condenser Air Sup.						358.200	95.210		13076.00	60	15

Design Basis

85% Cell H_2 Use
95% Fuel Conversion
18700 Btu/Lb JP-4 (NHV)
52018 Btu/Lb H_2
21758 Btu/Lb Ch_4
4348 Btu/Lb CO
2.0 Cell Stoair
1.15 Burner Stoair
60 °F, 0% Rel. Hum.
69 kW Gross Power
60 kW Net Power

Heat Exchanger Loads, (Btu/Hr)

	Sensible	Latent	Area, Ft^2
**1. Fuel Heater	8,646	6,845	5.0
2. Steam Vaporizer	624	14,867	2.3
3. Air Heater	40,348	-	8.0
4. Steam Superheater	104,516	-	50.0
5. Gas Cooler	51,022	-	11.7
6. Gas Cooler	15,455	-	6.3
7. Gas Cooler	44,142	-	51.0
8. Interstage Cooler	37,255	-	4.0
9. Air Preheater	27,121	-	112.0
10. Water Condenser	24,655	145,434	563.0

* Numbers Correspond to (NO) in Figure 7-2.

** Numbers Correspond to Heat Exchanger Nos. in Figure 7-2.

*** At Design Point

heat is used in the fuel processing system to preheat water to near saturation temperature prior to entering the steam generators.

Waste heat is removed from the fuel cell via a separate air cooling loop operating at atmospheric pressure. Heat absorbed by the cooling air is exhausted from the system, and partially recirculated to control inlet cooling air temperature. Makeup cooling air is partially preheated in a gas/air heat exchanger located at the turbocharger exhaust outlet. This arrangement reduces the amount of recirculated cooling air required to maintain inlet air temperatures, and reduces the amount of heat which must be removed in the water condenser. Since the water recovery dewpoint temperature for the system is low (100°F), this upstream heat exchanger reduces condenser fan parasitic power, and improves water recovery capability.

7.3.1.3 SYSTEM PERFORMANCE

The overall design basis of the previously described process design is as follows:

Power Output, kW at STP	60
Voltage, Regulated AC	120/208/416
Fuel Type	JP-4 (Prime)
Ambient Temperature, °F	-65 to +125
Altitude, Feet Above SL	0 to 10,000

The design parameters for the fuel cell and fuel conditioning subsystems at rated load (60 kW) at Standard Pressure and Temperature (STP) are as follows:

Fuel Cell Subsystem	
Design Pressure, psia	150
Design Temperature, °F	375
Cell Hydrogen Utilization, %	85
Process Air Stoichiometry,	2.0
Cooling Load, 10^3 Btu/Hr	236
Output Voltage, VDC	300

No. of Cells Required	450
Active Cell Area, Ft^2	0.76
Operating Point, vpc at ASF 100% Design	0.67 at 300
Cooling Air Required, CFM	1,390

Fuel Conditioning Subsystem

Design Pressure, psia	150
Reformer Design Temperature, °F	1,800
Space Velocity, $v/v/Hr^{-1}$	2,000
Catalyst Type	Nickel
Catalyst Volume, Ft^3	4.3
Shift Catalyst Type,	Cu/ZnO
Shift Catalyst Volume, Ft^3	3.2
Desulfurization Catalyst	ZnO
Desulfurization Catalyst Volume, Ft^3	0.75
Design Fuel Sulfur, wppm	300
Replacement Schedule (ZnO only) Hrs.	1,175
Design Combustion Stoichiometry	1.15
Turbocharger Output, CEM	200
Turbocharger Compression Ratio (2 Stages)	10.2
Turbocharger Efficiency (overall), %	69

The performance profile for the FCPU at STP is as follows:

	% Load		
	75	100	110
Gross Power, kW	52.70	69.00	75.5
Fuel Cell Volts, vpc	0.71	0.67	0.64
Hydrogen Needs, Lbs/Hr	6.09	8.47	9.69
Hydrogen Produced, Lbs/Hr	7.17	9.97	11.39
Total Fuel Use, gph	4.30	5.90	6.70
Electric Output, NkW	45.00	60.00	66.00
Electric Efficiency, % (*)	29.60	28.90	28.00
Heat Rate, Btu/NkW	11,530	11,800	12,180

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*18,700 Btu/Lb JP-4, 3,413 Btu/NkW

The foregoing performance projections are based on beginning-of-life cell performance. Some decay can be expected over the system life with proportional increases in fuel consumption. Although performance loss cannot be assessed at this time, assumption of a 10 percent loss over 40,000 hours is current estimation practice.

If a heavier fuel, such as DF-2, is used in the unit, the gallons/hour fuel rate will decrease about 10 percent but the actual heat rate will increase about 0.2 percent. Because DF-2, on the average, contains more sulfur and forms carbon more readily than JP-4, an increase in maintenance related to JP-4 use can be anticipated.

7.3.2 FUEL CELL POWER UNIT CHARACTERISTICS

7.3.2.1 SYSTEM OPERATION AND CONTROL

The primary control functions needed for operation of the FCPU are listed in Table 7-3. Because the logistic fuel processor and the turbocharger are developmental units, it is possible that additional control over and above the system primary control functions listed in Table 7-3 will be required. In any case, microprocessor control will be needed to provide automatic FCPU

TABLE 7-3
MAJOR CONTROL FUNCTIONS

Load Following	Current Measurement Feedback to Control Valves
Fuel, Air, and Steam Flows	Proportioning Control Valves
Furnace Temperature	RTD Feedback to Supplemental Fuel Burner
Reformer Temperature	RTD Feedback to Air Control Valve
Fuel Cell Temperature	RTD Feedback to Recirculation Cooling Air Flow Valve
Shift Outlet Temperature ZnO Bed Temperature	Thermostatic Bypass Flow
System Pressure	Turbocharger Output Pressure Regulation
Fuel Cell Pressure	Differential Pressure Regulation on Anode and Cathode
Water Condenser Temperature	Number and Speed of Air Cooler Fans and Damper Flow Control
Exhaust Gas Water Concentration	Load Following Process Air Control to Maintain 2.0 Stoair Supply

operation. Therefore, added requirements can be accommodated without major increases in system weight, volume or costs over and above those estimates presented hereafter.

Two key operational problems may occur within the reformer subsystem which will require developing a means of detection and avoidance. The ATR may be subject to carbon deposition and loss in reformer gas quality. The reformer must be designed to avoid this problem during startup and over the operational range of output, and a means of detection and control must be built into the unit. Also, sulfur removal rate in the ZnO bed should be monitored to protect downstream catalysts. As the ZnO bed ages and absorption capacity drops, sulfur removal will decrease, resulting in poisoning and deactivation in the shift converter and fuel cell. A means of detection, other than establishing replacement schedules, will be needed. Both of these problems will need additional study to adequately assess the design and control options.

Power Unit starting commences after the fuel cell, reformer, desulfurizer, and shift catalyst are raised to operating temperatures. In this system, starting time will be governed, probably, by heating in the fuel processing subsystem due to the higher operating temperature. Combustion of liquid fuel in the furnace provides a source of heat. Combustion gases are used to operate the turbocharger and provide heat to the fuel cell cooling air loop through the air preheat and startup heat exchanger. Heat is transferred to the stack by air circulating through the heat exchanger. When operating cell temperatures are reached, stack temperature is maintained by adjusting the recirculation air flow rate.

An inert gas system may be required to prevent moisture condensation in the fuel processing catalyst during initial startup. If so, nitrogen would be circulated between the furnace and catalyst vessels until the catalyst are heated above dewpoint temperature. This would require a cylinder of compressed nitrogen gas. It may be possible to start the heating cycle with compressed air supplied through the turbocharger and air preheat coil. When sufficient temperatures are reached in the system catalysts, stoichiometric combustion would be initiated in the ATR to accelerate the heating cycle. Combustion gas from the ATR would be passed through the external heat exchangers, desulfurizer catalyst and shift catalyst, and then vented to atmosphere. An ignitor would be needed, probably, to initiate combustion in the ATR.

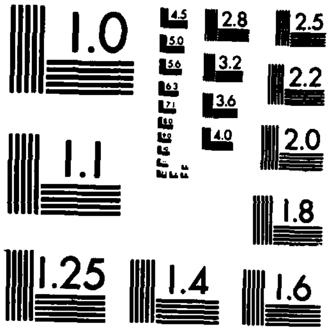
Although starting time cannot be fully assessed at this time, a minimum of one half hour would be needed. Start power would be supplied by on-board batteries. A minimum battery capacity of one kW is projected for a one half-hour start.

Load Following is obtained by measuring fuel cell current (demand) and adjusting air, steam, and fuel flow to the ATR, accordingly. This controls the volume of reactants entering the catalyst bed and hydrogen output to the fuel cell. Rapid demand is tied into the burner control to provide increased heat for fuel and water vaporization and air preheat. Gas flow valves are needed to modulate steam, fuel, and air flow to the ATR. Combustion air, and fuel cell process air must also be controlled in response to demand to maintain operating stoichiometry.

Thermal System Control is obtained by monitoring reformer catalyst, shift catalyst, desulfurizer bed, and fuel cell temperatures and adjusting flow rates, accordingly. Desulfurizer and shift catalyst temperatures are maintained by controlling the amount of ATR product gas entering or by-passing the external water vaporizer.

Fuel cell plate temperatures are controlled by the rate of heat removal from the cooling air loop. This is performed by adjusting makeup and exhaust cooling air rates. Combustion rate in the furnace is altered to prevent overheating of the fuel vaporizer. ATR catalyst temperature would be maintained by either adjusting the operating S/C ratio or adjusting air and steam temperatures. Experimentation will be needed to assess the best control technique for the ATR.

AD-A126 121 U S (UNITED STATES) AIR FORCE FUEL CELL APPLICATION 4/5
ANALYSIS..(U) WESTINGHOUSE ELECTRIC CORP PITTSBURGH PA
ADVANCED ENERGY SYST.. W D POUCHOT ET AL. JAN 82
UNCLASSIFIED WAESD-TIME-3134 AFWAL-TR-82-2004 F/G 10/2 NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

System Pressures would be maintained by pressure regulators at the fuel and water pump discharge and at the turbo-compressor air discharge. The turbocharger should be designed for marginally higher discharge pressure to maintain operating conditions at low kW output. The system should also include pressure switches to signal overpressure in the vaporizers, and air preheater and loss of pressure in the fuel cell.

Water Recovery Rate in the exhaust condenser would be subject to changes in system flows. To ensure adequate recovery, the condenser air flow must be controlled to maintain a minimum exhaust temperature for the system.

7.3.2.2 SYSTEM SIZE AND WEIGHT

The projected volumes and weights of major system components and the assembled power unit are shown in Table 7-4. These projections are based on scaleup of existing designs with allowance for additional components, including water equipment. Inert gas vessels which may be needed for system starting, are not included. In addition, the state-of-art weight for the output power conditioner is nearer to 2,200 lbs than 1,500 lbs. Development effort to reduce output power conditioner weight will be required.

7.3.2.3 SYSTEM RELIABILITY

An estimate of the reliability of the FCPU is given in Table 7-5. As can be seen, the estimated MTBF is 2,621 hours. This compares most favorably with diesel engine specifications of 500 hours of MTBF for tactical mobile duty. It compares unfavorably, however, to the estimated 3,770 hours MTBF for a 23 kW methanol fueled unit for individual MX shelter power. Both estimates were done on a consistent basis. Major differences in reliability between this tactical mobile unit and the MX unit are caused by differences in the fuels to be used; JP-4 for the tactical mobile unit and alcohol for the MX unit.

The element of most concern in the JP-4 fuel processing subsystem is the fuel vaporizer. In industrial practice, naphtha fuel vaporizers (and JP-4 is a heavy naphtha) coke up. Without cleaning, the fuel vaporizer could be expected to coke up about every six months, giving a failure rate of approximately 230

TABLE 7-4
TACTICAL MOBILE SYSTEM SIZE

	Weight, Lbs	Volume, Ft^3
Fuel Cell Stack w/Manifolds	700	15
Autothermal Reformer	300	6
Burner/Furnace Assembly	30	2
External H_2O Vaporizer	70	8
Steam Superheater	60	10
Desulfurizer	60	2
HT Shift	200	4
Turbocharger/Compressor	100	1
Interstage Cooler	20	2
Air Heater/Startup HX	30	5
Water Condenser	150	30
Water Purifier & Storage	40	8
Pumps, Blowers, Valving	150	-
Housekeeping Power Supplies & Controls	150	5
Output Power Conditioner	1,500	45
Battery Pack (1 kW)	130	2
Misc. Ducting, Piping, Insulation, Skid Base	360	-
Packaging Factor (66%)	-	76
	4,050	225

Footprint - 37.5 Ft^2

TABLE 7-5

RELIABILITY ESTIMATE(1)
60 KW TACTICAL MOBILE POWER UNIT

Components	Failure Rate, Per 10^6 Hrs
Fuel Cell	25.0 (2)
Reformer	25.0 (2)
Fuel Vaporizer	1.0 (with periodic cleaning)
Burner	15.0
Heat Exchangers	9.0
Fuel Pump	7.5
Water Pump	2.8
Air Blowers	9.0
Turbocharger	10.0
Microprocessor	20.0 (3)
Housekeeping Power Supply	20.0 (3)
Power Conditioner	20.0 (3)
Valves	
Flow	66.4
Press Reg.	9.6
Solenoid	8.0
Relief	4.8
Check	12.0
Sensors	
Pressure	5.4
Level	4.8
Temperature	58.0
Current, Power	3.2
Ducting	15.0
Tubing	30.0
	381.5, MTBF = 2,621 hours

1. Based on average data from non-electric parts reliability data NPRD-1, Rome Air Development Center, 1978.
2. Assumes fuel cell and reformer catalyst life of 40,000 hours.
3. Assumed values for high reliability designs.

failures per million hours. With periodic cleaning, it is assumed to act like another heat exchanger with a low failure probability.

Additional improvement in the overall fuel processing reliability of the tactical mobile unit relative to the MX unit will be difficult to achieve. This is because a major source of the unreliability is the increased number of valves, piping sensors and higher temperatures required for a JP-4 fuel processing system compared to a methanol fuel processing system.

7.3.2.4 SYSTEM DESIGN LIFE AND MAINTENANCE REQUIREMENTS

The major component life and maintenance characteristics for the Tactical Mobile Power Unit are shown in Table 7-6 assuming continuous operation (8760 hours per year). The fuel cell stack represents the primary maintenance cost driver, with replacement anticipated within five years equivalent continuous operating time. Life testing of fuel cell stacks have demonstrated performance of 40,000 hours (and more) without major voltage losses. Typical voltage loss is 5-10 percent over this life span, and is due to deactivation of fuel cell platinum. The current industry standard estimated replacement time for phosphoric acid fuel cell stacks is 40,000 hours or 4.5 years of equivalent continuous operation.

Replacement of the ZnO desulfurizer unit is expected to occur about every seven weeks of continuous system operation. This projection is based on operation at design output using JP-4 fuel with a sulfur content of 300 wppm, a catalyst bed of 50 lbs and a maximum bed capacity of 20 lbs sulfur per 100 lbs of catalyst.

Replacement of reformer and shift catalyst are anticipated within five year equivalent continuous operating time intervals.

Cleaning and potential replacement of the reformer fuel vaporizer unit and fuel/steam mixing nozzle are expected to occur frequently, relative to other maintenance needs.

TABLE 7-6
SYSTEM MAINTENANCE CHARACTERISTICS

Major Component Replacement	Continuous Operating Time
Fuel Cell Stack	4.5 Years
Reformer Catalyst	4.5-5 Years
Shift Catalysts	4.5-5 Years
Forced Outage Maintenance	
Desulfurizer Catalyst	7 Weeks
Fuel Vaporizer Cleaning	6 Months
Inspection and Cleaning	1 Year
On-Line Maintenance	
Acid Replenishment	1 Year
Calibration and Adjustment	1 Year
Fuel and Air Filter Replacement	6 Months

7.3.3 POWER PLANT USAGE CONCEPT/CONSIDERATIONS

7.3.3.1 AVAILABILITY OF POWER

This subsection considers FCPU usage in terms of supplying the power needs of a Foreward Air Controller Radar System. As previously described in Section 7.2, electric power is presently supplied to a Foreward Air Controller Radar by a mobile cart containing two 60 kW gas turbine power units. A typical mission for the cart is a two week stay in the field during which 60 kW power is required on a continuous basis.

The reason for using two gas turbine units is to provide a high degree of certainty of power availability. A characteristic specification for gas turbine units MTBF is 1500 hours. On a random failure basis this implies about a 14 percent chance of failure of a given unit during any two week period of continuous operation. The chance of both gas turbine units failing during the same two week period is much lower, about two percent. Without field repair, the availability of electric power is about 98 percent. It is, therefore, close to 100 percent considering field repair of an inoperable unit while power is being produced by the other unit on the cart.

To provide the same kind of power availability using FCPU's, two units are also required. This is so even if the MTBF of the FCPU's is improved to 3,000 hours from the 2,600 hours projected here through preventive maintenance. A 3,000 hours MTBF single unit power train will have an approximate 7 percent chance of failure in two weeks of continuous operation, on a random failure basis. Hence, to provide nearly 100 percent power availability, using the FCPU's, will require two units plus field repair. The number of field repairs required on the FCPU's will be less than on the gas turbine units.

A comparison between the FCPU's and gas turbine units of the total weight that would have to be transported to conduct a typical Foreward Air Controller Radar two week exercise is as follows:

	Gas Turbine	FCPU's
Round Trip Power Unit Wt (lbs)	4,000	16,000
Fuel Wt. (lbs)	36,400*	12,800**
Total Wt. (lbs)	40,400	38,000

*17 Gal/Hr
**6 Gal/Hr

Even though the FCPU's are heavy compared to the gas turbine units, there is a marginal overall weight advantage for the FCPU's. The longer the mission, the greater this advantage because of the much lower FCPU fuel consumption.

7.3.3.2 MAINTENANCE FREQUENCY

In powering of a Foreward Air Controller Radar, the units are only used about 20 percent of the total available time. Therefore, the maintenance periods, in calendar time, can be stretched out by a factor of about five over those for continuous operation as given in previous Table 7-6. This results in maintenance calendar periods as illustrated in Table 7-7.

In principle, because of the small amount of operating time per year for a unit, operations such as inspection, cleaning, calibration, and adjustment can be done on a five year basis. However, equipment gets dirty when idle, as well as when operating, so more frequent attention to these items is indicated than results from a pure operating time projection. The pacing item here is replacement of the desulfurizer catalyst every 35 weeks.

The most important thing to be observed from Table 7-7 is that a low rate of replacement of major components is to be expected during a twenty year unit lifetime. In operations requiring continuous power, such as for MX missile shelter power, these large component replacements were the bulk of the

TABLE 7-7

FOREWARD AIR CONTROLLER RADAR POWER MAINTENANCE PERIODS

Major Component Replacement (on the average)	Continuous Operating Time
Fuel Cell Stack	22.5 Years
Reformer Catalyst	22.5 Years
Shift Catalyst	22.5 Years
Forced Outage Maintenance	
Desulfurizer Catalyst	35.0 Weeks
Fuel Vaporizer Cleaning	35.0 Weeks
Inspection and Cleaning	35.0 Weeks
On-Line Maintenance	
Acid Replenishment	5.0 Years
Calibration and Adjustment	Between Each Use
Fuel and Air Filter Replacement	2.5 Years

maintenance cost. Since the replacement rate on large components is low, maintenance costs for the tactical mobile application on a yearly basis are modest.

7.3.3.3 FCPU CAPITAL COST AND MAINTENANCE COST

An estimate of FCPU capital costs by account number is given in Table 7-8. As shown, the original FCPU cost is estimated at about $152,000 or $2,300 per kW electrical using the 10 percent overload plant rating of 66 kW. A characterization of the equipment included under each account number may be found in Appendix B.

The data base for the cost estimate is derived from cost studies in support of Westinghouse Electric Corporation programs on FCPU's for Electric Utilities and much smaller On Site/Integrated Energy Systems. The breadth of the data base covers the FCPU power size of interest here.

The data base is for prototype units. These estimates are based on a mature FCPU market with 1,000 units of cumulative production. For the non-commercial components an experience curve effect was assumed. No experience curve effects were applied to commercially available components, such as pumps, heat exchangers, valves, fans, sensors, etc., even though some cost reduction because of volume production will be experienced.

Experience curve effects have been observed in many types of production processes and they are a measure of the cost reductions that occur with increases in the cumulative size of a production run. These cost reductions are due to combined effects of improved labor efficiencies, technical and manufacturing improvements, economies of scale, and volume purchasing of components and materials.

Based on analysis of experience curves for similar types of equipment, an 85 percent experience curve was used. An 85 percent experience curve will result in a 15 percent cost reduction when the cumulative number of units is doubled. For a cumulative production of 1,000 FCPU's, the experience curve reduces non-commercial components costs to 20 percent of prototype values.

TABLE 7-8
60 KW TACTICAL MOBILE FCPU CAPITAL COST ESTIMATE (1980$)

Account No.	Item	Cost ($)
1000	Fuel Cell Assembly	23,200
2000	Fuel Processing	32,800
3000	Fuel Delivery	3,800
4000	Water Delivery	4,700
5000	Air Delivery	17,900
6000	Heat Exchangers	31,700
7000	Controls & Instrumentation	6,400
8000	Power Regulators	27,300
9000	Structure	4,200
	Total	152,000

A breakdown by account number leading to an estimated total yearly hardware replacement cost of $2,600 per year is illustrated by Table 7-9. The failure rates per million operating hours are the same as previously presented in Table 7-5. It is assumed that the high potential component failure rate of the fuel vaporizer, because of coking, can be controlled by cleaning the vaporizer at 35 week intervals. This is at the same time that the sulfur removal catalyst would be scheduled for replacement. Other scheduled maintenance can be accomplished at the same time, such as changing fuel and air filters.

In constructing Table 7-9, the major subsystems (Account Nos. 1000 through 9000) were assumed to be totally replaced in case of a failure. The [illegible]ed parts were assumed to have a salvage value that ranged from 40 percent of the replacement part for the fuel cell, to 80 percent of the replacement part cost for structure. Replacement part costs of the major subsystems were cumulated without regard to the costs of valves, ducting, tubing and sensors associated with these subsystems.

Valves, ducting, etc., and the battery were evaluated under the special accounts at the bottom of Table 7-9. Here the failures were treated as individual valve, sensor, etc., replacements with no salvage value for the failed part.

In addition to scheduled maintenance, Table 7-9 indicates that an unscheduled repair because of a unit failure can be expected on the average every 1.5 years of 1,750 hours per year operation. The nature of the maintenance skills required would be trained E4 level skills: (1) trouble shoot modular system, (2) replace modules, and (3) return unit to operating condition. The same skills are required for servicing and repair of all the FCPUs of this study.

The total servicing and maintenance costs are estimated as follows:

Maintenance Crew Size	2 Persons
Costing Rate per Crew	$42/Hr ($42,000/Yr ea. person)
Hours of Maintenance & Service	40 Hours/Year
Service & Maintenance Labor Cost	$1,680/Year

TABLE 7-9

60 KW TACTICAL MOBILE FCPU REPLACEMENT HARDWARE COSTS (1980 $)

Account No.	Item	Failure Rate Per 10 Hrs.	Operating Hrs. Per Year	Failures Per Year	Yearly Average Hardware Replacement Cost - $
1000	Fuel Cell Assembly	25.0	1,750	0.044	540
2000	Fuel Processing	45.0	1,750	0.079	570
3000	Fuel Delivery	7.5	1,750	0.013	10
4000	Water Delivery	2.8	1,750	0.005	10
5000	Air Delivery	19.0	1,750	0.033	260
6000	Heat Exchangers	5.0	1,750	0.009	130
7000	Controls & Instrumentation	20.0	1,750	0.035	60
8000	Power Regulators	40.0	1,750	0.070	500
9000	Structure	5.0	1,750	0.009	10
Special	Valves & Sensors	172.2	1,750	0.301	460
Special	Startup Battery	1,000.0	40	0.002	<1
Special	Ducting & Tubing	40.0	1,750	0.070	50
			Totals	0.670	2,600

Special Equipment	None
Hardware Replacement Costs	$2,600/Year
Supplies (Filters, Sulfur Catalyst, etc.)	$200/Year
Sub Total	$4,480/Year
Repair Transportation	$180/Year
Total	$4,660/Year

7.3.3.4 UNIT OPERATION COSTS

Significant effort will be required during field operational periods in loading and unloading the units from the air transport plane; deployment to the operating site; and placing the unit in operation. For accomplishing this, two men and a jeep should be adequate.

Once in operation, the only effort required, except those incurred by a seven percent chance of a unit failure in each two week period, will be to fill the 50 gallon fuel tank about every eight hours.

Based on 1,750 hours total operating time per year, per unit, the yearly fuel consumption of JP-4 would be approximately 21,000 gallons for a pair of FCPU's.

A rough comparison of the operating costs per year for a pair of FCPU's and a pair of gas turbine electrical generators is as follows:

	Gas Turbines	FCPU's
Air Transport Cost[1]	$ 3,600	$14,400
Crew Cost[2]	28,640	28,640
Special Equipment (Jeep) Cost[3]	3,960	3,960
Fuel Cost[4]	77,350	27,200
Total	$113,550	$74,200

1. $.20/Ton Mile, 3000 Miles Round Trip.
2. $40/Crew Hour, 6 Deployments: 66 Crew Hours Ea.,
   40 Weeks: 8 Crew Hours/Week.
3. $10/JEEP Hour, 6 Deployments: 66 JEEP Hours Each.
4. FOB Cost: $.80/Gallon; Delivery Cost: $.10/Ton Mile, 1,500 Miles
   or $.50/Gallon or Total: $1.30 Gallon On Site.

The numbers in the preceding table show an operating cost advantage of about 35 percent in using FCPU's rather than gas turbines.

7.4 DEVELOPMENT RISK ASSESSMENT

A technical development risk assessment was performed at both the subsystem/major component level and the overall system level. The technology status rating criteria is presented in Table 7-10. Each subsystem or major component was evaluated with respect to the following factors:

- Current technology status
- Technology rating (Table 7-10 criteria)
- Required technology status to meet design requirements for the proposed applications
- Proposed developmental program to achieve the required technology status
- Estimated developmental effort expressed in terms of man hours of R&D personnel (engineering plus technicians)
- Estimated developmental effort expressed in terms of development dollars (labor and materials)

TABLE 7-10

TECHNOLOGY STATUS RATING CRITERIA

REQUIREMENTS FOR APPLICATION
AT (A) TECHNOLOGY RATING LEVEL

TECHNOLOGY RATING	TECHNOLOGY STATUS	PERFORMANCE DATA BASE	EXTRAPOLATION FROM PERFORMANCE DATA BASE	APPLICATION OR DEVELOPMENT PROGRAMS REQUIREMENTS	R&D PROGRAM CHARACTERISTICS	
					RATIONALE	SUCCESS PROBABILITY
Established (A)	Firm selections can be made. Equipment is commercially available in form required.	Sufficient	None	Minimal, routine applications engineering.	Not Applicable	Not Applicable
Near Term (B)	A number of equipment candidates are identified. Candidates are commercial or near commercial.	*Incomplete*	*Short extrapolations* from existing data base are involved.	*Confirmatory testing* and minimal R&D.	*Straight-forward*	*Virtually Certain*
Developmental (C)	Equipment not previously designed, but engineering data base exists for design.	Incomplete; important gaps exist	Large extrapolations from existing data required.	Considerable R&D is required	A credible rationale exists. Alternative avenues are evident.	Good to excellent
Speculative (D)	Equipment not previously designed with major materials, design or manufacturing uncertainties.	Sparse or Absent	Highly speculative or not possible.	Extensive R&D is required.	Rationale is not clear, or requires a break-through or serendipity.	Fair to poor.

- Probability of success of the proposed developmental program
- On-going programs or potential design alternatives.

A summary of the development risk assessment is given in Table 7-11. Those areas presenting the greatest risk (and largest development requirements) are as follows:

Fuel Processor

The production of hydrogen by steam reforming of hydrocarbons is a well established technology, and is used extensively in the petrochemical industry for the production of ammonia, etc. However, the hydrocarbon feedstock is normally a mixture of low molecular weight compounds, such as natural gas or light naphtha. Heavy naphtha, with a distillation end point up to 350°F and containing up to 30 percent aromatics, has also been used in some instances, primarily in India.

This tactical mobile application calls for the production of hydrogen from JP-4 as the primary fuel. This fuel has a distillation end point of 320°F, contains up to 400 ppm sulfur, and has a high aromatic content. These properties require a non-conventional steam reformer design. The use of heavy fuels, such as JP-4, in conventional steam reformers results in coke formation and sulfur poisoning of the nickel catalyst. Extensive preheating, to lower the sulfur content to less than 1 ppm and partially crack the larger compounds, is deemed uneconomical and impractical for fuel cell applications.

Based on the results of an EPRI-sponsored study (Ref. 7-4), the most promising fuel-processing alternatives are high temperature steam reforming and autothermal reforming. Autothermal reforming was chosen as the preferred process for this tactical mobile application because of its rapid response characteristics relative to high temperature steam reforming.

The Department of Energy has sponsored a development program for distillate fuel steam reforming technology. A summary of the status of this program was presented in a recent report by Catalytica Associates, Inc. (Ref. 7-5).

TABLE 7-11

DEVELOPMENT RISK ASSESSMENT
60 kW TACTICAL MOBILE POWER UNIT

SUBSYSTEM/MAJOR COMPONENT	CURRENT TECHNOLOGY STATUS	TECHNOLOGY RATING	REQUIRED TECHNOLOGY STATUS	REQUIRED DEVELOPMENTAL PROGRAM	ESTIMATED MANHOURS (THOUSANDS)	ESTIMATED DEV. COST ($)	PROBABILITY OF SUCCESS	ONGOING PROGRAMS & POTENTIAL ALTERNATIVES
1.0 FUEL PROCESSING								
1.1 Fuel Handling and Storage	Existing on-site facilities and experience with DF-A diesel fuel.	A	No change required.	No development program is required.	0	0	N/A	N/A
1.2 Fuel Vaporizer	Commercial experience in petrochemical industry primarily with direct-fired heaters.	B	Special shell and tube to make use of regenerative heat. Continuous operation without coke formation.	1. Experimental testing to determine rate of coke formation. 2. Detail modifications to reduce coke formation.	4.0	400	Very Good	
1.3 High Temperature Steam Reformer	Extensive commercial experience with conventional steam reforming on fuels from methane to heavy naphtha. Laboratory experience with ATR of No. 2 fuel oil.	C	Stable performance on JP-4 and diesel fuels without coking or sulfur poisoning steam-to-carbon ratio _ 4.0. Fuel conversion to carbon oxides _ 95%.	1. Catalyst testing. 2. Multi-tube reformer testing. 3. Full-scale system evaluation and analysis. 4. Cost study.	20.0	2,000	Very Good	Existing DOE and EPRI sponsored studies on autothermal reforming. HRSR of No. 2 fuel oil. Potential alternative which is also under DOE development.

TABLE 7-11 (Continued)

SUBSYSTEM/MAJOR COMPONENT	CURRENT TECHNOLOGY STATUS	TECHNOLOGY RATING	REQUIRED TECHNOLOGY STATUS	REQUIRED DEVELOPMENTAL PROGRAM	ESTIMATED MANHOURS (THOUSANDS)	ESTIMATED DEV. COST ($)	PROBABILITY OF SUCCESS	ONGOING PROGRAMS & POTENTIAL ALTERNATIVES
2.0 FUEL CELL								
2.1 Fuel Cell Stack	Laboratory and prototype experience. Life tests up to 80,000 hrs. with H_2 fuel. Large, multi-cell stacks being tested for utility applications. 4.8 MW demonstration plant under construction but cooling and cell passages at same pressure.	C	Cell life 40,000 hours. Pressurized (150 psia) cell operation. Cell voltage = 0.67 VDC at current density of 300 amps per ft^2. Minimal acid loss. Low cost design with high reliability cooling passages at low pressure with cells at high pressure.	1. Stack (multi-cell testing to determine issues of thermal expansion, current collection, electrical isolation, manifold seals, flow distribution, acid management, startup/shutdown, and cooling design viability. 2. Basic bipolar plate and special cooling plate development and performance improvement. 3. Pressurized stack, unpressurized cooling development and testing. 4. Cost improvement studies (lower catalyst loadings, manufacturing improvement, etc.)	30.0	3,000	Very Good	Several development programs sponsored by DOE, U. S. Army, EPRI, and various electric utilities. In-house development by potential suppliers. None on low pressure air cooling with high pressure cells.
2.2 Cooling Systems and Fuel Cell Auxiliaries	Existing designs have water, air, and dielectric cooled designs. Laboratory and prototype experience with both atmospheric and pressurized systems.	B	High reliability and low cost. Pressurized (60 psia) operation.	Stack pressurization and cooling issues to be resolved as part of fuel cell stack development. No development effort is recommended for the auxiliary components (blowers, heat exchangers, etc.).	0	0	N/A	N/A

TABLE 7-11 (Continued)

SUBSYSTEM/MAJOR COMPONENT	CURRENT TECHNOLOGY STATUS	TECHNOLOGY RATING	REQUIRED TECHNOLOGY STATUS	REQUIRED DEVELOPMENTAL PROGRAM	ESTIMATED MANHOURS (THOUSANDS)	ESTIMATED DEV. COST ($)	PROBABILITY OF SUCCESS	ONGOING PROGRAMS & POTENTIAL ALTERNATIVES
3.0 POWER CONDITIONING								
3.1 DC-AC Inverter	Existing technology. Package units being developed for photovoltaic and fuel cell applications.	A	High efficiency (90-95%) low cost. Seventeen percent reduction in weight from current technology.	Weight reduction program.	2.0	100	N/A	Suppliers developing standard units for various alternate energy systems.
4.0 BALANCE OF PLANT								
4.1 Instrumentation and Control	Developed for small mobile systems and large (5 MWe) stationary plants. Assumes manned operation.	A	High reliability and safety. Design for attended remote operation.	No developmental program is recommended.	0	0	N/A	N/A
4.2 Turbo-Compressor, Heat Recovery	Conventional technology.	A	Automatic operation. High reliability.	None	0	0	N/A	N/A
5.0 OVERALL SYSTEM	Complete, small (1.5 kWe) units delivered to U. S. Army for premixed methanol/water fuel. Large (5 MWE) stationary system under construction using natural gas fuel. Various levels of experience with intermediate site units. No experience to our knowledge with 150 psia units.	B	High reliability operation/with automatic control. Proper interfacing with load demand and 150 psia turbocompressor unit. Long-life (20 years). Low performance degradation during operating life-time. Capability to handle diesel fuels.	Qualification program and field testing including: 1. Breadboard modules. 2. House development units (2). 3. Field test qualification units (1).	20.0	4,000	Very Good	None to verify this particular design and application requirements.
TOTAL DEVELOPMENT PROGRAM					76.0	9,600		

Autothermal reforming is receiving the largest share of DOE funding, and development programs are being carried out by United Technologies Corporation (UTC), Engelhard Industries, and the Jet Propulsion Laboratories. In addition, analysis-oriented work is being conducted by several other organizations. Research on high temperature steam reforming is included in the Englehard DOE contract. The Electric Power Research Institute (EPRI) has also sponsored several studies of high temperature steam reforming, including contracts with Catalytica, UTC, and Kinetics Technology International Corporation.

It is felt that a further developmental effort is required to qualify an ATR for Fuel Cell Power Unit service. The areas of concern are:

- Carbon Formation in the Feed Preheater
- Methane Slip (i.e., conversion in reactor)
- Catalyst Stability and Life
- Thermal Response and Startup Rate
- Subsystem Cost

The proposed developmental program would include lab-scale catalyst testing and evaluation, a multi-tube reformer test, and a design, analysis, and economic study of a full-scale fuel processing system. Total estimated man-hours (engineers plus technicians) required are 20,000. Estimated development cost (including materials) is $2,000,000.

Fuel Cell Stack

The proposed fuel cell operation conditions are:

- Current Density at Peak Load - 340 amps per Ft^2
- Cell Temperature - 375°F
- Nominal Cell Pressure - 150 psia
- Cooling Air Pressure - 15 psia

- Cell Voltage at 100 Percent Output - 0.67 VDC
- Active Cell Area - 0.76 Ft^2
- Number of Cells - 450
- Stack Output Voltage - 300 VDC
- Reformed JP-4 Fuel

Although phosphoric fuel cells have been tested and operated successfully under similar conditions, several areas require further investigation and development. Most existing PAFC stacks are operated under atmospheric pressure at approximately 350°F with equal pressures in the cell and cooling passages. In addition they are usually fueled by pure hydrogen or a clean, reformed gas derived from methanol or natural gas. The reformed JP-4 fuel gas will be cleaned prior to entering the fuel cell stack, but the effect of trace impurities, such as heavy metals or nitrogen, and the high carbon oxide content, require further testing.

A development program is suggested to verify and optimize fuel cell performance, to establish scale-up factors, and to verify the differential pressure cooling concept. The proposed development program would include the following:

- Bipolar and cooling plate development, particularly the latter.
- High-temperature, high-pressure electrode development - to evaluate low platinum loadings, performance at pressure, effect of JP-4 reformed fuel gas on electrode stability, etc.
- Multi-cell stack testing to determine issues of thermal expansion, current collection, electrical isolation, manifold seals, flow distribution, acid management, other stack-related characteristics, and cooling system viability and structural integrity.
- Pressurized stack development to determine plate tolerances, seal requirements, acid management, etc.
- Cost improvement studies aimed at the potential for lower capital costs by lower catalyst loadings, manufacturing improvements, etc.

Several development programs are presently being conducted on phosphoric acid fuel cell technology. The primary sources of funding are DOE, EPRI, various electric utilities, the U. S. Army, and the fuel cell developers. Work is being conducted by Westinghouse/Energy Research Corporation, United Technology Corporation, and Engelhard Industries. The various applications that these development programs are directed at include:

- Small, Mobile Units for the U. S. Army (3-5 kW)
- On-Site Integrated Energy Systems (40-150 kW)
- Dispersed Utility Power Plants (5-10 MW)

The extent of these programs, and the applicability to the tactical mobile application design, are uncertain at this time. It is estimated that the fuel cell development program just discussed, will be required in addition to the ongoing development programs. The estimated effort is 30,000 man-hours (engineers plus technicians) at a total cost (including materials) of $3,000,000. This effort could be substantially reduced if further development in one of the related programs proves to be directly applicable.

System Integration and Testing

The packaging and integration of the various subsystems/major components into a Fuel Cell Power Unit is developmental in the sense that previous units of the required capacity, reliability, fuel type, etc., have not been built and operated. The requirements for an autothermal reformer and pressurized cell operation (using a turbo-compressor unit) present unique system considerations. In addition, the FCPU must be designed for water recovery. It is therefore suggested that a system verification and qualification program be conducted. The verification program would include construction and testing of the following units:

- Breadboard Modules
- House Development Units (2)
- Full-Scale Field Test Unit

The estimated cost of materials and test apparatus is approximately $2,000,000. Estimated manpower requirements (engineers and technicians) are 20,000 hours. Total developmental cost for the system verification and qualification program is $4,000,000.

The total recommended developmental program, based on the development risk assessment as discussed above, requires 76,000 man-hours of development labor (engineers plus technicians). The total program cost is approximately $9,600,000. These estimates are based on the present status of technology development. Considerable research, development, and testing are presently being conducted, or are planned, in all areas of appreciable developmental risk. The impact of these programs, most of which are subject to funding review, on the tactical mobile design development risk is highly speculative. The estimated development risk assumes moderate input from these parallel programs. Accelerated development in these areas may substantially reduce the development risk whereas an absence of parallel development will require a larger developmental program.

7.5 LIFE CYCLE COST (LCC)

The following assumptions were made in computing the cost of the various LCC elements for a single FCPU.

R&D - Total cost of $9,600,000 spread over 1,000 units.
Production - Same as estimated capital cost (Table 7-8).
Initial Spares - One-year's replacement parts cost from Section 7.3.3.3.
FCPU Replacements - None
FCPU Maintenance - Cost per year from Section 7.3.3.3.
Fuel - Initial 1980 cost - $1.30 per gallon, 5%/year price escalation.
Operating Personnel - From Section 7.3.3.4.
Transportation - Repair from Section 7.3.3.3, Operation from Section 7.3.3.4.
Technical Data - Cost from Ref. 7-6 spread over 1,000 units.
Period of Use - 20 years from 1980.
Costs - 1980 $.

The results of the LCC analysis for a single FCPU are as follows:

LCC COST ELEMENTS	20 YEAR COST ($)
R&D	9,600
Production	152,000
Initial Spares	2,600
FCPU Replacement	0
Maintenance & Supplies	89,600
Operating Personnel	286,000
Repair Transportation	3,600
Fuel	451,500
Operations Transport & Special Equip.	187,600
Technical Data	200
TOTALS	1,182,700

A similar estimate for the 20 year LCC of a gas turbine-generator is as follows:

LCC COST ELEMENTS	20 YEAR COST ($)
R&D	0
Production	0
Initial Spares	0
FCPU Replacement*	32,400
Maintenance*	137,200
Operating Personnel	286,000
Repair Transportation*	11,900
Fuel**	1,279,000
Operational Transportation	75,600
Technical Data	0
TOTALS	1,822,100

*Extrapolated from Ref. 7-6, an internal USAF study on tactical mobile maintenance power supply.

**Initial 1980 cost - $1.30/gal, 5%/year price escalation, 17 gph fuel consumption, 1,750 hours per year operation.

The 20 year LCC savings from substituting an FCPU for the gas turbine-generator is $639,400.

7.6 CONCLUSIONS

A 60 kW FCPU for tactical mobile use has been designed to a generic application specification based, primarily, on diesel engine generators as used for mobile electric power. The FCPU more than meets the requirements of the generic application.

A specific application for the Air Force of a 60 kW tactical mobile FCPU is that of providing power to a Foreward Air Controller Radar System. Power to such systems is now provided by gas turbine units.

The desires of TAFIG, Langley AFB, Virginia, for replacement power units for the gas turbines are substantial improvements in weight, volume, and fuel consumption over the current gas turbines.

The 60 kW FCPU design given herein cannot offer substantial improvement in weight and volume over current gas turbine units. In fact, the FCPU design is approximately four times heavier (4,050 lbs versus 950 lbs) than current turbine units. However, the FCPU is much more fuel efficient than current turbines (6 gph versus 17.5 gph). Because of the much lower FCPU fuel consumption, the all-up weight, power units plus fuel, that must be transported from the base to field for a typical two week Foreward Air Controller Radar exercise is actually lower for the FCPU's than for the gas turbine units. This, of course, assumes that the fuel as well as the power units must be transported from the basing point to a distant (1,500 miles), remote, temporary Foreward Air Controller Radar site.

At a JP-4 fuel cost of $1.30 per gallon*, escalated at 5 percent per year, 20 year LCC advantage for FCPU's over gas turbine power units of approximately $600,000 per unit is estimated.

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*$0.80/gal base cost plus $0.50/gal transportation cost to a remote site.

The risk associated with development of this 60 kW tactical mobile design has been as assessed as approximately $10,000,000.

Phosphoric acid fuel cell technology, even when stretched considerably beyond current state-of-art towards lighter weight FCPU's, results in power units that are much heavier than current gas turbine power units. The FCPU's are, however, well within air transportability limits and are much more fuel efficient than current gas turbine power units. A straight economic's study comparison between FCPU's and gas turbine units shows a considerable economic advantage in favor of the FCPU's. This is because the cost of fuel over any extended period of time is a dominant factor. Such an economic study does not consider, however, the intangibles of transporting four tons of FCPU's to accomplish what can be accomplished, currently, with one ton of gas turbine units.

8.0 60 KW TACTICAL MOBILE FCPU (AIRCRAFT MAINTENANCE POWER EXAMPLE)

8.1 INTRODUCTION AND SUMMARY

An application analysis, preliminary conceptual design, development risk assessment and a Life Cycle Cost (LCC) estimate of a phosphoric acid fuel power unit (FCPU) has been carried out. The U. S. Air Force application taken as an example was that of a ground power cart to provide power for: (1) maintenance, (2) air conditioning during maintenance, and (3) starting tactical (fighter) aircraft.

The power cart is designed to be able to provide close to 200 kW output, but spends most of the operating time generating power at an energy effective level of 50 kW or less. This latter effective level of power generation is masked by the use of inefficient air cycle refrigeration. As a consequence, the demand on the power cart remains at the 175 kW level during maintenance duty instead of dropping to the 50 kW level. The average fuel consumption is a very inefficient 39 gph. However, even if a more efficient air conditioner were used with the A/M32A-60/-60A cart, the average fuel consumption would remain in the 30+ gph range because the no load fuel consumption of the A/M32A-60/-60A is 23.5 gph.

Direct substitution of a 175 kW FCPU for the A/M32A-60/-60A, leaving the characteristics of the air conditioner unchanged, will save substantial amounts of fuel. However, a broad systems approach to the replacement of the current A/M32A-60/-60A, A/M32C-10/-10A/-10B combination is required to minimize fuel consumption and maximize the reliability advantages of FCPU's. To this end, the following approach was invented.

1. The A/M32A-60/-60A cart would be retained for aircraft engine starting duty only.

2. The air cycle refrigeration system, A/M32C-10/-10A/-10B, would be replaced by a heat-using and energy efficient lithium-bromide absorption air conditioner.

3. The FCPU unit would be sized to provide a maximum projected continuous 60 kW for maintenance electricity, plus 140 pounds per hour of 150 psia export steam to provide the motive heat to a 7.5 ton absorption air conditioner.

The preliminary conceptual design, development risk assessment and the LCC estimate of the 60 kW Tactical Mobile FCPU were carried out in terms of the foregoing approach.

The design was executed to a generic application specification, based primarily on diesel electric generators as used for mobile electric power. The FCPU more than meets the requirements of the generic application specification.

As a "stand-alone development," the R&D cost of the FCPU is estimated as approximately $11 million. Because this maintenance power FCPU has much in common with a previously designed FCPU to provide Forward Air Controller Radar power, the cost of a combined development of both units would be only slightly more than for the "stand-alone development" of one of them.

The concept advanced does complex the ground support power supply situation by increasing the number of ground cart types to be provided from two to three. However, the total fuel savings and hence, cost savings over a twenty year life span, are very large. The fuel cost savings per FCPU cart, over A/M32A-60/60A use, in twenty years is, estimated to be $650,000. The complete twenty year LCC savings are slightly smaller and are estimated to be $600,000 per FCPU. If the total number of FCPU's required to service F-15 and F-16 aircraft is taken as 800*, the total twenty year LCC savings would be $480 million.

Characteristics of the FCPU design are summarized in Table 8-1. An artist's concept of the 60 kW FCPU as mounted on a self-propelled cart is shown in Figure 8-1. Basically, the FCPU system is the same as the skid mounted 60 kW tactical mobile FCPU of Section 7.0, except for the addition of a steam generator to provide 150 psia steam for export to an air conditioning unit. Physically most of the components of the two units are the same but are arranged differently to accomodate to the two different styles of mounting. An important exception to this are the components of the fuel processing subsystem. These components are more squat in the self-propelled unit than in the skid mounted unit. There is less head room in the self-propelled unit than in the skid mounted unit for equivalent overall unit height.

8.2 SYSTEM REQUIREMENTS

The generic application considered herein is a tactical mobile electric power system with a power requirement between 120 kW and 250 kW (Ref. 8-1*). The specific application to be considered (Ref. 8-2) is a ground power cart to provide power to service, air condition and start tactical fighter aircraft.

8.2.1 BACKGROUND

Currently, the ground power required during tactical fighter aircraft maintenance, cooling and starting is provided by the A/M32A-60/60A cart. The power cart couples with an air cycle refrigeration cart, A/M32C-10/-10A/-10B, to provide air conditioning. The gas turbine unit of the A/M32A-60/-60A drives a 400 Hz alternator to provide electric power plus pressurized air to operate either the air cycle refrigeration cart or to air start fighter aircraft engines.

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*A U. S. Air Force estimate of the number of A/M32A-60/60A carts required to service F-15 and F-16 aircraft is 1,000. Because of the reliability of FCPU's, it is projected here that only 800 FCPU's would be required.

TABLE 8-1
POWER PLANT DESIGN SUMMARY

As applicable, the following summary of the FCPU maintenance power cart parameters are based on an operating time of 600 hours per year and an average continuous power output of 48 kW plus 140 pounds per hour of 150 psia export steam.

PHYSICAL PARAMETERS

a) Type of Fuel: JP-4 Primary, Diesel Fuels Secondary

b) Fuel Consumption: 2,880 gallons/year operating fuel plus
144 gallons/year startup fuel

c) Volume/Size:

Volume: 273 ft^3
Size: 45 ft^3

d) Weight: 5,030 lbs.

e) Environment Constraint:

Thermal Discharge - 426,000 Btu/hr @ 60 kW output
Air Pollution - NO_x <0.024 lbs/MWH generated
Noise - <84 dbA at 4 meters
Solid Waste - 38 lbs Zinc Sulfide/Zinc Oxide per year
Chemical Discharge - Trace H_3PO_4
Radioactive Waste - None

PERFORMANCE PARAMETERS

a) Reliability

Mean Line Between Failures - 2,000 hours with preventative maintenance
Availability - 98.6% without on-site repair,
∿100% with on-site repair

b) Lifetime: 63 years without major component replacement

TABLE 8-1 (Continued)

c) Operation and Maintenance:

Ease of Operation - Unattended operation with refueling every 8 hours of continuous rated power output.

Ease of Maintenance - Failure maintenance requires trouble shooting, component replacement, and checkout. Preventative maintenance requires cleaning of fuel vaporizer and replacement of sulfur removal catalyst, plus other routine cleaning and adjustment.

Maintenance Skills Required - E4 or Civilian equivalent

d) Growth Potential: Major elements are of modular construction. Power unit growth potential without size increase is low. Growth potential with size increase is large.

e) Startup/Shutdown Time:

Startup - One-half hour
Shutdown to Hot Standby - <15 minutes
Cold Shutdown - One hour

f) Thermal Energy Available: 140 lbs/hr of 150 psia, 358°F steam

g) Electrical Output: 60 kW rating at 0.8 power factor, 400 Hz, 120/208V or 240/416V, 66 kW peak continuous

COST PARAMETERS (1980 $)

a) Capital Costs:

Fuel Cell Power Unit - $160,000
Other Capital Costs - $1,650 (initial spare parts provisioning)

b) Maintenance Cost:

Transportation for Repair - $234/year
Personnel Cost - $672/year
Special Equipment Cost - Not applicable
Replacement Hardware Costs - $1,645/year
TOTAL - $2,551/year

TABLE 8-1 (Continued)

c) Operation Cost:	
Fuel and Fuel Transportation Costs	$3,024/year
Supplies	$100/year
Operating Personnel Costs	$4,800/year
Transportation To and From Operating Sites Cost	$4,560 per round trip
Special Equipment at Site Cost	Not applicable
d) Life Cycle Cost: $429,000 (20 years total)	

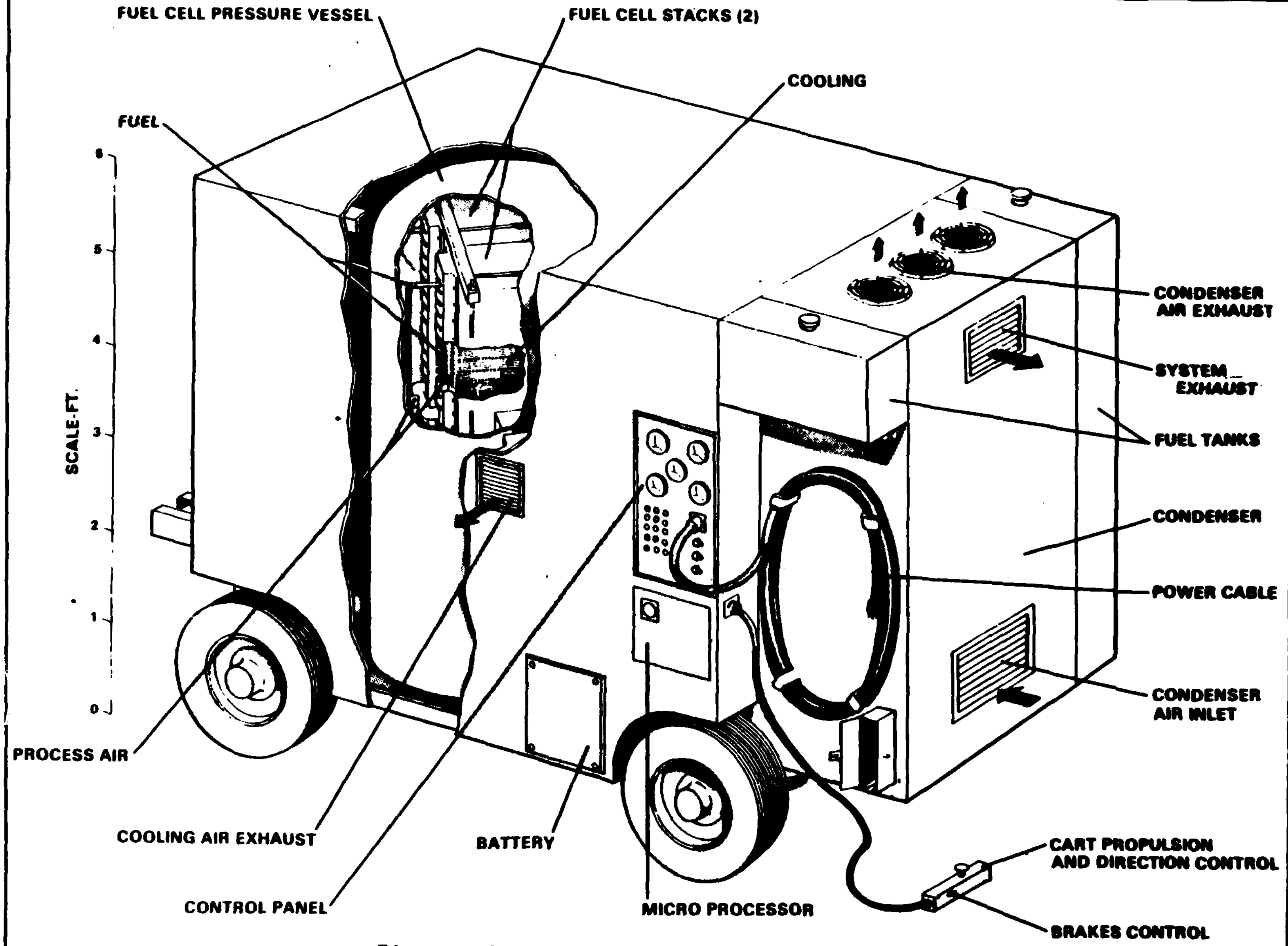

Figure 8-1. 60 kW Tactical Mobile FCPU
(Aircraft Maintenance Power Example)

The gas turbine power cart coupled with the air cycle refrigeration cart is an excellent operational solution to ground servicing of fighter aircraft. It is also very fuel use intensive.

A major reason for its fuel use intensiveness is the desirable operational linkage of three functions of greatly differing power input requirements. For example, present flight line requirements for the various power services at a maximum are: (Ref. 8-3)

Air Starting Power
(FB-111A) - 197 kW (127#/min @ 51 psig)
Electric Power
(FB-111A)
  Continuous - 42 kW
  5 Minutes - 52 kW
  5 Seconds - 56 kW
Air Conditioning (F-15) - 7.5 Tons ∿7.5 kW

Note: 1 Ton ∿1 kW for Freon Cycle Air Conditioning

As can be observed, the power cart is designed to be able to provide close to 200 kW but spends most of the operating time generating power at an effective level of 50 kW or less.

The reader can object that air cycle air conditioning is being used, not Freon cycle. Hence, the average power cart effective level of output is much more than 50 kW, perhaps as much as 175 kW. This is part of the problem fuel use-wise, not a part of a solution. The linkage of the air start power with the air conditioning power is a neat operational solution. So neat, that perhaps it masks the fuel price being paid for the linkage.

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*References for Section 8.0 may be found in Appendix A-6.

The A/M32A-60/-60/-60A cart fuel consumption is:

Fuel Load - 44.3 gph
No Load - 23.5 gph

This is a large amount of fuel to use for an average of less than 50 kW of effective power output. In round numbers the energy efficiency is less than four percent.

8.2.2 GENERAL CONCEPT

The U. S. Air Force has recognized that in times of high fuel cost such as today (1981) there is a strong need to replace the A/M32A-60/-60A cart with something more efficient. In addition, future growth will require even higher power capabilities than those of today. Also, the A/M32A-60/-60A/-60A cart, plus A/M32C10/-10A cart cannot always meet current air conditioning needs.

Power requirements for future growth have been estimated as: (Ref. 8-3)

Electric Power
  2 Seconds - 96 kW
  5 Minutes - 60 kW
  Continuous - 48 kW
Air Conditioning
  106 pounds per minute of 65°F air
  (equivalent to 7.6 tons refrigeration at 125°F dry bulb temperature, 59°F wet bulb temperature)
Air Start Power 203 kW (150#/min @ 40 psig)

To Westinghouse knowledge, Air Force studies to date for replacement of the A/M32A-60/-60A, A/M32C-10/10B combination have concentrated on improvements in power generator efficiency. This involves the replacement of the simple open cycle gas turbine engine in the power cart by more efficient thermal engines. These are such as recuperated gas turbines, diesels, or fuel cell power units.

There is much to be gained in fuel savings by use of a more efficient thermal engine in the power cart. A recuperated -60A power generator is estimated to have a full load fuel consumption of 23.5 gph versus the present 44.3 gph. Even more can be gained, however, if in addition to use of a more fuel efficient engine, the functions of supplying maintenance power and air conditioning are separated from supplying air starting power.

The concept of this study is to incorporate both an efficient fuel cell power generator into the power cart and to break the link between the starting function and maintenance functions. The fuel cell power unit cart would be designed to provide maintenance power only, that is, electric power and air conditioning power. The air conditioning power would be provided to an absorption air conditioning cart in the form of heat (steam). This allows a portion of the fuel cell power unit waste heat to be used towards the air conditioning, as a fuel conservation measure.

The starting power function would still be performed by the A/M32A-60/-60A cart. Since the A/M32A-60/-60A would be used only for starting jet engines, it would operate for only a very short part of the total power needed periods. Its high fuel consumption would no longer contribute much to the total flight line fuel requirement. The continuous power needs would be supplied by the efficient fuel cell power unit at the continuous power levels required.

Using the fuel cell power unit for maintenance power and the gas turbine for air start power will reduce average fuel consumption from 39 gph to five gph per individual power supply system. Assuming an average total power usage period of 50 hours per month and an average of $1.30 per gallon fuel delivered cost, the fuel cost saving over a twenty year period would be in excess of one-half million dollars per individual power supply system.

The fuel cost savings does have some qualifications. There are added capital, transportation, handling and personnel costs associated with using three carts instead of two. On the other hand, there should be a reduction of maintenance costs because the gas turbine unit builds up little operating time. The fuel cell power unit's maintenance cost for equal hours of operation should be about two-thirds that of the gas turbine; $4,300 per year* versus $6,300 per year (Ref. 8-4).

Prior to starting the design of the maintenance power only FCPU, an order-of-magnitude estimate of the net 20 year life cycle cost (LCC) saving using the three cart concept in place of the present two cart system was made. The result was as follows:

Saving	
Fuel	$500,000
Maintenance	$ 30,000
Gross Savings	$530,000
Added Costs	
Personnel	$120,000**
Transport & Handling	$ 60,000**
Capital	$200,000
Total Added Costs	$380,000
Net Savings	$150,000

Approximately 1,000 maintenance power units are required to service U. S. Air Force fighter planes (Ref. 8-4). Therefore, the system-wide saving in twenty years would be $150 million, on a preliminary basis.

Under peacetime conditions, the three cart system cost savings seem worth the extra bother over a two cart system. Under combat conditions, this may not be so. Under combat conditions it might be advantageous to revert to a two cart situation by feeding the starting air output of A/M32A-60/-60A to the absorption air conditioner for power (heat). This is technically feasible, but of

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*Based on the investigation of the skid-mounted 60 kW FCPU of Section 7.0

**40 Percent of the "Stand-Alone" costs for the comparable fuel cell power unit of Section 7.0 operated as a totally independent unit.

course, reverts to the fuel inefficiency of the present gas turbine/air cycle refrigeration combination.

8.2.3 FUEL CELL POWER UNIT DESIGN REQUIREMENTS

As was noted previously, in the Section 7.0 design study of a skid-mounted 60 kW mobile power generator as applied to supplying power to a Foreward Air Controller Radar System, the United States Armed Forces has two types of tactical mobile electrical generator systems. One is based on the use of a diesel engine as the prime mover. The other uses a gas turbine as the prime mover. The diesel units are relatively heavy and fuel efficient. The gas turbine units are relatively light but fuel inefficient.

The maintenance power cart is required to be an "on call" type unit. It must be moved, readily, anywhere in the world and respond quickly to the needs of the situation. Its primary design requirements are reliability, mobility and fast startup and electrical response in a rough handling situation.

A set of design requirements for a maintenance power cart using a 60 kW fuel cell power unit has been derived. The basic background information used in preparing the design requirements was that of current diesel power units*; but modified to force lower fuel consumption, higher reliability, and multifuel capability into the FCPU design.

The requirements data sheet (W-RDS-5) for the mobile maintenance power cart is given in Appendix C-5. Some of the important requirements for a FCPU from W-RDS-5 are as follows:

Power Rating:	60 kW at 0.8 power factor, 400 Hz 120/208V or 240/416V; 140 lb/hr of 150 psia (sat'd) steam
Type:	I (tactical)
Class:	1 (precise)

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*Primary Source of Information: U. S. Army Mobile Electric Power, Col. Rowe, et al.

Mobility: Air Transportable, Self-Propelled
Maximum Dimensions: 110 in x 67 in x 72 in
Maximum Volume: 310 cubic feet
Maximum Allowable Weight: 5,000 lbs
Noise Level: Shall not exceed 84 db at 4 Meters
The unit shall be designed to withstand a 12 inch end drop test.
Reliability: 1,500 hours MTBF

	Voltage	Frequency
Application of Load	12% Dip	14% Undershoot
Recovery	0.5 Sec	1.0 Sec
Rejection of Rated Load	12% Rise	1.5% Overshoot
Recovery	0.5 Sec	1.0 Sec
Application of Simulated Motor Load	2% Dip	
Recovery	0.7 Sec	
Total Harmonic Distortion	5.0%	
Individual Harmonic	2.0%	

8.3 SYSTEM DESIGN

Previous to this 60 kW electrical maintenance power cart design effort, the Section 7.0, 60 kW FCPU to provide power to a Foreward Air Controller Radar unit, was designed. The basic FCPU for the maintenance power cart is essentially the same as that for Foreward Air Controller Radar power. The FCPU for the maintenance power cart differs from the previous Foreward Air Controller Radar power unit in two respects. These are: (1) the unit is mounted on a wheeled self-propelled base, rather than being skid-mounted, and (2) a steam generator to provide 140 lb/hr of 150 psia, 358°F steam to an absorption air conditioner has been added.

A Westinghouse study (Ref. 8-5) of some years ago compared a number of air conditioning options for cooling a universal combat garment. One of the options considered was a lithium bromide adsorption refrigeration system. Based on the results of that study, a flow of 18.2 pounds per hour of 150 psia/358°F steam to the adsorption unit will produce one ton of air conditioning. To produce the 7.5 tons required, the steam flow rate would be 136.5 pounds per hour or in round numbers, 140 pounds per hour.

The weight of the air conditioner, as extrapolated from the Reference 8-5 material, is estimated as 220 pounds per ton for a 125°F ambient capability. This equates to 1,650 pounds for a 7.5 ton unit. The weight of the A/M 32C-10B air cycle air conditioner is approximately 1,300 pounds.

8.3.1 SYSTEM/COMPONENT OPTIONS AND PERFORMANCE

The requirements and constraints that the design should meet are those of W-RDS-5 as given in Appendix C-6. The basis for W-RDS-5 was discussed, previously, in Section 8.2.3.

Also, as previously mentioned, the FCPU for this maintenance power cart is very similar to that of a previous design for Foreward Air Controller Radar power. This is because the power levels are similar and both units are for tactical mobile applications. Therefore, the rationale for selection of most of the system and component options available is the same for the two FCPU's. However, for the convenience of the reader, a discussion of selections rationale will be repeated here.

8.3.1.1 SYSTEM OPTIONS AND COMPONENTS

The general system arrangement for PAFC power units is well established. Important detail system options available are: system operating pressure level, degree of recovery of water from the system for reuse in the fuel reforming step and the fuel cell waste heat cooling medium. The most important component options are the selection of the type of fuel reformer and, given a system operating pressure level, the selection of the individual fuel cell current-voltage design point.

Based on previous work (Ref. 8-6), there are only two types of reformers capable of successfully handling JP-4 and other USAF logistic fuels. These are an autothermal reformer (ATR) and a high temperature steam reformer (HTSR). An ATR was selected for this application. Although the ATR generates a larger volume of product gases for a given hydrogen demand than a HTSR, it operates at higher gas space velocities (smaller reactor volumes) and offers better response characteristics. The amount of reformer catalyst needed by the ATR is approximately 50 percent of the catalyst needed in a HTSR. Since an ATR uses insitu combustion to generate reaction heat, transient response and starting time are not limited by surface heat transfer rates as in a HTSR. ATR transient response capabilities are needed in this tactical mobile application.

The size and volume constraints for this tactical mobile application are severe in terms of phosphoric acid fuel cell (PAFC) FCPU capabilities. The system design pressure was selected as high as practicable, 150 psia. This is the maximum pressure currently being projected for PAFC systems. High system operating pressure allows the use of high fuel cell current density at reasonable electrical efficiency (cell voltage). This reduces the size of the fuel cell module with little or no penalty in system fuel rate and hence fuel processor size. Pressurization also reduces gas specific volumes, resulting in size and weight savings in ATR and shift catalyst, and heat exchanger sizes. Pressurized operation does increase piping and vessel wall thickness, but even so, results in a net weight savings, as well as volume reduction. To a first approximation, the weight of the boundary components (piping and vessels) does not change with pressure because the decrease in surface area from increase in pressure is balanced out by the required increase in wall thickness to support the increased pressure. However, the weight of the interior components does decrease as system pressure is increased and system volume declines.

Atmospheric pressure air-cooled cell design was selected over water or liquid cooling or pressurized air-cooling. This eliminates the need for an extra waste heat exchanger over and above that needed to provide cogeneration waste heat to a steam vaporizer. Only about 14 percent of the waste heat of the fuel cells can be effectively used to help provide 150 psia steam. The temperature level of the remaining waste heat is too low to be useful and must be rejected. The elimination of an extra waste heat exchanger is an important consideration in satisfying design weight and volume limits.

Use of atmospheric pressure air-cooling does introduce a development risk over and above the norm for air-cooled PAFC design. Current hardware is designed to operate with nearly equal cooling and process air pressures and will not sustain a pressure differential of 135 psi between the two. The state-of-art fuel cell stack and module designs will have to be changed to sustain the increased pressure differential and the design changes substantiated by experiment.

Water recovery from the FCPU exhaust has been incorporated into the unit. Between -65°F and +90°F ambient temperature, the unit can recover sufficient water to cover fuel reforming needs on an instantaneous basis. On days when the maximum ambient temperature exceeds 90°F, excess water is condensed and stored during the cooler hours of the day for make-up during the hotter hours.

On a day where the maximum ambient temperature reaches 125°F, the storage of excess condensate, which equals make-up required, is about 30 gallons. Storage is in the condenser sump.

A design current density of 300 ASF was selected arbitrarily. It is the maximum value currently projected for PAFC design. A cursory analysis indicates that the 300 ASF current density selected results in a FCPU design of near minimum weight. At higher current density design, the savings in fuel cell stack size and weight are only marginally larger than the increase in size and weight of the fuel processing subsystem and air cooling and supply system. At lower current density design, the overall system weight starts to increase markedly. Based on cost-current density parametering for the MX shelter FCPU under this Air Force Fuel Cell Application Analysis program, the minimum current density that satisfies other requirements will result in minimum FCPU life cycle cost.

8.3.1.2 PROCESS DESIGN DESCRIPTION

The PAFC system shown in Figure 8-2 identifies the major components, operating conditions, and flow paths in the proposed 60 kW tactical power unit design. The design is based on reforming JP-4 in an ATR operating at 150 psia, 1,800°F, a steam/carbon ratio of 3.0, and an air/carbon ratio of 1.8*. The process flow rates shown in Table 8-2 are based on 95 percent fuel conversion and a near equilibrium ATR outlet concentration of 24 percent volume hydrogen. Product gases from the ATR are cooled and treated in successive stages to remove sulfur (H_2S) and increase hydrogen yield (CO shift).

The fuel cell consumes 85 percent of the available hydrogen to produce dc power. The remaining combustibles are used to provide system heat requirements for water vaporization, fuel vaporization, and air heating in a separate furnace. Approximately 50 percent of the heat requirements for vaporization are supplied in the furnace. The remaining water vaporization needs are obtained in an external vaporizer heated by ATR product gases and fuel cell waste heat. State point conditions at the design point for the design are given in Table 8-2. In preparing the schematic and design conditions table, it was assumed that all the heat above ambient contained in the return water from the air conditioning cart is lost. If there were no heat loss from the water leaving the air conditioning cart, FCPU fuel consumption would be reduced about four percent.

The steam vaporizer arrangement is split. One vaporizer is designed to make use of system waste heat from the reformer gases and the fuel cell cooling air exhaust. The other vaporizer is designed to make use of furnace heat, which will generate 140 lbs/hr steam for air conditioning use and as an aid in system starting and thermal control. The system also contains a superheater for raising the steam to ATR inlet temperature.

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*Developmental ATR test data indicate that an air/carbon ratio of 1.6 may be possible with advanced catalyst and reformer design. This would reduce system fuel consumption by about seven percent below the values given hereafter.

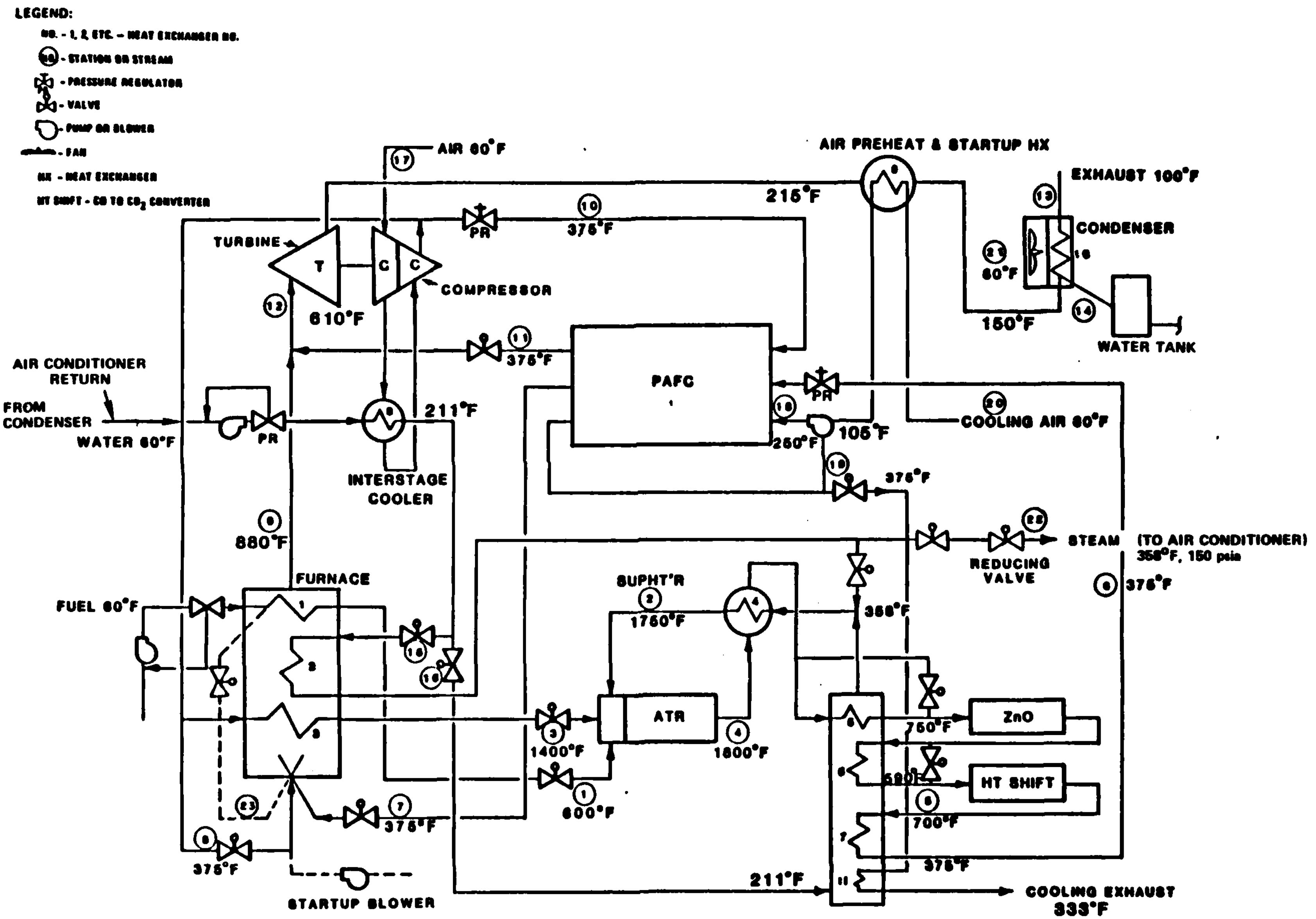

Figure 8-2 Process Schematic, 60 kW Tactical Mobile FCPU (Adapted to Supply Aircraft Maintenance and Air Conditioning Power)

TABLE 8-2

60 kW TACTICAL MOBILE MAINTENANCE CART FCPU

	STREAM*	MOLAR FLOW, LB-M/Hr								FLOW LBS/HR	Temp. °F	Press PSIA
		H_2	CO	CO_2	CH_4	H_2O	N_2	O_2	HC			
1	ATR Fuel								2.595	36.03	600	150
2	ATR STEAM					7,786				140.16	1750	150
3	ATR Air						3.709	0.986		135.41	1400	150
4	ATR Products	4.049	1.090	1.376	0.130	5.918	3.709			311.60	1800	150
5	Shift Exit	4.983	0.156	2.310	0.130	4.983	3.709			311.60	700	150
6	Fuel Cell Feed	4.983	0.156	2.310	0.130	4.983	3.709			311.60	375	150
7	Exit Feed Gas	0.747	0.156	2.310	0.130	4.983	3.709			303.13	375	150
8	Burner Air						6.227	1.655		227.32	375	150
9	Furnace Exhaust			3.09		6.458	9.936	0.215		537.29	860	150
10	Cell Process Air						15,935	4.236		581.74	375	150
11	Cell Exhaust Air					4.236	15.935	2.118		590.17	375	150
12	Turbine Exh. Sup.			3.09		10.694	25.871	2.333		1127.46	610	150
13	System Exhaust			3.09		2.784	25.871	2.333		987.30	100	15
14	Recovery Water					8.536				153.65	100	15
15	Water to Furn./Vap.					7.786				140.16	193	150
16	Water to Cooler/Vap.					7.786				140.16	193	150
17	Compressor Air Sup.						25.871	6.877		944.47	60	15
18	Cell Cooling Air						193.330	51.400		7058.00	250	15
19	Recycle Air						106.922	28.540		3907.10	375	15
20	Makeup Cooling Air						86.408	22.860		3150.90	60	15
21	Condenser Air Sup.						358.200	95.210		13076.00	60	15
22	Generating Steam					7.786				140.16	300	30
23	Burner Fuel								0.495	6.88	60	150

Design Basis			Heat Exchanger Loads, (Btu/Hr)		
			Sensible	Latent	Area, Ft²
85% Cell H_2 Use	**1.	Fuel Heater	8,646	6,845	5.0
95% Fuel Conversion	2.	Steam Vaporizer	20,600	121,095	24.0
18700 Btu/Lb JP-4 (NHV)	3.	Air Heater	40,348	--	8.0
5218 Btu/Lb H_2	4.	Steam Superheater	104,516	--	50.0
21758 Btu/Lb CH_4	5.	Gas Cooler		51,022	11.7
4348 Btu/Lb CO	6.	Gas Cooler		15,455	6.3
2.0 Cell Stoair	7.	Gas Cooler		44,142	51.0
1.15 Burner Stoair	8.	Interstage Cooler	42,420	--	4.0
60 °F, 0% Rel. Hum.	9.	Air Preheater	36,495	--	150.0
69 kW Gross Power	10.	Water Condenser	28,075	146,762	575.0
60 kW Net Power	11.	Air Cooler	20,600	10,480	20.0

* Numbers Correspond to $\boxed{\text{NO}}$ in Figure 8-2

** Numbers Correspond to Heat Exchanger Nos. in Figure 8-2

ATR air, furnace combustion air, and fuel cell process air are supplied by a two-stage turbocharger compressor operating at an overall efficiency of 69 percent. Two hundred ten (210) cfm of air at STP is compressed to 150 psia, requiring 38.5 AHP and a total gas side energy input of 55.0 GHP. This energy is supplied by furnace and fuel cell exhaust air which enters the turbine at 600°F and a system exhaust pressure slightly below 150 psia. To reduce turbocharger size and improve efficiency, an interstage air cooler is provided. Interstage cooler heat is used in the fuel processing system to preheat water prior to entering the steam generators.

Water heat is removed from the fuel cell via a separate air cooling loop operating at atmoshperic pressure. Heat absorbed by the cooling air is used to supply the steam vaporizer and partially preheated in a gas/air heat exchanger located at the turbocharger exhaust outlet. This arrangement reduces the amount of recirculated cooling air required to maintain inlet air temperatures, and reduces the amount of heat which must be removed in the water condenser. Since the water recovery dew point temperature for the system is low (100°F), this upstream heat exchanger reduces condenser fan parasitic power, and improves water recovery capability.

8.3.1.3 SYSTEM PERFORMANCE

The overall design basis of the previously described process design is as follows:

Power Output, kW at STP	60
Voltage, Regulated AC	120/208 or 208/416
Fuel Type	JP-4
Ambient Temperature, °F	-65 to +125
Altitude, Feet Above SL	0 to 10,000

The design parameters for the fuel cell and fuel conditioning subsystems at rated load (60 kW) at Standard Pressure and Temperature (STP) are as follows:

Fuel Cell Subsystem

Design Pressure, psia	150
Design Temperature, °F	375
Cell Hydrogen Utilization, %	85
Process Air Stoichiometry,	2.0
Cooling Load, 10_3 Btu/Hr	236
Output Voltage, VDC	300
Number of Cells, Required	450
Active Cell Area, Ft^2	0.76
Operating Point, vpc at ASF	
100% Design power	0.67 at 300 ASF
Cooling Air Required, CFM	1,390

Fuel Conditioning Subsystem

Design Pressure, psia	150
Reformer Design Temperature, °F	1,800
Catalyst Type	Pt + Ni
Shift Catalyst Type,	Fe_2O_3/Cr_2O_3
Shift Catalyst Volume, Ft^3	3.2
Desulfurization Catalyst	ZnO
Desulfurization Catalyst Vol., Ft^3	0.75
Design Fuel Sulfur, wppm	300
Replacement Schedule (ZnO only) Hrs.	1,175
Design Combustion Stoichiometry	1.15
Turbocharger Output, CFM	200
Turbocharger Compression Ratio (2 stages)	10.2
Turbocharger Efficiency (overall), %	69

The performance profile for the FCPU at STP is as follows:

	% Load		
	75	100	110
Gross Power, kW	52.7	69.0	75.5
Fuel Cell Volts, vpc	0.71	0.67	0.64
Hydrogen Needs, Lbs/Hr	6.09	8.47	9.69
Total Fuel Use, gph	4.84	6.72	7.67
Electric Output, NkW	45.0	60.0	66.0
Electric Efficiency, % (*)	26.6	25.5	24.6
Heat Rate, Btu/NkW	12,843	13,374	13,877

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*18,700 Btu/Lb (LHV) JP-4, 3,413 Btu/NkW

The foregoing performance projections are based on beginning-of-life cell performance. Some decay can be expected over the system life with proportional increases in fuel consumption. Although performance loss cannot be assessed at this time, assumption of a 10 percent loss over 40,000 hours is current estimation practice.

If an alternate fuel, such as DF-2, is used in the unit, the gallons/hour fuel rate will decrease about 10 percent, but the actual heat rate will increase about 0.2 percent.

Because DF-2, on the average, contains more sulfur and forms carbon more readily than JP-4, an increase in maintenance relative to JP-4 use can be anticipated.

8.3.2 FUEL CELL POWER UNIT CHARACTERISTICS

8.3.2.1 SYSTEM OPERATION AND CONTROL

The primary control functions needed for operation of the FCPU are listed in Table 8-3. Because the logistic fuel processor and the turbocharger are developmental units, it is possible that additional control over and above the system primary control functions listed in Table 8-3 will be required.

TABLE 8-3
MAJOR CONTROL FUNCTIONS

Load Following	Current Measurement Feedback to Control Valves
Fuel, Air, and Steam Flows	Proportioning Control Valves
Furnace Temperature	RID Feedback to Supplemental Fuel Burner
Reformer Temperature	RTD Feedback to Air Control Valve
Fuel Cell Temperature	RTD Feedback to Recirculation Cooling Air Flow Valve
Shift Outlet Temperature	Thermostatic Bypass Flow ZnO Bed Temperature
System Pressure	Turbo Output Pressure Regulation
Fuel Cell Pressure	Differential Pressure Regulation on Anode and Cathode
Water Condenser Temperature	Air Cooler Fan Number, Speed and Damper Flow Control
Exhaust Gas Water	Load Following Process Air Control to Maintain 2.0 Stoair Supply
Air Conditioning Process	Back Pressure Sensing, Throttle Steam to Air Conditioner Demand

Microprocessor control will be needed to provide automatic FCPU operation, in any case. Therefore, added requirements should be accomodated without major increases in system weight, volume or costs over and above these estimates presented hereafter.

Two key operational problems may occur within the reformer subsystem which will require developing a means of detection and avoidance. The ATR may be subject to carbon deposition and loss in reformer gas quality. The reformer must be designed to avoid this problem during startup and over the operational range of output, and a means of detection and control must be built into the unit. Also, sulfur removal rate in the ZnO bed should be monitored to protect downstream catlysts. As the ZnO bed ages and absorption capacity drops, sulfur removal will decrease, resulting in poisoning and deactivation in the shift converter and fuel cell. A means of detection, other than establishing replacement schedules will be needed. Both of these problems will need additional study to adequately assess the design and control options.

Power Unit starting commences after the fuel cell, reformer, desulfurizer, and shift catalyst are raised to operating temperatures. In this system, starting time will be governed, probably, by heating in the fuel processing subsystem due to the higher operating temperature. Combustion of liquid fuel in the furnace provides a source of heat. Combustion gases are used to operate the turbocharger and provide heat to the fuel cell cooling air loop through the air preheat and startup heat exchanger. Heat is transferred to the stack by air circulating through the heat exchanger. When operating cell temperatures are reached, stack temperature is maintained by adjusting the recirculation air flow rate.

An inert gas system may be required to prevent moisture condensation in the fuel processing catalyst during initial startup. If so, nitrogen would be circulated between the furnace and catalyst vessels until the catalyst are heated above dewpoint temperature. It may be possible to start the heating cycle with compressed air supplied through the turbocharger and air preheat coil. When sufficient temperatures are reached in the system catalysts, stoichiometric combustion would be initiated in the ATR to accelerate the heating cycle. Combustion gas from the ATR would be passed through the external heat exchangers, desulfurization catalyst and shift catalyst, and then vented to atmosphere. An ignitor will probably be needed to initiate combustion in the ATR.

Although starting time cannot be fully assessed at this time, a minimum of one half hour would be needed. Start power would be supplied by on-board batteries. A minimum battery capacity of one kW is projected for one half-hour start.

Load following is obtained by measuring fuel cell current (demand) and adjusting air, steam, and fuel flow to the ATR, accordingly. This controls the volume of reactants entering the catalyst bed and hydrogen output to the fuel cell. Rapid demand is tied into the burner control to provide increased heat for fuel and water vaporization and air preheat. Gas phase flow valves are needed to modulate steam, fuel, and air flow to the ATR. Combustion air, and fuel cell process air must also be controlled in response to demand to maintain operating stoichiometry.

Thermal system control is obtained by monitoring reformer catalyst, shift catalyst, desulfurizer bed, and fuel cell temperatures and adjusting flow rates accordingly. Desulfurizer and shift catalyst temperatures are maintained by controlling the amount of ATR product gas entering or by-passing the water vaporizer.

Fuel cell plate temperatures are controlled by the rate of heat removal from the cooling air loop. This is performed by adjusting makeup and exhaust cooling air rates. Combustion rate in the furnace is altered to prevent overheating of the fuel vaporizer. ATR catalyst temperature would be maintained by either adjusting the operating S/C ratio or adjusting air and steam temperatures. Experimentation will be needed to assess the best control technique for the ATR.

System pressures would be maintained by pressure regulators at the fuel and water pump discharge and at the turbocompressor air discharge. The turbocharger should be designed for marginally higher discharge pressure to maintain operating conditions at low kW output. The system should also include pressure switches to signal overpressure in the vaporizers, and air preheater and loss of pressure in the fuel cell.

Water recovery rate in the exhaust condenser would be subject to changes in system flows. To ensure adequate recovery, the condenser air flow will be controlled to maintain a minimum (but above 32°F) exhaust temperature for the system. This is subject to water storage tank fill level over-ride.

8.3.2.2 SYSTEM SIZE AND WEIGHT

The projected volumes and weights of major system components and the assembled power unit are shown in Table 8-4. These projections are based on scaleup of existing designs with allowance for additional components, including water equipment. In addition, the state-of-art weight for the output power conditioner is more like 2,200 lbs rather than 1,500 lbs. Development effort to reduce output power conditioner weight will be required.

8.3.2.3 SYSTEM RELIABILITY

An estimate of the reliability of the FCPU is given in Table 8-5.

As can be seen, the estimated MTBF is 1,998 hours. This is somewhat less than for the 60 kW skid-mounted unit because of the self-propelled cart feature. It does, however, compare most favorably with diesel engine specifications of 500 hours MTBF for tactical mobile duty. It compares unfavorably to the estimated 3,770 hours MTBF for the 23 kW methanol fueled unit for individual MX shelter power. Both estimates were done on a consistent basis. A major difference in reliability between this tactical mobile unit and the MX unit is caused by the differences in fuels to be used; JP-4 for the tactical mobile unit and methanol for the MX unit.

TABLE 8-4
TACTICAL MOBILE SYSTEM SIZE

	Weight, Lbs	Volume, Ft^3
Fuel Cell Stack w/Manifolds	700	15
Autothermal Reformer	300	6
Burner/Furnace Assembly	40	4
External H2O Vaporizer	150	3
Steam Superheater	300	6
Desulfurizer	60	2
HT Shift	200	4
Turbocharger/Compressor	100	1
Interstage Cooler	20	2
Air Heater/Startup HX	30	5
Water Condenser	150	30
Water Purifier & Storage	40	8
Pumps, Blowers, Valving	150	-
Housekeeping Power Supplies & Controls	150	5
Output Power Conditioner	1,500	37
Battery Pack (1 kW)	130	2
Misc. Ducting, Piping Insulation Fuel Tank	180	7
Packaging Factor (77%)	-	44
Sub-Total w/o Cart	4,150	195
Self-Propelled Cart	900	78
Total	5,030	273

Footprint - 45 ft^2 w/Cart

TABLE 8-5

RELIABILITY ESTIMATE (1)
60 kW TACTICAL MOBILE POWER UNIT

Components	Failure Rate, Per 10^6 Hrs
Fuel Cell	25.0 (2)
Reformer	25.0 (2)
Fuel Vaporizer	1.0 (w/Periodic Cleaning)
Burner	15.0
Heat Exchangers	9.0
Fuel Pump	7.5
Water Pump	2.8
Air Blowers	9.0
Turbocharger	10.0
Microprocessor	20.0 (3)
Housekeeping Power Supply	20.0 (3)
Power Conditioner	20.0 (3)
Self-Propelled Cart	100.0
Valves	
Flow	83.0
Press Reg.	9.6
Solenoid	8.0
Relief	7.2
Check	12.0
Sensors	
Pressure	5.4
Level	4.8
Temperature	58.0
Current, Power	3.2
Ducting	15.0
Tubing	30.0
	500.5 MTBF = 1998 Hours

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1. Based on average data from non-electric parts reliability data NPRD-1, Rome Air Development Center, 1978.

2. Assumes fuel cell and reformer catalyst life of 40,000 hours.

3. Assumed values for high reliability designs

The single element of most concern in the JP-4 fuel processing subsystem is the fuel vaporizer. In industrial practice, naphtha fuel vaporizers (and JP-4 is a heavy naphtha) coke-up. Without cleaning, the fuel vaporizer would be expected to coke-up about every six months or its failure rate would be of the order of 230 failures per million hours. With periodic cleaning it is assumed to behave as just another heat exchanger with a very low failure probability.

Another possible way to prevent the coking of the heavy fuel is to pre-mix the liquid fuel with some steam prior to entering the vaporizer. The steam will also help the vaporization of the liquid fuel. Additional improvement in the overall fuel processing reliability of the tactical mobile unit relative to the MX unit will be difficult to achieve. This is because the source of the unreliability is the increased number of valves, piping, sensors and higher temperatures required for a JP-4 fuel processing system compared to a methanol fuel processing system.

8.3.2.4 SYSTEM DESIGN LIFE AND MAINTENANCE REQUIREMENTS

The major component life and maintenance characteristics for the Tactical Mobile Power Unit are shown in Table 8-6 assuming continuous operation (8,760 hours per year). The fuel cell stack represents the primary maintenance cost driver, with replacement anticipated within five years equivalent continuous operating time. Life testing of fuel cell stacks have demonstrated performance of 40,000 hours and above without major voltage losses. Typical voltage loss is 5-10 percent over this life span, and is due to deactivation of fuel cell platinum. The current industry standard estimated replacement time for phosphoric acid fuel cell stacks is 40,000 hours or 4.5 years of equivalent continuing operation.

Replacement of the ZnO desulfurizer unit is expected to occur about every seven weeks of continuous system operation. This projection is based on operation at design output using JP-4 fuel with a sulfur content of 300 wppm, a catalyst bed of 50 lbs and a maximum bed capacity of 20 lbs sulfur per 100 lbs of catalyst.

TABLE 8-6

SYSTEM MAINTENANCE CHARACTERISTICS

Major Component Replacement	Continuous Operating Time
Fuel Cell Stack	4.5 Years
Reformer Catalyst	4.5 - 5 Years
Shift Catalysts	4.5 - 5 Years
Forced Outage Maintenance	
Desulfurizer Catalyst	7 Weeks
Fuel Vaporizer Cleaning	6 Months
Inspection and Cleaning	1 Year
Oiling and Greasing	1 Year
On-Line Maintenance	
Acid Replenishment	1 Year
Calibration and Adjustment	1 Year
Fuel and Air Filter Replacement	6 Months

Replacement of reformer and shift catalyst are anticipated within five year equivalent continuous operating time intervals.

Cleaning and potential replacement of the reformer fuel vaporizer unit and fuel/steam mixing nozzle are expected to occur frequently relative to most other maintenance needs.

8.3.3 POWER PLANT USAGE CONCEPT/CONSIDERATIONS

8.3.3.1 AVAILABILITY OF POWER

For tactical aircraft maintenance duty (Ref. 8-7), the equipment must be available for use in all operating locations including dispersed bases and bare bases. The equipment must be designed to operate at these dispersed locations for 30 days with minimum maintenance. Only common hand tool kits and limited select spares will be available at these locations. The equipment must be in a mission capable status 90 percent of the time.

The current average utilization of the maintenance equipment during a month is given as 40 hours in Ref. 8-4. Using the previous figure of 2,000 hours MTBF for a periodically serviced FCPU derived in Section 8.3.2.3, the probability of a failure in 40 hours of operation is 1.4 percent. The projected availability during a normal month, even without repair, is 98.6 percent, far higher than the 90 percent required.

Perhaps the current Air Force 90 percent availability requirement is predicated partly on the reliability of the A/M32A-60/60A unit at 300 hours MTBF. A MTBF of 300 hours implies a nine percent change of failure on a 91 percent chance of continuous success in 40 hours of operation for a particular cart.

This suggests that substitution of an FCPU for the A/M32A-60/60A unit would allow a reduction in the total number of maintenance power units required. For example, for every ten A/M32A-60/60A units on site, there is a 48 percent chance that at least three units will go out of service in one month's time. Whereas, of every ten FCPU's, there is an 86 percent change that all ten will be operating at the end of a month's service.

These foregoing numbers suggest that substitution of FCPU's for the A/M32A-60/60A in the maintenance category, as outlined previously in Section 2.0, will allow a 20 percent reduction in the number of maintenance units carried. That is, to be quite sure of having at least seven operational units at a particular site, ten A/M32A-60/60A units would be needed but only eight FCPU's. The effect will be that of increasing the utilization of the maintenance units to 50 hours per month against the present 40 hours per month.

A value of 50 hours per month utilization has been used throughout this study in connection with FCPU's operation.

8.3.3.2 MAINTENANCE FREQUENCY

In providing maintenance power and cooling for tactical air ground support, the FCPU's are utilized only about seven percent of calendar time. Hence, in principle, the maintenance periods can be stretched out by a factor of 14 over those for continuous operation as given in previous Table 8-6. This results in maintenance calendar periods as illustrated in Table 8-7, in the column marked "Continuous Operating Time".

In principle, because of the small amount of operating time per year for a unit, inspection, cleaning, calibration and adjustment could be done on a seven to fourteen year basis. However, equipment gets dirty and out-of-adjustment when idle, as well as when operating, so more frequent attention to these items is indicated than results from a pure operating time projection. An adjustment to the continuous operating time projection of the middle column of Table 8-7 is given in the right-hand column.

An important observation from Table 8-7 is that a very low rate of major component replacement is to be expected during a twenty-year unit use period. This is similar to that of the FCPU for the Foreward Air Controller Radar power example, but even more so.

TABLE 8-7

POWER CART MAINTENANCE PERIODS

	Continuous Operating Time	Adjusted Maintenance Periods
Major Component Replacement (on the average)		
Fuel Cell Stack	63 years	No change
Reformer Catalyst	63 years	No change
Shift Catalyst	63 years	No change
Forced Outage Maintenance		
Desulfurizer Catalyst	2 years	No change
Fuel Vaporizer Cleaning	7 years	1 year
Inspection and Cleaning	14 years	1 year
Oiling and Greasing	14 years	1 year
On-Line Maintenance		
Acid Replenishment	70 years	10 years
Calibration and Adjustment	14 years	1 year
Fuel and Air Filter Replacement	7 years	1 year
Tire Replacement (ozone attack)	5 years	5 years

8.3.3.3 FCPU CAPITAL COST AND MAINTENANCE COST

An estimate of FCPU capital costs by account number is given in Table 8-8. A characterization of the equipment included under each account number may be found in Appendix B.

The data base for the cost estimate is derived from costing studies in support of Westinghouse Electric Corporation programs on FCPU's for Electric Utilities and much smaller On-Site/Integrated Energy Systems. The breath of the data base covers the FCPU power size of interest here.

The data base is for prototype units. The estimates here are based on a mature FCPU market with a 1,000 units of cummulative production. For the non-commercial components an experience curve effect was assumed. No experience curve effects were applied to commercially available components, such as pumps, heat exchangers, valves, fans, sensors, etc., even though some cost reduction because of volume production will be experienced.

Experience curve effects have been observed in many types of production processes and they are a measure of the cost reductions that occur with increases in the cummulative size of a production run. These cost reductions reflect the combined effects of improved labor efficiencies, technical and manufacturing improvements, economics of scale, and volume purchasing of components and materials.

Based on analysis of experience curves for similar types of equipment, an 85 percent experience curve was used. An 85 percent experience curve will result in a 15 percent cost reduction when the cummulative number of units is doubled. For a cummulative production of 1,000 FCPU's, the experience curve reduces non-commercial components costs to 20 percent of prototype values.

The estimated capital cost of $160,000 is somewhat more than the $152,000 cost estimate for the basically similar tactical mobile unit for supplying power to a Foreward Air Controller Radar. This was to be expected since the maintenance power unit has more features than the Foreward Air Controller Radar power

TABLE 8-8

60 kW MAINTENANCE POWER CART CAPITAL COST ESTIMATE (1980 $)

Account No.	Item	Cost ($)
1000	Fuel Cell Assembly	$ 23,200
2000	Fuel Processing	32,200
3000	Fuel Delivery	4,200
4000	Water Delivery	7,000
5000	Air Delivery	20,400
6000	Heat Exchangers	30,600
7000	Controls & Instrumentation	6,500
8000	Power Regulators	27,800
9000	Structure	3,600
10000	Cart - Self-Propelled	4,500
	TOTAL	$160,000

unit. It is self-propelled. It supplies 140 pounds per hour of 150 psia steam in addition to electrical power.

A breakdown by account number leading to an estimated total yearly hardware replacement cost of $1,645 is illustrated by Table 8-9. The failure rates per million operating hours are the same as previously presented in Table 8-5.

In constructing Table 8-9, the major subsystems (Account Nos. 1000 through 8000 and 10,000) were assumed to be totally replaced in case of failures. The failed parts were assumed to have a salvage value that ranged from 40 percent of the replacement part for the fuel cell, to 70 percent of the replacement part cost for power regulation.

Replacement part costs of the major subsystems were less costs of valves, ducting, tubing and sensors associated with this subsystem.

Valves, ducting, etc. and the battery were evaluated under the special accounts at the bottom of Table 8-9. Here the failures were treated as individual valve, sensor, etc. replacements with no salvage value for the failed part.

In addition to scheduled maintenance, Table 8-9 indicates that an unscheduled repair because of a unit failure can be expected on the average of every 1.5 years of 600 hours per year operation. It will be noted that over half of the failure rate is because of the battery. On the average, the battery will be replaced every three years and one other component will need unexpected replacement every three years. It is assumed that the battery is used, at least once, every day of the year to start the unit.

The nature of the maintenance skills required would be trained E4 level skills: (1) trouble shoot modular system; (2) replace modules; and (3) return unit to operating condition. These are the same skills required for servicing and repair of the other FCPU's of this study.

The total servicing and maintenance costs, in toto, are estimated as follows:

TABLE 8-9

60 kW MAINTENANCE POWER CART REPLACEMENT HARDWARE COSTS (1980 $)

Account No.	Item	Failure Rate Per 10^6 Hours	Operating Hrs. Per Year	Failures Per Year	Yearly Average Hardware Replacement Cost - $
1000	Fuel Cell Assembly	25.0	600	0.0150	184
2000	Fuel Processing	45.0	600	0.0270	194
3000	Fuel Delivery	7.5	600	0.0045	6
4000	Water Delivery	2.8	600	0.0017	4
5000	Air Delivery	19.0	600	0.0114	116
6000	Heat Exchangers	9.0	600	0.0054	83
7000	Controls & Instrumentation	20.0	600	0.0120	23
8000	Power Regulators	40.0	600	0.0240	171
9000	Structure	Not Applicable - Included under Cart Self-Propelled and Ducting and Tubing			
10000	Cart - Self-Propelled	100.0	600	0.0600	135
Special	Valves and Sensors	191.2	600	0.1147	600
Special	Startup Battery	1000.0	365	0.3650	110
Special	Ducting & Tubing	45.0	600	0.0270	19
	TOTALS			0.6677	1645

Maintenance Crew Size	- Two persons
Costing Rate per Crew	- $42/Hour
Hours of Maintenance and Service	- 16 Hours/Year
Service and Maintenance Labor	- $672/Year
Special Equipment	- None
Hardware Replacement	- $1,645/Year
Return and Replacement Hardware Transportation	- $150/Year
Supplies	- $100/Year
TOTAL	- $2,562/Year

8.3.3.4 UNIT OPERATION COSTS

The model used in estimating the cost of operating presumes the most likely use of these units will be at permanent or at least very long lived temporary bases. The units are very reliable and fuel efficient. They are also larger and heavier than the gas turbine units they would replace. Usage would be as follows. The unit is started and stopped and moved about by one person. The unit is used 300 days per year for an average effective service time of two hours per day, to which must be added 0.4 hour per day of startup and shutdown time. One person attendance is required during the 0.4 hour per day startup and shutdown, but not during actual aircraft servicing, or a total of 240 person hours per year actual attendance is required. During aircraft servicing the average power required of the unit is 48 kW and the fuel consumption is 4.8 gph, including providing 140 pound per hour of air conditioning motive steam. During the startup period the average fuel consumption is 2.4 gph. No fuel is being used during shutdown and secure.

Using the foregoing model, the yearly fuel consumption for a unit would be 3,024 gallons of JP-4.

A rough comparison of the operating costs per year between the FCPU and an A/M32A-60/60A unit for 600 hours of effective servicing is as follows:

	A/M32A-60/60A	FCPU
Transportation Cost	Not Applicable	
Special Equipment Cost	Not Applicable	
Crew Cost[1]	$2,400	$4,800
Fuel Cost[2]	23,985	3,024
TOTAL	$26,385	$7,824

[1] $20 per hour, 240 hours FCPU, 120 hours A/M32A-60/60A

[2] $1.00 per gallon, 39 gal/hr for A/M32A-60/60A

The numbers in the preceding table show a very large cost advantage in using FCPU's instead of A/M32A-60/60A.

8.4 DEVELOPMENT RISK ASSESSMENT

A technical development risk assessment was performed at both the subsystem/major component level and the overall system level. The technology status rating criteria is presented in Table 8-10.

Each subsystem or major component was evaluated with respect to the following factors:

- Current technology status
- Technology rating (Table 8-10 criteria)
- Required technology status to meet design requirements for the proposed applications
- Proposed developmental program to achieve the required technology status
- Estimated developmental effort expressed in terms of man hours of R&D personnel (engineering plus technicians)
- Estimated developmental effort expressed in terms of development dollars (labor and materials)

TABLE 8-10

TECHNOLOGY STATUS RATING CRITERIA

REQUIREMENTS FOR APPLICATION
AT (A) TECHNOLOGY RATING LEVEL

TECHNOLOGY RATING	TECHNOLOGY STATUS	PERFORMANCE DATA BASE	EXTRAPOLATION FROM PERFORMANCE DATA BASE	APPLICATION OR DEVELOPMENT PROGRAMS REQUIREMENTS	R&D PROGRAM CHARACTERISTICS	
					RATIONALE	SUCCESS PROBABILITY
Established (A)	Firm selections can be made. Equipment is commercially available in form required.	Sufficient	None	Minimal, routine applications engineering.	Not Applicable	Not Applicable
Near Term (B)	A number of equipment candidates are identified. Candidates are commercial or near commercial.	Incomplete	Short extrapolations from existing data base are involved.	Confirmatory testing and minimal R&D.	Straight-forward	Virtually Certain
Developmental (C)	Equipment not previously designed, but engineering data base exists for design.	Incomplete; important gaps exist	Large extrapolations from existing data required.	Considerable R&D is required	A credible rationale exists. Alternative avenues are evident.	Good to excellent
Speculative (D)	Equipment not previously designed with major materials, design or manufacturing uncertainties.	Sparse or Absent	Highly speculative or not possible.	Extensive R&D is required.	Rationale is not clear, or requires a break-through or serendipity.	Fair to poor.

- Probability of success of the proposed developmental program
- On-going programs or potential design alternatives.

A summary of the development risk assessment is given in Table 8-11. Those areas presenting the greatest risk (and largest development requirements) are as follows:

Fuel Processor

The production of hydrogen by steam reforming of hydrocarbons is a well established technology, and used extensively in the petrochemical industry for the production of ammonia, etc. However, the hydrocarbon feedstock is normally a mixture of low molecular weight compounds, such as natural gas or light naphtha. Heavy naphtha, with a distillation end point up to 350°F and containing up to 30 percent aromatics, has also been used in some instances, primarily in India.

This tactical mobile application calls for the production of hydrogen from JP-4 as the primary fuel. This fuel has a distillation end point of 320°F, contains up to 400 ppm sulfur, and has a high aromatic content. These properties can result in coke formation and sulfur poisoning of the nickel catalyst. Extensive preheating, to lower the sulfur content to less than one ppm and partially crack the larger compounds, is marginal with JP-4 and is deemed uneconomical and impractical with diesel fuel. Since the fuel processor must be capable of utilizing either type of fuel, a nonconventional steam reformer design is required.

Based on the results of an EPRI-sponsored study (Ref. 8-8), the most promising fuel-processing alternatives are high temperature steam reforming and autothermal reforming. Autothermal reforming was chosen as the preferred process for this tactical mobile application because of its compact geometry and rapid response characteristics relative to high temperature steam reforming.

The Department of Energy has sponsored a development program for distillate fuel steam reforming technology. A summary of the status of this program was

TABLE 8-11

DEVELOPMENT RISK ASSESSMENT
AIRCRAFT MAINTENANCE POWER EXAMPLE

SUBSYSTEM/MAJOR COMPONENT	CURRENT TECHNOLOGY STATUS	TECHNOLOGY RATING	REQUIRED TECHNOLOGY STATUS	REQUIRED DEVELOPMENTAL PROGRAM	ESTIMATED MANHOURS (THOUSANDS)	ESTIMATED DEV. COST ($)	PROBABILITY OF SUCCESS	ONGOING PROGRAMS & POTENTIAL ALTERNATIVES
1.0 FUEL PROCESSING								
1.1 Fuel Handling and Storage	Existing on-site facilities and experience with DF-A diesel fuel.	A	No change required.	No development program is required.	0	0	N/A	N/A
1.2 Fuel Vaporizer	Commercial experience in petrochemical industry primarily with direct-fired heaters.	B	Special shell and tube to make use of regenerative heat. Continuous operation without coke formation.	1. Experimental testing to determine rate of coke formation. 2. Detail modifications to reduce coke formation.	4.0	400	Very Good	
1.3 High Temperature Steam Reformer	Extensive commercial experience with conventional steam reforming on fuels from methane to heavy naphtha. Laboratory experience with ATR of No. 2 fuel oil.	C	Stable performance on JP-4 and diesel fuels without coking or sulfur poisoning steam-to-carbon ratio ≤ 4.0. Fuel conversion to carbon oxides $\geq 95\%$.	1. Catalyst testing. 2. Multi-tube reformer testing. 3. Full-scale system evaluation and analysis. 4. Cost study.	20.0	2,000	Very Good	Existing DOE and EPRI sponsored studies on autothermal reforming. HRSR of No. 2 fuel oil. Potential alternative which is also under DOE development.
1.4 Steam Generator for Air-Conditioning Motive Steam	Custom Design	B	Special integration into fuel processing system.	1. Complicates full-scale system evaluation and analysis of Item 1.3.	4.0	400	Very Good	

TABLE 8-11 (Continued)

SUBSYSTEM/MAJOR COMPONENT	CURRENT TECHNOLOGY STATUS	TECHNOLOGY RATING	REQUIRED TECHNOLOGY STATUS	REQUIRED DEVELOPMENTAL PROGRAM	ESTIMATED MANHOURS (THOUSANDS)	ESTIMATED DEV. COST ($)	PROBABILITY OF SUCCESS	ONGOING PROGRAMS & POTENTIAL ALTERNATIVES
2.0 FUEL CELL								
2.1 Fuel Cell Stack	Laboratory and prototype experience. Life tests up to 80,000 hrs. with H_2 fuel. Large, multi-cell stacks being tested for utility applications. 4.8 MW demonstration plant under construction but cooling and cell passages at same pressure.	C	Cell life 40,000 hours. Pressurized (150 psia) cell operation. Cell voltage = 0.67 VDC at current density of 300 amps per ft^2. Minimal acid loss. Low cost design with high reliability cooling passages at low pressure with cells at high pressure.	1. Stack (multi-cell testing to determine issues of thermal expansion, current collection, electrical isolation, manifold seals, flow distribution, acid management, startup/shutdown, and cooling design viability. 2. Basic bipolar plate and special cooling plate development and performance improvement. 3. Pressurized stack, unpressurized cooling development and testing. 4. Cost improvement studies (lower catalyst loadings, manufacturing improvement, etc.)	30.0	3,000	Very Good	Several development programs sponsored by DOE, U. S. Army, EPRI, and various electric utilities. In-house development by potential suppliers. None on low pressure air cooling with high pressure cells.
2.2 Cooling Systems and Fuel Cell Auxiliaries	Existing designs have water, air, and dielectric cooled designs. Laboratory and prototype experience with both atmospheric and pressurized systems.	B	High reliability and low cost. Pressurized (60 psia) operation.	Stack pressurization and cooling issues to be resolved as part of fuel cell stack development. No development effort is recommended for the auxiliary components (blowers, heat exchangers, etc.).	0	0	N/A	N/A

TABLE 8-11 (Continued)

SUBSYSTEM/MAJOR COMPONENT	CURRENT TECHNOLOGY STATUS	TECHNOLOGY RATING	REQUIRED TECHNOLOGY STATUS	REQUIRED DEVELOPMENTAL PROGRAM	ESTIMATED MANHOURS (THOUSANDS)	ESTIMATED DEV. COST ($)	PROBABILITY OF SUCCESS	ONGOING PROGRAMS & POTENTIAL ALTERNATIVES
3.0 POWER CONDITIONING								
3.1 DC-AC Inverter	Existing technology. Package units being developed for photovoltaic and fuel cell applications.	A	High efficiency (90-95%) low cost. Seventeen percent reduction in weight from current technology.	Weight reduction program.	2.0	100	N/A	Suppliers developing standard units for various alternate energy systems.
4.0 BALANCE OF PLANT								
4.1 Instrumentation and Control	Developed for small mobile systems and large (5 MWe) stationary plants. Assumes manned operation.	A	High reliability and safety. Design for attended remote operation.	No developmental program is recommended.	0	0	N/A	N/A
4.2 Turbo-Compressor, Heat Recovery	Conventional technology.	A	Automatic operation. High reliability.	None	0	0	N/A	N/A
4.3 Self-Propelled Cart	Conventional technology.		Light weight, high reliability.	None	0	0	N/A	N/A
5.0 OVERALL SYSTEM	Complete, small (1.5 kWe) units delivered to U. S. Army for premixed methanol/water fuel. Large (5 MWE) stationary system under construction using natural gas fuel. Various levels of experience with intermediate site units. No experience to our knowledge with 150 psia units.	B	High reliability operation/with automatic control. Proper interfacing with load demand and 150 psia turbocompressor unit. Long-life (20 years). Low performance degradation during operating life-time. Capability to handle diesel fuels.	Qualification program and field testing including: 1. Breadboard modules. 2. House development units (2). 3. Field test qualification units (1).	24.0	4,700	Very Good	None to verify this particular design and application requirements.
TOTAL DEVELOPMENT PROGRAM					84.0	10,600		

presented in a recent report by Catalytica Associates, Inc. (Ref. 8-9). Autothermal reforming is receiving the largest share of DOE funding, and development programs are being carried out by United Technologies Corporation (UTC), Englehard Industries, and the Jet Propulsion Laboratories. In addition, analysis-oriented work is being conducted by several other organizations. Research on high temperature steam reforming is included in the Englehard DOE contract. The Electric Power Research Institute (EPRI) has also sponsored several studies of high temperature steam reforming, including contracts with Catalytica, UTC, and Kinetics Technology International Corporation.

It is felt that a further developmental effort is required to qualify an ATR for Fuel Cell Power Unit service. The areas of concern are:

- Carbon Formation in the Feed Preheater
- Methane Slip (i.e., conversion in reactor)
- Catalyst Stability and Life
- Thermal Response and Start-up Rate
- Integration of Air Conditioner Motive Steam Generator
- Subsystem Cost

The proposed developmental program would include lab-scale catalyst testing and evaluation, a multi-tube reformer test, and a design, analysis, and economic study of a full-scale fuel processing system. Total estimated man hours (engineers plus technicians) required are 24,000. Estimated development cost (including materials) is $2,400,000.

Fuel Cell Stack

The proposed fuel cell operating conditions are:

- Current Density at Peak Load - 300 amps per ft^2
- Cell Temperature - 375°F
- Nominal Cell Pressure - 150 psia

- Cooling Air Pressure - 15 psia
- Cell Voltage at 100 Percent Output - 0.67 VDC
- Active Cell Area - 0.76 ft^2
- Number of Cells - 450
- Output Voltage - 300 VDC
- Reformed JP-4 Fuel

Although phosphoric fuel cells have been tested and operated successfully under similar conditions, several areas require further investigation and development. Most existing PAFC stacks are operated under atmospheric pressure at approximately 350°F with equal pressures in the cell and cooling passages. In addition they are usually fueled by pure hydrogen or a clear, reformed gas derived from methanol or natural gas. The reformed JP-4 fuel gas will be cleaned prior to entering the fuel cell stack, but the effect of trace impurities, such as heavy metals or nitrogen, and the high carbon oxide content require further testing.

A development program is suggested to verify and optimize fuel cell performance, to establish scale-up factors, and to verify the differential pressure cooling concept. The proposed development program would include the following:

- Bipolar and cooling plate development, particularly the latter.
- High temperature, high-pressure electrode development to evaluate low platinum loadings, performance at pressure, effect of JP-4 reformed fuel gas on electrode stability, etc.
- Multi-cell stack testing to determine issues of thermal expansion, current collection, electrical isolation, manifold seals, flow distribution, acid management, other stack-related characteristics, and cooling system viability and structural integrity.

- Pressurized stack development to determine plate tolerances, seal requirements, acid management, etc.
- Cost improvement studies aimed at the potential for lower capital costs by lower catalyst loadings, manufacturing improvements, etc.

Several development programs are presently being conducted on phosphoric acid fuel cell technology. The primary sources of funding at DOE, EPRI, various electric utilities, U. S. Army, and the fuel cell developers. Work is being conducted by Westinghouse/Energy Research Corporation, United Technology Corporation and Englehard Industries. The various applications that these development programs are directed at include:

- Small, Mobile Units for the U. S. Army (3-5 kW)
- On-Site Integrated Energy Systems (40-150 kW)
- Dispersed Utility Power Plants (5-10 MW)

The extent of these programs, and the applicability to the tactical mobile application design, are uncertain at this time. It is estimated that the fuel cell development program just discussed, will be required in addition to the ongoing development programs. The estimated effort is 30,000 man-hours (engineers plus technicians) at a total cost (including materials) of $3,000,000. This effort could be substantially reduced if further development in one of the related programs proves to be directly applicable.

System Integration and Testing

The packaging and integration of the various subsystems/major components into a Fuel Cell Power Unit is developmental in the sense that previous units of the required capacity, reliability, fuel type, etc., have not been built and operated. The requirements for an autothermal reformer and pressurized cell operation (using a turbo-compressor unit) present unique system considerations. In addition, the FCPU must be designed for water recovery. It is therefore suggested that a system verification and qualification program be conducted. The verification program would include construction and testing of the following units:

- Breadboard Modules
- House Development Units (2)
- Full-Scale Field Test Unit

The estimated cost of materials and test apparatus is approximately $2,400,000. Estimated manpower requirements (engineers and technicians) are 24,000 hours. Total developmental cost for the system verification and qualification program is $4,700,000.

The total recommended developmental program, based on the development risk assessment as discussed above, requires 84,000 man-hours of development labor (engineers plus technicians). The total program cost is approximately $10,600,000. These estimates are based on the present status of technology development. Considerable research, development, and testing are presently being conducted or are planned in all areas of appreciable developmental risk. The impact of these programs, most of which are subject to funding review, on the tactical mobile design development risk is highly speculative. The estimated development risk assumes moderate input from these parallel programs. Accelerated development in these areas may substantially reduce the development risk whereas an absence of parallel development will require a larger developmental program.

8.5 LIFE CYCLE COST

The following assumptions were made in computing the cost of the various Life Cycle Cost elements (LCC) for a single FCPU.

RD&D - Total cost of $10,600,000 (Table 8-11) spread over 800 units.
PRODUCTION - Same as estimated capital cost (Table 8-8)
INITIAL SPARES - One-years replacement parts cost from Section 8.3.3.3
FCPU REPLACEMENTS - None

FCPU MAINTENANCE - Cost per year from Section 8.8.3.3
FUEL - Initial 1980 cost - $1/gallon, 5%/year price escalation.
TRANSPORTATION - Cost per year from Section 8.3.3.3
TECHNICAL DATA - Cost from Ref. 8-4 spread over 800 units.
PERIOD OF USE - 20 years from 1980.
COSTS - 1980 $

The LCC elements used are those of (Ref. 8-4) that are applicable to a maintenance power cart.

LCC COST ELEMENTS	20 YEAR COST ($)
R&D	13,250
Production	160,000
Initial Spares	1,650
FCPU Replacements	0
FCPU Maintenance	53,020
Fuel	99,970
Operating Personnel	96,000
Transportation for Repair	4,680
Technical Data	250
TOTAL	428,820

The total cost for 20 years for 800 units is estimated to be $343 million.

The fuel cost alone for an equivalent 1000 A/M32A-60/60A units for the same 20 year cycle would be in excess of $600 million.

Estimates of the 20 year LCC for an A/M32A-60/60A unit are given in the following table. The fuel cost is taken as $1 per gallon escalated at five percent per year. The maintenance cost per year and the average yearly fuel consumption for the A/M32A-60/ 60A are derived from Ref. 8-4.

LCC COST ELEMENTS	20-YEAR COST ($)
R&D	0
Production	0
Initial Spares	0
A/M32A-60/60A Replacement	32,400
Maintenance	137,200
Fuel	618,880
Operating Personnel	48,000
Transportation for Repair	11,920
Technical Data	0
TOTAL	$848,400

For the 1000 A/M32A-60/60A units required to service F-15 and F-16 aircraft, the total 20 year life cycle cost becomes $848 million.

Substitution of the required 800 FCPU's to provide the same service will save $505 million over the 20 year cycle. This is an average savings per FCPU of $631,000.

The fuel cost savings alone per FCPU amounts to $670,000, but this is reduced on a total LCC basis because of the production and development costs associated with the FCPU.

8.6 CONCLUSIONS

A self-propelled, cogeneration 60 kW FCPU for tactical mobile use has been designed. The design was executed to a generic application specification based primarily on diesel electric generators as used for mobile electric power. The FCPU more than meets the requirements of the generic application specification.

The specific application of the Air Force for the FCPU is that of providing ground support maintenance power, air conditioning, and starting air for tactical aircraft. Currently, the motive power for these ground support services in provided by the gas turbine A/M 32A-60/60A ground support cart.

The FCPU was designed to supply motive power for maintenance electricity and air conditioning. The design of the FCPU is the same, essentially, as that previously constructed for providing electric power to a Foreward Air Controller Radar. Two features have been added over the Foreward Air Controller Radar power unit. These are: self-propelled cart mounting and the capability of providing 150 psia steam for export. The FCPU was designed to produce up to 66 kW (10% overload), or a continuous basis, and 140 pounds per hour of 150 psia motive steam to an absorption air conditioner. The absorption air conditioner would occupy a separate cart. This approach is similar in concept to that currently used with the A/M 32A-60/60A cart where air is provided to a separate air cycle refrigeration cart. The A/M 32A-60/60A cart would be retained for air starting duty.

The concept advanced does complex the ground support power supply situation by increasing the number of cart types to be provided from two to three. However, the total fuel savings and hance, cost savings over a 20 year life span, are very large.

The savings are partly because of the improved energy efficiency of FCPU relative to open cycle gas turbines. Equally important to fuel savings is the concept of supplying maintenance/air conditioning power from a source separate from that used to supply air for aircraft engine starting.

There is a large difference between the power required for air starting and that required for maintenance/air conditioning if each power element is supplied with equal energy efficiency. Approximately 200 kW of power is required to provide starting air. The time that starting air is required is a very small fraction of the total power demand elapsed time. At present, when starting air is not required, the available air supply from the gas turbine is fed to the air cycle refrigerator to provide air conditioning. During the electric power plus air conditioning power demand time period the average effective power output of the gas turbine decreases to about 175 kW from 200 kW. This is still a very large power output relative to that needed if maintenance/air conditioning power is supplied most efficienctly. Using an FCPU supplying electric power and motive steam to an absorption air conditioner, the average effective output of the FCPU need be only about 50 kW. The net result is that the gas turbine-air cycle refrigeration combination uses an average of 39 gph (Ref. 8-4) of JP-4 fuel, whereas the FCPU adsorption refrigeration scheme will require only 4.8 gph for equivalent services.

Even though the utilization of the power cart in maintenance service is expected to be only 50 hours per month, fuel cost savings per FCPU cart, over A/M32A-60/60A use in 20 years, is estimated at $670,000. The complete 20 year LCC savings are slightly smaller. They are estimated at $630,000 per FCPU over equivalent A/M32A-60/60A service. If the total number of FCPU's required to service F-15 and F-16 aircraft is taken as 800, the total 20 year LCC savings would be $505 million.

The reason that the LCC cost savings using FCPU's is only slightly smaller than the fuel savings alone is because of the reduced maintenance costs of an FCPU of 2,000 hours MTBF compared to the 300 hours MTBF A/M32A-60/60A. The reduced maintenance costs of the FCPU almost outweigh the increased costs of development and purchase of new units attributable to FCPU replacement of the A/M32A-60/60A.

It is concluded that, however desirable its simplicity, the current A/M32A-60/60A air cycle refrigeration combination is no longer a viable way of providing aircraft maintenance electricity and air conditioning because of fuel cost. The current ground maintenance power supply system should be replaced by a three piece combination of FCPU, absorption air conditioner, and the A/M32A-60/60A retained and used for aircraft engine starting duty only.

As a "stand-alone development," the R&D cost of the FCPU maintenance power cart is estimated as approximately $11 million. Because of the commonality of the basic FCPU for maintenance power and Foreward Air Controller Radar power, the cost of a combined development of both units will be only slightly more than for the "stand-alone development" of one of them.

APPENDICES
TO REPORT ON:
DESIGN, APPLICATION, AND COST ESTIMATES
OF
FUEL CELL POWER UNITS
FOR
SIX UNITED STATES AIR FORCE GENERIC APPLICATIONS

APPENDIX A-1
SECTION 3.0 REFERENCES

APPENDIX A-1

SECTION 3.0 REFERENCES

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SECTION 4.0 REFERENCES

APPENDIX A-2

SECTION 4.0 REFERENCES

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5-4 Ushiba, K.K., "Assessment of R&D Programs for Fuel Processors for Fuel Cells," Catalytica File No. 3/63, January, 1981.

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APPENDIX A-4
SECTION 6.0 REFERENCES

APPENDIX A-4

SECTION 6.0 REFERENCES

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6-5 Stumpf, Thomas, Lt., and Gary Martin, "Cost Effectiveness of Generator and Air Conditioner Support Equipment Alternatives for F-15 and F-16 Aircraf," Aeronautical Systems Division, Air Force Systems Command, Wright-Patterson AFB, Ohio, Technical Memorandum ENEG-TM-8D-1.

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SECTION 7.0 REFERENCES

APPENDIX A-5
SECTION 7.0 REFERENCES

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APPENDIX B

FCPU EQUIPMENT ACCOUNTS FOR COSTING PURPOSES

APPENDIX B

FCPU EQUIPMENT ACCOUNTS FOR COSTING PURPOSES

The following is a generalized set of equipment groupings by account numbers for costing purposes. A particular FCPU model, probably, will not contain all the equipment groupings listed.

Account No.	Item
1000	Fuel Cell Assembly
1100	Fuel Cell Stacks
1200	Manifolds
1300	Assembly Structure and Enclosures
1400	Ducting, Valves and Sensors
2000	Fuel Processing System
2100	Fuel Reformer
2200	Fuel Vaporizer
2300	Auxiliary Furnaces or Burners
2400	Steam Generators
2500	Shift Reactors
2600	Sulfur Removal Subsystem
2700	Ducts, Pipes, Valves and Sensors
2800	Assemblies Structure and Enclosures
3000	Fuel Delivery System
3100	Storage Tanks
3200	Pumps
3300	Fuel Lines, Valves, and Sensors
4000	Water Delivery System
4100	Storage Tanks
4200	Water Treatment
4300	Pumps
4400	Water Lines, Valves, and Sensors

Account No.	Item
5000	Air Delivery System
5100	Process Air Supply Equipment
5200	Cooling Air Circulator
5300	Cooling Make-Up Air Compressor or Blower
5400	Ducting, Valves, and Sensors
6000	Heat Exchangers
6100	Air Coolers or Condensors
6200	Air Preheater
6300	Recirculation Air Cooler
6400	Heat Exchangers for Cogeneration Heat
6500	Other Heat Exchangers Not Specifically Associated with Other Accounts
7000	Controls and Data Acquisition
7100	Data Acquisition System
7200	Microprocessors and Controllers
7300	Display Panel and Wiring
8000	Electric Power Regulators
8100	Output Power Conditioner
8200	Auxiliary Power Supply to FCPU
8300	Startup Battery
9000	Structure
9100	FCPU Skid or Other Base
9200	Overall Unit Enclosure or Covering
9300	Supports, Brackets, or Bed Plates for Mounting of Subsystems
9400	Thermal or Noise Insulation
9500	Other Miscellaneous Structure
10000	Cart - Self-Propelled
10100	Drive Motor/Engine and Transmission
10200	Frame and Suspension
10300	Instruments and Controls
10400	Wheels, Axles and Steering (Trucks)

APPENDIX C-1A

APPLICATIONS DATA SHEET, W-ADS-1/6

W-ADS-1/6
15 August 1981

APPENDIX C-1A
APPLICATIONS DATA SHEET
Application No. 1/6
MX Shelter Prime Power System
Fuel Cell Power Unit

1.0 SCOPE

This document provides specific requirements and characteristics of the MX Shelter Prime Power System as they apply to an on-site fuel cell power unit. It is intended to identify the system requirements; for fuel cell power unit design characteristics see the Requirements Data Sheet, W-RDS-1/6.

2.0 APPLICATION DESCRIPTION

The USAF MX Weapon System will consist, when completed, of 200 missiles each housed in a linear cluster of 23 shelters. Each of the 4600 shelters requires a continuous electric power supply. This power supply is presently planned as a conventional transmission grid with standby diesel generators as backup. The Fuel Cell Power Units would replace the baseline system. One Fuel Cell Power Unit would be located at each MX shelter, with sufficient shelter-to-shelter interconnect and backup units to provide the required systems availability.

3.0 SYSTEM REQUIREMENTS

3.1 ELECTRIC POWER DEMAND

Steady-state = 15.0 kW DC
Daily Peak = 19.0 kW DC
Max. Peak = 23.0 kW DC

3.2 POWER CHARACTERISTICS

Frequency = 120 VDC
Voltage Regulation = ± 5% VDC

AD-A126 121 U S (UNITED STATES) AIR FORCE FUEL CELL APPLICATION 5/5
ANALYSIS..(U) WESTINGHOUSE ELECTRIC CORP PITTSBURGH PA
ADVANCED ENERGY SYST.. W D POUCHOT ET AL. JAN 82
UNCLASSIFIED WAESD-TIME-3134 AFWAL-TR-82-2004 F/G 10/2 NL

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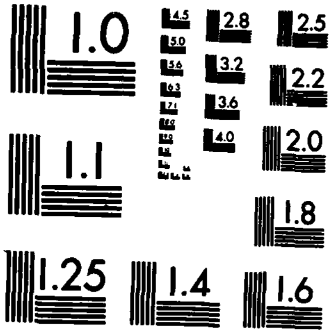
1.0
4.5
5.0
5.6
6.3
7.1
8.0
2.8
3.2
3.6
4.0
2.5
2.2
2.0
1.1
1.8
1.25
1.4
1.6

3.3 AVAILABILITY

Power system availability, at input to shelter, is required to be at least 99.9 percent.

3.4 VOLUME AND WEIGHT RESTRICTIONS

None. Minimize within cost and operational capabilities constraints.

3.5 DESIGN LIFE

Systems should be designed for a minimum useful operating life of 12.5 years.

3.6 FUEL AND FUEL COST

The fuel will be a commercial grade ethanol or methanol

Ethanol

C_2H_5OH = 95.6 Percent (min.)

Other Hydrocarbons = Trace

Water = 4.4%

Gross Heating Value = 12,206 Btu/lb Minimum at 15.5°C

Methanol

CH_3OH = 96 Percent (min.)

Other Hydrocarbons = 1.5 Percent Max.

Water = Balance

Gross Heating Value = 9500 Btu/lb Minimum at 15.5°C

Fuel costs, FOB Los Angeles, California, shall be assumed as follows*:

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*Report to the Management Committee of the Electric Utility Fuel Cell Users Group, prepared by the Fuels and Fuel Processing Subcommittee, September 1980.

$/MM BTU

	1980	1985	1990	2000
High Price Projection	5.79	7.04	8.16	10.97
Low Price Projection	3.11	6.14	7.04	7.04

3.7 OPERATIONAL SCHEDULE

Initial operational power will be required by 1986 and increase to full power (4600 shelters) by 1989.

APPENDIX C-1B

REQUIREMENTS DATA SHEET, W-RDS-1/6

W-RDS-1/6
15 August 1981

APPENDIX C-1B
REQUIREMENTS DATA SHEET
Fuel Cell Power Unit
Unattended Remote, 23 kW DC

1.0 SCOPE

This document summarizes the general requirements and characteristics of a phosphoric acid fuel cell (PAFC) electric power unit for USAF use. It covers a 23 kW, 120 VDC unattended remote application. For application description and requirements see Application Data Sheet, MX Shelter Prime Power System, W-ADS-1. For comparison of the PAFC power unit requirements with existing military standards for diesel engine - driven electric power generators see MIL-STD-633E-18 (MEP-004A, 15 kW, 50-60 Hz, Diesel Engine-Driven Generator Set, Characteristics Data Sheet).

2.0 PHYSICAL REQUIREMENTS

2.1 CLASSIFICATION

Power Rating: 23 kW, 120 VDC
Type: II (Prime)
Class: 2 (Utility)
Mode: IV (DC Output)

2.2 DIMENSIONS

No size restrictions are imposed.

2.3 WEIGHT

No weight limitations are imposed.

2.4 MOBILITY/TRANSPORTABILITY

The fuel cell power unit shall be fully-housed and mounted on a skid base. The entire unit shall be designed for replacement by a backup unit and shall be truck-transportable to a common maintenance facility.

2.5 PAFC POWER UNIT

The PAFC power unit shall consist of a fuel processor, phosphoric acid fuel cell stack, power conditioner, and supporting auxiliary equipment (cooling systems, etc.). Fuel cell power output at full load = 23 kW, 120 VDC.

Fuel storage shall be external to the PAFC Power unit.

2.6 FUELS

Fuel Grade ethanol containing: C_2H_5OH = 95.6% (min.)
Other Hydrocarbons = Trace
Water = 4.4%
Gross Heating Value = 12,206 Btu/lb (minimum) at 15.5°C

Fuel Grade Methanol CH_3OH = 96% (Min)
Other Hydrocarbons = 15% (Max.)
Water = Balance
Gross Heating Value = 9,500 Btu/lb at 15.5°C

2.7 ELECTRICAL

Capable of parallel operation. NEMA Type 2, driptight enclosure.

2.8 VOLTAGE CONNECTION

120 VDC, 2 Wire

2.9 PROTECTIVE DEVICES

Short circuit protection. Overvoltage protection. High temperature control. Low fuel level alarm. Others, as may be required by the fuel processor and PAFC subsystem.

2.10 INSTRUMENTATION

Complete instrumentation shall be included to permit remote control and status indication of the power unit.

3.0 FUNCTIONAL /OPERATIONAL REQUIREMENTS

3.1 RELIABILITY

Mean Time Between Failures (MTBF) = 3,000 hours MX application only
1,000 hours as a generic unit

3.2 FUEL CONSUMPTION AND UNIT HEAT RATE

Fuel consumption from 65 percent to rated load (23 kW) shall not exceed a unit heat rate of 10,000 Btu per kilowatt-hour.

3.3 ELECTRICAL PERFORMANCE

	Voltage
Steady-State Stability (Variation)	
Short Term (30 sec)	2% Bandwidth
Long Term (4 hours)	2% Bandwidth
Transient Performance	
Application of Rated Load*	30% Dip
Recovery	2 Seconds
Rejection of Rated Recovery Load**	40% Rise
Recovery	2 Seconds
Regulation	3%
DC Voltage Ripple	5.5%

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* For MX Application 14.5 kW to 23 kW

** For MX Application 19.5 kW to 16.5 kW

3.4 ELECTROMAGNETIC INTERFERENCE

Suppression to MIL-STD-461 limits.

3.5 STARTUP AND RESPONSE TIME

Cold start to max. power = 1 hour at ambient temperature of -20°F (-28.9°C)
Min. power to max. power = 2 seconds

4.0 ENVIRONMENTAL REQUIREMENTS

4.1 ENVIRONMENTAL CONDITIONS

Ambient temperatures from minus 25°F (-31.7°C) to plus 107°F (+41.7°C) for generic unit

Ambient temperatures from minus 25°F (-31.7°C) to plus 120°F (+48.9°C) for MX unit

Altitude to 5,000 feet above sea level for generic unit

Altitude to 7,000 feet above sea level for MX unit

4.2 SHOCK AND ROUGH HANDLING

Ten mph railroad impact. Twelve inch drop. Six inch end drop. Truck and trailer transportation.

4.3 ATTITUDE

Operate with base level or inclined no more than 15 degrees from level.

4.4 NOISE LEVEL

70 dbA at 25 feet (specified)

5.0 LIFETIME REQUIREMENTS

Power unit useful life = 20 years.

Time between major overhauls:

Fuel Cell Stack = 40,000 Operating Hours
Reformer = 10 Years

Continuous operation without major maintenance = 5,000 hours.

6.0 REFERENCE DOCUMENTS

MIL-STD-1332B

MIL-STD-633E

MIL-STD-633E-17 (MEP-414A)

MIL-STD-633E-18 (MEP-004A)

MIL-G-52884/GEN

MIL-G-52884/2

MIL-STD-461A

APPENDIX C-2
REQUIREMENTS DATA SHEET W-RDS-2

APPENDIX C-2

REQUIREMENTS DATA SHEET
FUEL CELL POWER UNIT

Attended Remote, 60 KW, 60 Hz

1.0 SCOPE

This document summarizes the general requirements of a phosphoric acid fuel cell power unit (FCPU) for USAF use. It covers a 60 kWe, 60 Hz attended remote application. For comparison of the PAFC requirements data with existing military standards for alternate generator sets, see MIL-STD-633E-25 (MEP-105A, 60 kW, 50-60 Hz, Diesel Engine - Driven Generator Set), MIL-STD-633E-27 (MEP-404A, 60 kW, 400 Hz, Gas Turbine Engine - Driven Generator Set), and MIL-G-5288418 (Diesel Engine Generator Set, 60 kW, 50/60 Hz, Utility, Tactical). Also, see MIL-STD-705 (Generator Sets, Engine Driven, Methods of Tests and Instruction) for further definition of terms and tests.

2.0 PHYSICAL REQUIREMENTS

2.1 CLASSIFICATION

Power Rating: 60 kW @ 0.8 power factor, 60 Hz, 120/208 V, 240/416 V
Type: II (prime)
Class: 2 (utility)
Mode: I (50/60 Hz)

2.2 DIMENSIONS

Maximum dimensions: 78 in. x 66 in. x 68 in. (Power Generator)
Maximum volume: 200 cubic feet (Power Generator)

2.3 WEIGHT

Maximum allowable weight (excluding fuel) = No specified limit. Minimize as much as possible.

2.4 MOBILITY/TRANSPORTABILITY

Power unit shall be shop-assembled to the maximum extent. Field assembly shall consist of module interconnect only. Lifting and tie-down attachments shall be provided. Air transportability in C-130 or C-141 aircraft required.

2.5 PAFC POWER UNIT

Phosphoric acid fuel cell electric power system consisting of a fuel processor, fuel cell stack (electrochemical generator), power conditioner, and supporting auxillary equipment. Fuel cell power unit output at full load = 6[illegible] kWe (AC) at 0.8 power factor, 60 Hz, 24 VDC electric start. Fuel tank shall [illegible] external to the FCPU.

2.6 FUEL

Primary: DF-A, Arctic grade diesel Fuel oil, Federal Spec. VV-F-800B.
Alternate Fuel: JP-4, aviation turbine fuel, MIL-T-5624.

2.7 ELECTRICAL

Self-commutating design. Capable of parallel operation. NEMA type 2, driptight enclosure.

2.8 VOLTAGE CONNECTION

60 Hz: 120/208V, 3 phase, 4 wire. 240/416V, 3 phase, 4 wire.
DC: 24V, 2 wire.

2.9 PROTECTIVE DEVICES

Short circuit protection. Overvoltage protection. High temperature control. Low fuel level cut-off switch. Ground fault protection. Others, as required by fuel reformer and PAFC subsystem.

2.10 INSTRUMENTATION AND OPERATION

Instrumentation shall include voltmeters, ammeters, temperature indicators, pressure gages, etc., as required for operation and control of the power system. Operation shall be automatic and designed for minimal operator requirements. Full-time operators shall not be required.

3.0 FUNCTIONAL/OPERATIONAL REQUIREMENTS

3.1 RELIABILITY

Mean Time Between Failures (MTBF): 1500 hours (specified)

3.2 FUEL CONSUMPTION AND UNIT HEAT RATE

Not to exceed five (5) gph at rated load, or a specific electrical output of 12.0 kilowatt-hours per gallon. Specified unit heat rate shall be less than 12,000 Btu per kilowatt-hour, based on DF-A Fuel with HHV = 133,500 Btu per gallon.

3.3 ELECTRICAL PERFORMANCE

	Voltage	Frequency
Steady-state stability (variation)		
Short term (30 sec)	0.5% Bandwidth	0.25% Bandwidth
Long term (4 hours)	0.5% Bandwidth	0.25% Bandwidth
Transient performance		
Application or rated load	15% Dip	1.5% Undershoot
recovery	0.1 Sec	1 Sec.
Rejection of rated load	15% Rise	1.5% Overshoot
recovery	0.1 Sec.	1 Sec.
Application of simulated motor load	30% Dip	
recovery	0.15 Sec.	
Total Harmonic Distortion	5%	
Individual Harmonic	1.5%	
Regulation	0.75%	0.25%

3.4 ELECTROMAGNETIC INTERFERENCE

Suppressed to the requirements of part 9 of MIL-STD-461.

3.5 START-UP AND RESPONSE TIME

Cold start to max. power = 1 hour at ambient temperature of -20°F (-28.9°C).
Hot standby to max. power = 2 minutes (requires 24 hour electrical preheating).
Min. power to max. power = 1 second.

4.0 ENVIRONMENTAL REQUIREMENTS

4.1 ENVIRONMENTAL CONDITIONS

Ambient temperatures from +85°F (29.4°C) to -65°F (-53.9°C). Altitude up to 10,000 feet above sea level. FCPU to be located inside of a shelter.

4.2 SHOCK AND ROUGH HANDLING

This set shall not be damaged by rough handling which could be encountered during rail, truck, aircraft and helicopter transportation.

4.3 ATTITUDE

Operate with base level.

4.4 NOISE LEVEL

84 dbA at 4 meters (specified).

5.0 LIFETIME REQUIREMENTS

Power System Useful Life = 20 years
Time Between Major Overhauls
  Fuel Cell Stack = 5 years
  Fuel Reformer = 5 years
Continuous Operation without major maintenance = 5,000 hours

6.0 REFERENCE DOCUMENTS

MIL-STD-1332B
MIL-STD-633E
MIL-STD-633E-25 (MEP-105A)
MIL-STD-633E-27 (MEP-404A)
MIL-G-52884/GEN
MIL-T-5624L
MIL-G-38195C and Amendment
MIL-STD-705
MIL-STD-461
Fed. Spec. VV-F-800B

APPENDIX C-3
REQUIREMENTS DATA SHEET, W-RDS-3
(FUEL CELL POWER UNIT
ATTENDED REMOTE, 100 KW, 60 Hz)

W-RDS-3
1 June 1981
Sheet 1 of 5

REQUIREMENTS DATA SHEET

Fuel Cell Power Unit
Attended Remote, 100 KW, 60 Hz

1.0 SCOPE

This document summarizes the general requirements of a phosphoric acid fuel cell power unit (FCPU) for USAF use. It covers a 100 kWe, 60 Hz attended remote application. For comparison of the PAFC requirements data with existing military standards for alternate generator sets, see MIL-STD-633E-30 (MEP-007B, 100 KW, 50-60 Hz, Diesel Engine - Driven Generator Set), MIL-STD-633E-27 (MEP-404A, 60 KW, 400 Hz, Gas Turbine Engine - Driven Generator Set), and MIL-G-5288418 (Diesel Engine Generator Set, 60 kW, 50/60 Hz, Utility, Tactical). Also, see MIL-STD-705 (Generator Sets, Engine Driven, Methods of Tests and Instructions) for further definition of terms and tests.

2.0 PHYSICAL REQUIREMENTS

2.1 CLASSIFICATION

Power Rating: 100 KW @ 0.8 power factor, 60 Hz, 120/208 V, 240/416 V
Type: II (prime)
Class: 2 (utility)
Mode: I (50/60 Hz)

2.2 DIMENSIONS

Maximum dimensions: 10 ft x 7 ft x 6 ft
Maximum volume: 420 cubic feet

2.3 WEIGHT

Maximum allowable weight (excluding fuel) = No specified limit. Minimize as much as possible.

2.4 MOBILITY/TRANSPORTABILITY

Power unit shall be shop-assembled to the maximum extent. Field assembly shall consist of module interconnect only. Lifting and tie-down attachments shall be provided. Air transportability in C-130 or C-141 aircraft required.

2.5 PAFC POWER UNIT

Phosphoric acid fuel cell electric power system consisting of a fuel processor, fuel cell stack (electrochemical generator), power conditioner, and supporting auxillary equipment. Fuel cell power unit output at full load = 100 kWe (AC) at 0.8 power factor, 60 Hz. 24 VDC electric start. Fuel tank shall be external to the FCPU.

2.6 FUEL

Primary: DF-2, Regular grade diesel Fuel oil, Federal Spec. VV-F-800B.
Alternate Fuels: JP-4, aviation turbine fuel, MIL-T-5624.

2.7 ELECTRICAL

Self-commutating design. Capable of parallel operation. NEMA type 2, driptight enclosure.

2.8 VOLTAGE CONNECTION

60 Hz: 120/208V, 3 phase, 4 wire. 240/416V, 3 phase, 4 wire.
DC: 24V, 2 wire.

2.9 PROTECTIVE DEVICES

Short circuit protection. Overvoltage protection. High temperature control. Low fuel level cut-off switch. Ground fault protection. Others, as required by fuel reformer and PAFC subsystem.

2.10 INSTRUMENTATION

Instrumentation shall include voltmeters, ammeters, temperature indicators, pressure gages, etc., as required for operation and control of the power system. Operation shall be automatic and designed for minimal operator requirements. Full-time operators shall not be required.

3.0 FUNCTIONAL/OPERATIONAL REQUIREMENTS

3.1 RELIABILITY

Mean Time Between Failures (MTBF): 1500 hours (specified)

3.2 FUEL CONSUMPTION AND UNIT HEAT RATE

Not to exceed eight (8) gph at rated load, or a specific electrical output of 12.5 kilowatt-hours per gallon. Specified unit heat rate shall be less than 11,000 Btu per kilowatt-hour, based on DF-2 Fuel with HHV = 138,600 Btu per gallon.

3.3 ELECTRICAL PERFORMANCE

	Voltage	Frequency
Steady-state stability (variation)		
Short term (30 sec)	1.0% Bandwidth	0.5% Bandwidth
Long term (4 hours)	2.0% Bandwidth	1.0% Bandwidth
Transient performance		
Application of rated load	15% Dip	4% Undershoot
recovery	0.5 Sec.	2 Sec.
Rejection of rated load	15% Rise	4% Overshoot
recovery	0.5 Sec.	2 Sec.

Application of simulated motor load	30% Dip	
recovery	0.7 Sec.	
Total Harmonic Distortion	5%	
Individual Harmonic	2%	
Regulation	1%	0.3%

3.4 ELECTROMAGNETIC INTERFERENCE

Suppressed to the requirements of part 9 of MIL-STD-461.

3.5 START-UP AND RESPONSE TIME

Cold start to max. power = 1 hour at ambient temperature of -20°F (-28.9°C).
Hot standby to max. power = 2 minutes (requires 24 hour electrical preheating).
Min. power to max. power = 5 seconds.

4.0 ENVIRONMENTAL REQUIREMENTS

4.1 ENVIRONMENTAL CONDITIONS

Ambient temperatures from +85°F (29.4°C) to +32°F (0.0°C). Altitude up to 1000 feet above sea level. FCPU to be located inside of a shelter.

4.2 SHOCK AND ROUGH HANDLING

This set shall not be damaged by rough handling which could be encountered during rail, truck, aircraft and helicopter transportation.

4.3 ATTITUDE

Operate with base level.

4.4 NOISE LEVEL

84 dbA at 4 meters (specified).

5.0 OPERATING LIFETIME

Power System Useful Life = 20 years

Time Between Major Overhauls

- Fuel Cell Stack = 5 years
- Fuel Reformer = 5 years

Continuous Operation without major maintenance = 4,000 hours

6.0 REFERENCE DOCUMENTS

MIL-STD-1332B
MIL-STD-633E
MIL-STD-633E-30 (MEP-007B)
MIL-STD-633E-27 (MEP-404A)
MIL-G-52884/GEN
MIL-T-5624L
MIL-G-38195C and Amendment
MIL-STD-705
MIL-STD-461
Fed. Spec. VV-F-800B

APPENDIX C-4A
APPLICATION DATA SHEET, W-ADS-4

APPENDIX C-4A

APPLICATION DATA SHEET, W-ADS-4

Fuel Cell Power Unit for
Foreward Air Controller Radar System
Tactical Mobile, 60 kW, 400 Hz

1.0 SCOPE

This document summarizes the requirements of a phosphoric acid fuel cell power unit (FCPU) for USAF use as an electric power supply for a Foreward Air Controller Radar System. It covers a 60 kWe, 400 Hz tactical mobile application. For comparison of the PAFC requirements data with existing military standards for alternate generator sets, see MIL-STD-633E-26 (MEP-115A, 60 kW, 400 Hz, Diesel Engine - Driven Generator Set), MIL-STD-633E-27 (MEP-404A, 60 kW, 400 Hz, Gas Turbine Engine - Driven Generator Set), and MIL-G-38195C and Amendment (Gas Turbine Engine Generator Set, 60 kW, 400 Hz, General Purpose). Also, see MIL-STD-705 (Generator Sets, Engine Driven, Methods of Tests and Instructions) for further definition of terms and tests.

2.0 PHYSICAL REQUIREMENTS

2.1 CLASSIFICATION

Power Rating: 60 kW @ 0.8 power factor, 400 Hz, 120/208 V, 240/416 V
Type: I (tactical)
Class: 1 (precise)
Mode: II (400 Hz)

2.2 DIMENSIONS

Maximum dimensions: 60 in. x 36 in. x 30 in.
Maximum volume: 36 cubic feet

2.3 WEIGHT

Maximum allowable weight (excluding fuel) = 950 lbs. (431 Kg).

2.4 MOBILITY/TRANSPORTABILITY

Power unit shall be fully housed and mounted on a skid base. Lifting and tie-down attachments shall be provided. Air transportability in C-130 or C-141 aircraft required. Power units shall be capable of vertical stacking up to three units high.

2.5 PAFC POWER UNIT

Phosphoric acid fuel cell electric power system consisting of a fuel processor, fuel cell stack (electrochemical generator), power conditioner, and supporting auxiliary equipment. Fuel cell power unit output at full load = 60 kWe (AC) at 0.8 power factor, 400 Hz. 24 VDC electric start. Fuel tank capacity = 50 gallons (approximately 8 hours at rated load).

2.6 FUEL

Primary: JP-4, aviation turbine fuel, MIL-T-5624.
Alternate Fuels: JP-5, JP-8, DF-1, DF-2, DF-A. Maximum multifuel capability preferred.

2.7 ELECTRICAL

Self-commutating design. Capable of parallel operation. NEMA type 2, driptight enclosure.

2.8 VOLTAGE CONNECTION

400 Hz: 120/208V, 3 phase, 4 wire. 240/416V, 3 phase, 4 wire.
DC: 24V, 2 wire.

2.9 PROTECTIVE DEVICES

Short circuit protection. Overvoltage protection. High temperature control. Low fuel level cut-off switch. Ground fault protection. Others, as required by fuel reformer and PAFC subsystem.

2.10 INSTRUMENTATION

Instrumentation shall include voltmeters, ammeters, temperature indicators, pressure gages, etc., as required for operation and control of the power system. Remote sensing and remote control capability.

3.0 FUNCTIONAL/OPERATIONAL REQUIREMENTS

3.1 RELIABILITY

Mean Time Between Failures (MTBF): 1500 hours (specified)

3.2 FUEL CONSUMPTION AND UNIT HEAT RATE

Not to exceed 8.5 gph at rated load.

3.3 ELECTRICAL PERFORMANCE

	Voltage	Frequency
Steady-state stability (variation)		
Short Term (30 sec)	0.5% Bandwidth	0.25% Bandwidth
Long term (4 hours)	0.5% Bandwidth	0.25% Bandwidth
Transient performance		
Application of rated load	15% Dip	1.5% Undershoot
recovery	0.1 Sec.	1 Sec.
Rejection of rated load	15% Rise	1.5% Overshoot
recovery	0.1 Sec.	1 Sec.
Application of simulated motor load	30% Dip	
recovery	0.15 Sec.	
Total Harmonic Distortion	5%	
Individual Harmonic	1.5%	
Regulation	0.75%	0.25%

3.4 ELECTROMAGNETIC INTERFERENCE

Suppressed to the requirements of part 9 of MIL-STD-461.

3.5 START-UP AND RESPONSE TIME

Cold start to max. power = 1 hr. at ambient temperature of -20°F (-28.9°C).
Hot standby to max. power = 2 minutes (requires 24 hour electrical preheating).
Min. power to max. power = 1 second.

4.0 ENVIRONMENTAL REQUIREMENTS

4.1 ENVIRONMENTAL CONDITIONS

Ambient temperature from +125°F (51.7°C) to -65°F (-53.9°C).
Altitude up to 8,000 feet above sea level.

4.2 SHOCK AND ROUGH HANDLING

This set shall not be damaged by rough handling which could be encountered during rail, truck, aircraft and helicopter transportation. It shall be designed to withstand an 18 inch end drop and a 10 mph railroad impact.

4.3 ATTITUDE

Operate with base level or inclined no more than 15 degrees from level.

4.4 NOISE LEVEL

Inaudible at 100 meters (328 feet) when operating at any load level.

5.0 LIFETIME REQUIREMENTS

5.1 OPERATING LIFETIME

Power System Useful Life - 20 years
Time Between Major Overhauls
    Fuel Cell Stack = 5 years
    Fuel Reformer = 5 years
    Continuous Operation without major maintenance = 5,000 hours.

6.0 REFERENCE DOCUMENTS

MIL-STD-1332B

MIL-STD-633E

MIL-STD-633E-26 (MEP-115A)

MIL-STD-633E-27 (MEP-404A)

MIL-G-52884/GEN

MIL-T-5624L

MIL-G-38195C and Amendment

MIL-STD-705

MIL-STD-461

APPENDIX C-4B
REQUIREMENTS DATA SHEET, W-RDS-4

APPENDIX C-4B

REQUIREMENTS DATA SHEET, W-RDS-4

Fuel Cell - Driven Generator Set
Application No. 4
Tactical Mobile, 60 kW, 400 Hz

1.0 SCOPE

This document summarizes the general requirements of a phosphoric acid fuel cell (PAFC) electric power generator set for U. S. Military use. It covers a 60 kWe, 400 Hz tactical mobile application. For comparison of the PAFC requirements data with existing military standards for alternate generator sets, see MIL-STD-633E-26 (MEP-115A, 60 kW, 400 Hz, Diesel Engine Driven Generator Set), MIL-STD-633E-28 (MEP-356A, 60 kW, 400 Hz, Gas Turbine Engine - Driven Generator Set), and MIL-G-38195C, Amendment 1 (Gas Turbine Engine Generator Set, 60 kW, 400 Hz, General Purpose).

2.0 PHYSICAL REQUIREMENTS

2.1 CLASSIFICATION

Power Rating: 60 kW @ 0.8 power factor, 400 Hz, 120/208 V
Type: I (tactical)
Class: 1 (precise)
Mode: I (400 Hz)

2.2 DIMENSIONS

Maximum dimensions: 90 in. x 72 in. x 67 in.
Maximum volume: 250 cubic feet

2.3 WEIGHT

Maximum allowable weight (excluding fuel) = 4,000 lbs. (1800 Kg).

2.4 MOBILITY/TRANSPORTABILITY

Generator set shall be fully housed and mounted on a skid base. Lifting and tie-down attachments shall be provided. Air transportability in C-130 or C-141 aircraft required.

2.5 ENGINE

Phosphoric acid fuel cell electric power system consisting of a fuel processor, fuel cell (electrochemical generator), and power conditioning system. Fuel cell power output at full load = 66 kWe, 300 VDC. Power conditioner output at full load = 60 kWe (AC) at 0.8 power factor, 400 Hz. 24 VDC electric start. Fuel tank capacity = 50 gallons (approximately 8 hours at rated load).

2.6 FUEL

Primary: JP-4, aviation turbine fuel, gasoline type, MIL-T-5624.
Alternate Fuels: JP-5, JP-8, DF-1, DF-2, DF-A.

2.7 ELECTRICAL

Self-commutating design. Capable of parallel operation. NEMA type 2, driptight enclosure.

2.8 VOLTAGE CONNECTION

400 Hz: 120/208V, 3 phase, 4 wire.
DC: 28V, 2 wire.

2.9 PROTECTIVE DEVICES

Short circuit protection. Overvoltage protection. High temperature control. Low fuel level cut-off switch. Others, as required by fuel reformer and PAFC subsystem.

2.10 INSTRUMENTATION

Instrumentation shall include voltmeters, ammeters, temperature indicators, pressure gages, etc. as required for operation and control of the power system.

3.0 FUNCTIONAL/OPERATIONAL REQUIREMENTS

3.1 RELIABILITY

Mean Time Between Failures (MTBF): 1500 hours

3.2 FUEL CONSUMPTION

Not to exceed six (6) gph at rated load.

3.3 ELECTRICAL PERFORMANCE

	Voltage	Frequency
Steady-state stability (variation)		
Short term (30 sec)	+ 1%	+ 0.5%
Long term (4 hours)	+ 2%	+ 1%
Transient performance		
Application of rated load	12% Dip	1.5% Undershoot
recovery	0.5 Sec.	1 Sec.
Rejection of rated load	12% Rise	1.5% Overshoot
recovery	0.5 Sec.	1 Sec.
Application of simulated motor load	25% Dip	
recovery	0.7 Sec.	
Total Harmonic Distortion	5%	
Individual Harmonic	2%	

3.4 START-UP AND RESPONSE TIME

Cold start to max. power = 1 hour at ambient temperature of -20°F (-28.9°C).
Hot standby to max. power = 2 minutes (allows 24 hour electrical preheating).
Min. power to max. power = 15 seconds.

4.0 ENVIRONMENTAL REQUIREMENTS

4.1 ENVIRONMENTAL CONDITIONS

Ambient temperatures from +125°F (51.7°C) to -65°F (-53.9°C).
Altitude up to 10,000 feet above sea level.

4.2 SHOCK AND ROUGH HANDLING

This set shall not be damaged by rough handling which could be encountered during rail, truck, aircraft and helicopter transportation. It shall be designed to withstand a 12 inch end drop.

4.3 ATTITUDE

Operate with base level or inclined no more than 15 degrees from level.

4.4 NOISE LEVELS

84 dbA at 4 meters.

5.0 LIFETIME REQUIREMENTS

Power System Useful Life = 20 years
Time Between Major Overhauls =
    Fuel Cell Stack = 5 years
    Fuel Reformer = 5 years
Continuous Operation without Major Maintenance - 5000 hours.

6.0 REFERENCE DOCUMENTS

MIL-STD-1332B
MIL-STD-633E
MIL-STD-633E-26 (MEP-115A)
MIL-STD-633E-28 (MEP-356A)
MIL-G-52884/GEN
MIL-T-5624L
MIL-G-38195C

APPENDIX C-5

Requirements Data Sheet, W-RDS-5

APPENDIX C-5

REQUIREMENTS DATA SHEET, W-RDS-5

Fuel Cell - Driven Generator Set
Application No. 5
Tactical Mobile, 60 kW, 400 Hz
Aircraft Ground Support Power Cart

1.0 SCOPE

This document summarizes the general requirements of a phosphoric acid fuel cell (PAFC) electric power generator set for USAF use. It covers a 60 kW, 400 Hz tactical power cart for aircraft ground support use. The power cart, in conjunction with a companion Air Conditioner Cart, produces electrical power and cooling air required for performing maintenance on tactical fighter aircraft. The Air Conditioner Cart utilizes superheated steam from the power cart to produce a minimum of 7.5 tons of refrigeration by absorption cooling. Due to its low fuel consumption and quiet operation, the PAFC ground support cart is intended for extended maintenance tasks. It is a maintenance cart only, and no compressed air is available for air-operated engine starting.

For comparison of the PAFC requirements data with existing military standards for alternate generator sets, see MIL-STD633E-26 (MEP-11A, 60 kW, 400 Hz, Diesel Engine - Driven Generator Set), MIL-STD-633E-28 (MEP-356A, 60 kW, 400 Hz, Gas Turbine Engine - Driven Generator Set), and MIL-G-38195C, Amendment I (Gas Turbine Engine Generator Set, 60 kW, 400 Hz, General Purpose).

2.0 PHYSICAL REQUIREMENTS

2.1 CLASSIFICATION

Power Rating:	60 kW @ 0.3 power factor, 400 Hz, 120/208 V 140 pounds per hour steam at 175 psia/375°F
Type:	I (tactical)
Class:	I (precise)
Mode:	II (400 Hz)

2.2 DIMENSIONS

Maximum Dimensions:	110 in x 67 in x 72 in
Maximum Volume:	310 cubic feet

2.3 WEIGHT

Maximum allowable weight (excluding fuel) = 5000 lbs (2275 kg).

2.4 MOBILITY/TRANSPORTABILITY

Generator set shall be fully housed and trailer mounted on an electric self-propelled cart. Lifting and tie-down attachments shall be provided. Air transportability in C-130 or C-141 aircraft required.

2.5 ENGINE

Phosphoric acid fuel cell electric power system consisting of a fuel processor, fuel cell (electrochemical generator), power conditioning system, and auxiliary steam generator. Fuel cell power output at full load = 66 kW, 300 VDC. Power conditioner output at full load = 60 kW (AC) at 0.8 power factor, 400 Hz steam generator output at full load - 140 lbs per hour (net) which is sufficient to produce a minimum of 7.5 tons of refrigeration from an absorption air conditioning system.

2.6 FUEL

Primary:	JP-4, aviation turbine fuel, gasoline type, MIL-T-5624.
Alternate Fuels:	JP-5, JP-8, DF-1, DF-2, DF-A

2.7 ELECTRICAL

Self commutating design. Capable of parallel operation. NEMA Type 2, driptight enclosure.

2.8 VOLTAGE CONNECTION

400 Hz	120/208 V, 3 phase, 4 wire
DC:	28 V, 2 wire

2.9 PROTECTIVE DEVICES

Short circuit protection. Overvoltage protection. High temperature control. Low fuel level cut-off switch. Others, as required by fuel reformer and PAFC subsystem.

2.10 INSTRUMENTATION

Instrumentation shall include voltmeters, ammeters, temperature indicators, pressure gages, etc., as required for operation and control of the power system.

3.0 FUNCTIONAL/OPERATIONAL REQUIREMENTS

3.1 RELIABILITY

Mean Time Between Failures (MTBF): 1500 hours

3.2 FUEL CONSUMPTION

Not to exceed seven (7) gph at rated load.

3.3 ELECTRICAL PERFORMANCE

	Voltage	Frequency
Steady-state stability (variation)		
Short term (30 sec)	+1%	+0.5%
Long Term (4 hours)	+2%	+1.0%
Transient performance		
Application of rated load	12% Dip	1.5% Undershoot
recovery	0.5 Sec	1 Sec

Rejection of rated load	12% Dip	1.5% Overshoot
recovery	0.5 Sec	1 Sec
Application of simulated	0.7 Sec.	
motor load	25% Dip	
recovery	0.7 Sec	
Total Harmonic Distortion	5%	
Individual Harmonic	2%	

3.4 START-UP AND RESPONSE TIME

Cold start to max power = 1 hour at ambient temperature of -20°F (-28.9°C)

Hot standby to max power = 2 minutes (requires 24 hour electrical preheating)

4.0 ENVIRONMENTAL REQUIREMENTS

4.1 ENVIRONMENTAL CONDITIONS

Ambient temperature from +125°F (51.7°C) to -65°F (-53.9°C) Altitude up to 10,000 feet above sea level.

4.2 SHOCK AND ROUGH HANDLING

This set shall not be damaged by rough handling which could be encountered during rail, truck, aircraft and helicopter transportation. It shall be designed to withstand a twelve inch end drop.

4.3 ATTITUDE

Operate with base level or inclined no more than 15 degrees from level.

4.4 NOISE LEVEL

84 dbA at 4 meters

5.0 LIFETIME REQUIREMENTS

Power system useful life = 20 years

Time between major overhauls =
  Fuel Cell Stack = 5 years
  Fuel Reformer = 5 years

Continuous operation without major maintenance = 5000 hours

6.0 REFERENCE DOCUMENTS

MIL-STD-1332B
MIL-STD-633E
MIL-STD-633E-26 (MEP-115A)
MIL-STD-633E-28 (MEP-356A)
MIL-G-52884/GEN
MIL-T-5624L
MIL-G-38195C

APPENDIX D-1
MX FACILITIES DETAILS

APPENDIX D-1

MX FACILITIES DETAILS

D-1.1 MX ACRONYMS

ASC - Area Support Center
BMO - Ballistic Missile Office
BPS - Baseline Power System
C^3 - Command, Control, Communication
CMF - Cluster Maintenance Facility
DAA - Designated Assembly Area
DDA - Designated Deployment Area
DTN - Designated Transportation Network
ECS - Environmental Control System
G&C - Guidance and Control
MOSE - Mobile Operational Support Equipment
MX - Missile X
OB - Operating Base
OBTS - Operational Base Test Site
O&S - Operation and Support
OSE - Operational Support Equipment
PLU - Preservation of Location Uncertainty
PS - Protective Structure
PSS - Physical Security System
QD - Quantity Distance
RCG - Representative Cluster Group
ROSE - Resident Operational Support Equipment
ROSEE - Resident Operational Support Equipment Enclosure
RSS - Remote Surveillance Site
SAL - Strategic Arms Limitation
SCADA - Supervisory, Control and Data Acquisition
STML - Separate Transporter and Mobile Launcher
UPS - Uninterruptible Power Supplies
VHMPS - Verifiable Horizontal Multiple Protective Structure

D-1.2 MX DETAILS

Cluster Maintenance Facility (CMF)

Each cluster will contain a Cluster Maintenance Facility providing limited checkout and repair capabilities for selected missile system components.

Remote Surveillance Sites (RSS's)

RSS's will provide unmanned, remote detection of shelter threats. There are 183 RSS's planned.

Area Support Centers (ASC's)

Four ASC's are being proposed and are strategically located throughout the deployment area. An ASC will be collacted with each of the two operating bases. Two other ASC's will be located in the Designated Deployment Area. ASC's will provide facilities to support security alert response teams and their associated helicopters, crews, and maintenance personnel.

Designated Deployment Area (DDA)

The DDA encompasses the area in which the MX weapons systems is deployed. The DDA applies to all the shelter, RSS, CMF, and ASC sites that are not co-located with OBs.

Operational Base Test Site (OBTS)

The OBTS is located in close proximity to Operating Base No. 1.

The function of the OBTS is to test each component of the MX weapon system under actual field operating conditions. The OBTS contains three shelters, one CMF, one RSS and a large test support building.

Designated Assembly Area (DAA)

The DAA will be collocated with Operating Base No. 1. The DAA will provide a launcher assembly area, major maintenance facilities, and capabilities to support security, storage, munitions, and depot requirements at the depot level.

Operating Bases (OB's)

Five sites are being considered for the MX system Operating Bases. For purposes of this study, it will be assumed that there are two OB's; they are OB No. 1 and OB No. 2 located at Beryl, Utah and Ely, Nevada, respectively.

Operating Base No. 1 will accommodate maintenance, supply, offloading facilities, an airfield complex and base/community support complexes. Associated with OB No. 1 is a DAA, an OBTS, and an ASC, all colocated (near proximity) with the OB.

Operating Base No. 2 supports a colocated (near proximity) ASC and potentially an airfield complex.

System Operations and Process

Only one missile will be assigned to each of 200 clusters. Missiles will be housed within an integral canister. To preserve location uncertainty within the cluster, the missile-transporter will periodically be moved over the linear network from shelter to shelter. Mobility will be provided by a highly specialized vehicle called the Separate Transporter and Mobile Launcher (STML). The missile will be operationally ready for launch while in the shelter. To comply with Strategic Arms Limitation (SAL) being incorporated. The entire concept is therefore referred to as the Verifiable Horizontal Multiple Protective Structure (VHMPS) basing mode.

System components will be delivered to the OB/DAA. Missile canister assembly will then be accomplished at the DAA, colocated with an OB. The assembled missile-canister will be transported to a specific cluster. At the CMF the missile-canister will be shelter to shelter. The launcher section may be deposited at any one of the 23 shelters. For major maintenance or checkout, the entire process may be reversed, returning the missile to the CMF or DAA, as required.

APPENDIX D-2A
PIN-1 AUXILIARY RADAR
STATION FACILITIES DETAILS

PIN-1 AUXILIARY RADAR
STATION FACILITIES DETAILS
(as given in DEWLine Civil Engineering
Information Brochure, January, 1976)

LOCATION AND TOPOGRAPHY

Location:	Clinton Point, Canada, on the Arctic Ocean shore of Amundsen Gulf (see arrow above). PIN-1 is located some five miles northwest of Clinton Point and ten miles east of Mount Rennell.
Terrain:	Relatively high (about 300' above SL) poorly drained unstable ground (except when frozen).
Topography:	Coastal cliffs, interrupted by broad-mouthed deeply entrenched river valleys, and the rxtensive gravel beaches in such valley areas are the most prominent features.

CLIMATE

Precipitation:	Annual (including 32" snowfall)	8"
Temperature:	Absolute Minimum and Maximum (degrees Fahrenheit)	-43, + 83
GROUNDS	Total acres	29

BUILDINGS Refer to following Table (D-2A-1, of Particulars for details.

1. Total Number	9
2. Semipermanent	4
3. Temporary	3
4. DIAND Eskimo Housing Units	2

TABLE [illegible] 2A-1

TABLE OF PARTICULARS - PIN-1 BUILDINGS - REAL PROPERTY

Page 1 of 2

BUILDING DESCRIPTION	CONSTRUCTION DATA		FACILITIES AND/OR PURPOSE	UTILITY DATA					COMMENTS
	FOUNDATION	BUILDING		ELECTRIC	HEAT	WATER	SEWAGE	VENTILATION	
Module Train (28' x 436') FAC No. 00001	Post-timber sill	Prefab-unit, modular type (approx 16' x38' per unit) a. Occupied Units (23) Wd frame with insulated plywood panels b. Unoccupied with fire barrier units (3) Unheated steel box type with heated cross corridor	a. Electric powerplant b. Water purification & internal storage c. C&E mission equipment d. Officers & first aid e. Kitchen, bakery & cold/dry storage f. Dining & recreation	a. 2-Bus System (1 bus for tech loads & 1 for utility loads) b. Emer Lights (Battery powered with auto lighting & charging controls)	a. Basic System Circulating hot water utilizing powerplant engine heat recovery system b. C&E Area Ducted forced air utilizing C&E equipment heat recovery system Note: For details see "Heating" in associated BCE Data pages.	Plumbing systems supplied with potable water pumped from internal, steel storage tanks	a. Int plumbing system terminating at int storage tank connected to outfall line b. Emer dry hd toilet facility	Ducted system equipped with mixitrol dmpr for auto control fresh & recir air mixture	
Garage (42' x 82') FAC No. 00002	Concrete footings on fill	Steel frame with insulated metal panels	a. Vehicle M&R b. Standby electric powerplant unit c. Emer/Disaster Radio System	a. Ext supply via station plant utility bus b. Emer Lights (Battery powered with auto lighting & charg-controls)	Ducted forced air system from oil fired furnace	No system	No system	Exhaust Fan	

TABLE D-2A-1 (Continued)

TABLE OF PARTICULARS - PIN-1 BUILDINGS - REAL PROPERTY

Page 2 of 2

BUILDING DESCRIPTION	CONSTRUCTION DATA		FACILITIES AND/OR PURPOSE	UTILITY DATA					COMMENTS
	FOUNDATION	BUILDING		ELECTRIC	HEAT	WATER	SEWAGE	VENTILATION	
Warehouse (40' x 100') FAC No. 00032	Concrete footings on fill	Steel frame with insulated metal panels	a. General storage b. Receiving dock c. Office d. Security crib	a. Ext supply via station plant utility bus b. Emer Lights (Battery powered with auto lighting & charging controls)	Ducted forced air system from oil fired furnace	No system	No system	No mechanical system	
POL Pumphouse (8' x 8') FAC No. 00003	Concrete slab on fill	Steel frame with metal exterior (uninsulated)	POL Pumps	Ext supply via station plant utility bus	No system	No system	No system	No mechanical system	
Hazard storage (18' x 31') FAC No. 03005	Timber sills	Timber frame with wood exterior	General storage	Ext supply via station plant utility bus	Oil burning space heaters	No system	No system	No mechanical system	

AIRCRAFT FACILITIES	Total Aircraft Facility Surface (gravel)	95,018 SY
Runway:	1. Distance from Main Building Site	8100'
	2. Elevation (approximate mean feet above SL)	40'
	3. Surface: Gravel on 24" wearing course on non-frost acting base	55,159 SY
	4. Overruns: a. Total Area	8396 SY
	b. Southern end	110' x 195'
	c. Northern end	110' x 492'
	d. Surface: Gravel, compacted, stabilized, and graded	
Shoulder:	Gravel	25,150 SY
Taxiway:	Gravel	2910 SY
Apron:	Gravel	3404 SY
Lighting:		
Runway:	1. Sides: White lights 10' from 200' interval	44
	2. Threshold: a. Green marker lights, 10' interval (10 each end)	20
	b. Strobeacon (2 each end 90' from sides)	4

Taxiway:	Outlining blue lights	19
Apron:	Outlining blue lights	44
Wind Cone:	White lights	4
Navaids:	AN/FRT-37 Beacon	1
Aerovane:		1
Projector:	(ceiling)	1
Wind Cone:	(lighted)	1
ROADS	1. Total road surface (gravel)	26,226 SY
	2. Paved surface	none
	3. 12-foot wide roadway (length)	7270'
	4. 16-foot wide roadway (length)	9300'
	5. Surface: Gravel on 6" wearing course on 3' non-frost acting base on existing ground	
EXTERNAL SANITARY SEWER	3" sewer line (Module Train) to outfall area (length)	240'

System: In buildings provided with running water toilet and drain facilities, liquid sewage waste is accumulated at internal tanks for temporary storage. The waste from such tanks is periodically pumped via sewage pipeline to outfall points or into waste wannigans for transporting to disposal areas as indicated in the following Table of Particulars. When filled, steel drums from dry-head toilets are discarded at the station garbage dump for subsequent burial.

STORM DRAIN SYSTEM

Note: There is no pipeline storm drain system.

System: Surface water is permitted to drain away by following natural run-off pattern of terrain, except where blocked by buildings, gravel pads, roadways, etc., at which points culverts are provided.

Culverts:		
	1. Approximate Number	6
	2. Approximate total length	200'

EXTERNAL WATER DISTRIBUTION

Note: There is no external, primary pipeline system

External water distribution is accomplished by water-haul from fresh water lake to storage tank in Module Train

1. Summer haul	4500'
2. Winter haul	2 MI

INTERNAL WATER DISTRIBUTION, TREATMENT

System is located in Module Train and consists of steel receiving tank, filter plant, softner, chlorinator, primary and secondary portable water storage tanks, electric hot water heaters, assorted pumps, and hot and cold water lines, valves, etc.

Steel Tanks:	1. Receiving (1) (U.S. gallons)	2000 GAL
	2. Primary (Two, 2500 gallons each)	5000 GAL
	3. Secondary (Two, 2500 gallons each)	5000 GAL

ELECTRIC POWER

Power is generated at Station (total capacity).	360 KW

Powerplant: Diesel-Electric Units

1. Primary Units: Five, GMC Model 6027J 60 KW, 1200 rpm, 120/208 v, 3 ph, 60 cy at 80% pf, located in Module Train.	300 KW
2. Secondary Unit: One, 60 KW located in Garage, GMC Model 6016J	60 KW

Distribution:

Internal: System consists of switchboard, single bus system (servicing both Technical & Utility loads), and assorted branch circuits in Module Train, with single bus service provided to the technical and utility load.

External: System consists of ground and drum supported cable runs, in general (with short buried runs under man-made obstructions), servicing buildings and areas requiring electric power and such transformers associated therewith.

	1. Number of primary power transformers	4
	a. Powerplant to Garage (one, 120/208/2400 v)	75 KVA
	b. Garage (one, 2400/120/ 208 v)	75 KVA
	c. Powerplant to Airstrip Area (one, 120/208/2400v)	30 KVA
	d. Airstrip Area (one, 2400/ 120/208 v)	30 KVA
Demand & Consumption:	1. Peak Demand	
	a. Total (Single Bus) Peak	208 KW
	b. Total (Single Bus) Average	192 KW
	2. Average Power Consumption (Monthly)	138,240 KWH
	a. Annual, singel bus average	1,658,880 KWH
	3. Fuel Oil Consumption (Total for site, all purposes)	
	a. Monthly average (U.S. Gallons)	13,300 GAL
POL STORAGE <u>DISTRIBUTION</u>	Total Storage Capacity, external tanks (U.S. Gallons)	282,550 GAL
Storage:	1. Avgas: (5 drums, emergency stock)	225 GAL
	2. Diesel Oil: Total Capacity	260,000 GAL

	a. Total number of tanks (steel)	4
	b. Beach Area: (1) 2 tanks (65,000 each)	130,000 GAL
	c. Building Site Area: (2) 2 tanks (65,000 each)	130,000 GAL
	3. Mogas: Total capacity	20,525 GAL
	a. Beach Area: (1) 1 tank	20,000 GAL
	b. POL Pad	525 GAL
	4. Athey Wagon	1,800 GAL
Pipelines:	Total length (including building feeder lines)	2" x 8560'
Pumphouses:	Total Number	
	a. Module Train Tank Area	1

System: Product delivered by sealift to receiving tanks for redistribution via pipeline to Building Site and other secondary tanks is transferred via pumphouse to various fill stands and building day tanks. The day tanks of isolated buildings are serviced by tank vehicle. Drum stocks transferred via portable pump units or tank vehicle, as required.

HEATING

Module Train:

1. Primary System: Circulating hot water servicing single-tube, finned convectors. Heat recovered from powerplant engine

coolant and exhaust gases is transferred to heating system via heat exchangers.

2. Supplementary System: Electric unit heaters in areas not fully serviced by convectors.

3. Emergency System: During periods when an insufficient number of engine-alternator units are operating to fulfill heating requirements, an oil fired boiler (450,000 BTU/hr output) is available to supply hot water for the heating system.

4. C&E Mission Modules: Heat recovered from electronic equipment is distributed and recirculated via fans and ductwork.

Other Buildings:	1. Garage: Hot air, oil fired furnace (4500 cfm)	400,000 BTU/hr
	2. Warehouse: Hot air, oil furnace (3400 cfm)	240,000 BTU/hr

FIRE PROTECTION

Fire Alarm: Automatic fire detectors are installed throughout all building areas, which are divided into Fire Alarm Zones. A coded, closed-circuit alarm system centralizes all calls at the Annunciator Panel near the Control Console to facilitate further announcements over the closed areas and an outdoor siren sound whenever the fire detectors, CO_2 systems, or manually operated pull boxes are actuated.

Fire Fighting Systems:	
Module Train:	1. Standpipe System consisting of three, 225 gallon water tanks pressurized by nitrogen gas (50 psi) and hose stands located in corridor cabinets.
	2. Deluge System consisting of fixed CO_2 tanks equipped for manual and automatic discharge. a. System automatically operated in water supply modules b. System manually operated in powerplant and fire barrier modules Note: Actuation of CO_2 system automatically turns in fire alarm, deactivates associated heating and ventilating fans, and releases associated normally open fire doors to confine fire.
	3. Fire Extinguishers: CO_2 dry chemical and loaded-stream water hand extinguishers are placed at strategic locations throughout the Train.

Other Buildings: Except as follows, fire fighting equipment in other buildings is limited to the hand extinguishers listed above.

1. Garage: Automatic CO_2 deluge system in Mechanical Room
2. Warehouses: Same as Garage

ANTENNAS

(see Plot Plan for location and type)

REFUSE DISPOSAL

Collection: Refuse is collected periodically and trucked to dump.

Disposal: Note: Refuse dumped at landbound disposal areas is periodically buried under material (gravel, etc.) stockpiled in the area for this purpose.

1. Dump Haul (distance): 2 MI

FACILITIES INVENTORY VALUE

Total $5,291,000

FACILITIES INDEX PIN-1

1.	Module Train
2.	Garage
3.	POL Pumphouse
6.	Communication "DISH"
7.	Communication "DISH"
8.	Diesel Fuel Tank (Steel) (Site Area)
9.	Diesel Fuel Tank (Steel) (Site Area)
10.	Diesel Fuel Tank (Steel) (Beach Area)
11.	Diesel Fuel Tank (Steel) (Beach Area)
14.	POL Line
15.	Road
16.	Primary Power Cable (UG)
17.	Open Storage Areas
18.	Runway Overrun
19.	Airstrip Taxiway
20.	Airstrip Apron
21.*	Runway Shoulder
26.	Runway Lights
27.	Taxiway Lights
28.	Beacon Light
29.	Wind Cone
32.	Warehouse

33. Sewer Line

34. Communication "BILLBOARD"

35. Communication "BILLBOARD"

37. Runway Strobeacons

38. Runway Threshold Lights

1191. Runway

3005. Hazard Storage

3009. Dormitory (12 Man)

3017. Shed Storage

Eskimo Housing (Plan #286)

APPENDIX D-2B
POWER SYSTEM AVAILABILITY

APPENDIX D-2B

POWER SYSTEM AVAILABILITY, PIN-1

The PIN-1 Radar Station has an average electric demand of 145 kW. This requires three operating 60 kW FCPU's. Since the system design includes four FCPU's there will only be a failure of the power system to supply the average electric demand when two or more units are unavailable. Units may be unavailable due to either unscheduled outages (unit failures) or scheduled maintenance. The overall FCPU availability, including scheduled and unscheduled outages, was shown in Section 3.4.1 to be 98.9 percent. The most conservative method to calculate power system availability (at least three operable units) is to use the overall availability for each FCPU and neglect the option of postponing scheduled outages during times when other units are unavailable. The actual system availability will be higher than this simplified estimate since scheduled maintenance on two or more units would normally not be scheduled at the same time, nor would scheduled maintenance normally be intitiated during an unscheduled outage of another unit.

The system availability can be determined by calculating the probability of three or more successful events (i.e., operating units) out of four total events. The probability of success for any single eventis 0.989.

Probability of three or more successful events = Number of combinations with three out of four successful events X Probability of any single combination with three successful events

+ Number of Combinations with four out of four successful events X Probability of any single combination with four successful events

$$\text{System Availability} = (4)(.011)(.989)(.989)(.989) + (1)(.989)(.989)(.989)(.989)$$

$$= 0.9993$$

Since most critical station loads (i.e., radar units, etc.) can be met even in the case of only two operating FCPU's, it is also of interest to calculate the availability of two or more operating units.

$$\begin{aligned}\text{Availability of two or more successful events} &= (6)(.011)(.011)(.989)(.989) + \\ &\quad (4)(.011)(.989)(.989)(.989) + \\ &\quad (1)(.989)(.989)(.989)(.989) \\ &= 0.999995\end{aligned}$$

APPENDIX D-3A
MENORCA COMMUNICATIONS
SITE FACILITIES DETAILS

APPENDIX D-3A
MENORCA COMMUNICATIONS
SITE FACILITIES DETAILS

The power plant requirements for the MENORCA site were provided by Mr. John Siska, Chief Civil Engineering, USAF Communications Group (AFCS), Torrejan AFB, Madrid, Spain. A Requirements Sheet requesting information was sent to Mr. Siska, and the following information contained in Table D-3-1 was obtained.

TABLE D-3-1
MENORCA REQUIREMENTS SHEET
FUEL CELL POWER UNIT

SITE NAME: Menorica, Spain (Islas Baleares)
AVERAGE ELECTRIC LOAD, KWe: 180Kw
PEAK ELECTRIC LOAD, KWe: 200Kw
VOLTAGE CONNECTION: 3 phase 4 wire wye
POWER REGULATION CLASS (Precise or Utility): Utility
AVAILABLE FUELS: Diesel & Jet
PREFERRED FUEL: Diesel
ENGINE ROOM SITE LIMITATION OR POWER UNIT CUBAGE: 59' x 39'
MAXIMUM PERMISSIBLE WEIGHT:
MEAN TIME BETWEEN FAILURE (Specified): 99.99% per year Power Reliability is required
REQUIRED SYSTEM AVAILABILITY: 100% Class A Prime Power Plant
REQUIRED START-UP TIME, MINUTES: 0-8 Seconds
LOAD RESPONSE, MIN. TO MAX. POWER, SECONDS: Approx 5 Seconds
AMBIENT TEMPERATURE RANGE: 38°F to 88°F
BAROMETRIC PRESSURE OR SITE ALTITUDE: 853 ft
PERMISSIBLE NOISE LEVEL: 84dBA (without hearing protection) (at 20 ft)
SYSTEM USEFUL LIFE: 40 to 50 years
FUEL COST ($ Per Gallon) 1.22
DIESEL UNIT CAPITAL COST, $ Per KWe: $500
DIESEL UNIT FUEL CONSUMPTION, gph: 11.5 (kW-hr/gal)
DIESEL UNIT O & M COSTS: 10 Man Plant = $245,000 (personnel costs) AFP 173-13
4 Gen Units = 40,936 maintenance costs include overhaul
Total O&M Costs = 285,936 dollars

Note: Present plant arrangements consists of 4,250 kw units. One unit on line with automatic start back-up unit available at all times. No commercial power available. Other than Engine room site limitations (above) space available on site location is limited.

APPENDIX D-3B
POWER SYSTEM AVAILABILITY
MENORCA, SPAIN SITE

APPENDIX D-3B

POWER SYSTEM AVAILABILITY

The MENORCA communications site has an average electrical demand of 180 kW. Since the proposed system design utilizes three 100 kW FCPU's, there will only be a power outage (< 180 kW) when two or more FCPU's are unavailable. It should be noted, however, that even in the case of a single operating FCPU, that the station technical load of 100 kW can be satisfied.

Since FCPU's will routinely be removed from service to perform scheduled maintenance, the calculation of power availability requires a knowledge of the duration of scheduled outages. From Table 6-12 of the main text, the following values can be obtained:

Duration of Scheduled Outages

YEAR	1	2	3	4	5
Hours Sch. Maint.	72	72	180	72	324
%	0.82	0.82	2.05	0.82	3.70

The MTBF of any individual FCPU is 2680 hours and the Mean Time to Repair (MTTR) is eight hours. Therefore, the availability (not including scheduled outages) is 99.7 percent.

The probability of a power outage (< 180 kW operating capacity) is the summation of the probabilities of one or more units failing during a scheduled outage period (two units online) and two or more unit failing during periods when all three units are operating. The probability of a unit failure is 0.003 (= 1 - .997). Therefore, the power unavailability during Year 1 is:

$$\text{Fraction Unavailable} = [2(.997)(.003) + (.003)^2] (.0082) + [3(.997)(.003)^2 + (.003)^3](.9918) = 0.00008$$

$$\text{Percent Power Availability} = (1 - \text{Fraction Unavailable}) \times 100\% = 99.992$$

The power availability during the remaining operating years can be calculated in a similar manner. The results are as follows:

<u>Power Availability</u>

YEAR	1	2	3	4	5
Power Avail. (%)	99.992	99.992	99.985	99.992	99.975

5-Year Avg. = 99.99%

*USGPO: 1983 659-062-776

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