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Front End Analysis of Soldier Individual Power Systems

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Editor — Eleanor Raskovich

Report Date

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Belvoir RD&E Center

United States Army
Belvoir Research, Development and Engineering Center
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13. ABSTRACT (*Maximum 200 words*) The 1991 Army Science Board (ASB) Summer Study on "The Soldier as a System" identified power as a major barrier to maximizing the soldier's warfighting capabilities. Individual Power was identified as an essential component of the "Soldier System" concept.

The Front End Analysis (FEA) of power, conducted 1 May 1991 to 15 March 1992, delineates the requirements/constraints for achieving the power levels needed by the dismounted soldier. The FEA drew upon the achievements and advances in power technology from the Army, other services, allies, and industry to evaluate state-of-the-art technologies and integrate them into a system with synergistic improvement in combat effectiveness.

The FEA covers primary nonrechargeable and secondary rechargeable batteries, fuel cells, internal combustion engines, Stirling cycle engines, vapor and liquid cycle engines, and radioactive isotope power sources. Several other technologies were examined, but were judged not suited for further development. They are discussed in the FEA appendices.

The operating and performance parameters of each technology were evaluated using a computerized parametric model. The model results indicate that primary battery-driven systems satisfied the short duration (8 hours), low energy mission and fuel-driven system satisfy longer duration, higher energy missions.

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BACKGROUND

The Plan: Today's technology allows greatly increased electronic capabilities for the individual soldier. Providing power for these electronics is a critical issue because the soldier must still maintain individual autonomy in all battlefield conditions. The Front End Analysis (FEA) is one effort leading the Army to the realization of this requirement.

History: The 1991 Army Science Board (ASB) Summer Study on "The Soldier as a System" identified power as a major barrier to maximizing the capabilities being demonstrated in the Soldier Integrated Protective Ensemble (SIPE) program. Individual Power was identified as an essential component of the "Soldier System" concept.

Approach: The objective of this FEA is to provide guidance for a power technology program. The program will research, develop, and demonstrate technology for power sources intended for a backpack-mounted cooling and electrical generation system for future soldiers with advanced equipment.

Scope: The program's FEA, conducted 1 May 1991 to 15 March 1992, covers the requirements, constraints, and potential technologies for achieving individual soldier system power needed by the dismounted soldier.

STRATEGY

The basic strategy of the FEA was to draw upon the achievements and advances in power technology from the Army, the other Services, allies, and industry to provide state-of-the-art technologies, and then to integrate these technologies to produce a system concept with synergistic improvement in combat effectiveness.

CONCLUSION

The FEA determined that a battery-driven system was the desired approach for missions of short duration (8 hours) and low energy. Missions with higher energy requirements and/or of longer duration must use a fuel-driven system.

KEY RECOMMENDATIONS

Short Term: Pursue primary (non-rechargeable) battery technology. Optimize engine-driven systems.

Mid Term: Continue investigation of batteries (especially rechargeable lithium batteries) for low energy missions. Improve engine-driven systems for missions with cooling. Begin investigation of fuel cells. Examine high risk photovoltaics and thermoelectrics.

Long Term: Place most emphasis on fuel cell investigation. Continue scrutiny of photovoltaics and thermoelectrics.

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Section I
Introduction

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PURPOSE

The Front End Analysis (FEA) of power, conducted 1 May 1991 to 15 March 1992, defines the requirements and constraints for achieving the power levels needed by the dismounted soldier. The FEA also assesses potentially applicable power technologies capable of providing that power. It provides a synopsis of the scenarios, proposed systems, analysis processes, and rationale for the down selection of power sources.

The basic strategy of the FEA draws upon the achievements and advances in the area of power technology from the Army, the other Services, allies, and industry to provide state-of-the-art technologies. Technologies were integrated into lightweight, efficient power system concepts with synergistic improvements in combat effectiveness. Integration objectives were selected to minimize the weight and maximize the efficiency of the complete systems.

BACKGROUND

A Technology Base Executive Steering Committee (TBESC) was created and tasked by the Army Science Board (ASB) to coordinate and direct the Army R&D community in a FEA of available and future power technologies. The TBESC consisted of members from the Army Research Laboratories (ARL)—Harry Diamond Laboratory (HDL) and Electronic and Technology Device Laboratory (ETDL); the Army Research Office (ARO); Belvoir RD&E Center (BRDEC); and Natick RD&E Center (NRDEC). The objective of the Front End Analysis was to provide guidance for a power technology program. The program researched, developed, and demonstrated technology for power sources intended for a lightweight, signature suppressed, backpack-mounted cooling and electrical generation system for future soldiers with advanced equipment.

ARO acted as the general advisor for the FEA. BRDEC, responsible for leading the analysis, provided expertise on various power technologies such as radioisotopes, internal combustion engines, and fuel cells. ETDL provided the study with expertise on primary and secondary battery technologies. HDL contributed expertise on vapor cycle systems. Natick, the FEA study sponsor, supplied expertise on Stirling engine technology.

DEFINITION OF THE SOLDIER SYSTEM

The Soldier Modernization Plan (SMP), released on 21 March 1991, describes the development of the "Soldier System." This plan defines a concept which will develop all of the equipment, weapons, and subsistence items the individual soldier carries or uses into an integrated system.

The 1991 Army Science Board Summer Study on "The Soldier as a System" identified power as a major barrier to maximizing the potential capabilities of the soldier. Power was further defined as an essential component of the "Soldier System" concept and crucial to the success of Individual Microclimate Cooling.

Cooling will ensure effective operation in adverse climates. It is crucial for the soldier's survival in a chemical or biologically contaminated environment. Other specialized electrical components envisioned for the "Soldier System" include a soldier computer, individual navigation, enhanced hearing, night vision, helmet displays, voice/data communications, and weapon ranging. The power source will provide the means to maximize and support the warfighting capabilities of the individual soldier by enhancing lethality and C4I through the improvement of MOPP IV protection, sustainment, mobility, and overall combat effectiveness on the future battlefield.

Integration of these components will ensure extended, effective operation, and soldier survival in an NBC environment. Therefore, the availability of high energy, high performance power sources is critical to the success of the Soldier System.

SCOPE

The FEA considered various energy sources, energy storage devices, and energy conversion mechanisms which could potentially meet the needs of the individual soldier. Based on a preliminary down select, the FEA covers primary nonrechargeable batteries, secondary rechargeable batteries, fuel cells, internal combustion engines, Stirling cycle engines, vapor and liquid cycle engines, and radioactive isotope power sources. Each of these technologies is covered in detail in an appendix of this report. In addition, several other technologies were examined, but were judged not suited for further development for the Individual Power Program. They are also included in the appendices.

Developing a power source for the individual soldier involves consideration of environment, equipment, activity level, weight limitations, and duration of mission. Power level and energy requirements vary with the type of mission. Since the mission drives the power requirement, it was necessary to define a range of operational scenarios representative of the dismounted infantry soldier using the Soldier System. Section II of the FEA, entitled "Requirements," details the formulation of these scenarios.

Section II
Requirements

POWER REQUIREMENTS FOR THE SOLDIER SYSTEM

(Author: Mr. Richard Jacobs, BRDEC, SATBE-FEA)

Belvoir RD&E Center, along with other qualified organizations, is investigating technologies that will provide electrical power and environmental protection for the projected "Soldier System." This integrated effort aims to provide the future soldier with the equipment and energy required to meet the needs stated in the current Soldier Modernization Plan. The forthcoming requirements will be the basis of plans and programs to provide the future soldier with the necessary capabilities to perform effectively on a 21st century battlefield. Of particular importance will be equipment characteristics, mission scenarios, and soldier activity levels. Defining these needs today in terms of power and environmental control is difficult when the future battlefield must be envisioned beyond the year 2000.

The Soldier System must consider the projected threat from enemy forces and be functional in all environmental conditions. Future needs, therefore, fall into five categories of required capabilities: LETHALITY; COMMAND AND CONTROL; SURVIVABILITY; SUSTAINMENT; and MOBILITY. According to the Soldier Modernization Annex, power supplies lie primarily in the Sustainment and Mobility categories; climatic control devices fall under the survivability category. The requirements for power and climatic control also will be influenced by the remaining categories since the amount of power and use of climatic control depend on the mission scenario and equipment used.

The Soldier System of the future will include a wide variety of electronic devices, such as:

- Night Vision Devices
- Thermal Imaging Devices
- Visual Helmet Display
- Communications Equipment
- Individual Computers
- Enhanced Hearing
- Global Positioning System
- Weapon Ranging System
- CB Monitors.

Although the exact equipment complement of the Soldier System is unknown at this time, the power draw estimates of the individual devices can be used to estimate the power requirements of various configurations and combinations. It is more difficult to estimate the amount of energy required to support the climatic control/protection devices. Although the range of environments can be determined, mission duration and physical activity levels can vary significantly, producing large changes in the energy required. The power level for electronics and environmental control is estimated to be less than 500 watts. There are desired capabilities not addressed in this document that require a much larger power source. These include exoskeletal devices and power tools. An assessment of the Soldier System power requirements can be performed in the same manner as other

Army systems. This is done by determining the pieces of equipment, the environment, and the mission scenario. The primary information required is in the mission scenario. It details the duration, activities, and equipment usage rates for a given mission. There are no user-generated scenarios containing this information for the future Soldier System at this time. Major efforts are underway in the user community to develop this critical information. The types of soldiers, their equipment, and the missions are all considered when discussing scenarios. The types of soldiers fall into three main categories:

- Dismounted Combat Soldiers
- Combat Crew Soldiers (ground and air)
- Other Soldiers

When considering the various needs of these soldiers, it is apparent that an almost endless variety of mission scenarios exist. This occurs because of the wide variety of functions which each type of soldier performs and the numerous subcategories of each major category. The "other soldier" category has identified numerous requirements for various branches of the Army, such as:

- Transportation
- Military Police
- Engineer
- Ordnance
- Missile and Munitions
- Intelligence
- Chemical
- Signal
- Quartermaster
- Aviation Logistics

When "other soldier" environment, mission length, and interactions are considered, the problem of determining the proper power source becomes evident. Just as there is no one size of engine generator set in the field that meets all mission requirements (i.e., 3 kW, 5 kW, and 10 kW), so the size of the power source for the Soldier System depends on the mission. A field reconnaissance soldier would not use the same power source as an engineer using an exoskeletal system to clear obstacles.

Current analysis shows that the power required for the cooling system is much larger than the power required for the electrical loads. A correct definition of the cooling load is essential for optimal, effective sizing of the integrated system. There are several items that are particularly important when considering the environmental aspects of the overall Soldier System. They include equipment and clothing characteristics, mission scenarios, and activity levels.

The Soldier System of the future includes a variety of clothing and protective equipment that affects the cooling requirements of the individual soldier. These include:

- NBC Protective Clothing
- Ballistic Protection Equipment
- "Smart" Helmets with Integrated Respiratory/Ventilation Features
- Cooling Vests

Despite the unknowns, some determination of the power levels and energy requirements must be made so that promising technologies can be evaluated. The following sections represent some of the possible scenarios and provide a basis for looking at various power sources in a range that covers most of the missions.

The exact power and environmental control requirements are unavailable because this is an emerging system. It is necessary to do several things to accelerate the development and refinement of technical scenarios to provide an optimal system. The system electrical load must be estimated, inrush and transient performance must be approximated, and some duty cycles must be estimated. These estimates provide the information necessary to begin the technical assessment and to put in place a system whereby the electrical and environmental characteristics can be tracked and optimized. The following scenarios give a list of equipment, assume an environment, describe the assumed mission, and provide a power level and energy requirement. When a usage rate is given as X/Y, the X refers to the percentage of time in operation at one power level and the Y refers to the percentage of time in operation at a different power level. 0.6/0.3 would mean 60 percent at one level and 30 percent at another. When this is done, a corresponding power level also is given, such as 50/100 watts. In this case the power draw would be 50 watts for 60 percent of the time and 100 watts for 30 percent of the time.

These numbers are used to calculate the watt-hour requirements. For one hour of operation, the above formulas yield (0.6 hours x 50 watts) + (0.3 hours x 100 watts) = 60 watt-hours. When the watt-hours are given as X/Y, the X refers to the energy used on an 8-hour mission. The Y refers to the energy used on a 24-hour mission. The 24-hour mission consists of 20 hours of activity and a usage rate of 0 for the 4 hours of downtime. The watt-hours for the ordnance mechanic mission are for three hours of activity. The peak power is calculated by adding up all the largest wattages for the equipment on a given mission. The average power is calculated by adding all the equipment watt-hours for a given mission and mission time and dividing by the length of the mission. The energy for a given mission and mission time is calculated by adding all the watt-hours for the mission and time.

The estimates for power draw were obtained from various equipment developers or estimated when information was not available. Usage rates are the best estimate of the material developer and will be refined as the actual missions are defined by the user community.

Dismounted Combat Mission

This scenario is for a soldier on foot carrying out a mission that has high activity rates (rapid marching, fortification, firefight) for 20 percent of the time and a low level of activity (reconnaissance, communication, command and control) for 80 percent of the time. It is in a hot environment and is analyzed for 8- and 24-hour missions. When analyzing the 24-hour mission, a downtime of 4 hours is used.

PROPOSED LIST OF EQUIPMENT—All Equipment Using 28 VDC Source

Nomenclature	Usage Rate	Watts	Watt-Hours (8-hr/20-hr)
Thermal Vision	0.9	10	72/180
Thermal Sight	0.2	10	16/40
Flat Display	0.9	3	22/54
Enhanced Hearing	0.9	5	36/90
Navigation/Monitor	1.0	5	40/100
Soldier Computer	1.0	5	40/100
Voice Comm	0.1/0.9	2/1	9/22
LAN Comm	0.1/0.9	10/2	22/56
CB Monitor	0.9	1	7/18
ECU (400w/150w)	0.2/0.8	267/100	1067/2668

These values give a peak power of (10 +10 +3 +5 +5 +5 +2 +10 +1 +267) watts = 318 watts and an average power of 72 +16 +22 +36 +40 +40 +9 +22 +7 +1,067) watt-hours/8 hours = 166 watts. The energy for an 8-hour mission is (72 +16 +22 +36 +36 +40 +40 +9 +22 +7 +1,067) watt-hours = 1,331 watt-hours; the energy for a 24-hour mission is (180 +40 +54 +90 +100 +100 +22 +56 +18 +2,668) watt-hours = 3,328 watt-hours.

Perimeter Reconnaissance Mission

This scenario is for a soldier who is delivered to the mission site by vehicle and picked up at the end of the mission. It is primarily a reconnaissance mission for the detection and identification of enemy forces and for use in command and control. The activity level is low and the environmental conditions are moderate. Cooling is done with forced ambient air. Mission length is the duration of time at the mission area. The watt-hours are given for an 8-hour mission and a 24-hour mission with 4 hours of downtime.

PROPOSED LIST OF EQUIPMENT—All Equipment Using 28 VDC Source

Nomenclature	Usage Rate	Watts	Watt-Hours (8-hr/20-hr)
Enhanced Vision	0.9	10	72/180
Flat Display	0.9	3	22/54
Enhanced Hearing	0.9	5	36/90
Navigation/Monitor	0.5	5	20/50
Soldier Computer	0.5	5	20/50
Voice Comm	0.05/0.45	2/1	4/11
LAN Comm	0.08/0.64	10/2	17/42
ECU (ambient air)	0.8	50	320/800

These values give a peak power of (10 +3 +5 +5 +5 +2 +10 +50) watts = 90 watts and an average power of (72 +22 +36 +20 +20 +4 +17 +320) watt-hours/8 hours = 64 watts. The energy for an 8-hour mission is (72 +22 +36 +20 +20 +4 +17 +320) watt-hours = 511 watt-hours; the energy for a 24-hour mission is (180 +54 +90 +50 +50 +11 +42 +800) watt-hours = 1,277 watt-hours.

Long-Term Reconnaissance Mission

This scenario is for a soldier who is located behind enemy lines and is autonomous for long periods of time. The mission is to locate and identify enemy forces and movements. Intermittent communications with command and control functions are made as necessary. The activity level is low and the ambient conditions are cold to moderate. No cooling or ventilation is provided. The watt-hours are given for an 8-hour mission and a 24-hour mission with 4 hours of downtime.

PROPOSED LIST OF EQUIPMENT—All Equipment Using 28 VDC Source

Nomenclature	Usage Rate	Watts	Watt-Hours (8-hr/20-hr)
Thermal Vision	0.75	10	60/150
Thermal Sight	0.01	10	1/2
Helmet Display	0.75	3	18/45
Enhanced Hearing	0.75	5	30/75
LAN Comm	0.02/0.08	10/2	3/7
Navigation/Monitor	0.05	5	2/5
Soldier Computer	0.75	5	30/75

These values give a peak power of (10 +10 +3 +5 +10 +5 +5) watts = 48 watts and an average power of (60 +1 +18 +30 +3 +2 +30) watt-hours/8 hours = 18 watts. The energy for an 8-hour mission is (60 +1 +18 +30 +3 +2 +30) watt-hours = 144 watt-hours; the energy for a 24-hour mission is (150 +2 +45 +75 +7 +5 +75) watt-hours = 359 watt-hours. A long autonomous mission of 30 days would require (18 watts x 30 days x 24 hours/day x 20 hours/24 hours) = 10,800 watt-hours.

Ordnance Mechanic Mission

This scenario is for ordnance maintenance and repair. The soldier is transported to the job site and picked up after a fixed amount of time. A need exists for power tools which may be hydraulic or electric. A rough estimate of the tool's power requirements is 400 watts. The typical mission would last three hours at which time the item under repair would be abandoned or evacuated. The activity level is moderate to high and the environment is moderate to hot. The watt-hours are given for three hours of activity.

PROPOSED LIST OF EQUIPMENT—All Equipment Using 28 VDC Source

Nomenclature	Usage Rate	Watts	Watt-Hours (3-hr)
Thermal Vision	0.75	10	22
Power Tools	0.1	700	210
Helmet Display	0.75	3	7
Enhanced Hearing	0.75	5	11
LAN Comm	0.1/0.9	10/2	8
Navigation/Monitor	0.1	5	2
Soldier Computer	0.9	5	14
Voice Comm	0.1/0.9	2/1	3
ECU (400/150w)	0.2/0.8	267/100	400

These values give a peak power of (10 +700 +3 +5 +10 +5 +5 +2 +267) watts = 1,007 watts and an average power of (22 +210 +7 +11 +8 +2 +14 +3 +400) watt-hours/3 hours = 226 watts. The energy requirement for a 3-hour mission is (22 +210 +7 +11 +8 +2 +14 +3 +400) watt-hours = 677 watt-hours.

An exoskeletal system's power requirements are estimated as 4 to 5 kW. These requirements are not considered in this analysis nor are directed energy weapons. However, there are a number of desired capabilities mentioned in the Soldier Modernization Annex that require enhanced strength/mobility.

Mission	Peak Power	Average Power
Dismounted Combat	318 watts	166 watts
Perimeter Reconnaissance	90 watts	64 watts
Long-Term Reconnaissance	48 watts	18 watts
Ordnance Mechanic	1,007 watts	226 watts

The analysis of the preceding scenarios indicates that the maximum power needs of the Soldier System will be about a kilowatt since the ordnance mechanic mission has a peak power of 1,007 watts. The kilowatt level is for a soldier on the ordnance mechanic mission carrying power tools, a 400-watt cooling system, and electronics. A soldier carrying only electronics needs approximately 50 watts since the long-term reconnaissance mission has a peak power of 48 watts. If ambient air cooling is needed it raises the level to about 100 watts since the perimeter reconnaissance mission has a peak power of 90 watts. The main case where the soldier has 400 watts of cooling and the electronic load requires approximately 300 watts since the dismounted combat mission has a peak power of 318 watts.

Having fixed the power levels, the other system parameters may be varied to obtain additional information. Using the watt-hours developed, the average power can be calculated and used to determine power supply weights for various mission lengths. These vary according to what technology is used, but the general trend is indicated in Figure 1 below. The slope increasing with power level indicates the fuel required for a higher average power.

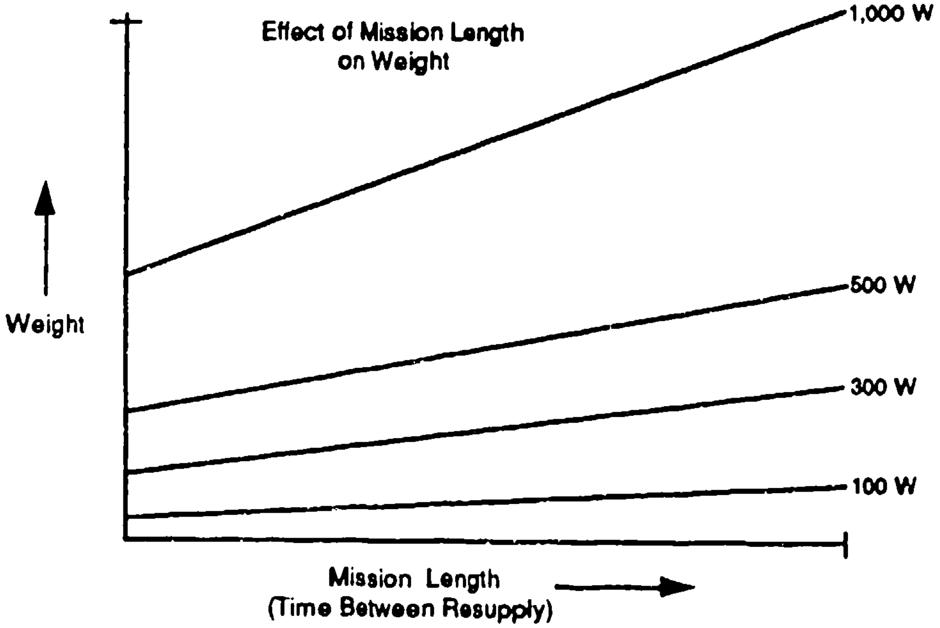

Figure 1. Effect of Mission Length on Weight

The point on the weight axis where the power lines begin indicates the dry weight of the power source. The increase in weight with time indicates the weight of the fuel required to provide the average power.

Figure 2 is an example of how mission power and duration affect the power source. The energy expended on the mission is fixed at 2,000 watt-hours. There are four cases shown. The first is with no cooling and an electronic load. The peak power is 50 watts. The second case is for ambient cooling with an electronic load. The peak power is 100 watts. The third case is with chilled liquid cooling and an electronic load. The peak power is 300 watts. The fourth case is for chilled liquid cooling, power tools (1 horsepower), and an electronic load. The peak power is 1,000 watts.

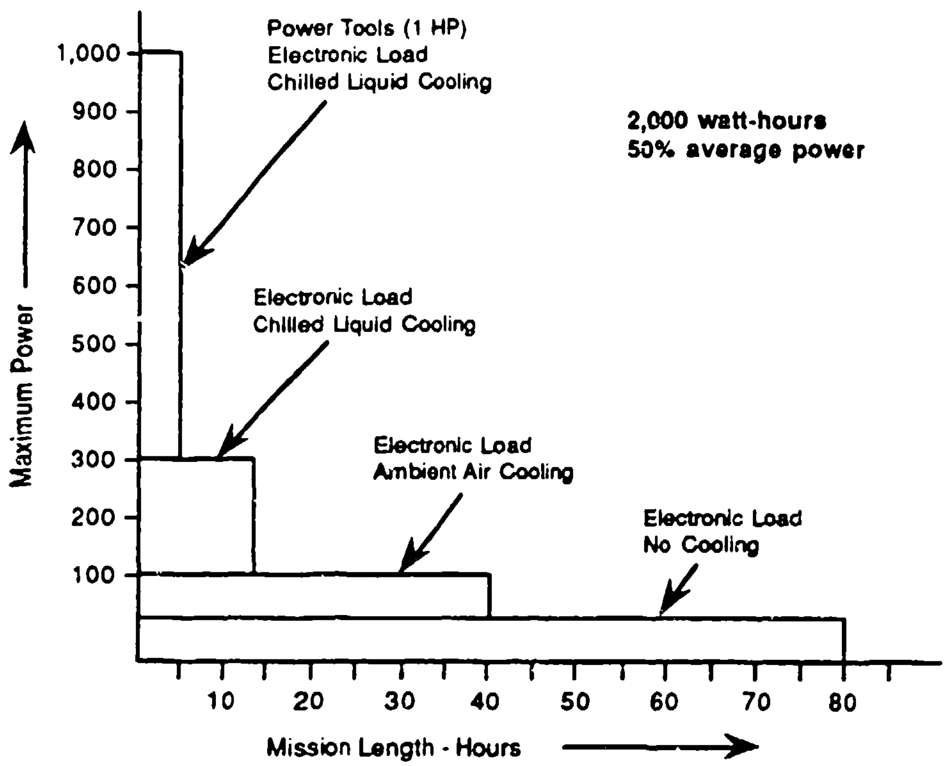

Figure 2. Effect of Mission Power and Length on Power Source

For the no cooling case the power source would need to be sized at 50 watts. If the average power was 25 watts, an 80-hour, 2,000 watt-hour mission would determine the fuel requirements.

For the ambient cooling case the power source would need to be sized at 100 watts. If the average power was 40 watts, a 50-hour, 2,000 watt-hour mission would determine the fuel requirements. For the chilled liquid cooling case the power source would need to be sized at 300 watts. If the average power was 133 watts, a 15-hour, 2,000 watt-hour mission would determine the fuel requirements. For the power tools case the power source would need to be sized at 1,000 watts. If the average power was 400 watts, a 5-hour, 2,000 watt-hour mission would determine fuel requirements.

Figure 3 is for illustration and does not reflect actual scenarios. The environment and activity level determines the level of cooling required; the level of cooling required determines the size of the power supply.

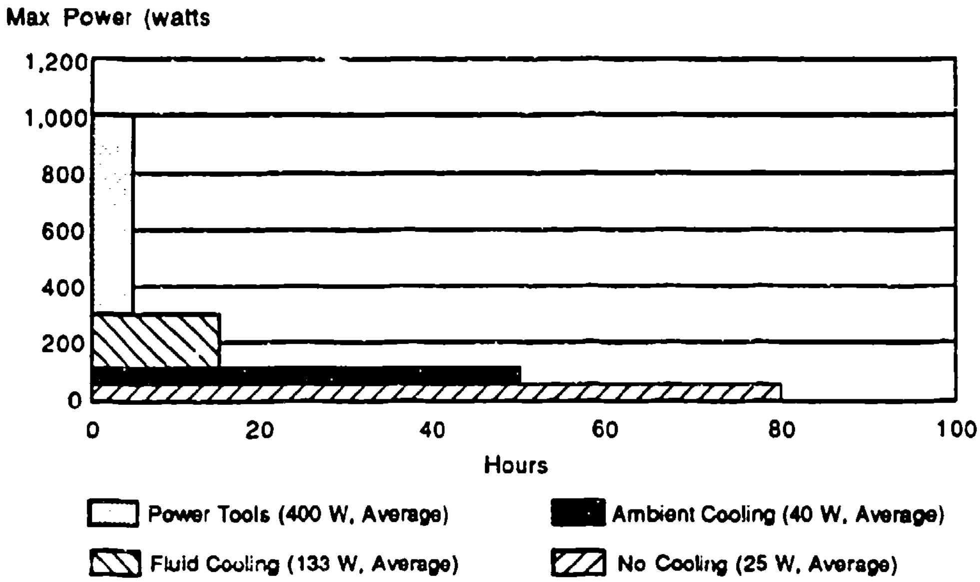

Figure 3. Mission Length—2,000 Watt-Hours

COOLING REQUIREMENTS FOR THE SOLDIER SYSTEM

(Author: Mr. Christopher Bolton, BRDEC, SATBE-FED)

The Army is currently investigating candidate technologies to provide environmental protection for the projected Soldier System. The program envisions a completely integrated effort that provides the future soldier with the equipment and energy required to fulfill the needs stated in the Soldier Modernization Annex. This will provide capabilities to perform effectively on the future battlefield. A correct definition of the cooling load is essential for optimal and effective sizing of the integrated system because current analysis shows that the power required for the cooling system is much larger than the power required for the electrical loads. There are several items that are particularly important when considering the environmental aspects of the overall soldier system; they include equipment and clothing characteristics, mission scenarios, and activity levels.

As noted above, the Soldier System of the future includes a variety of clothing and protective equipment that will affect the cooling requirements of the individual soldier. These include:

- NBC Protective Clothing
- Ballistic Protection Equipment
- "Smart" Helmets with Integrated Respiratory/Ventilation Features
- Cooling Vests

The configurations and combinations of these and other similar devices are not known presently. Predicting the amount of cooling required to protect the soldier presents a complex problem. Although the range of environments can be determined, the duration and physical activity levels for a given mission are very hard to define and can have order of magnitude effects on the size of the system required. The mission scenario is the primary piece of information needed. It establishes the duration, activities, and equipment usage rates for a given mission. There are no user-generated scenarios that contain these particulars for the future Soldier System at this time. For a more detailed description of this problem, see Section II, "Power Requirements of the Soldier System." Despite unknown factors, some determination of the cooling level must be made in order to evaluate the various technologies. The following sections present the methodology and data this report used to determine cooling rates.

The heat production rates for individuals working at various tasks are documented by many studies. A list of soldier-oriented tasks is included in Figure 4 (Reference 1). Even though these rates are affected by the different metabolic rates of the individuals, they are sufficient for estimating the cooling required. However, these figures represent steady-state work/heat production rates. They do not address changing loads. Designing a cooling system to handle the worst case load is an additional problem because it would result in a very large, heavy system. A preferred approach is to design for reasonable "average" loads and allow for higher peak loads of shorter duration. Long-term cooling is used to remove body heat stored during short-term periods of intense activity. This approach is realistic because the physically fit, average soldier would be unable to sustain high work rates in warm/hot/humid environments even without the added burden of protective clothing and equipment. Many tests verify work/rest cycles that support the concept of average cooling applied to varying loads. In these tests, individuals in protective clothing worked for up to 30 minutes with low cooling, and then rested while being cooled. No physical harm was done and endurance was greatly increased as long as the rate of cooling was sufficient to remove the stored body heat. Natick RD&E

Center recommends that body heat storage not exceed 100 watts (Reference 2). They also recommend that the body not be subject to this storage rate for more than 90 minutes (Reference 1).

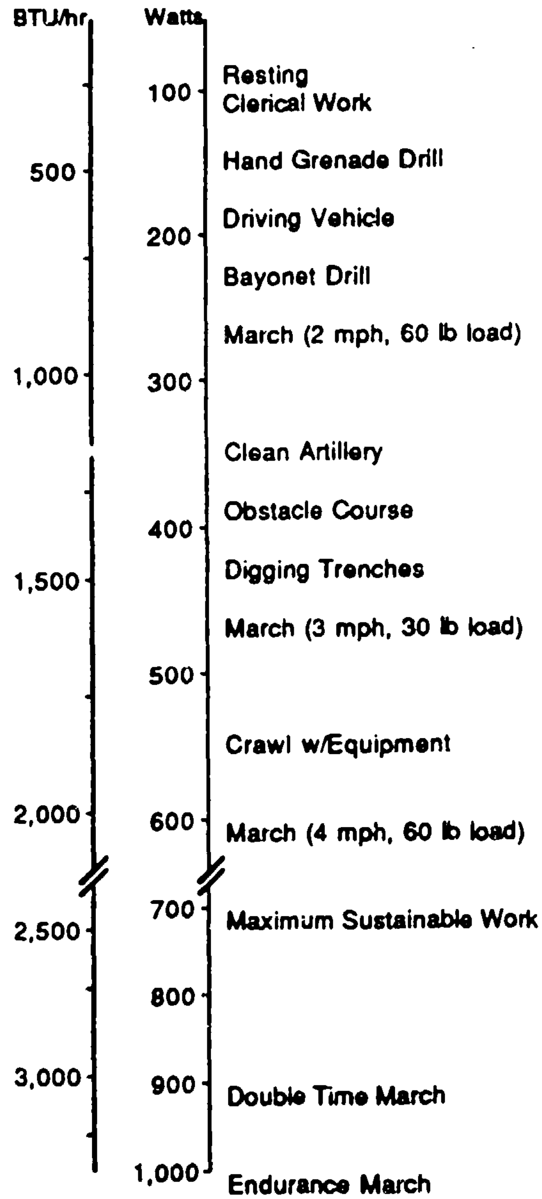

Figure 4. Metabolic Heat Output from Performing Various Military Tasks

Assuming a 600-watt work rate and 400 watts of available cooling results in 200 watt-hours of heat storage over a one-hour period; 100 watt-hours of heat storage would enable an individual to work for 30 minutes without exceeding this limit. The individual could then rest and be cooled to a safe level in 15 to 20 minutes and then repeat these cycles as required; or, tailor the work rate to match the worker's cooling capability and continue at a slower pace. Higher work rates (up to and exceeding 900 watts) could be expected of a soldier, especially during high threat conditions. Unfortunately, even with 400 watts of cooling, an individual would reach the heat storage limit in just 12 minutes;

but an individual without cooling, in the same protective clothing, would be in jeopardy in 7 minutes or less.

Several variables must be considered to estimate heat storage in varying load situations. The first is thermal lag. Core temperature, and thus heat storage, can lag behind changes in metabolic heat production and applied cooling by five to ten minutes. Additional variables include the amount of cooling available through the suit and the amount of ambient heat load caused by the suit. Solar load can be particularly significant, especially in small, localized, high-gain areas such as non-shaded visors and black rubber gloves and boots.

Based on the above physiological limits, it appears that 400 watts is a reasonable value for sustained cooling. Studies of crews in the M1A1 tank show that extended missions are possible given cooling rates of 350 watts. This is very close to the average workload of the loader, who was working the hardest (Reference 3). Given that 30 to 45 minutes of continuous cooling is required at this work rate, and given the small physical size of the cooling components, it is probable that this peak rate will be the design rate as well. A short duration peak load might be handled through some "extra" thermal mass in the system that could result in a smaller, lighter cooling system requiring less peak input energy and a smaller power system. But, due to the duration of the peak cooling load and the logistics burden of thermal storage mediums, thermal storage does not appear practical for this application.

Choosing a lower limit for available cooling is more difficult than selecting an upper limit. In a very hot environment, soldiers resting in current protective clothing are not rejecting heat due to the restrictive nature of the clothing. Selecting a cooling rate equal to a base metabolic rate is not sufficient for removing additional stored heat from individuals in this situation. Such a low cooling rate would not allow for load growth due to system degradation, increased solar loading, or other unforeseen problems. Requiring too large a ratio between high and low cooling rates would require more complexity in the cooling system control mechanism and hardware. A lower rate of 150 watts has been arbitrarily selected to provide some growth above an "average" resting rate of 100 watts.

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EVALUATION FACTORS FOR THE SOLDIER SYSTEM

(Author: Mr. Richard Jacobs, BRDEC, SATBE-FEA)

Introduction

The selection of existing technologies for potential use in a future Soldier System power source must consider the various factors used to evaluate military power and environmental control systems over the past several decades. These factors are generally the same but the relative importance varies depending on the type of system required.

The military's needs differ considerably from the needs of other possible users. For example, the military system design may be different because the individual soldier wears or carries the system. The following factors are significant in the early stages of development. They will be refined as the program matures.

Cost	Effects of Attitude
Weight	Shelf Life
Signature	Integrated Logistic Support
Size	Reliability/Availability/Maintainability (RAM)
Safety	Starting/Restarting
Vibration	Production Base
Gyroscopic Forces	Human Factors Engineering

These factors do not represent truly independent variables since there is some overlap among the various factors. A brief discussion of each of the factors follows later in this section. First, it helps to discuss the military environment and point out the extreme difficulty of meeting all of its possible requirements. The military environment may be defined as any locale where the Soldier System is used. It covers the temperature extremes and altitudes found worldwide. The density of air and its oxygen content can vary by a factor of two, posing design difficulties. Another problem is that the soldier can encounter blowing dust/sand salt fog/spray, and chemical/biological agents. The military environment also includes the area inside the soldier's protective suit. When considering the inside environment, the following excerpts from MIL-STD-1472C are germane:

5.8.1.6 Personal Equipment Thermal Control.

When special protective clothing or personal equipment, including full and partial pressure suits, fuel handler suits, body armor, arctic clothing and temperature regimented clothing are required and worn, a comfortable microclimate between 20°C (68°F), 14 mm ambient water vapor pressure and 35°C (95°F), 3 mm ambient water pressure is desirable and, where possible, shall be maintained by heat transfer systems.

5.8.1.8 Limited Thermal Tolerance Zones.

Where hard physical work is to be required for more than two hours, an environment not exceeding a (WBGT)* or (WD)** index of 25°C (77°F) shall be provided. Where the wearing of protective clothing systems (which reduce evaporation of sweat from the skin) is required, this index shall be decreased 5°C (10°F) for complete chemical protective uniforms, 4°C (7°F) for intermediate clothing systems, and 3°C (5°F) for body armor.

* Wet Bulb Glove Temperature.

**Wet Dry.

Evaluation Factors

- COST—The cost factor is probably the least definable yet one of the most important factors in the long term. Life cycle cost is analyzed by using estimates of the various research, development, procurement, sustainment, and disposal costs for a given technological approach. Technological barriers and the state-of-the-art of some of the technologies make cost estimating difficult. If a particular technology presently has prohibitive production costs, a manufacturing methods and technologies program can be instituted. If material costs are prohibitive, research and development programs aimed at specific items will be needed. The production cost will be influenced considerably by the quantities that are estimated at this time.

- WEIGHT—The weight factor is the most important consideration but the system must still be affordable. The weight of the power and environmental control equipment must be minimized because the weight of the equipment carried by the soldier on the battlefield is already a substantial burden. The addition of new pieces of equipment will not relieve the need for much of the current inventory, particularly in the non-power-consuming area. The weight factor is influenced by power requirements (peak, continuous, and average) and by the time between resupply/refueling. Weight should be considered from the perspective of total mission weight. This includes unit weight, the weight of fuel, and the weight of any expendables required for various mission lengths.

- SIGNATURE—When considering the signature of the Soldier System, there are several categories that the power source may impact. These need to be evaluated.

  Noise—The noise generated by the power source and environmental control systems can be broken out into noise that is a health hazard, noise that interferes with communications, and noise that renders the soldier detectable by enemy forces. Speech communication must not be adversely impacted. The first two categories of noise are covered by various human engineering documents. Detectability is more difficult to assess because it depends on environmental conditions, frequency spectrum, and the capabilities of the opposing forces. The future threat may involve amplified, frequency-selective enhanced hearing devices. The desired noise should not contain bands or characteristics that differ significantly from the natural background.

  Electromagnetic—This category involves the same issues as audible noise. The interference with communications refers to electromagnetic interference with signals either sent or received by the soldier. The soldier is vulnerable to detection if electromagnetic emittances are present. The system also should not contain detectable radar sources.

  Infrared—The infrared signature is one of the most difficult methods of detection to defeat. No power source is 100 percent efficient; some waste heat is always given off. The sophistication of present IR detection devices permits the detection of small objects that are only a few degrees above or below ambient conditions. It can be anticipated that future opposing forces will have quite formidable IR detection capabilities, so the Soldier System needs a high degree of suppression in this area.

  Visual—Detection by visual means is a continued threat, although some enhancement against visual detection is gained using typical camouflage methods. Designs should avoid obvious shortfalls such as shiny surfaces or sharply contrasted packaging.

- SAFETY—The safety and well being of the individual soldier is one of the primary driving forces of the soldier modernization program. The power source and cooling system must be safe. The power source/environmental control unit must not subject the soldier to high temperatures, noise hazards, toxic exhausts, dangerous chemicals/fuels, electric shock, fragmentation, explosion, or any other safety hazards.

- VIBRATION/GYROSCOPIC FORCES—The power source and environmental control unit can generate vibrations and/or gyroscopic forces that affect the soldier. Degradation of visual displays or vision that is caused by vibration should be avoided. MIL-STD-1472 does not specifically cover the vibration caused by equipment but does recognize that vibration may impair human performance and could decrease effectiveness. Gyroscopic forces should be limited so that the soldier retains full freedom of movement without exerting additional effort. Gyroscopic forces are exhibited by rotating components. A gyroscopic couple should be used to minimize this effect when necessary. If this is not practical, the impact on the overall Soldier System must be considered.

- ATTITUDE—Soldiers may have to run, dodge, jump, crawl, and engage in other activities that drastically change the attitude of the power source/environmental control unit and/or its fuel supply. Adverse effects of rapid changes in attitude must be considered when evaluating candidate technologies for the Soldier System.

- SHELF LIFE—Shelf life refers to the ability to store the units in a non-operating mode when not required. It also involves any special equipment or facility needed for storage and any special requirements prior to initial operation.

- INTEGRATED LOGISTIC SUPPORT (ILS)—Consideration must be given to requirements for unique functions/tasks, personnel skills; Test, Management, and Diagnostic Equipment (TMDE); training; spare parts; manuals; special tools; and any other logistic resources critical to the operation of the system. A key factor in the ILS area is the type of fuel utilized. The use of any special fuel should be coordinated within the logistic supply community as early as possible. This avoids proceeding with a technical solution that is not logistically supportable.

- RELIABILITY/AVAILABILITY/MAINTAINABILITY (RAM)—The power source and environmental control unit used in the Soldier System must be reliable, easily maintained, and available when required. These factors are interrelated and are tied to the ILS aspects of the system. To achieve high reliability, the system should be simple, rugged, and capable of operation in all environmental conditions. Simplicity of design and operation should provide improved maintainability characteristics. There are no current numbers for the RAM requirements of the Soldier System; however, similar systems in command and control have extremely high values for operational availability that are generally met through redundancy. This power system requires high reliability since the soldier's life may be in jeopardy if it fails. This factor is greatly influenced by the aspects of environment discussed earlier.

- SIZE—The size of the unit is a function of its weight. Size must be considered because it can hamper the soldier during the task performance and/or increase target size. Another consideration of size is the carrying requirement. Systems should be designed to provide maximum ease of handling with weight distributed so that the center of gravity is near the spinal axis.

- STARTING/RESTARTING—This factor considers the method and time required to start/restart the system. The method should be simple and quick. The user needs to determine if start-up time is critical since some of the systems need to be brought up to operating temperature before a full load can be supported. The effect of numerous start-stop cycles also should be considered.

- EFFICIENCY—This factor directly affects weight since a less efficient system requires more fuel (weight) for a given mission. The relationship between technologies is not straight forward since the types of fuel used may differ. A high efficiency system might require more pounds of fuel if the fuel is low in energy density.

- HUMAN FACTORS ENGINEERING (HFE)—HFE refers to designs that are usable and maintainable by the soldier. MIL-STD-1472 and MIL-H-46855 provide comprehensive requirements for HFE Specific consideration should be given, but not limited, to the following paragraphs of MIL-STD-1472: 4 (General Requirements); 5.1 (Control/Display Integration); 5.4 (Controls); 5.5 (Labeling); 5.6 (Anthropometry); 5.8 (Environment); and 5.13 (Hazards and Safety).

- PRODUCTION BASE—A technology with a large production base is desirable from the aspects of cost, competition, availability, and variable demand profiles.

The above evaluation factors are meant to guide the program away from designs and technologies that are obviously not appropriate for the Soldier System. However, they should not be constraints that preclude the investigation of promising systems because some of the factors are not achievable today. When an approach is deficient, a program to correct the deficiency should be considered from the aspects of cost and achievement in a realistic time frame.

Section III
System Analysis

PRIMARY NONRECHARGEABLE BATTERIES FOR THE SOLDIER SYSTEM

(Author: Mr. Fee Leung, ARL)

Introduction

The Soldier System requires a lightweight portable power pack that can provide energy and power for the following scenarios:

	Max Power	Mission Length	Energy Needed
CASE 1	100 watts	24 hours	1,325 watt-hours
CASE 2	300 watts	10 hours	2,400 watt-hours
CASE 3	700 watts	4 hours	1,750 watt-hours

CASE 1 represents the maximum power and total energy needed to operate the Soldier System's helmet electronics, the Soldier Computer, and the blower for a 24-hour mission.

CASE 2 represents the maximum power and total energy needed to operate the Soldier System's helmet electronics, the Soldier Computer, and the Microclimate Cooling Pack for a 10-hour mission.

CASE 3 represents the maximum power and total energy needed to operate the Soldier System's helmet electronics, the Soldier Computer, and the Microclimate Cooling Pack designed to keep the soldier cool during intense activity for four hours.

A battery system can be designed to power Case 1 and Case 2. A lithium anode system is used to provide high power at a reasonable weight.

Lithium metal is preferred due to its chemical characteristics. Lithium is one of the lightest conductive metals. It is highly reactive and currently used in many battery systems.

A battery system of reasonable size and weight cannot be designed to operate Case 3. The power requirements of 700 watts requires a battery with a minimum weight of 20 pounds plus the weight of the Microclimate Cooling Pack, which isn't available now.

Illustrated in Figures 5 and 6 are the energy and power densities of four lithium battery systems: Lithium Sulfur Dioxide, Lithium Manganese Dioxide, Lithium Thionyl Chloride, and Lithium Sulfuryl Chloride (alkaline is added for comparison purposes only—it is not a lithium system). All four systems are used in industry and/or military applications.

Lithium Sulfuryl Chloride is the most energetic system of the four candidates listed in terms of power and energy capabilities. The Soldier Systems' battery pack will utilize this chemistry.

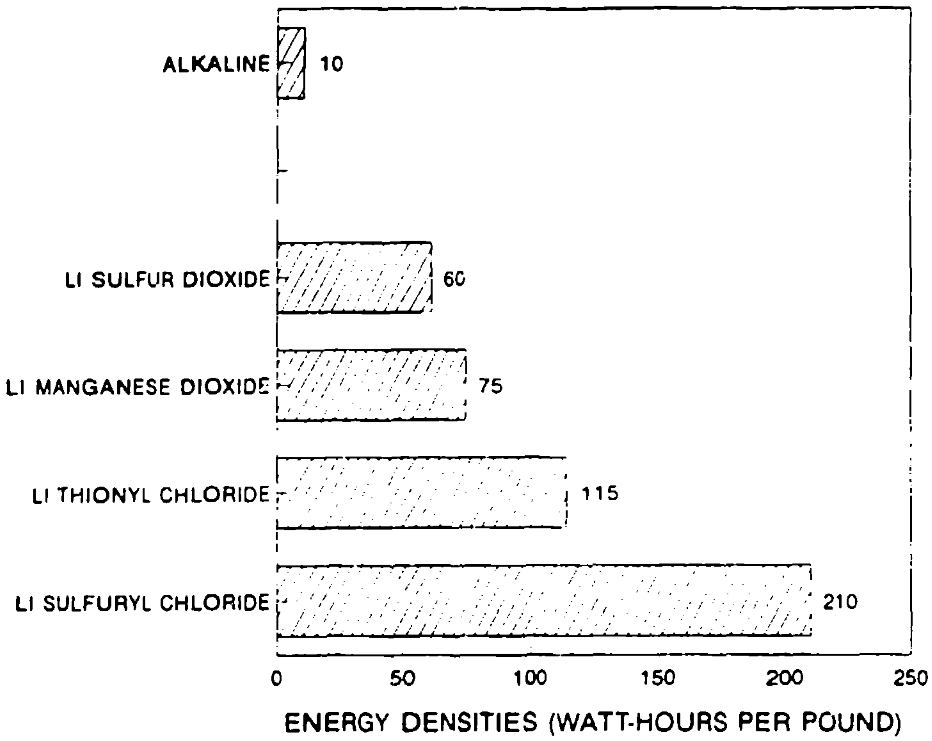

Figure 5. Comparison of Energies Lithium Systems

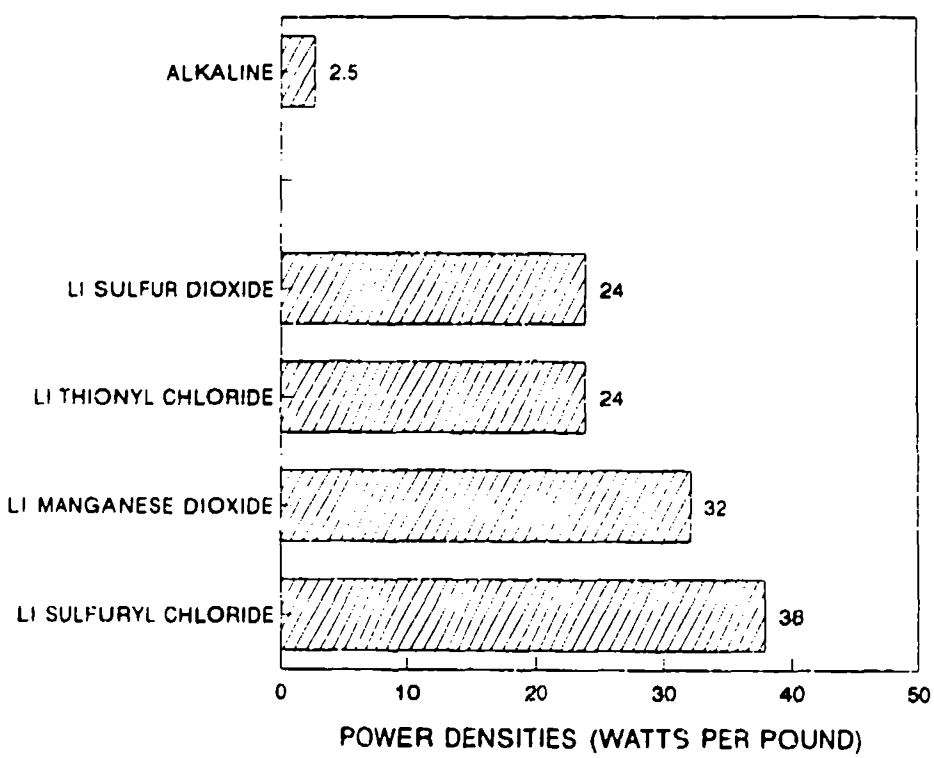

Figure 6. Comparison of Power Lithium Systems

Principle of Operation

Lithium Sulfuryl Chloride cells produce energy through electro-chemical reactions that occur in two sites. These reaction sites are called electrodes (anode or cathode). For the Lithium Sulfuryl Chloride cell, the reactions at the two electrodes are:

Anode Reaction:

$$Li \longrightarrow Li^{+} + e$$

Cathode Reaction:

$$SO_2Cl_2 + 2e \longrightarrow 2Cl^{-} + SO_2$$

The overall cell reaction can be expressed as:

Overall Reaction:

$$2Li + SO_2Cl_2 \longrightarrow 2LiCl + SO_2$$

The change in the standard free energy of this reaction is the driving force which enables a cell to deliver electrical energy to an external circuit. For the Lithium Sulfuryl Chloride cell, the open circuit potential is 3.909 volts.

Design for the Soldier System

The proposed battery pack for the Soldier System contains eight large size "3D" or "long F" sealed, spirally wound cells connected in series and packaged into a high impact plastic case to provide 28 volt DC nominal. The battery pack will be capable of providing 1,344 watt-hours of energy at 224 watts. The general characteristics of the battery pack are listed below:

Open Circuit Voltage	32 VDC
Nominal Operating Voltage	28 VDC
Minimum Operating Voltage	20 VDC
Maximum Power	224 watts
Energy	1,344 watt-hours
Weight	7.5 pounds
Width	7.5 inches
Length	3.0 inches
Height	6.5 inches

The general internal layout of the battery pack is illustrated in Figure 7. The battery pack's case serves as a protective envelope for the cells/internal components as well as a battery box for the manpack cooling system. The battery pack's case will be constructed of high impact plastic (i.e., xenoy), capable of protecting the cells/internal components from the external environment as well as the rigors of rugged use. The battery pack latches onto the bottom of the manpack cooling system, thus eliminating the extra weight/bulk of the traditional equipment battery box.

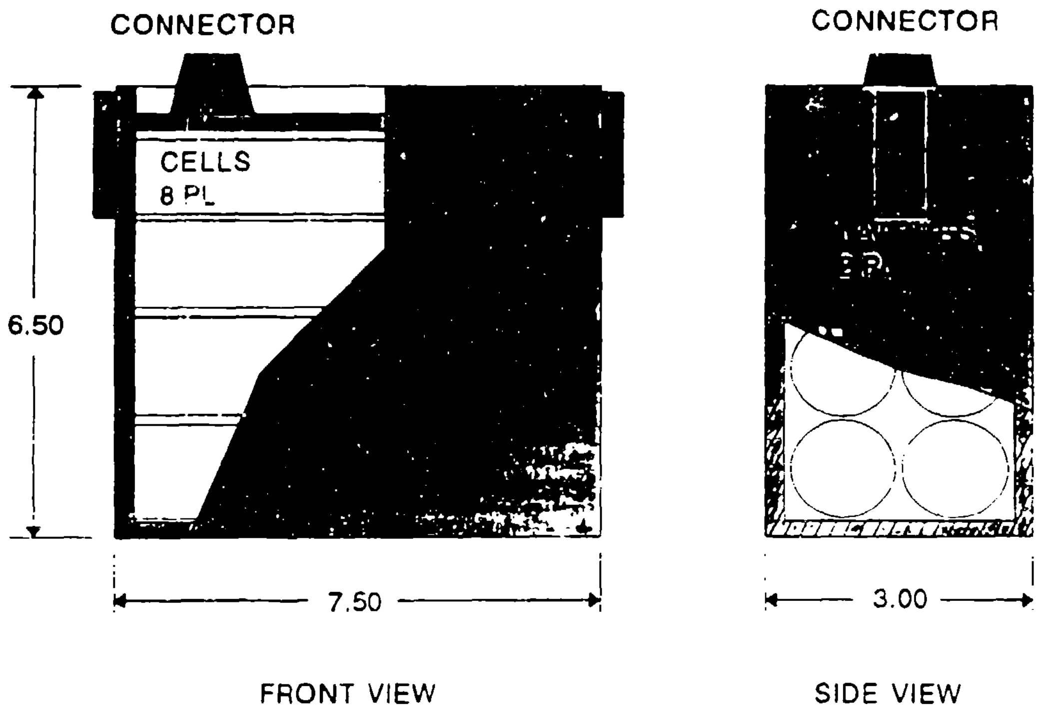

Figure 7. General Battery Layout

The battery pack design has several safety devices to protect the battery from abuse and improper usage. An in-line slow blow fuse will cut the battery off if the discharge current exceeds 8 amperes or an accidental short occurs across the terminals. The fuse can be resettable or nonresettable. The battery will also have an in-line diode to prevent accidental charging by the user. One or more thermal switches located between cells will cut the battery off if internal battery temperatures rise above safe levels. Each of the cells will contain a vent and the battery case will contain a pressure relief device for relieving the internal pressure buildup within the battery pack in the event of a cell venting.

Constructing the battery pack out of xenoy plastic is an added safety feature. The material has been tested by the Army and was able to withstand violent battery ventings without fragmentation.

The weights of the battery pack's components and the projected total weight are listed in Table 1.

Table 1. Weight of Battery Components

3D Cells	6.00 pounds
Diode, Fuse, Thermoswitch	0.05 pounds
Connector	0.05 pounds
Wires, Tabs	0.25 pounds
Battery Case, Latches	1.15 pounds
TOTAL WEIGHT	**7.50 pounds**

This battery pack serves as a building block to power the Soldier System. One battery pack will meet the CASE 1 scenario and two identical battery packs will meet the mission requirements of the CASE 2 scenario. It is believed that this approach of one common power pack/module versus two separate optimized battery packs (one for each scenario) is less expensive, more flexible, and simpler to support.

Using the given weights of the manpack liquid cooled system (see Table 2), the weight impact on each of the scenarios is as follows:

	Battery Weight	Cooling System Weight	Total Weight
CASE 1	7.5 pounds	0.0 pounds	7.5 pounds
CASE 2	15.0 pounds	10.6 pounds	25.6 pounds

Table 2. Weight of Liquid Cooling System

Compressor	1.6 pounds
Condenser	1.2 pounds
Evaporator	1.5 pounds
Fan for Condenser	0.8 pounds
Freon	0.4 pounds
Additional Coolant	1.4 pounds
Tubing/Controls	1.5 pounds
Water Pump	1.2 pounds
Vest	1.0 pounds
TOTAL WEIGHT	**10.6 pounds**

According to Natick RD&E Center, the cooling system (circulating liquid) is hermetically sealed and not dependent on external air for operations. The soldier needs this cooling system when completely sealed in a chemical/biological/radiation protective suit. A power pack not dependent on air, thus immune to the potential effects of contaminants, makes the power pack very compatible with the purpose of the cooling system/protective suit being designed.

Operation of the battery packs requires no special skills or training. The soldier simply latches the battery pack on and turns the cooling system/electronics on. If the battery pack needs to be replaced, it can be done by the soldier in the field without the need for special tools or maintenance skills.

Advantages/Disadvantages

The Lithium Sulfuryl Chloride battery system represents a portable, silent, and reliable power pack. The battery system does not have moving parts, making it a silent and non-signature system. It will not add to the noise and infrared signature given off by the cooling system's pumps and heat exchangers.

The batteries do not need air to operate, thus external environmental conditions won't affect their operations. The only external protection that must be provided is shielding from the elements (i.e., water, salt corrosion) and rugged field handling. This has been addressed by utilizing a plastic battery case and hermetically sealed cells.

By coupling the battery pack with a hermetically sealed cooling system, the soldier will enjoy tactical flexibility in terms of quick movements through streams with no special requirements for fording equipment/preparation.

Replacement of the battery pack in the field is simple. No special training, tools, or extra personnel are required to change the power packs in the event of a malfunction or end of use. The battery packs can be brought forward from the rear area with the food and ammunition.

Developments in Lithium Sulfuryl Chloride technology are applicable to all Army battery operated systems. The battery pack technology is NOT SOLDIER SYSTEM LIMITED. The Army currently buys 600,000 lithium batteries annually, has established a quality assurance program to ensure that safe and reliable products are fielded, and has done extensive testing and analysis of a lithium system (lithium thionyl chloride) similar to the advanced Lithium Sulfuryl Chloride system.

Despite its high energy density, Lithium Sulfuryl Chloride battery systems have not been widely used in industry/military because of their short storage life when compared to other lithium battery systems. Lithium Sulfuryl Chloride battery systems utilize a highly reactive and corrosive electrolyte (sulfuryl chloride) that provides the system its high voltage but also reacts with the lithium, causing excessive film passivation and high rate self-discharge in storage.

Consequently, the Lithium Sulfuryl Chloride system can lose up to 15 percent of its energy in the first year of typical warehouse storage and 7 percent per year afterwards. The Army considers a battery usable if it can provide 85 percent of its rated energy. The Lithium Sulfuryl Chloride system can lose its usefulness within 12 months; other lithium systems can be stored for up to 5 or more years. Research and development needs to be done to improve the Lithium Sulfuryl Chloride's storage life to make it an economical and viable battery power source for military usage.

A 3D or "long" F cell will be one of the largest and most energetic cells ever mass produced and fielded by the Army. The issues of safety, transportation, and disposal must be resolved.

Conclusions

Despite the technical barriers and risks, successful development of a Lithium Sulfuryl Chloride battery system will increase the energy capabilities of current lithium batteries threefold or 300 percent and represents a quantum leap in Army portable battery technology.

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SECONDARY RECHARGEABLE BATTERIES FOR THE SOLDIER SYSTEM

(Author: Mr. Fee Leung, ARL)

Introduction

The Soldier System can use a rechargeable battery pack to provide the user "autonomous" operations away from his/her charging site. The basis of the size and weight for this battery is the nonrechargeable battery pack/module described in Section III, "Primary Nonrechargeable Batteries for the Soldier System." The battery pack will not exceed the 7.5-pound weight and the dimensions given in Figure 8.

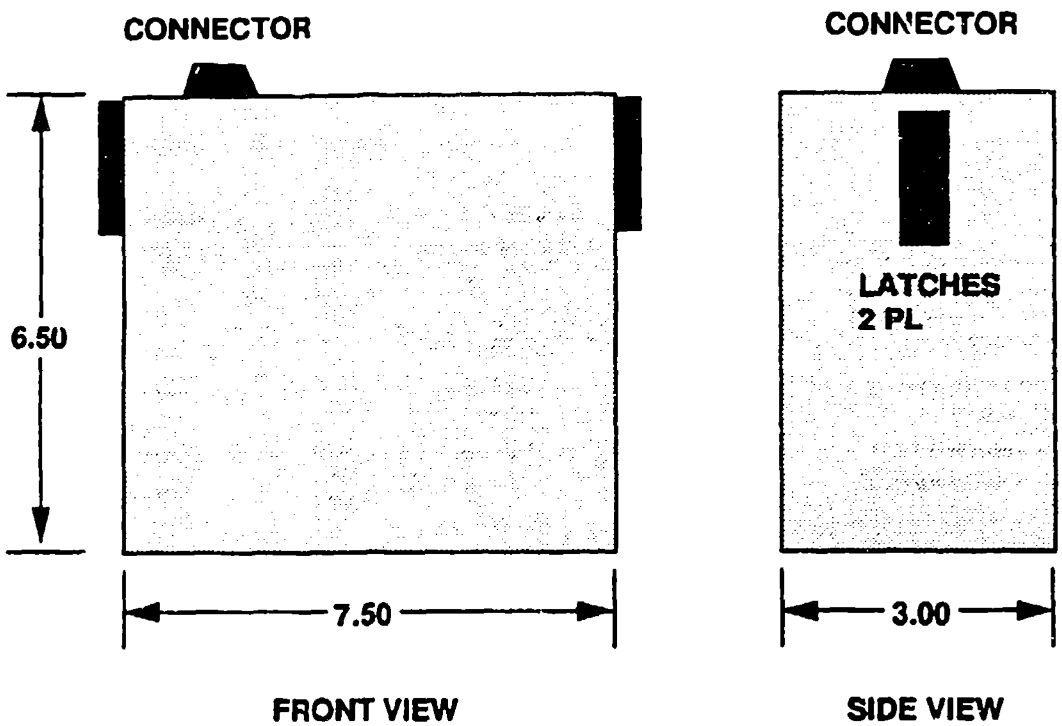

Figure 8. Nonrechargeable Battery

The maximum power requirement of CASE 1 is 100 watts and the nominal power requirement is 55 watts. The maximum power requirement of CASE 2 is 300 watts and the nominal power requirement is 240 watts.

Determining which electrochemical system to use is not simple, because the designer must consider the power, the weight limit of 7.5 pounds, the effects of size on the energy densities of the various candidates, the charging schemes, the required preventive maintenance, and the cost of the system.

The key to the survey of potential systems is the anticipated size of the rechargeable battery and its impact on the projected energy and power densities of each candidate system. Analysis of energy/power densities quoted by commercial brochures and literature on zinc cathode and silver anode systems (i.e., silver cadmium, nickel zinc, silver iron, silver zinc, and silver metal hydride) are based on large plate cells with weights exceeding 10 pounds. These cell designs offer optimal energy and power densities and are often quoted by commercial vendors or proponents.

The energy/power densities of these zinc and silver systems actually decline substantially when scaled down to a smaller 7-pound battery system. Using actual military silver zinc, silver cadmium, and prototype nickel zinc batteries (see Table 3), the energy content versus weight curves are derived in Figure 9. Silver iron systems have the same energy densities and are similar to silver zinc systems. They will share the same proration curve. Silver metal hydride systems are similar to the silver iron system, but their energy density is 25 percent higher. The silver metal hydride energy density curve versus battery weight is based on the silver cadmium energy versus weight proration factors adjusted to the differences in energy densities. The lithium rechargeable battery energy/power densities are based on actual 2- to 4-pound prototype batteries being tested and evaluated by the Army. The comparable energy and power densities of the various systems are illustrated in Figures 10 and 11.

Using the energy/power densities of the candidate systems and applying them against the maximum power requirements and the 7.5-pound weight limit, the battery operating times are listed below:

	CASE 1 100 W Max 55 W Nom	CASE 2 300 W Max 240 W Nom
Silver Cadmium	0.0 hrs	0.0 hrs
Nickel Zinc	1.2 hrs	0.0 hrs
Silver Iron	1.2 hrs	0.5 hrs
Silver Zinc	1.2 hrs	0.5 hrs
Lead Acid	1.3 hrs	0.6 hrs
Nickel Cadmium	1.3 hrs	0.6 hrs
Silver Metal Hydride	2.0 hrs	0.0 hrs
Lithium Solid State	6.8 hrs	3.2 hrs
Lithium Nickel Oxide	6.6 hrs	3.0 hrs

Table 3. Actual Energy Densities

Battery	Chemistry	Energy (WH)	Weight (lb)	WH/lb
BB-523/U	Silver Zinc	66	6	11.0
BB-524/U	Silver Zinc	120	8	15.0
BB-525/U	Silver Zinc	186	11	17.0
BB-526/U	Silver Zinc	300	16	19.0
BB-559/U	Silver Cadmium	54	7	7.7
BB-565/U	Silver Cadmium	108	9	11.1
BB-566/U	Silver Cadmium	180	16	11.3
BB-562/U	Silver Cadmium	210	19	11.1
BB-567/U	Silver Cadmium	264	21	12.6
BB-659/U	Nickel Zinc	168	15	11.2
BB-660/U	Nickel Zinc	312	21	14.8
BB-661/U	Nickel Zinc	480	31	15.5

NOTES:

1. Silver Iron energy density is same as Silver Zinc.
2. Silver Metal Hydride is similar to Silver Iron except 25 percent more energy.

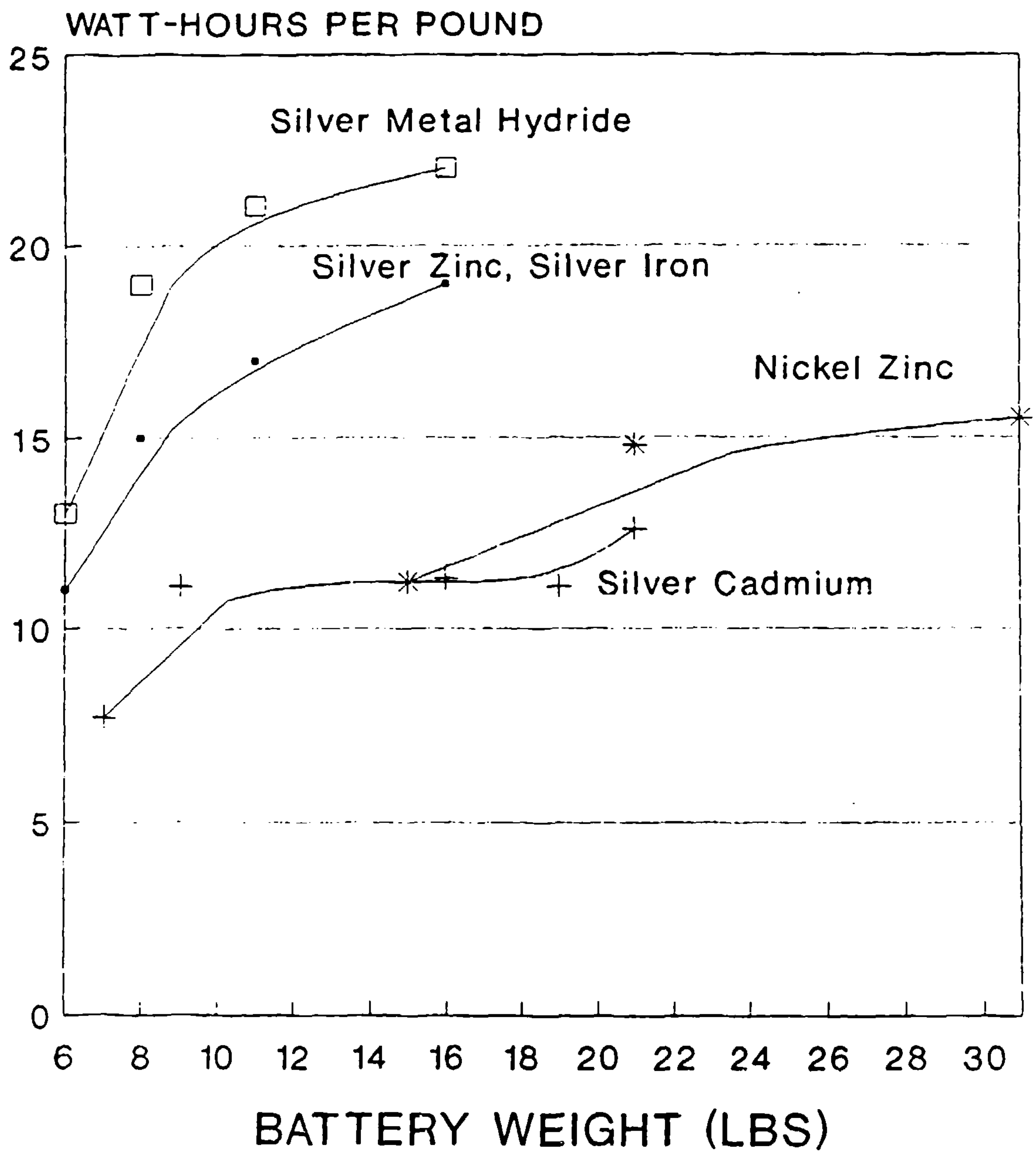

Figure 9. Energy Densities Prorated by Weight

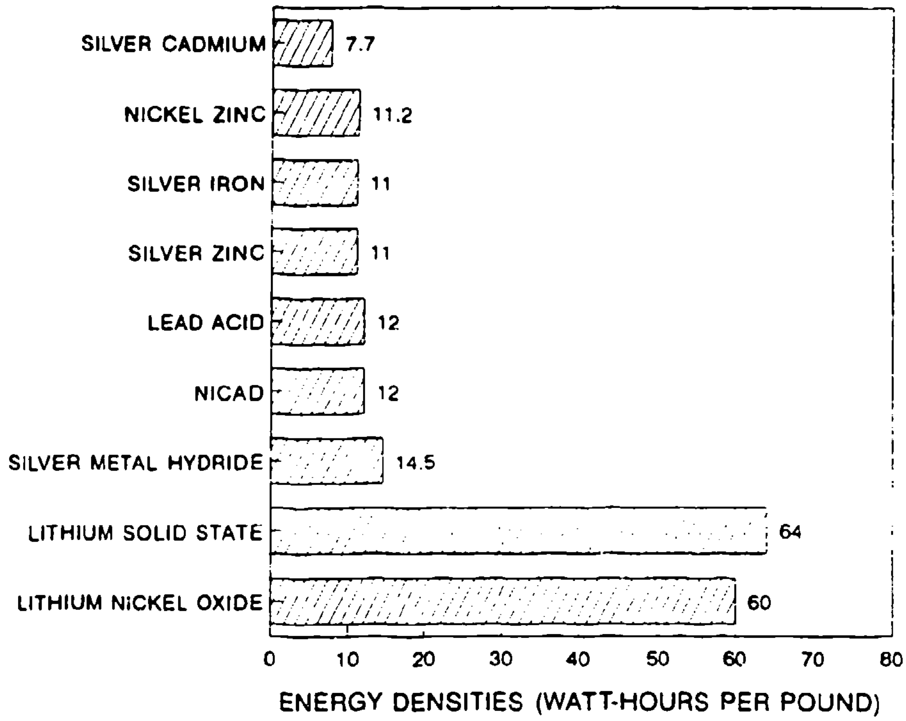

Figure 10. Comparison of Energies Rechargeable Systems

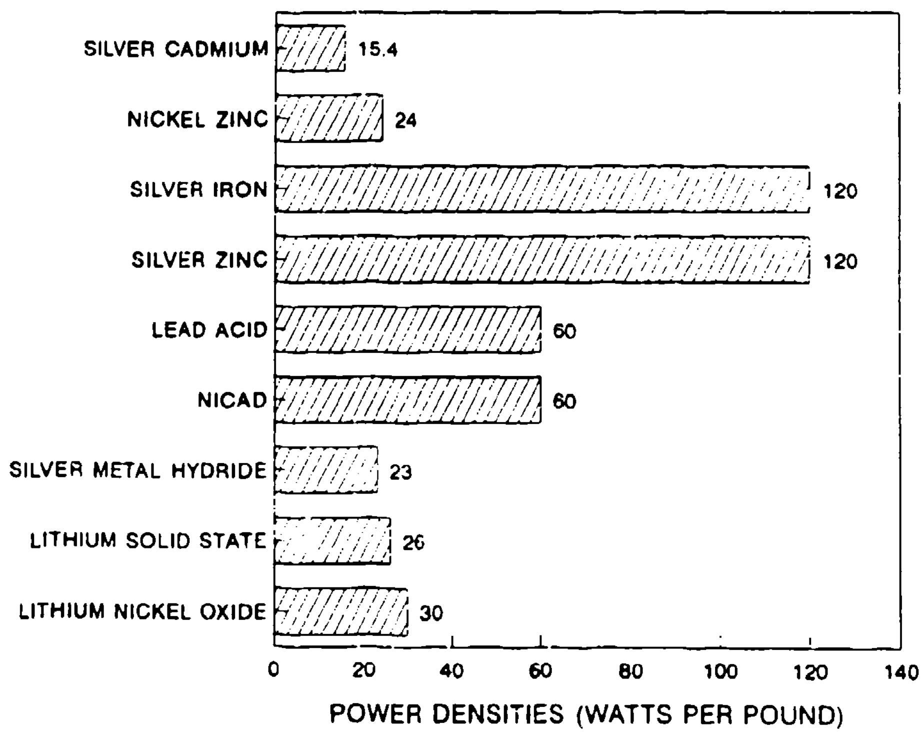

Figure 11. Comparison of Power Rechargeable Systems

It should be pointed out that in CASE 2 the soldier can use two 7.5-pound battery packs. Therefore, the operating times in CASE 2 represent two 7.5-pound battery packs. Overall, the rechargeable lithium systems (both solid and liquid) provide the longest operating times between charges in a 7.5-pound battery pack or packs. The rest of the report concentrates on the rechargeable lithium technologies.

Two rechargeable lithium systems (Lithium Solid State and Lithium Nickel Oxide) are described in this report. These systems are currently being tested and evaluated by the Army to establish baseline data for research and development.

Principle of Operation

The Lithium Solid State bi-polar cells produce energy through electrochemical-chemical reactions that occur in a solid-state ion exchange reaction:

$$Li_xN_{(s)} + M \longrightarrow N_{(s)} + Li_xM_{(s)}$$

where M, N are solid electrode materials which can form insertion compounds with lithium and, if N is absent, the anode is a non-insertion material (lithium metal or lithium alloy).

The change in the standard free energy of this reaction is the driving force which enables a Lithium Solid State cell to deliver electrical energy to an external circuit. For the Lithium Solid State cell, the open circuit potential is 3.2 volts. Unlike nonrechargeable batteries, these reactions are reversible. When an electrical energy is applied to the cell, the reaction reverses. The change in the standard free energy of the reverse reaction enables the cell to convert the electrical energy into stored chemical energy.

The Lithium Nickel Oxide cells also produce energy through electrochemical-chemical reactions at two electrodes (anode and cathode). The reactions are:

Anode:

$$0.30\ Li \longrightarrow 0.30\ Li+ + 0.30\ e$$

Cathode:

$$LiO_{0.60}NiO_2 \longrightarrow Li_{0.90}NiO_2{}^{+0.30}$$

The overall cell reaction is:

$$0.3\ Li + LiO_{0.60}NiO_2 \longrightarrow Li_{0.90}NiO_2$$

The open circuit potential for the cell is 4.10 volts. When an electrical energy is applied to the cell, the electrodes reverse roles, anode becomes cathode and cathode becomes anode, and the reactions reverse. The free energy changes of the reversed reactions cause the cell to convert the electrical energy to stored chemical energy.

Design for the Soldier System

The proposed battery pack for the Soldier System contains eight D cells or ten sealed bi-polar cells connected in series and packaged into a plastic case to form a 24-volt DC nominal power pack. The Lithium Solid State pack can provide 384 watt-hours of energy, and the Lithium Nickel Oxide pack can provide 360 watt-hours of energy. The general characteristics of the battery packs are listed below:

	Lithium Solid State	Lithium Nickel Oxide
Open Circuit Voltage	32.0 VDC	32.8 VDC
Nominal Operating Volt	25.6 VDC	24.0 VDC
Minimum Operating Volt	20.0 VDC	20.0 VDC
Maximum Power	120 watts	120 watts
Energy	384 watt-hours	360 watt-hours
Weight	7.5 pounds	7.5 pounds
Width	7.5 inches	7.5 inches
Length	3.0 inches	3.0 inches
Height	6.5 inches	6.5 inches
Cell Design	bi-polar	spiral wound

The general internal layout of the two lithium systems are illustrated in Figures 12 and 13. The battery pack's case serves as a protective envelope for the cells/internal components as well as a battery box for the manpack cooling system. The battery pack's case will be constructed of high impact plastic (i.e., xenoy), capable of protecting the cells/internal components from the external environment as well as the rigors of rugged use. The battery pack latches onto the bottom of the manpack cooling system, thus eliminating the extra weight/bulk of the traditional equipment battery box.

The battery packs will have an electrical circuit which regulates the charging process, prevents the battery from discharging at rates beyond 5 amperes, monitors the energy content in the battery during discharge and charging, and shuts the battery down when high internal temperature conditions occur. The Lithium Solid State bi-polar cells utilize a solid polymer electrolyte and will produce very little internal pressure during charge. They may not require a vent on the cell design. The Lithium Nickel Oxide cells utilize liquid electrolytes and will build up pressure during charging. In the event that the internal pressure of the cell reaches unsafe levels, the cell would be equipped with a vent to relieve any pressure buildups.

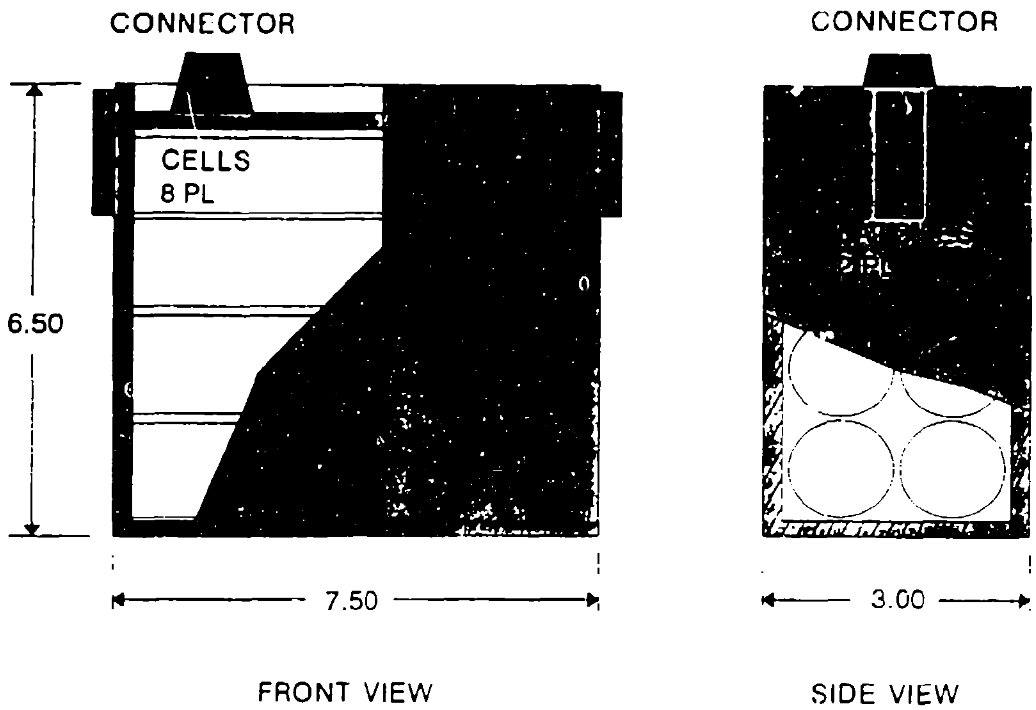

Figure 12. General Battery Layout for the Lithium/Nickel Oxide Battery

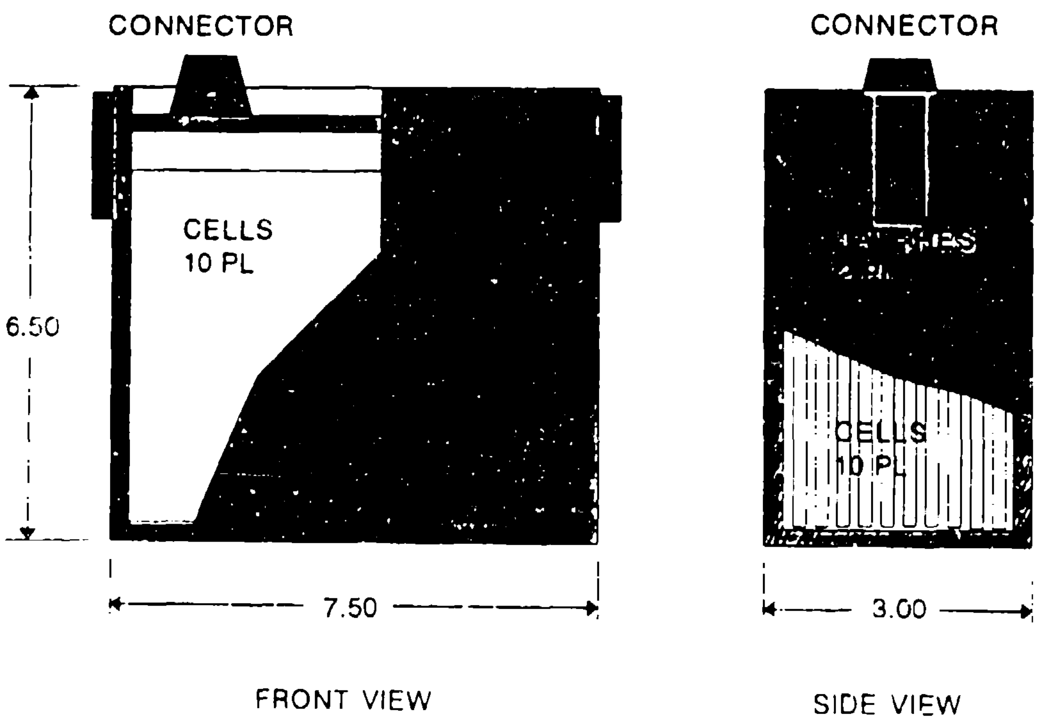

Figure 13. General Battery Layout for the Lithium Solid State Battery

Advantages/Disadvantages

The Lithium Solid State and Lithium Nickel Oxide rechargeable battery systems represent a portable, silent, and reliable power pack. The battery system does not have moving parts, making it a silent and non-signature system. It will not add to the noise and infrared signature given off by the cooling system's pumps and heat exchangers.

The batteries do not need air to operate, thus external environmental conditions will not affect its operations. The only external protection that must be provided is shielding from the elements (i.e., water, salt corrosion) and rugged field handling. This has been addressed by utilizing a plastic battery case and hermetically sealed cells.

Coupling the battery pack with a hermetically sealed cooling system, the soldier will enjoy tactical flexibility in terms of quick movements through streams with no special requirements for fording equipment/preparation.

Replacement of the battery pack in the field is simple. No special training, tools, or extra personnel are required to change the power packs in the event of a malfunction or end of use. The battery packs will be brought forward from the rear area with the food and ammunition.

The Lithium Solid State and Lithium Nickel Oxide rechargeable batteries will provide the soldier a low cost, renewable power source for peacetime training.

Development of the Lithium Solid State and Lithium Nickel Oxide technology will be applied to all Army battery-powered systems. The battery pack technology is NOT SOLDIER SYSTEM LIMITED. The Army currently buys 600,000 lithium batteries annually, and has established a quality assurance program that ensures safe and reliable products are fielded.

Despite its high energy density, rechargeable lithium batteries are not ready for industrial, commercial, and military use. Work needs to be done on developing stable lithium anode/electrolyte stability during cycle life. Current lithium rechargeable battery systems can provide up to 75 charge/discharge cycles. In order to make the system cost effective against lead acid and nickel cadmium batteries, the lithium systems must achieve 100 plus cycles. The issues of safety during charging and overcharging, and rapid charging must be resolved. The Lithium Solid State systems must overcome their poor energy and power densities at low temperature conditions. The lithium rechargeable cells will be one of the largest and most energetic rechargeable cells ever mass produced and fielded by the Army. The issues of safety, transportation, and disposal must be resolved.

Conclusions

Despite the technical barriers and risks, successful development of a Lithium Solid State and/or Lithium Nickel Oxide system will increase the energy capabilities of current Army rechargeable batteries fivefold or 500 percent and represents a quantum leap in Army portable rechargeable battery technology.

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FUEL CELL POWER SOURCES FOR THE SOLDIER SYSTEM

(Author: Mr. Richard Jacobs, BRDEC, SATBE-FGE)

Introduction

Fuel cells convert the chemical energy of fuels directly into electrical energy and heat. The simplest operation is obtained when hydrogen and oxygen are electrochemically combined to produce water, electrical power, and heat. When different fuels are used, the system becomes more complex. The performance of fuel cell systems is not limited by the Carnot Cycle. Electrical efficiencies in excess of 40 percent are obtainable. The energy efficiency of fuel cells is even higher when practical use of the waste heat is a factor, and that can be as high as 80 percent. This waste heat can be utilized productively in heating systems or bottoming cycles.

These and other characteristics make the fuel cell a candidate for many general and specific applications. The general applications are primarily in the electric utility field and range from multi-kilowatt through multi-megawatt sizes. The more specific applications refer to smaller quantities/sizes and are found in outer space, under water, and in areas where the positive attributes of fuel cells can be exploited. Many of these are in environments where the oxidant for the power source is not available from ambient surroundings and must be supplied.

Fuel cells operate like a battery that has a continuous supply of energy. In the fuel cell, the electrodes are not consumed (as in batteries) and function to provide the structure, flow, electrical contact, and catalytic sites where the reactions occur. The consumables are supplied from an external source. The cell can operate as long as the supply continues. This gives the fuel cell the mechanical advantages of a battery and the logistic advantages of a refuelable power source such as an engine.

When determining the best approach, many factors must be considered. The type of fuel cell, source of fuel, and oxidant must all be considered. Types include alkaline, acid, solid oxide, molten carbonate, and solid polymer. The type usually refers to the electrolyte used to promote the reaction. Fuel cells are also referred to by the type of chemicals used in the system (hydrogen/oxygen, methanol/air, metal hydride/hydrogen peroxide). Some of the possible fuels usable are hydrogen, methanol, lithium, hydrides, hydrocarbons, and aluminum. Possible oxidants include air, oxygen, water, and various oxides.

Fuel cell power sources of almost any kind can theoretically be tailored to meet the demands of the soldier system. The primary technical obstacles of these systems are the start-up characteristics, waste heat removal, and the method of processing the fuel/fuels. Although high temperature fuel cells and fuel cell systems utilizing complicated fuel processing techniques may someday be considered for this application, the logical starting point is a low temperature cell (<200°F) operating on hydrogen and oxygen. Once the operational merits of this type of system are demonstrated, other technical approaches may be considered. These considerations led to the selection of a Proton Exchange Membrane (PEM) cell. Even this type of cell, which is approaching commercialization, has several technical obstacles to overcome before it can meet the tough requirements of a portable military power source. These problems are discussed in the section on advantages/disadvantages below.

Principles of Operation

A fuel cell is an electrochemical device that combines chemical fuels to produce electrical power, heat, and chemical by-products. In the proposed system the chemicals are hydrogen and oxygen. The by-product is water. The components of a fuel cell are the matrix, electrodes, bipolar plates, and structural members. The matrix in this case is a Proton Exchange Membrane (PEM). This component allows hydrogen ions (along with water) to migrate from the hydrogen electrode to the oxygen electrode where they combine with oxygen to form water. The reaction at each electrode and the overall reaction are represented as:

Anode:

$$2\ H_2 > 4\ H+ + 4e$$

Cathode:

$$4\ e + 4\ H^+ + O_2 > H_2O$$

Overall:

$$2\ H_2 + O_2 > 2\ H_2O + \text{heat}$$

The electrodes consist of a catalyzed layer that provides the sites for the electrochemical reactions. They must provide a structure that allows gases, electrons, water, and the catalyst to interact so that the electrochemical reactions can proceed in an optimal fashion. The catalyst used in the PEM cell is typically a highly dispersed platinum. A typical fuel cell is depicted in Figure 14. As shown, the bipolar plates on either end of the stack are really half plates and are where the electrical power output is connected.

When single cells are connected to produce a cell stack, it is necessary to provide a component that conducts electrons, routes gases to the proper electrode, and separates reactants. This component is called a bipolar plate. In a cell stack, bipolar plates contact the anode (negative hydrogen electrode) of one cell and the cathode (positive oxygen electrode) of the next cell. The bipolar plates must have high electrical conductivity to reduce losses caused by electron flow through the plates. They must also be impermeable to the reactants so that the hydrogen and oxygen do not mix directly to form water and heat without the desired proton/electron flow. Figure 15 depicts the arrangement of a typical stack using repeating elements.

In a fuel cell stack there is also a need for gas manifolds, heat management, endplates (mechanical compression), and, in the case of the PEM cells, a technique for water management. The manifolds route the incoming gases to either the anode or cathode side of each bipolar plate. The structure of the bi-polar plate then distributes the gas evenly over the surface of each electrode. Heat management techniques can range from simple conduction to forced air to recirculated liquid cooling. The endplates of the fuel cell stack maintain compression to provide low resistance and gas sealing. Water management in PEM cells is of considerable importance since too much or too little water will cause performance to drop off. The various techniques for water management vary with power level, construction technique, and manufacturer.

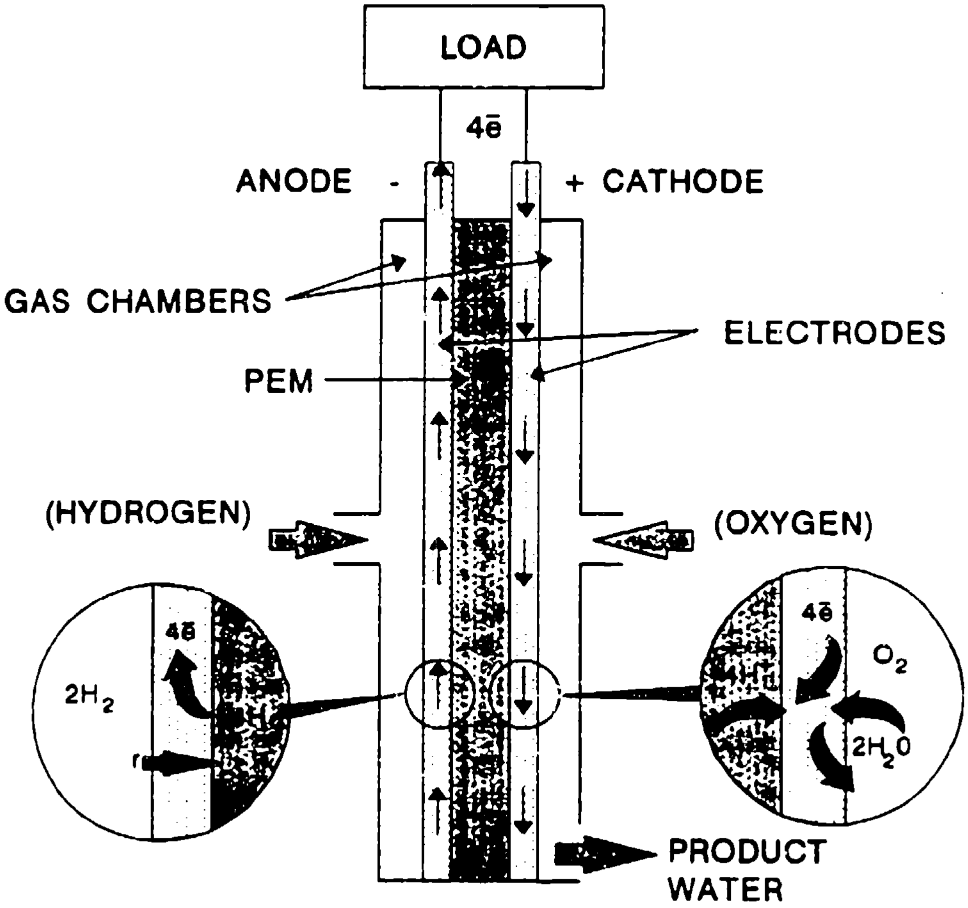
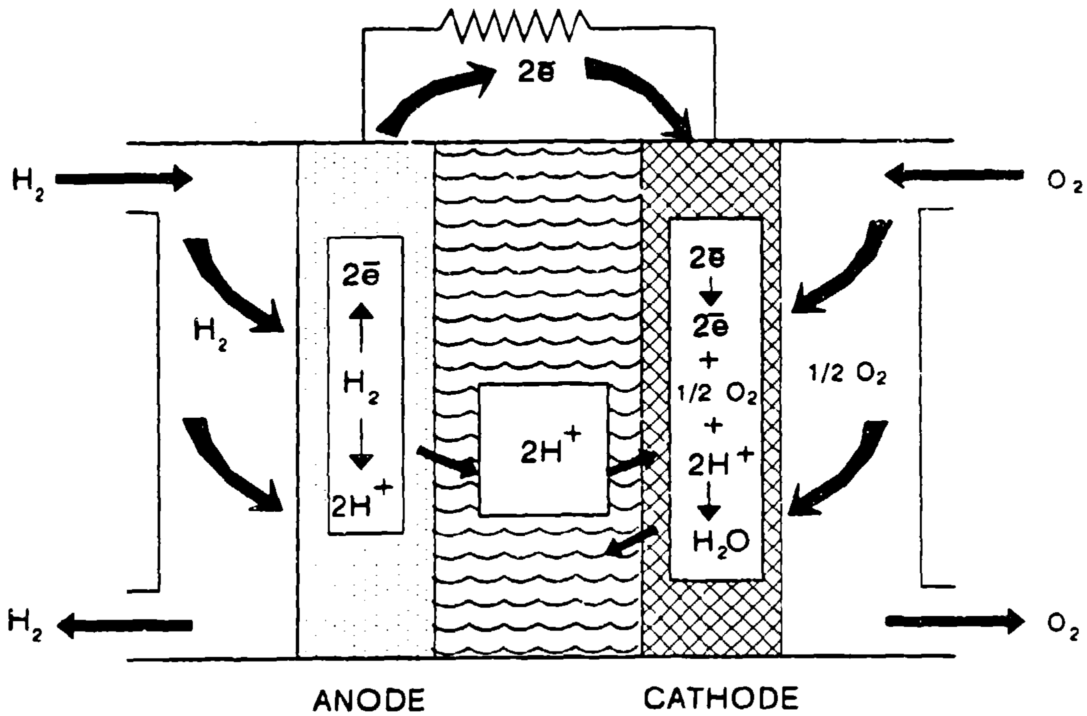


Figure 14. Schematic of a Fuel Cell



ACID ELECTROLYTE

ANODE REACTION

$$H_2 \longrightarrow 2H^+ + 2\bar{e}$$

CATHODE REACTION

$$1/2\ O_2 + 2H^+ + 2\bar{e} \longrightarrow H_2O$$

OVERALL

$$H_2 + 1/2\ O_2 \longrightarrow H_2O$$

A fuel cell is a device which produces electricity cleanly, silently and efficiently. Like the familiar dry cells and lead acid batteries, fuel cells work by virtue of electrochemical reactions in which the energy of a fuel and an oxidant are directly transformed into direct current electricity. Unlike batteries, however, fuel cells do not consume the chemicals that are part of or stored within their structure. The reactant chemicals used by fuel cells are supplied from an external source. This feature, in principle, allows the fuel cell to operate as long as fuel and oxidant are supplied and reaction products removed. The schematic below shows general construction and reaction equations.

Figure 14. Schematic of a Fuel Cell – continued

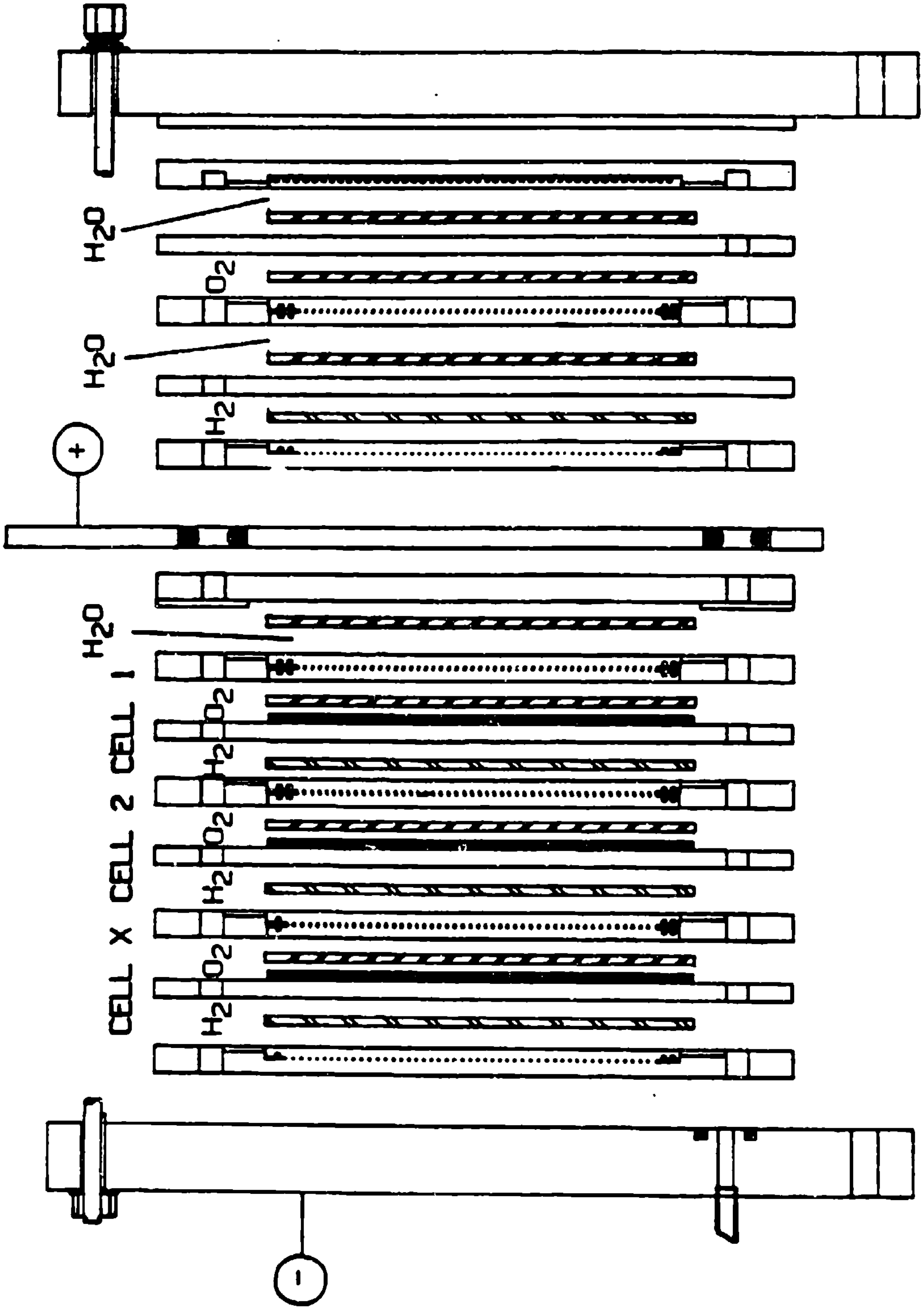


Figure 15. Fuel Cell Stack Cross Section

Design for the Soldier System

The PEM fuel cell is the current choice for soldier system development efforts. This cell electrochemically combines hydrogen and oxygen to produce water, heat, and electrical power. The proposed system stores the gases in high pressure gas vessels and supplies hydrogen to the anode and oxygen to the cathode via gas regulators. The reaction is: $2\ H_2 + O_2 = 2\ H_2O$. Using an immobilized electrolyte such as the PEM provides a cell that has low corrosion, is simple to seal, and exhibits high efficiency. The proposed operating point is 0.8 volts per cell and 650 amps per square foot (ASF). This performance is obtained at operating temperatures of 85 to 90°C. The amount of hydrogen is derived using 26.8 amp-hours per gram of hydrogen. The amount of oxygen is derived using 3.35 amp-hours per gram of oxygen. The reaction produces a gram of water for every 2.98 amp-hours. These reaction numbers are for a single cell. To obtain the number of cells required, the output voltage (24 volts) is divided by the per cell voltage (0.8 volts) to yield 30 cells. A case where the output voltage is 24 volts and the mission is 2,400 watt-hours gives a value of 100 amp-hours.

For Hydrogen:

100 amp-hours/26.8 amp-hours per gram/cell = 3.73 grams/cell x 30 cells = 111.9 grams

For Oxygen:

100 amp-hours/3.35 amp-hours per gram/cell = 29.8 grams/cell x 30 cells = 895.5 grams

The amount of water produced is 1,007.4 grams. This gives a total fuel weight of about 1 kg for a 2,400 watt-hour mission. To estimate the size of the fuel cell, a maximum output of 300 watts is used in this example. At 24 volts, this gives 12.5 amps. The size of each cell is 12.5 amps divided by 650 amps per square foot or 0.019 square feet (2.77 square inches). A cell 1.66 inches x 1.66 inches is needed. Using a pitch of 3 cells per inch and allowing for seals gives a stack size estimate of 2 inches x 2 inches x 10 inches and a weight of 3 pounds.

The hydrogen and oxygen for the proposed system is contained in lightweight, high pressure, Kevlar/Carbon Filter Fiber wrapped gas cylinders. For the proposed 2,400 watt-hours, a volume of approximately 340 cubic inches for the hydrogen and 170 cubic inches for the oxygen is required. An estimate of the gas cylinder size is 12 inches high and 6 inches in diameter for the hydrogen and 12 inches high and 4.5 inches in diameter for the oxygen. The total weight of these cylinders is 5 pounds. The rest of the system consists of a one-pound controller/conditioner that monitors the system and regulates the output (this may not be necessary if the using equipment can accept voltages in the military range of 20 to 32 volts); gas regulators to control the flow and pressure of the reactants (1 pound); a housing that weighs 3 pounds; and, in the 300 watt case, an air conditioning subsystem described in the cooling sections of this report. For the 100 watt, 1,325 watt-hour case, the fuel cell weight estimate is 2 pounds; the cylinder's weight drops to 3 pounds; fuel weight is 1.2 pounds; the controller/conditioner is 0.5 pound; and the housing is 2 pounds.

Advantages/Disadvantages

A pressurized fuel cell power unit is one of the candidate systems being considered as a power source for the Soldier System. This technology is not yet mature. It is expected to require several years of development. Units could be available for testing by 1994 with adequate funding. The pros and cons of a fuel cell system are well known and have been discussed in detail in various technical publications. Each application requires its own evaluation based on its requirements. The power source used for the Soldier System must meet military requirements and be man portable. The following is a discussion of the proposed fuel cell system using our investigation's evaluation criteria.

- COST—The cost of this system is expected to be high. It is an emerging technology in this application and requires significant development costs. It also requires new logistic capabilities, additional training, and new items in the Army's inventory. The proposed system uses hydrogen and oxygen as reactants. Supplying special fuels is costly so this will impact operating costs.

- WEIGHT—Current fuel cell systems for this application are too heavy. Considerable development efforts in fuel cell stack and reactant delivery systems will be required to meet the desired system weight.

- SIGNATURE—The fuel cell system is a static device. It exhibits low noise, low IR, and low vibration. The fuel cell system is efficient and has no exhaust products except water. If convective cooling of the fuel cell is used, it will lower the IR signature even further.

- SAFETY—The safety of this system is comparable to the other systems. Using high pressure hydrogen and oxygen is a problem. If this negative issue can't be resolved, different sources of fuel must be developed.

- SIZE—The size of the system is relatively large due to the storage of reactants in gas cylinders. Other means of supplying the reactants are being investigated for consideration.

- VIBRATION/GYROSCOPIC EFFECTS—The fuel cell system is strong in this area because of the static nature of the device.

- EFFECTS OF ATTITUDE—This system will not be affected by changes in attitude.

- SHELF LIFE—The PEM fuel cell contains no lubricated parts. It can be stored for several years if properly packaged.

- INTEGRATED LOGISTIC SUPPORT (ILS)—This system requires special fuels and additional training, and it will add to the Army's inventory. The issue of utilizing a special fuel could cause problems.

- RELIABILITY/AVAILABILITY/MAINTAINABILITY (RAM)—The fuel cell stack in this system requires no maintenance. Laboratory tests show thousands of hours without failure. The challenge for the Soldier System will be to prove the reliability of the entire system in the military environment, including the ability to withstand hundreds of start/stop cycles.

- START/RESTART—The PEM fuel cell requires time to reach full power and has difficulty starting below freezing without some type of start-up system. Once started, the fuel cell is easily stopped by shutting off the gas supplies. The cell may need to be sealed, depending on the water management technique used, but this is a simple procedure.

- PRODUCTION BASE—The production base for fuel cells depends on current commercialization efforts. The larger (100 kW to 10 MW) systems are of greatest interest to most manufacturers, but efforts are underway to produce small power sources in the range of the Soldier System.

- HUMAN FACTORS ENGINEERING (HFE)—The fuel cell system is designed to meet the requirements of human factors engineering and should be comparable to other systems in this area.

Conclusion

Fuel cell technology has been in development for several decades. The Army cannot provide the vast funding needed to bring the state-of-the-art fuel cell to the point of successful commercialization. The Army can leverage efforts underway at the Department of Energy, the Department of Transportation, Los Alamos National Laboratory, the Electric Power Research Institute, and other agencies to provide a strong technical basis for consideration of fuel cell technology for use in the Soldier System. This can be accomplished with a relatively minor investment. Past fuel cell programs in the Army demonstrated the feasibility of fuel cell systems but did not overcome the cost and logistics problems associated with fielding fuel cell power sources. Advances have been substantial in the past several years, as PEM technology has matured. Experimental current densities have increased tenfold. Today there is great interest in the fuel cell for transportation and very high power utility applications (>200 kW). The challenge for the Soldier System application is to apply the successful efforts in these areas to an individual power supply scenario. The current state-of-the-art fuel cells must improve considerably before the fuel cell is a viable candidate for the Soldier System application. Long term performance in the field and fuel delivery techniques are the primary concerns of the Army and the transportation industry. Efforts in utility, transportation, and space applications parallel the needs of the Soldier System but are at a much higher power level. The PEM fuel cell is currently the best candidate for the Soldier System. Other fuel cell technologies such as solid oxide and direct methanol oxidation should be followed to see if these technologies advance to the point where programs can be initiated. The development of a fuel cell power source for the Soldier System would bring all the benefits of the technology like silence, high efficiency, low signature, high reliability, low maintenance, and high power density. These advantages will have to be measured against the cost and logistics difficulties when the program transitions from the technology base arena to an engineering development effort.

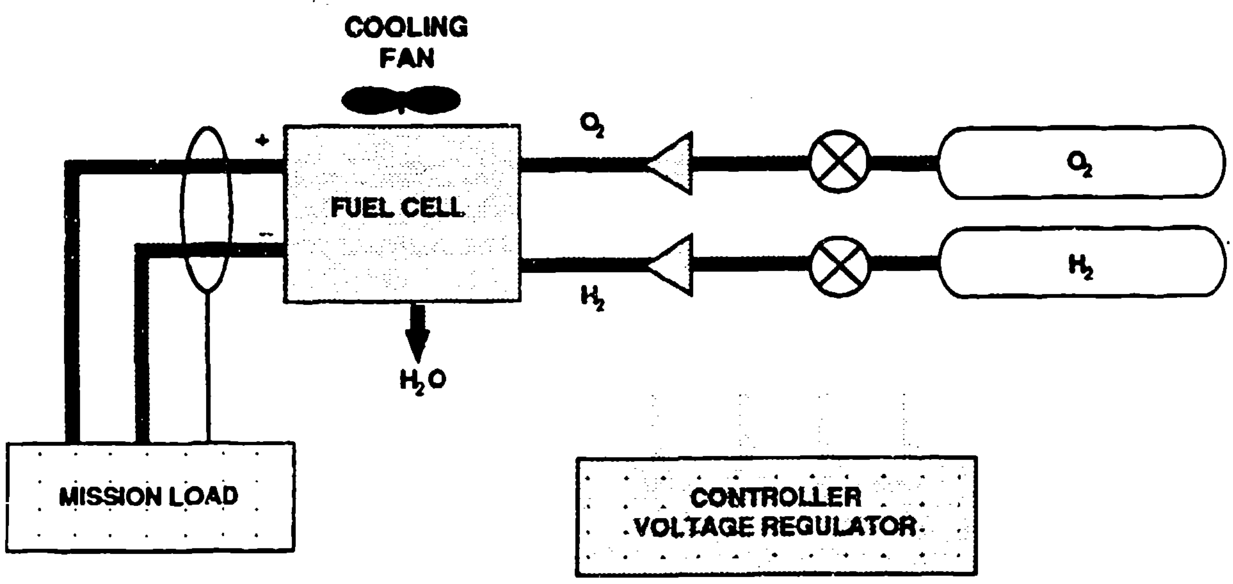


Figure 16. PEM Fuel Cell

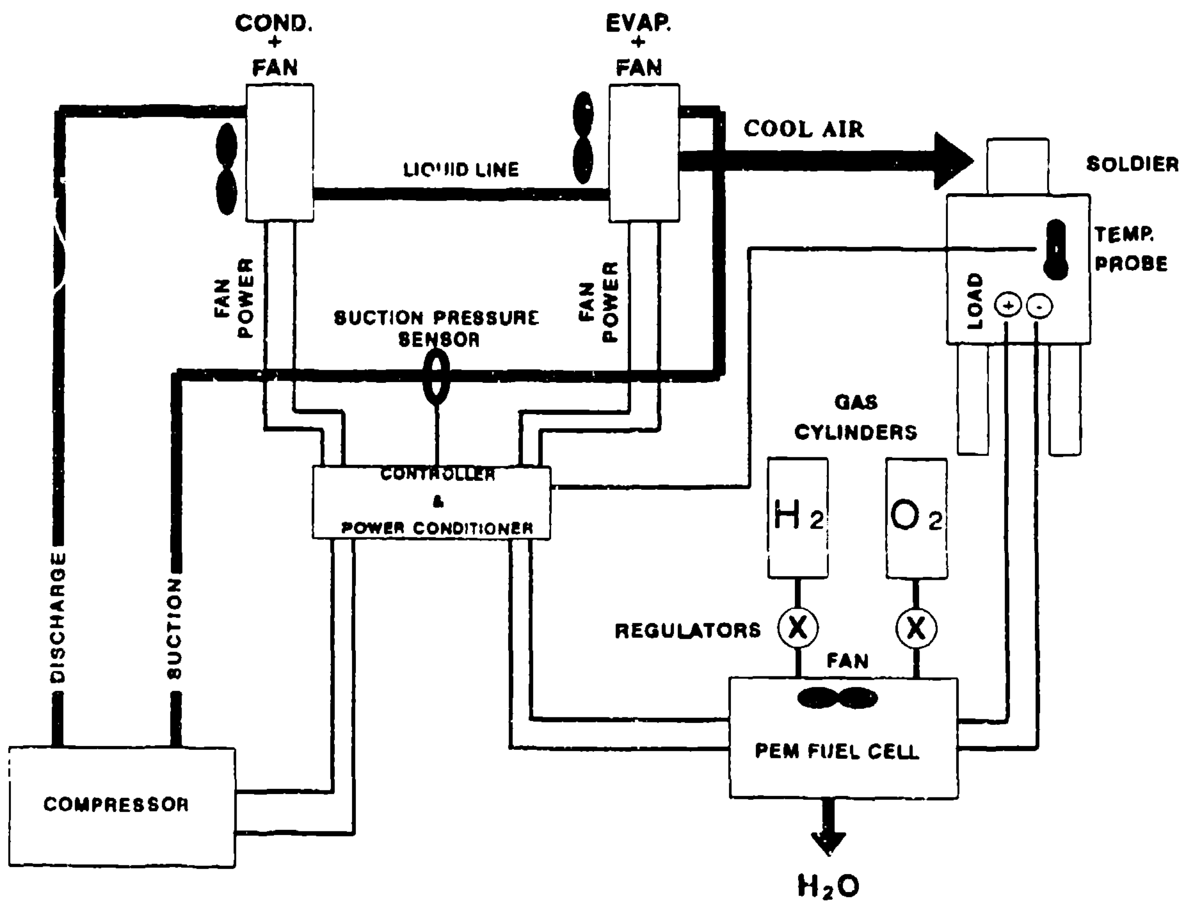


Figure 17. Concept Pressurized PEM Fuel Cell System—300 W

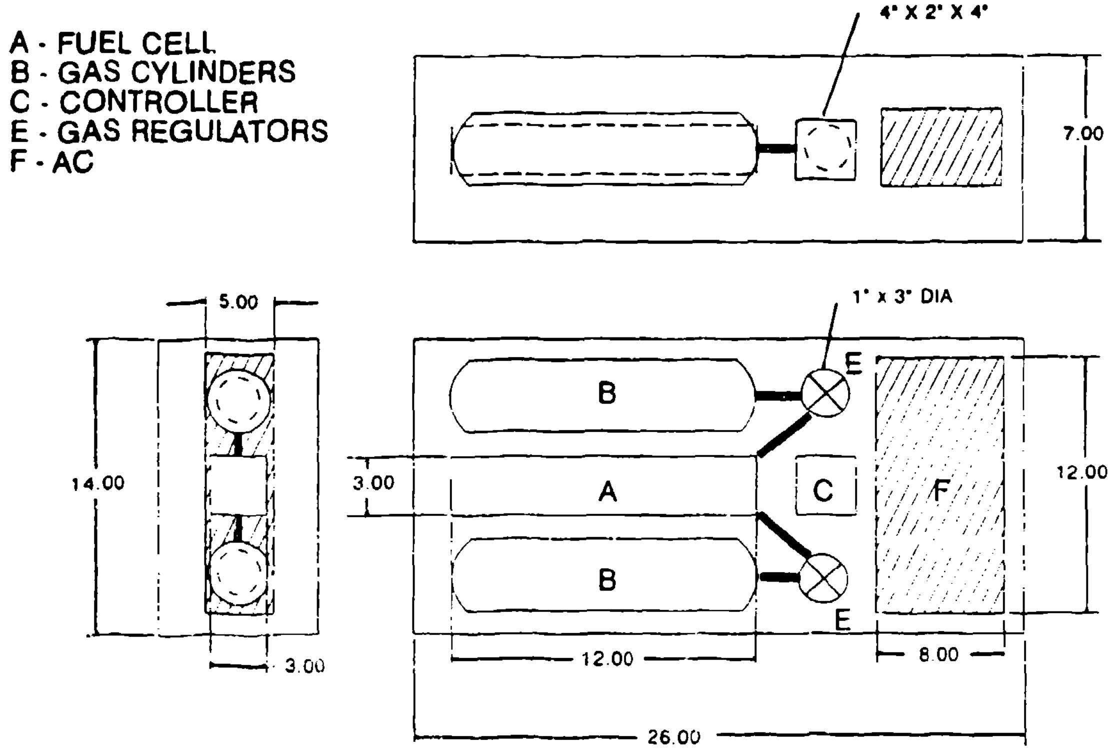


Figure 18. 300-Watt PEM Fuel Cell, Pressurized, Vapor Cycle AC

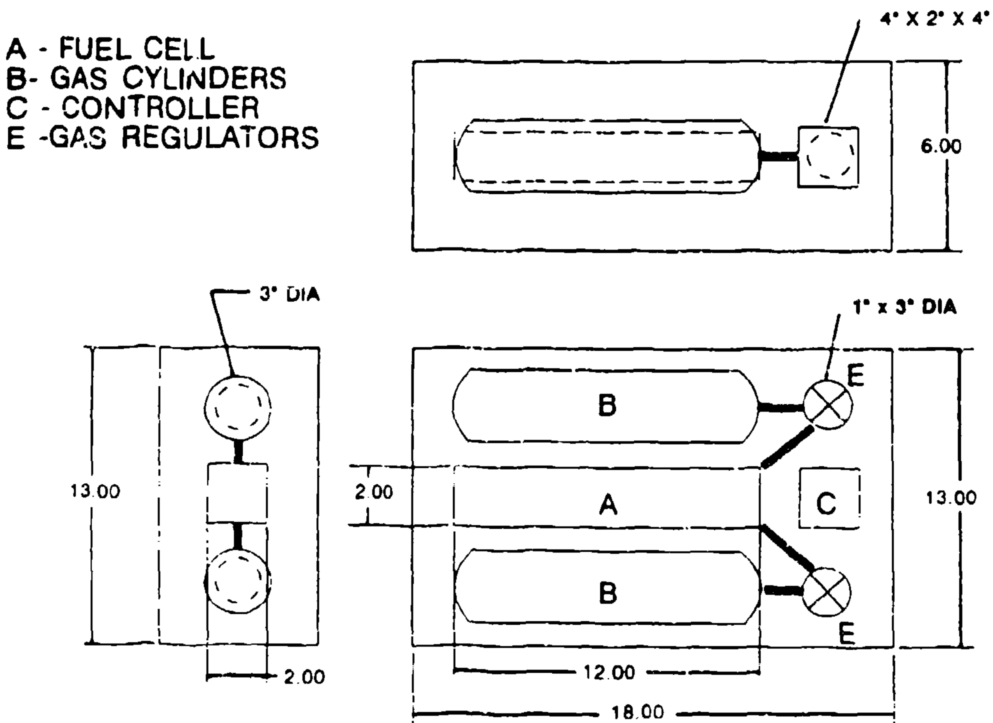


Figure 19. 100-Watt PEM Fuel Cell

SUGGESTED READING LIST FOR FUEL CELLS

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INTERNAL COMBUSTION ENGINE TECHNOLOGY FOR THE SOLDIER SYSTEM

(Authors: Mr. K. Mike Miller, BRDEC, SATBE-FGE and Mr. Robert Ware, BRDEC, SATBE-FGS)

Introduction

In an effort to meet the electric power needs and source size requirements of the Soldier System, use of the internal combustion (IC) engines as both a primary and secondary source is under consideration. IC engines offer a relatively mature technology that is capable of meeting the high energy density requirements of a backpack portable power source. There are several engines in production using this technology. The model airplane and string trimmer engines were chosen for their obvious advantages of speed, compact size, and low cost. They were procured and tested to determine operational characteristics. The string trimmer engines were tested for performance characteristics with respect to the battlefield environments (see Figures 20 through 22). Presently, the technology does not meet our requirements. Improvements in combustion processes, vibration isolation, and noise absorption would produce a viable solution.

Small IC engines are now in production in two-stroke, four-stroke, and rotary versions. This report concentrates on the two- and four-stroke piston engines used by model aircraft hobbyists and those produced for use in portable power tools. These engines are available in sizes ranging from 0.3 to 12.0 cubic inches of displacement and horsepower ratings from 0.3 to 5.0.

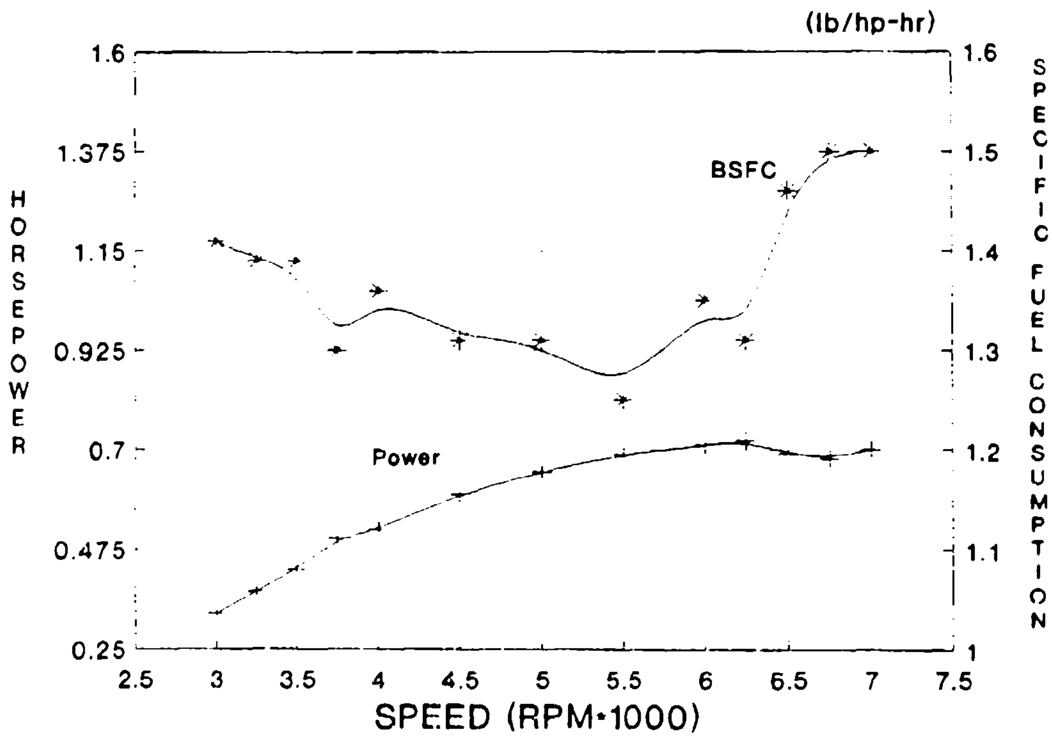

Figure 20. Performance Curves—Homelite 24 cc

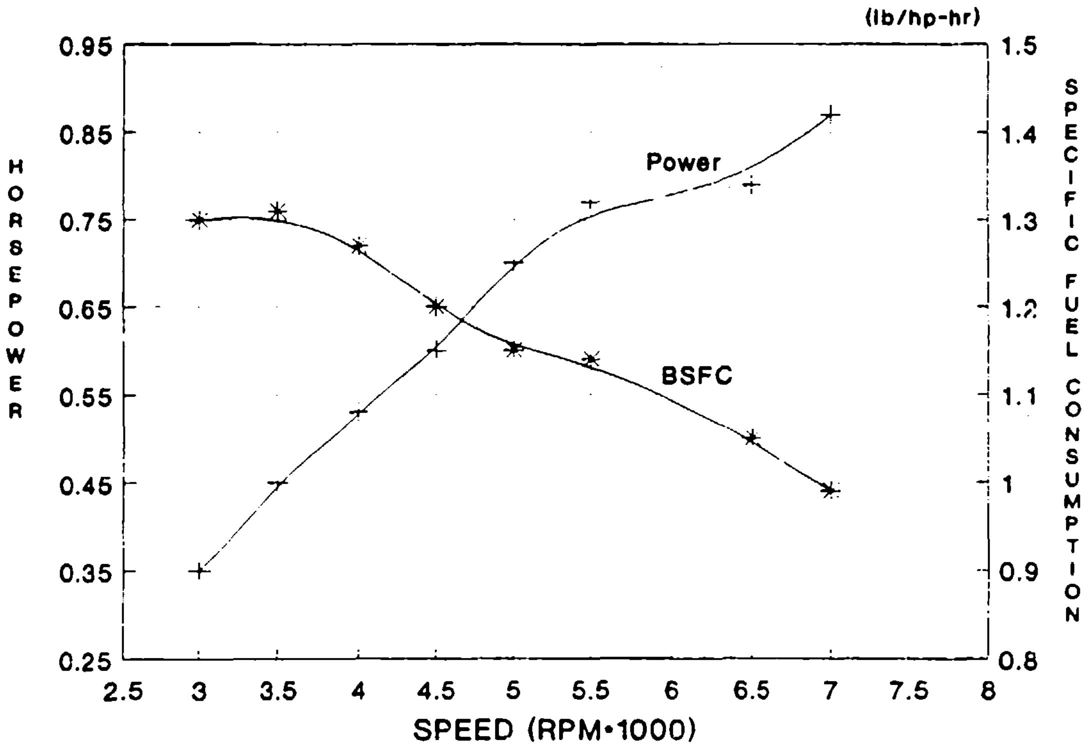

Figure 21. Performance Curves—Astron TD-24 24 cc

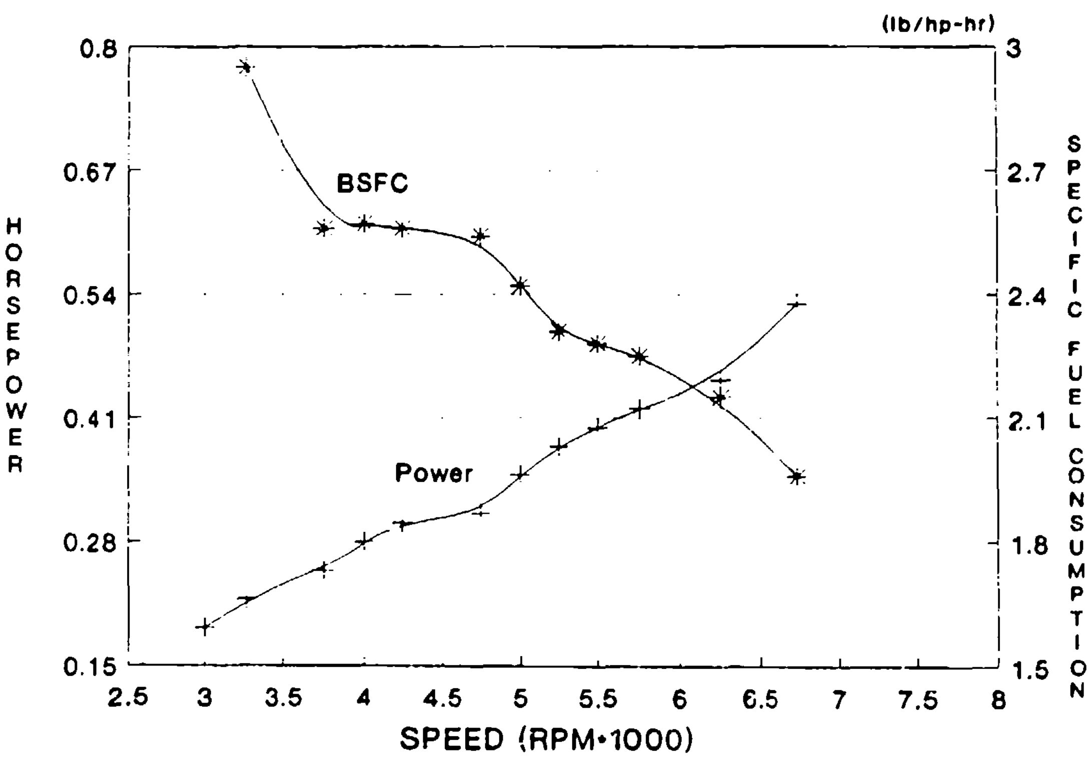

Figure 22. Performance Curves--Astron SW-164 16 cc

Presently, these engines operate on either alcohol/oil or gasoline/oil fuels. These are not logistically available fuels. To consider these small engines seriously as a power source, the capability to operate on middle distillate fuels must be achieved. There are several ongoing programs at both Belvoir RD&E Center and Natick RD&E Center working to convert them to logistically available fuels. Methods for achieving this will be discussed further in this report.

Principles of Operation

Designed for easy starting when enriched fuels are used, model airplane engines are dependable, self-contained units that demonstrate reasonable thermal efficiencies. The small engines tested are low in thermal efficiency due to their small diameter cylinders and high operational speeds (10-18,000 rpm). Combustion limits such as flame speed result in unburned fuel exiting in the exhaust. A thermal efficiency of 20 to 30 percent for a small air-cooled engine running at 3,600 rpm was assumed during the initial analysis. Testing was done for verification. These engines need no special tools for maintenance. Since the exhaust muffler is adjustable on many models, the possible hazard of exhaust smoke burning the soldier can be eliminated.

The string trimmer engines represent the highest power density engines available in production that operate on gasoline. They are high speed (8-10,000 rpm), air-cooled, two-cylinder engines complete with fuel systems and cooling shrouds, etc. The tested engines represent the power range of interest (1 to 2 horsepower) but are too heavy for that application in their current configuration. However, they are fully developed and should survive many missions and provide an acceptable level of reliability. Integrating the engine with a fly-wheel generator and a close-coupled, speed-matched compressor efficiently may allow the system to fall into the range of consideration.

Engine cooling is required for maintaining any engine at safe operating temperatures. The selection of the fan was accomplished by matching the operating characteristics of the fan with the total air flow requirements of the system. The fan is required to move air effectively and efficiently under varying load and environmental conditions. Air cooling is more easily achieved in the four-stroke than in the two-stroke engine due to the intermittent combustion process of the four-stroke engine.

There are both two- and four-stroke engines currently available commercially. The primary difference between these engines is the method in which they breathe. A naturally aspirated two-stroke engine of the type being considered in this report is a loop-charged engine. This engine uses the downward stroke of the piston to force the air/fuel mixture from the crankcase through a port in the side of the cylinder head into the combustion chamber. As the piston begins its upward motion, the intake and exhaust ports are closed and the air/fuel mixture is compressed and then ignited. The piston then travels downward again delivering power to the crankshaft of the engine and forcing another charge to travel the loop into the combustion chamber. This configuration allows for one power stroke per revolution of the engine crankshaft, which explains the high power density usually associated with the two-stroke engine.

The inlet from the carburetor to the crankcase of the engine is controlled by either a reed valve (back pressure forces the valve to seal, thus preventing the air/fuel mixture from being pushed back out of the carburetor) or a rotary valve. The rotary valve in small model airplane engines is nothing more than a hollow in the crankshaft that is aligned with the carburetor throat when flow is desired and is usually called a Schnuerle porting. The Schnuerle porting is becoming more prevalent in the smaller engines as it requires less space and allows for more finesse in tuning.

A typical four-stroke cycle would start with the piston at the top of its travel or at top dead center (TDC). As the piston starts its downward motion, the intake valve opens, allowing the air/fuel mixture to travel into the engine cylinder. This occurs until the piston reaches the bottom of its travel in the cylinder or bottom dead center (BDC), and then the intake valve closes. At this time, the piston begins upward travel in the engine cylinder until it again reaches TDC and forms a combustion chamber in the volume between the top of the piston and the cylinder head compressing the air/fuel mixture. In a spark-ignited engine, an electrical charge is carried across the spark plug electrode initiating combustion. The hot gases that result force the piston downward on its power stroke. As the piston passes BDC, the exhaust valve opens, allowing the combustion products to exit into the exhaust manifold as the piston once again returns to TDC and the next cycle begins.

Design for the Soldier System

As a primary source of electrical power and cooling, an IC engine-driven unit would consist of an engine, generator, refrigerant compressor, evaporator, and cooling fans. Layout of the engine, generator, compressor, and fans could be either directly coupled inline, where power transmission would occur through some type of flexible couplings and all of the components would be operated at the same speed, or through a belt and pulley system that would allow the ability to offset the components and possibly better utilize both the enclosed volume of the unit and the optimum operating speeds of the components.

Advantages/Disadvantages

Two-stroke engines typically have higher fuel consumption rates than four-stroke engines of comparable horsepower. This is attributed to the time when the piston is at the bottom of its travel and a small amount of the incoming and unburned air/fuel mixture passes over the piston and exits the cylinder through the exhaust port. Engine designers attempt to minimize this activity but are somewhat limited because they must be able to replace the combustion products with a fresh charge. This process is usually called scavenging. The effect of not fully scavenging the combustion chamber is more detrimental to the engine's performance than the lost power from the air/fuel mixture passing through the exhaust port. The "pumping" power used to force the air/fuel mixture into the engine cylinder also adds to engine loss and increases fuel consumption.

Four-stroke engines, unlike the two-stroke, deliver power on every other engine revolution as the piston is used to pump either an air/fuel mixture or combustion products through poppet valves. These valves usually are located in the cylinder head in an overhead position. The valves are activated by a camshaft that is indexed to the engine crankshaft and turns at one half of the crankshaft speed. The size and spacing of the lobes on the camshaft dictate the timing and duration of the valve openings.

When a comparison is made between the two- and four-stroke engines, several generally true statements can be made. First, because a two-stroke engine has a power stroke for every revolution of the crankshaft while a four-stroke has a power stroke for every other revolution of the crankshaft, the two-stroke usually has twice the power for a given displacement. Second, because a four-stroke does not present the incoming air/fuel mixture with an open exhaust port as previously discussed, it usually has a lower fuel consumption. Third, two-stroke engines tend to function well within a narrow rpm band due to the port sizing and placement, whereas the four-stroke engines tend to have broader power bands due to a higher degree of tuning made available through valve sizing and timing.

There are several technical difficulties in the application of these small engines to the Soldier System, including the ability to start and operate on logistically available fuel. The present Army doctrine mandates the ability to operate equipment on whichever middle distillate fuel is available. Depending on the theater in which the troops are deployed, this could be JP-5, JP-8, DF-2, DF-1, or DFA. These fuels are not as volatile as alcohol or gasoline, so it is a challenge to atomize the fuel particles in the combustion chamber sufficiently to begin combustion.

The main disadvantage of the smaller high speed engines is that they suffer considerably from the effects of unbalance. Vibration due to unbalanced mass accelerations is quadrupled when speed is doubled. The effects of this vibration are transmitted through the mounting system to the soldier. A second disadvantage is the introduction of gyroscopic effects generated by the angular momentum. These can be minimized by using smaller rotating components. Possibly parts can be fabricated using ceramics to keep weight and inertia to a minimum. Positioning the cooling fans so that they are "counter-rotating" also may be possible to reduce the inertial effects. A third problem area is the noise generated by rotating machinery. Active noise attenuation may be required for the system in order to meet nondetectability and survivability requirements. Unfortunately, reducing the signatures would grossly increase the system cost, mass, and volume. These factors apply to all internal combustion engines. It will take a significant effort to achieve acceptable performance in the heat rejection and system cooling fans and associated equipment area. The small two-cycle engines should have an inherent advantage in reliability due to their simplicity. The small four-cycle engines may offer superior fuel consumption, which would offset their additional complexity. The small model airplane engine's endurance may be a critical factor in its application. The extreme example may be a single 24-hour mission life.

In larger diesel engines, high pressure pumps and injectors are used to spray a fine mist of fuel into the combustion chamber where the heat caused by the high compression ratio initiates combustion. The losses incurred in this process are negligible and so is the physical size of the components. This is not the case in the Soldier System application. With displacements on the order of one cubic inch, the amount of fuel required per injection is about 0.0005 cc (0.00008 cubic inches); controlling the injection of such a small amount of fuel is very difficult.

Conclusions

The internal combustion engine is the lightest power source commercially available in a brassboard configuration. Considerable development in the areas of vibration, noise, and adaptability to logistic fuels will be needed to make it a power source acceptable to the user. Two approaches appear viable. The first adapts the alcohol burning model engines to logistic fuels. The second further reduces the weight of the lightest string trimmer engine. Both engines need their signatures reduced. There are advantages as well as disadvantages to both approaches. The model engines are very light weight, but they are far from capable of burning logistic fuels. Also, their efficiency and cooling system capabilities are limited. The string trimmer engines and their air cooling systems are mature designs, but they are heavy, mainly due to low cost production techniques. Also, they do not burn middle distillate fuels, but they do burn gasoline. The internal combustion engine does lend itself to integration with an alternator and air conditioning compressor, so a compact mechanical arrangement is plausible in the long run.

STIRLING CYCLE ENGINE FOR THE SOLDIER SYSTEM

(Author: Mr. Gary Proulx, NRDEC)

Introduction

External combustion engines and, more specifically, Stirling Cycle engines have been in existence since the early 1800s. This energy source was extensively used in industrial applications up until the early 1900s when more efficient internal combustion and electrical power alternatives were developed. It wasn't until just recently, when significant advances in metallurgy allowed the development of components to withstand high temperatures, that interest in Stirling technology resurfaced as an alternative to internal combustion engines. Because of the unique attributes associated with this type of engine, it is currently being considered for space exploration, battlefield, and commercial applications.

The engine employs the alternate heating and cooling of an enclosed working fluid (hydrogen). The heat source is a continuous flow external burner.

Principles of Operation

A Stirling engine has five primary components: two pistons (or a piston and displacer), a regenerator, and two volumes. The regenerator is a heat exchanger—alternately absorbing and releasing heat. One of the volumes is maintained at a low temperature and is the compression space. The two pistons are used to change the cylinder volume and to shuttle the working fluid back and forth.

The P-V diagram and theoretical piston arrangement at terminal points are shown in Figure 23.

The cycle starts at Point 1 with the compression piston and the expansion piston (displacer) to the right of their fluid spaces. The working fluid is in the cold space. As the piston moves to the left, the fluid is compressed. At Point 2, the displacer is to the right of the hot space, the piston is to the left of the cold space, and compression is complete. As the displacer travels to the left, the cold fluid flows through the regenerator into the hot space. At Point 3, the piston is to the left, the displacer is to the left, and the working fluid is in the hot space. As the fluid is heated, it expands, forcing the displacer to the far left of its space. The piston is also to the left. At Point 4, the piston and displacer are to the left of their spaces, and the expanded fluid is still in the hot space. As the displacer moves back to the right of the expansion space, the working fluid is forced through the regenerator into the cold space and the piston moves to the right. This completes one cycle—the piston is to the left, the displacer is to the right, and the fluid is in the cold space. Work in the Stirling engine is generated by this compressing and expanding of the working fluid at different temperatures. The working fluid choice is critical to the effectiveness of the Stirling engine. The most widely used gases are helium, hydrogen, and air.

The components needed for a Stirling engine can be arranged in a multitude of ways. The Free Piston and the Kinematic Stirling engines are single-acting engines with the piston and displacer in the same cylinder. The Free Piston version uses fluid forces to move the components. There are no mechanical linkages to the piston or displacer (see Figure 24).

Additionally, the power output must be obtained from the engine using a linear alternator. This type of engine can be hermetically sealed.

The proposed system consists of a Stirling engine driving a linear alternator and a Stirling cooler. The engine and cooler are coupled together and share a power piston which reduces weight and bulk while increasing efficiency. The Stirling cooler accepts heat directly from the coolant, eliminating a vapor compression system (e.g., condenser, evaporator, compressor, etc.) and uses helium as the working fluid. The double Stirling configuration is hermetically sealed. The power generator is driven by the power piston and is included in the engine as well as the fuel system (see Figure 25).

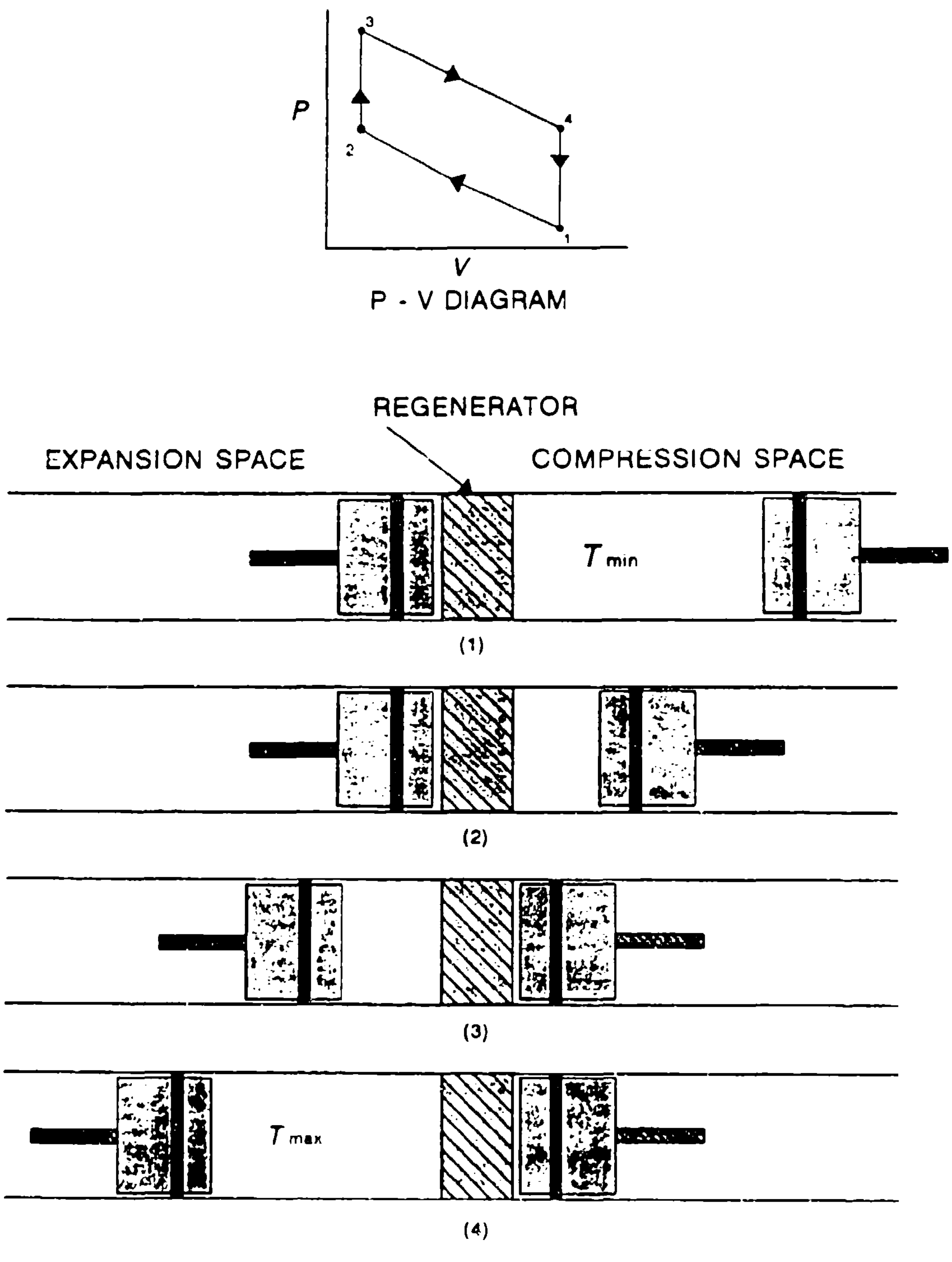

Figure 23. P-V Diagram: Piston Position Diagram

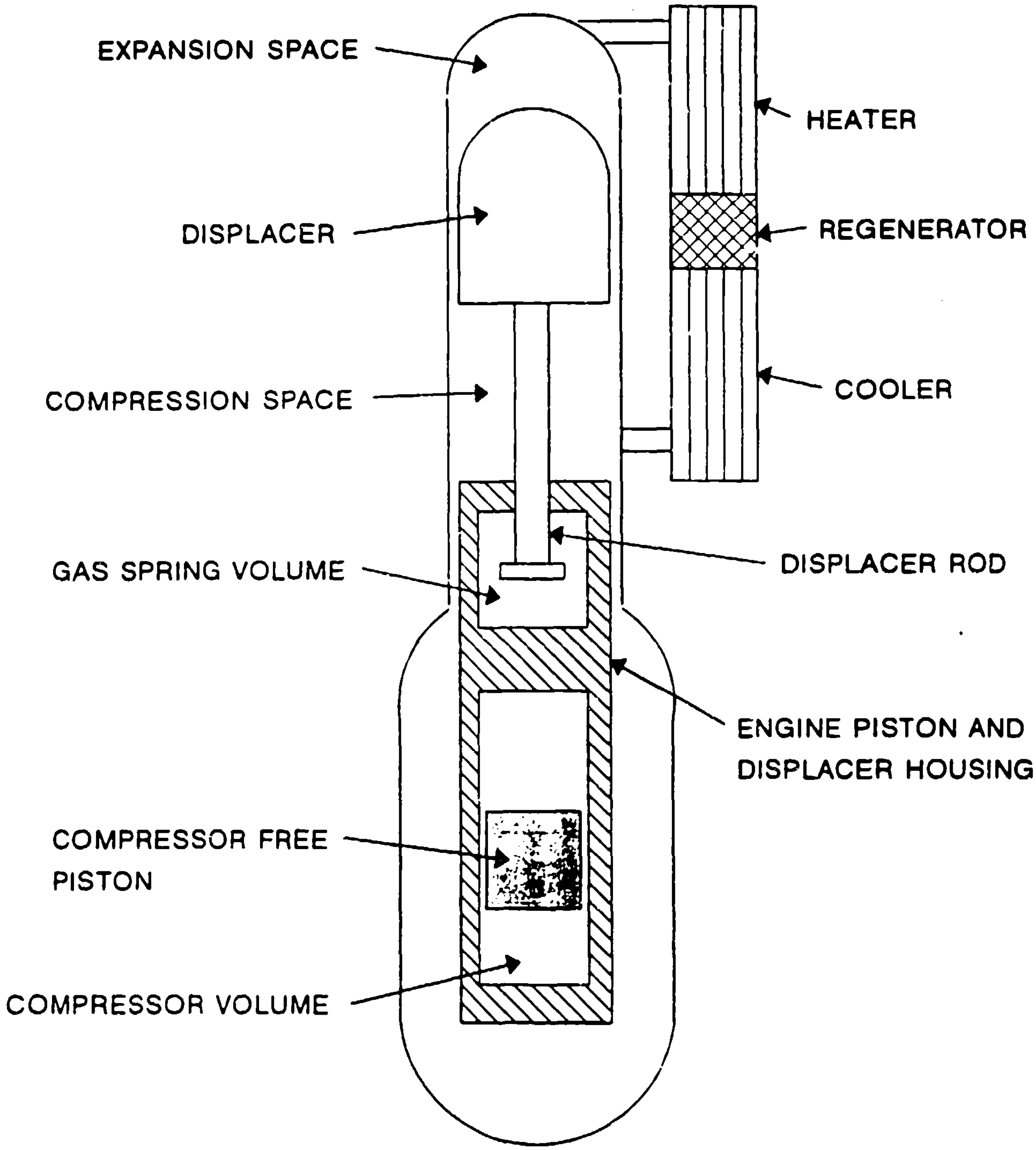

Figure 24. Free-Piston Stirling Engine (FPSE) Concept

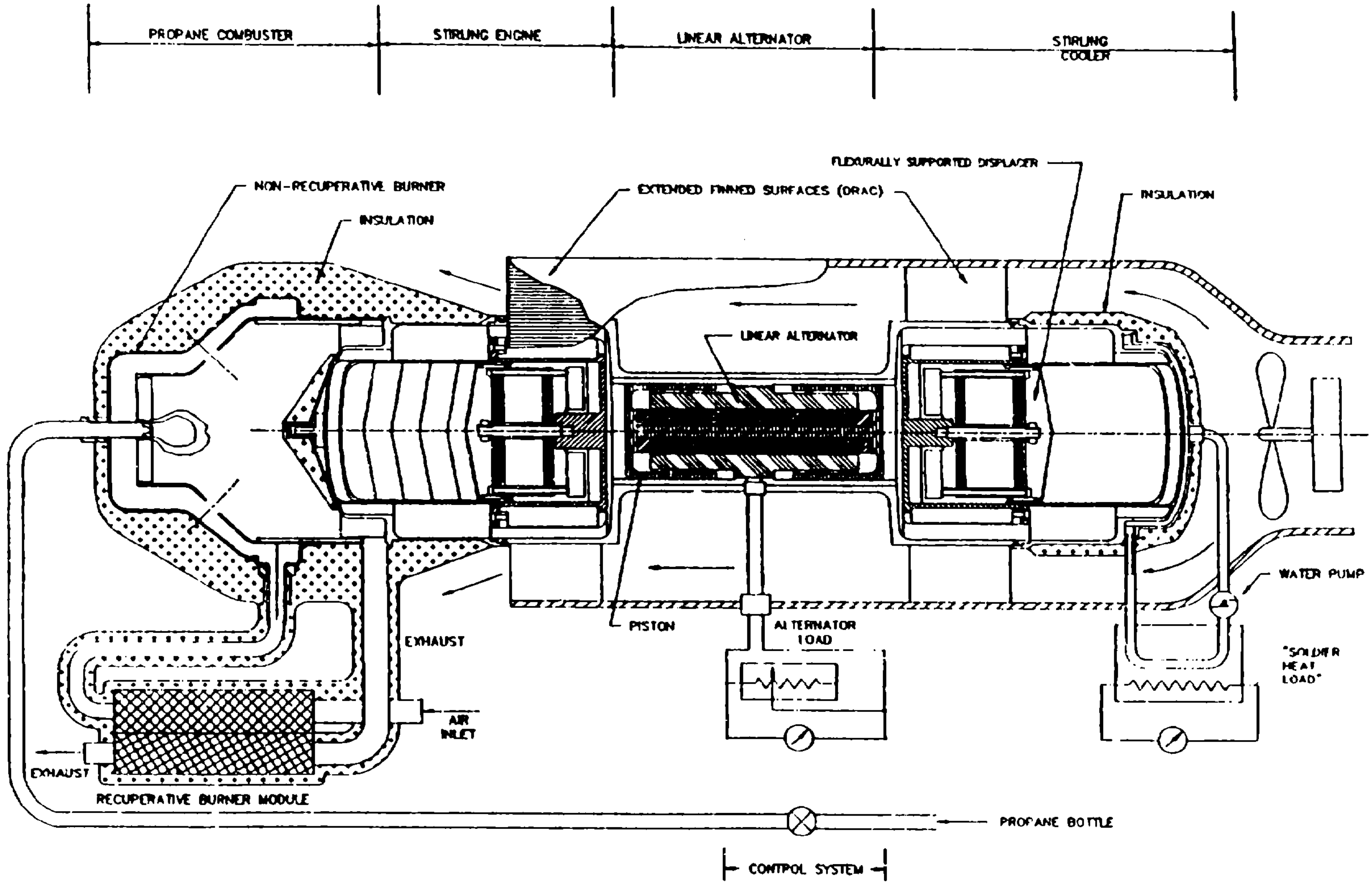

Figure 25. Phase II Microclimate Cooling Duplex Stirling Machine (DSM)

Design for the Soldier System

The Soldier System utilizes a Duplex Stirling engine. The preliminary maintenance concept is fo modular design with line replacement of major components and no component repair. Basic modu... are: (a) burner/engine/alternator/cooler, which includes fuel subsystem; (b) fans and coolant pumps; (c) a controller, which governs engine/cooler operation; (d) a soldier interface, which allows the soldier to operate and monitor the system; and (e) a power distribution junction for supplying power to other soldier systems. All fluid and electric lines are quick disconnect. Each module can be replaced at unit level. For this first analysis, all modules are considered non-repairable. It currently is recognized that all modules may be designed to be repairable, but current information is unavailable to determine to what subcomponent or part level that may be.

A Ni-Cad battery is used to start the system. This battery would be rechargeable. The useful life is assumed to be equal to its failure rate, including recharging. The same battery and assumptions have been made for all other systems requiring a battery for start-up and/or backup.

The engine as currently designed runs on diesel/JP-8, but may be converted to run on any heat source (e.g., metal combustion, propane, gasoline, etc.). The fuel consumption rate is based on the required power, cooling, and efficiencies of various components. The amount of fuel available is based on meeting a 10-hour sustained mission, after which refueling would be required. Additional costs for resupply, manpower, transportation, and handling are not included at this time. The fuel cost value has not been adjusted to include any of these costs. The fuel consumption rate is based on an estimate of 0.19 pounds of fuel per hour. This was converted to gallons per hour by using a rounded estimate of 7 pounds of diesel per gallon.

An electric fan is required to circulate cooling air over the engine to extract heat from the compression space. The fan would be powered by electricity generated by the linear alternator (after start-up). A liquid pump is used to circulate coolant through a vest and over the cooling head of the Stirling cooler. Only a basic concept of how the controller would be designed exists. It would likely be a black box module with microprocessor chips. It would be non-repairable and non-programmable. The soldier interface module allows for the soldier to turn the system on or off, adjust the cooling temperature, and monitor the system. The technology currently considered will use readily available standard, inexpensive components. The power distribution design is very simple at this time. It is assumed that significant power conditioning requirements will be addressed to a maximum extent in the other Soldier System components. The basic concept incorporates interconnecting cables, connectors, and something similar to a voltage regulator. (More correctly, a DC/DC filter or converter and ripple device will be required.)

Advantages/Disadvantages

- COST—The cost of the engine is based on information provided in a technical report on the engine with a cost estimate for developing a prototype system. A learning curve and quantity of scale (volume purchase) factor was added to arrive at the cost provided here.

  The cost estimate is based on a larger version used in the newly designed motor controller module for the 18K BTU Air Conditioner. This item is currently being negotiated for procurement at a cost estimate of $590 each. Due to miniaturization and somewhat more complex function, the cost of this item was increased by approximately 70 percent.

The soldier interface module technology currently considered will use standard, inexpensive components that are readily available. The cost estimate is based on a composite cost of switches, adjustment controls, temperature probe, and voltage readout. The cost estimate is based on a composite of currently available like components.

- SIZE/WEIGHT—The size and weight are anticipated to be slightly larger than the internal combustion engine. Because the Stirling is an external combustion engine, it must have a greater amount of heat rejected through the radiator. Therefore, the radiator will be larger and heavier. Additionally, the combustor is anticipated to be larger.

- SIGNATURE—Signature on the Stirling engine should be a significant improvement over the IC engine. Because the engine operates on constant and almost complete combustion, emission of pollutants should be minimal. There are no valves or periodic explosions; therefore, noise is greatly reduced. The overall thermal image of the unit will be the same as any engine; however, the exhaust will be cooler and have fewer pollutants. This results in a lower thermal signature.

- SAFETY—Safety should be comparable to other engines. While the heater head is maintained at a high temperature, it can be insulated. The exhaust gases will be close to ambient temperature, and the engine emits no toxic elements.

- VIBRATION/GYROSCOPIC EFFECTS—Because the engine can be designed with opposing pistons and there are no valves or periodic explosions, vibration is anticipated to be at a minimum. The only component that could contribute to gyroscopic forces is the radiator fan. This is not expected to present a difficulty.

- EFFECTS OF ATTITUDE—The engine can be designed to have a pressurized bladder fuel tank and effective wicking mechanism. These features should allow the engine to operate in any orientation. However, it should be started in the upright position.

- SHELF LIFE—If the engine is designed to be hermetically sealed, no lubrication would be necessary and the engine would theoretically have an infinite shelf life. If it is not sealed (e.g., Kinematic engine), the shelf life would be comparable to other engines.

- INTEGRATED LOGISTIC SUPPORT (ILS)—The Stirling engine should have a multifuel capability. If hermetically sealed, it should require no lubrication. The only maintenance required would be the changing of the wick. For these reasons, the ILS is considered a benefit of the Stirling engine.

- RELIABILITY, AVAILABILITY, MAINTAINABILITY (RAM)—The RAM system characteristics are comparable to those for IC engines. The only impact on this would be the need to use exotic materials. This may affect the availability of materials.

- START/RESTART—The Stirling engine controls can be designed to allow for easy push button operation. Approximately two minutes of start up time would be required.

- PRODUCTION BASE/INITIAL COST—Few Stirling engines in the 100- to 500-watt range have been produced. At this size, a production base does not currently exist.

- HUMAN FACTORS ENGINEERING (HFE)—This system uses no CFCs (i.e., no freon). This fact, coupled with the engine efficiency and low emissions, makes the double Stirling an environmentally sound system.

- EFFICIENCY—The Stirling design is anticipated to be 35 to 40 percent more fuel efficient than the internal combustion engine, while reducing HC, CO, and NOx emissions due to the continuous combustion process.

- HERMETICALLY SEALED—The double Stirling configuration is hermetically sealed, resulting in a longer life.

- NOISE—Because the engine can be designed with opposing pistons and there are no valves or periodic explosions, noise is greatly reduced.

- MULTIFUELED—The working fluid choice is critical to the effectiveness of the Stirling engine. The most widely used gases are helium, hydrogen, and air. Each has benefits and disadvantages for a given system. Air is inexpensive and readily available. Therefore, sealing is not imperative. However, it has low thermal conductivity and specific heat and high viscosity and density. These characteristics make it acceptable only for slow running and low power machines. Helium has higher thermal conductivity and specific heat and lower density than air. These features make it an attractive working fluid. It is also inert and would probably be used in confined areas. Hydrogen has the best thermal transport properties of the three working fluids. At high speeds, it is the most efficient. However, hydrogen is flammable and can cause hydrogen embrittlement of metals. Additionally, because hydrogen is so light, it is difficult to contain. Seals become crucial. All of the above must be considered when choosing a working fluid.

- NO CFCs (FREON)—This system uses no CFCs (i.e., no freon). This fact, coupled with the engine efficiency and low emissions, makes the double Stirling an environmentally sound system.

- MEAN TIME BETWEEN FAILURE (MTBF)—A mature system should exhibit a fairly high MTBF.

- LIFE CYCLE COST—The Stirling engine has some inherent benefits and some distinct disadvantages in regard to Army application. The life cycle cost of a Stirling engine is anticipated to be comparable to that of an internal combustion (IC) engine. While some of the materials may be more expensive, the low maintenance characteristic will balance this.

Conclusion

The Stirling powered Soldier System has some very attractive features such as low noise, low vibration, and low IR signatures. The system would be inherently expensive due to the exotic materials and very demanding manufacturing methods required. The Stirling engine has potentially low fuel consumption characteristics, which has shown to be one of the systems of choice based on the parametric analyses performed as a part of the FEA at mission lengths of greater than 75 hours. The upper limit deemed to be realistic is presently equal to or less than a mission length of 72 hours.

The Stirling engine has been in advanced development as an automotive power plant for about 15 years. The problems associated with high temperatures and hydrogen working fluids have not been totally resolved. Scaling the engine down to Soldier System size would be difficult. A demonstrator program has been successful to a degree, particularly in the combustor area. However, the best size and weight projected are prohibitive.

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VAPOR AND LIQUID CYCLE ENGINE TECHNOLOGY FOR THE SOLDIER SYSTEM

(Author: Mr. David Overman, ARL)

Introduction

In contrast to the Internal Combustion (IC) engine where the fuel is burned directly in the working substance (air), external combustion engines use a working substance such as steam, nitrogen, or oil that is heated in one location and then delivers its thermal energy to a remote location, similar to a home heating system.

There are four basic types of external combustion engines. They are classified according to the working substance used: gas, vapor, liquid, and solid. The Stirling external combustion power system is the primary example of an external combustion engine that uses gas as a working substance. The Stirling engine has a high efficiency thermodynamic cycle. Engines utilizing NITINOL memory metal wires or strips are the chief example of the use of a solid as the working medium (Reference 1). When vapor is considered as the working substance, the primary example is the steam engine. Some engines have also used fluorocarbon-based substances and other working fluids (Reference 2). Very few engines have been demonstrated that use a compressible liquid as the working substance. This section of the report focuses only on the vapor and liquid cycle external combustion engines.

Principles of Operation for Vapor Cycle System

Vapor cycle engine systems generally operate by converting the working substance between its liquid and gaseous form. This allows for more compact pumping and heat exchanger components when compared to those used with a gas as the working substance. The vapor cycle power system includes a steam generator (consisting of a burner, boiler, and super heater), an expander (engine), a condenser, and a pump as shown in Figure 26. A temperature-entropy (T-S) diagram for the ideal simple steady-flow Rankine thermodynamic vapor cycle is also shown.

The processes that comprise the Rankine vapor cycle are:

- 1-2: Reversible adiabatic pumping process in the liquid pump
- 2-3: Constant pressure transfer of heat in the steam generator
- 3-4: Reversible adiabatic expansion of the vapor in the engine
- 4-1: Constant pressure transfer of heat in the condenser.

Obviously the above process involves accessory components such as a blower to aid heat transfer in the condenser and boiler, a heat exchanger to recover waste exhaust heat, a fuel delivery system, and a control system to maintain desired operating conditions. The usual type of expander is a steady-flow turbine-generator system. In this case, the expander is a small (0.44 cubic inch) intermittent-flow reciprocating engine operating at approximately 150 Hz to expand relatively small quantities of steam (about 7 lb/hr). Under steady-state conditions, the engine behaves in a fashion similar to the turbine as far as selection and analysis of a Rankine thermodynamic vapor cycle is concerned.

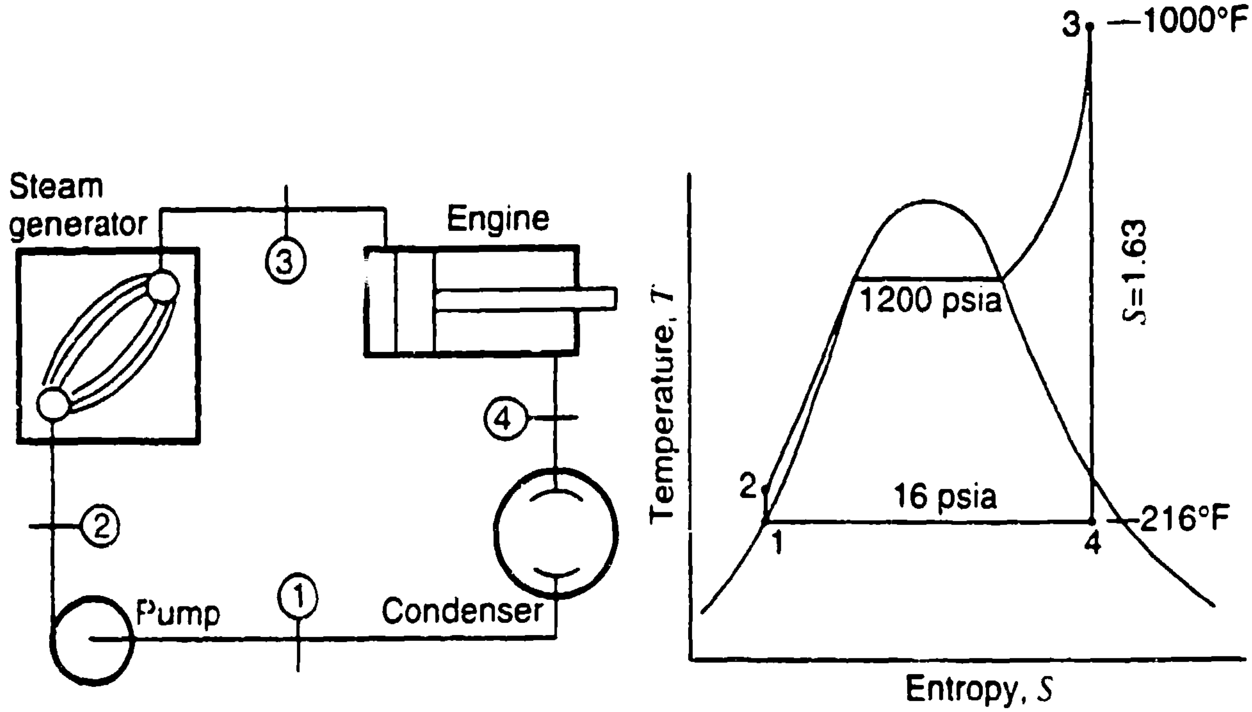

Figure 26. Simple Steam Power Plant and Rankine Vapor Cycle

The type of steam engine suggested is a high-compression, uniflow, single-expansion, non-condensing unit operating on high pressure, super-heated vapor. The engine also operates in a cyclic fashion as illustrated in Figure 27. Here the ideal pressure-volume (P-V) diagram is similar to that for the ideal air-standard diesel engine thermodynamic circle, except that it is not a true thermodynamic vapor cycle, as shown by the vertical line on the T-S diagram.

Ideally, the engine cycle consists of:

- 1-2: Reversible adiabatic compression process where the residual exhaust steam left in the cylinder is compressed to high pressure and temperature as determined by the exhaust steam properties and the volumetric compression ratio of the engine.
- 2-3: Constant pressure admission of steam from the steam generator through valves in the cylinder head and its mixing with the compressed steam.
- 3-4: Reversible adiabatic expansion of the vapor in the cylinder after cut-off of the admission process and until release of the steam to the exhaust process.
- 4-1: Constant volume exhaust process where expanded steam escapes into the condenser through ports uncovered at the bottom of the engine cylinder.

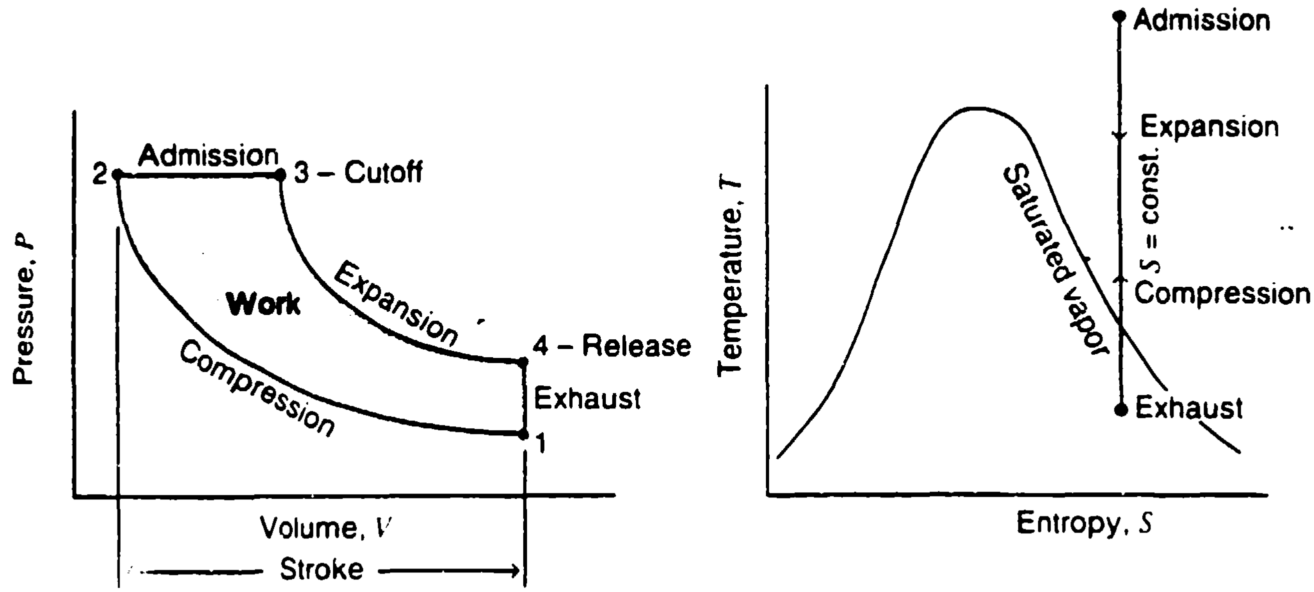

Figure 27. Single Expansion Uniflow Steam Engine Cycle

Principles of Operation for Liquid Cycle System

Liquid cycle external combustion power systems are similar to vapor cycle power systems in that heat exchangers are needed to heat and cool the fluid, a burner and pump are required, and the engine cycle is controlled by valves timed from the engine crankshaft. They are based on compressing, heating, and then expanding a liquid substance such as acetone or an oil. A liquid thermal engine has the potential of delivering a large amount of horsepower from a relatively small engine. It has the capability of extracting heat energy and converting it to useful work when relatively low temperature differentials exist. Figure 28 is a diagram for a liquid thermal regenerative thermodynamic cycle from a 1960 information paper by the Cleveland Pneumatic Tool Company (Reference 3).

The cycle of the liquid thermal engine consists of introducing a cooled liquid at near atmospheric pressure into a cylinder and adiabatically compressing the fluid with a piston to a high pressure (approximately 30,000 psi). The act of compression increases the fluid temperature. The fluid is delivered to a high pressure heat exchanger in which the fluid temperature is further raised at constant pressure. The heated compressed fluid is introduced to a cylinder where it is adiabatically expanded against a piston to the original low pressure, and in doing so performs useful work, part of which consists of compressing the cooled liquid as mentioned initially. At the end of the cycle, the expanded fluid is exhausted, cooled, transferred to the compression chamber, and the cycle repeats. The operating cycle of the engine is two-stroke. The up-stroke exhausts the expansion cylinder and permits or causes the compressing cylinder to be filled with cooled liquid. The down-stroke, caused by the expanding liquid, compresses the cooled liquid and also delivers the engine output.

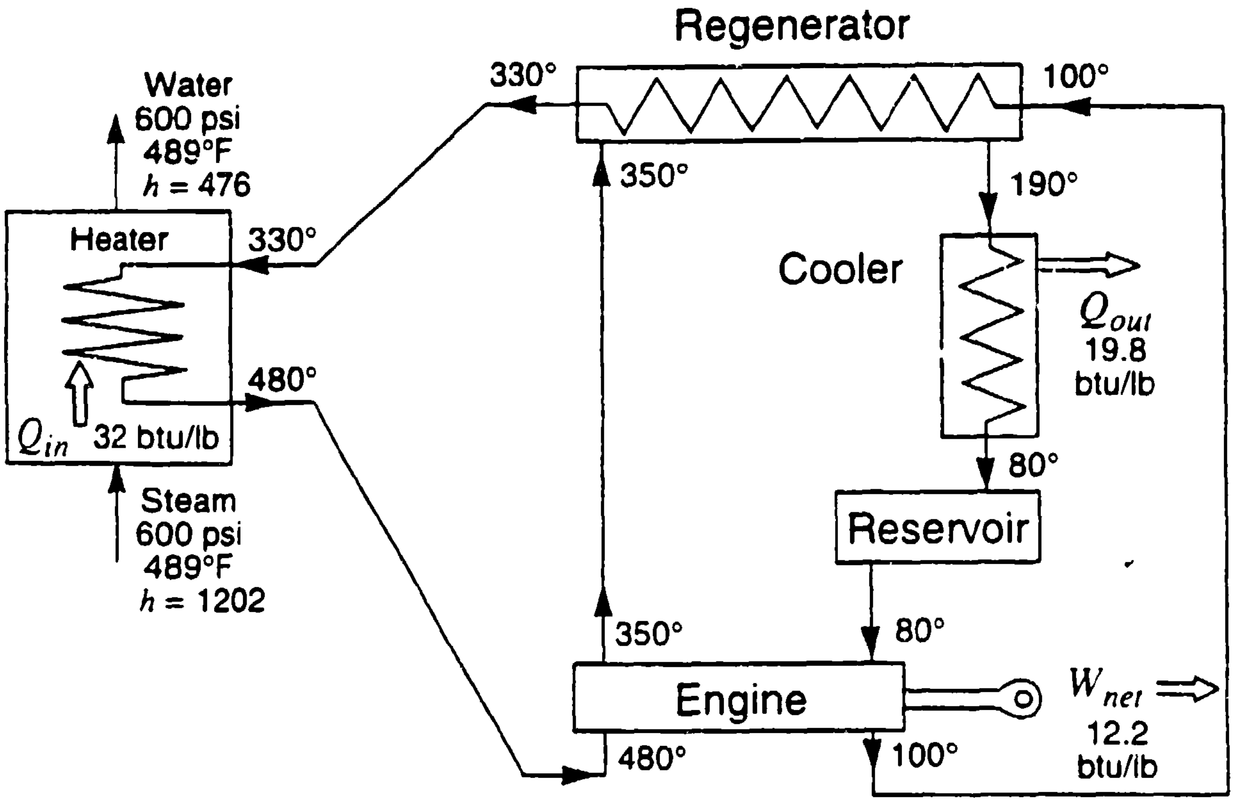

Figure 28. Heat Balance Diagram for a Regenerative Liquid Cycle Power System

As shown in Figure 29, the cylinder/piston combination is of the conventional double-acting type. The cylinder volume at the piston rod end is used for compression and the larger volume at the other end of the cylinder is used for expansion. This balances the force of compression so that only net work is delivered to the crankshaft. Flow of the fluid through the various stages of the cycle is accomplished by valves timed from the crankshaft rotation.

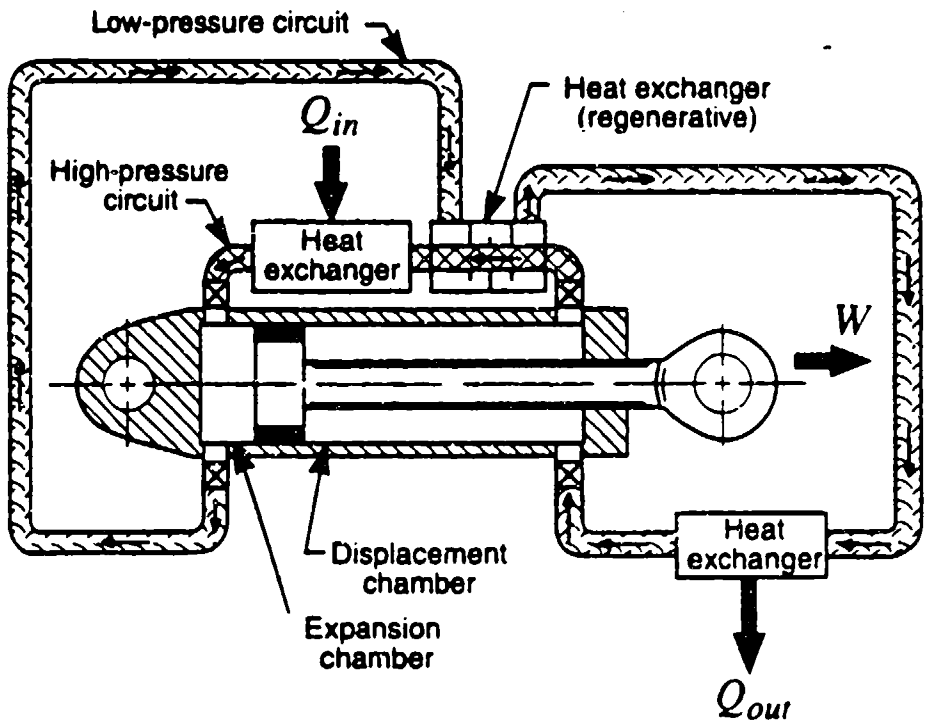

Figure 29. Schematic of Regenerative Liquid Thermal External Combustion Engine

Design for the Soldier System

A block diagram for a steam plant for Individual Soldier Power is shown in Figure 30. It is assumed that a motor generator would be used for engine starting/restarting and electrical power production. It also serves as the engine flywheel. The system battery would be large enough to meet total system power requirements, not only for engine starting but also for all operations, including driving the refrigeration compressor during periods of up to one-half hour whenever quiet operation and low thermal signature conditions must be met. It also serves as a load-leveling device to accommodate needed power surges and other transient requirements. The refrigeration compressor for cooling requirements can be driven directly by the engine to save an additional electric motor and improve efficiency. The fan is assumed to represent the air-handling requirements for the condenser as well as the steam generator's burner. The control system box represents the composite of all sensors and actuators that would be required for fully automatic control of the various fuel, water, and steam flow-rate functions and the pressure and temperature. A feed-water, pre-heater element in the condenser is assumed to recover available exhaust heat from the engine.

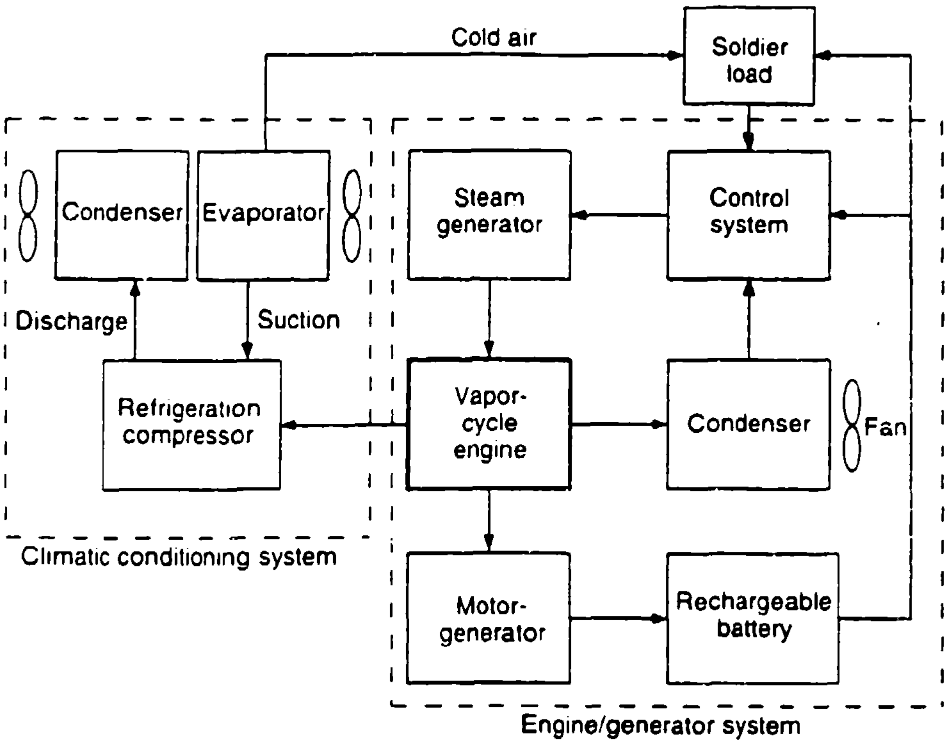

Figure 30. Block Diagram of a Vapor Cycle System for Individual Soldier Application

A preliminary layout of the suggested power system general arrangement is shown in Figure 31. A modular arrangement has been devised, wherein the compressor or other such auxiliary item can be attached externally as required by the mission. It assumes a box of dimensions 6.25 inches x 8.25 inches x 10.0 inches (0.3 cubic foot) to contain all of the system components, including an "L"-shaped fuel tank for 24 hours of operation, and an allowance of 105 cubic inches for a removable refrigeration module. The engine generator and vapor cycle system components are packaged in a volume of 0.14 cubic foot. There are obviously numerous different arrangements that can be pursued in order to obtain optimum packaging. However, more detailed design of the components and their inter-relationships needs to be done before an optimum packaging design can be determined.

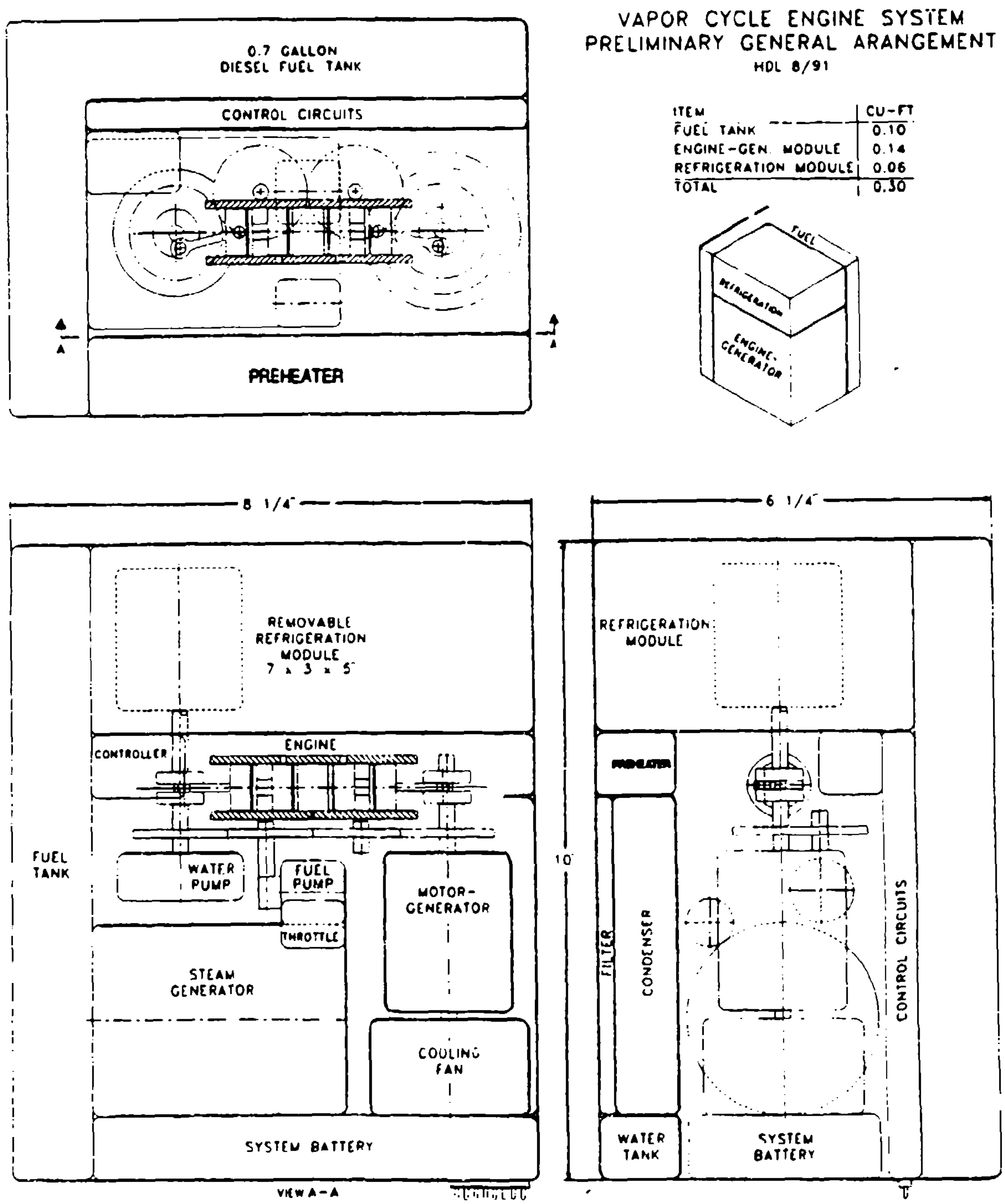

Figure 31. Preliminary General Arrangement for a Vapor Cycle Power System

Table 4 lists the various components for the power system general arrangement. The assumed sizes and weights for the components, especially for the heat exchangers, might not be very accurate. A wet weight of approximately 21.5 pounds is estimated for the power system without the refrigeration module and while assuming enough fuel for a four kW-hour day. The system battery, used for starting, load leveling, and a half-hour "run silent" mode, is conservatively sized at two pounds and 21 cubic inches for an approximately 200 W future rechargeable lithium unit having a capacity of about 100 W-hour.

Table 4. Estimated Component Sizes for General System Arrangement of Vapor Cycle Engine

	Item	Diameter (inches)	Length (inches)	Height (inches)	Width (inches)	Volume (cu. ft.)	Weight (pounds)
1.	Mot-Gen Housing		7.00	7.00	5.00	(245.0)	0.3
2.	Fuel Tank		13.25	10.00	1.25	(165.6)	0.3
3.	System Battery		7.00	1.25	3.50	30.6	2.0
4.	Control Circuits		7.00	7.00	0.50	24.5	0.4
5.	Preheater		7.00	1.00	1.25	8.3	0.7
6.	Condenser		7.00	5.00	1.00	35.0	0.8
7.	Water Tank		7.00	1.00	10.25	71.8	0.1
8.	Air Filter		7.00	5.00	0.25	8.8	0.1
9.	Controller		1.50	1.00	1.00	1.5	0.5
10.	Engine		6.50	1.75	2.00	22.8	3.5
11.	Cooling Module		7.00	3.00	5.00	(105.0)	TBD
12.	Motor-Generator	2.00	2.50			7.9	2.0
13.	Steam Generator	3.00	4.00			28.3	3.0
14.	Cooling Fan	2.50	1.50			7.4	0.3
15.	Water Pump	2.00	1.00			3.1	0.4
16.	Fuel Pump	1.00	1.00			0.8	0.2
17.	Throttle	0.75	1.00			0.4	0.2
18.	Miscellaneous Parts						1.4
19.	Water						0.3
20.	Fuel - 4 kW-hr					151.2	5.0
	TOTALS					**(0.3)**	**21.5**

Preliminary engine sizing is based on an assumed peak output capacity of 375 W, a motor-generator and refrigeration compressor efficiency of 70 percent, an engine speed of 9,000 rpm, an engine accessory requirement of 100 watts, and an engine mechanical efficiency of 85 percent. These values result in a conservative engine indicated power of 1.0 horsepower. An engine displacement of 0.44 cubic inch is obtained based on an assumed indicated-mean-effective-pressure (IMEP) of 100 psi. A two-cylinder opposed-piston engine configuration (common steam admission area) is used to obtain good control over the high compression ratio desired (about 30-35 to 1), to consolidate the high temperature portions of the engine for best thermal management, and to provide optimum balance of the reciprocating forces. The result is an engine bore of 0.75 inches and a stroke for each piston of 0.5 inches. Based on conventional IC engine practice, an engine of this size should not have any problem in attaining the 9,000 rpm speed requirement.

A layout of the suggested engine configuration is also shown in Figure 31. The "cross-head" piston configuration allows for separation of the high temperature ceramic crown from the low temperature section attached to the lubricated connecting rod. Synchronization of the two pistons is by means of four spur-gears, although high performance belt or chain technology might be considered for this function during detail design. All gears are shown as the same size, but they can be made different sizes if needed to drive auxiliary loads at higher or lower optimum speeds. The central engine component is about 1.0 inches in diameter by 5.0 inches long. Its size will increase when the valves, inlet and exhaust manifolds, and certain accessory items are added.

The steam generator size is based on an assumed engine thermal efficiency of 26.5 percent, a boiler efficiency of 87 percent, an excess boiler capacity of 50 percent, and an estimated heat rate performance of 2,000,000 BTU/hr/cubic feet of volume. Assuming double volume for a small-scale design yields a steam generator size of 3 inches in diameter by 4 inches long. Peak steam rate is estimated at 9.6 lb/hr, which allows for the engine efficiency to be as low as 17.7 percent. Sizing of the fuel tank is based on assuming 633 BTU/cubic inches of diesel fuel and an average daily power rate of 166 W. A conservative tank size of approximately 186 cubic inches (6 inches x 8 inches x 3.9 inches) holding 0.8 gallon is obtained.

Design of a liquid cycle external combustion power plant for the Soldier System has not been done. If a value of about 10 horsepower/cubic inch at an engine speed of 3,000 rpm is assumed, an engine of one horsepower (indicated) would have a cylinder volume of 0.033 cubic inch, which translates to a bore and stroke for a single cylinder of about 0.25 inches diameter by 0.67 inches long.

Advantages/Disadvantages

External combustion engines can be contrasted in general with IC engines as follows:

Advantages:

- Essentially continuous combustion versus high frequency intermittent combustion.
- Very low air pollution in terms of nitrogen oxides, carbon monoxide, and unburned hydrocarbon emissions (Reference 2).
- Engine operates in thermally insulated environment (compared to the water- or air-cooled environment of the IC engine).
- Relatively low temperature engine operation, i.e., 500°F to 1,500°F (compared to the fuel combustion temperature experienced in the IC engine).
- Relatively low pressure operation (compared to the fuel combustion and detonation pressures experienced in the IC engine).
- Wide range of power available from a single engine size (depends on the capacity of heater for working substance).
- Engines develop maximum torque at stall and can be run in reverse to produce braking force (gives transmissionless operation for vehicular applications).
- Pay-as-you-go operation (engine stops when power demand stops) improves economy.

- Ability to burn any fuel (particularly diesel fuel).
- Generally quiet operation.

Disadvantages:

- Not in common use; "new" technology; developmental status.
- Combustion heat must be transferred through a barrier to the working substance.
- Requires burner and heat exchanger separate from engine.
- Past practice has been generally inefficient (except for certain designs).
- Past practice has been somewhat heavy and bulky.
- Proper lubrication is often difficult to achieve.
- Controls and auxiliary items tend to be more extensive than for IC engine.
- Generally necessary to have "closed cycle" operation (recycle working fluid) and this tends to create sealing problems.

It is believed that the potential disadvantages of external combustion engines can be overcome by modern materials and design practices, such as the use of advanced ceramic and metallic materials; modern solid lubricants and special coatings; high performance insulation and seals based on those used in the spacecraft, nuclear, and water-jet cutting industries; advanced heat exchanger, burner, and electronic control system practice; and generally higher operating pressures, temperatures, and speeds than have been early practice. The fact that the engines are small and intended for service in combination with a generator and battery (and possibly electric or hydraulic drive systems), which can be used to level the load and tend toward constant speed operation, may also prove to be an advantage to external combustion technology for this low power application.

When water vapor is used as the working substance, the advantages of a vapor cycle type of external combustion power system are: ready availability, highly characterized properties, and generally tractable performance. This is seen in the system's long and successful history of application. Other advantages of a vapor cycle system include its quiet operation, multifuel capability; compact size and reasonable weight; and the ability to cover a wide power range (on the order of five to one) with a single engine size.

Disadvantages of steam as a working substance include poor lubricity, problems accommodating cold temperature engine operation, and the need to manage the heats of vaporization and liquefaction while constantly converting the working substance back and forth between the vapor and liquid states. Other disadvantages of a vapor cycle system are difficulty in achieving operation at any attitude and the need to redevelop the technology and the industrial base.

The advantages of a liquid cycle-based thermodynamic power system are expected to be: compact size due to the high working pressures involved (about 10 horsepower per cubic inch of engine displacement), even when operating at low speeds (1,000 to 3,000 rpm); relatively low working temperatures on the order of 400 to 800°F; no change in state of the working substance gives quiet operation and smaller amounts of heat exchange; relatively efficient heat transfer performance due to liquid-to-metal interfaces; and suitable lubricity from the working fluid (for certain liquids).

The major disadvantages of the liquid cycle system would be expected to derive from its relatively undeveloped state of technology; the high working pressures (20,000 to 30,000 psi) needed to achieve adequate compression/expansion ratios and the associated high performance seals; the efficiency may be low due to the low peak temperature although the extreme pressure conditions may offset this effect to some extent; at least one high pressure heat exchanger will be required and this will add weight to the power system; throttling of fluid through high pressure valves may result in high energy losses and unacceptable wear of seating surfaces; and a relatively low coefficient of expansion and small compressibility of the fluid could result in critical relationships between respective volumes within the engine and heat exchanger elements. This may require rather close control over some of the temperature conditions.

Conclusion

The vapor and liquid cycle engine technologies potentially offer a distinct combination of advantages for Soldier System power. These are: quiet and efficient operation, diesel fuel compatibility, compact size, a broad power range, and long duration mission capability. However, these advantages probably come at a slight penalty in cost and weight compared to an internal combustion (IC) engine system. Another consideration is the fact that these technologies have to be developed much further than does the IC technology that already has a partially established industrial base. Liquid cycle engine technology is not nearly as advanced as vapor cycle engine technology, so a larger investment in research will be required to fully explore its potential.

Because the Army is faced with a new and especially difficult to meet need in a specialized military field, it seems appropriate to reconsider the special advantages of external combustion technology. The advantages of the external combustion engine, particularly its multifuel capability and quiet operation, are attractive enough in view of the individual soldier application that the Army should focus some research effort to seriously explore its potential.

It is recommended that the Army explore both vapor and liquid cycle technologies, by analysis and laboratory experiment, to the extent necessary to validate their capabilities and to establish their viability for applications that may require their unique combination of characteristics.

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RADIOACTIVE ISOTOPE POWER SOURCE FOR THE SOLDIER SYSTEM

(Author: Dr. James Ferrick, BRDEC, SATBE-FGE)

Introduction

In an effort to meet the power and size requirements of the Soldier System, radioactive isotope power is being considered as a source for power generation. The radioactive isotope-based power supply, unlike any other technological approach, has an almost unlimited capability to provide energy for the Soldier System. On a stored energy density basis one finds the following characteristics:

Nuclear Energy	10^6 – 10^{11}	MJ/kg
Chemical Energy	10 – 20	MJ/kg
Thermal Energy	> 1 MJ/kg	
Inertial Energy	0.5 MJ/kg	
Electrical Energy	> 2 kJ/kg	
	(1 kWh = 3.6 MJ)	

Source: Mobile Battlefield Power Workshop, 30 Oct - 1 Nov 1990, Durham, NC, Dr. M. Frank Rose, Co-Director, Contract DAAL03-86-D-0001, Delivery Order 2263, ARO Scientific Services Program

In order to take advantage of this overwhelming energy storage difference at the individual power level, we need to devise a power source that is man-rateable and politically and environmentally acceptable to deploy on the battlefield or in rear areas. Man rateability requires that the cumulative radiated dosage of whatever emissions emanate from the power package received by a person carrying/wearing the power source fall below the threshold for biological damage for humans. This consideration affects the selection of isotopes that may be used and the shielding that is required.

Principles of Operation

The graph in Figure 32 taken from the American Institute of Physics Handbook gives the mean range in air (in centimeters) of alpha particles (helium nuclei—2 protons, 2 neutrons), protons, and electrons (beta rays). At energies of interest, alpha particle ranges are about 1/1000 of equivalent energy betas. A 10 MeV alpha particle has only a 10 cm range in air, and these are easily absorbed in shields. A 10 MeV beta ray, on the other hand, has about a 4,300 cm range in air, and thus is clearly harder to shield. Gamma rays have even more of a penetrating ability. Clearly, the ideal radioactive isotope power supply for individual soldier use would involve pure alpha emitters, minimizing the shielding required and gross weight of the unit. Heavy metals such as lead are often used as shielding material to reduce the total volume of shielding required.

The most common Radioisotope Thermoelectric Generators (RTGs) use Pu 238 as their fuel, taking advantage of plutonium's long half-life of 86.4 years for providing power for space exploration missions. Because Pu 238 is an alpha emitter, relatively little shielding is needed to attain low radiation levels external to the RTG package. Power sources capable of supplying 4-5 W/kg in the 100 watt class have been designed or demonstrated using this fuel.

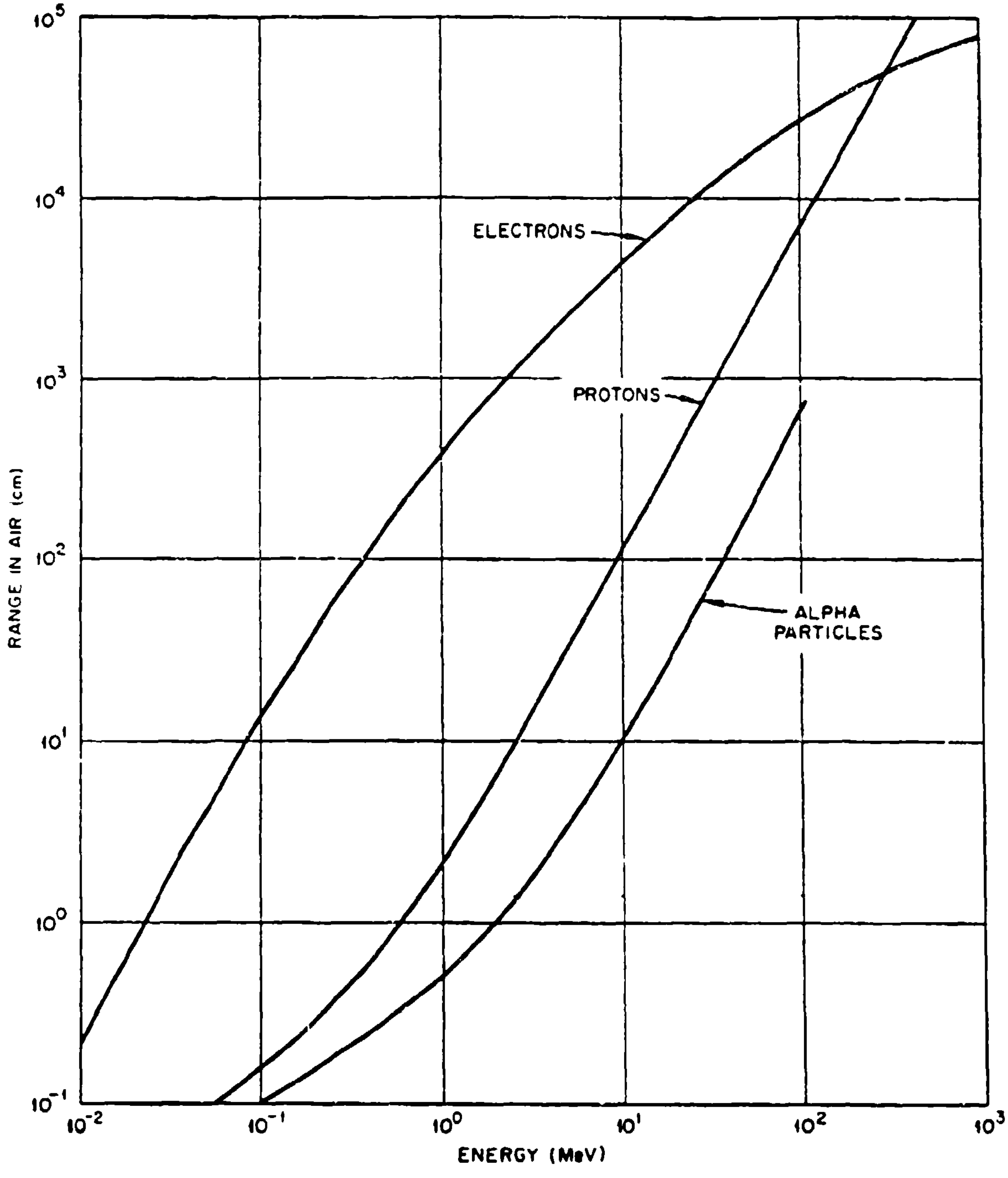

Figure 32. Mean Ranges of Electrons, Protons, and Alpha Particles in Air ($\rho = 0.001293$ g/cm^3)

Design for the Soldier System

The Radioactive Isotope Power Source (RIPS) consists of a spontaneously decaying radioactive "fuel" supply which emits alpha, beta, or gamma radiation; an absorbing shield around the fuel supply, which captures the energy of the radiation and turns it into heat; a series of thermoelectric elements that convert some of the heat to electricity in the form of direct current (dc); and a heat exchange mechanism to eliminate the unusable thermal energy. One typical supply is depicted in Figure 33.

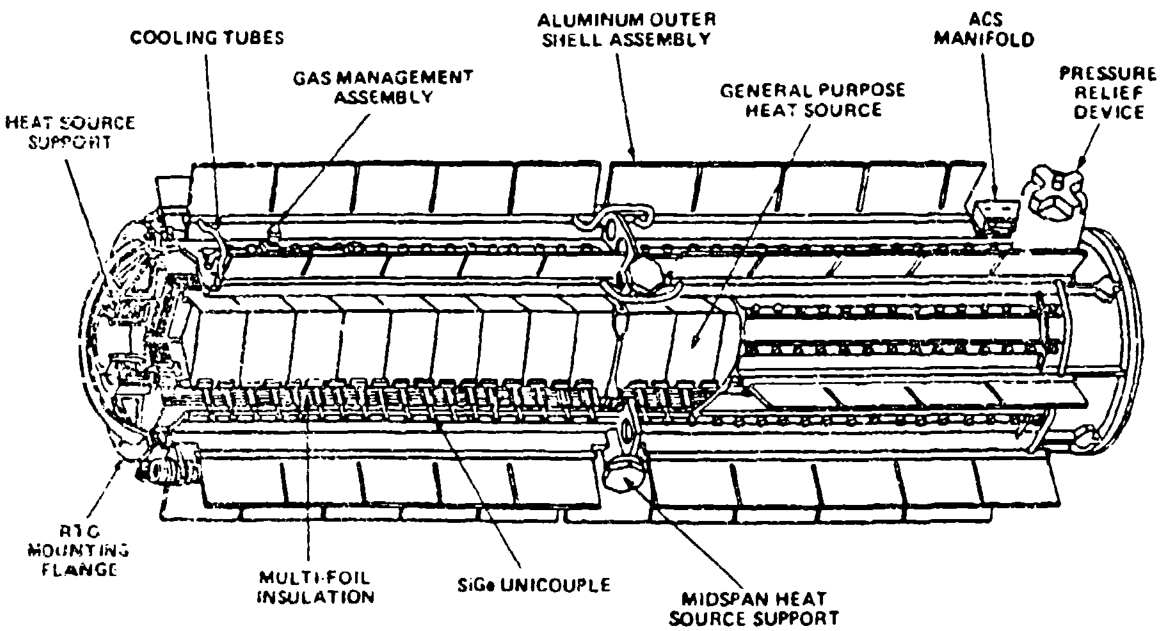

Figure 33. General Purpose Heat Source RTG

A system based on this kind of power source can be completely or nearly passive. It would consist of the RIPS, at present simply a Radioisotope Thermoelectric Generator (RTG) as described above; a dc-dc converter for providing constant or controlled output voltage independent of load; and a thermoelectric cooler with a fan for air movement or a pump for liquid flow. In its simplest configuration, the RTG has external fins sized to radiate the waste heat. A system block diagram is shown in Figure 34.

The dc-dc converter for the Soldier System electronics requirements being considered is small. Units obtained from Vicor, for instance, which are nominally rated at up to 100 watts output, weigh just 86 and 166 grams (3 and 6 ounces) without a heat exchanger; a more robust, fully heat sunk 120 watt unit from International Power Devices (IPD) weighs 676 grams (1.5 pound).

One variation would replace the low coefficient of performance thermoelectric cooler with an electric motor driven vapor cycle cooler, increasing the number of moving parts and sacrificing some of the simplicity for lower overall system size and weight.

A thermoelectric cooler capable of 400 watts peak cooling output is projected to weigh 2.7 kg (6 pounds) and to operate at a Coefficient of Performance (COP) of 0.5, thus requiring about 800 watts of input power at the maximum heat removal conditions projected. A vapor cycle cooler that could be electrically driven would require about 270 watts of input power (COP of 1.5 est.) for similar heat removal performance. Both of these would also need fans or pumps for the heat exchange loops.

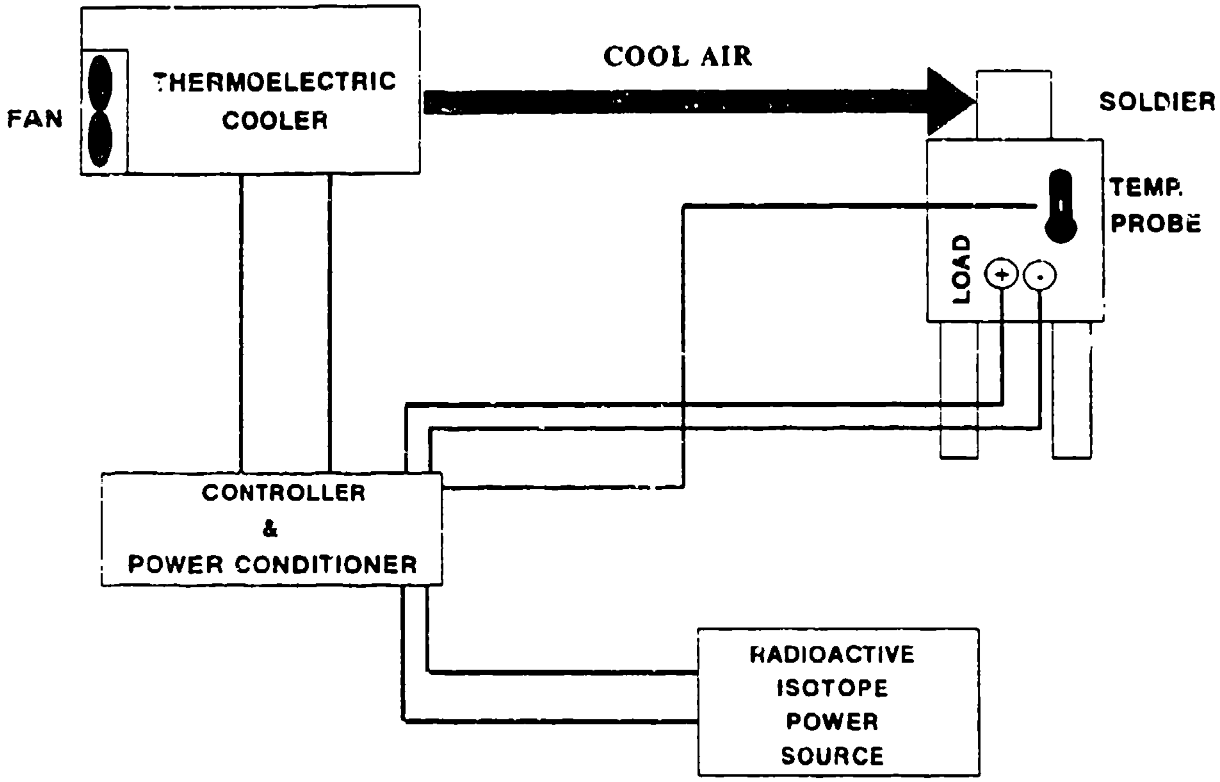

Figure 34. Concept Radioactive Isotope Power Source and Thermoelectric Cooler

In an effort to estimate the potential size and weight of a unit that might meet some postulated Soldier System scenarios, Dr. M. Frank Rose arrived at a conceptual design of an RTG that weighs less than 6 kg (13 pounds) for a system with a "beginning of life" (BOL) capability of 150 watts continuous peak electric power delivered (Reference 1). The dimensions are about 24 cm (9.5

inches) tall and 20 cm (7.9 inches) in diameter. This design was based on consideration of available technology as represented by the General Purpose Heat Source (GPHS) and the SiGe thermoelectric elements used therewith in the state-of-the-art MOD-GPHS-RTG, but with the fuel being polonium 210, with a half life of 138.4 days, in the form of a gadolinium polonide (GdPo) alloy. This design is illustrated in Figure 35. A critical element of the design is the use of a fan to assist in the package cooling. With a thermoelectric element conversion efficiency of only 8 percent, a major problem with any RTG is eliminating the waste heat, which is in the 2 kW range for this unit.

Thermoelectric couple performance represents the most critical technical barrier to the development of quasi-static radioisotope-based power sources for Soldier Individual Power applications. Identifying a selection of acceptab dioactive sources (considering safety, shielding requirements, environmental issues, cost, etc.) is a strong second, though it appears that there are several potential candidates, Po 210 among them.

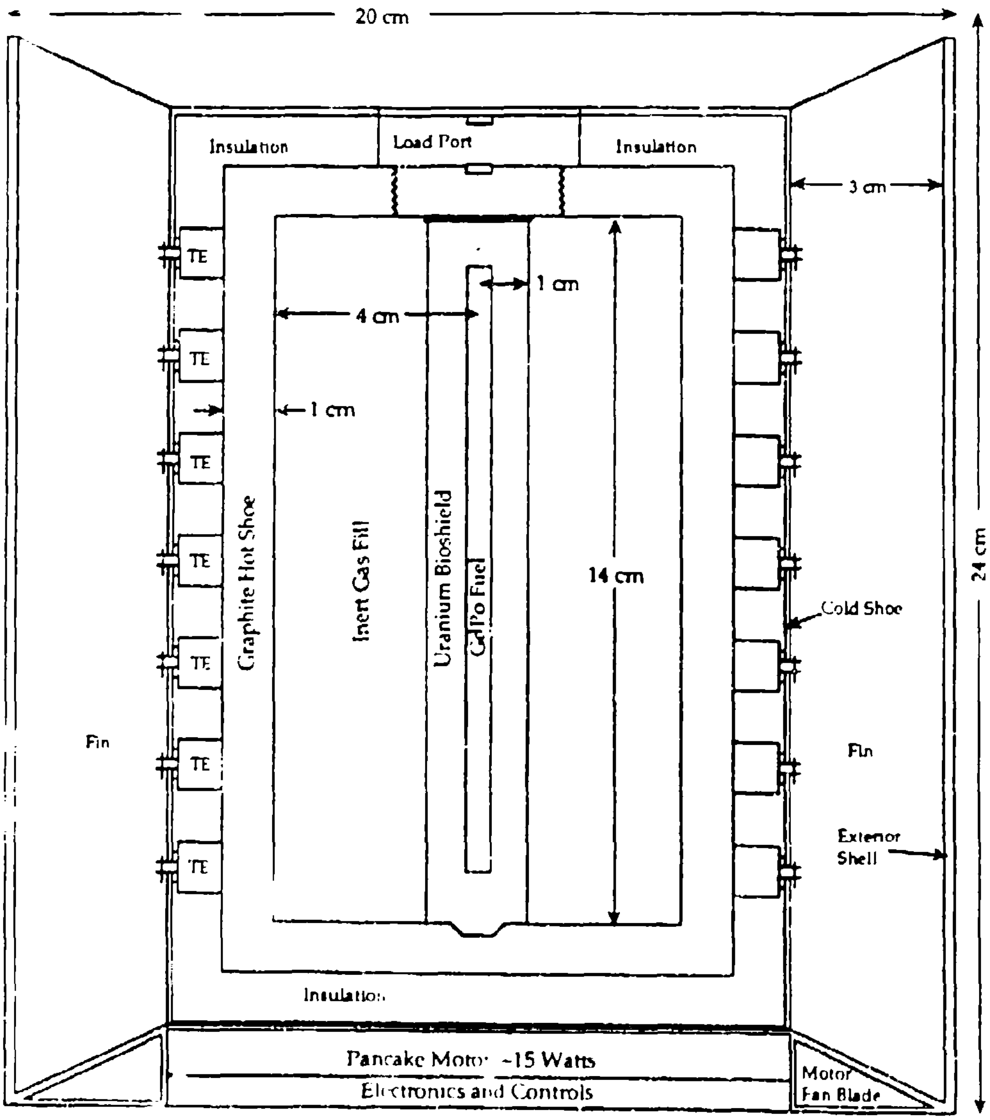

Figure 35. Cross Section of the SIPE RTF

Combining the conceptual changes in design from Rose's approach with the projected thermoelectric element conversion efficiency improvements, we can conservatively estimate the specific power of future radioisotope-based power sources as:

Year	W/lb
1992	2.4
1994	3.0
1998	6.0
2002	10.0
2006	15.0

The data is illustrated in Figure 36. These are preliminary, rather conservative estimates. Better data may result from the Workshop: "Radioisotope Power Technologies and Applications," scheduled 22-25 March 1992 in Park City, Utah.

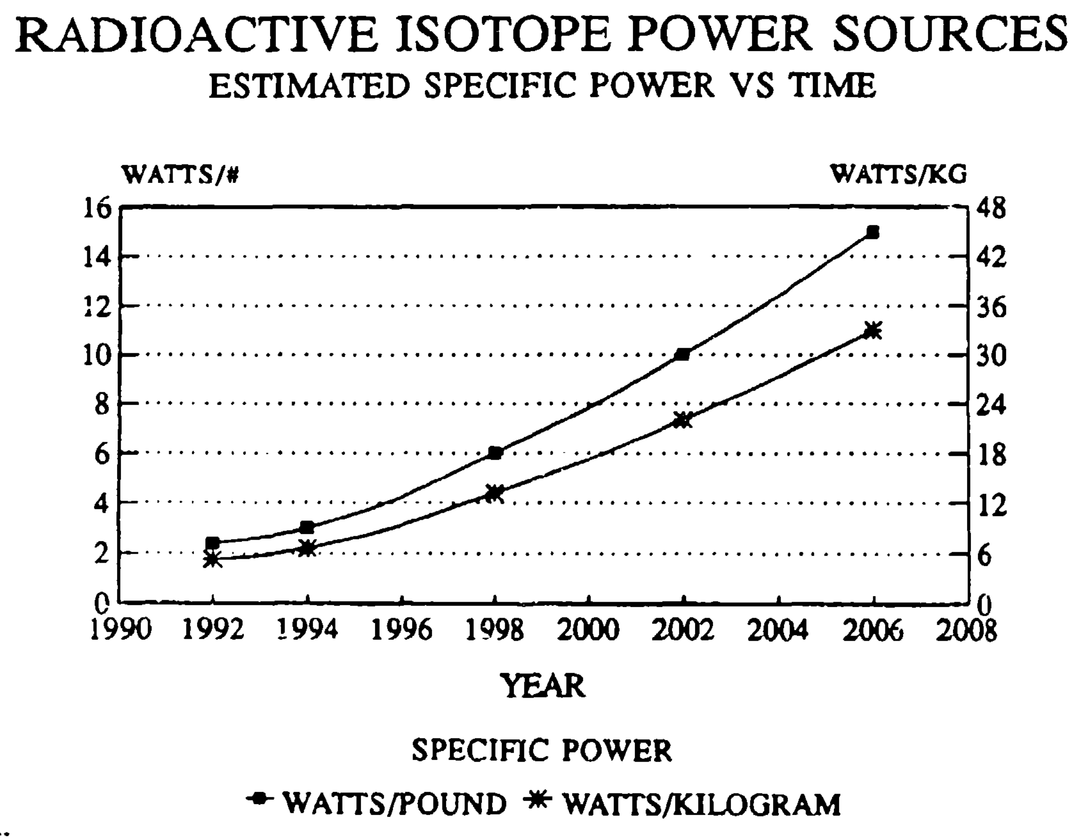

Figure 36. Radioactive Isotope Power Sources Estimated Specific Power Versus Time

Advantages/Disadvantages

Radioactive Isotope Power Sources are best suited to provide power under fixed, steady load conditions; they have the disconcerting feature of not being able to be turned off after activation. This implies that a means to maintain electrical load under all external demand conditions from no load to rated load must be provided, typically by using a shunt regulator and by dumping unneeded electrical energy in the form of heat. However, certain characteristics of plutonium make it clearly politically and environmentally unacceptable as a widely proliferated power source fuel on future battlefields.

Use of short half-life isotopes in RIPS is suggested as a way to alleviate environmental concerns. In this concept, the power source is designed with isotopes having a 6- to 18-month life so that the fuel sources will become essentially inert in about 2 to 6 years after they are first processed. Table 5 lists several isotopes that may be used in RIPS.

A principal difference that the short half life isotopes offer is a significantly higher power density (on a 100 percent basis) than that of plutonium. Compared to plutonium-based power sources that may have almost 50 percent of their total mass allocated to the fuel, the short half life isotopes can lead to systems in which the fuel is only a small percentage of the total system mass; and, such systems may be within the range of feasibility for the Soldier System. The counter aspect of this is found with short half life isotopes. Then, power sources will have a very definite "shelf life" after being fueled. This implies either having a BOL power capability that allows for full required rating at some time after the initial fueling, or having a scheme to combine partially spent fuel loads to recoup adequate capability.

Thermoelectric converters are not the only candidates for thermal energy conversion. Table 6 (taken from Reference 1) illustrates some other possibilities. The dynamic cycle devices will be much like the external combustion engine-generators with a semi-infinite, uninterruptable heat supply. Their great advantage at present is efficiency. Their principal disadvantage is complexity, the requirement to have rotating equipment that cannot be readily turned off, and, simultaneously, the problem of managing the waste heat over all operating conditions.

Alkali Metal Thermal to Electric Conversion (AMTEC) is described by Suitor, Hunt, and Sievers as "....a static electrochemical conversion system that uses sodium as the working fluid and a sodium ion-conducting electrolyte. The sodium is heated from the heat source before it passes through the beta-alumina solid electrolyte (BASE). Electrons removed from the sodium on the high temperature/pressure side of the BASE are recombined on the low pressure side after passing through the electrical system load. The sodium vapor is then condensed and returned to the heat source by an electromagnetic (EM) pump." This approach has reportedly demonstrated a cycle efficiency of 19 percent in laboratory tests and purportedly has the potential to go as high as 30 percent. This is about a 4:1 power to size advantage over existing RTGs used on Voyager.

Table 5a. Isotope Properties

Property / Isotope	Power Density (W/gm)	Power Density in common form (W/gm)	Form for use	Half life (years)	Melting Point (K)	Power Density (W/cm^3)	Emission Type	Estimated cost/gm	Source	Energy of most emission	Explanatory Notes
^{60}Co	17.8	17.8	metal	5.24	1772	15.7	γ,β	low	spent reactor fuels	1.33 (γ)	Primary concern is 1.33 MeV γ ray. Requires ~25 cm/kWth of Pb equivalent shield for biocompatibility. Shielding totally drives system mass for man rating.
^{90}Sr	0.93	0.2	$SrTiO_3$	28.6	2317	1.27	γ,β	low	spent reactor fuel	2.26 (γ)	Recoverable from reactor fuels. Bremstrahlung from high energy β makes heavy shielding necessary. Since Bremstrahlung process is inefficient, shielding requirement only about 1/2 that for ^{60}Co. Shielding mass dominates design.
^{106}Ru	33.1		metal alloy	1.0	2587	14.8	γ,β		spent reactor fuels	3.35 (β)	High energy β from daughter ^{106}Rh (33.5 MeV) requires massive shielding.
^{210}Po	144	82.4	metal (alloy)	0.38	531 (metal) 2000 (GdPo)	805.8	α		spent fuels and power reactors	5.3 (α) 0.8 (γ)	Fuels suitable demonstrated by MOUNDLAB in 1965. 0.8 MeV γ as a result of secondary processes requires about 2 cm Pb equivalent/kWth for biocompatibility. Ultra-high power density.
^{238}Pu	0.56	0.39	PuO_2	87.8	2509	4.0	α	high	spent fuel and power reactors	5.5 (α) 0.04(γ)	Fuels of choice for almost all current applications. Long half-life makes high power terrestrial applications environmentally sensitive. Low shielding required for biocompatibility. Special restrictions. Low Power density.
^{244}Cm	2.84	2.45	Cm_2O_3	18.1	2200	6.22	γ,n		spent fuel by-product	n (SF) 0.04 (γ)	Neutron shielding required. About 5 cm/kWth Pb equivalent needed for biocompatibility. Manufacturing technology demonstrated at Oak Ridge and Savannah River.

Table 5b. Characteristics of Radioisotopic Heat Sources

	^{460}Co	^{63}Ni	^{85}Kr	^{90}Sr	^{106}Ru	^{137}Cs	^{144}Ce	^{147}Pm	^{170}Tm	^{210}Po	^{241}Am	^{238}Pu	^{242}Cm	^{244}Cm
*Watts/Gram (100% Basis)	17.8	0.0057	0.589	0.933	33.1	0.416	25.6	0.333	13.6	144	0.112	0.557	120	2.84
*Half-Life Years	5.24	100.1	10.72	28.6	1.0	30	0.78	2.62	0.35	0.38	432.7	87.74	0.45	18.1
*Curies/Gram (100% Basis)	1,141	56.7	392.3	139	3,394	87	3,180	928	6,048	4,500	3.428	17.119	3,320	81
*Curies/Watt	64.2	9,950	666	149	102	209	124	2,786	445	31	30.6	30.7	28	29
*Compound Form	Metal	Metal	Gas	SrF_2	Metal	CsCl	Ce_2O_3	Pm_2O_3	Tm_2O	Metal	AmO_2	PuO_2	Cm_2O_3	Cm_2O_3
*Watts/Gram Compound	1.78	0.00057	0.0589	0.252	1.19	0.143	1.08	0.273	1.2	137	0.100	0.39	90	2.35
*Melting Point of Compund °C	1,495	1,455	—	2,040	2,310	645	2,190	2,320	2,375	254	—	2,232	2,230	2,230
*Compund Density g/cm^3, actual or 90% TD	8.8	8.9	—	5.03	12.4	3.8	6.9	6.6	8.0	9.2	11.7	10.3	11.7	11.7
*Power Density W/Cm^3 Compound	15.7	0.0053	—	1.27	14.8	0.545	7.47	1.8	9.6	1,260	1.2	4.0	1,053	27.5
*Capsule Dimensions 50 Wt. 1:1 Cyl. (cm)	2.2	—	—	4.3	2.2	5.5	2.6	3.9	2.5	1.7	4.4	3.1	1.7	1.9
*Major Types of Radiation	Beta Gamma	Beta	Beta Gamma	Beta Bremst Gamma	Gamma Beta Bremst	Beta Gamma Bremst	Gamma Beta Bremst	Beta	Beta Bremst	Alpha Bremst	Alpha Bremst	Alpha	Alpha Neut	Alpha Neut
*Lead Shielding(in of Pb) [Mev of Significant B or G]	Heavy (9.5) [1.33G]	Minor (—) [.008B]	Minor (—) [0.0687B]	Heavy (6) [2.26B]	Heavy (9) [3.35B]	Heavy (4.6) [1.17B 0.67G]	Heavy (10.2) [2.98B 2.18G]	Minor (1) [0.23B]	Medium (2.5) [0.97B]	Minor (1) [0.8G]	Minor (—) [0.06G]	Minor (0.1) [0.04G]	Minor (0.4) [0.04G]	Medium (2) [0.04G]
*Availability	Avail.	Poten. Avail.	Avail.	Avail.	Poten. Avail.	Avail.	Avail.	Avail.	Avail.	Avail.	Poten. Avail.	Avail.	Poten. Avail.	Avail.

Table 5c. Properties of Several Radioisotopes That Might be Used in Nuclear-Fueled Generators

Isotopes	Fuel form	Decay mode	Compound Power density W/cm^3	Compound power density W/gm	Half-life years	Shielding required	Maximum operating temp, °C	Availability kW/yr (thermal)	Cost dollars/watt
Polonium 210	GdPo	α	820	82	0.38	minor	1600	70	150
Plutonium 238	PuO_2	α	3.7	0.41	86.4	minor	1000	11	750
Curium 242	Cm_2O_3	α	1050	98	0.45	neutron	1600	1.5	
Curium 244	Cm_2O_3	α	28.6	2.6	18.0	neutron	1600	8	3650
Promethium 147	Pm_2O_3	β	2.1	0.28	2.6	minor	1000	2	1000
Strontium 90	SrO SrF_2	β	1.2	0.24	28	heavy	1000	31	90

Table 6. Comparison of Energy Conversion Schemes

Technique	Current SOA Efficiency (%)	Developmental Potential (%)	Comments
Dynamic Cycles (Stirling, Rankine, Brayton)	25-30	35	Conversion is to kinetic energy. Generator must be added to produce electricity. Unknown reliability. Not widely used. Active prototyping in R&D community.
Thermophotovoltaics	—	20-30	Laboratory version in small-scale, proof-of-principle experiments.
AMTEC	—	20-30	Laboratory version in small-scale, proof-of-principle experiments.
Thermionics	8-10	10-15	Undergoing extensive testing for use in small nuclear reactors. Proof-of-principle for RTG use long established.
Thermoelectrics	6-8	10-15	Extensively used RTG technology. Well established, high reliability technology. All current RTG power supplies use this technology. Major R&D program to improve units.

Conclusion

Significant efforts to improve the prospects of RTGs are planned or underway. Figure 37 illustrates the Jet Propulsion Laboratory's GPHS system efficiency goals between now and the year 2000. Achieving the projected 80 percent improvement by the end of 1994 would yield a system efficiency better than 14 percent, reducing the waste heat to the 1 kW range, while meeting the 1998-2000 efficiency goal (exceeding 21 percent) would reduce this to less than 700 watts waste heat rejection required. The corresponding specific power ratings (W/kg or W/lb) would be nearly 1.7 and 2.5 times greater than present values, respectively. Jet Propulsion Laboratory modeling estimates predict that it may be possible to go another 30 percent or so beyond this level of improvement, so that factors of three in power density above today's level are conceivable.

Applied to design approaches as illustrated by Dr. Rose's report, this indicates that 450 to 500 watts might be achievable in a 6 kg package. This has the added benefit of a lower thermal rejection requirement, so any thermal design that is adequate with today's TE elements will be more than adequate for the higher power capabilities of the future.

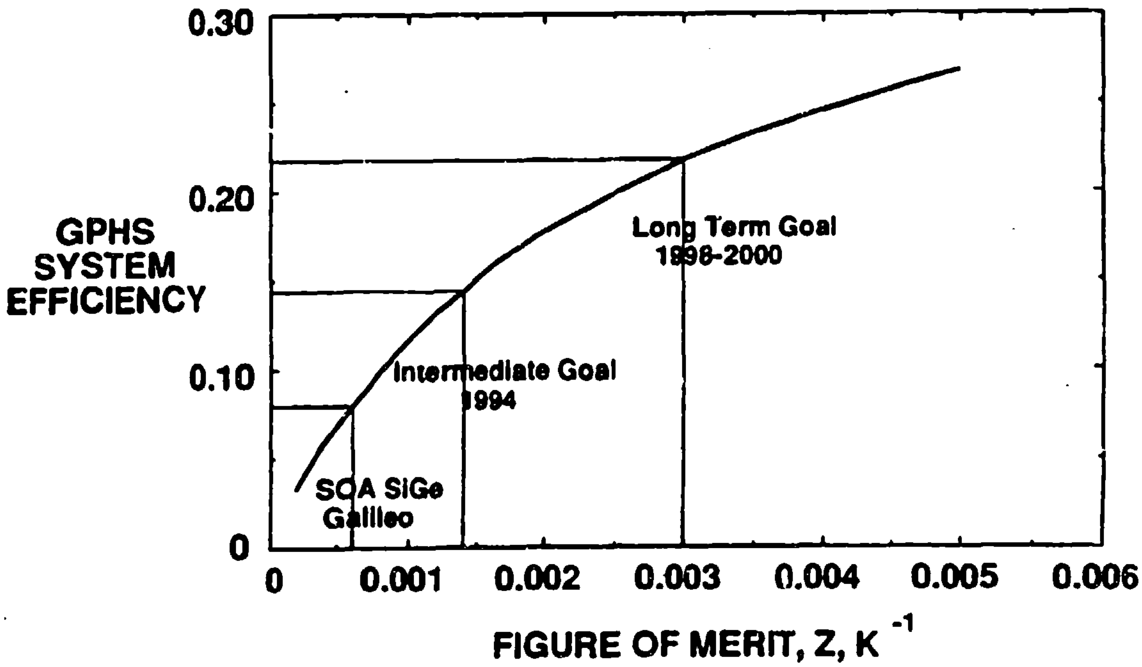

Figure 37. GPHS System Efficiency

Other Radioactive Isotope Power Supply Concepts

Several additional concepts that may be amenable for use in the Soldier System include:

A thermophotovoltaic (TPV) power source proposed by Dr. Rose, et al, of the Space Power Institute at Auburn University, Auburn, AL (Reference 2). In this concept, a heat source provides thermal energy which is converted to relatively narrow spectrum electromagnetic radiation, as in a Coleman lantern, and the radiation is then converted to electricity in a band gap tailored semiconductor photovoltaic material. An intriguing possibility of this concept is the creation of a fossil or synthetic fuel-driven device for normal use and training which converts to nuclear-based energy sources when long periods of autonomy without refueling are required. Estimated efficiencies for such a converter are 20 to 30 percent.

A concept known as Photon Intermediate Direct Energy Conversion (PIDEC). This is being advanced by Dr. Prelas, et al, of the University of Missouri, Columbia, MD (Reference 3). In this concept, a radioactive source is used to cause a surrounding gas to fluoresce, and the resultant electromagnetic radiation is converted to electricity in a band gap tailored semiconducting photovoltaic material. The proponents indicate that the net conversion efficiency might be in the 20 to 40 percent range, due in part to a better match between the fluorescer radiation spectrum and the PV material than what occurs with the solar spectrum.

A concept for higher power "betavoltaics," being proposed by Caltech scientists (Reference 4) working for NASA's Jet Propulsion Laboratory. In this concept, beta emissions from radioactive sources would be converted directly to electricity in an analog of the conventional photovoltaic process. The difference here is that the emitting and absorbing materials could be stacked in layers as in a battery, with appropriate shielding or backscattering material surrounding the whole pack. Present Gallium-Phosphide (GaP) cells have shown a measured 8.4 percent conversion efficiency (similar to thermoelectrics) and have nearly 25 percent theoretical power conversion efficiency. Preliminary calculations for cells using Thallium 204, a beta emitter with an energy of 0.77 MeV and a four year half life, are reported to show an initial specific power as high as 8 W/kg (3.6 W/lb).

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Section IV
Conclusion

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EVALUATION

Introduction

Once the operational scenarios were developed, the evaluation criteria to review power technologies were chosen. The list of evaluation considerations includes cost, weight, signature, safety, vibration/gyroscopic forces, attitude, shelf life, integrated logistic support (ILS), reliability, availability/maintainability (RAM), size, starting/restarting, efficiency, human factors engineering (HFE), and production base. These criteria are further detailed in the section of the FEA entitled "Evaluation Factors for the Soldier System."

Using a computerized parametric model developed at BRDEC, candidate technologies were evaluated for a full range of mission lengths, cooling modes, operating hours, quantity procured, soldier equipment loads, cooling requirements, and technological maturity. Additional issues considered included safety, signature, environmental impact, and human factors/MANPRINT concerns. Technical data for each technology was input into the parametric model. The candidate technologies were then compared using a set of mission scenarios generated with extensive TSM Soldier collaboration. The parametric model output predicted a relative life-cycle cost, size, and weight for each technology.

The parametric model can quickly calculate energy and power levels required based on mission lengths and operational scenarios. The model also calculates total system weights based on scaling formulas determined during the analysis of the technologies. The model is envisioned as a briefing tool, since estimated system performance can easily be shown with multiple changes in mission scenarios, equipment loads, or usage ratios. The parametric model is discussed in Appendix F of the FEA, entitled "Parametric Model Development."

The parametric model results led to the following selected technology solutions: primary battery-driven power systems, internal combustion engine-driven systems, and fuel cell-driven systems.

Cooling Technologies

Although power technologies were the central subject of the FEA, cooling technologies were also reviewed. As the cooling system represents the largest potential power draw, choosing the most efficient cooling technology is obviously important for overall energy use. Integration of the power and cooling systems for maximum weight savings also demands a careful look at the available cooling technologies for interface requirements and operating characteristics. Several of the more qualitative criteria were also reviewed, such as noise, vibration, and safety concerns, in order to make the final selections.

Cooling technologies reviewed in the FEA appendices include vapor compression cycle, air cycle, thermoelectric, absorption/adsorption systems, cryogenic systems, and metal hydride systems. In addition, "passive" systems such as ice and desiccant systems are addressed. An analysis is also made of the cooling loops around the body of the soldier, i.e., a liquid vest versus an air vest.

After analysis, it was decided to use a vapor cycle system with an air cooling vest for all of the power technologies. This provides the maximum efficiency of the available technologies, offers the lightest weight, and is the most developed system. An electrically-driven system is specified for those power technologies which have electrical output (i.e., fuel cells), and a shaft-driven system is specified for those systems with mechanical outputs (i.e., IC engines). The one exception to this selection is the consideration of a Duplex Stirling, where a power Stirling runs an attached cooling Stirling. This concept was selected due to the integration efficiencies offered by this design.

RECOMMENDATIONS

This section provides the FEA conclusions based on the overall Soldier System requirements and mission scenarios. It should be noted that the conclusions presented at the end of previous sections of the FEA do not necessarily reflect the analysis of the system as a whole.

Performance Drivers

The performance drivers of the program are weight, fuel, and the need for autonomy (i.e., no resupply). To enhance and maintain mobility and survivability, system weight must be kept to a minimum. The future battlefield fuel supply requires that the system be capable of operation on military specification fuels such as DF-2 and JP-8. To date, there is no available power source, capable of reliable operation with this type of fuel for a sustained mission (>8 hours) mission, which can meet the weight and size constraints.

Recommended Efforts

The FEA showed that for the majority of individual soldier missions which do not require cooling, battery-powered systems are the preferred approach. However, these systems are presently feasible only for low energy (no cooling), short duration (less than 8 hours) missions. For missions requiring more energy, such as cooling in hot climates, a fueled system is required. The two most technically promising fueled options are fuel cell-driven and small engine-driven systems. The conclusions in each section of the FEA do not reflect the analysis of the system as a whole.

Batteries

The only current battery technology which will meet future Army needs appears to be based upon lithium. In sizing the battery, both power and energy density requirements must be met. However, both parameters cannot be maximized simultaneously. Generic lithium technologies are approaching the practical and realizable limits of the chemistry in both energy and power density.

Advanced lithium technology currently in development can power the electronics-only scenario and, marginally, the electronics plus forced ambient air scenario. No current battery is capable of meeting the power and energy requirements projected for the electronics and refrigerated air Soldier System within the current weight limit of 10 pounds. Future R&D may produce a battery of the lithium sulfuryl chloride type with sufficient power density to power this scenario. The current state-of-the-art for achievable energy and power density is on the order of 25 to 30 percent of the theoretical values. It may be possible to achieve 50 percent with a concerted research effort.

Fuel Cells

Fuel cells of the hydrogen-oxygen type have several attractive advantages. They have little or no signature, are inherently efficient in most modes, ingest no external fuel, need no intake filters, and produce only drinkable condensed water as an exhaust product. However, there is no current fuel cell system available in the weight and size envelope required by the Soldier System. Fuel cells will also require the addition of hydrogen (and possibly oxygen) as a battlefield fuel. Development is likely to take five to six years longer than the engine-based system. If the projected 1999 technology levels are achieved, a slightly higher but possibly acceptable size and weight as compared to IC engines will be obtained.

Combustion Engines

Hydrocarbon fuel-derived approaches include external and internal combustion engines. External combustion cycle approaches include Stirling engines or Rankine type engines. The primary advantages of these approaches are continuous combustion allowing relatively straightforward start procedures, low noise potential, and possible multi-fuel capability. Unfortunately, these approaches also exhibit poor thermal efficiency when using the small engine sizes required, are inherently complex, and are consequently very heavy. Thus, the internal combustion engine is favored.

The internal combustion engine-driven approach is potentially the smaller, lighter, and less expensive of the two fueled approaches—provided that the technology levels projected by this analysis are met. It is important to the Army because it has the potential to achieve high power density and has inherently low manufacturing costs.

The engine-based systems can be realized only if the technological barriers defined in the FEA are overcome. These barriers are signature, combustion/conversion efficiency, limitations in ignition characteristics, and component service life.

- *Signature Suppression:* Achieving adequate signature suppression (noise, thermal, and vibration) is critical to making engine-driven systems compatible with human use. One major area of development focuses on attenuating noise through the use of active and passive noise cancellation techniques, minimizing vibration through component design and integration, and reducing the thermal signature by eliminating "hot spots" and reducing fuel exhaust particulate.

- *Combustion/Conversion Efficiency:* Improving the combustion/conversion efficiency is critical because the weight of the fuel required for many missions is a significant part of the soldier's added load. To achieve the necessary efficiency, fuel consumption must be minimized using precision fuel injection systems; thermal efficiency may be improved by using ceramic combustion chamber/piston materials, and overall fuel atomization will require improvement.

- *Ignition Characteristics:* Overcoming limitations in ignition characteristics is critical to achieving cold start and to operating on military specification fuels (middle distillate fuels commonly used in military equipment). Techniques incorporating fuel/air heating devices and innovative ignition systems—such as high-energy, multi-spark, multi-mini spark plugs, and plasma ignition systems—that are compatible with miniature engine sizes should be demonstrated.

- *Component Service Life:* Component service life is a cost driver for fielded systems. Once the required level of performance is achieved, component life must be addressed to assure affordability. The target is to field a system with an operating life of at least 350 hours. Other efforts to improve durability may involve the application of synthetic lubricants, high performance seals, ceramic bearings, and high performance heat-exchange surfaces.

Summary

The future soldier's fighting capabilities will be enhanced through the addition of microclimate cooling for protective clothing, a soldier computer, individual navigation, enhanced hearing, night vision, helmet displays, communication, and weapons ranging. These components are being integrated into a safer, more effective Soldier System. However, without power, these technologies cannot operate.

The Army's Soldier System must operate in many mission scenarios with a wide range of power requirements. These requirements pose a technological challenge which will be met with the Soldier Individual Power Program. This program will integrate various complementary technologies to create an efficient and reliable source of manportable power for the Soldier System.

The short-term focus includes an aggressive pursuit of primary (non-rechargeable) battery technology and optimization of engine-driven systems.

The mid-term emphasis continues to look at batteries (especially rechargeable lithium types) for low energy missions and improved engine-driven systems as the most promising for meeting cooling requirements. However, considerable focus is shifting to fuel cells. Higher risk technologies such as photovoltaics and thermoelectrics will also be investigated.

The long-term solution will most likely be fuel cells. Thermoelectrics and photovoltaics are alternates for the longer term but represent a higher risk than fuel cells. Safety and environmental concerns will undoubtedly affect the final technology selection.

The ultimate achievable performance will be limited by operational scenarios and requirements rather than simple energy conversion. The program will be continually updated to detail research and technology directions and funding commitments.

Appendix A
Air *versus* Liquid for Body Cooling

(Author: Mr. Christopher Bolton, BRDEC, SATBE-FED)

Microclimatic cooling works by cooling inside the soldier's clothing or protective ensemble rather than conditioning the surrounding environment. Testing shows that subjects exposed to hot environments while wearing the armored vehicle regulation ensemble and the standard chemical protective gear have core temperatures that increase even while resting (Reference 1). When wearing protective clothing, it is difficult to do even short-term, light intensity work in hot environments. Combat vehicle's microclimate cooling requires much less cooling than conditioning the entire interior of the vehicle. For cooling infantry soldiers and hazardous materials workers, it may not be possible to condition the open environment in which they operate. Providing immediate body cooling to the interior of their suits can remove metabolic heat from individuals even under extreme conditions.

Air and liquid are the two primary mediums for transferring heat from the body to the outside environment via mechanical cooling. Air cooling evaporates the sweat normally produced by the body and carries it off to the outside environment. Due to the complexities of air recirculation and protection factors, all current air systems are "once through" systems. The cooled air is not recirculated. Air can be brought into the suit directly through a hose or fitting opening, or it can be dispersed over the body through a distribution garment. Liquid cooling functions by conducting the heat directly from the skin into a circulating fluid loop. Each of these approaches has inherent advantages and disadvantages which will be discussed later.

Development of microclimate systems follows three distinct but interrelated paths. The Army is primarily concerned with heat stress caused by wearing Nuclear, Biological, and Chemical (NBC) protective clothing, so effort is driven by NBC and military operating constraints. Some development of microclimate systems in the civilian market has occurred, primarily for race car drivers and equipment operators exposed to hot environments. NASA pioneered this area, although their operating environment (zero G and deep vacuum) led to unique solutions.

The currently type classified and fielded air vest shows the inherent advantages of an air system. No direct skin contact with the vest is needed since the cooling effect depends on convective and evaporative cooling of the body. Ninety-five percent of the Army population can use the one-size vest with adjustable straps. It is very lightweight, can be easily stored and cleaned, is relatively rugged, and degrades well. As normal operation of an air cooling system pressurizes the suit, any leak in the vest will merely allow air to escape before its designated distribution path. This leak may not appreciably affect overall cooling. Even a larger leak, or a leak outside of the suit, may reduce the total cooling but still allow system operation. The current vest is primarily an open mesh design, which does not add to the heat stress of the individual if the cooling air flow is lost completely. One other major advantage of the air vest is the highly effective cooling method of sweat evaporating from the body. In hot, dry environments, this can result in "free" cooling. Latent sweat evaporation cools the body more than cooling done during the initial mechanical cooling of the air, which is primarily a sensible process. The sweat evaporation also provides a drier ensemble for the individual, although the dry area is primarily limited to the body area exposed to the air flow. Soldiers still accumulate sweat in their gloves and boots while wearing a vest providing only torso coverage.

The primary disadvantage of the air vest is the requirement to filter incoming air for NBC agents before it can circulate inside the suit. The NBC filters have an appreciable weight, a limited life, and induce a significant pressure drop. This pressure drop, combined with the air flow requirements of the garment itself, demands a blower with significant power requirements. The heat exchanger required for mechanical air cooling is also of significant size and weight. The current vest has distribution tubes running over the shoulders. Users complain about chafing and harness interference. The vest also has hard plastic distribution manifolds in the center of the chest and back, prompting user complaints about comfort and equipment interference. This vest is currently being redesigned. The new vest promises to be more comfortable and may be more efficient, although its one-piece construction might add a static heat load to the user. The efficiency of the vest is discussed later.

Current liquid vests come in two configurations. The first is comprised of flat vinyl panels that have welded-in liquid passages. This vest usually has a low pressure drop and a large surface area, although the large vinyl panels add to heat stress when the system is not operating. The second type of liquid vest is comprised of tubing attached to a woven cloth material. The open weave of this material allows some air circulation. It substantially reduces the heat stress to the individual when the system is not operating. This vest has a larger pressure drop due to the long lengths of tubing involved.

The primary advantage of the liquid vests is the compact size of its associated heat exchanger and circulating pump. Even with vest pressure drops of up to 45 psi, the pump will require an order of magnitude less power than a blower that operates against an eight-inch water gauge (W.G.) head.

The liquid vest does not require any filtration. It depends on skin contact for the conduction process, so this imposes some constraints on its sizing and effectiveness. More skin coverage, and thus more cooling, may be obtained readily by increasing the size of the garment. NASA has been utilizing full body suits for many years. The vest also requires a sufficient amount of liquid to cover the skin and transport the heat. The larger the garment, the more liquid (and weight) it will require. A leak in a liquid system might eventually shut down the cooling system. A leak inside a protective suit might reduce the effectiveness of that protection. Additional sweat evaporation does not occur with a liquid vest, although at equivalent cooling rates both air and liquid systems reduce sweat rates on a similar basis. Storage of the liquid vest is more difficult than the air vest, especially if the vest has been previously used. Two concerns are the liquid freezing and bacterial growth. Additives in the liquid can prevent both of these problems.

Air vests are type classified and fielded and primarily used by the crew of the M1A1 Abrams tank. Other users include the M109A6 Paladin howitzer and Air Force ground crews. A modification of this vest is planned for Army helicopter use. It may be transferred to the armor/artillery users as well. Future air vest applications are planned for vehicles of the Armored Systems Modernization Program and the V-22 aircraft. All air systems to date have utilized umbilicals to tether individuals to a multi-outlet central system.

Liquid vests saw limited production for civilian markets. During the recent Desert Shield/Desert Storm effort, several types of liquid systems and vests were deployed for military users. All self-contained individual systems to date use liquid vests, except for some special-use suits that use evaporation of liquid gases. Any impermeable protective system is limited to a liquid vest cooling system, unless some method of air recirculation is developed. There is an obvious benefit towards standardization of one cooling method, provided that this method meets the diverse needs of its many users and missions. For Army applications, there is also an obvious benefit derived from having an individual system that interfaces with the vehicle system.

System interface or integration is a key issue for the individual system as a stand-alone unit. If the assumption is made that cooling is required primarily for NBC operations, then the individual must carry a filter for breathing air. If it is assumed that individuals are wearing protective masks and hoods, then head cooling has psychological as well as physiological benefits. If the individual system includes helmet-mounted sights, displays, or communication gear, then added heat from the electronics may make head cooling even more important.

Given that an individual system requires head cooling and breathing air filtration, an air system would allow for superior integration and comfort. Forced air relieves the effort required to inhale through a face mask filter. It also provides an increase in the protection factor due to over-pressurization of the mask. Cooling the breathing air might provide a 5 to 10 percent increase in metabolic heat removal over an ambient air system (Reference 2). The dry air blowing across the face not only cools and dries the head, but defogs the vision lens and display screens.

A liquid system, by contrast, requires an additional liquid to-air heat exchanger and a small fan to provide the same benefits. Liquid cooling of the head via a skull cap and forced ambient air for ventilation/breathing would not be as comfortable as a cooled air system. It would also require additional water weight and a separate face mask fan. Integration of the face mask filter and the suit filter is possible, but weight savings might not be significant for one big filter versus two smaller ones. The amount of carbon filtration material is based directly on total air flow; the housing material weight is very light. Mission flexibility and equipment standardization might also require a separate filter for the face mask. A detailed breakout of the weight impact of these integration issues is presented later.

Vest efficiency is a key issue in the selection of a heat removal system. In anticipated future Soldier Systems and mission scenarios, the cooling system requires up to 80 percent of the total power produced by the power source. The actual body heat removal mechanism becomes more critical. NRDEC unofficially advises interested parties that the current air vest has an effectiveness of 66 percent. This is based on early development work, copper mannequin testing, and human subject testing. This effectiveness is the portion of the potential cooling available that actually acts upon the body. As an example, 15 cubic feet per minute (CFM) of air that enters the vest at a dry bulb temperature of 68°F and a wet bulb temperature of 55°F has a potential cooling rate of 2,300 BTUH when the mass flow and the enthalpy is calculated. Potential cooling is taken as the mass flow times the enthalpy difference between the state of the air entering the vest and that of air leaving the vest at 95°F dry bulb, 100 percent saturated. If the vest is 66 percent effective, this vest inlet and flow condition could provide 1,500 BTUH of body cooling (2,300 BTUH * 0.66 = 1,500 BTUH). However, if the vest is only 30 percent effective, these conditions would result in only 690 BTUH of available cooling.

Recent evaluation of test data compiled during human subject testing indicates that air vest effectiveness is actually closer to 40 percent (References 3 and 4). In the referenced studies, the researchers could not stabilize subject core temperatures at metabolic work rates of 315 watts (1,075 BTUH). Because the core temperatures continued to rise, the cooling supplied to the subjects was impossible to determine but inadequate for thermal equilibrium. The exact amount of cooling supplied to the subjects was impossible to determine. One possible variable is the amount of ambient loading imposed on individuals within protective ensembles. Not only must the cooling system remove all of the individual's metabolic heat, but it must also counteract any additional heat due to high outside temperatures and solar loading. Natick states that some degree of insulation is provided by the ensemble, but exact figures are not given (Reference 5). Just as in any air conditioning problem, determination of the heat load is critical for proper equipment sizing. If the actual cooling load is higher than that represented by the soldier's metabolic load, then the mission effectiveness and duration will be reduced. Depending on the ambient air conditions, it is still possible to obtain "free" cooling even at an effectiveness value of 40 percent. However, total body cooling is greatly reduced and the advantage of the air vest over the liquid system is lessened. The efficiency of a liquid vest system is much easier to determine within certain limits. The temperatures of the entering and exiting water can easily be determined. The temperature difference times the specific heat times the mass flow of the water determines the cooling supplied by the vest. There are some losses in the lines due to ambient heat gain, but these are usually small, especially for a backpack system with short connection paths. The liquid vest is limited to an approximate operating range of 60°F to 85°F. A lower temperature tends to decrease the body cooling because of vasoconstriction. The blood vessels near the surface of the skin shrink and reduce blood flow, which reduces heat loss. The upper end is limited as cooling reduces the skin temperature. Vest-skin heat transfer also limits the upper value that the liquid can reach. In the detailed breakdown presented later, liquid vest cooling will be presumed to be 99 percent effective.

Heat exchangers vary greatly in performance. Usually increasing the efficiency of a heat exchanger requires an increase in size and weight of that device. A refrigerant-to-air heat exchanger is usually much less efficient than a refrigerant-to-liquid unit of equivalent capacity. This is primarily due to the increased heat transfer coefficients of liquids versus gases, typically four times greater. Counteracting this figure is the latent cooling available in a refrigerant-to-air evaporator through condensation of moisture in the air stream. Current technology allows a liquid system evaporator to be approximately two-thirds the weight of an air system evaporator. The liquid evaporator could be 95 percent efficient, while the air system is approximately 80 percent efficient. The condensers of an air garment system and a liquid garment system are approximately equal in size and weight for systems of equal capacity. The condenser must reject the heat of compression (which is a function of input power) to the ambient air. The system that requires the least amount of input power will have the smaller condenser. The actual power difference, and hence compressor difference, is relatively small and may be neglected.

In order to calculate total system weights and arrive at a logical decision point, many system parameters must be identified. To provide a range of options, several variables are presented. The most important variables are the ambient conditions; Army Regulation 70–38 presents standard military design practice for environmental control equipment. In particular, the hot-dry condition (120°F dry bulb, DB, and 3 percent relative humidity, R.H.) and the warm/wet condition (95°F DB and 74 percent R.H.) are used as worst-case situations for environmental loads and power requirements. Solar loading is neglected because it affects both cooling systems equally and because its effect on the cooling hardware can be minimized with careful design. However, solar loading may play a large part in the actual cooling system load.

Steady-state system analysis is used to simplify this process. Real-time analysis of dynamic constraints would be more accurate, but would also be very specific due to the large number of assumptions required such as heat soak time, pull-down time desired, utilization factors, etc. The coefficient of performance or COP of a system is the ratio of cooling performed over work required, both in watts. A system COP of 2.0 is assumed for the liquid system at the high temperature case of 120°F. The air system, due to its lower evaporator effectiveness, is assumed to have a COP of 1.68

because the compressor in the air system must work harder to produce the same amount of cooling as the liquid system. In actual practice, system COPs would be higher at the 95°F ambient condition. However, both systems would benefit and the exact amount of improvement is hard to quantify, so this effect will be neglected. The input power for COP calculations includes the compressor power and the condenser fan power. Since the liquid pump and the air blower require input power of a different magnitude, this power is calculated and addressed separately.

The air system is assumed to cool inlet air down to 70°F dry bulb in either the 120°F or 95°F ambient conditions. This air is assumed to be at a dew point of 19.5°F for the 120°F inlet condition (no moisture added), and at a dew point of 70°F for the 95°F condition (moisture removed). A 20 cfm flow rate and a rise in the delivered air temperature of 5°F (heat gain through the system) will be assumed for both cases. Using psychrometric data for both of these points and the potential cooling calculation described above results in potential cooling of 3,470 BTUH for the 120°F condition and 2,269 BTUH for the 95°F condition. Assuming an air vest effectiveness of 40 percent results in actual body cooling of 1,388 BTUH and 908 BTUH, respectively. The assumption is made that the delivered air flow is split between the face mask and the garment (3–4 cfm to the mask and 16–17 cfm to the garment). This assumption further surmises that head cooling and respiratory cooling is equally as effective as vest/torso cooling.

Calculations

Flow Rate x Density x Delta Enthalpy = Cooling Rate

@ 75°F DB, 19.5°F DP, Enthalpy = 20.45 BTU/lb, air density = 0.0675 lb dry air/ft^3

@ 95°F DB, 100% RH, Enthalpy = 63.29 BTU/lb, air density = 0.0675 lb dry air/ft^3

20 ft^3/min x 60 min/hr x 0.0675 lb dry air/ft^3 x (63.29–20.45) BTU/lb air = 3,470 BTUH Potential cooling

3,470 BTUH x 0.40 = 1,388 BTUH actual cooling = 407 watts @ 120°F ambient

@ 95°F DB, 100% RH, Enthalpy = 63.29 BTU/lb, air density = 0.0675 lb dry air/ft^3

@ 75°F DB, 70°F DP, Enthalpy = 35.28 BTU/lb, air density = 0.0675 lb dry air/ft^3

20 ft^3/min x 60 min/hr x 0.0675 lb dry air/ft^3 x (63.29–35.28) BTU/lb air = 2,269 BTUH Potential cooling

2,269 BTUH x 0.40 = 908 BTUH actual cooling = 266 watts @ 120°F ambient

The actual cooling work done on the air is taken as the change from 120°F to 70°F and from 95°F to 70°F. Assuming a COP of 1.68 and using similar calculations as those shown above results in: 170 watts of input power required to get 972 BTUH of actual cooling work done; and 260 watts of input power required to get 1,491 BTUH of actual cooling work done.

Calculations

Flow Rate x Density x Delta Enthalpy = Cooling Rate

@ 120°F DB, 19.5°F DP, Enthalpy = 31.12 BTU/lb, air density = 0.0682 lb dry air/ft^3

@ 70°F DB, 19.5°F DP, Enthalpy = 19.24 BTU/lb, air density = 0.0682 lb dry air/ft^3

20 ft^3/min x 60 min/hr x 0.0682 lb dry air/ft^3 x (31.12–19.24) BTU/lb air = 972 BTUH cooling

972 BTUH/1.68 = 579 BTUH input power req'd = 170 watts

@ 95°F DB, 74% RH, Enthalpy = 52.19 BTU/lb, air density = 0.0685 lb dry air/ft^3

@ 70°F DB, 70°F DP, Enthalpy = 34.05 BTU/lb, air density = 0.0685 lb dry air/ft^3

20 ft^3/min x 60 min/hr x 0.0685 lb dry air/ft^3 x (52.19–34.05) BTU/lb air = 1,491 BTUH cooling

1,491 BTUH/1.68 = 888 BTUH input power req'd = 260 watts

The values for the 95°F ambient conditions are very conservative. An actual system would have a higher COP at the lower ambient temperature. The system would probably cool the air to a lower temperature, resulting in more cooling and less power. The power differential due to increased discharge pressure relating to higher ambients increases faster than the power differential due to the increased refrigerant flow required for dehumidification. To achieve a 400-watt cooling rate (1,365 BTUH), the air system would have to deliver air to the vest at no more than 51°F wet bulb temperature. This would require an input power of 447 watts. It might be more reasonable to increase the flow rate to 25 cfm, which would then require a vest inlet of no more than 64°F wet bulb, and lower the input power to 399 watts.

The air required for the system must overcome substantial head pressure before finally escaping back to the outside environment. The air must pass through the NBC filters, the evaporator coil, and the distribution garment. The blower required for this system must supply the required flow rate at this pressure for the system to function. Based on the theoretical power required to move 20 cfm of air at 11 inches of water static pressure, the blower requires 26 watts. Current high speed blowers in this small size range seldom exceed 50 percent efficiency. This efficiency would then require 52 watts of input power.

Calculation

cfm x in. w.g. x (745.7 watts/HP) x 1/(6,344 cfm in. w.g./HP x efficiency) = amount watts

20 cfm x 11" w.g. x 745.7 watts/HP x 1/(6,344 cfm in. w.g./HP x 1.0) = 26 watts @ 100% efficiency (Reference 6)

The total air system requires: 222 watts of power at the 120°F ambient condition; 499 watts (or 463 watts at the higher air flow rate) at the 95°F ambient condition. Based on a fuel consumption of one pound of fuel per kilowatt hour, the air system requires either 0.22 pounds or 0.46 pounds of fuel per hour of operation, assuming full output. The air system also requires at least four pounds of NBC filter material and housing. This excludes the face mask filter requirements, which are common to both air and liquid systems. Finally, using the current liquid evaporators developed by NRDEC as a baseline, the air system evaporator would weigh approximately 0.6 pounds more than the liquid evaporator required for 400 watts of cooling. The blower itself would weigh approximately 1.6 pounds.

The liquid garment system would be much less affected by ambient conditions than the air system, since it is operating on a closed cycle loop. The temperature of the liquid entering the evaporator would never exceed 90°F under steady state conditions. In order to provide 400 watts of cooling to the body, the vest would require approximately 410 watts of cooling input. This accounts for any heat gain from outside the suit or other inefficiencies. If the liquid-to-air heat exchanger is 95 percent effective, the system must supply 432 watts of cooling. A COP of 2.0 applied to this figure results in an input power requirement of 216 watts. Again, this figure would be lower for ambient conditions less than 120°F, although the exact amount is difficult to estimate. A blower for the face mask, if required, would add another 7 watts and approximately 1.2 pounds. A liquid-to-air heat exchanger for this blower would weigh about 0.3 pounds, complete with added liquid. A skull cap with added liquid would weigh about 0.2 pounds. The liquid garment itself, plus the liquid it requires, would weigh at least one pound more than an equivalent air garment. The liquid pump at a worst case flow of 0.3 gallons per minute and 45 psi head pressure would only require 6 theoretical watts, and 12 watts at a pump efficiency of 50 percent. The pump itself weighs approximately 0.5 pounds.

Calculation

((gallons/minute) times head(in psi)) divided by ((1,714 (gal/min times psi)/HP) x efficiency) = amount HP

((0.3 gal/min x 45 psi) / ((1,714 (gal/min x psi)/HP) x 0.5)) x 745.7 watts/HP = 12 watts (Reference 7)

The sum of these power requirements, at the same one pound of fuel per kilowatt hour used above, results in 0.228 pounds of fuel required for a basic system, and 0.235 pounds per hour for the system with head cooling added. The liquid cooling garment reduces the sweat rate, but it does not provide any additional sweat evaporation. At least one test has quantified the difference in sweat evaporation rates between air and liquid cooling systems (Reference 8). Over a period of time, the accumulation of sweat will be quite noticeable. The air system will evaporate appro.imately 0.2 pounds of sweat per hour more than a liquid system, so the liquid system is assessed a 0.2 pound per hour penalty over the air system.

The two systems can be compared directly by graphing the initial weight deltas and the fuel costs per hour. Obviously the power source will affect the initial weights, but only to the extent that the power source can be tailored to the specific power required. As an example, an internal combustion engine of 50 watts shaft output can be made lighter than one of 500 watts output. However, it is doubtful that the difference between an engine of 222 watts output (air system @ 120°F) and an engine of 235 watts output (total liquid system) would be noticeable.

As can be seen from the graph is Figure A-1, the liquid system is initially lighter and weighs less than the air system even at the end of a 12-hour mission. The fuel rates are calculated on the basis of 100 percent utilization, which is not practical. A lower utilization rate would increase the gap between the air and liquid systems. The air system is not rated at the 95°F ambient condition, where it requires additional power/fuel. Although there are other considerations that may indicate valid reasons for choosing an air system, it is clear that initial and operating weights would favor the liquid system.

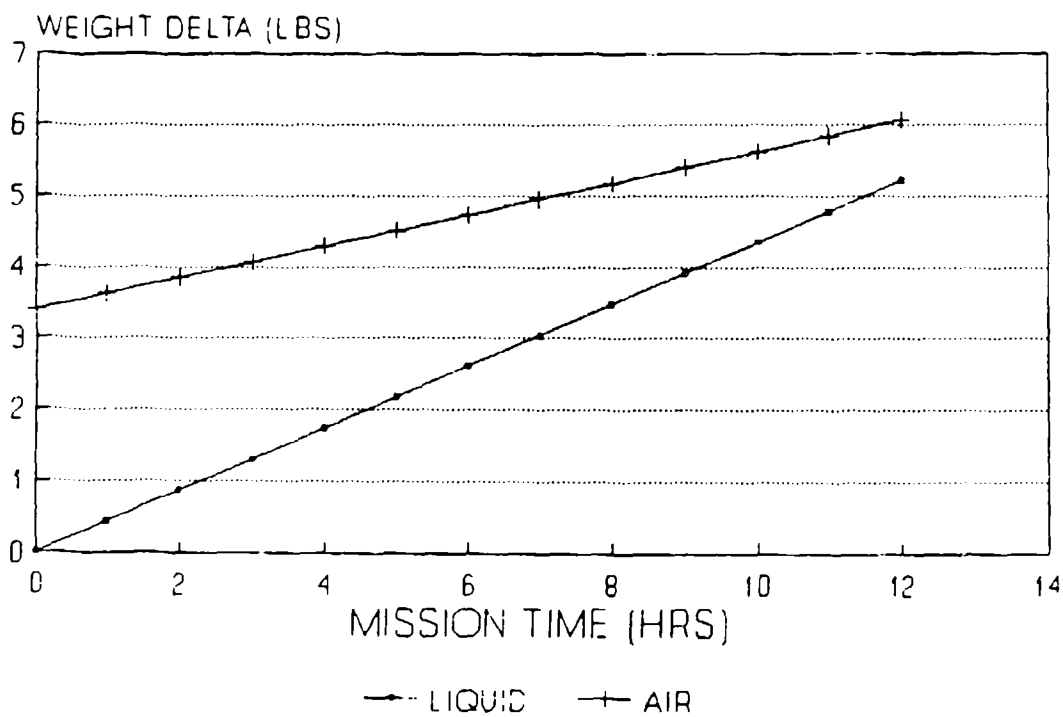

Figure A-1. Weight Comparison of Liquid vs. Air MCS

Table A-1. Weight Comparison of Liquid vs. Air MCS

	WEIGHT BREAKDOWN		
	Air System	Liquid System	
Evaporator HX	1.5	0.8	
Vest Blower	1.6	–	
Vest Pump	–	0.5	
NBC Filter (vest)	4.0	–	
Face Mask Blower	–	1.2	
Skull Cap	–	0.2	
Face Mask HX	–	0.3	
Air Vest	1.0	–	
Liquid Vest	–	2.0	
Totals	8.1	5.0	Delta = +3.1 lb for air system
	Variable Weight		
	Air	Liquid	
Fuel	0.222 lb/hr	0.235 lb/hr	
Accumulated Sweat	–	0.20 lb/hr	

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Appendix B

Boiling Cryogen Cooling

(Author: Dr. James Ferrick, BRDEC, SATBE-FGE)

THE SIMPLEST SYSTEM

It may be possible to obtain a simple and noise-free operation of powered and cooled soldier systems by using batteries for the electronics loads and tanked cryogens for the cooling function. Using cryogenic liquids for heat removal is a simple cooling system. The system would use a cryogenic liquid storage vessel operating under very slight pressure, an expansion valve/nozzle, and a heat exchanger to transfer heat from the cooling medium used for the soldier's garment/protective suit. The concept requires only a very low technology storage vessel such as a vacuum or foam insulated bottle (Thermos) or a simple styrofoam container.

Some common cryogens, with their boiling points, are given in Table B-1, Boiling Points of Gases. This listing includes common gases like nitrogen and oxygen, the predominant components of air (78.1 percent nitrogen, 20.9 percent oxygen), as well as several possible fuels. Liquid nitrogen, oxygen, or air can be obtained from the operation of transportable bulk processing plants already in use in the military.

The first step is to consider the soldier's cooling requirements and the mass of coolant necessary to meet those requirements over time. If the mass is not too large, the second step to estimate the mass and volume of the hardware needed for this approach.

The maximum heat removal capacity of any cryogen is the sum of its heat of vaporization and its sensible heat over the temperature range from the boiling point to about 300°K (80°F). These can be determined separately if values of the integrated sensible heat from the boiling point are available. A combined value can be determined from the change in enthalpy between the quiescent liquid and the 300°K gaseous states of the fluid, as given on typical temperature-entropy charts.

Lacking integrated values of the sensible heat, one can estimate the heat absorbing capability by assuming a constant value for the specific heat of the gas determined at a temperature between the boiling point and 300°K.

For gaseous nitrogen, the American Institute of Physics Handbook gives the specific heat as 6.96 cal/mol°K over the temperature range from 100 to 300°K, and the heat of vaporization as 1,335 cal/mol at a boiling temperature of 77.35°K, 760 mm Hg pressure. Thus, the total heat capacity from the saturated liquid state to 300°K is 2,885 cal/mol. The molar weight of nitrogen is 28.013 grams, giving a total heat capacity of 103 cal/gm or 431 J/gm or 185 BTU/lb. This is virtually identical to the value arrived at by looking at the enthalpy change on the nitrogen temperature-entropy chart in "Cryogenic Engineering" by R.B. Scott (D. Van Nostrand Company, Inc., 1959, p. 278); the enthalpy change from the boiling point at one atmosphere pressure to 300°K is just over 2,900 kg cal/kg mol, or 103.5 cal/gm.

At 430 J/gm, a 300 watt average heat load implies a nitrogen consumption rate of 0.7 gm/s or 2.5 kg/hr (5.5 lb/hr). Figure B-1 illustrates the cryogen weight required versus time for various average heat removal rates. In this representation, the 100 watt line corresponds to a person sitting still, while the 900 watt line corresponds to a person engaged in strenuous activity.

Table B-1. Boiling Points of Gases

Substance B.P. (approx. at 1 Atmosphere)		°C	°F	°K
Helium	He_3	- 269.9	- 453.8	3.2
Helium	He_4	- 268.9	- 452.0	4.2
Hydrogen	H_2	- 252.8	- 423.0	20.3
Deuterium	D_2	- 249.5	- 417.1	23.6
Tritium	T_2	- 248.1	- 414.6	25.0
Neon	Ne	- 246.0	- 410.8	27.1
Nitrogen	N_2	- 195.8	- 320.4	77.3
Carbon Monoxide	CO	- 191.5	- 312.7	81.6
Fluorine	F_2	- 188.1	- 306.6	85.0
Argon	Ar	- 185.9	- 302.5	87.2
Oxygen	O_2	- 183.0	- 297.4	90.1
Methane	CH_4	- 161.5	- 258.7	111.6
Krypton	Kr	- 153.4	- 244.1	119.7
Ozone	O_3	- 111.9	- 169.4	161.3
Xenon	Xe	- 108.1	- 162.6	165.0
Ethylene	C_2H_4	- 103.7	- 154.7	169.4
Ethane	C_2H_6	- 88.6	- 127.5	184.5
Nitrous Oxide	N_2O	- 88.5	- 127.3	184.6
Acetylene	C_2H_2*	- 84.0	- 119.2	189.1
Carbon Dioxide	CO_2	- 78.5	- 109.3	194.6
Ketene	C_2H_2O	- 56.0	- 68.8	217.1
Propylene	C_3H_6	- 47.7	- 53.9	225.4
Propane	C_3H_8	- 42.1	- 43.8	231.0
$Freon_{22}$	$CHClF_2$	- 40.8	- 41.4	232.3
Ammonia	NH_3	- 33.4	- 28.1	239.7
$Freon_{12}$	CCl_2F_2	- 30.5	- 22.9	242.6
Methyl Chloride	CH_3Cl	- 24.1	- 11.4	249.0
Isobutane	$(CH_3)_2C_2H_4$	- 11.7	+ 10.9	261.4
Sulphur Dioxide	SO_2	- 10.0	14.0	263.1
Butane	C_4H_{10}	- 0.5	31.1	272.6
Methyl Bromide	CH_3Br	+ 3.5	38.3	276.6
Ethyl Chloride	C_2H_5Cl	12.3	54.1	285.4
Carbon Disulfide	CS_2	46.3	115.3	319.4
Carbon Tetra'ride	CCl_4	76.7	170.1	349.8

*Sublimes

(1) 0°K = - 273.1°C (2) °F = 9/5(°C) + 32.0

BOILING CRYOGEN COOLING
(LIQUID NITROGEN)

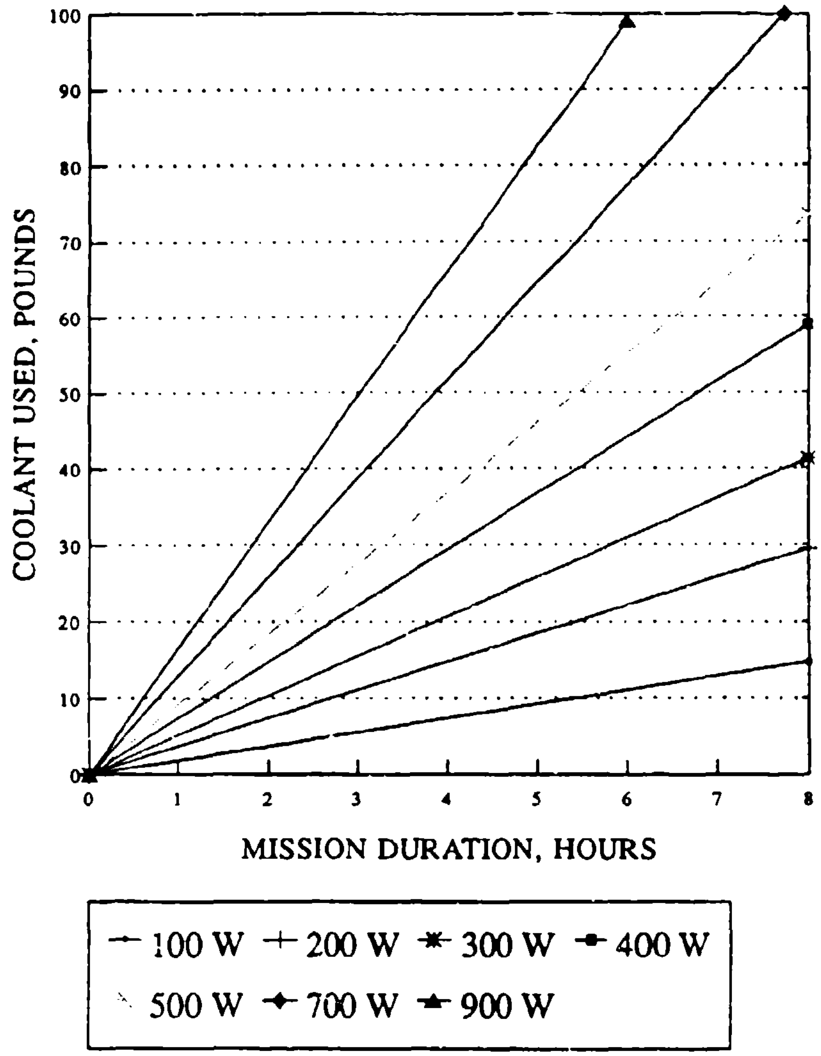

Figure B-1. Liquid Nitrogen Required for Various Mission Lengths and Average Heat Loads

ALTERNATIVE SYSTEMS

Liquefied fuels could also be used for cooling. Some of the potential candidate fuels are listed in Table B-1. The heats of combustion for these fuels are listed in Table B-2. Note that the total variation in heat of combustion over the range of fuels is less than 10 percent so all systems based on such fuels would be roughly equivalent in energy availability from the combustion process. It is possible to compare the cooling capabilities of liquefied fuels vs. cryogens.

In Table B-2, the sensible heat is given as the approximate value of the heat capacity of the gas from its boiling point to 300°K. Data comes principally from the CRC Handbook of Tables for Applied Engineering Science, 2nd Edition, R. E. Bolz and G. L. Tuve, Eds., 1970.

Table B-2. Properties of Some Fuels Having Low Boiling Points

Gas	Boiling Point (KELVIN)	Heat of Vap. (J/GM)	Specific Heat (J/GM-K)	Sensible Heat (J/GM)	Total Heat Cap. (J/GM)	Heat of Comb. (KJ/GM)
Methane	111.6	510	2.23	420	930	50.0
Ethylene	169.4	484	1.55	202	686	47.2
Ethane	184.5	489	1.75	202	691	47.5
Acetylene	189.1	614	1.69	187	801	48.2
Propylene	225.4	438	1.51	113	551	45.8
Propane	231.0	428	1.66	114	542	46.4
Isobutane	261.4	366	1.63	63	429	45.6
Butane	272.6	386	1.68	46	432	45.7

The fuels properties table shows a potential advantage of using cryogenic liquid fuels rather than liquid nitrogen, oxygen, or air; that of extracting up to twice as much heat from the soldier per unit mass of coolant carried. Considering liquid methane's 930 J/gm total heat capacity from free-boiling liquid to 300°K, a 300 watt average heat load would vaporize and warm 0.32 gm/s or 1.16 kg/hr (2.55 lb/hr) if no secondary refrigeration equipment were powered.

This is not as advantageous as the numbers might indicate. One difficulty is that the volumes of gaseous fuels would have to be on hand and ready to liquefy for the application intended, unlike nitrogen/oxygen/air which comes without added logistic penalty (other than the liquefier itself).

Once liquefied, distribution becomes a problem because there is the potential for creating a hazardous explosive gas mixture if all of the vaporized fuel is not combusted. Some of these gases are heavier than air and will collect around their point of issue, yielding both the danger of asphyxiation or of an explosion.

It is clear from these calculations that the hydrocarbon fuels should only be considered for use in systems where they are totally controlled and fully combusted or reacted. Fuels contained in adequately designed pressure bottles might be acceptable; it is inadvisable to use fuels that are free-boiling cryogens.

Even by excluding the cryogen storage and heat exchange apparatus that would be required, the non-fuel cryogens have too low of a heat capacity to provide enough cooling for four- to eight-hour active missions at acceptable weights. This fact is clearly illustrated in Figure B-2, which shows that for a four-hour mission, 10 pounds of liquid nitrogen would cool a 136 watt average heat load. By way of comparison, an ice vest containing 10 pounds of water would cool a 145 watt average heat load, excluding any consideration of sub-cooling below the melting point, and going to 30°C (86°F) on the high temperature end.

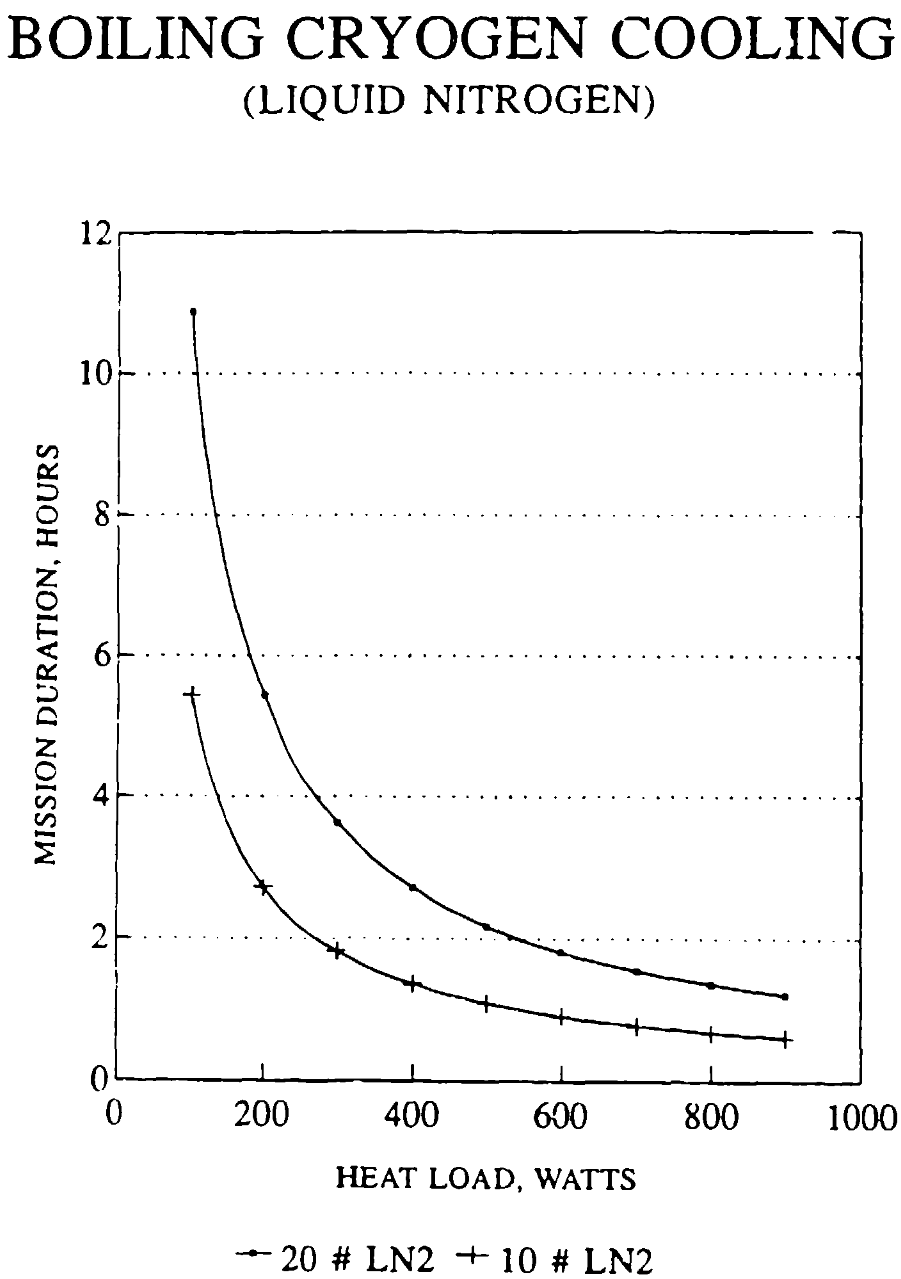

Figure B-2 Mission Duration vs. Heat Load for 10 and 20 lb Cryogen Fills

HYBRID SYSTEMS

A hybrid system employing cryogenic liquid coolants would use the vaporized cryogen in a further energy conversion process. With either oxygen or air, the warmed gas could be used as the oxidizer in a power generation device; if a combustible or reactable fuel were chosen, oxygen would need to be supplied from another source.

The quietest approach would use the fuel or oxygen in either a fuel cell or a thermoelectric generator with a thermoelectric cooler added to provide additional heat removal capability; an engine driven system could be used where the sound level is not a major issue.

Using liquid methane would capitalize on its 930 J/gm heat absorption capability. If the warmed gas could be combusted to power a thermoelectric converter or reacted in a fuel cell at 10 percent efficiency (this may be high for a real TEC, low for FC), the electrical output would be 5,000 J/gm. If this powers a thermoelectric cooler having a Coefficient of Performance (COP) of 0.5, the cooling would amount to 2,500 J/gm of methane entering the converter. The total cooling capacity would be 3,430 J/gm. A 300 watt average load would require 0.0875 gm/sec or 315 gm/hr or 0.7 lb/hr.

The efficacy of this approach depends on the actual energy conversion efficiencies of the components used. Clearly, if a 20 percent fuel to electrical energy conversion efficiency can be obtained, or if higher thermoelectric cooler COP is possible, then the contribution of the cryogens contributes a small part (<16 percent) of the total cooling capacity, and the logistics difficulties associated with providing the fuels as cryogens are not worth the trouble.

Appendix C

External Combustion Engine Technology (Vapor and Cycles) for Individual Solider Power Systems

(Author: Mr. David L. Overman, ARL)

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Appendix D
Fuels Consideration

(*Author: Dr. James Ferrick, BRDEC, SATBE-FGE*)

Unless nuclear sources or high energy density energy storage devices are employed, the energy for Soldier System operation will come from converting the chemical energy of a combustible substance. For such systems there will be a fixed equipment weight and volume representative of the hardware required. There will be a variable fuel weight and volume dependent on the power draw, the mission duration, the net conversion efficiency achievable by the technique and apparatus selected, and the characteristics of the fuel itself.

What combustible or reactable fuels should be considered? The ideal fuel for this application would:

a. Be safe for the soldier to carry and use,
b. Not add to the logistics burden,
c. Have a high energy density, and
d. Be usable in high efficiency energy conversion process.

One way to approach the fuels issue is to begin by identifying the presently used fuels. A succinct listing of the types, characteristics, and NATO equivalents of fuels presently in use in Army materiel is reproduced from the BRDEC "FUEL USERS GUIDE," as Tables D-1 and D-2. Table D-1 clearly indicates that both gasoline and diesel fuel are still required for present operations, but that employing the "Single Fuel on the Battlefield" policy is a desired objective (Note 4). This establishes a tendency toward common use of JP-8 or JP-5 in lieu of DF-2, and works toward eliminating gasoline from the fuels inventory. Eliminating gasoline from the inventory would improve the logistical situation while reducing the hazards associated with handling volatile fuels.

The "Typical Fuel Properties" table in Table D-1 shows that the heat of combustion for the JP-5/JP-8/DF-X fuels is about 18,450 Btu/lb. This translates to 19.46 MJ/lb or 5.4 kWh/lb (1 kWh = 3.6 MJ), thus an energy converter operating above 18.5 percent net efficiency is required to achieve a 1 lb/kWh specific fuel consumption (SFC).

Table D-3 lists the specific energy of some combustible or reactable fuels. From this listing it is abundantly clear that at 15.15 kWh/lb, hydrogen is the most energy dense fuel available for chemical energy conversion. The presumption here is that the oxygen is "free", i.e., that the oxygen is obtained from ambient air. The table also shows that if the oxygen must be carried along with the hydrogen, the maximum specific energy for the pure elements is only 1.7 kWh/lb. Both values ignore any special requirements for the tankage (pressure bottles, cryogenic liquid vessels, metal hydride storage systems, etc.); tankage reduces the fuel system specific energy for all systems because it adds weight and volume. Total systems including tankage must be considered when assessing efficacy. (Note: a converter operating on hydrogen and oxygen produces water as its principal byproduct; in some instances such water could be recovered for use by the soldier.)

Table D-3 also shows that if a methanol-based vehicular fuel economy is instituted in the United States, the fuel would have less than 50 percent of the specific energy of the gasoline/diesel fuel stocks, thus requiring twice the fuel weight for similar conversion efficiency and energy delivery; ethanol derived from grains has 63 percent of the specific energy of present motor fuels, and thus would require a 60 percent increase in fuel weight for the same conditions.

Table D-1. Fuel Users' Guide

NATO Fuel Designations and U.S. Equivalent Specifications/Standards

NATO Code No	NATO Title	Military/Federal Specification	Industry Equivalent Standard
F-18	Gasoline, Aviation Grade 100/130	ASTM D 910 Aviation Gasoline	ASTM D 910 Aviation Gasoline
F-46	Gasoline, Auto Military (91 RON*)	—	—
F-57	Gasoline, Auto Low Lead (98 RON)	STANAG* 2845	CEN* EN-228
F-67	Gasoline, Auto Unleaded (95 RON)	STANAG 2845	CEN EN-228
—	—	ASTM D 4814 S-I Engine Fuel	ASTM D 4814 S-I Engine Fuel
—	—	MIL-G-53006 Gasohol	—
—	—	MIL-G-3056 Gasoline	—
F-40	Turbine Fuel, Aviation, Widecut Type + FSII (S-748/S-1745)	MIL-T-5624 Turbine Fuel, Aviation, Grade JP-4	—
F-34	Turbine Fuel Aviation Kerosene + FSII (S-748/1745)	MIL-T-83133 Turbine Fuel, Aviation, JP-8	—
F-35	Turbine Fuel, Aviation, Kerosene	MIL-T-83133 Turbine Fuel, Aviation	ASTM D 1655 Aviation Turbine Fuel, Jet A-1
F-44	Turbine Fuel, Aviation, High-Flash Type+FSII (S-1745)	MIL-T-5624 Turbine Fuel, Aviation Grade JP-5	—
F-54	Diesel Fuel, Military	VV-F-800 Fuel Oil, Diesel Grade DF-2 (OCONUS)	—
F-65	Low-Temperature Diesel Fuel Blend	1:1 mix F-54 with F-34/F-35	—
—	—	VV-F-800 Fuel Oil, Diesel Grades DF-A, DF-1 & DF-2 (CONUS)	ASTM D 975 Diesel Fuel, Grades 1-D & 2-D
F-75	Fuel, Naval Distillate, Low Pour Point	—	—
F-76	Fuel, Naval Distillate	MIL-F-16884 Fuel, Naval Distillate	—
S-748	Fuel System Icing Inhibitor (FSII)	MIL-I-27686 Inhibitor, Icing Fuel System	ASTM D 4171 Fuel System Icing Inhibitors
S-1745	Fuel System Icing Inhibitor (FSII) High Flash Point Type	MIL-I-85470 Inhibitor, Icing Fuel System, High Flash	—

*Abbreviations:

CEN Comite Europeen de Normalisation
RON Research Octane Number
STANAG Standardization Agreement

Table D-2. Fuels Used in Army Materiel

Fuels Used in Army Materiel

Item	Primary Fuel	Alternate Fuel (See Note 1)	Emergency Fuel
Ground gasoline-consuming materiel:			
OCONUS environments	MIL-G-3056 (MOGAS)	F-57 (Gasoline) F-67 (Gasoline) F-18 (AVGAS)	—
CONUS environments	ASTM D 4814 (S-I Fuel) (See Note 2)	MIL-G-53006 (Gasohol) ASTM D 910 (AVGAS)	—
Ground diesel fuel-consuming materiel:			
OCONUS environments	VV-F-800 (Diesel). F-54 (See Note 3)	MIL-T-83133 (JP-8). F-34 MIL-T-5624 (JP-5). F-44 MIL-F-16884, F-76* F-75 (Navy Distillate)* ASTM D 1655 (Jet A-1)(See Note 4) F-65 (Diesel Blend)	MIL-G-3056 (MOGAS) F-57 (Gasoline) F-67 (Gasoline) F-18 (AVGAS) MIL-T-5624 (JP-4). F-40
CONUS environments	VV-F-800 (Diesel)	ASTM D 975 (Diesel) ASTM D 1655 (Jet A) (See Note 4) ASTM D 396 (FO1 & FO2)*	ASTM D 4814 (S-I Fuel) ASTM D 910 (AVGAS) MIL-T-5624 (JP-4),F-40
Aviation materiel:			
Gasoline-consuming	ASTM D 910 (AVGAS), F-18	F-18 (AVGAS)	ASTM D 4814 (S-I Fuel)
Turbine fuel-consuming	MIL-T-83133 (JP-8), F-34	MIL-T-5624 (JP-5), F-44 MIL-T-5624 (JP-4), F-40 ASTM 1655 (Jet A/A-1) ASTM 1655 (Jet B)	---

Notes:

1. Environmental conditions may limit use of certain alternate fuels designated with an asterisk (*).
2. ASTM D 4814 is a spark-ignition engine fuel (S-I fuel) that allows use of oxygenates for enhancement of antiknock quality.
3. Although VV-F-800 is shown as the primary fuel, MIL-T-83133 (JP-8) or MIL-T-5624 (JP-5) will be used as the primary fuel in those theaters where the Single Fuel on the Battlefield is implemented in accordance with DOD Directive 4140.25 and, more recently, with U.S. ratification of STANAG 4362.
4. Jet A-1/F-35 or Jet A is acceptable for continuous use in cold to moderate temperature environments. For moderate to high temperature, Jet A-1/F-35 or Jet A is not recommended and should be replaced with JP-8/F-34.

Table D-3. Specific Energy of Some Combustibles (Net or Lower Heating Value)

Substance		Btu/lb	JM/kg	JM/lb	kWh/kg	kWh/lb
Hydrogen		51,623	119.95	54.52	33.32	15.15
Carbon		14,093	32.79	14.90	9.11	4.14
$H_2 = O_2 \rightarrow H_2O$		6,019	13.44	6.11	3.73	1.70
Methanol	*(1)*	9,066	19195	9.07	5.54	2.52
Ethanol	*(1)*	11,917	26.84	12.20	7.46	3.39
Propane	*(1)*	19,937	45.96	20.89	12.77	5.80
Methane	*(g)*	21,495	49.98	22.72	13.88	6.31
Ethane	*(g)*	20,418	47.39	21.54	13.16	5.98
Propane	*(g)*	20,097	46.32	21.05	12.87	5.85
Butane	*(g)*	19,678	45.67	20.75	12.69	5.77
Pentane	*(g)*	19,540	45.35	20.61	12.60	5.73
Hexane	*(g)*	19,430	45.10	20.50	12.53	5.69
Heptane	*(g)*	19,354	44.92	20.42	12.48	5.67
Octane	*(g)*	19,298	44.79	20.36	12.44	5.66
Nonane	*(g)*	19.255	44.69	20.31	12.41	6.64
Decane	*(g)*	19,216	44.60	20.26	12.39	5.63
Gasoline		18,861	43.80	19.91	12.17	5.53
DF/JP fuels		18,450	42.82	19.46	11.90	5.41
Explosives		2,154	5.0	2.27	1.39	0.63

Propane, on the other hand, is slightly more energy dense than the motor fuels in widespread use, and could be a good choice if other than motor fuels are considered. There is a substantial propane supply and distribution capacity. The very familiar hobbyist/camper/homeowner propane bottle has a mass about equal to its propane content. There is an opportunity to reduce the tankage weight to a small fraction of the propane fuel weight by using state-of-the-art pressure vessels, regaining most of the fuel's specific energy.

In Table D-3, the alkanes (methane —> decane) are all represented from their gaseous state and from their n-alkane isomer, giving the most net energy available from the fuel. The alkanes listed are the principal constituents of the light and lower middle distillate "diesel" fuels (DF/JP).

A simple representation of the specific energy available from representative fuels as a function of conversion efficiency is given in Figure D-1. Conversion efficiency is defined as the ratio of the energy converter or total system output divided by the available energy in the fuel consumed. Note the clear energy density superiority of hydrogen as a fuel if oxygen is "free" and if tankage is not considered. Similarly, note its inferiority where pure oxygen must be provided, unless very good conversion efficiency can be attained for the hydrogen-oxygen converter (read: fuel cell) as compared to the hydrocarbon-air converters (engines).

FUELS DATA
ENERGY VS. EFFICIENCY

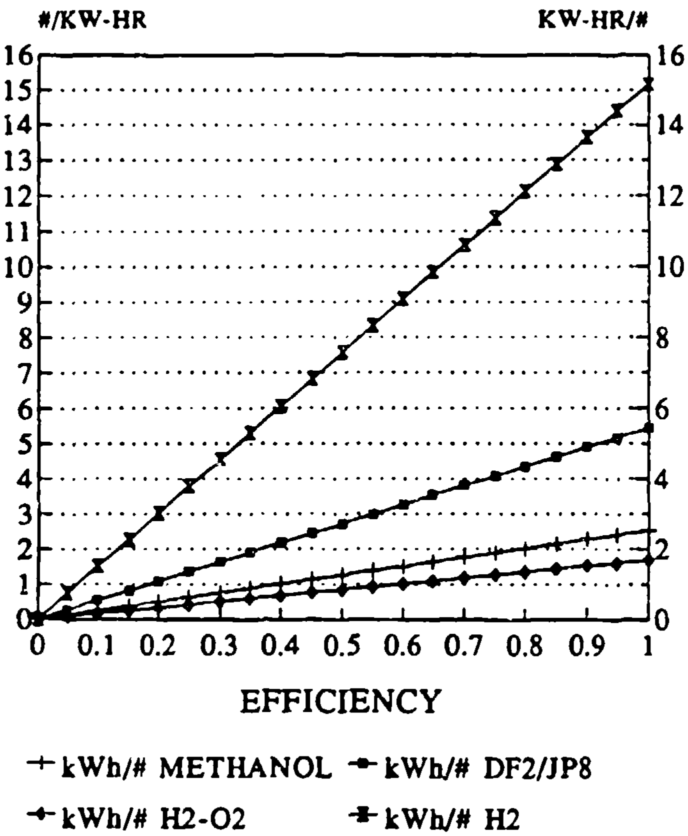


Figure D-1. Fuels Data Energy vs. Efficiency—Methanol, DF2/JP8, H_2O_2, H2: kW-hr/lb vs. Efficiency

Figure D-2 eliminates the hydrogen-air data of Figure D-1 for better readability. It shows that for equal mass consumption per kWh delivered, operation on hydrogen-oxygen would require about 60 percent conversion efficiency and on methanol about 40 percent conversion efficiency to achieve the same mass consumption rate as DF2/JP8 at 20 percent conversion efficiency. Figure D-3 replots this data in the form of mass of fuel required per kilowatt-hour delivered versus energy conversion efficiency achieved. This specific fuel consumption formatting of the data illustrates the importance of high fuel energy density and high conversion efficiency in achieving lightweight systems capable of providing several kW-hr of energy delivery. It likewise shows that to achieve a fuel consumption rate of 1 lb/kWh or less, the process conversion efficiency must be about 20 percent for DF2/JP8, 40 percent for methanol, and 60 percent for hydrogen-oxygen. Because the incremental fuel consumption rate varies as $1/n^2$, small increases in conversion efficiency have a larger impact at low efficiencies, and are critical to achieving acceptable performance.

Hydrogen is the fuel of choice for approaches in which the converter efficiency can be made very high (like fuel cells) if the tankage penalties can be minimized, if air is available, and if IR and acoustic signatures are a significant concern. Fuel cell systems can be made with low signatures.

From the logistics perspective, the most desirable fuels are the JP/DF fuels already used in most military vehicles. These fuels rank among the highest in specific energies, are reasonably safe for transport or for carry and utilization on a personal basis, are low in cost, and are fully supported in the logistics chain. They would be used in engine-based systems of either internal or external combustion configuration.

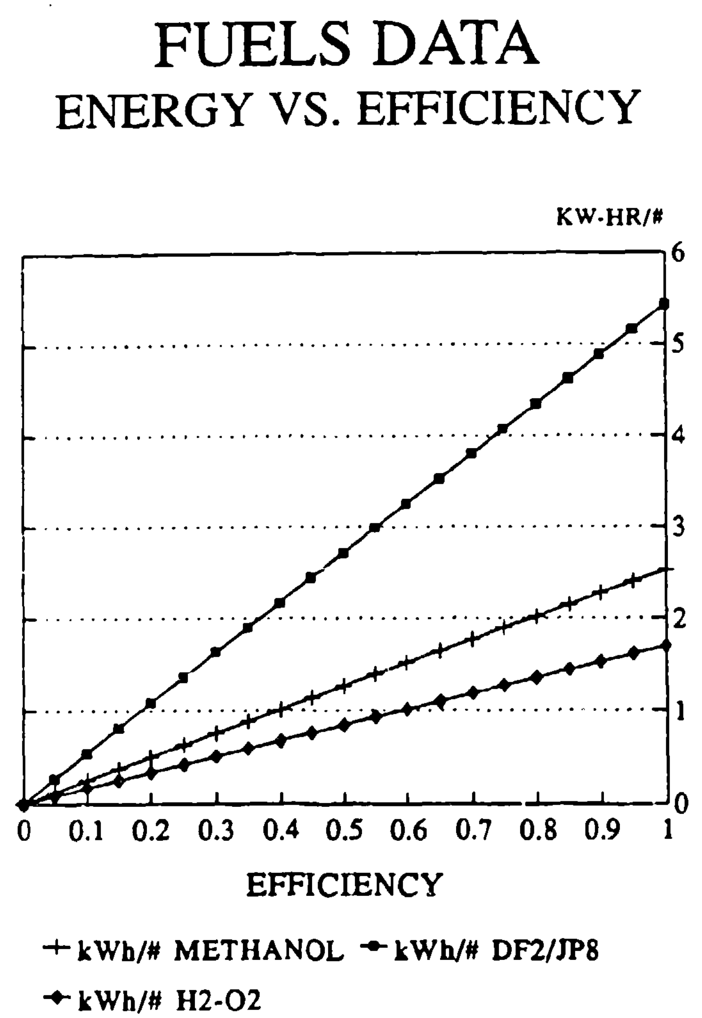


Figure D-2. Fuels Data Energy vs. Efficiency—Methanol, DF2/JP8, H_2O_2: kW-hr/lb vs. Efficiency

FUELS DATA
ENERGY VS. EFFICIENCY

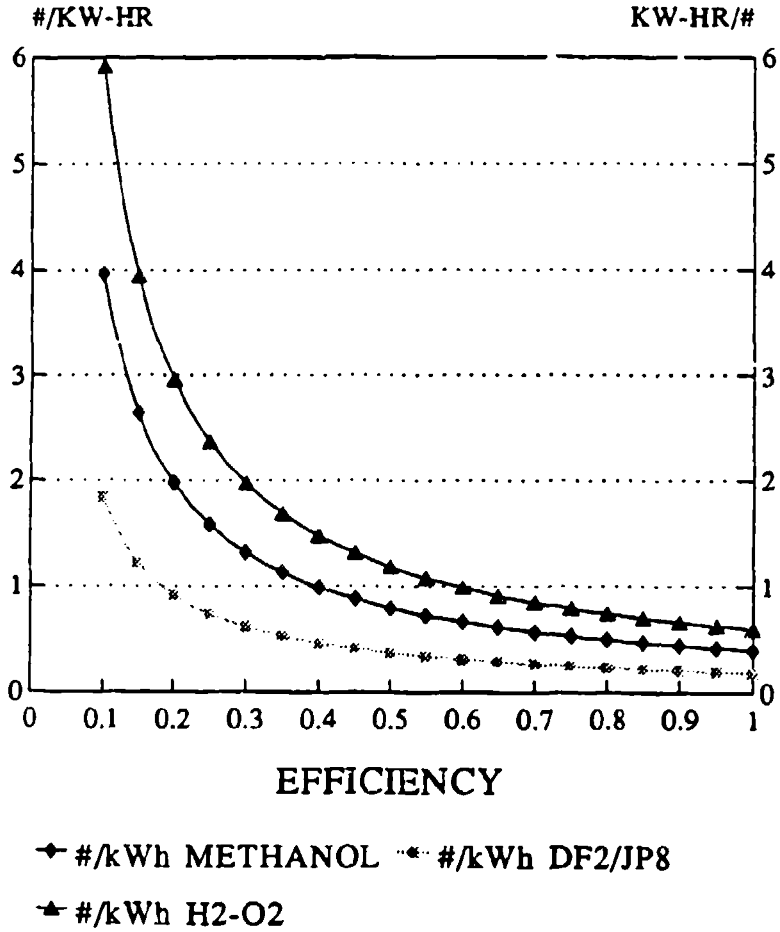


Figure D-3. Fuels Data Energy vs. Efficiency—Methanol, DF2/JP8, H_2O_2: lb/kW-hr vs. Efficiency

Appendix E

Evaluation of the Migrating Combustion Chamber (MCC) Engine

(Authors: Mr. K. Mike Miller, BRDEC, SATBE-FGE and Mr. Dorin Morar, BRDEC, SATBE-FGS)

This appendix has been published as BRDEC Report No. 2538, January 1993.

Appendix F
Parametric Model Development

(Author: Mr. Keith Dugas, BRDEC, SATBE-HP)

INTRODUCTION

Several technologies have been identified as feasible power sources for the Soldier System. Based on a given scenario, any or several of these technologies may provide the necessary power and energy requirements for the soldier. Because of the many scenarios and the numerous variables involved, hand calculation of power and energy requirements for each technology is impractical.

This model was developed to determine Soldier System power and energy requirements based on a given scenario. The model enables the user to perform parametric analyses. The model functions as a decision aid in selecting the appropriate technology or technologies to power the Soldier System. Because the model automates the calculations, more cases can be calculated for the user to analyze. Based on user-defined scenarios, the model generates the weight, size, and cost of the power sources in each feasible technology.

DISCUSSION

Background

Belvoir Research, Development and Engineering Center (BRDEC) was tasked to develop electric power in the Soldier System. BRDEC did a preliminary study to determine the feasible power sources for powering the Soldier System. From this group, one or more would be selected as the best power source for the Soldier System. The study included two scenarios in which the mission lengths and power consumptions for the soldier were varied. After development of the scenarios, it was realized that there were too many parameters affecting power requirements to make quick and accurate calculations by hand. A computer model was developed to do the calculations, freeing the user to perform parametric analyses on the data in order to make a valid decision on which power source(s) to pursue.

Scenario Descriptions

There are two scenarios which served as the basis for model development.

Scenario 1 - This scenario involves a dismounted infantry soldier using the Soldier System in a temperate or cool climate. The mission details are outlined below:

Average Power Requirements:	55 Watts
Peak Power:	125 Watts
Energy Requirements:	1,325 Watt-Hours
Mission Length:	24 Hours

This scenario describes the soldier 'ı a low power, long duration mode. The soldier uses fan-forced ambient air cooling and has an ele 'tronic load consisting of thermal vision, thermal sight, flat display, enhanced hearing, navigation monitor, soldier computer, voice comm, lan comm, and CB monitor.

Scenario 2 - This scenario involves a dismounted infantry soldier using the soldier system in a temperate or hot climate. The mission details are outlined below:

Average Power Requirements	240 Watts
Peak Power	375 Watts
Energy Requirements	2,400 Watt-Hours
Mission Length	10 Hours

This scenario describes the soldier in a medium power, medium duration mode. The soldier uses chilled air cooling and has the same electronic load as in Scenario 1.

For each scenario, detailed hand calculations were made to determine the weight and size of the power source for each of the seven technology areas. These two points served as the basis for developing the equations in the model to perform extrapolations to other power and energy requirements. During the validation process, the working group members determined through additional calculations that the model would be useful in the approximate range of 50 to 1,000 watts power.

Initial Work

Several feasible power source technology candidates arose from the initial study. They included primary batteries, secondary batteries, internal combustion engines, vapor cycle engines, Stirling engines, fuel cells, and radioactive isotopes. A working group of government experts was established to address each of these technologies. The following is a list of the working group members and their responsibilities:

TECHNOLOGY	WORKING GROUP MEMBER
Primary Batteries	ARL (ETDL)
Secondary Batteries	ARL (ETDL)
Internal Combustion Engines	BRDEC
Vapor Cycle Engines	HDL
Stirling Engines	NRDEC
Fuel Cells	BRDEC
Radioactive Isotopes	BRDEC

Once the working group was formed, it was their responsibility to assemble as much data and information as possible in their area of expertise. This data and information was used to build the computer model.

In addition to selecting the various technologies to study, it was necessary to evaluate the state of the technology at different points in time. The state of the technology included what the size, weight, and cost of the power source would be for a given mission scenario. The timeframes chosen were 1992, 1994, and 1998. This information demonstrates the technologies available today and predicts the technologies available in the near future.

The software chosen for creating the computer model was Lotus Symphony for the PC (DOS). Symphony provided a powerful spreadsheet tool for making a reliable model and data structure that could be easily modified.

Model Considerations and Development

A modular design was chosen within Symphony, with each technology (data, formulas, and costs) in each time frame occupying a block of cells. Separate areas of the spreadsheet were set aside for the input data, each power source calculation, the summary output information for each of the 3 years, and the help screen. Each power source calculation included areas to calculate size, weight, and cost of the power source. The resulting calculations were then extracted and placed in summary tables. Macros were written to ease movement within and around the spreadsheet and menus were developed for easier model manipulation. Figure F-1 shows the overall layout of the model.

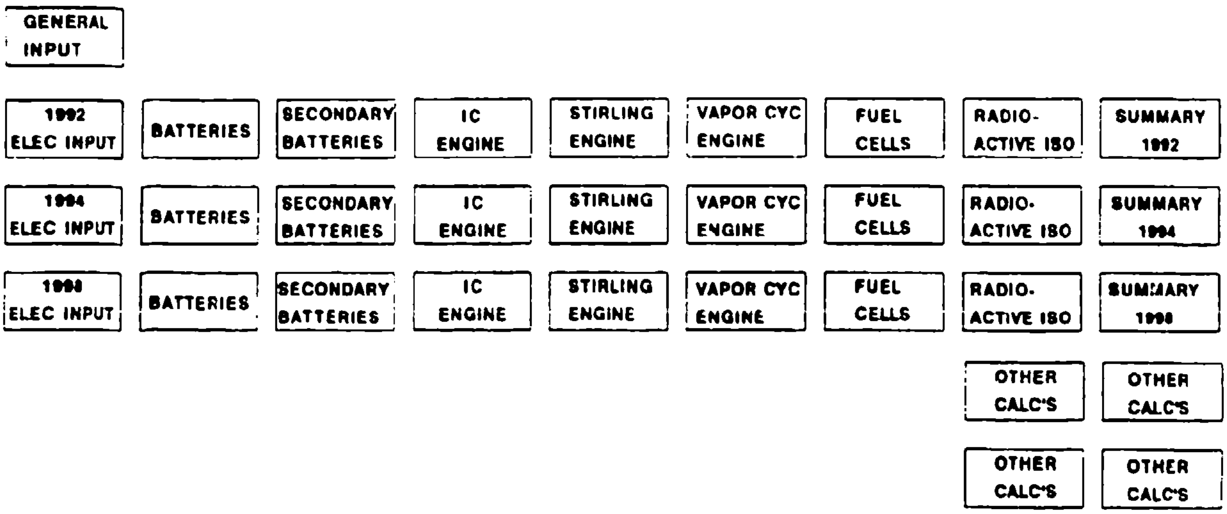


Figure F-1. Overall Layout of the Parametric Model

Since two previous scenarios were written based on mission length (one per scenario), the first version of the model allowed only one input for mission length. A revised model allows for a range of values input for mission length. The values range from a minimum mission length to a maximum mission length. The minimum and maximum are used as bounding values. Calculations were made using these two mission length values and nine data points equally spaced in between the bounding values. Other important inputs for the model include: whether the soldier was cooled (using either ambient or refrigerated air); length of cooling time; type of electronics the soldier carries; and how they are used during the mission. From the data, calculations are made for peak power (watts) and energy (watt-hours) required. This is the basis for calculating the size (cubic inches), weight (pounds), and cost (dollars) for each of the power sources.

It was important to build a model able to duplicate the results from the two scenarios already developed. Formulas were developed that represented scaling relationships for size and weight for each power source over a range of peak power and energy requirements. The data points from the two existing scenarios serve as reference points to calculate the scaling relationship constants. There are examples of the derivation of the technology scaling equations for 1992 and 1998 in the back of the text.

As the model was enhanced and a range of mission lengths became an input option, it became difficult to display the output as a summary sheet. Displaying seven technologies over three time frames and eleven mission lengths in tabular form was impractical. Additional menus were developed to allow the user to graphically display the output from the model.

The Electric Power Parametric Model

The first input page is shown in Figure F-2. On this page the user inputs data on mission lengths, cooling option, cooling time, and whether or not electronics weights will be included in the results. The menu bar, not shown here, appears at the top of the page. These inputs are general and apply to all timeframes from 1992 to 1998.

```
PRESS ALT-H FOR COMPLETE LIST OF KEY FUNCTIONS
PRESS {HOME} TO RETURN TO FIRST DATA ENTRY PAGE
PRESS ALT-X FOR MENU                              1
For A Single Mission Time enter s,
For Range of Mission Times enter r->r
- Maximum Mission Length (hrs)-->             80.00
                                                      Ratio of cooling/ML
- Minimum Mission Length (hrs) -->            12.00   0.15
- Cooling hours required------>               12.00
Soldier Cooling - Choose one or none
1.  If Fan Forced Air enter 1 --->                1   (if not, enter 0)
2.  If Refrigeration Used enter 1->               0   (if not, enter 0)
Enter Maximum Cool (% time) ---->              0.65   (fraction)
(Nominal Cool time=1-Max Cool time)
Electronics Weights Included? --->yes                 yes or no
Annual Oper Req'mts -Peace (hrs)-->             150
Quantity Needed - Peace (# units)->           20000   PRESS "PgDn" FOR
Annual Oper Req'mts - War (hrs)-->             1800   MORE INPUT
Quantity Needed - War (# units)-->            60000   (pg. 1 of 3)
```

Figure F-2. Parametric Model First Data Input Page

A PgDn will display the second input page as shown in Figure F-3. This page is for 1992 calculations. Electronics technology could change over the 1992 to 1998 timeframe. The inputs on this page concern the weights, power, and energy requirements of the various electronic components the soldier carries. The total power and energy requirements are calculated and displayed on this page and are good for 1992 only.

Weight (lbs)	1992 Equipment Name	Input # Of Units (User)	Power Watts	Peak Pwr Watts	Input Utiliz. Factor	Energy Watt-Hrs
10	Thermal Vision	1	10.00	10.00	0.90	720.00
5	Thermal Sight	1	10.00	10.00	0.20	160.00
5	Flat Display	1	3.00	3.00	0.90	216.00
5	Enhanced Hearing	1	5.00	5.00	0.90	360.00
5	Navigation/Monitor	1	5.00	5.00	1.00	400.00
5	Soldier Computer	1	5.00	5.00	1.00	400.00
5	Voice Comm	1	1.00	2.00	0.90	72.00
5	Lan Comm	1	2.00	10.00	0.90	144.00
5	CB Monitor	1	1.00	1.00	0.90	72.00
	Electric Fan	1	50.00	50.00	0.10	390.00

PRESS "PgDn" FOR MORE RESULTS (pg.2 of 3)

Electronics Sub-Total ----> 2934.00 watt-hrs

50 Tot. Elec. Wt.

Cooling (Refrigerated System)

	Power Watts	Peak Pwr Watts	Input Utiliz. Factor	Energy Watt-Hrs
Enter Nominal Watts ---->	150.00		0.00	0.00
Enter Maximum Watts ---->		400.00	0.00	0.00

Chilled Air Sub-Total ---> 0.00 watt-hrs

Peak Pwr	WATTS	101
Total Energy	WATT-HRS	2934
	KW-HRS	2.93

PRESS ALT-S TO VIEW '92 SUMMARY CALCULATIONS pg.3 of 3

PRESS "PgDn" 3 TIMES FOR 94 CALCULATIONS

Figure F-3. Parametric Model Second Data Input Page 1992 Time Frame

Three more PgDn's will reveal the same data input page as page 2, only this information is for the 1994 timeframe. See Figure F-4.

Weight (lbs)	1994 Equipment Name	Input # Of Units (User)	Power Watts	Peak Pwr Watts	Input Utiliz. Factor	Energy Watt-Hrs
10	Thermal Vision	1	10.00	10.00	0.90	720.00
5	Thermal Sight	1	10.00	10.00	0.20	160.00
5	Flat Display	1	3.00	3.00	0.90	216.00
5	Enhanced Hearing	1	5.00	5.00	0.90	360.00
5	Navigation/Monitor	1	5.00	5.00	1.00	400.00
5	Soldier Computer	1	5.00	5.00	1.00	400.00
5	Voice Comm	1	1.00	2.00	0.90	72.00
5	Lan Comm	1	2.00	10.00	0.90	144.00
5	CB Monitor	1	1.00	1.00	0.90	72.00
	Electric Fan	0	0.00	50.00	0.00	0.00

PRESS "PgDn" FOR MORE RESULTS (pg.2 of 3)

---------- Electronics Sub-Total ----> 2544.00 watt-hrs

50 Tot. Elec. Wt.

Cooling (Refrigerated System)

Enter Nominal Watts ---->	150.00		0.00	0.00
Enter Maximum Watts ---->		400.00	0.00	0.00

Chilled Air Sub-Total ---> 0.00 watt-hrs

Peak Pwr	WATTS	101
Total Energy	WATT-HRS	2544
	KW-HRS	2.54

PRESS ALT-T TO VIEW '94 SUMMARY CALCULATIONS pg.3 of 3

PRESS "PgDn" 3 TIMES FOR '98 CALCULATIONS

Figure F-4. Parametric Model Second Data Input Page 1994 Time Frame

Three more PgDn's reveal the same data as page 2 again, only this time the data is for the 1998 timeframe. See Figure F-5.

Once all the input is complete (in most cases pages 2, 3, and 4 will be the same unless future electronic changes are estimated), macros help the user move to the summary tables in the case of the single mission input option. Pressing ALT-S, for example, brings the user to the summary table for 1992. The tables list the power and energy requirements, the seven power sources, and the size, weight, and life cycle costs for each power source. For the multiple mission length input option, the user can still move to the summary tables but only the maximum mission length calculations will be shown. To show all the results over the range of mission lengths, the user can invoke the menu bar and select the option to graph the results as seen in Figures F-6 and F-7.

Summary

The Electric Power Parametric Model was useful in conducting parametric analyses as a part of the power source selection effort. The model provided an automated means of calculating the results of many different scenarios instead of only a few scenarios. The model saves time and effort and is more accurate than doing the calculations by hand.

Weight (lbs)	1998 Equipment Name	Input # Of Units (User)	Power Watts	Peak Pwr Watts	Input Utiliz. Factor	Energy Watt-Hrs
10	Thermal Vision	1	10.00	10.00	0.90	720.00
5	Thermal Sight	1	10.00	10.00	0.20	160.00
5	Flat Display	1	3.00	3.00	0.90	216.00
5	Enhanced Hearing	1	5.00	5.00	0.90	360.00
5	Navigation/Monitor	1	5.00	5.00	1.00	400.00
5	Soldier Computer	1	5.00	5.00	1.00	400.00
5	Voice Comm	1	1.00	2.00	0.90	72.00
5	Lan Comm	1	2.00	10.00	0.90	144.00
5	CB Monitor	1	1.00	1.00	0.90	72.00
	Electric Fan	0	0.00	50.00	0.00	0.00

PRESS "PgDn" FOR MORE RESULTS (pg.2 of 3)

---------- Electronics Sub-Total ----> 2544.00 watt-hrs

50 Tot. Elec. Wt.

Cooling (Refrigerated System)	Power Watts	Peak Pwr Watts	Input Utiliz. Factor	Energy Watt-Hrs
Enter Nominal Watts ---->	150.00		0.00	0.00
Enter Maximum Watts ---->		400.00	0.00	0.00
Chilled Air Sub-Total --->			0.00 watt-hrs	

Peak Pwr	WATTS	101
Total Energy	WATT-HRS	2544
	KW-HRS	2.54

PRESS ALT-U TO VIEW `98 SUMMARY CALCULATIONS pg.3 of 3

Figure F-5. Parametric Model Second Data Input Page 1998 Time Frame

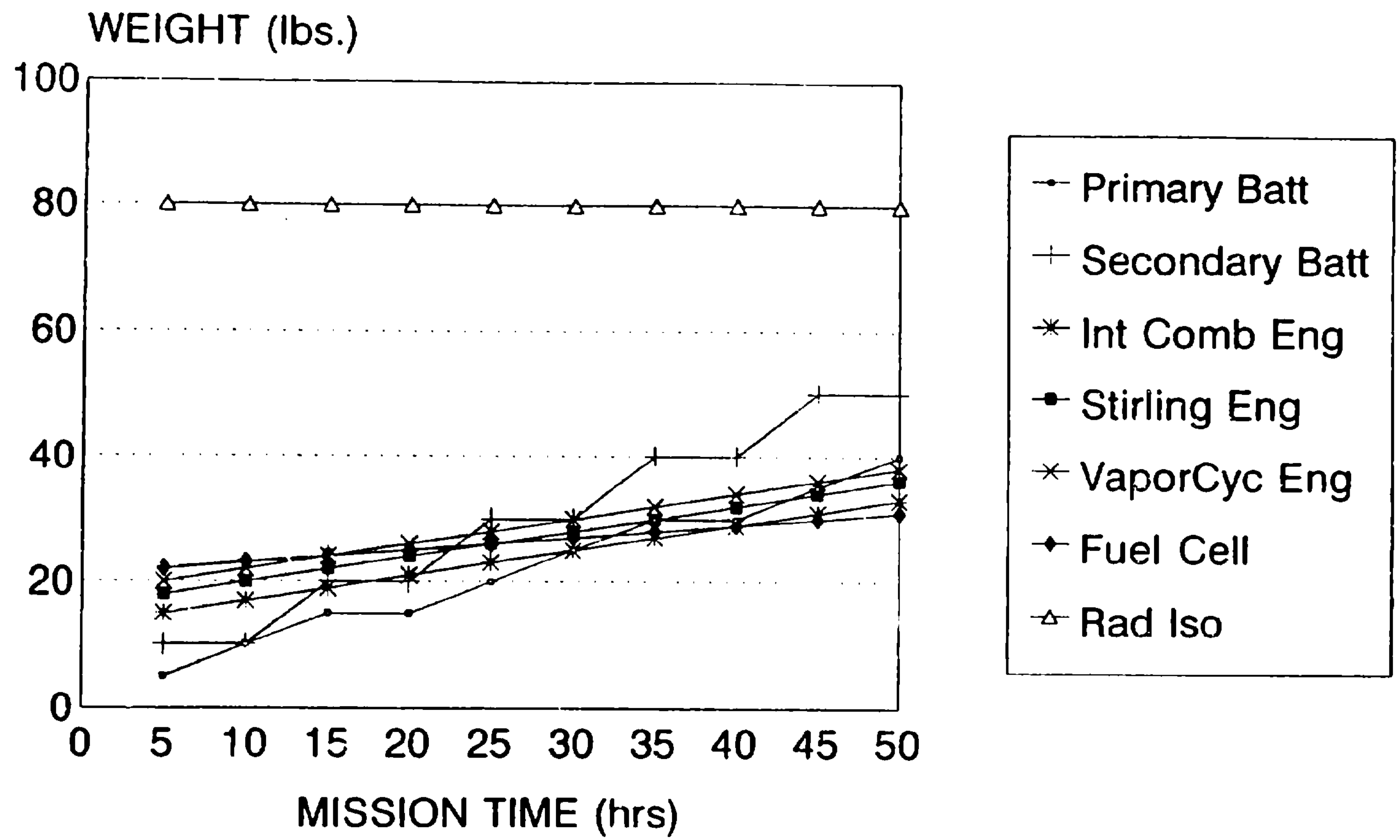


Figure F-6. Weight vs Time (1998 Technology)

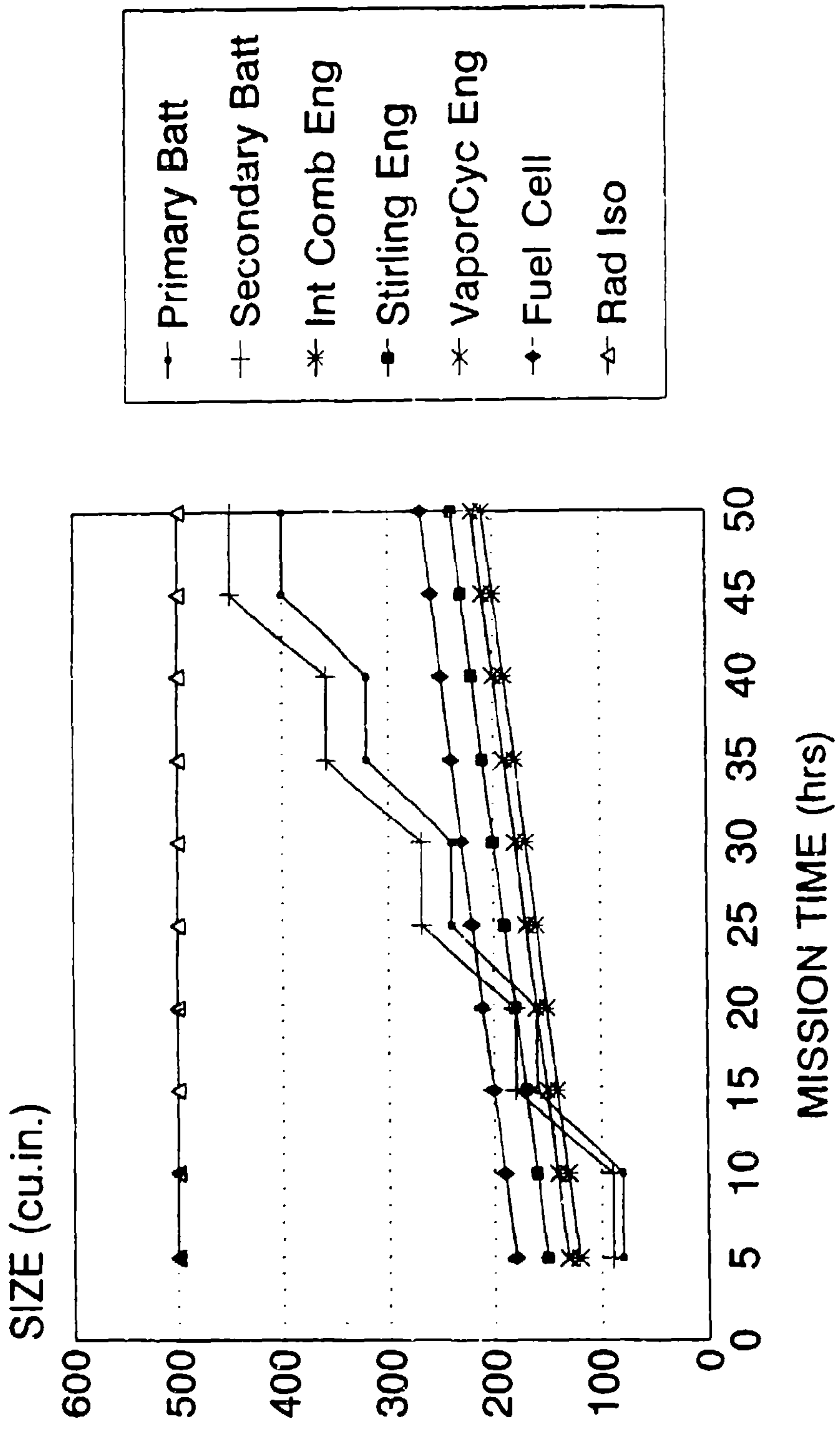


Figure F-7. Size vs Time (1998 Technology)

TECHNOLOGY SCALING EQUATIONS (1992 PROJECTIONS)

Primary Battery

Based on standard BR-5590 battery pack; 3.1 pounds per battery, 187 watt-hours (62 wh/lbs)

Battery weight proportional to energy:
Mission Energy wh / 187 wh = number of batteries x 3.1 lbs

Model incorporates "IF/THEN" function to allow only whole batteries to be used; 120 percent energy overload allowed to account for some uncertainty in scenario. Battery weight is thus seen as a step function of 3.1 pounds.

Other Components:

Hermetic compressor:
2 lbs (Max. cool. rate w /300 watts initial case)**0.37

Condenser coil:
0.8 lbs (Max. cool. rate w /300 watts)**0.65

Evaporator coil (air-to-refrigerant):
1.6 (Max. cool. rate/300)**0.65

Condenser Fan:
0.9 (Max. cool. rate/300)**0.65

Process Fan:
1.6 (Max. cool. rate/300)**0.65

Freon: Fixed weight 0.3 lbs
Tubing/controls: Fixed weight 0.7 lbs

Frame/Housing (ratio to total weight):
0.0387 (total component weight)

Size: Model incorporates function for cooling and power only cases.
Cooling: Total wt/ (0.035 lbs/cu.in.)
Power Only: Total wt/(0.0396 lbs/cu.in.)

Secondary Battery

Based on standard battery pack; 4 pounds per battery, 60 watt-hours (15 wh/lbs)

Battery weight proportional to energy:
Mission Energy wh / 60 wh = number of batteries x 4 lbs

Model incorporates "IF/THEN" function to allow only whole batteries to be used; 120 percent energy overload allowed to account for some uncertainty in scenario. Battery weight is thus seen as a step function of 4 pounds.

Other Components:

Hermetic compressor:
2 lbs (Max. cool. rate w /300 watts initial case)**0.37

Condenser coil:
0.8 lbs (Max. cool. rate w /300 watts)**0.65

Evaporator coil (air-to-refrigerant):
1.6 (Max. cool. rate/300)**0.65

Condenser Fan:
0.9 (Max. cool. rate/300)**0.65

Process Fan:
1.6 (Max. cool. rate/300)**0.65

Freon: Fixed weight 0.3 lbs

Tubing/controls: Fixed weight 0.7 lbs

Frame/Housing (ratio to total weight):
0.0387 (total component weight)

Size: Model incorporates function for cooling and power only cases.
Cooling: Total wt/(0.035 lbs/cu.in.)
Power Only: Total wt/(0.0396 lbs/cu.in.)

Internal Combustion Engine

Engine weight proportional to power:
Engine weight = 0.9 lbs (Peak Power watts/300 watts baseline)**0.37

Fuel proportional to Energy:
0.004 lbs/wh x 1.2 x Mission Energy wh

(This represents 5 percent engine efficiency with an additional 1.2 penalty factor assessed based on observed model engine performance.)

Other Components:

Flywheel/Fan: Fixed weight 1.0 lbs

Carburetor/preheat mechanism: fixed weight 1.0 lbs

Shaft-driven compressor:
2 lbs (Max. cool. rate/300 watts initial case)**0.37

Condenser coil:
0.8 lbs (Max. cool. rate/300 watts)**0.65

Evaporator coil (air-to-refrigerant):
1.6 (Max. cool. rate/300)**0.65

Condenser Fan:
0.4 (Max. cool Rate/300)**0.65

Generator:
0.8 (Peak electrical load w / 100 w)**0.37

Rectifier:
0.375 x generator weight

Power Controller: Fixed weight 0.3 lbs

Battery Backup:
0.0667 lbs/whr x 2/3 peak electrical load w x 0.5 hr

Process Fan:
1.6 (Max. cool. rate/300)**0.65

Freon: Fixed weight 0.3 lbs

Tubing/controls: Fixed weight 0.7 lbs

Frame/Housing (ratio to total weight):
0.21 (total component weight)

Size: Model incorporates function for cooling and power only cases.
Cooling: Total wt/(0.17 lbs/cu.in.)
Power Only: Total wt/(0.17 lbs/cu.in.)

TECHNOLOGY SCALING EQUATIONS (1998 PROJECTIONS)

Primary Battery

Based on standard battery pack; 2.5 pounds per battery, 300 watt-hours (120 wh/lbs)

Battery weight proportional to energy:
Mission Energy wh / 300 wh = number of batteries x 2.5 lbs

Model incorporates "IF/THEN" function to allow only whole batteries to be used; 120 percent energy overload allowed to account for some uncertainty in scenario. Battery weight is thus seen as a step function of 2.5 pounds.

Other Components:

Hermetic compressor:
1.5 lbs (Max. cool. rate w /300 watts initial case)**0.37

Condenser coil:
0.6 lbs (Max. cool. rate w /300 watts)**0.65

Evaporator coil (air-to-refrigerant):
1 (Max. cool. rate/300)**0.65

Condenser Fan:
0.8 (Max. cool. rate/300)**0.65

Process Fan:
1.1 (Max. cool. rate/300)**0.65

Freon: Fixed weight 0.3 lbs

Tubing/controls: Fixed weight 0.7 lbs

Frame/Housing (ratio to total weight):
0.0387 (total component weight)

Size: Model incorporates function for cooling and power only cases.
Cooling: Total wt/(0.035 lbs/cu.in.)
Power Only: Total wt/(0.0396 lbs/cu.in.)

Secondary Battery

Based on standard battery pack; 7.5 pounds per battery, 360 watt-hours (60 wh/lbs)

Battery weight proportional to energy:
Mission Energy wh / 360 wh = number of batteries x 7.5 lbs

Model incorporates "IF/THEN" function to allow only whole batteries to be used; 120 percent energy overload allowed to account for some uncertainty in scenario. Battery weight is thus seen as a step function of 7.5 pounds.

Other Components:

Hermetic compressor:
1.5 lbs (Max. cool. rate w /300 watts initial case)**0.37

Condenser coil:
0.6 lbs (Max. cool. rate w /300 watts)**0.65

Evaporator coil (air-to-refrigerant):
1 (Max. cool. rate/300)**0.65

Condenser Fan:
0.8 (Max. cool. rate/300)**0.65

Process Fan:
1.1 (Max. cool. rate/300)**0.65

Freon: Fixed weight 0.3 lbs

Tubing/controls: Fixed weight 0.7 lbs

Frame/Housing (ratio to total weight):
0.0387 (total component weight)

Size: Model incorporates function for cooling and power only cases.
Cooling: Total wt/(0.035 lbs/cu.in.)
Power Only: Total wt/(0.0396 lbs/cu.in.)

Internal Combustion Engine

Engine weight proportional to power:
Engine weight = 0.9 lbs (Peak Power watts/300 watts baseline)**0.37

Fuel proportional to Energy:
0.001 lbs/wh x 1.2 x Mission Energy wh

(This represents 20 percent engine efficiency with an additional 1.2 penalty factor assessed based on observed model engine performance.)

Other Components:

Flywheel/Fan: Fixed weight 1.0 lbs

Carburetor/preheat mechanism: fixed weight 1.0 lbs

Shaft-driven compressor:
0.75 lbs (Max. cool. rate/300 watts initial case)**0.37

Condenser coil:
0.6 lbs (Max. cool. rate/300 watts)**0.65

Evaporator coil (air-to-refrigerant):
1 (Max. cool. rate/300)**0.65

Condenser Fan:
0.4 (Max. cool Rate/300)**0.65

Generator:
0.6 (Peak electrical load w /100 w)**0.37

Rectifier:
0.375 x generator weight

Power Controller: Fixed weight 0.3 lbs

Battery Backup:
0.0167 lbs/wh x 2/3 peak electrical load w x 0.5 hr

Process Fan:
1.1 (Max. cool. rate/300)**0.65

Freon: Fixed weight 0.3 lbs

Tubing/controls: Fixed weight 0.7 lbs

Frame/Housing (ratio to total weight):
0.21 (total component weight)

Size: Model incorporates function for cooling and power only cases.
Cooling: Total wt/(0.17 lbs/cu. in.)
Power Only: Total wt/(0.17 lbs/cu. in.)

Fuel Cell

Fuel Cell weight proportional to power:
Weight = 2 lbs (Peak Power watts/100 watts baseline)**0.37

Fuel proportional to Energy:
0.00093 lbs/wh x Mission Energy wh

Other Components:

Gas Cylinder: 0.00093 x Mission Energy + Fixed weight 1.77

Hermetic compressor:
1.5 lbs (Max. cool. rate w /300 watts initial case)**0.37

Condenser coil:
0.6 lbs (Max. cool. rate w /300 watts)**0.65

Evaporator coil (air-to-refrigerant):
1 (Max. cool. rate/300)**0.65

Condenser Fan:
0.8 (Max. cool. rate/300)**0.65

Process Fan:
1.1 (Max. cool. rate/300)**0.65

Freon: Fixed weight 0.3 lbs

Tubing/controls: Fixed weight 0.7 lbs

Rectifier:
0.375 x generator weight

Controller/conditioner: Fixed weight 1 lbs

Frame/Housing (ratio to total weight):
0.22 (total component weight)

Size: Model incorporates function for cooling and power only cases.
Cooling: Total wt/(0.00797 lbs/cu.in.)
Power Only: Total wt/(0.00676 lbs/cu.in.)

Appendix G
Reliability Analysis

(Author: Mr. Collin Drennan BRDEC, SATBE-TQR)

ANALYSIS

The objective of this analysis is to provide a relative ranking of the system concepts based on their estimated Mean Time Between Failure (MTBF) and to provide the MTBF data to the replenishment cost analysis. In the early phases of system development, the concepts for hardware can be analyzed to estimate their potential system reliability. This estimate provides data for other analyses and for the system engineer to use in determining where additional research or design effort might be best focused.

In the early phase of design, the systems proposed are primarily paper concepts. In order to estimate their MTBF, the functions of the systems are analyzed and very preliminary hardware identified to accomplish these functions. Functional Block Diagrams (FBD) are used to define the systems and support development of Reliability Block Diagrams (RBD). Based on each system's RBD, a reliability math model (RMM) was developed.

With the RMM defined and preliminary hardware identified, failure rate data was collected for each system. This data was obtained from Non-electronic Parts Reliability Data (NPRD-3), MIL-HDBK 217E, Rome Air Development Center (RADC) Reliability Notebook, Government-Industry Data Exchange Program (GIDEP), and manufacturers and engineering estimates. Whenever possible, data from comparable hardware was used in the estimate. Engineering estimates, based on a related piece of hardware, were used when an exact match could not be located in the data sources. Guidelines were prepared for establishing failure rates. These guidelines are provided as an attachment.

The RMM was exercised using identified failure rate data. The overall system MTBF was then determined. This supported a ranking of the components by the system MTBF. For the cost analysis, the failure rates of various components were appropriately grouped and the MTBF calculated for modules. This data could then be used in the cost estimate for determining spares requirements.

ANALYSIS WRITE-UPS

For each system concept, preliminary design diagrams were provided by the project engineers. From these diagrams, a short write-up on the Modes of Operations for the system was developed. The Modes were written out in sufficient detail to understand the operation of the system, but were not intended to be a full, detailed description of the system.

The Modes were verified with the engineers and used in the development of the FBD. In determining the functions of the system, certain assumptions were made in order to support hardware identification. Different types of flow lines are used in the diagram to represent the flow of functions in the operation of the system. A solid line ( ) is used to represent basis system operation. A dashed line (_ _ _) is used to represent the other electrical and soldier systems that are not part of the power supply/distribution or environmental control systems, which are considered to be the only essential functions for this analysis. A broken dashed line (_ _ . . _ _) is used to represent a return of information between components.

The RBD is a graphic representation of the reliability relationships between the components. If a subsystem/component in a series relationship fails, the result will be system failure. If subsystem/ components are in a parallel relationship, failure of the system does not occur until all portions of the parallel fail. Different line types have been used to show how components are grouped into modules/subassemblies to support the cost analysis.

The RMM translates the RBD into a mathematical expression used to calculate the system reliability. The Failure Rate Worksheet documents the failure rate data obtained for the components and the computation of the system reliability.

FAILURE RATE GUIDELINES

The following guidelines were used to determine the failure rates for the system components.

a. Although the SIPE system can be used in a variety of scenarios (i.e., air/sea/land strikes), the primary use will be in ground-based conflicts. The following three environmental factors will be used as guidelines for selecting failure rates:

- Ground Mobile (GM)—Vibration and shock conditions experienced on wheeled or tracked vehicles.
- Ground Fixed (GF)—Ground-based equipment with a minimum of transportation involved.
- Manpack (MP)—Portable electronic equipment being manually transported while in operation.

b. When determining the failure rate where MP, GM, and GF factors are present, either the MP or GM failure rate will be used. The higher of the two is to be used for the failure rate. This is done for two reasons: (1) Either MP or GM will more closely represent the type of environment the soldier is in, or (2) it will provide a conservative failure rate estimate.

c. Where only GF and GM failure rates are used, the GM failure rate will be used.

d. Where only GF is available, the following will be used as a rule of thumb: GM=GF*4.

e. Where only GM is available, its failure rate will be used.

f. When comparing failure rates, the above criteria applies. If, for example, three data sources for a component all have a GM failure rate, the largest failure rate will be selected. This is done to provide conservative values due to limited design data.

g. Engineering judgment/estimates shall be used where it can be reasonably determined the failure rate selected is not representative of the item. Use of engineering judgment/estimates (based on conversations with program engineers, basing a failure rate on different environmental factors, etc.) shall be properly documented to show an audit trail.

h. GIDEP data source: The use of replacement rate data will be used as an approximation to the failure rate.

Replacement Rate: The unscheduled removal or repair of an item suspected of failure may include the following circumstances:

a) Secondary failures

b) Unconfirmable errors

c) Failure due to operator data

Though not used for determination of system MTBFs, the data will be applied in this program for the following reasons:

1) The current system configurations are in an early design stage. Most components within these systems are described only in the most general terms.

2) Failure rates provided by other data sources are assumed to be for components of larger systems (i.e., MIL-STD air conditioners/generators). Nearly all components in all the systems will be of a substantially smaller size and will therefore be assumed to have an increased failure rate unless otherwise established.

Pressurized Fuel Cell And Environmental Control Unit (ECU)

Mode Of Operation:

1. This system is Fuel Cell powered, with soldier interface controls (possibly both manual and automatic). The system has a master "control system," known as a controller. The controller helps regulate the cooling process as well as the voltage output requirements.

2. Pressurized Fuel Cell:

a. Pressurized H_2 gas flows from the cylinder to the gas regulator to one cell stack in the fuel cell. The same also applies to the pressurized O_2 gas.

b. Fuel Cell produces low power DC voltage. A fan is used in the fuel cell to cool it, due to heated H_2. The water by-product produced by the combo of the pressurized H_2 and O_2 needs to be disposed of.

c. Fuel cell provides DC power to load. A Power conditioner is used to get rid of ripple on DC signal. DC-to-DC converter gets rid of voltage variation.

3. Controller: Controller regulates H_2/O_2 sent to Fuel cell (power to load). Signal sent from temperature probe to controller regulates controller which, in turn, regulates the ECU.

4. Cooling System:

a. The Electric compressor discharges freon vapor via the discharge line to the condenser.

b. The freon vapor inside the compressor becomes a high-pressure liquid. Heat is produced during condensation, so the fan is used to cool the condenser and freon.

c. Liquid travels via the liquid line to the evaporator and its fan. The liquid is transformed into low-pressure air inside the evaporator. When this happens, the air produces a cooling effect on the evaporator coils.

d. This cooling effect produces cool air which rises off the evaporator coils. The evaporator fan then blows this cool air to the soldier.

e. Any remaining freon vapor is suctioned back to the compressor via the return line.

5. The Controller performs the following functions:

a. Controls the amount of H_2 to be released into the system via the pressure relief valve.

b. Receives a signal from the suction pressure sensor, which in turn regulates the compressor.

c. The Temperature probe sends a signal to the controller, which in turn regulates the amount of freon released from the compressor.

d. Can override manual controls.

6. Power Requirements:

Power comes from battery; output voltage is regulated by a power conditioner for constant DC voltage. Power conditioner also controls output voltage in cases of inrush current or increased compressor usage.

NOTE: Based upon engine-driven system (no clutch used), everything is electric-driven.

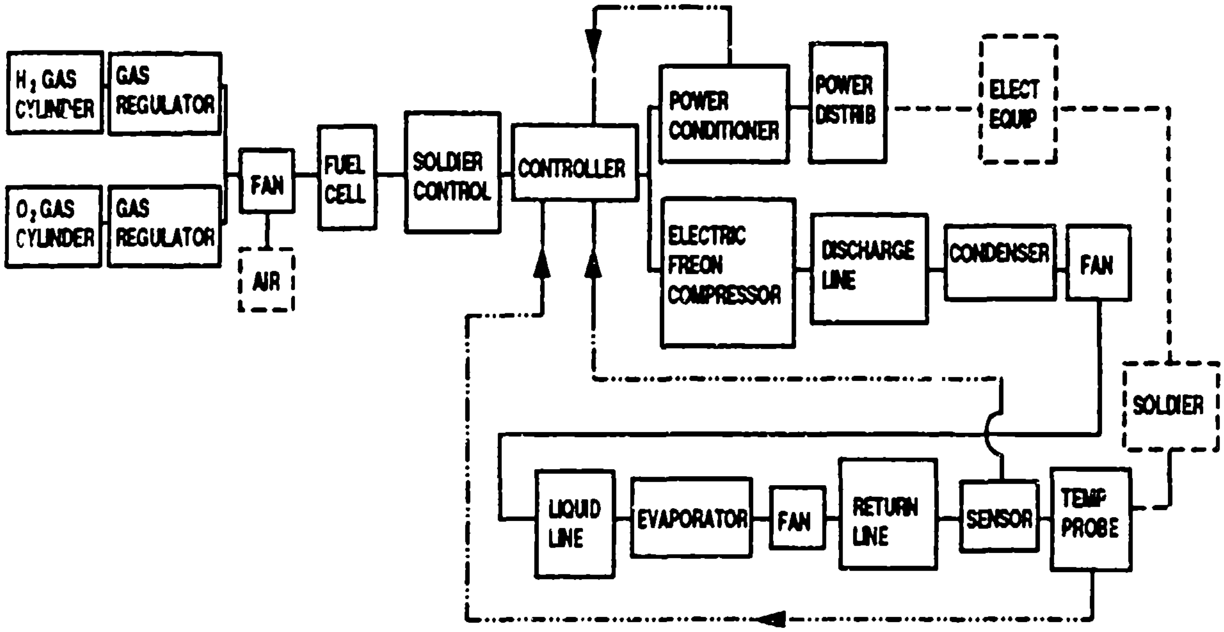


Figure G-1. Pressurized Fuel Cell and ECU Functional Block Diagram

Assumptions to FBD

1. Failure of electrical equipment (i.e., Laser Rangefinder, etc.) is not relevant to this system. This system is only responsible for cooling the soldier and providing the proper power output (which includes power distribution capabilities as well).

2. Controller failure is a mission failure due to the compressor's inability to properly cool the soldier.

3. Power source/distribution and ECU (Environmental Control Unit; known as our cooling system) are assumed to be operating simultaneously at all times.

4. Failure of the temperature probe is considered to be a mission failure (cannot regulate compressor output well enough to cool solider).

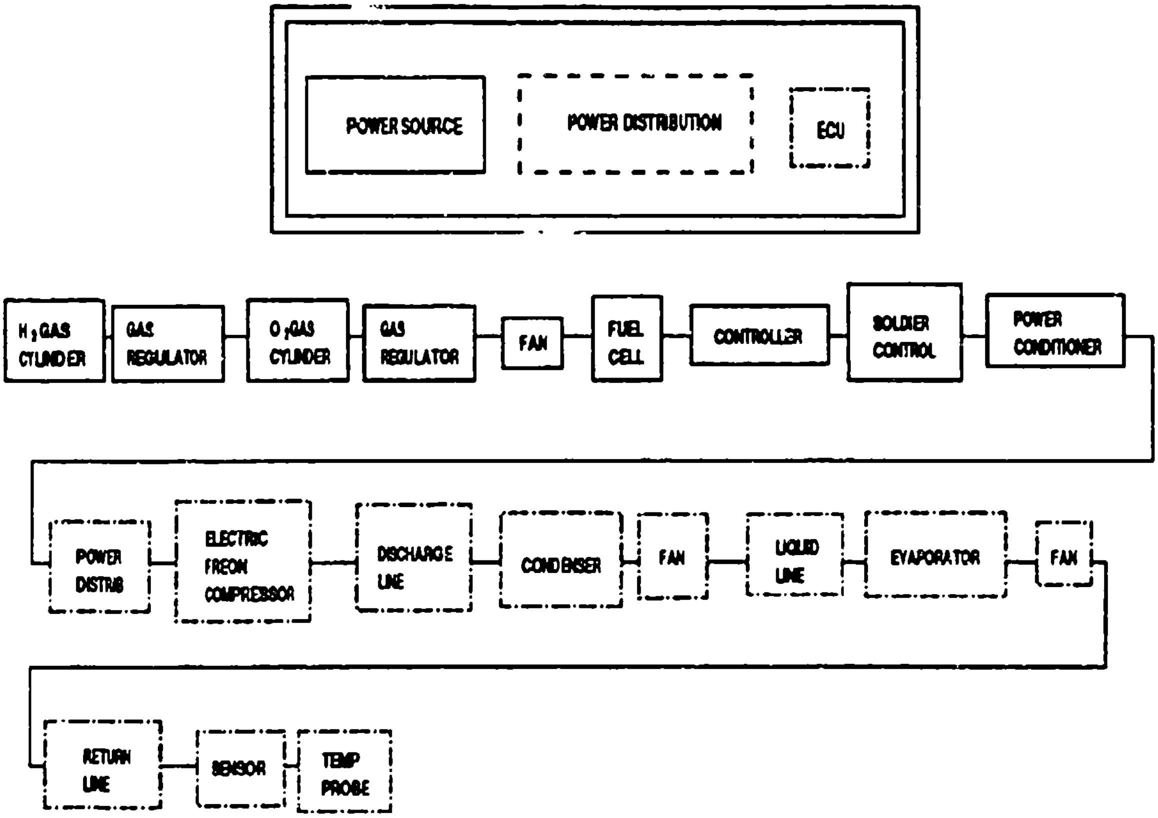


Figure G-2. Pressurized Fuel Cell and ECU Reliability Block Diagram

Assumptions

1. RBD based on mission essential functions:

   Mission Success = The simultaneous operation of the ECU, power source, and the power distribution system.

2. Based on the above assumption, the ECU, PWR distribution, and PWR source are in series.

Reliability Math Model (RMM)

Since the RBD represents a series system:

τ system = τ H_2 cylinder + τ regulator + ... + τ sensor + τ temp probe.

MTBF system = $1/\tau$ system.

Table G-1. Pressurized Fuel Cell and ECU Failure Rate Worksheet

Component	Quantity	Component Failure Rate	Total Failure Rate
Cylinder, H_2 Gas	1	161.191	161.191
Regulator, Gas Pressure (equiv: pressure relief valve)	1	2190.096	2190.096
Cylinder, O_2 Gas	1	161.191	161.191
Regulator, Gas Pressure (equiv: pressure relief valve)	1	2190.096	2190.096
Fan, Fuel cell, axial (electric-driven)	1	895.976	895.976
Controller	1	186.209	186.209
Interface, Soldier			389.648
switch, toggle (on/off)	1	0.243	
knob, temp adjust	1	264.550	
readout, voltage	1	102.891	
probe, temperature	1	21.964	
Cell, Fuel	1	36.000	36.000
Conditioner, Power (voltage reg, includes Filter, ripple DC-to-DC converter)	1	115.915	115.915
Distribution, Power			
Cable, Shielded	5	150.561	757.360
Connectors, Quick Disconnect	5	0.911	
Compressor, Freon Electric (Hermetically sealed)	1	200.000	200.000
Tube, Discharge (rubber tubes w/wire mesh)	1	553.097	553.097
Condenser, electric-driven (equiv: cooling coil)	1	4.02	4.02
Tube, Liquid Line (rubber line w/wire mesh)	1	553.097	553.097
Fan, Condenser (axial)	1	895.976	895.976
Evaporator, electric driven (equiv: cooling coil)	1	4.02	4.02
Fan, Evaporator (centrifugal)	1	41.592	41.592
Tube, suction (rubber tube w/wire mesh)	1	553.097	553.097
Sensor, suction pressure (equiv: pressure transducer air pressure sensor)	1	539.100	539.100
		τ system =	**10,427.681**
		MTBF system =	**95.899**

Pressurized Fuel Cell And Thermoelectric Cooler (TEC)

Mode Of Operation:

1. This system is Fuel Cell powered, with soldier interface controls (possibly both manual and automatic). The system has a master "control system," known as a controller. The controller helps regulate the cooling process as well as the voltage output requirements.

2. Pressurized Fuel Cell:

a. Pressurized H_2 gas flows from the cylinder to the gas regulator to one cell stack in the fuel cell. The same also applies to the pressurized O_2 gas.

b. Fuel Cell produces low power DC voltage. A fan is used in the fuel cell to cool it, due to heated H_2. The water by-product produced by the combination of the pressurized H_2 and O_2 needs to be disposed of.

c. Fuel cell provides DC power to load. A Power conditioner is used to get rid of ripple on DC signal. DC-to-DC converter gets rid of voltage variation.

3. Controller:

a. Regulates H_2/O_2 sent to Fuel cell (power to load). Signal sent from temperature probe to controller regulates controller which, in turn, regulates the TEC.

4. TEC:

a. TEC contains:

24 thermocouples connected in series.
2 electrically-driven axial fans.
2 solid state control chips.
2 relays.

b. TEC blows cool air to the solider.

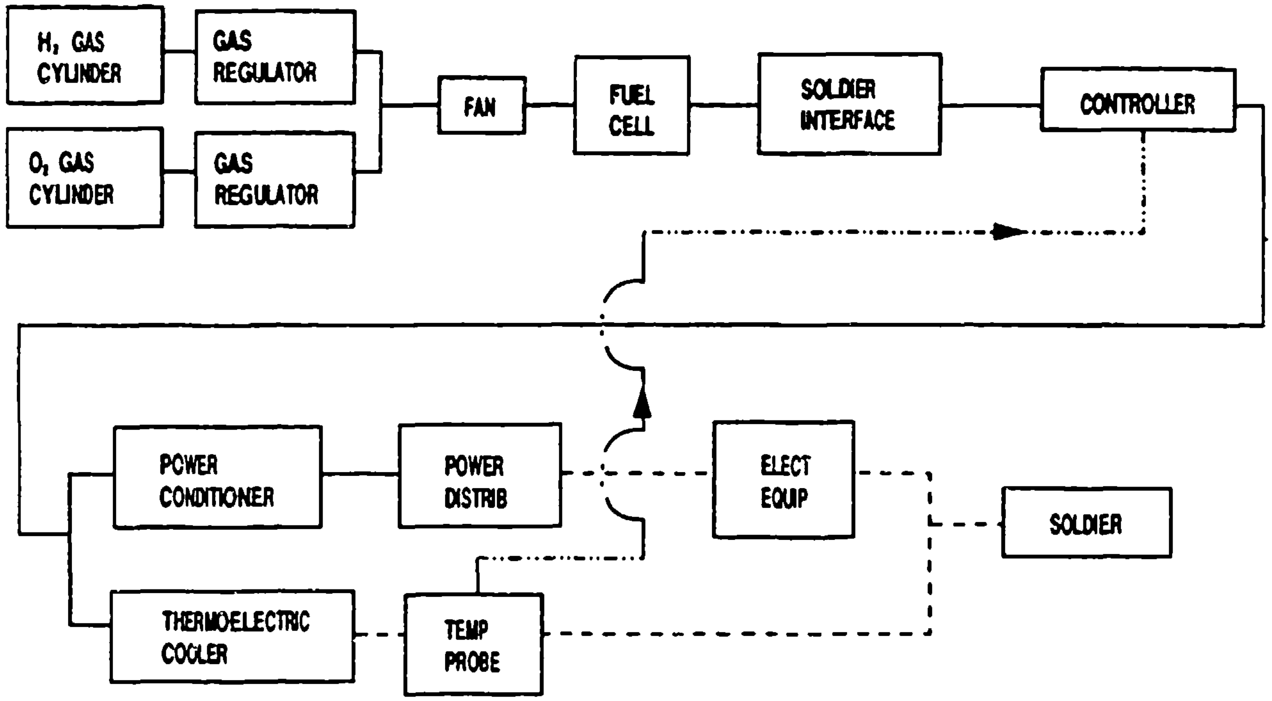


Figure G-3. Pressurized Fuel Cell and Thermoelectric Cooler (TEC) Functional Block Diagram

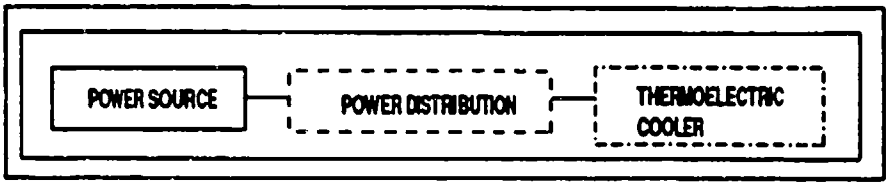
Assumptions to FBD

1. Failure of electrical equipment (i.e., Laser Rangefinder, etc.) is not relevant to this system. This system is only responsible for cooling the soldier and providing the proper power output (which includes power distribution capabilities).

2. Controller failure is a mission failure due to the compressor's inability to properly cool the soldier.

3. Power source/distribution and ECU (Environmental Control Unit; known as our cooling system) are assumed to be operating simultaneously at all times.

4. Failure of the temperature probe is considered to be a mission failure (cannot regulate compressor output well enough to cool soldier).



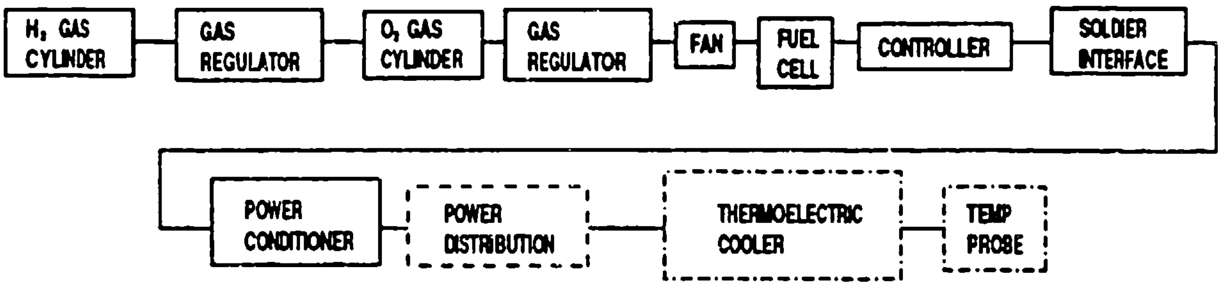


Figure G-4. Pressurized Fuel Cell and Thermoelect¨ic Cooler (TEC) Reliability Block Diagram

Assumptions

1. RBD based on mission essential functions:

   Mission Success = The simultaneous operation of the ECU, power source, and the power distribution system.

2. Based on the above assumption, the ECU, PWR distribution, and PWR source are in series.

Reliability Math Model (RMM)

Since the RBD represents a series system:

τ system = τ H_2 cylinder + τ regulator + ... + τ tec + τ temp probe.

MTBF system = 1/τ system.

Table G-2. Pressurized Fuel Cell and TEC Failure Rate Worksheet

Component	Quantity	Component Failure Rate	Total Failure Rate
Cylinder, H_2 Gas	1	161.191	161.191
Regulator, Gas Pressure (equiv: pressure relief valve)	1	2190.096	2190.096
Cylinder, O_2 Gas	1	161.191	161.191
Regulator, Gas Pressure (equiv: pressure relief valve)	1	2190.096	2190.096
Fan, Fuel cell, axial (electric-driven)	1	895.976	895.976
Controller	1	186.209	186.209
Interface, Soldier			389.648
switch, toggle (on/off)	1	0.243	
knob, temp adjust	1	264.550	
readout, voltage	1	102.891	
probe, temperature	1	21.964	
Cell, Fuel	1	36.000	36.000
Conditioner, Power (voltage reg, includes Filter, ripple DC-to-DC converter)	1	115.915	115.915
Distribution, Power			
Cable, Shielded	5	150.561	757.360
Connectors, Quick Disconnect	5	0.911	
Cooler, Thermoelectric			2,493.322
24 thermocouples	24	13.273	
2 axial fans	2	895.976	
2 general relays	2	5.2	
2 controller chips	2	186.209	
		τ system =	**9,577.004**
		MTBF system =	**104.417**

Internal Combustion Engine System: Air Cooled

Mode of Operation:

Preliminary Assumptions:

a. Compressor/fans/condenser/evaporator/Permanent Magnet (PM) generator are shaft-driven. Fan speed not regulated by controller.

b. Variable transmission not used.

c. Power conditioner used.

1. This system is battery/generator powered and has soldier interface controls (possibly both automatic and manual). The system has a master "control system," known as a controller. The controller helps regulate the cooling process as well as voltage output requirements.

2. Cooling System:

The shaft from the engine drives the compressor (freon based). The compressor discharges freon gas, via the discharge tube, to the condenser. The freon gas is transformed to a high-pressure liquid in the condenser. The condenser fan is used to cool the condenser.

The liquid travels, via the liquid line, to the evaporator. The evaporator transforms the freon liquid into a low pressure gas. This produces a cooling effect on the evaporator coils. The evaporator fan blows cool air off the coils to the soldier.

Any remaining freon vapor inside the evaporator coils travels back to the compressor.

Suction pressure sensor measures amount of vapor traveling back to compressor. Sensor provides input to the controller which in turn regulates the engine-compressor and therefore the amount of freon to be released into the system.

A clutch is used to regulate the use of compressor. The clutch has the ability to stop the compressor when cooling is not required by the soldier.

3. Power Requirements:

The engine powers the PM generator (shaft-driven). Voltage/current from generator is sent to the load. Battery is used as back-up in cases of inrush current.

A power conditioner is used to regulate the voltage (takes variable DC voltage from the generator, filters out any ripples, gives solid DC voltage).

Voltage sensing wires send signal back to controller. Controller will then regulate engine/generator to provide proper output voltage.

4. Controller:

The controller helps regulate the engine, which in turn regulates the PM generator and compressor.

The controller receives input from the following devices to help regulate the cooling and voltage requirements:

Temperature Probe
Voltage Sensing Wires

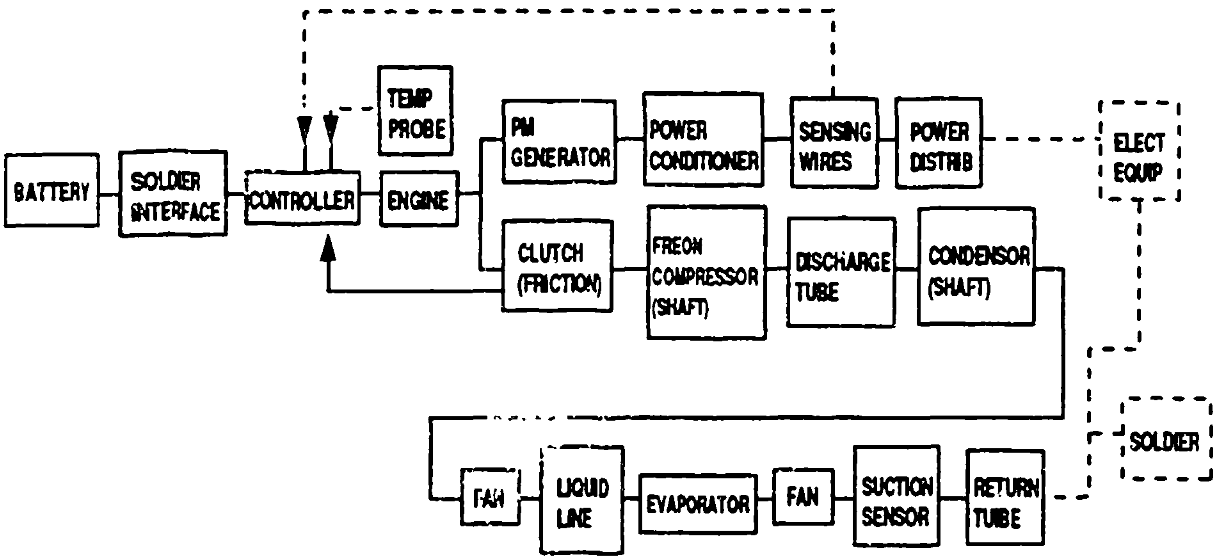


Figure G-5. Internal Combustion Engine System Air Cooled Functional Block Diagram

1. Power conditioner used as a type of voltage regulator. The battery can be used as "back-up" to the power conditioner but will be assumed to be used for starting purposes only.

2. Mission success = The simultaneous operation of the power source, power distribution system, and ECU (Environmental Control Unit; the cooling system).

3. System is only responsible for power source/distribution and ECU and not for functioning electrical equipment.

4. Power distribution configuration: five shielded cables and quick disconnect connector.

5. Controller failure equals mission failure (system will not work).

6. Failure of suction sensor and temperature probe equals mission failure (inadequate cooling to soldier).

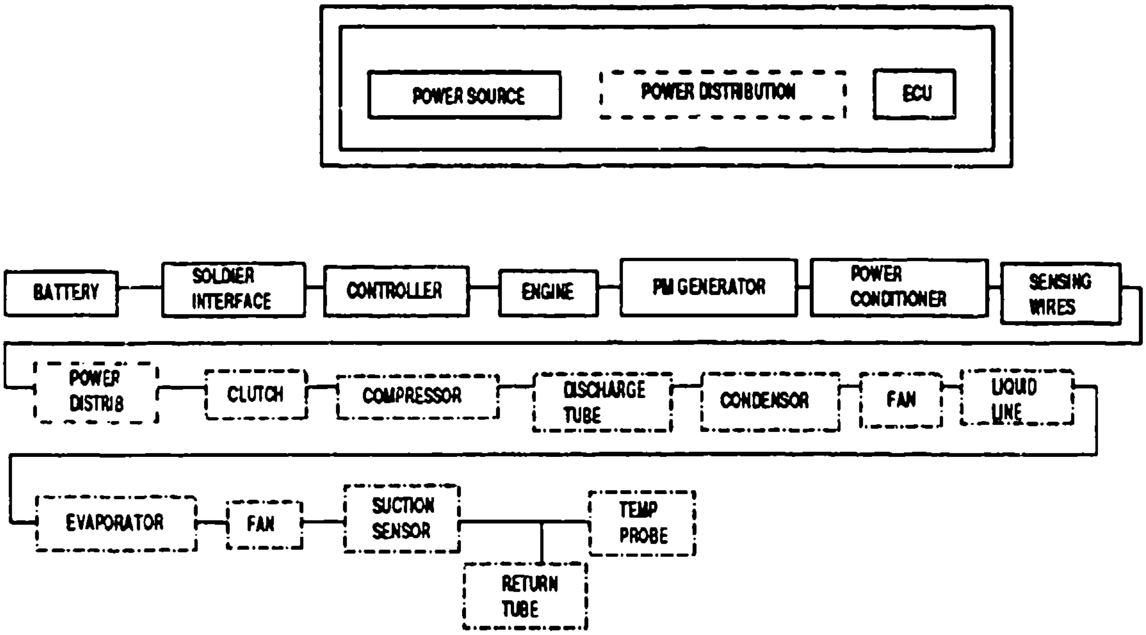


Figure G-6. Internal Combustion Engine System Air Cooled Reliability Block Diagram

Assumptions

1. RBD is based upon mission essential functions. These are: the simultaneous operation of the ECU, power source, and power distribution system.

2. Based on this assumption, a series reliability model will be applied.

Reliability Math Model (RMM)

Since the RBD represents a series system:

τ system = τ battery + ... + τ sensor + τ temp probe.

MTBF system = $1/\tau$ system.

Table G-3. Internal Combustion Engine System Failure Rate Worksheet

Component	Quantity	Component Failure Rate	Total Failure Rate
Battery, NiCd Rechargeable, 24V	1	710.468	710.468
Interface, Soldier			389.648
Switch, toggle (on/off)	1	0.243	
Knob, Temp Adjust	1	264.550	
Readout, Voltage	1	102.891	
Probe, Temperature	1	21.964	
Controller	1	186 209	186.209
Engine (fractional hp engine)	1	2,857.140	2,857.140
Generator, Permanent Magnet Generator, AC Bridge, Rectifier (AC to DC) (includes flywheel, gen fan)	1	98.417	98.417
Conditioner, Power (equiv: voltage regulator) (includes DC-to-DC converter filter and ripple device)	1	115.915	115.915
Wires, voltage, Sensing (Shielded wires w/armor coating)	2	150.561	301.122
Distribution, Power			
Cables, Shielded (armored)	5	150.561	757.360
Connectors, Quick, Disconnect	5	0.911	
Clutch, Friction	1	38.155	38.155
Compressor, Freon, Shaft-driven (Less Reliable than electric-driven)	1	400.000	400.000
Tube, Discharge, Freon (Rubber tube w/metal mesh)	1	553.097	553.097
Condenser, Shaft-driven, Hermetically sealed (Less reliable than electric-driven) *(equiv: cooling coil)	1	8.04	8.04
Fan, Condenser (Axial)	1	895.976	895.976
Tube, Line, Liquid (Rubber Tube w/wire mesh)	1	553.097	553.097
Evaporator, Shaft-driven (equiv: cooling coil) (Less reliable than electric-driven)	1	8.04	8.04
Fan, Evaporator (Centrifugal)	1	41.592	41.592
Tube, Suction (Rubber tube w/wire mesh)	1	553.097	553.097
Sensor, Pressure, Suction (equiv: Pressure transducer air pressure sensor)	1	529.100	529.100
		τ system =	**8,996.493**
		MTBF system =	**111.155**

Stirling Back-to-Back

Mode of Operation:

1. This system is battery operated and has soldier interface controls (possibly both manual and automatic). The battery sends a voltage signal to the controller. The controller is the master "control system." The controller helps regulate the cooling process as well as voltage output requirements.

2. The fuel pump provides fuel to the Stirling engine.

3. Stirling Engine/Generator/Compressor

Stirling back-to-back engine performs the following functions:

a. Engine (Internal Combustion type; Engine Converter)

b. Generator (Permanent Magnet; Linear Alternator) provides AC voltage output

c. Compressor (assume shaft driven type; Cooler Converter)

d. Stirling generator provides AC output voltage.

4. The Power Conditioner takes the AC output voltage and:

a. Rectifier bridge (halfway) to convert AC voltage signal to a halfway DC voltage signal.

b. A voltage filter converts the halfway DC voltage signal to a straight DC voltage signal.

c. A DC-to-DC converter takes care of any DC voltage variation.

5. Then the rectified DC voltage signal goes to power the load.

6. Cooling system:

Stirling compressor sends freon vapor to the cooling subsystem.

a. The discharge tube carries the freon vapor to the condenser.

b. The condenser compresses the freon vapor to a high-pressure liquid. The condenser fan helps to cool the vapor.

c. The liquid line tube takes the freon liquid to the evaporator.

d. The freon liquid in the evaporator now becomes a low-pressure gas; the freon gas produces a cooling effect on the evaporator coils (producing a cool mist).

e. The evaporator fan then blows the cool air to the soldier.

f. Any freon vapor remaining in the return line passes through suction pressure sensor (sending a signal to the controller, which in turn regulates the amount of freon released from the compressor).

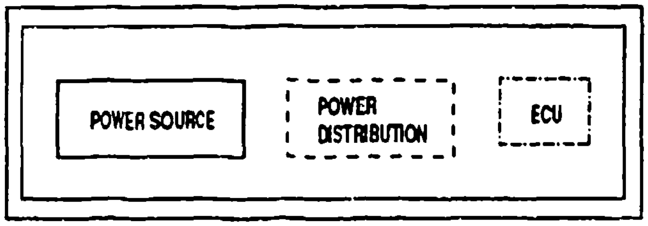
7. Controller:

The controller, which "controls" all major functions of the system, regulates the following items:

Stirling
Fuel Pump

The reading the suction pressure sensor sends to the controller allows the controller to regulate the compressor inside the Stirling (similar functioning for the temperature probe).

For this system, the temperature probe is considered to be part of the controller.



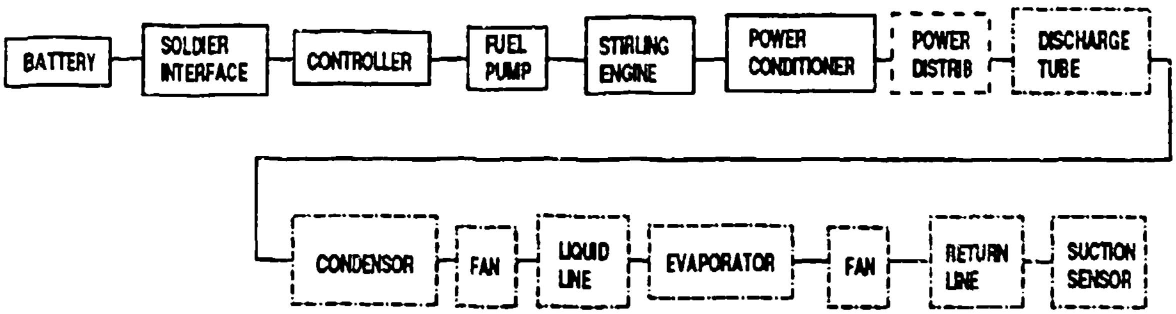


Figure G-7. Stirling Back-to-Back Functional Block Diagram

Assumptions

1. Mission success = Simultaneous operation of the power source, power distribution, and ECU (Environmental Control Unit; the cooling system).
2. Failure of the controller is a mission failure, due to inability to properly cool the soldier.
3. Failure of sensor is a mission failure (would not properly regulate compressor).
4. Power distribution system has five cables and quick-disconnect connectors.

   Failure of electrical equipment (i.e., Laser Rangefinder) is not a mission failure.

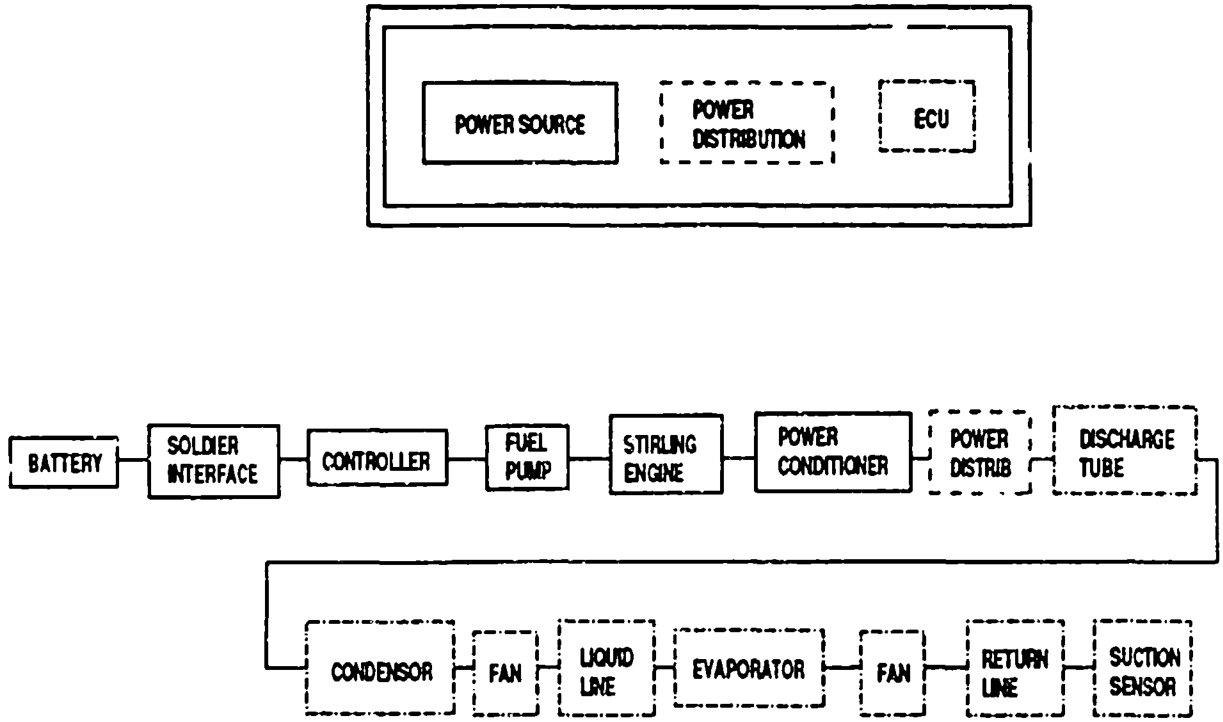


Figure G-8. Stirling Back-to-Back Reliability Block Diagram

Assumptions

1. RBD is based on simultaneous operation of the power source, power distribution, and ECU. When any of these operations do not taken place, it is a mission failure.

2. Based on this assumption, the subsystems are in a series configuration.

Reliability Math Model (RMM)

Since the RBD represents a series system:

τ system = τ battery + ... + τ return line + τ sensor

MTBF system = $1/\tau$ system.

Table G-4. Stirling Back-to-Back Failure Rate Worksheet

Component	Quantity	Component Failure Rate	Total Failure Rate
Battery, NiCd Rechargeable, 24V	1	710.468	710.468
Interface, Soldier			389.648
Switch, toggle (on/off)	1	0.243	
Knob, Temp Adjust	1	264.550	
Readout, Voltage	1	102.891	
Probe, Temperature (Temp Sensor)	1	21.964	
Controller	1	186.209	186.209
Pump Fuel	1	158.086	158.086
Back-to-Back, Stirling (Engine/AC Generator/Compressor)	1	3,333.333	3,333.333
Conditioner, Power (equiv: voltage regulator) (includes: rectifier, bridge converter, DC-to-DC Ripple controller)	1	115.991	115.991
Distribution, Power			757.360
Cables, Shielded	5	150.561	
Connectors, Quick, Disconnect	5	0.911	
Tube, Discharge (rubber tube w/wire mesh)	1	553.097	553.097
Condenser, electric-driven (equip: cooling coil)	1	4.02	4.02
Fan, Condenser (Axial)	1	895.976	895.976
Tube, Liquid Line (Rubber Tube w/wire mesh)	1	553.097	553.097
Evaporator, electric-driven (equiv: cooling coil)	1	4.02	4.02
Fan, Evaporator (Centrifugal)	1	41.592	41.592
Tube, Suction (Rubber tube w/wire mesh)	1	553.097	553.097
Sensor, Pressure, Suction (equiv: Pressure transducer air pressure sensor)	1	529.1	529.1
		τ system =	**8,785.094**
		MTBF system =	**113.829**

Vapor Cycle Engine

Mode Of Operation:

Battery Starts Up System; Soldier Controls (i.e., Blower, Control System)

1. This system is battery/engine/generator powered, with soldier interface controls (possibly both manual and automatic). The system has a master "control system" (otherwise known as a controller). The control system helps regulate the cooling process as well as power output requirements.

2. Some Basic Operations:

Air flows into the blower (started up by the battery). The blower churns air into the burner, which has its own fuel supply. The heated air goes into the boiler. Liquid is already present in the boiler, where the liquid is under high pressure. The heated air transforms the liquid into vapor. The air exhaust vent on the boiler is for exit of heated air. Vapor goes into throttle. Control System regulates the burner to regulate engine speed (i.e., boiler/throttle/ regenerator).

3. Power Requirements:

Voltage is produced via generator through engine-generator hook-up. Output voltage then goes through a power conditioner. The power conditioner takes a varying DC voltage signal and transforms it to a stable DC signal. The stable DC voltage then goes to the load.

Voltage sensing wires are used to send signal back to controller. If the power output requirements are not being met, the controller will regulate the operation of the engine/ generator. The battery can also be used as a back-up voltage source in cases of inrush currents.

4. Cooling System:

Freon vapor is released from compressor and travels via discharge line to the condenser. The condenser transforms the freon vapor into a high-pressure liquid. The condenser fan cools down the condenser.

The freon liquid travels through the liquid line to the evaporator. The liquid is transformed into a low-pressure gas, which produces a cooling effect on the evaporator coils. An evaporator fan is used to blow the cool air off the coils to the soldier.

Any remaining freon is sent back to the compressor via the return line. The remaining freon will pass through a suction pressure sensor, which sends a signal to the controller to regulate the amount of freon being released into the cooling system.

There is a clutch used on the compressor. This clutch is regulated by the compressor. The clutch is used to stop compressor operation when not required.

5. Basic Vapor Cycle Engine Operation:

While the engine is operating, a low-pressure exhaust exits from the engine. This low-pressure exhaust passes through the regenerator (a type of heat exchanger) to help cool down the exhaust.

The exhaust then goes into the condenser and then into the water tank (where there is liquid storage collection). Air flows through condenser and water tank. Cool air, as a result, blows back into the blower.

Water flows out of the water tank, via a water pump (the V.C. engine regulates the water pump). Water goes back into the regenerator, except this time the water is pre-heated.

Pre-heated liquid flows back into the boiler where, when hot air heats the liquid, the liquid becomes vapor.

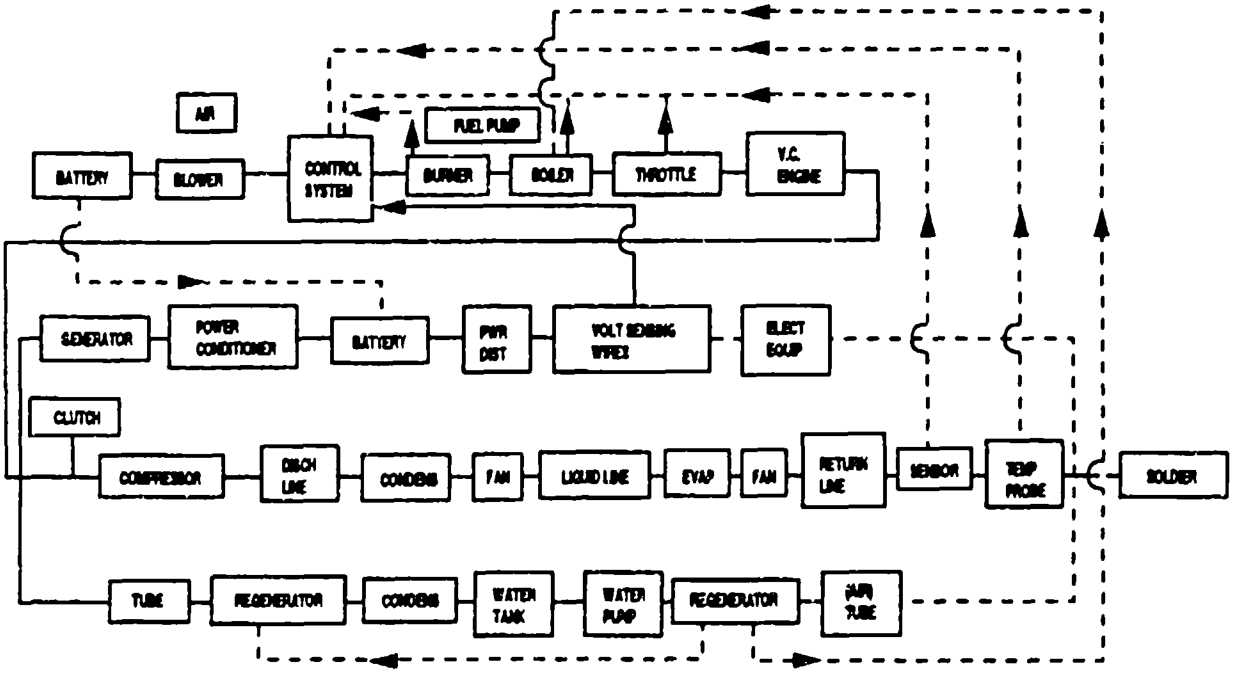


Figure G-9. Vapor Cycle Engine Functional Block Diagram

Assumptions

1. Power conditioner is responsible for regulating voltage. Battery will only be used for start-up purposes.
2. The exhaust flow from the condenser/water tank to the blower is represented by a tube.
3. Failure of control system (or controller) results in failure of the system.
4. The power source, power distribution, and ECU (Environmental Control Unit) all operate simultaneously.
5. Failure of electrical equipment (i.e., Laser Rangefinder) is not relevant.
6. Regenerator is considered to perform dual functions, but is counted as only one component.
7. Throttle is assumed to be part of the V.C. engine.

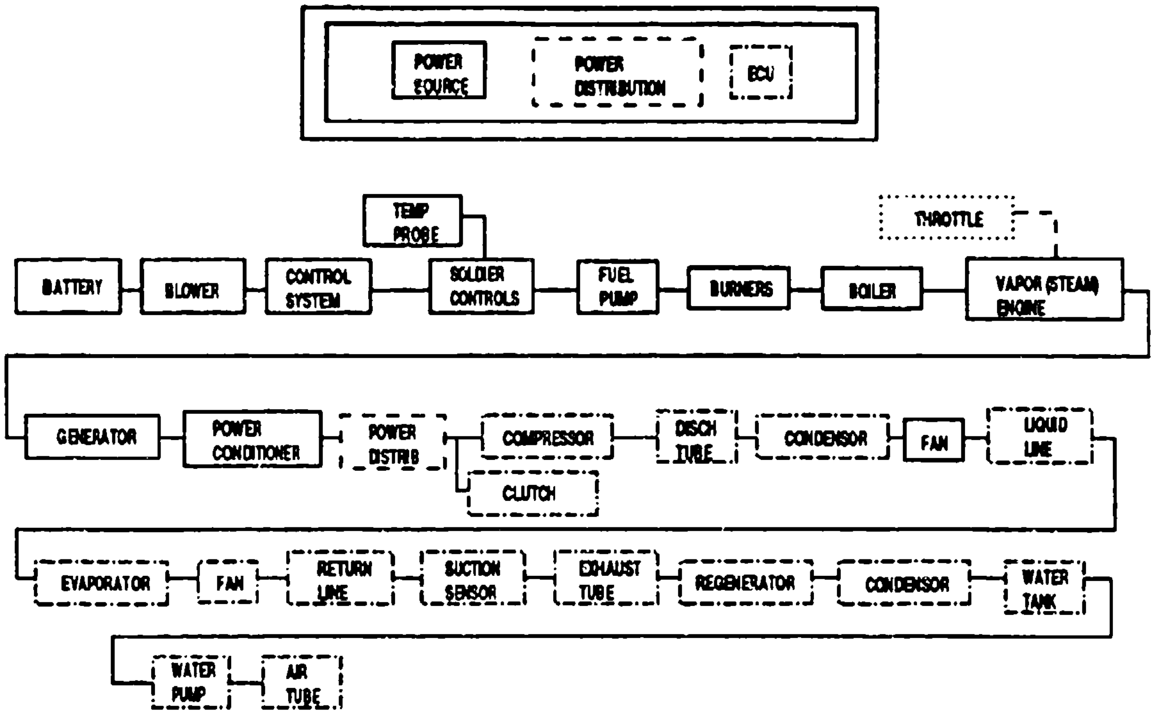


Figure G-10. Vapor Cycle Engine Reliability Block Diagram

Assumptions

1. The RBD is based on its mission essential function—the simultaneous operation of the power source, power distribution, and ECU.
2. Although the engine performs various functions, a series model is still used, since failure of engine impacts on the mission essential functions. (All of these functions are required at all times.)
3. Based on these assumptions, RBD is in series.

Reliability Math Model (RMM)

Since the RBD represents a series system:

τ system = τ battery + ... + τ air tube

MTBF system = $1/\tau$ system.

Table G-5. Vapor Cycle Engine Failure Rate Worksheet

Component	Quantity	Component Failure Rate	Total Failure Rate
Battery, NiCd Rechargeable, 24V	1	710.468	710.468
Blower (Centrifugal Fan)	1	41.592	41.592
Interface, Soldier			389.648
Switch, toggle (on/off)	1	0.243	
Knob, Temp Adjust	1	264.550	
Readout, Voltage	1	102.891	
Probe, Temperature	1	21.964	
Controller	1	186.209	186.209
Pump, Fuel, Electrical Boost (Low pressure pump)	1	158.086	158.086
Burner (equiv: home heating oil burner)			
Hose, Rubber	1	553.097	1,449.225
Igniter, Electric	1	0.152	
Fan, Axial Housing	1	895.976	
Boiler (essentially a tube w/liquid) Do not use electric heater	1	47.619	47.619
Engine, Steam (Includes Throttle)	1	3,333.333	3,333.333
Generator		98.417	98.417
AC Generator	1		
Bridge Rectifier (4 half-rectifier)	1		
Conditioner, Power DC Filter DC-to-DC (equiv: Voltage regulator)	1	115.915	115.915
Distribution, Power		757.360	757.360
Cables, Shielded, (Armor)	5		
Connectors, Quick, Disconnect	5		
Compressor, Freon, Shaft driven (Less reliable than electric-driven)	1	400.000	400.000
Tube, Discharge (Rubber Tube w/wire mesh)	1	553.097	553.097
Condenser, Electric-driven (equiv: cooling coil)	1	4.02	4.02
Fan condenser (axial)	1	895.976	895.976
Tube, Liquid Line (Rubber tube w/wire mesh)	1	553.097	553.097
Evaporator, Electric-driven (equiv: cooling coil)	1	4.02	4.02
Fan, evaporator (centrifugal)	1	41.592	41.592
Tube, Return (Rubber tube w/wire mesh)	1	553.097	553.097
Sensor, Suction pressure (equiv: pressure transducer air pressure sensor)	1	529.1	529.1
Tube, exhaust (see discharge tube)	1	553.097	553.097
Regenerator (equiv: Tube and shell liquid exchange radiator: last resort)	1	94.885	94.885
Tank, Water (equiv: non-pressurized Storage Tank)	1	529.1	529.1
Pump, Water (med-to-hi press)	1	342.377	342.377
Tube, Air (Rubber tube w/wire mesh)	1	553.097	553.097
Clutch, Friction wires	1	38.155	38.155
Voltage Sensor	2	150.561	301.122
		τ system =	**13,233.704**
		MTBF system =	**75.565**

Battery (Primary) System–Air Cooled:

Mode of Operation:

1. This system is battery powered and has soldier interface controls. The system has a master "control system," known as a controller. The controller helps regulate the cooling process.

2. Power Requirements:

One lithium, non-rechargeable, DC voltage output battery supplies all power to cooling system and the power distribution network.

3. Controller:

Soldier flips switch/temperature control knob and the controller turns on cooling system.

Controller activates the temperature probe worn by soldier; probe regulates the compressor (i.e., turns the compressor on and off to maintain proper temperature). Controller also activates the suction pressure sensor, which regulates the flow rate of the freon. The controller may or may not regulate the fans.

4. Cooling system:

Compressor discharges freon vapor to the condenser. In the condenser, the vapor is transformed into a high-pressure liquid. The condenser fan is used to help cool down the condenser due to the "vapor to liquid" transformation.

Freon liquid is sent to evaporator/fan. The high pressure freon liquid becomes a low pressure gas. This has the effect of producing a cooling effect on the evaporator coils (chilled air). This cooled air is blown onto the soldier via the evaporator fan.

Low pressure freon gas is returned to compressor. Gas is compressed into high pressure freon liquid.

NOTE: Cooling operation usage and/or configuration is based upon engine-driven system. (Clutch is not used).

The system is electric driven.

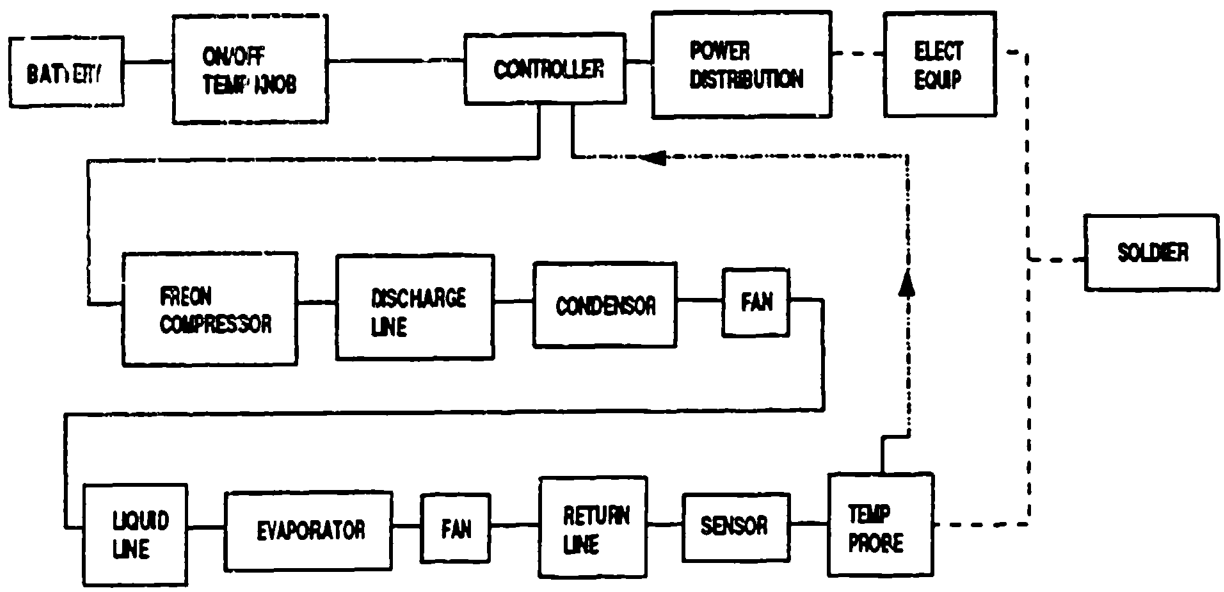


Figure G-11. Battery (Primary) System–Air Cooled Functional Block Diagram

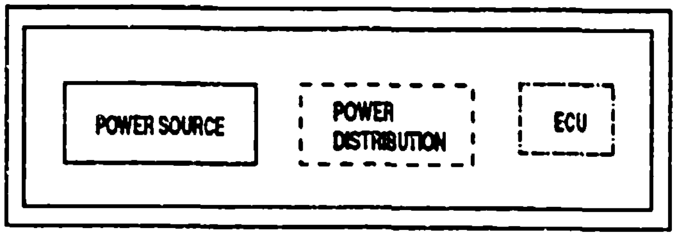
Assumptions

1. The failure of any electrical equipment (i.e., Laser Rangefinder) is not a mission failure. This system is only responsible for the simultaneous operation of the power source, power distribution, and ECU (Environmental Control Unit; the cooling system).

2. Failure of the controller is a mission failure (compressor would not be properly regulated).

3. The power distribution system consists of shielded cables and quick disconnect connectors.

4. Failure of the temperature probe and/or the suction pressure sensor is a mission failure (compressor could not be properly regulated).



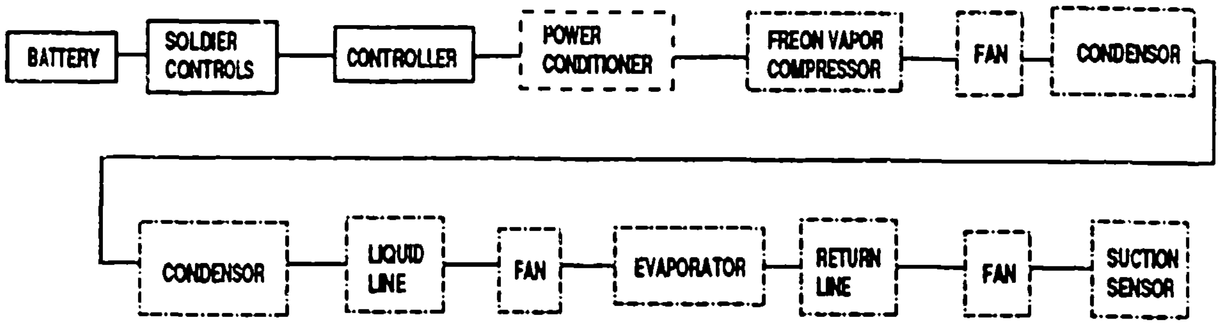


Figure G-12. Battery (Primary) System–Air Cooled Reliability Block Diagram

Assumptions

1. The RBD is based on the mission essential functions: the simultaneous operation of the power source, power distribution system, and ECU.

2. Based on this assumption, we have a series configuration.

Reliability Math Model (RMM)

Since the RBD represents a series system:

τ system = τ battery + ... + τ temp probe

MTBF system = 1/τ system

Table G-6. Battery (Primary) System–Air Cooled Failure Rate Worksheet

Component	Quantity	Component Failure Rate	Total Failure Rate
Battery, Lithium, Non-rechargeable	1	425.592	425.592
Fan, Axial (Condenser)	1	895.976	895.976
Fan, Centrifugal (Evaporator)	1	41.592	41.592
Sensor, Suction Pressure (equiv: Pressure air pressure sensor)	1	529.1	529.1
Compressor, Freon, Electric-Driven (Hermetically sealed)	1	200.000	200.000
Condenser, Electric-Driven (equiv: cooling coil)	1	4.02	4.02
Evaporator, Electric-Driven (equiv: cooling coil)	1	4.02	4.02
Tube; Discharge (Rubber tube w/armor covering Braided-type)	1	553.097	553.097
Tube, return (Rubber tube w/armor covering)	1	553.097	553.097
Tube, Liquid, Line (Rubber Tube, w/armor covering)	1	553.097	553.097
Power Distribution			
Cables, Shielded	5	150.561	757.360
Connectors, Quick Disconnect	5	0.911	
Controller	1	186.209	186.209
Interface, Soldier			389.648
Switch, toggle (on/off)	1	0.243	
Knob, Temp Adjust	1	264.550	
Readout, Voltage	1	102.891	
Probe, Temperature (equiv: Temp Sensor)	1	21.964	
		τ system =	**5,092.808**
		MTBF system =	**196.355**

H_2O_2 Fuel Cell And Electric Compressor

Mode Of Operation:

1. This system is fuel-cell powered and has soldier interface controls (both manual and automatic). The system has a master "control system," known as a controller. The controller helps regulate the cooling process as well as voltage output requirements.

2. H_2O_2 Fuel Cell:

a. Pressurized H_2 gas is released from the cylinder, through the relief valve, then to the fuel cell.

b. The H_2O_2 liquid (non-pressurized) is pumped to the fuel cell via the H_2O_2 pump.

c. H_2 and H_2O_2 mix in fuel cell and produce required voltage and current.

d. The fan is used in the fuel cell for cool down, due to the heated H_2 gas.

3. Cooling System:

a. Electric compressor releases freon vapor to the discharge tube.

b. From the discharge tube, the freon travels to the condenser, where freon vapor condenses into a high-pressure liquid. A fan assists in cooling both vapor and the condenser.

c. Condensed liquid flows through a tube to the evaporator, where the liquid is transformed into a low-pressure gas. When the freon goes from the liquid to gas phase, it produces a cooling effect on the evaporation tubes.

d. The evaporator fan then blows this cool air to the soldier.

c. Excess freon vapor is channeled back to the compressor via the return tube.

f. The return tube has a suction pressure sensor on it that tells the controller whether the compressor needs to pump more or less freon into the system.

4. Controller:

a. Regulates the amount of freon to be put into the system, based on input from the suction pressure sensor and temperature probe.

b. Receives a signal from the power conditioner, which in turn regulates the amount of H_2 released into the system.

5. Power Requirements:

a. Power to load is provided by battery; power conditioner regulates for constant DC voltage.

NOTE: Cooling is based on engine-driven system (no clutch used). All components are electric-driven.

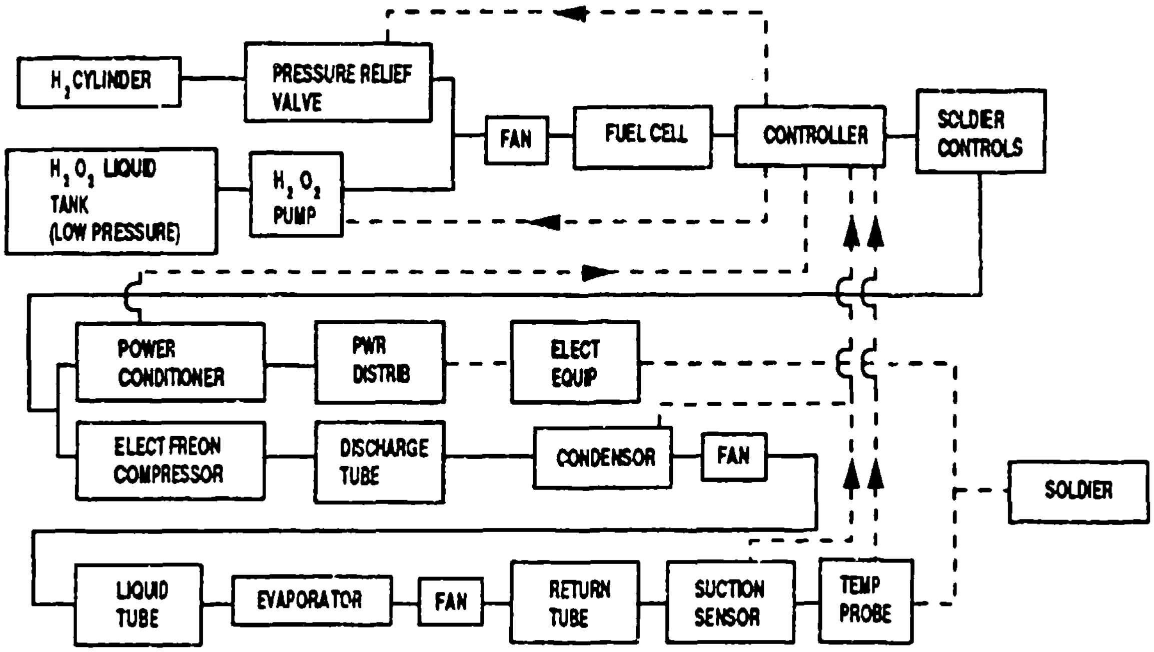


Figure G-13. H_2O_2 Fuel Cell and Electric Compressor Functional Block Diagram

Assumptions

1. Mission success = Power source, power distribution, and ECU (Environmental Control Unit; the cooling system) are properly operating at all times.

2. Controller failure is a mission failure due to inability to properly cool soldier.

3. Failure of sensor also is a mission failure (would not properly regulate compressor).

4. Power distribution has five cables and quick-disconnect connectors.

5. There is a separate relief valve for H_2 cylinder.

6. Failure of electrical equipment (i.e., Laser Rangefinder) is not considered a mission failure.

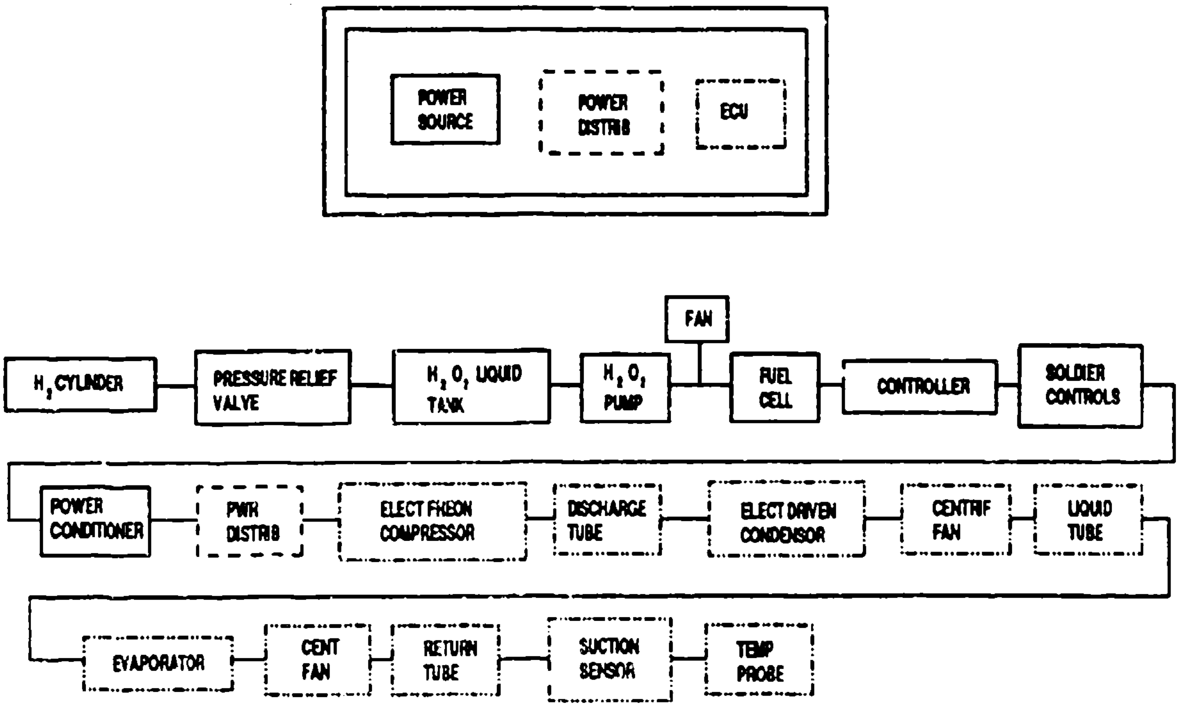


Figure G-14. H_2O_2 Fuel Cell and Electric Compressor Reliability Block Diagram

Assumptions

1. RBD is based on simultaneous operation of the power source, power distribution, and ECU. If any of these operations are not fulfilled, a mission failure has taken place.

2. Based on this assumption, the subsystems are in a series configuration.

Reliability Math Model (RMM)

Since the RBD represents a series system:

τ system = τ H_2 cylinder + ... + τ temp probe

MTBF system = $1/\tau$ system

Table G-7. Fuel Cell— H_2O_2 Fuel Cell Failure Rate Worksheet

Component	Quantity	Component Failure Rate	Total Failure Rate
Tank, H_2O_2 Liquid (equiv: Non-press storage tank)	1	529.1	529.1
Pump, H_2O_2 (equiv: fluid pump)	1	108.108	108.108
Fuel Cell-Air (total failure rate from fuel cell-air system)	1	8,066.394	8,066.394
		τ system =	8,703.602
		MTBF system =	114.895

Radioactive Isotopes And Thermoelectric Cooler (TEC)

Mode of Operation:

1. This system is powered by radioactive isotopes and has soldier interface controls (possibly both manual/automatic). This system has a master "control system," known as a controller. The controller helps regulate the cooling process as well as voltage output requirements.

2. Power Source/Requirements:

Radioactive isotopes are the main power source. The isotopes are contained in a lead-based container. Power output from the isotopes is converted into a stable DC voltage output via the power conditioner.

3. Cooling system:

The thermoelectric cooler is based on the concept that the electric potential within a thermocouple is converted to a temperature differential (resulting in cooler air being produced above the thermocouple). The fans within the TEC blow the cooled air to the soldier. TEC contains:

- 24 thermocouples connected in series.
- 2 electrically-driven axial fans.
- 2 solid state control chips.
- 2 relays.

4. Controller:

Receives input from the temperature probe, which in turn regulates the amount of cooled air being provided to the soldier.

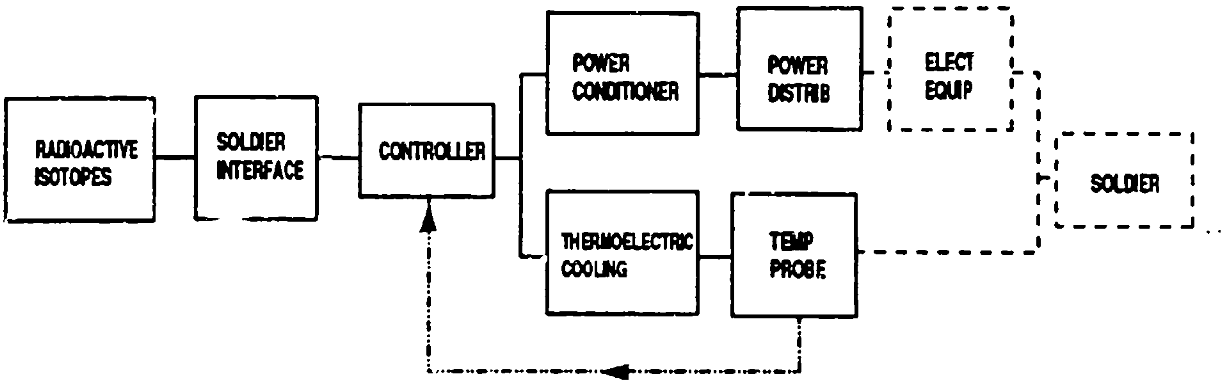


Figure G-15. Radioactive Isotopes and Thermoelectric Cooler (TEC) Functional Block Diagram

Assumptions

1. Failure of electrical equipment (i.e., Laser Rangefinder, etc.) is not relevant to this system. This system is only responsible for cooling the soldier and providing the power output (which includes power distribution capabilities).

2. Controller failure considered a mission failure due to the compressor's inability to properly cool the soldier.

3. Power source/distribution and ECU (Environmental Control Unit; known as our cooling system) are assumed to be operating simultaneously at all times.

4. Failure of the sensor and/or temperature probe is considered to be a mission failure (cannot regulate compressor output well enough to cool the soldier).

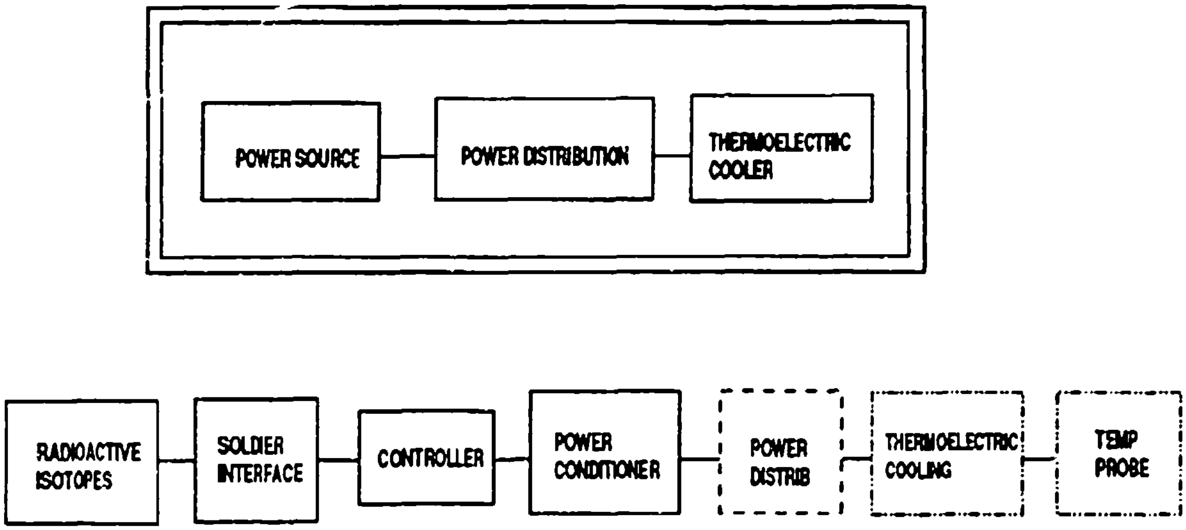


Figure G-16. Radioactive Isotopes and Thermoelectric Cooler (TEC) Reliability Block Diagram

Assumptions

1. RBD is based on mission essential functions: Mission Success = The simultaneous operation of the TEC, power source, and the power distribution system.

2. Based on this assumption, the TEC, power source, and power distribution are in series.

Reliability Math Model (RMM)

Since the RBD represents a series system:

τ system = τ radioactive isotope + ... + τ temp probe

MTBF system = 1/τ system.

Table G-8. Radioactive Isotopes Failure Rate Worksheet

Component	Quantity	Component Failure Rate	Total Failure Rate
Isotope, Radioactive	1		100.00
Controller	1	186.209	186.209
Interface, Soldier			389.648
Switch, toggle (on/off)	1	0.243	
Knob, Temp Adjust	1	264.550	
Readout, Voltage	1	102.891	
Probe, Temperature	1	21.964	
Conditioner, Power (equiv: voltage regulator) (includes: rectifier, bridge converter, DC-to-DC Ripple controller)	1		115.991
Distribution, Power			757.360
Cables, Shielded	5	150.561	
connectors, quick, disconnect	5	0.911	
Cooler, Thermoelectric			2,493.322
Thermocouples	24	13.273	
Axial Fans	2	895.976	
Relays (solid state)	2	5.2	
Controller Chips	2	186.209	
		τ system =	**4,042.530**
		MTBF system =	**247.370**

Appendix H
Replenishment Cost Analysis

(Author: Ms. Barbara Howard, BRDEC, SATBE-TQL)

OVERVIEW

This cost analysis provides a measure of the relative impact of each one of the proposed hardware concepts on the Operation and Support (O&S) cost for the program. However, since design data is not available to a level that would allow for a complete O&S cost estimate, the analysis was based on replenishment costs only. Replenishment cost has, historically, dominated O&S costs for Army systems and therefore is considered an adequate indicator of the overall O&S cost for a program.

For the purposes of this analysis, replenishment is defined as the cost of spare parts, fuel, and batteries consumed. The result of the analysis is a relative ranking of the proposed hardware concepts based on the cost of replenishment.

The overall cost results and system rankings are provided in Tables H-1 through H-3. Separate results are provided using the Peacetime annual operating requirement (AOR), Wartime, and Wartime without the Environmental Controlling Unit (ECU). The values represent a single operating year and do not include any procurement costs. Although carried in the charts, it should be noted that no fuel costs are shown for the Radioactive Isotope. Information is unavailable for calculating this cost at this time.

It can be seen that the overall system rankings do not change between the Peacetime, Table H-1, and Wartime, Table H-2. The difference in values is caused by the difference in values between the peacetime and wartime AOR.

Table H-1. Peacetime Replenishment Costs
(in $Millions)

Concept	Spares	Battery	Fuel	Total
H_2O_2 Fuel Cell	33.372	0.000	3.000	36.372
Internal Combustion	36.126	0.360	0.123	36.609
PEM Fuel Cell w/VC	34.646	0.000	2.400	37.046
Air Fuel Cell	32.054	0.000	30.000	62.054
Radioactive Isotope	75.874	0.000	*	75.874
Stirling	78.003	0.360	0.084	78.447
PEM Fuel Cell w/Thermo	79.459	0.000	4.800	84.259
Battery w/VC	30.848	63.300	0.000	94.148
Vapor Cycle Engine	120.919	0.360	0.099	121.378

*Radioactive Isotope fuel costs unavailable

Table H-2. Wartime Replenishment Costs (in $Millions)

Concept	Spares	Battery	Fuel	Total
H_2O_2 Fuel Cell	1201.391	0.000	108.000	1309.391
Internal Combustion	1300.536	12.960	4.428	1317.924
PEM Fuel Cell w/VC ECU	1247.243	0.000	86.400	1333.643
Air Fuel Cell	1153.978	0.000	1080.000	2233.978
Radioactive Isotope	2731.482	0.000	*	2731.482
Stirling	2808.094	12.960	3.024	2824.078
PEM Fuel Cell w/Thermo	2860.510	0.000	172.800	3033.310
Battery w/VC ECU	1110.516	2278.800	0.000	3389.316
Vapor Cycle Engine	4353.098	12.960	3.564	4369.622

*Radioactive Isotope fuel costs unavailable

For the total system concepts, power supply/distribution, and environmental control unit the results fall into three cost groupings. The lowest cost grouping includes the H_2O_2 Fuel Cell, the Internal Combustion Engine, and the Proton Exchange Membrane (PEM) Fuel Cell with a Vapor Cycle (VC) ECU. The next cost grouping includes the Ambient Air Fuel Cell, Radioactive Isotope, Stirling engine, and the PEM Fuel Cell with Thermoelectric ECU. The Battery and Vapor Cycle engine make up the next grouping.

The Vapor Cycle engine had the highest cost for spares. This resulted from high replacement rates for the engine and ECU and a high cost for the engine. Further analysis is needed to study how the components were grouped for the Mean Time Between Failure (MTBF) calculation to determine if this significantly impacted the results.

The highest cost for batteries was for the Battery System concept, as expected. The costs were driven by the fact that the battery proposed is anticipated to be non-rechargeable so replacement would be required after each mission.

Given that the radioactive isotope fueling costs are indeterminable at this time, the highest cost for fuel was for the Fuel Cell concepts. The Ambient Air Fuel Cell was the most expensive with fuel costs running $100 per mission. This concept and the Hydrogen Peroxide (H_2O_2) fuel cells have been dropped from further analysis.

Table H-3. Wartime Replenishment Costs Without Cooling System (in $Millions)

Concept	Spares	Battery	Fuel	Total
Radioactive Isotope	38.215	0.000	*	38.215
Internal Combustion	151.601	12.960	2.214	166.775
H2O2 Fuel Cell	121.391	0.000	54.000	175.391
PEM Fuel Cell w/VC ECU	167.243	0.000	43.200	210.443
PEM Fuel Cell w/Thermo	167.243	0.000	86.400	253.643
Air Fuel Cell	73.978	0.000	540.00	613.978
Stirling	1961.699	12.960	1.512	1976.171
Primary Battery	30.516	2278.800	0.00	2309.316
Vapor Cycle Engine	2836.244	12.960	1.782	2850.986

*Radioactive Isotope fuel costs unavailable

The replenishment cost analysis was also run to determine system costs without an ECU. The project engineers included a projection that fuel efficiencies would improve without the power demand of the ECU. Several systems improved in the rankings without the inclusion of the spares replenishment for the ECU. The two most significant changes were the Radioactive Isotope concept and the PEM Fuel Cell w/Thermoelectric ECU. These two concepts utilized a very expensive Thermoelectric ECU, which represented the highest spares costs for each of these systems.

Supporting documentation for the analysis is provided in annexes to this appendix. A description of the approach taken for the analysis and the major assumption is provided below.

ANALYSIS APPROACH

The basic approach to this analysis has been to: (a) evaluate the system concepts; (b) define the anticipated hardware components and their functions; (c) estimate the failure rates for components and subassemblies; (d) identify comparative cost data; and (e) calculate the replenishment costs. The first three steps to this approach have been accomplished as part of the Reliability Analysis.

The basic system concepts were provided by the project engineering team. These concepts were reviewed with the engineers to determine the hardware envisioned for the system. This information was used to develop functional and reliability block diagrams. Comparative hardware was identified from standard data sources to determine component failure rates and costs. These were used to determine assembly and system failure rates and costs.

The data sources used for the cost data include HAYSTACK, manufacturers, and engineering estimates based on current BRDEC environmental programs. Whenever possible, data was based on components having the same technical characteristics as those identified for the system concepts. When like items could not be identified, similar items or engineering analysis were used. For several components, such as the fuel cell cylinders, manufacturers were contacted for price estimates.

The basic costs estimated for the systems were the cost of replacement spares, batteries, and fuel. Additional costs, such as other Petroleum, Oil, and Lubricants (POL) cannot be estimated based on the current level for the system designs.

The basic cost equations utilized are provided in Annex 1. The cost calculations included the use of an Annual Operating Requirement value and anticipated quantity of systems to be supported. An explanation of how these two values were estimated is provided in Annex 2. These values were based on available data as no user requirements have been defined. An explanation on how these values were derived is provided.

For each concept, the results of the equations were tabulated in a spreadsheet. Calculations were done for peacetime, wartime, and for a wartime system without the cooling system.

For each system concept, documentation is provided on the analysis in Annex 3. The concept specific assumptions are provided as part of these write-ups. General assumptions are provided below. A table showing peacetime, wartime, and wartime costs without cooling is provided for each system.

A number of general and hardware related assumptions were made while conducting this analysis. The general assumptions presented are for all the system concepts analyzed. In the documentation of each system, specific system assumptions are provided.

For the initial estimates, all the concepts were considered to be made up of modular components, with quick disconnects and easy replacement. These modules were assumed to be non-repairable and would be discarded at failure. These assumptions resulted in a high estimate of replenishment costs, as repairable components would require less expensive subcomponents, which would have lower MTBFs. This approach was taken because there was not sufficient data on the components.

All costs and reliability values are estimated based on available data and interpretation of the engineers' concepts into identifiable hardware components.

The same Annual Operation Requirement and Quantities were used for all systems.

Annex 1
Basic Cost Equations

SPARES:

The spares cost was based on the assumption that the major components/assemblies would be discarded at failure. No allowance was made for possible repair due to current level of the hardware design.

The assembly failure rate and the cost were plugged into the basic spares equation:

SPARES = AOR/MTBF * QTY * Cost of item

where:

AOR	=	Annual Operating Requirement (in hours)
MTBF	=	Mean Time Between Failure (10E6/failure rate) (in hours)
QTY	=	Quantity of systems under analysis

BATTERIES:

For some systems, batteries are required as the initial or system power source. For these systems, the estimated useful life of the battery was used in place of the failure rate.

For non-rechargeable batteries, it was assumed that the battery would be drained before failure was reached. For rechargeable batteries, it was assumed that the recharging cost would be small and that useful life would be reached prior to failure. These assumptions were confirmed when the useful lives were found to be lower than the failure rates. Some battery failures would probably occur, but it is anticipated that their contribution to the overall replenishment cost would be low. The battery cost equation is:

BATTERIES = AOR/Battery life * QTY * Cost of battery

where AOR and QTY are defined above.

The estimate for the batteries does not include the added costs for recharging equipment, transportation, storage and handling costs, or other support equipment.

FUEL:

The fuel cost was based on consumption rates provided by the engineers and the annual operating requirements.

The fuel consumption rates were provided by the project engineers. For the combustion system, the fuel was assumed to be diesel. For the fuel cells, hydrogen and oxygen were used. The basic fuel equation is:

FUEL = Fuel Rate (in operating hours) * Fuel Cost * AOR * QTY

where AOR and QTY are defined above and:

Fuel Rate	=	gallons per hour (combustion)
	=	% of fuel load consumed per hour (fuel cells)
Fuel Cost	=	dollars per gallon (combustion)
	=	dollars per consumption rate.

Annex 2
Annual Operation Requirements and System Quantity

ANNUAL OPERATING REQUIREMENTS

The Annual Operating Requirement (AOR) was estimated.

The AOR hours were based on Case II, a 10-hour mission. Current Operation Mission Summaries for generators call for a wartime mission scenario of: 1 mission a day for 15 days, 15 times a year. For this analysis, the yearly missions were lowered to 12 per year. The result was 1,800 operating hours per year (10 hours * 15 days * 12 times per year).

The peacetime operating hours were based on a training schedule of 15 days per year at 10 hours per day. The Infantry School provided information that the field training time for an infantry soldier varies from 2 to 5 weeks. A soldier will get almost 4 months of Field Training Exercises (FTX) per year. It was assumed that full training in protective clothing would only be a portion of that total. Assuming a 10-hour training day, it was felt that 15 days would represent a reasonable annual requirement. Therefore, a peacetime AOR of 150 hours was used.

SYSTEM QUANTITY

The Quantity of soldiers to be outfitted with this equipment was also estimated. For this preliminary analysis, the focus was on the Infantry Combat Soldier. Information provided by the Infantry School was that there are between 150,000 and 178,000 infantry soldiers in the Army (approximately 12 percent of the total force).

The lower value represents an approximation of soldiers in a combat ready state, excluding those classified as transients, patients, or prisoners, those in initial training, and those assigned to recruitment or ROTC duty.

This lower estimate was then reduced by the estimated 25 percent force reduction plans currently being implemented. This reduced the number of infantry soldiers to 120,000. This number represents a world-wide force total.

For the purposes of this analysis, the Wartime annual quantity was estimated at half the total force. This assumption was on the basis that any conflict would be localized and not global. This resulted in a total quantity of 60,000.

For the Peacetime estimate, it was assumed that one third of the estimated Wartime quantity would be used in training in any one year.

Annex 3
Analysis of System Concepts

PRIMARY BATTERIES WITH VAPOR CYCLE COOLING SYSTEM

Assumptions:

1. The preliminary maintenance concept is for modular a design with line replacement of major components and no component repair. The five basic modules are: (a) a battery cell; (b) environmental control unit (ECU); (c) a controller, which governs the ECU operation; (d) a soldier interface, which allows the soldier to operate and monitor the system; and (e) a power distribution subsystem, for supplying power to other Soldier Systems. All electrical lines are quick disconnect.

   Each module can be replaced at unit level. For this first analysis, all modules are considered non-repairable. Currently, it is recognized that all modules may be designed to be repairable but current information is unavailable to determine to what subcomponent or part level that may be.

2. The current design incorporates a Lithium type non-rechargeable battery cell. This battery cell provides power to the ECU and all other Soldier Systems. Based on information available on current lithium batteries, it is projected that the battery would have a useful life of one mission cycle (10 hours). Using the concept of disposable batteries, battery replacement would be after every mission.

   The cost of the battery was estimated to be $211. This value was provided by project engineers based on information from the Electronics Technology and Devices Laboratory (ETDL).

3. As a battery powered system, there are no fuel requirements for this concept.

4. Batteries are not included as spares. The estimated failure rate for the batteries, recognizing that failures can occur before end of useful life, resulted in a very low additional cost. The replacement costs for these spares came to less than one-half of 1 percent of the total estimated replenishment costs.

5. The ECU is an electrically-driven compressed gas refrigerant system. The cool air is vented to the soldier through air lines into a cooling vest.

   The ECU price is based on the $2,500 project cost of the smallest MIL-STD air conditioner (AC), with a 20 percent increase to cover the compressor design. Currently, the ECU is assumed to be the same technology as the freon-based ACs but will be significantly reduced in physical size. This reduction in size accounts for the increased cost as manufacturing will be more expensive and there is currently no commercial market for a system of the projected size.

   It is difficult to interpret individual component part data relative to the reduction in size, so the system has been addressed as a whole. It is not currently anticipated that the ECU will be repairable, but with the compressor having the highest failure rate it could become a repair part.

There are risks associated with this cost estimate. One project engineer stated that past estimates for small vapor cycle cooling systems have run between $15,000 and $17,000. Taking these as prototype model estimates, manufacturing costs could still be in the neighborhood of $10,000. As the basic ECU concept is the same for all systems except those using thermoelectric cooling, and with only minor differences between electrically and mechanically driven compressors, the overall cost relationship between systems would probably not change.

6. Only a basic concept of how the controller would be designed exists. It will likely be a black box module with microprocessing chips. It would be non-repairable and non-reprogrammable.

   The cost estimate is based on a large version used in the newly designed motor controller module for the 18K BTU AC. This item is currently being negotiated for procurement at a cost estimate of $590 each. With future miniaturization and somewhat more complex function, the cost for this item was increased by approximately 70 percent.

   The same or a very similar concept is being used for all systems at this time and the same MTBF and cost have been used for all.

7. The soldier interface module allows the soldier to turn the system on and off, adjust the cooling temperature, and monitor the system. The technology currently considered will use standard, inexpensive components that are readily available. The cost estimate is based on a composite cost of switches, adjustment controls, temperature probe, and voltage readout.

8. The power distribution design is very simple at this time. It is assumed that significant power conditioning requirements will be addressed to a maximum extent in the other Soldier Systems. The basic concept incorporates only interconnecting cables and connectors. The cost estimate is based on a composite of currently available like components.

9. Special Note: It is recognized that a significant portion of the total system life cycle cost will be involved in the transportation, storage, handling, and disposal of the batteries. Due to the limitations of this analysis and constraints on the availability of data, these costs have not been included.

REPLENISHMENT COSTS FOR PRIMARY BATTERY WITH VAPOR CYCLE COOLING

	AOR (hrs)	Quantity
Peacetime Requirement	150	20,000
Wartime Requirement	1,800	60,000

BATTERY CONSUMPTION

Type	Use Life	Price	Peacetime Cost ($K)	Wartime Cost ($K)	Uncooled Wartime
Lithium	10	211.00	63,300.00	2,278,800.00	2,278,800.00

FUEL CONSUMPTION

Type	Fuel Rate	Price	Peacetime Cost ($K)	Wartime Cost ($K)	Uncooled Wartime
N/A	0	0.00	0.00	0.00	0.00

Components	MTBF	Price	Peacetime Cost ($K)	Wartime Cost ($K)	Uncooled Wartime
Battery	2,350	0.00	0.00	0.00	0.00
ECU	300	3,000.00	30,000.00	1,080,000.00	
Controller	5,370	1,000.00	558.66	20,111.73	20,111.73
Soldier Interface	2,566	150.00	175.00	6,313.33	6,313.33
Power Distrib	1,320	50.00	113.64	4,090.91	4,090.91
SPARES TOTAL			30,847.67	1,110,515.97	30,515.97
TOTALS			94,147.67	3,389,315.97	2,309,316.97

INTERNAL COMBUSTION ENGINE WITH VAPOR CYCLE COOLING SYSTEM

Assumptions:

1. The preliminary maintenance concept is for a modular design with line replacement of major components and no component repair. The five basic modules are: (a) engine, which includes fuel system; (b) environmental control unit (ECU); (c) a controller, which governs engine and ECU operation; (d) a soldier interface, which allows the soldier to operate and monitor the system; and (e) power generation/distribution subsystem, for generating and supplying power to other Soldier Systems. All fluid and electrical lines are quick disconnect.

   Each module can be replaced at unit level. For this first analysis, all modules are considered non-repairable. Currently it is recognized that all modules may be designed to be repairable but current information is unavailable to determine to what subcomponent or part level that may be.

2. A NiCad battery is used to start the system. This battery would be rechargeable. The useful life is assumed to be equal to its failure rate, including recharging. Only one battery is required for the system. The battery cost estimate was provided by the engineer and no additional data was available yet from other sources. The same battery and assumptions have been made for all other systems requiring a similar secondary battery.

3. The engine as currently designed is meant to run on an alcohol/ether mixture for improved performance. The fuel consumption rate is based on an estimate of this consumption slightly degraded to cover a conversion to JP-8/diesel to meet the one fuel forward doctrine.

   The amount of fuel available is based on meeting a 10-hour sustained mission. After 10 hours, refueling would be required. Additional costs for resupply, manpower, transportation, and handling costs are not included at this time. The fuel cost value has not been adjusted to include any of these costs.

   The fuel consumption rate is based on an estimate of 0.28 pounds of fuel per hour. This was converted to gallons per hour using a rounded estimate of 6.8 pounds of diesel per gallon.

4. The engine is anticipated to be something between a commercially available model airplane engine and a weed whacker engine with an anticipated useful life of 350 operating hours. No testing has been done by the government or industry to determine the validity of this value; it is an estimate provided by both engineers and hobbyists familiar with this engine. The MTBF associated with the fuel subsystem is minor compared to the low life expectancy of the engine itself. For this analysis it is assumed that no engine failures will occur before the end of the useful life of the engine.

   There are risks associated with making this assumption. However, it is estimated that the costs associated with engine failures will be significantly lower than those from engine wearout.

5. The ECU is a shaft-driven compressed gas refrigerant system. The cool air is vented to the soldier through air lines into a cooling vest. The ECU price is based on the $2,500 project cost of the smallest MIL-STD air conditioner (AC), with a 20 percent increase to cover the compressor design. Currently, the ECU is assumed to be the same technology as the freon-based ACs but will be significantly reduced in physical size. This reduction in size accounts for the increased cost as manufacturing will be more expensive and there is currently no commercial market for a system of the projected size.

It is difficult to interpret individual component part data relative to the reduction in size so the system has been addressed as a whole. It is not currently anticipated that the ECU will be repairable but with the compressor having the highest failure rate it could become a repair part.

There are risks associated with this cost estimate. One project engineer stated that past estimates for small vapor cycle cooling systems have run between $15,000 and $17,000. Taking these as prototype model estimates, manufacturing costs could still be in the neighborhood of $10,000. As the basic ECU concept is the same for all systems except those using thermoelectric cooling, and with only minor differences between electrically and mechanically driven compressors, the overall cost relationship between systems would probably not change.

6. Only a basic concept of how the controller would be designed exists. It will likely be a black box module with microprocessing chips. It would be non-repairable and non-reprogrammable.

   The cost estimate is based on a large version used in the newly designed motor controller module for the 18K BTU AC. This item is currently being negotiated for procurement at a cost estimate of $[illegible]0 each. With future miniaturization and somewhat more complex function, the cost for this item was increased by approximately 70 percent.

   The same or very similar concept is being used for all systems at this time and the same MTBF and cost have been used for all.

7. The soldier interface module allows the soldier to turn the system on and off, adjust the cooling temperature, and monitor the system. The technology currently being considered will use standard, inexpensive components that are readily available. The cost estimate is based on a composite cost of switches, adjustment controls, temperature probe, and voltage readout.

8. The power distribution design is very simple at this time. It is assumed that significant power conditioning requirements will be addressed to a maximum extent in the other Soldier Systems. The basic concept incorporates power generation, interconnective cables, and connectors. The power generation source is a permanent magnetic generator. The cost estimate is based on a composite of currently available like components.

REPLENISHMENT COSTS FOR INTERNAL COMBUSTION ENGINE WITH VAPOR CYCLE COOLING SYSTEM

	AOR (hrs)	Quantity
Peacetime Requirement	150	20,000
Wartime Requirement	1,800	60,000

BATTERY CONSUMPTION

Type	Use Life	Price	Peacetime Cost ($K)	Wartime Cost ($K)	Uncooled Wartime
NiCad	1,000	120.00	360.00	12,960.00	12,960.00

FUEL CONSUMPTION

Type	Fuel Rate	Price	Peacetime Cost ($K)	Wartime Cost ($K)	Uncooled Wartime
Diesel	0.041	1.00	123.00	4,428.00	2,214.00

Components	MTBF	Price	Peacetime Cost ($K)	Wartime Cost ($K)	Uncooled Wartime
Engine	350	350.00	3,000.00	108,000.00	108,000.00
ECU	282	3000.00	31,914.89	1,148,936.17	0.00
Controller	5,370	1,000.00	558.66	20,111.73	20,111.73
Soldier Interface	2,566	150.00	175.37	6,313.33	6,313.33
Power Distrib	786	125.00	477.10	17,175.57	17,175.57
SPARES TOTAL			36,126.02	1,300,536.80	151,600.63
TOTALS			36,609.02	1,317,924.80	1,66,774.63

STIRLING ENGINE WITH INTEGRATED COOLING SYSTEM (STIRLING BACK-TO-BACK)

Assumptions:

1. The preliminary maintenance concept is for a modular design with line replacement of major components and no component repair. The five basic modules are: (a) engine, which includes fuel subsystem and power generator; (b) environmental control unit (ECU); (c) a controller, which governs engine and ECU operation; (d) a soldier interface, which allows the soldier to operate and monitor the system; and (e) a power distribution junction, for supplying power to other Soldier Systems. All fluid and electrical lines are quick disconnect.

   Each module can be replaced at unit level. For this first analysis, all modules are considered non-repairable. Currently, it is recognized that all modules may be designed to be repairable but current information is unavailable to determine to what subcomponent or part level that may be.

2. A NiCad battery is used to start the system. This battery would be rechargeable. The useful life is assumed to be equal to its failure rate, including recharging. Only one battery is required for the system. The battery cost estimate was provided by the engineers and no additional data was available yet from other sources. The same battery and assumptions have been made for all other systems requiring a similar secondary battery.

3. The engine as currently designed runs on a diesel/JP-8. Currently, information on the design does not provide information on the fuel consumption rate. Therefore, the consumption rate is based on an engineering estimate of power provided by the engine and an efficiency fa[illegible] the engine.

   The amount of fuel available is based on meeting a 10-hour sustained mission. After 10 hours, refueling would be required. Additional costs for resupply manpower, transportation, and handling costs are not included at this time. The fuel cost value has not been adjusted to include any of these costs.

   The fuel consumption rate is based on an estimate of 0.19 pounds of fuel per hour. This was converted to gallons per hour using a rounded estimate of 6.8 pounds of diesel per gallon. The Stirling design is anticipated to get between 35 and 40 percent more fuel efficiency than the internal combustion engine.

4. The engine proposed is a Stirling design. This design integrates the compressor for the vapor cycle cooling with the engine design for improved performance. For this analysis, the compressor was included as part of the engine and not the ECU. The fuel system and power generator are also considered parts of the engine.

   The cost of the engine is based on information provided in a technical report on the engine with a cost estimate for developing a prototype system. A learning curve and quantity of scale (volume purchase) factor was added to arrive at the cost used.

5. The ECU is a vapor cycle cooling system, with electrically driven fans and evaporator/condenser. (NOTE: Compressor is integrated into engine design and accounted for with the engine). The cool air is vented to the soldier though air lines into a cooling vest.

The ECU price is based on the $2,500 project cost of the smallest MIL-STD air conditioner (AC). Currently the ECU is assumed to be the same technology as the freon-based ACs but will be significantly reduced in physical size. This reduction in size could account for an increase in cost as manufacturing will be more expensive and there is currently no commercial market for a system of the projected size. Currently no modification of price has been made for the compressor technology, which is included with the engine, or to reduce the cost due to removing the compressor.

It is difficult to interpret individual component part data relative to the reduction in size so the system has been addressed as a whole.

6. Only a basic concept of how the controller would be designed exists. It will likely be a black box module with microprocessing chips. It would be non-repairable and non-reprogrammable.

   The cost estimate is based on a large version used in the newly designed motor controller module for the 18K BTU AC. This item is currently being negotiated for procurement at a cost estimate of $590 each. With further miniaturization and somewhat more complex function, the cost of this item was increased by approximately 70 percent.

   The same or very similar concept is being used for all systems at this time and the same MTBF and cost have been used for all.

7. The soldier interface module allows the soldier to turn the system on and off, adjust the cooling temperature, and monitor the system. The technology currently considered uses standard, inexpensive components that are readily available. The cost estimate is based on a composite cost of switches, adjustment controls, temperature probe, and voltage readout.

8. The power distribution design is very simple at this time. It is assumed that significant power conditioning requirements will be addressed to a maximum extent in the other Soldier Systems. The basic concept incorporates interconnecting cables, connectors, and something similar to a voltage regulator. (More correctly, a DC/DC filter or converter and ripple device will be required). The cost estimate is based on a composite of currently available like components.

REPLENISHMENT COSTS FOR STIRLING (BACK-TO-BACK)

	AOR (hrs)	Quantity
Peacetime Requirement	150	20,000
Wartime Requirement	1,800	60,000

BATTERY CONSUMPTION

Type	Use Life	Price	Peacetime Cost ($K)	Wartime Cost ($K)	Uncooled Wartime
NiCad	1,000	120.00	360.00	12,960.00	12,960.00

FUEL CONSUMPTION

Type	Fuel Rate	Price	Peacetime Cost ($K)	Wartime Cost ($K)	Uncooled Wartime
Diesel	0.028	1.00	84.00	3,024.00	1.512.00

Components	MTBF	Price	Peacetime Cost ($K)	Wartime Cost ($K)	Uncooled Wartime
Engine	286	5000.00	52,447.55	1,888,111.89	1,888,111.89
ECU	319	2500.00	23,510.97	846,394.98	0.00
Controller	5370	1000.00	558.66	20,111.73	20,111.73
Soldier Interface	2566	150.00	175.37	6,313.33	6,313.33
Power Distrib	1145	500.00	1,310.04	47,161.57	47,161.57
SPARES TOTAL			78,002.60	2,808,093.50	1,961,698.52
TOTALS			78,446.60	2,824,077.50	1,976,170.52

VAPOR CYCLE ENGINE DRIVEN COMPRESSOR

Assumptions:

1. The preliminary maintenance concept is for a modular design with line replacement of major components and no component repair. The five basic modules are: (a) engine, which includes fuel system; (b) environmental control unit (ECU); (c) a controller, which governs engine and ECU operation; (d) a soldier interface, which allows the soldier to operate and monitor the system; and (e) a power generation/distribution subsystem, for generating and supplying power to other Soldier Systems. All fluid and electrical lines are quick disconnect.

   Each module can be replaced at unit level. For this first analysis, all modules are considered non-repairable. Currently it is recognized that all modules may be designed to be repairable but current information is unavailable to determine to what subcomponent or part level that may be.

2. A NiCad battery is used to start the system. This battery would be rechargeable. The useful life is assumed to be equal to its failure rate, including recharging. Only one battery is required for the system. The battery cost estimate was provided by the engineer and no additional data was yet available from other sources. The same battery and assumptions have been made for all other systems requiring a similar secondary battery.

3. The burner used in the vapor cycle engine is currently designed to run on a diesel/JP-8. Currently, information on the design does not provide information on the fuel consumption rate. Therefore, the consumption rate is based on an engineering estimate of a power provided by the engine and an efficiency factor for the engine.

   The amount of fuel available is based on meeting a 10-hour sustained mission. After 10 hours, refueling would be required. Additional costs for resupply manpower, transportation, and handling costs are not included at this time. The fuel cost value has not been adjusted to include any of these costs.

   The fuel consumption rate is based on an estimate of 0.22 pounds of fuel per hour. This was converted to gallons per hour using a rounded estimate of 6.8 pounds of diesel per gallon.

4. The external engine design is for a vapor cycle system, with a burner-boiler arrangement for heating vapor. This vapor is run through a throttle mechanism and the vapor engine. This engine requires a fuel system, fluid system (for creating vapor), the vapor engine, and appropriate controls. This design is somewhat similar to the concept of a steam power plant on a much smaller scale.

   An estimate by the project engineers of $5,000 was given. After checking on the components identified in the engine, this appears to be a reasonable figure. However, nothing has been addressed on the complexity of manufacturing the system, so some variation may exist.

5. The ECU is a shaft-driven compressed gas refrigerant system. The cool air is vented to the soldier through air lines into a cooling vest.

   The ECU price is based on the $2,500 project cost of the smallest MIL-STD air conditioner (AC). Design engineering to reduce the size of the system would raise the cost. However, for this application, some components associated with the compressor are part of the engine.

Therefore, it is estimated that the engineering costs would be offset by the removal of some components and $2,500 has been used for the cost calculation.

6. Only a basic concept of how the controller would be designed exists. It will likely be a black box module with microprocessing chips. It would be non-repairable and non-reprogrammable.

   The cost estimate is based on a large version used in the newly designed motor controller module for the 18K BTU AC. This item is currently being negotiated for procurement at a cost estimate of $590 each. With future miniaturization and somewhat more complex function, the cost for this item was increased by approximately 70 percent.

   The same or a very similar concept is being used for all systems at this time and the same MTBF and cost have been used for all.

7. The soldier interface module allows the soldier to turn the system on and off, adjust the cooling temperature, and monitor the system. The technology currently considered is to use standard, inexpensive components that are readily available. The cost estimate is based on a composite cost of switches, adjustment controls, temperature probe, and voltage readout.

8. The power distribution design is very simple at this time. It is assumed that significant power conditioning requirements will be addressed to a maximum extent in the other Soldier Systems. The basic concept incorporates power generation, interconnecting cables, and connectors. The power generation source is a permanent magnetic generator. The cost estimate is based on a composite of currently available like components.

REPLENISHMENT COSTS FOR VAPOR CYCLE ENGINE-DRIVEN COMPRESSOR

	AOR (hrs)	Quantity
Peacetime Requirement	150	20,000
Wartime Requirement	1,800	60,000

BATTERY CONSUMPTION

Type	Use Life	Price	Peacetime Cost ($K)	Wartime Cost ($K)	Uncooled Wartime
NiCad	1,000	120.00	360.00	12,960.00	12,960.00

FUEL CONSUMPTION

Type	Fuel Rate	Price	Peacetime Cost ($K)	Wartime Cost ($K)	Uncooled Wartime
Diesel	0.033	1.00	99.00	3,564.00	1,782.00

Components	MTBF	Price	Peacetime Cost ($K)	Wartime Cost ($K)	Uncooled Wartime
Engine	197	5,000.00	76,142.13	2,741,116.75	2,741,116.75
ECU	178	2,500.00	42,134.83	1,516,853.93	0.00
Controller	5,370	1,000.00	558.66	20,111.73	20,111.73
Soldier Interface	2,566	150.00	175.37	6,313.33	6,313.33
Power Distrib	786	500.00	1,908.40	68,702.29	68,702.29
SPARES TOTAL			120,919.39	4,353,098.03	2,836,244.10
TOTALS			121,378.39	4,369,622.03	2,850,986.10

AMBIENT AIR FUEL CELL WITH VAPOR CYCLE COOLING SYSTEM

Assumptions:

1. The preliminary maintenance concept is for a modular design with line replacement of major components but with no component repair. The basic modules and components are: (a) disposable hydrogen cylinder and gas regulators, which provide the fuel for the fuel cell; (b) the fuel cell, which produces the electrical power; (c) the environmental control unit (ECU); (d) a controller, which governs the fuel cell and the ECU operation; (e) a soldier interface, which allows the soldier to operate and monitor the system; and (f) a power distribution subsystem, for supplying power to other Soldier Systems. All gas and electrical lines are quick disconnect.

   Each module can be replaced at unit level. For this first analysis, all modules are considered non-repairable. Currently, it is recognized that all modules may be designed to be repairable but current information is unavailable to determine to what subcomponent or part level that may be. The gas cylinder and regulators are considered replaceable components separate from the fuel cell.

2. No battery is currently identified for the system, but one may be later added to assist in starting the system. This battery would most likely be a rechargeable NiCad battery. Until positively identified as required, it has not been included in this estimate.

3. The fuel cell uses hydrogen (in the form of hydride) and air in the generation of power. The hydrogen is contained in a disposal vessel under some pressure. The fuel costs in this analysis represent the consumption of the hydride and container in this process.

   It is currently assumed that to meet weight requirements only one mission's worth of hydride would be carried at a time. The fuel consumption rate is based on the consumption of one-tenth of the mission fuel consumed per hour for a 10-hour mission.

   The cost of the fuel is estimated, based on the engineers' information, at $100 per mission requirement. This value covers both the hydride and container costs.

   This calculation does not include the time, labor, storage equipment, raw material, or transportation costs involved.

4. A standard gas regulator is required to regulate the flow of hydrogen to the fuel cell. The average cost of this type of regulator is $100. A small electric fan is also needed to provide air to the fuel cell. Fans of this size are available for about $45.

5. The fuel cell concept is currently used on a larger scale in commercial power generation and on a smaller scale in the commercial video camera market. Current studies estimate the cost of a cell of the size required would cost approximately $2,000. Other data has not been found to confirm or reject this estimate at this time.

6. The ECU is an electrically-driven compressed gas refrigerant system. The cool air is vented to the soldier through air lines into a cooling vest. (The vest is not included in this analysis.)

   The ECU price is based on the $2,500 project cost of the smallest MIL-STD air conditioner (AC), with a 20 percent increase to cover the compressor design. Currently, the ECU is assumed to be the same technology as the freon-based ACs but will be significantly reduced in physical size. This reduction in size accounts for the increased costs as manufacturing will be more expensive and there is currently no commercial market for a system of the projected size.

It is difficult to interpret individual component part data relative to the reduction in size so the system has been addressed as a whole. It is not currently anticipated that the ECU will be repairable but with the compressor having the highest failure rate it could become a repair part.

There are serious risks associated with this cost estimate. One project engineer stated that past estimates for small vapor cycle systems have run between $15,000 and $17,000. Taking these as prototype model estimates, manufacturing costs could still be in the neighborhood of $10,000. As the basic ECU concept is the same for all systems except those using thermoelectric cooling, and with only minor differences between electrically and mechanically driven compressors, the overall cost relationship between systems would probably not change.

7. Only a basic concept of how the controller would be designed exists. It will likely be a black box module with microprocessing chips. It would be non-repairable and non-reprogrammable. The exact requirements for the control of the fuel cell are currently undefined. The technology for the fuel cell could greatly reduce the requirements for the controller. A primary function of the controller may be the regulation of the gases to the fuel cell.

   The cost estimate is based on a large version used in the newly designed motor controller module for the 18K BTU AC. This item is currently being negotiated for procurement at a cost estimate of $590 each. With future miniaturization and somewhat more complex function, the cost for this item was increased by approximately 70 percent.

   The same or very similar concept is being used for all systems at this time and the same MTBF and cost have been used for all.

8. The soldier interface module allows the soldier to turn the system on and off, adjust the cooling temperature, and monitor the system. The technology currently considered will use standard, inexpensive components that are readily available. The cost estimate is based on a composite cost of switches, adjustment controls, temperature probe, and voltage readout.

9. The power distribution design is very simple at this time. It is assumed that significant power conditioning requirements will be addressed to a maximum extent in the other Soldier Systems. The basic concept incorporates a voltage regulator (or similar item), interconnecting cables, and connectors. The cost estimate is based on a composite of currently available like components.

REPLENISHMENT COSTS FOR AIR FUEL CELL WITH VAPOR CYCLE COOLING SYSTEM

	AOR (hrs)	Quantity
Peacetime Requirement	150	20,000
Wartime Requirement	1,800	60,000

BATTERY CONSUMPTION

Type	Use Life	Price	Peacetime Cost ($K)	Wartime Cost ($K)	Uncooled Wartime
N/A	1	0.00	0.00	0.00	0.00

FUEL CONSUMPTION

Type	Fuel Rate	Price	Peacetime Cost ($K)	Wartime Cost ($K)	Uncooled Wartime
Hydride	0.1	100.00	30,000.00	1,080,000.00	540,000.00

(fuel rate 10% of fuel per hour, $100/mission, 10 hour mission)

Components	MTBF	Price	Peacetime Cost ($K)	Wartime Cost ($K)	Uncooled Wartime
Gas Regulator	457	100.00	656.46	23,632.39	23,632.39
Air Fan	1,116	45.00	120.97	4,354.84	4,354.84
Fuel Cell	27,778	2,000.00	216.00	7,775.94	7,775.94
ECU	300	3,000.00	30,000.00	1,080,000.00	0.00
Controller	5,370	1,000.00	558.66	20,111.73	20,111.73
Soldier Interface	2,566	150.00	175.37	6,313.33	6,313.33
Power Distrib	1,145	125.00	327.51	11,790.39	11,790.39
SPARES TOTAL			32,054.96	1,153,978.61	73,978.61
TOTALS			62,054.96	2,233,978.61	613,978.61

HYDROGEN PEROXIDE FUEL CELL WITH VAPOR CYCLE COOLING SYSTEM

Assumptions:

1. The preliminary maintenance concept is for a modular design with line replacement of major components but with no component repair. The basic modules and components are: (a) pressurized hydrogen gas cylinders and gas regulator and a hydrogen peroxide tank and pump, which provide the fuel for the fuel cell; (b) the fuel cell, which produces the electrical power; (c) the environmental control unit (ECU); (d) a controller, which governs the fuel cell and possibly the ECU operation; (e) a soldier interface, which allows the soldier to operate and monitor the system; and (f) a power distribution subsystem, for supplying power to other Soldier Systems. All gas and electrical lines are quick disconnect.

   Each module can be replaced at unit level. For this first analysis, all modules are considered non-repairable. Currently, it is recognized that all modules may be designed to be repairable but current information is unavailable to determine to what subcomponent or part level that may be. The gas cylinder and regulators are considered replaceable components separate from the fuel cell.

2. No battery is currently identified for the system but one may be added later to assist in starting the system. This battery would most likely be a rechargeable NiCad battery. Until positively identified as required, it has not been included in this estimate.

3. The fuel cell consumes hydrogen gas and hydrogen peroxide liquid in the generation of power. The gas is contained under high pressure to reduce weight. The fuel costs in this analysis represent the consumption of the elements in this process.

   It is currently assumed that to meet weight requirements only one mission's worth of gas would be carried at a time. The fuel consumption rate is based on the consumption of one-tenth of the mission fuel consumed per hour for a 10-hour mission.

   The cost of the hydrogen is estimated, based on the engineers' information, at $4 per gas per mission requirement (same consumption quantity as the hydrogen and oxygen gas system). No data was provided for the hydrogen peroxide. It was assumed to be about 50 percent more expensive than the hydrogen alone. Therefore, the calculation for this cost is estimated to be to $10/mission (hydrogen and hydrogen peroxide).

   This calculation does not include the time, labor, gas generation and storage equipment, raw material, or transportation costs involved in recharging the gas cylinders after each mission.

4. The hydrogen gas is stored at very high pressure (6,000 psi) to reduce volume and weight requirements. To contain gas at this pressure a very strong cylinder is required, but a weight penalty would exist with standard cylinders. Therefore, the current concept calls for the use of a Kevlar wrapped cylinder with a high strength/low weight advantage. These cylinders are currently produced in small quantities for satellite programs. The manufacturing costs will be high as the processes required are labor and material intensive. It is currently estimated that a single cylinder would cost approximately $2,000, taking into account a large production base and manufacturing learning curve. This estimate was provided by a manufacture in this field.

A standard gas regulator, non-adjustable, is required to reduce the gas pressure from the storage pressure of 6,000 psi to the fuel cell pressure of 30 psi. The average cost of this type of regulator is $100.

5. The hydrogen peroxide is stored at low pressure in a liquid state. A standard storage tank is assumed to be comparable to the type of container that will be used. A fluid pump (electrically driven) will be used to pump this liquid into the fuel cell.

6. The fuel cell concept is currently used on a larger scale in commercial power generation and on a smaller scale in the commercial video camera market. Current studies estimate the cost of a cell of the size required would cost approximately $2,000. Other data has not been found to confirm or reject this estimate at this time.

7. The ECU is an electrically-driven compressed gas refrigerant system. The cool air is vented to the soldier through air lines into a cooling vest.

   The ECU price is based on the $2,500 project cost of the smallest MIL-STD air conditioner (AC), with a 20 percent increase to cover the compressor design. Currently, the ECU is assumed to be the same technology as the freon-based ACs but will be significantly reduced in physical size. This reduction in size accounts for the increased cost as manufacturing will be more expensive and there is currently no commercial market for a system of the projected size.

   It is difficult to interpret individual component part data relative to the reduction in size so the system has been addressed as a whole. It is not currently anticipated that the ECU will be repairable but with the compressor having the highest failure rate it could become a repair part.

   There are serious risks associated with this cost estimate. One project engineer stated that past estimates for small vapor cycle systems have run between $15,000 and $17,000. Taking these as prototype model estimates, manufacturing costs could still be in the neighborhood of $10,000. As the basic ECU concept is the same for all systems except those using thermoelectric cooling, and with only minor differences between electrically and mechanically driven compressors, the overall cost relationship between systems would probably not change.

8. Only a basic concept of how the controller would be designed exists. It will likely be a black box module with microprocessing chips. It would be non-repairable and non-reprogrammable. The exact requirements for the control of the fuel cell are currently undefined. The technology for the fuel cell could greatly reduce the requirements for the controller. A primary function of the controller may be the regulation of the gases to the fuel cell.

   The cost estimate is based on a large version used in the newly designed motor controller module for the 18K BTU AC. This item is currently being negotiated for procurement at a cost estimate of $590 each. With future miniaturization and somewhat more complex function, the cost for this item was increased by approximately 70 percent.

   The same or a very similar concept is being used for all systems at this time and the same MTBF and cost have been used for all.

9. The soldier interface module allows the soldier to turn the system on and off, adjust the cooling temperature, and monitor the system. The technology currently considered will use standard, inexpensive components that are readily available. The cost estimate is based on a composite cost of switches, adjustment controls, temperature probe, and voltage readout.

10. The power distribution design is very simple at this time. It is assumed that significant power conditioning requirements will be addressed to a maximum extent in the other Soldier Systems. The basic concept incorporates a voltage regulator (or similar), interconnecting cables and connectors. The cost estimate is based on a composite of currently available like components.

REPLENISHMENT COSTS FOR H_2C_2 FUEL CELL WITH VAPOR CYCLE COOLING

	AOR (hrs)	Quantity
Peacetime Requirement	150	20,000
Wartime Requirement	1,800	60,000

BATTERY CONSUMPTICN

Type	Use Life	Price	Peacetime Cost ($K)	Wartime Cost ($K)	Uncooled Wartime
N/A	1	0.00	0.00	0.00	0.00

FUEL CONSUMPTION

Type	Fuel Rate	Price	Peacetime Cost ($K)	Wartime Cost ($K)	Uncooled Wartime
Hydride Paroxide	0.1	10.00	30,000.00	1,080,000.00	54,000.00

(fuel rate 10% of fuel per hour, $100/mission, 10 hour mission)

Components	MTBF	Price	Peacetime Cost ($K)	Wartime Cost ($K)	Uncooled Wartime
Gas Cylinder	6,204	2,000.00	967.12	34,816.25	34,816.25
Gas Regulator	457	100.00	656.46	23,632.39	23,632.39
Air Fan	1,116	45.00	120.97	4,354.84	4,354.84
H_2O_2 Fuel Tank	1,890	200.00	317.46	11,428.57	11,428.57
H_2O_2 Fuel Pump	9,250	100.00	32.43	1,167.57	1,167.57
Fuel Cell	27,778	2,000.00	216.00	7,775.94	7,775.94
ECU	300	3,000.00	30,000.00	1,080,000.00	0.00
Controller	5,370	1,000.00	558.66	20,111.73	20,111.73
Soldier Interface	2,566	150.00	175.37	6,313.33	6,313.33
Power Distrib	1,145	125.00	327.51	11,790.39	11,790.39
SPARES TOTAL			33,371.97	1,201,391.00	121,391.00
TOTALS			36,371.97	1,309,391.00	175,391.00

PROTON EXCHANGE MEMBRANE (PEM) FUEL CELL WITH VAPOR CYCLE COOLING SYSTEM

Assumptions:

1. The preliminary maintenance concept is for a modular design with line replacement of major components but with no component repair. The basic modules and components are: (a) pressurized oxygen and hydrogen gas cylinders and gas regulators, which provide the fuel for the fuel cell; (b) the fuel cell, which produces the electrical power; (c) the environmental control unit (ECU); (d) a controller, which governs the fuel cell and possibly the ECU operation; (e) a soldier interface, which allows the soldier to operate and monitor the system; and (f) a power distribution subsystem, for supplying power to other Soldier Systems. All gas and electrical lines are quick disconnect.

   Each module can be replaced at unit level. For this first analysis, all modules are considered non-repairable. Currently, it is recognized that all modules may be designed to be repairable but current information is unavailable to determine to what subcomponent or part level that may be. The gas cylinder and regulators are considered replaceable components separate from the fuel cell.

2. No battery is currently identified for the system but one may be later added to assist in starting the system. This battery would most likely be a rechargeable NiCad battery. Until positively identified as required, it has not been included in this estimate.

3. The fuel cell consumes hydrogen and oxygen in the generation of power. These gases are contained under high pressure to reduce weight. The fuel costs in this analysis represent the consumption of these gases in this process.

   It is currently assumed that to meet weight requirements only one mission's worth of gas would be carried at a time. The fuel consumption rate is based on the consumption of one-tenth of the mission fuel consumed per hour for a 10-hour mission.

   The cost of the fuel is estimated, based on the engineers' information, at $4 per gas per mission requirement. Therefore, the calculation for this cost is simplified to $8/mission (hydrogen and oxygen).

   This calculation does not include the time, labor, gas generation and storage equipment, raw material, or transportation costs involved in recharging the gas cylinders after each mission.

4. The hydrogen and oxygen gases are stored at very high pressure (6,000 psi) to reduce volume and weight requirements. To contain gas at this pressure a very strong cylinder is required, but a weight penalty would exist with standard cylinders. Therefore, the current concept calls for the use of a Kevlar wrapped cylinder with a high strength/low weight advantage. These cylinders are currently produced in small quantities for satellite programs. The manufacturing costs will be high as the processes required are labor and material intensive. It is currently estimated that a single cylinder would cost approximately $2,000, taking into account a large production base and manufacturing learning curve. This estimate was provided by a manufacturer in this field.

   A standard gas regulator, non-adjustable, is required to reduce the gas pressure from the storage pressure of 6,000 psi to the fuel cell pressure of 30 psi. The average cost of this type of regulator is $100.

5. The fuel cell concept is currently used on a larger scale in commercial power generation and on a smaller scale in the commercial video camera market. Current studies estimate the cost of a cell of the size required would cost approximately $2,000. Other data has not been found to confirm or reject this estimate at this time.

6. The ECU is an electrically-driven compressed gas refrigerant system. The cool air is vented to the soldier through air lines into a cooling vest.

   The ECU price is based on the $2,500 project cost of the smallest MIL-STD air conditioner (AC), with a 20 percent increase to cover the compressor design. Currently, the ECU is assumed to be the same technology as the freon-based ACs but will be significantly reduced in physical size. This reduction in size accounts for the increased cost as manufacturing will be more expensive and there is currently no commercial market for a system of the projected size.

   It is difficult to interpret individual component part data relative to the reduction in size so the system has been addressed as a whole. It is not currently anticipated that the ECU will be repairable, but with the compressor having the highest failure rate it could become a repair part.

   There are risks associated with this cost estimate. One project engineer stated that past estimates for small vapor cycle cooling systems have run between $15,000 and $17,000. Taking these as prototype model estimates, manufacturing costs could still be in the neighborhood of $10,000. As the basic ECU concept is the same for all systems except for those using thermoelectric cooling, and with only minor differences between electrically and mechanically driven compressors, the overall cost relationship between systems would probably not change.

7. Only a basic concept of how the controller would be designed exists. It will likely be a black box module with microprocessing chips. It would be non-repairable and non-reprogrammable. The exact requirements for the control of the fuel cell are currently undefined. The technology for the fuel cell could greatly reduce the requirements for the controller. A primary function, of the controller may be the regulation of the gases to the fuel cell.

   The cost estimate is based on a large version used in the newly designed motor controller module for the 18K BTU AC. This item is currently being negotiated for procurement at a cost estimate of $590 each. With future miniaturization and somewhat more complex function, the cost for this item was increased by approximately 70 percent.

   The same or very similar concept is being used for all systems at this time and the same MTBF and cost have been used for all.

9. The soldier interface module allows the soldier to turn the system on and off, adjust the cooling temperature, and monitor the system. The technology currently being considered will use standard, inexpensive components that are readily available. The cost estimate is based on a composite cost of switches, adjustment controls, temperature probe, and voltage readout.

10. The power distribution design is very simple at this time. It is assumed that significant power conditioning requirements will be addressed to a maximum extent in the other Soldier Systems. The basic concept incorporates a voltage regulator (or similar item), interconnecting cables and connectors. The cost estimate is based on a composite of currently available like components.

REPLENISHMENT COSTS FOR PROTON EXCHANGE MEMBRANE (PEM) FUEL CELL WITH VAPOR CYCLE COOLING SYSTEM

	AOR (hrs)	Quantity
Peacetime Requirement	150	20,000
Wartime Requirement	1,800	60,000

BATTERY CONSUMPTION

Type	Use Life	Price	Peacetime Cost ($K)	Wartime Cost ($K)	Uncooled Wartime
N/A	1	0.00	0.00	0.00	0.00

FUEL CONSUMPTION

Type	Fuel Rate	Price	Peacetime Cost ($K)	Wartime Cost ($K)	Uncooled Wartime
Hydrogen & Oxygen	0.1	8.00	2,400.00	86,400.00	43,200.00

(fuel rate 10% of fuel per hour, $4/mission, each H_2 & O_2, 10 hour mission)

Components	Quantity	MTBF	Price	Peacetime Cost ($K)	Wartime Cost ($K)	Uncooled Wartime
Gas Cylinder	2	6,204	2,000.00	1,934.24	69,632.50	69,632.50
Gas Regulator	2	457	100.00	1,312.91	47,264.77	47,264.77
Air Fan		1,116	45.00	120.97	4,354.84	4,354.84
Fuel Cell		27,778	2,000.00	216.00	7,775.94	7,775.94
ECU		300	3,000.00	30,000.00	1,080,000.00	0.00
Controller		5,370	1,000.00	558.66	20,111.73	20,111.73
Soldier Interface		2,566	150.00	175.37	6,313.33	6,313.33
Power Distrib		1,145	125.00	327.51	11,790.39	11,790.39
SPARES TOTAL				34,645.65	1,247,243.49	167,243.49
TOTAL				37,045.65	1,333,643.49	210,443.49

PROTON EXCHANGE MEMBRANE (PEM) FUEL CELL WITH THERMOELECTRIC COOLING

Assumptions:

1. The preliminary maintenance concept is for a modular design with line replacement of major components but with no component repair. The basic modules and components are: (a) pressurized oxygen and hydrogen gas cylinders and gas regulators, which provide the fuel for the fuel cell; (b) the fuel cell, which produces the electrical power; (c) the environmental control unit (ECU); (d) a controller, which governs the fuel cell and possibly the ECU operation; (e) a soldier interface, which allows the soldier to operate and monitor the system; and (f) a power distribution subsystem for supplying power to other Soldier Systems. All gas and electrical lines are quick disconnect.

   Each module can be replaced at unit level. For this first analysis, all modules are considered non-repairable. Currently, it is recognized that all modules may be designed to be repairable but current information is unavailable to determine to what subcomponent or part level that may be. The gas cylinder and regulators are considered replaceable components separate from the fuel cell.

2. No battery is currently identified for the system but one may be later added to assist in starting the system. This battery would most likely be a rechargeable NiCad battery. Until positively identified as required, it has not been included in this estimate.

3. The fuel cell consumes hydrogen and oxygen in the generation of power. These gases are contained under high pressure to reduce weight. The fuel costs in this analysis represent the consumption of these gases in this process.

   It is currently assumed that to meet weight requirements only one mission's worth of gas would be carried at a time. The fuel consumption rate is based on the consumption of one-tenth of the mission fuel consumed per hour for a 10-hour mission.

   The cost of the fuel is estimated, based on the engineers' information, at $8 per gas per mission requirement. Therefore, the calculation for this cost is simplified to $16/mission (hydrogen and oxygen). (Operation with thermocouple cooling is anticipated to be less efficient than with electric cooling. This loss of efficiency has been accounted for by doubling the amount of fuel required to complete the mission. The increase in fuel is included in the calculation by increasing the cost of the gas per mission).

   This calculation does not include the time, labor, gas generation and storage equipment, raw material, or transportation costs involved in recharging the gas cylinders after each mission.

4. The hydrogen and oxygen gases are stored at very high pressure (6,000 psi) to reduce volume and weight requirements. To contain gas at this pressure a very strong cylinder is required, but a weight penalty would exist with standard cylinders. Therefore, the current concept calls for the use of a Kevlar wrapped cylinder with a high strength/low weight advantage. These cylinders are currently produced in small quantities for satellite programs. The manufacturing costs will be high as the processes required are labor and material intensive. It is currently estimated that a single cylinder would cost approximately $2,000, taking into account a large production base and manufacturing learning curve. This estimate was provided by a manufacturer in this field.

A standard gas regulator, non-adjustable, is required to reduce the gas pressure from the storage pressure of 6,000 psi to the fuel cell pressure of 30 psi. The average cost of this type of regulator is $100.

5. The fuel cell concept is currently used on a larger scale in commercial power generation and on a smaller scale in the commercial video camera market. Current studies estimate the cost of a cell of the size required would cost approximately $2,000. Other data has not been found to confirm or reject this estimate at this time.

6. The ECU for these systems would be a thermoelectric cooling device. This device would be manufactured from a number of thermocouples, fans, relay(s), and solid state control chips. Utilizing the concept of the thermocouple, the electric potential would be converted to a temperature differential and the fan would blow the cooled air to the soldier.

   This technology is used on a small scale to cool electronics equipment. It is anticipated that while the material costs for such a system would be small, the manufacturing costs would be very high. Special processes would be required to consolidate all the thermocouples. The current engineering estimate is that such a device would cost approximately $10,000, primarily from manufacturing costs.

7. Only a basic concept of how the controller would be designed exists. It will likely be a black box module with microprocessing chips. It would be non-repairable and non-reprogrammable. The exact requirements for the control of the fuel cell and thermoelectric cooling device are currently undefined. The technology of these two components could greatly reduce the requirements for the controller. A primary function of the controller may be the regulation of the gases to the fuel cell.

   The cost estimate is based on a large version used in the newly designed motor controller module for the 18K BTU AC. This item is currently being negotiated for procurement at a cost estimate of $590 each. With future miniaturization and somewhat more complex function ,the cost for this item was increased by approximately 70 percent.

   The same or very similar concept is being used for all systems at this time and the same MTBF and cost have been used for all.

9. The soldier interface module allows the soldier to turn the system on and off, adjust the cooling temperature, and monitor the system. The technology currently considered will use standard, inexpensive components that are readily available. The cost estimate is based on a composite cost of switches, adjustment controls, temperature probe, and voltage readout.

10. The power distribution design is very simple at this time. It is assumed that significant power conditioning requirements will be addressed to a maximum extent in the other Soldier Systems. The basic concept incorporates a voltage regulator (or similar item), interconnecting cables, and connectors. The cost estimate is based on a composite of currently available like components.

REPLENISHMENT COSTS WITH PEM FUEL CELL WITH THERMOELECTRIC COOLING

	AOR (hrs)	Quantity
Peacetime Requirement	150	20,000
Wartime Requirement	1,800	60,000

BATTERY CONSUMPTION

Type	Use Life	Price	Peacetime Cost ($K)	Wartime Cost ($K)	Uncooled Wartime
N/A	1	0.00	0.00	0.00	0.00

FUEL CONSUMPTION

Type	Fuel Rate	Price	Peacetime Cost ($K)	Wartime Cost ($K)	Uncooled Wartime
Hydrogen & Oxygen	0.1	16.00	4,800.00	172,800.00	86,400.00

(fuel rate 10% of fuel per hour, $4/mission, each H_2 & O_2, 10 hour mission)

Components	Quantity	MTBF	Price	Peacetime Cost ($K)	Wartime Cost ($K)	Uncooled Wartime
Gas Cylinder	2	6,204	2,000.00	1,934.24	69,632.50	69,632.50
Gas Regulator	2	457	100.00	1,312.91	47,264.77	47,264.77
Air Fan		1,116	45.00	120.97	4,354.84	4,354.84
Fuel Cell		27,778	2,000.00	216.00	7,775.94	7,775.94
ECU		401	10,000.00	74,812.97	2,693,266.83	0.00
Controller		5,370	1,000.00	558.66	20,111.73	20,111.73
Soldier Interface		2,566	150.00	175.37	6,313.33	6,313.33
Power Distrib		1,145	125.00	327.51	11,790.39	11,790.39
SPARES TOTAL				79,458.62	2,860,510.33	167,243.49
TOTAL				84,258.62	3,033,310.33	253,643.49

RADIOACTIVE ISOTOPE WITH THERMOELECTRIC COOLING SYSTEM

Assumptions:

1. The preliminary maintenance concept is for a modular design with line replacement of major components and no component repair. Five basic modules are: (a) a Radioactive Isotope module; (b) environmental control unit (ECU); (c) a controller, which governs the ECU operation; (d) a soldier interface, which allows the the soldier to operate and monitor the system; and (e) a power distribution subsystem, for supplying power to other Soldier Systems. All electrical lines are quick disconnect.

   Each module can be replaced at unit level. For this first analysis, all modules are considered non-repairable. Currently, it is recognized that all modules may be designed to be repairable but current information is unavailable to determine to what subcomponent or part level that may be.

2. This concept calls for a radioactive isotope power source. Currently, larger scale versions are used in satellites and sonobouys. Most of the costs associated with this concept are indeterminate at this time. An isotope needs to be selected before many of the costs of refueling/replacing can be determined.

   It is unknown whether the whole isotope container will be disposed of or refueled. Currently, isotopes with half-lives of less than one year are being evaluated. There is the possibility that the isotope itself can be provided free of cost from another government agency. This cost, however, is only one of the many costs for this program.

3. The ECU for this system would be a thermoelectric cooling device. This device would be manufactured from a number of thermocouples, fans, relay(s), and solid state control chips. Utilizing the concept of the thermocouple, the electric potential would be converted to a temperature differential and the fan would blow the cooled air to the soldier.

   This technology is used on a small scale to cool electronics equipment. It is anticipated that while the material costs for such a system would be small, the manufacturing costs would be very high. Special processes would be required to consolidate all the thermocouples. The current engineering estimate is that such a device would cost approximately $10,000, primarily from manufacturing costs.

4. Only a basic concept of how the controller would be designed exists. It will likely be a black box module with microprocessing chips. It would be non-repairable and non-reprogrammable. The exact requirements for the control of the radioactive isotope cell and thermoelectric cooling device are currently undefined. The technology of these two components could greatly reduce the requirements for the controller.

   The cost estimate is based on a large version used in the newly designed motor controller module for the 18K BTU AC. This item is currently being negotiated for procurement at a cost estimate of $590 each. With future miniaturization and somewhat more complex function, the cost for this item was increased by approximately 70 percent.

   The same or very similar concept is being used for all systems at this time and the same MTBF and cost have been used for all.

5. The soldier interface module allows the soldier to turn the system on and off, adjust the cooling temperature, and monitor the system. The technology currently considered will use standard, inexpensive components that are readily available. The cost estimate is based on a composite cost of switches, adjustment controls, temperature probe, and voltage readout.

6. The power distribution design is very simple at this time. It is assumed that significant power conditioning requirements will be addressed to a maximum extent in the other Soldier Systems. The basic concept incorporates only interconnecting cables, connectors, and possibly some form of voltage regulator. The cost estimate is based on a composite of currently available like components.

7. Special Note: It is possible that the replenishment cost of actual parts could be fairly low for this concept. However, other associated operation and support costs could be very high. Special storage, handling, transportation, training, and security costs are likely to be high due to the hazardous nature of nuclear materials. Little information is available to estimate these costs as both the Navy sonobuoys and NASA satellites operate under much different support concepts. NASA launches radioactive sources into space and they are never maintained. The Navy disposes of the sources after use and utilizes higher grade personnel in the handling and maintenance of its sonobuoys.

REPLENISHMENT COSTS FOR RADIOACTIVE ISOTOPE + THERMOELECTRIC

	AOR (hrs)	Quantity
Peacetime Requirement	150	20,000
Wartime Requirement	1,800	60,000

BATTERY CONSUMPTION

Type	Use Life	Price	Peacetime Cost ($K)	Wartime Cost ($K)	Uncooled Wartime
N/A	1	0.00	0.00	0.00	10.00

FUEL CONSUMPTION

Type	Fuel Rate	Price	Peacetime Cost ($K)	Wartime Cost ($K)	Uncooled Wartime
Radioactive Isotope	1	0.00	0.00	0.00	0.00

(rate depends on half life of isotope, cost depends on availability)

Components	MTBF	Price	Peacetime Cost ($K)	Wartime Cost ($K)	Uncooled Wartime
Container	0	0.00	0.00	0.00	0.00
ECU	401	10,000.00	4,812.97	2,693,266.83	0.00
Controller	5,370	1,000.00	5598.66	20,111.73	20,111.73
Soldier Interface	2,566	150.00	175.37	6,313.33	6,313.33
Power Distrib	1,145	125.00	327.51	11,790.39	11,790.39
SPARES TOTAL			75,874.51	2,731,482.29	38,215.45
TOTALS			75,874.51	2,731,482.29	38,215.45

Appendix I
Rotary Engine for the Soldier System

(Author: Mr. Dorin Morar, BRDEC, SATBE-FGS)

INTRODUCTION

Most applications require a power unit with a rotary output, but the development of positive displacement internal combustion engines has been entirely based on early linear output engines. Rods and cranks must be added to convert the reciprocating motion of the piston into the rotary motion required to produce a rotary output. This is an indirect method of translating the energy of expanding gases into rotary motion.

Rotary piston configurations for pumps and compressors were a starting point for the development of a rotary piston internal combustion engine. Many inventors have designed various types of rotary engines. Most of these machines are of a rotary piston structure composed of rotary motion parts. The first successful type of rotary engine was invented by Dr. Felix Wankel in Germany in 1954.

The main goal was to eliminate most of the shortcomings of piston engines, which include:

1. reciprocating parts which cause vibration, noise, and power loss to become greater as the engine speed increases
2. a cranking mechanism which causes the engine to be heavy and large for the amount of power output
3. an intake and exhaust valve mechanism which generates mechanical noise and also contains many parts.

The rotary engine does not require an intake-exhaust mechanism and draws power directly from a rotating motion. However, most of the early concept rotary machines suffered from insufficient sealing and lack of durability. In a reciprocating engine, sealing is done with piston rings and is fairly simple to accomplish. The sealing of a Wankel engine is more difficult because the oddly shaped "piston" has to be sealed both radially and axially.

BASIC STRUCTURE

The basic structure of a Wankel type rotary engine is shown in Figure I-1. The inner surface of the rotor housing is cocoon shaped, and the rotor performs a rotating motion inside the housing. By placing side housings on both sides of the rotor housing, three working chambers are formed. The rotor housing and the side housings correspond to the cylinder and the cylinder block of the reciprocating engine, and the rotor corresponds to the piston.

Phasing gears control the rotating motion of the rotor. A rotor gear and a stationary gear are fitted to the rotor and side housing with a gear ratio of 3:2. As shown in Figure I-2, by having the rotor gear rotate while being meshed with the stationary gear, the apex of the rotor will rotate by drawing a peritrochoid, which is the basic curve of the rotor housing.

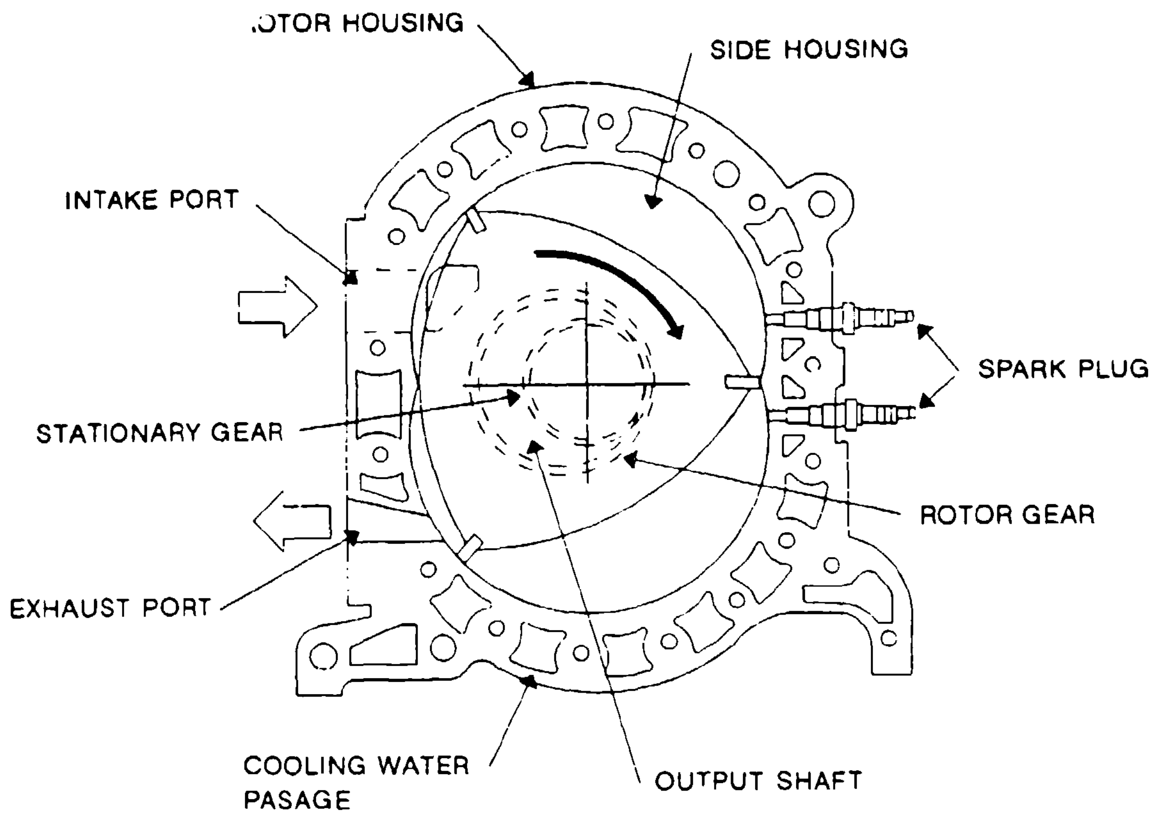


Figure I-1. Basic Construction of a Rotary Engine

PRINCIPLES OF OPERATION

Figure I-3 describes the operation of the Wankel type rotary engine. The intake port opens at 1, where the intake stroke begins. The volume of the working chamber gradually enlarges as the rotor turns, depicted by 2 and 3, and reaches maximum volume at 4. The intake port automatically closes at 5. The air-fuel mixture, or just air, is compressed by 6, 7, and 8, and goes into the expansion stroke after being ignited near the compression, at top dead center 9. After going through the expansion stroke 10, 11, and 12, the exhaust port opens at 13. The exhaust stroke goes through 14, 15, 16, and 17 and is completed at 18. From this point a new cycle begins with 1.

Like the four-stroke reciprocating engine, the rotary engine has an operating cycle in which each combustion chamber progresses through four distinct phases: intake, compression, expansion, and exhaust.

While one combustion chamber was completing its four cycles the other two chambers went through their four cycles as well, which means that the shaft speed is three times higher than the rotor speed or that for each shaft rotation the engine produces three power strokes.

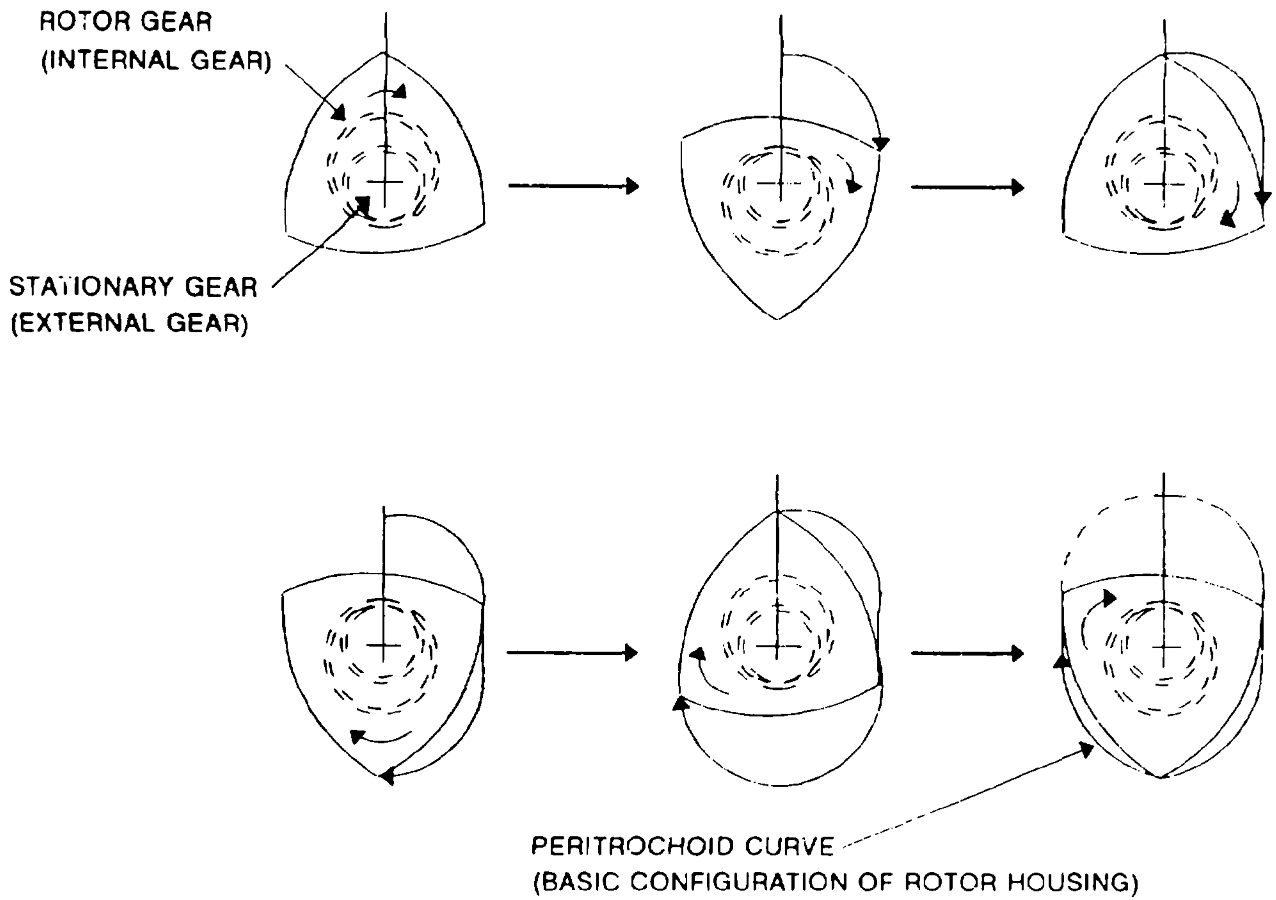


Figure I-2. Generation of Peritrochoid Curve

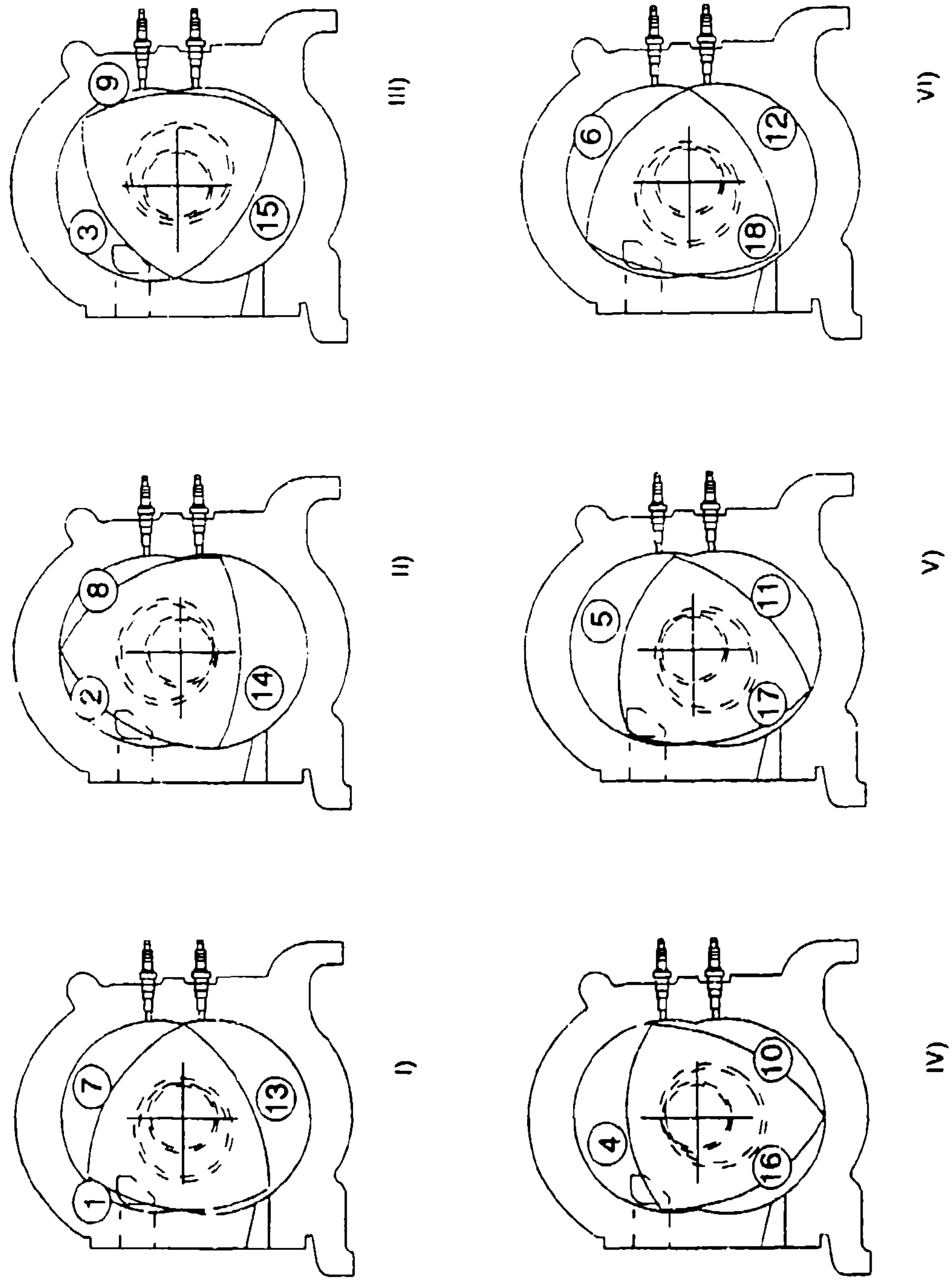


Figure I-3. Principle of Operation

CHARACTERISTICS OF THE ROTARY ENGINE

A comparison with the four stroke reciprocating engine is probably the best method of emphasizing the attributes of the Wankel type rotary engine, due to the similarity of the combustion cycles:

1. The rotary engine has no reciprocating parts. As a result, the problem of unbalance caused by the inertia of the reciprocating parts is eliminated. Vibration is exceptionally low, because it is possible to perfectly balance the engine by using balancing weights. The lack of a cranking mechanism leads to less mechanical loss, smoother motion, simpler construction, lower weight, and more compactness. Power-to-weight ratios approaching one horsepower per pound are common.

2. There is no intake-exhaust valve mechanism. This eliminates the mechanical noise generated by such a system, eradicates the air flow obstructions associated with the valve mechanism, and reduces the difficulties of high speed operation related to cams, valves, and springs. The elimination of the valve mechanism contributes to the weight savings of the Wankel type rotary.

3. The time for a complete stroke is 360 degrees in terms of the rotating angle of the output shaft, and there is one explosion for every rotation of the output shaft. The direct result of this characteristic is that the volumetric efficiency is scarcely influenced by the engine speed while reducing the torque drop. The torque variations are also diminished.

CONCLUSION

Although the rotary engine's typical fuel consumption is slightly higher than the 4-cycle engines, it is less than that of the 2-cycle engines. Their power density (power/weight and power/volume) is higher than both 2-cycle and 4-cycle engines. While the noise level is comparable to the 2-cycle engine, the exhaust emissions are less polluting. The vibration level is much lower than that of both the 2- and 4-cycle engines due to the absence of any reciprocating movement of parts. The rotaries can run on any fuel without major modifications using a variety of fuel systems. Some systems use a carburetor, direct or stratified charged high pressure mechanical fuel injection or electronically controlled high pressure fuel injection. Because of its combustion characteristics, the rotary (Wankel) engine is a good candidate for multifuel (including heavy distillate fuels) applications.

The positive attributes of high power/weight ratio, compactness, low mechanical noise and vibrations, flat torque characteristics, etc. qualify the rotary engine as an ideal candidate for the Soldier System. For example, the Rotary Power International model LCR800S engine produces 70 horsepower at 6,000 rpm and weighs 70 lbs. Several thousand small rotary engines were manufactured by Yanmar in Japan and by Fichtel & Sachs in Germany. Although the overall performance of the engines was outstanding when compared with the reciprocating engines, both companies abandoned the production because not enough customers were willing to pay a higher price associated with this superior quality product.

Mazda in Japan is still producing rotary engines for sports cars and Norton in England is still producing rotary engines for motorcycles and Unmanned Air Vehicles.

While both companies had gigantic successes in the racing (competition) arena (Mazda won the 1991, 24-hour endurance sport cars race at Le Mans, France), only Mazda is mass-producing the engine. Due to unique combustion characteristics, Mazda is now developing a hydrogen-burning rotary which will be introduced in Japan next year.

REFERENCES

1. Kenichi Yamamoto, 1981, Rotary Engine.

2. Peter G. F. Chinn, "Model Four-Stroke Engines," 1986, ISBN: 0-911295-04-6, Air Age Inc., Wilton, CT.

Appendix J
SLI Rechargeable Batteries for the Soldier System

(Author: Mr. Fee Leung, ARL, ETDL)

INTRODUCTION

The Soldier System can be powered by engines or fuel cells. These devices require a lightweight starting, lighting, and ignition (SLI) rechargeable battery capable of delivering 120 watts for 5 to 10 seconds. If the engine or fuel cell malfunctions, the SLI battery can also provide 100 watts of power for the electronics while the soldier moves to safety or attempts to restart the engine or fuel cell.

There is no established minimum time for the backup power. The SLI battery is envisioned being used in the following scenarios:

	Maximum Power	Nominal Power	Total Energy
Scenario 1	120 W for 5 sec	100 W for 30 min	50 WH
Scenario 2	120 W for 5 sec	100 W for 60 min	100 WH
Scenario 3	120 W for 5 sec	100 W for 90 min	150 WH
Scenario 4	120 W for 5 sec	100 W for 120 min	200 WH

A rechargeable SLI battery can be designed to provide the backup power for the Soldier System. Determining which electrochemical system to use is not a simple task. The designer must consider the power and energy needs of the mission, and the effect of size on the energy densities of the various candidate systems. The designer must also consider the charging schemes, the required preventive maintenance, and the cost of the various candidate systems.

The key to the survey of potential systems is the anticipated size of the SLI battery and its impact on the projected energy and power densities of each candidate system. Analysis of energy/power densities quoted by commercial brochures, and literature on zinc cathode and silver anode systems (i.e. silver cadmium, nickel zinc, silver iron, silver zinc, and silver metal hydride) are based on large plate cells with weights exceeding 10 pounds. These cell designs offer optimal energy and power densities and are often quoted by commercial vendors or proponents.

The energy/power densities of these zinc and silver systems actually decline substantially when scaled down to a smaller four pound battery system. Using actual military silver zinc, silver cadmium, and prototype nickel zinc batteries (see Table J-1), the energy content versus weight curves are derived in Figure J-1. Silver iron systems have the same energy densities and are similar to silver zinc systems, so they share the same proration curve.

Table J-1. Actual Energy Densities

Battery	Chemistry	Energy (WH)	Weight (lb)	WH/lb
BB-523/U	Silver Zinc	66	6	11
BB-524/U	Silver Zinc	120	8	15
BB-525/U	Silver Zinc	186	11	17
BB-526/U	Silver Zinc	300	16	19
BB-559/U	Silver Cadmium	54	7	7.7
BB-565/U	Silver Cadmium	108	9	11.1
BB-566/U	Silver Cadmium	180	16	11.3
BB-562/U	Silver Cadmium	210	19	11.1
BB-567/U	Silver Cadmium	264	21	12.6
BB-659/U	Nickel Zinc	168	15	11.2
BB-660/U	Nickel Zinc	312	21	14.8
BB-661/U	Nickel Zinc	480	31	15.5

NOTES:

1. Silver Iron energy density is same as Silver Zinc.
2. Silver Metal Hydride is similar to Silver Iron except 25 percent more energy.

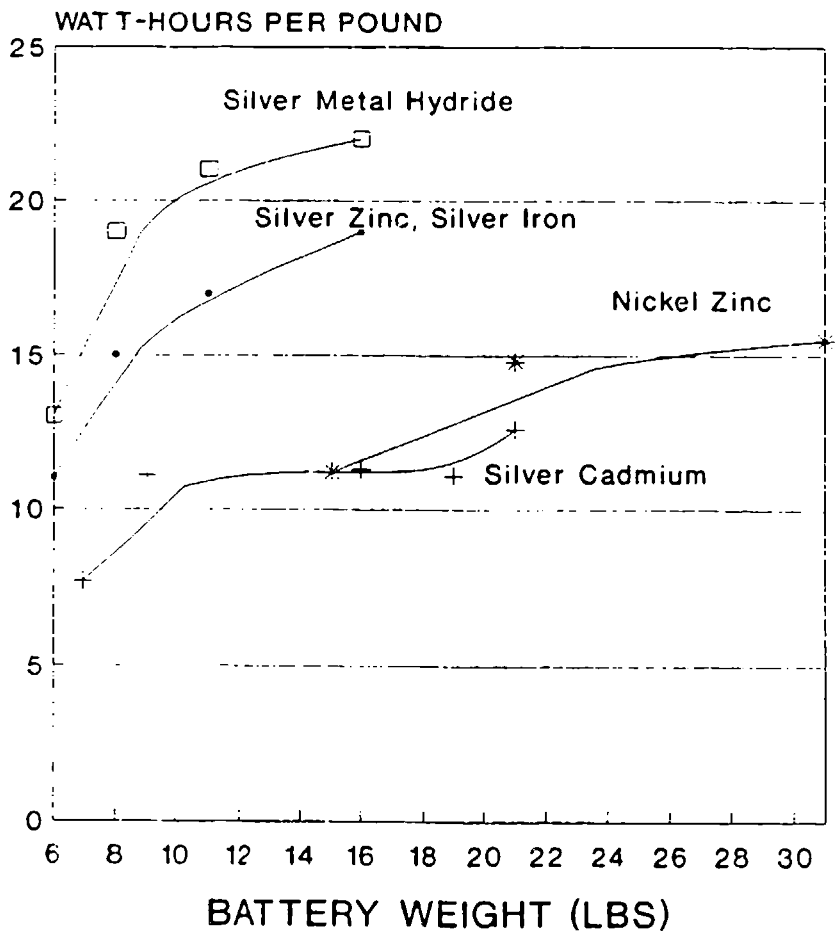


Figure J-1. Energy Densities Prorated by Weight

Silver metal hydride systems are similar to the silver iron system, but their energy density is 25 percent higher. The silver metal hydride energy density versus battery weight curve is based on the silver iron energy versus weight proration factors, but adjusted to reflect the differences in energy densities. The lithium rechargeable battery energy/power densities are based on actual two to four pound prototype batteries being tested and evaluated by the Army. The comparable energy and power densities of the various systems are illustrated in Figures J-2 and J-3.

By taking the energy/power densities of the candidate systems and applying them against the maximum power requirement of 120 watts and the backup power and duration of each scenario, battery weights are calculated and listed below:

	Scenarios			
	1	**2**	**3**	**4**
Silver Cadmium	8 lb	11.5 lb	14.7 lb	18.9 lb
Nickel Zinc	5.5 lb	9.1 lb	13.7 lb	15.4 lb
Silver Iron	4.6 lb	9.1 lb	13.7 lb	15.4 lb
Silver Zinc	4.6 lb	9.1 lb	13.7 lb	15.4 lb
Lead Acid	4.2 lb	8.3 lb	12.5 lb	16.6 lb
Nickel Cadmium	4.2 lb	8.3 lb	12.5 lb	16.6 lb
Silver Metal Hydride	4.3 lb	6.9 lb	10.3 lb	13.7 lb
Lithium Solid State	4.6 lb	4.6 lb	4.6 lb	4.6 lb
Lithium Nickel Oxide	4 lb	4 lb	4 lb	4 lb

Overall both rechargeable lithium systems (both solid and liquid) are the lightest power packs except in scenario 1. The lithium system's weights are generally fixed because they must meet the 120 W power requirements.

Since there is no established requirement for how long the battery must provide backup power, it is conjectured that the rechargeable lithium technology offers the most flexibility in meeting whatever scenario is developed for the Soldier System in the future with little or no weight increases. Therefore, the rest of the report concentrates on the rechargeable lithium technologies despite the fact that the silver metal hydride would make the second lightest battery for one scenario out of the four scenarios described.

In this report, two rechargeable lithium systems (Lithium Solid State and Lithium Nickel Oxide) are described. These systems are currently being tested and evaluated by the Army to establish baseline data for research and development.

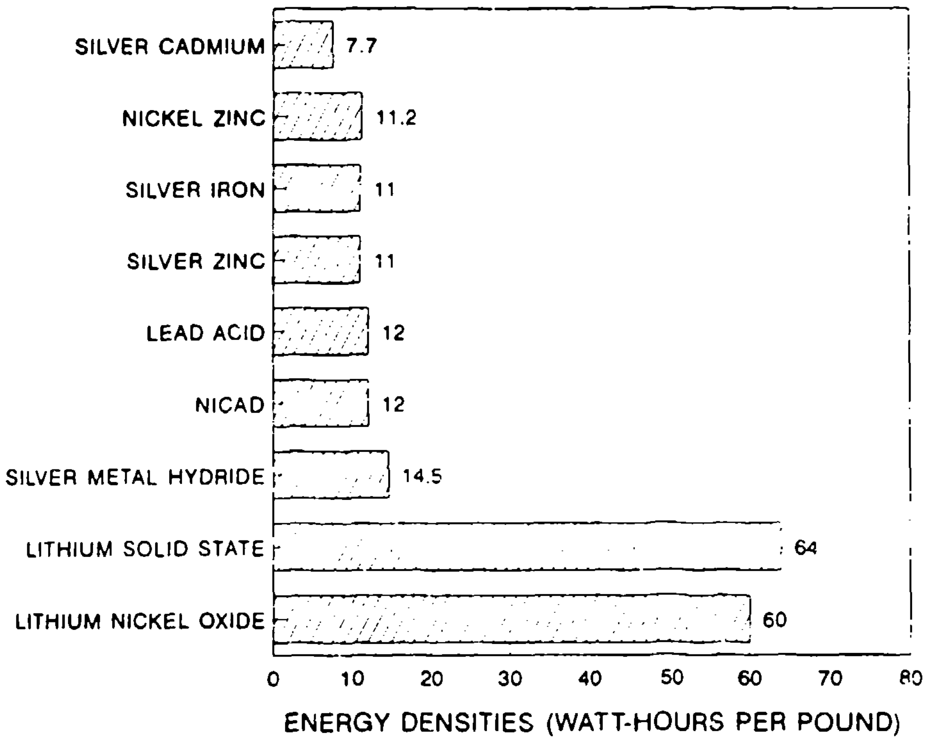


Figure J-2. Comparison of Energies Rechargeable Systems

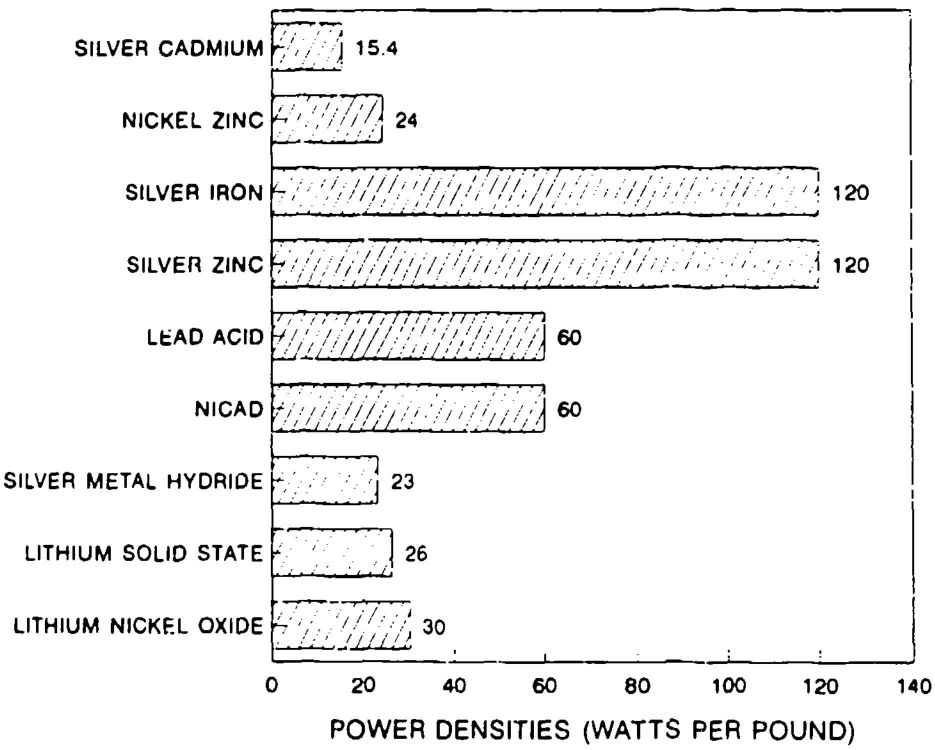


Figure J-3. Comparison of Power Rechargeable Systems

PRINCIPLES OF OPERATION

The Lithium Solid State bi-polar cells produce energy through electrochemical reactions that occur in a solid-state ion-exchange reaction:

$$Li_{\chi}N_{(s)} + M_{(s)} \longrightarrow N_{(s)} + Li_{\chi}N_{(s)}$$

M and N are solid electrode materials which can form insertion compounds with lithium. If N is absent, the anode is a non-insertion material (lithium metal or lithium alloy).

The change in the standard free energy of this reaction is the driving force which enables a Lithium Solid State cell to deliver electrical energy to an external circuit. For the Lithium Solid State cell, the open circuit potential is 3.2 volts. Unlike nonrechargeable batteries, these reactions are reversible. When an electrical energy is applied to the cell, the reaction reverses. The change in the standard free energy of the reverse reaction enables the cell to convert the electrical energy into stored chemical energy.

The Lithium Nickel Oxide cells also produce energy through electrochemical reactions at two electrodes (anode and cathode). The reactions are:

Anode: $0.30\ Li \longrightarrow 0.30\ Li^{+} + 0.30\ e$

Cathode: $LiO_{.60}NiO_2 \longrightarrow Li_{.90}NiO_2\ ^{+.30}$

The overall cell reaction is:

$$0.3\ Li + LiO_{.60}NiO_2 \longrightarrow Li_{.90}NiO_2$$

The open circuit potential for the cell is 4.10 volts. When an electrical energy is applied to the cell, the electrodes reverse roles, anode becomes cathode and cathode becomes anode, and the reactions reverse. The free energy changes of the reversed reactions cause the cell to convert the electrical energy to stored chemical energy.

DESIGN FOR THE SOLDIER SYSTEM

The proposed battery pack for the Soldier System contains eight D cells or ten sealed bi-polar cells connected in series and packaged in a plastic case to form a 24-volt DC nominal power pack. The Lithium Vanadium Pentaoxide pack provides 160 to 200 watt-hours of energy, and the Lithium Nickel Oxide pack provides 240 watt-hours of energy. The general characteristics of the battery packs are listed below:

	Lithium Solid State	**Lithium Nickel Oxide**
Open Circuit Voltage	32.0 VDC	32.8 VDC
Nominal Operating Volt	25.6 VDC	24.0 VDC
Minimum Operating Volt	20.0 VDC	20.0 VDC
Maximum Power:	120 watts	120 watts
Energy:	290 watt-hours	240 watt-hours
Weight:	4.6 pounds	4 pounds
Width:	4.4 inches	4.4 inches
Length:	4.6 inches	4.9 inches
Height:	5.0 inches	5.0 inches
Cell Design:	bi-polar	spiral wound

The general internal layout of the two lithium systems is illustrated in Figures J-4 and J-5. The battery pack's case serves as a protective envelope for the cells/internal components. The fuel cell/engine battery box serves as protection against the external environment. The battery pack sits inside the fuel cell/engine battery compartment/box and is connected by cable or equipment connector. The battery starts the fuel cell/engine. During the fuel cell/engine operation, the battery is charged. If the fuel cell/engine is shut down, the battery powers the Soldier System electronics.

The battery packs will have an electrical circuit that regulates the charging process, prevent the battery from discharging at rates beyond 5 amperes, monitor the energy content in the battery during discharge and charging, and shut the battery down when high internal temperature conditions occur. The Lithium Solid State bi-polar cells utilize a solid polymer electrolyte and will produce very little internal pressure while charging. The cell design may not require a vent. The Lithium Nickel Oxide cells utilize liquid electrolytes and will build up pressure during charging. In the event that the internal pressure of the cell reaches unsafe levels, the cell would be equipped with a vent to relieve any pressure buildups.

ADVANTAGES/DISADVANTAGES

The Lithium Solid State and Lithium Nickel Oxide rechargeable battery systems represent a portable, silent, reliable, and nonaerate power pack. Batteries do not have moving parts, making it a silent and non-signature system. Batteries won't contribute to the noise and infrared signature given off by the fuel cell/engine power sources.

The batteries do not need air to operate, thus external environmental conditions won't affect their operation. The only external protection that must be provided is shielding from the elements (i.e., water, salt corrosion) and rugged field handling. This has been addressed by mounting the battery in a battery compartment of the fuel cell/engine.

Replacement of the battery pack in the field is simple. No special training, tools, or extra personnel are required to change the power packs in the event of a malfunction or end of use. The battery packs are to be brought forward from the rear area with the food and ammunition.

Development of the Lithium Solid State and Lithium Nickel Oxide technology will be applied to all Army battery powered systems. The battery pack technology is NOT SOLDIER SYSTEM LIMITED. The Army currently buys 600,000 lithium batteries annually and has established a quality assurance program that ensures safe and reliable products are fielded.

Despite its high energy density, rechargeable lithium batteries are not ready for industrial, commercial, and military use. Work needs to be done on developing stable lithium anode/electrolyte stability during cycle life. Current lithium rechargeable battery systems can provide up to 75 charge/discharge cycles. In order to make the system cost effective against lead acid and nickel cadmium batteries, the lithium systems must achieve 100 plus cycles. The issues of safety during charging, overcharging, and rapid charging must be resolved. The Lithium Solid State systems must overcome their poor energy and power densities at low temperature conditions. The lithium rechargeable cells will be one of the largest and most energetic rechargeable cells ever mass produced and fielded by the Army. The issues of safety, transportation, and disposal must be resolved.

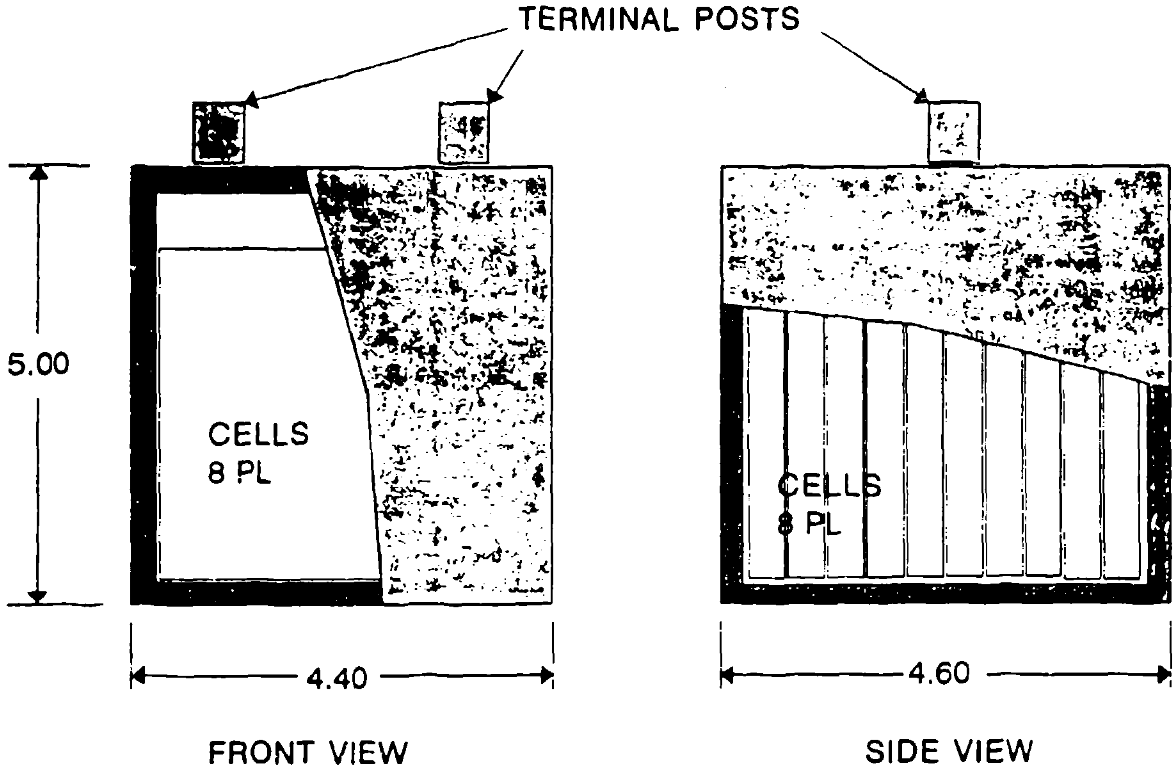


Figure J-4. General Battery Layout for the Lithium Solid State SLI Battery

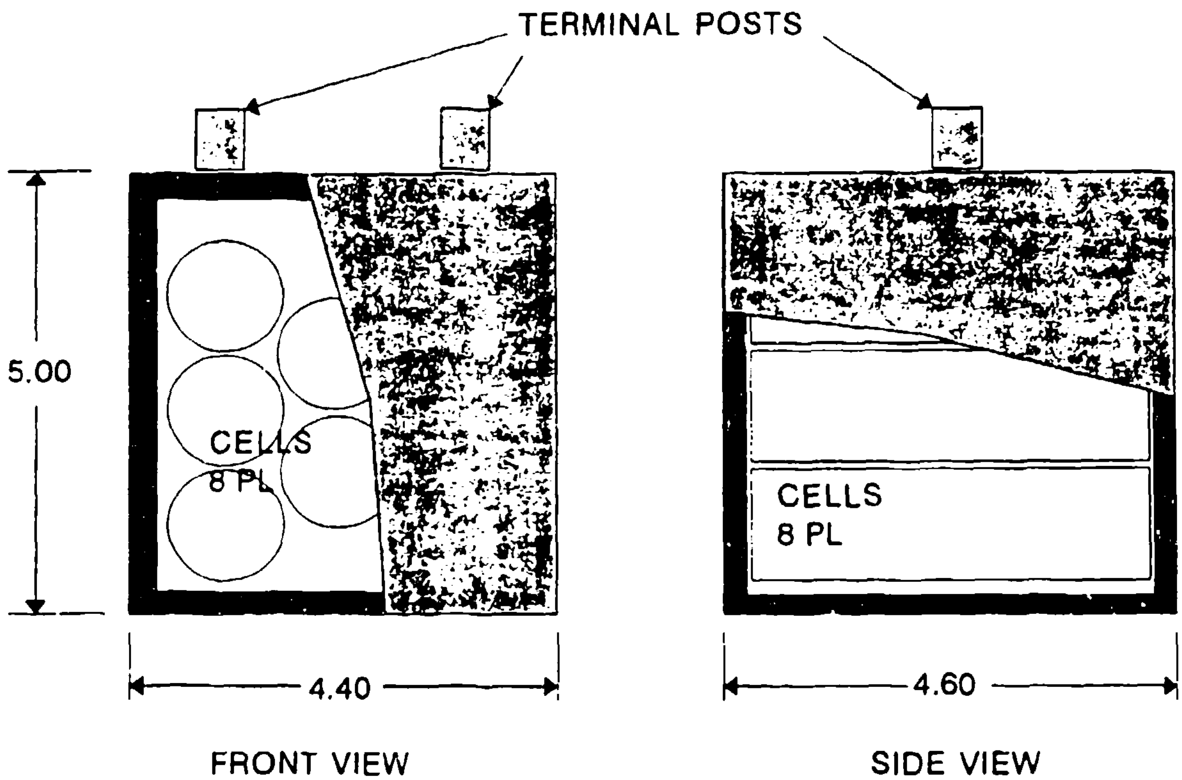


Figure J-5. General Battery Layout for the Lithium Nickel Oxide SLI Battery

CONCLUSIONS

Despite the technical barriers and risks, successful development of a Lithium Solid State and/or Lithium Nickel Oxide system will increase the energy capabilities of current Army rechargeable batteries fivefold or 500 percent and represents a quantum leap in Army portable rechargeable battery technology.

REFERENCES

1. Linden, D., *Handbook of Batteries and Fuel Cells*, McGraw-Hill, New York, NY, 1984, pp. 13-10 to 13-11.

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3. Westinghouse Electric Corp./Electronics Systems Group letter, "Battery Technology for Soldier Integrated Protective Ensemble (SIPE)," dated 5 July 1991.

4. Lorimer, J. W., "Rechargeable Lithium Batteries with Solid Polymer Electrolytes," 34th International Power Sources Symposium, Cherry Hill, NJ, June 1990.

5. Broussely. M., J. Labat, F. Perton, A. Romero, and R. J. Staniewicz, "Behavior of Lithiated Cobalt and Nickel Oxides in Lithium Rechargeable Cells," 35th International Power Sources Symposium, Cherry Hill, NJ, June 1992.

Appendix K
Solid Absorption Cooling

(Author: Mr. Christopher Bolton, BRDEC, SATBE-FED)

Absorption cooling involves a physical change or the formation of a chemical bond occurring during the sorption process. Adsorption cooling involves no physical or chemical change, just a physical storage of moisture as in a sponge. Absorption desiccants can achieve ratios greater than 100 percent (pounds of water to pounds of desiccant), compared to adsorption desiccant ratios in the 10 to 20 percent range. There is some overlap between these two processes because some materials exhibit both a chemical and a physical attraction to water. Solid absorption cooling depends on the molecular attraction between complex compounds; an example of this process is a metal inorganic salt and a ligand (refrigerant) held together by a coordinate covalent bond. Practical applications of this technology come from the use of advanced reactor designs. These designs allow for fast reaction rates so small amounts of salt or other desiccants can be used.

Three alternative methods of providing cooling using the absorption process are described in the following paragraphs. The absorption process can be constructed as a heat-driven recycling system, a vacuum-driven evaporative system, or a natural convention/diffusion system.

A simple heat-driven complex compound air conditioning cycle is described below. External heat is used to heat a reactor vessel and desorb refrigerant from the complex compound at State A. This refrigerant is de-superheated and condensed in condenser B, releasing its energy to the cooling ambient air. The liquid refrigerant is then directed to evaporator C. The refrigerant then passes to absorber D, where it forms a complex compound in the absorber. This absorption causes a reduction in vapor pressure, which causes evaporation of the refrigerant. This evaporation of the liquid refrigerant lowers the temperature of the evaporator, causing a cooling effect. The absorber is cooled by an ambient air stream to release the heat of the exothermic absorption reaction.

Depending on the amount of cooling required and the length of time of this cooling, this process can be either a one-time reaction or a cyclic reaction. For an extended operation, the system has to be set up as a regenerative cycle with the capability of switching from one reactor to another as the salt compound is dehydrated. A projected system shows 2,070 BTUH per pound of salt, an 8-minute cycling time, and a COP of 0.46 (fuel energy to cooling output). For continuous operation, two reactor vessels are required as well as three heat exchangers and a dual-burner arrangement. The evaporator would also incorporate an air or liquid heat exchanger. The total projected weight is broken down:

Absorbent	2.64 lbs
Reactor vessels	2.0 lbs
Heat exchangers	3.0 lbs
Fans	2.0 lbs
Burner	2.0 lbs
Total	11.64 lbs

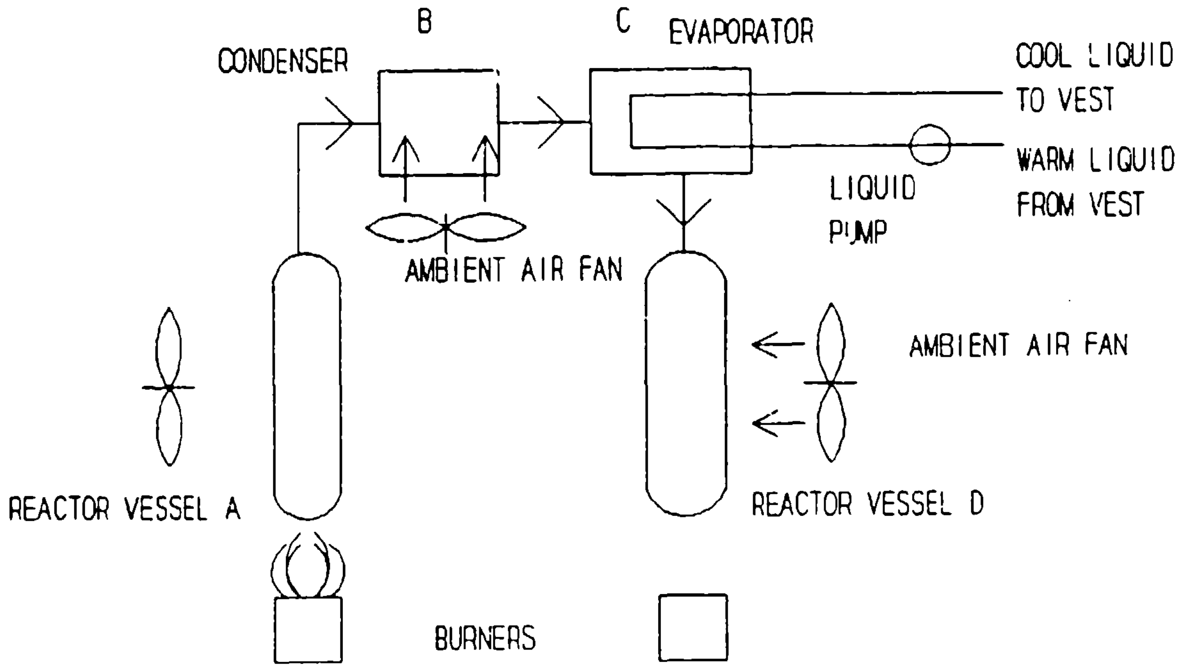

Figure K-1. Heat-Driven Absorbent Cooling

Waste heat from an internal combustion prime mover could also be used to drive this system at the expense of additional complexity. The system as described above has the advantage of operating on any available liquid fuel. Vibration and noise should be minimal, depending on burner design. The system also requires minimal electrical power to operate and thus could be teamed with a battery power source. Some degradation of the desiccant is likely to occur over many hours of continuous cycling.

A second system consists of an absorbent vessel connected to a liquid reservoir. A metering device is between these two containers. The absorbent vessel is evacuated to a specific vacuum level. The evaporation of the water as it is absorbed into the desiccant cools the water reservoir. In turn, it can provide cooling for a liquid vest. The metering device would maintain the vacuum to keep the water reservoir at a specific temperature. Sufficient water must be kept and circulated in the vest to facilitate heat transfer. This system functions similarly to the space suits which use a container of water bled off into the vacuum of space to achieve a cooling effect. The container of desiccant replaces the vacuum of space as a storage place for the evaporated water. Assuming an enthalpy of evaporation for water of 970 BTU/Lbs, our projected scenario requires 5.63 pounds of water. Magnesium Chloride is a potential desiccant material. It is able to hold 107.3 percent of its own weight in water so 5.24 pounds of desiccant is required.

This system would be very quiet and vibration free due to its lack of moving parts and inherent simplicity. The system is limited to a finite operational period because it is non-cycling. The system can be recharged, but no cooling is done during this process. The absorption process is an exothermic reaction; this additional emission of heat may require forced-air cooling to dissipate the heat. One proposed system described external surface temperatures over 180°F. This represents a clear safety hazard and requires significant shielding for both safety and signature reduction. The weight is determined by multiplying the length of the mission times the cooling rate required, because the desiccant weight and the "expended" water weight must both increase directly as the amount of cooling increases. As estimated weight breakdown is:

Absorbent	5.24 lbs
"Expended" water	5.63 lbs
Vest and water	2.4 lbs
Liquid pump	0.75 lbs
Finned absorber chamber	1.63 lbs
Accumulator	0.10 lbs
Controls	0.10 lbs
Housing	2.0 lbs
Total	17.85 lbs

A third approach to desiccant cooling is to apply desiccant pads directly to the interior of the chemical suit. The sweat off the body is absorbed into the desiccant material, providing evaporation and a cooling effect. This method is only suitable for impermeable suits, since permeable clothing allows outside moisture into the desiccant and reduces the cooling effect. Magnesium nitrate is the preferred absorbent for this system; it can absorb 73 percent of its weight in water. The 5.63 pounds of water from the previous example would come from the sweat of the individual in the suit. It would take 7.71 pounds of absorbent material to hold this amount of moisture.

There are several drawbacks to this method. Sweat may actually drip off the body, or otherwise not be in contact with the body, when the absorption takes place. This would drastically reduce any cooling effect from evaporation of this water. The rate of the absorption reaction would be very slow because the process would not take place in a vacuum, but be dependent on natural convention and diffusion. This slow absorption is somewhat alleviated by the relatively large surface area of the absorbent and by the short distance the moisture has to travel inside the suit. The exothermic reaction of absorption tends to heat up the interior to the suit and may create a more uncomfortable environment than one without the absorption system. Insulating the individual from the exothermic heat while allowing easy passage of water vapor is very difficult. The temperatures resulting from this exothermic reaction could damage the suit and attachment materials.

Weight Breakdown:

Absorbent pads	7.71 lbs
Support system	1.0 lbs
Total	8.71 lbs

Appendix L
Stirling Engines

(Author: Mr. Gary Proulx, NRDEC)

A preliminary design and analysis of a Stirling engine was conducted to help determine its viability for use as an Individual Portable Power (IPP) supply. The design information may be used to compare Stirling engines relative to other types of supplies for the Soldier Individual Power Front End Analysis (FEA).

ASSUMPTIONS

In order to design an engine, some assumptions are required as boundary conditions and design values. The values were chosen based on current technology and worst case scenarios.

a. *Thermodynamic:* The efficiency of a Stirling engine is strongly dependent on the temperature of the heat input space (expansion space temperature, Te) and the temperature of the heat rejection space (compression space temperature, Tc). The values chosen were (Te = 975°K) due to limits of the materials and (Tc = 322°K) due to limits of the ambient. The mean cycle pressure was selected to be 35 bar, which represents current seal and material strength technology. The power output of the engine is strongly correlated with the mean cycle pressure. As the mean pressure and Te increase, so does the power density of the engine.

b. *Geometric:* The engine speed chosen was 60 Hz (3,600 RPM) for reasons of direct coupling of the engine with a compressor or an alternator which would be run at 3,600 RPM without the use of a gear reduction/increase system. The engine could be designed to run at other speeds dependent on the requirements. It should be noted that for a given set of size, temperature, and pressure constraints, increased engine speed results in increased power. The ratio of the compression space swept volume (Vc) to the expansion space swept volume (Ve) (Vc/Ve = k = 0.88) was chosen from design charts which recommend values which are a function of the operating temperatures. The amount of volume required for the regenerator, heater, cooler, and other miscellaneous ducts is termed the dead space volume (Vd). A recommended value for Vd is 1.5 in order to provide the necessary heat transfer area. The phase angle ( ) by which Ve leads Vc was also chosen from design charts to be 96.2 deg (1.679 rad). The bore/stroke ratio was chosen to be 2/1 for minimization of wear, seal size, and overall engine size.

c. The fuels chosen for the analysis were $C_{12}H_{26}$ (Kerosene) and JP4.

d. The power levels chosen for sizing the engine were 100, 300, and 700 Watts based on the Case I, II, and III scenarios chosen for the IPP FEA.

ENGINE DESIGN RELATIONS:

The engine size was predicted by using the Schmidt analysis and the Beale relations for preliminary engine design [1] [2]. The Schmidt design is based on the ideal regenerative thermodynamic cycle while the Beale relation is a correlation to previously designed engines. A more detailed design and analysis would be required to design an actual engine.

The Schmidt and Beale design relations were incorporated into a computer code in order to easily vary the design parameters and predict/size the engine components. The following is a table summarizing the engine sizes.

Table L-1 Stirling Engine Design Sizes

Crankcase

Power (W)	Vt (cc)	Height (cm)	Width (cm)	Length (cm)	LxWxH (cc)	Drive Type
100	2.83	11.11	2.90	2.90	93.44	In-Line Slider Crank
300	8.49	16.02	4.18	4.18	279.91	" "
700	19.81	21.25	5.54	5.54	652.20	" "
100	2.83	13.52	6.76	2.90	265.05	Rhombic
300	8.49	19.50	9.75	4.18	794.12	" "
700	19.81	25.86	12.93	5.54	1852.41	" "

EFFICIENCY

The ideal thermodynamic efficiency of a Stirling engine is equal to the Carnot efficiency for heat engines:

$$eff_{th} = (Te\text{-}Tc) / Te$$

The actual efficiency of a Stirling engine system is actually lower due to the efficiency losses of the heat source (combuster for fossil fuels), mechanical efficiency of piston, linkage, etc., and other factors. To determine the amount of fuel consumption of a Stirling engine, a worst case efficiency was chosen. [2]

$$eff_{system} = 0.298\ eff_{th}$$

The definition of the system efficiency is as follows:

$$eff_{system} = \text{Shaft power out/heat energy in}$$

This relation was used to solve for the amount of heat required (FUEL Burned) to obtain the desired shaft power. Fuel flow rates and total fuel required for a given mission scenario have been listed in Table L-2.

WEIGHT PREDICTION

The weight of 100, 300, and 700 watt Stirling engines was predicted using current Stirling engine designs of a 120 W free piston and a 300 W kinematic engine as a possible baseline. Components whose size would change depending upon the power output of the engine were scaled to meet the 100, 300, and 700 Watt designs. Components which would not be significantly changed (e.g., controls, batteries for starting, etc.) were held constant. The scaled weights and power densities (W/lb) have been listed in Table L-3.

Table L-2 Stirling Engine Fuel Requirements

Fuel = Dodecane ($C_{12}H_{26}$) (Kerosene)
Qc = 20,445 (BTU/LB) Density = 50.2 (lb/cu ft)
SYSTEM EFFICIENCY 0.1996

Shaft Power	Mission Duration	Energy Supply		Fuel Rate		Total Fuel	
(W)	(Hr)	(W)	(BTU/Hr)	(lb/Hr)	(gal/Hr)	(lb)	(fluid oz)
100	24	501	1709	0.0836	0.0125	2.007	38.28
300	10	1503	5128	0.2508	0.0374	2.508	47.85
300	6	1503	5128	0.2508	0.0374	1.505	28.71
700	4	3507	11966	0.5853	0.0872	2.341	44.66
4000	8	20040	68380	3.3446	0.4984	26.757	510.35

Fuel = JP4
Qc = 18,400 (BTU/LB) Density = 50.2 (lb/cu ft)

Shaft Power	Mission Duration	Energy Supply		Fuel Rate		Total Fuel	
(W)	(Hr)	(W)	(BTU/Hr)	(lb/Hr)	(gal/Hr)	(lb)	(fluid oz)
100	24	501	1709	0.0929	0.0138	2.230	42.53
300	10	1503	5128	0.2787	0.0415	2.787	53.16
300	6	1503	5128	0.2787	0.0415	1.672	31.90
700	4	3507	11966	0.6504	0.0969	2.601	49.62
4000	8	20040	68380	3.7163	0.5538	29.730	567.07

Table L-3. Stirling Engine Weight Analysis

Component	Power (W)		
	100	300	700
Engine:			
Acceptor Fins	0.30	0.52	0.91
Rejector Fins	0.03	0.05	0.09
Steel Press Vessel	0.33	0.56	0.98
Al Pressure Vessel	0.57	0.98	1.72
Mechanism	0.58	0.99	1.73
Insulation	0.08	0.13	0.23
Shaft Seal	0.20	0.20	0.47
Heat Rejector	0.36	0.61	1.07
Subtotal	2.44	4.04	7.19
Generator/Output Shaft			
Generator	0.58	1.00	1.75
Power Train/Structure	0.29	0.50	0.88
Subtotal	0.88	1.50	2.63
Burner	1.13	1.94	3.40
System Accessories			
Fan	0.88	1.50	2.63
Pump/Motor	0.44	0.75	1.31
Controls	1.00	1.00	1.00
Capacitor	0.20	0.20	0.20
Batteries	0.70	0.70	0.70
Misc.	0.50	0.50	0.50
Subtotal	3.71	4.65	6.34
Total	8.16	12.13	19.54
Power Density (W/lb)	12.26	24.73	35.82

STIRLING ENGINE DESIGN/ANALYSIS ASSUMPTIONS

Engine Design:

Temperature of expansion space, Te: 975°K (1,295°F) ++
Temperature of compression space, Tc: 322°K (120°F) ++
Dead space/expansion space, X: 1.5 **
Compression volume/expansion volume, k: 0.88 **
Phase angle, alpha: 96.2 (deg) **
Engine speed, f: 60 Hz (3,600 RPM) #1
Mean pressure, pmean: 35 (bar) ++, #2
Bore/Stroke ratio, bs: 2.0/1.0 **, #3
Fuels: $C_{12}H_{26}$ (Kerosene), JP 4
Power levels: 100 W, 300 W, 700 W #4

Analysis Types:

Power vs. Size predictions: Beale Relation & Schmidt Analysis **, #5
Fuel consumption: used efficiency scaling factors which relate ideal to real engines.
Package size: length, width, and length are F(stroke) **
Weight analysis: scaled from previous work ++, &&

Source/Rationale:

&& Mechanical Technologies, Inc. (100 W Generator set review)
++ Stirling Technology Report/Proposal
** Stirling Engines Text
#1 Direct coupling to compressor
#2 Dependent upon material strength/wear characteristics
#3 Trade-off between wear, seal area, and heat transfer
#4 From IPP FEA standards
#5 Schmidt analysis is an ideal cycle model, Beale method scales to previously developed engines.

Current Input Values:

1) Required Power (W): 100.00, 300.00, 700.00
2) Engine Speed (Hz): 60.000000
3) Cooler Temp (°K): 322.000000
4) Heater Temp (°K): 975.000000
5) Mean Pressure (bar): 35.000000
6) swept volume ratio k: 0.880000
7) dead volume ratio X: 1.500000
8) phase angle alpha (deg): 96.199997
9) bore-to-stroke ratio: 2.000000

100 W engine

Beale Power Predictions:

Power: 100.00 (W)
Beale No.: 0.016827
Engine Speed (Hz): 60.00
Mean Press (bar): 35.00
Vo = 2.829975 (cc)
Bore = 1.965779 (cm)
Thermal efficiency (Carnot): 66.97 percent

Schmidt Analysis:

Total swept volume (cc): 6.045856
Press ratio (pmax/pmin): 2.009988
Max press (bar): 49.620918
Power per cycle (J): 3.951551
Total Power (W): 237.093072
Power per unit mass: 0.805833
Qe (J): 5.900095
Total Qe (W): 354.005728
Qc (J): -1.948544
Total Qc (W): -116.912656

Design stress of cylinder material (MPa): 60

Kinematic Engine Size Prediction

Bore (cm):	1.93
Stroke (cm):	0.97
Cylinder thickness (cm):	0.080

Drive Mechanism	Height (cm)	Crankcase Width (cm)	Crankcase Length (cm)
In-Line Slider Crank	11.11	2.90	2.90
Rhombic Drive	13.52	6.76	2.90

300 W engine

Beale Power Predictions:

Power: 300.00 (W)
Beale No.: 0.016827
Engine Speed (Hz): 60.00
Mean Press (bar): 35.00
Vo = 8.489925 (cc)
Bore = 2.785788 (cm)
Stroke = 1.392894 (cm)
Thermal efficiency: 33.487179 percent

Schmidt Analysis:

Total swept volume (cc): 18.137568
Press ratio (pmax/pmin): 2.009988
Max press (bar): 49.620918
Power per cycle (J): 11.854653
Total Power (W): 711.279202
Power per unit mass: 0.805833
Qe (J): 17.700285
Total Qe (W): 1062.017097
Qc (J): -5.845633
Total Qc (W): -350.737953

Design stress of cylinder material (MPa): 60

Kinematic Engine Size Prediction

Bore (cm):	2.79
Stroke (cm):	1.39
Cylinder thickness (cm):	0.115

Drive Mechanism	Height (cm)	Crankcase Width (cm)	Crankcase Length (cm)
In-Line Slider Crank	16.02	4.18	4.18
Rhombic Drive	19.50	9.75	4.18

700 W engine

Beale Power Predictions: 700 W

Power: 700.00 (W)
Beale No.: 0.016827
Engine Speed (Hz): 60.00
Mean Press (bar): 35.00
Vo = 19.809826 (cc)
Bore = 3.694936 (cm)
Stroke = 1.847468 (cm)
Thermal efficiency: 33.487179 percent

Schmidt Analysis:

Total swept volume (cc): 42.320992
Press ratio (pmax/pmin): 2.009988
Max press (bar): 49.620918
Power per cycle (J): 27.660858
Total Power (W): 1659.651489
Power per unit mass: 0.805833
Qe (J): 41.300667
Total Qe (W): 2478.040009
Qc (J): -13.639810
Total Qc (W): -818.388577

Design stress of cylinder material (MPa): 60

Kinematic Engine Size Prediction

Bore (cm):	3.69
Stroke (cm):	1.85
Cylinder thickness (cm):	0.153

Drive Mechanism	Height (cm)	Crankcase Width (cm)	Crankcase Length (cm)
In-Line Slider Crank	21.25	5.54	5.54
Rhombic Drive	25.86	12.93	5.54

Duplex Stirling Engine Information
Replenishment Costs Duplex Stirling

	AOR (hrs)	Quantity
Peacetime Requirement	150	20,000
Wartime Requirement	1,800	60,000
Battery Consumption Type	**Use Life**	
NiCad	1,408	
Fuel Consumption Type	**Fuel Rate (gal/hr)**	**Price ($/gal)**
Diesel	0.026	1.00

Components	MTBF	Price ($)
Burner/Engine/Cooler	1,000	7,500.00
Controller	5,370	1,000.00
Soldier Interface	2,566	150.00
Power Distribution	1,145	500.00
Pumps & Fans	400	1,000.00

	Peacetime Cost ($1000)	*Cooled Wartime Cost ($1000)	*Uncooled Wartime Cost ($1000)
Battery Consumption Type			
NiCad	255.68	9,204.55	9,204.55
Fuel Consumption Type			
Diesel	78.00	2,808.00	1,404.00
Components			
Burner/Engine/Cooler	22,500.00	810,000.00	810,000.00
Controller	558.66	20,111.73	20,111.73
Soldier Interface	175.37	6,313.33	6,313.33
Power Distribution	1,310.04	47,161.57	47,161.57
Pumps & Fans	7,500.00	270,000.00	270,000.00
Spares Total	32,044.07	1,153,586.63	1,153,586.63
Totals	$32,377.75	$1,165,599.18	$1,164,195.18

Note: Costs for uncooled wartime and cooled wartime are equal because the cooling unit is integral with the engine unit.

Double Stirling Size Analysis

Component	Length (in)	Diameter (in)
Burner	4.00	6.00
Engine	5.00	6.00
Linear Alternator	5.00	2.25
Cooler	5.50	6.00
Fan	2.50	3.50
Total/Max	22.00	6.00
Volume (cu in)		622

Component	Volume (cu in)
Controls	54
Batteries	18
Fuel (approx. 36 fluid oz)	65
System Total Volume	759

Duplex Stirling Weight Analysis

Component		Weight (lb)
Burner		2.00
Engine		
Acceptor Fins		0.50
Rejector Fins		0.50
Steel Pressure Vessel		0.70
Aluminum Pressure Vessel		0.50
Mechanism		1.40
Insulation		0.13
Heat Rejector		0.60
Engine Total		4.33
Linear Alternator		3.00
Cooler		
Acceptor Fins		0.40
Rejector Fins		0.75
Steel Pressure Vessel		0.70
Aluminum Pressure Vessel		0.30
Mechanism		1.40
Insulation		0.13
Heat Rejector		0.60
Cooler Total		4.28
Controls		1.00
Batteries		0.70
Capacitor/Motor		0.75
Fan		1.50
System Total	Dry Weight	17.56
	Fuel (10 hr mission	1.85
	Wet Weight	19.41

Duplex Stirling (Engine and Cooler)
Energy Balance

Required Electric Power 100 W
Required Cooling 300 W

Component	eff	Heat or Power In (Watts)	Heat or Power Loss (Watts)	Heat or Power Out (Watts)
Burner:	0.77	970	223	747
Stirling Engine:	0.33	747	501	247
Linear Alternator:	0.79	127	27	100
Stirling Cooler:	2.5	300		-120
COP:				

Summary:	Total Heat Required	
	(Fuel required) (W):	970
	(BTU/Hr):	3,314
	Total Heat/Power	
	Loss (W):	750
	(BTU/Hr):	2,563

Fuel: Diesel
Qc: 18,400 (BTU/lb)
Density: 50.2 (lb/cu ft)

Mission Duration: 10 (Hrs)

Fuel Rate (lb/Hr): 0.18010
(fluid oz/Hr): 3.4352

Total Fuel Req'rd: 1.80102 (Lb)
34.35238 (fluid oz)

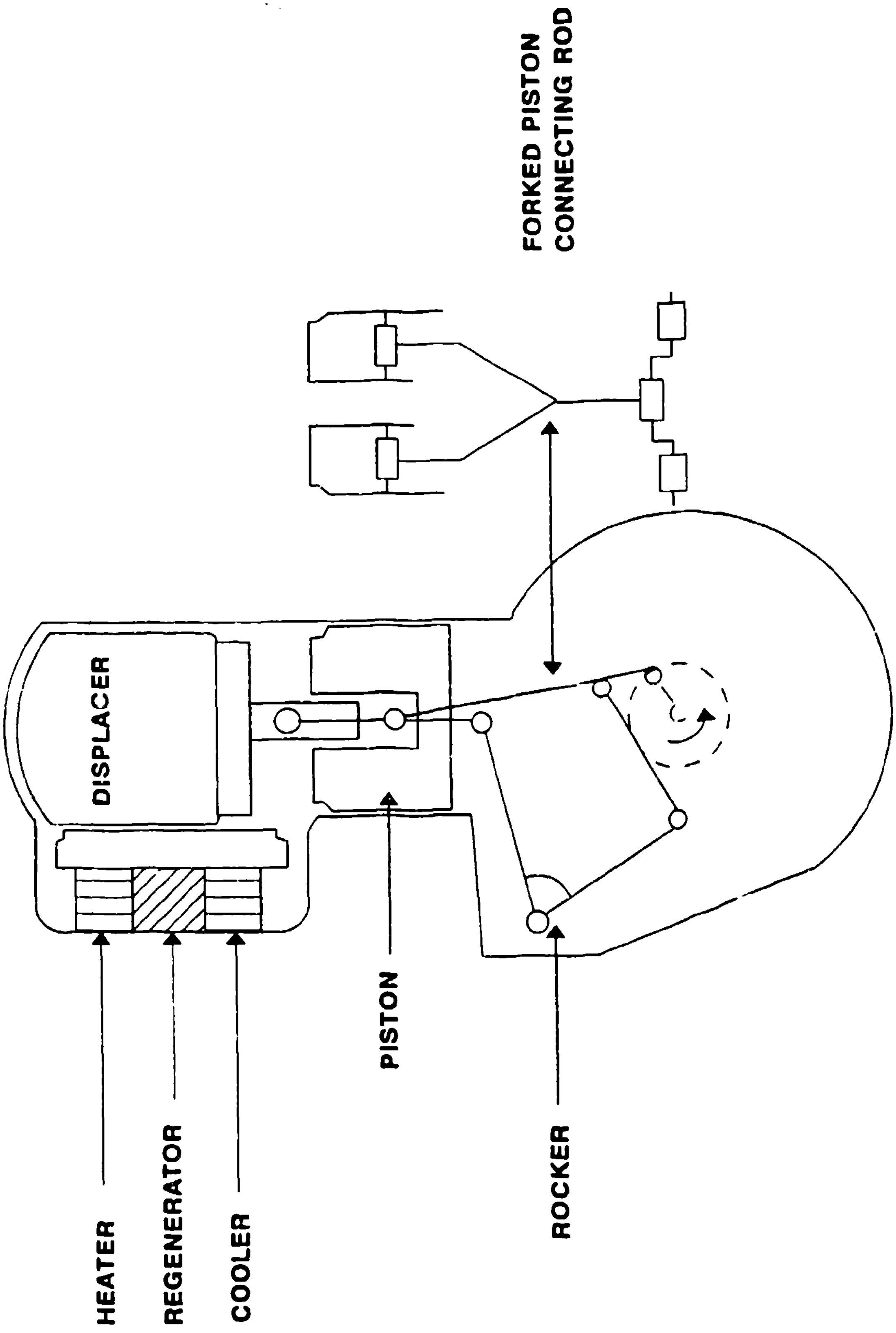

Figure L-1. Crank-Rocker Mechanism

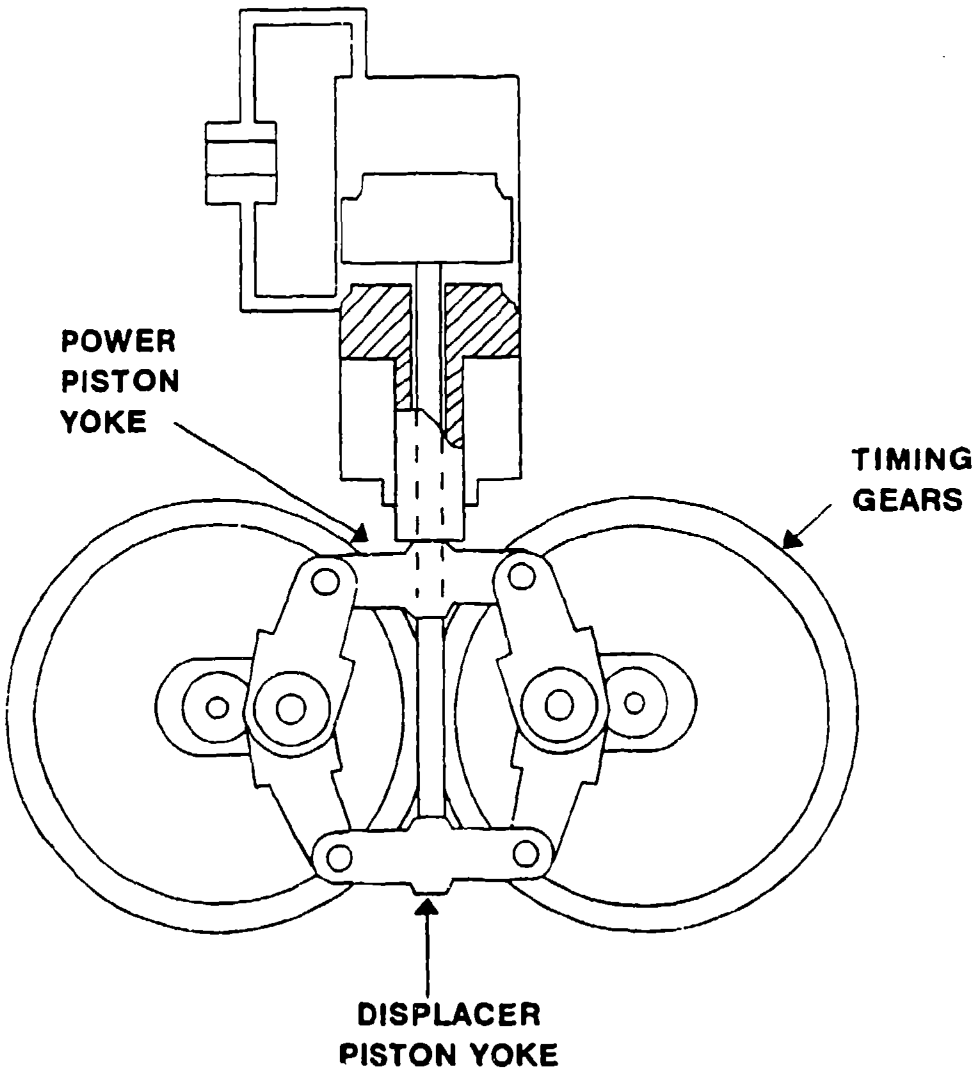

Figure L-2. Rhombic Drive

Appendix M
Superconducting Magnetic Energy Storage (SMES) or Superconducting Magnet Electric Power Source (SMEPS)

(Author: Dr. James Ferrick, BRDEC, SATBE-FGE)

Unlike normal conductors, superconducting materials have the ability to carry steady electric currents with no losses (time varying currents do result in some losses). Many concepts for storing energy in the magnetic field of coils made from superconducting wires, tapes, or ribbons have been investigated over the years. So-called "persistent switches" are used to couple the ends of a coil so that the current in the coil can be made to circulate essentially forever. When we want to withdraw energy from the coil, the switch is driven "normal," i.e., into its non-superconducting state, so that current can be diverted around the switch into an external circuit.

"Conventional" low temperature superconductors require cooling to the 4–20°K temperature range to be useful. This requires either an on-board refrigeration capability or the use of tanked cryogens, generally liquid helium (boiling point – 4.2°K at 760 mm Hg). Insulation from the normal 300°K ambient is frequently achieved by high vacuum techniques, as in a "Thermos" bottle. Thermal insulation integrity is critical for maintaining the cryogenic environment. For practical coolers, providing 1 watt of cooling at 4.2°K costs about 1 kW in the room temperature refrigeration equipment. The operating conditions required can be difficult to maintain, thus these approaches are not considered except in unusual circumstances.

Over the last several years, work has been done on high temperature superconductors (HTS). These materials, which are based on a variety of oxides, are ceramic-like materials that exhibit superconducting properties in the 60–120°K range. This begins to get into the range where low-cost liquid nitrogen (77.35°K boiling point) can provide the cryogenic environment.

Superconductors are characterized by interrelated maxima in temperature, magnetic field, and current density, which defines a three-dimensional surface bounding the superconducting state. The bulk HTS materials do not exhibit current densities sufficiently high to warrant consideration for power applications. Magnetic energy storage on a scale applicable to individual soldier use cannot compete with far less cumbersome alternatives such as batteries, fuel cells, or engine-generators.

For any configuration, the magnetic field established will be proportional to the current in the windings. An inductance is associated with the particular configuration of windings, so there will be energy stored as given by:

$E = 1/2\, LI^2$, where E is the energy in Joules (J),
L is the inductance in Henries (H), and
I is the current in Amperes (A).

Toroidal storage volumes are generally proposed in order to minimize the exposure of soldier and equipment to high magnetic fields. Since we cannot know the winding thickness or the limits of the current or current density that might apply as new superconducting materials are developed, we will find another way to gauge the usefulness of magnetic energy storage devices.

As noted, the magnetic field at any point will be proportional to the current in the windings. Also, the magnetic field in which a material will remain superconducting will have its limits. Let us assume that we can achieve continuous operation using some material at 10 Tesla (100 kilogauss), which is quite high in most instances. Ignoring the material, the winding configuration, the storage vessel, and all other aspects of the magnetic energy storage system, let us assume that we store energy in a uniform 10 Tesla field that is somehow constrained to 1 cubic foot. How much energy is stored?

We can calculate the total energy stored in a magnetic field by considering the energy density associated with the field and the volume over which it exists. The energy density of a magnetic field in free space ($H = B/\mu_0$) is given by:

$$u = (1/2)\, \mathbf{B} \cdot \mathbf{H} = (1/2\mu_0)\, \mathbf{B}^2, \qquad \text{where } \mu_0 = 4\Pi * 10^{-7} \text{ H/m}$$

and **B** is given in Teslas.

The total energy in a given volume at a particular field intensity is given as the product of the energy density and the volume, V, under consideration. Thus,

$$E = (1/\,(8\Pi * 10^{-7} \text{ H/m})\,) * (10 \text{ T})^2 * (0.3048 \text{ m})^3$$

for the condition of a 10 Tesla field over a 1–foot cube $(0.3048 \text{ m})^3$. This yields a value of 1.127 x 10^6 Joules, or 1.127 MJ.

Recall that 1 kWh = 3.6 MJ, so that the energy stored in the cubic foot volume is 0.313 kWh, or 313 watt-hours.

How does this measure up to competing approaches? The present day $LiSO_2$ primary battery in the BA-5590/U form stores about 166 watt-hours in a 4.4–inch by 2.45–inch by 5.0–inch package weighing 2.25 pounds (1 kg), so that 313 watt-hours stored would require 0.0624 cubic feet and weigh 4.5 pounds. Providing 1 kWh at the projected energy density would require a field volume of 3.2 cubic feet, not including the actual windings, dewar, refrigerator (if used), converter, etc. Thus, future SMES/SMEPS technology would be, at best, 16 to 20 times less energy dense as an energy storage approach than present day Lithium primary battery technology, which itself promises a doubling in energy density in the next 2 to 5 years.

Rose, Merryman and Johnson (Reference 1) recently assessed the characteristics of magnetic energy storage as part of a broad survey and comparison of energy storage media and techniques. They determined that a realistically achievable specific energy density for magnetic storage in a high strength beryllium-copper alloy system, when considered from a strength of materials perspective (operating at half the yield stress), would be about 27 kJ/kg (3.4 Wh/lb). Thus, a 1 kWh system would weigh 133 kg (290 lb). The operating flux density for this condition would be 50 Teslas (500 kilogauss), which is likely to be beyond the range of achievability for most superconducting materials, low or high temperature, in the foreseeable future.

REFERENCE

1. Rose, M. F., Merryman, S. A., and Johnson, C. R., "Comparative Analysis of Energy Storage Media and Techniques," IEEE Aerospace and Electronic Systems Magazine, Vol. 6, # 12, December 1991, pp. 26-32.

Appendix N
Thermoelectric Cooling

(Author: Mr. Christopher Bolton, BRDEC, SATBE-FED)

Thermoelectric (TE) cooling is accomplished by applying a DC voltage to a junction composed of dissimilar metals or semiconductors. One of the materials becomes hot and the other becomes cold. Bismuth-telluride semiconductors are the material of choice for current cooling systems. Current stocks of tellurium limit the number of cooling units that can be built on a production basis to less than 100,000 units. Current levels of performance show COPs in the range of 0.3 to 0.9, depending on the ambient temperatures. Thermoelectric units differ from common vapor cycle units. In thermoelectric units, as the temperature increases, the TE units draw less power. They also produce less cooling, resulting in a lower COP. An ambient temperature of 120°F is assumed for the worst-case scenario.

The advantages of TE units lie in their simplicity. There are no refrigerants to leak. The TE units have no moving parts except for fans and pumps. This makes them inherently quieter than vapor compression cycle systems. Fans are needed for heat rejection. These fans may represent a significant part of the overall noise signature. They are also relatively easy to control in part-load applications because their output can be adjusted by varying the voltage to the system or by reducing the number of modules that are in the circuit. Their disadvantages are primarily their inefficiency and the weight of the semiconductor modules, including heat exchanger surfaces. Thermoelectric coolers operate on DC voltage input.

Projected levels of performance for 400 watts of peak cooling result in a minimum cooler weight of six pounds with a COP of 0.5. The COP is the cooling output over the electrical input. This weight estimate does not include fans, pumps, or other ancillary equipment.

The best existing liquid units weigh 12 pounds. This includes the pump and hot-side fan, but not the liquid. These units have a COP of 0.4 for 400 watts output. The best air unit to date has a COP of 0.5 and weighs 16 pounds for 400 watts output. This weight does not include the blower or the NBC filter.

Sources: Midwest Research Institute

Appendix O
Vapor Compression Cycle Cooling

(Author: Mr. Christopher Bolton, BRDEC, SATBE-FED)

Vapor compression cycle cooling, or simply vapor cycle cooling, is the most common form of cooling found today. The vapor cycle cooling system offers several outstanding advantages over other candidate technologies. The major advantage is its demonstrated efficiency. The use of a refrigerant that undergoes a phase change allows for relatively large amounts of heat to be transferred by a relatively small amount of refrigerant. The basic principles of the technology are also well understood, and the industrial base is well established. There are a number of firms that specialize in development of systems to meet unique military needs. Vapor cycle systems will also be familiar to repair personnel already in the field and depots.

On the negative side, very few commercial systems have been developed in the size range required for individual cooling. Another problem is that these systems require rotating elements in order to compress and cool the refrigerant . The compression and expansion process, along with the movement of ambient air used to reject heat to the atmosphere, generates noise and vibration. The refrigerant itself is stored under pressure and thus will leak out of the system whenever opportunity allows.

Vapor cycle systems consist of a compressor, a condenser coil, an evaporator coil, and a refrigerant metering device. Fans are usually required for sufficient heat transfer across the coils. A refrigerant-to-liquid evaporator would require a pump to circulate the cooled liquid through the vest.

The compressor is the heart of the vapor cycle system and comes in several distinct types. Piston, rotary vane, rolling piston, scroll, and centrifugal compressors are all well known types of compressors and are available in a range of sizes. Each of these compressors can be put in two groups: hermetic, which contains its own electric motor within a sealed enclosure; or semi-hermetic, which is driven by a shaft through a seal that limits the leakage of refrigerant. Each type of compressor has its advantages and disadvantages. Any very small compressor for individual cooling has to be fully developed to successfully meet the challenges and requirements of military usage.

The primary advantage of the piston compressor is its mature development. Small sizes of piston compressors would be easy to make and would permit optimization of displacement for the small cooling loads required. The piston compressor requires both an intake and exhaust valve. These valves are the primary limit on compressor speed. They are also the main practical limit on the possible efficiency of a piston compressor. Optimization of these valves for volumetric efficiency, reliability, and small size is a key to successful design of the compressor. A one-cylinder compressor is the best solution from a weight, size, and cost standpoint, but it produces higher levels of vibration than a multi-cylinder design. The lightest compressor developed to date weighs approximately 13 ounces. This compressor has a displacement of 0.45 cubic inches and operates at a maximum speed of 3,000 rpm. Additional development is unlikely to produce significant gains in a free standing unit at this size and performance level.

The sliding action of one or more vanes rotating around an eccentric space operates the rotary vane compressor. An eccentric shape rotating past a stationary vane operates another type of compressor, but it is not suitable for this application. High speeds of 10,000 to 15,000 rpm are possible with the rotating vane compressor due to the lack of intake valves and a low inertial mass. At very high speeds, the exhaust valve may also be removed. These features also serve to improve the efficiency of the compressor and to reduce the noise and vibration of the unit. Oil circulation is critical for these high speed devices; current systems are attitude sensitive because of the oil flow constraint. Additional development is required if refrigerant/oil mixtures are used for total lubrication. Development of these compressors is judged to be of relative medium risk and medium payoff.

Rolling piston compressors are very common in small commercial applications such as water coolers. They are usually run at low speeds of less than 4,000 rpm and again have a heavier rotating mass. These compressors are very cheap to manufacture due to few critical tolerances. They are able to handle adverse conditions very well; the rotating cylinder can ride up over a liquid "slug" of refrigerant without suffering damage. An exhaust valve is used in these compressors but no intake valve is needed. The weight of the rolling piston itself may further limit development of these compressors but their simplicity and reliability may overcome their weight penalty.

The trochoidal rotary compressor is more commonly known by the Wankel designation. Again, the weight of the rotor may make this system unattractive for small cooling use, but this compressor is capable of speeds of up to 10,000 rpm and is relatively small for its capacity.

Scroll compressors are becoming more common as their efficiencies become more important for consumer applications. Scrolls do not use intake or exhaust valves and thus have a much higher theoretical efficiency. Their disadvantage is that they have a complex drive mechanism that is required to drive the scrolls in an orbital manner; and the scrolls themselves require complex and costly machining. Scrolls should be capable of speeds to 16,000 rpm, although current applications for refrigerant compressors run at much lower speeds. Scroll compressors would probably be heavier than other compressors due to the relatively large amount of material required for the scroll surfaces and drive mechanisms. Scrolls may also tolerate particles such as liquid, dirt, etc., in the compression area, which would make them more reliable than less compliant compressors. Scroll compressors have a higher development risk and a higher payoff relative to the other compressor types discussed.

Centrifugal compressors are widely employed in very large sizes for industrial applications, where they show the highest efficiency of any compressor types. Small cooling application system development has been insignificant. Centrifugal compressors are very high speed machines, operating at speeds between 50,000 and 100,000 rpm. For very small sizes, efficiency is expected to be lower than that of current large systems. The losses of a very small compressor due to tip clearance and flow restrictions would be greater in proportion to the overall flow of the device than in a large compressor. The centrifugal compressor can potentially be very light. The physical size of the turbine and housing would be very small. The drive mechanism of the device, either electric motor or shaft, would probably be larger than in other systems due to the high speed requirements of the device. Variable speed operation of the device is difficult because critical speeds of the impeller must be avoided. Development of this type of compressor involves a very high risk but may give a very high payback.

All of these compressors can be shaft driven or driven by an internal electric motor in a hermetic configuration. Magnetic couplings are also available and allow for an external drive of a hermetic system. Magnetic couplings are very heavy and are greatly affected by high temperatures. Maximum efficiency of operation suggests that converting shaft power into electrical power (engine-driven generator) and electrical power back into shaft power (hermetic motor-driven compressor) is not the preferred solution. Instead, an engine coupled directly to a shaft driven system would avoid the energy conversion losses. This does require the use of a shaft seal in order to keep the refrigerant in the compressor and air, moisture, and other substances out of the system. Current seals are not 100 percent leak proof and are especially prone to leakage when subjected to high pressures, high speeds, vibration, high temperatures, and long periods of storage. All of these factors are likely to be encountered in backpack cooling applications. For this reason, shaft-driven compressors will require much more development time than their hermetic counterparts and represent more risk, all due to the seal constraints.

The heat exchangers needed to "pump" the heat from the cooling medium to the ambient air are integral parts of the vapor cycle system. A condenser coil and an evaporator are both required. The gaseous refrigerant is changed into a liquid and gives up heat in the condenser coil. The liquid refrigerant is throttled into a gas and absorbs heat in the evaporator. Recent advances in manufacturing technology and computer modeling have resulted in very efficient and light coils being developed for personal cooling applications. These coils are characterized by their plate and fin construction, which is lighter and more effective than common tube and fin, and by their parallel flow arrangement. Additional development is still needed in this area, especially in the area of refrigerant-to-air evaporator coils. However, significant gains are unlikely to occur as current prototype coils aln ady approach 0.6 pounds.

Refrigerant controls are required to ensure stable operation of the system over a range of operating conditions and loads. Continuous operation at full load is not practical because of the energy costs due to fuel weight. Ambient conditions also greatly affect the operation of vapor cycle systems; the compressor can be damaged if operated in ambient temperatures below the system design point. Current systems typically use a Thermostatic Expansion Valve (TXV) to control the flow of a refrigerant. This valve senses the cooling load as a variation in suction pressure. The valve opens to increase refrigerant flow or closes to reduce flow. Common mechanical valves can only respond over a limited range. New generation residential heat pumps have introduced an electronic TXV. It is regulated by closed-loop logic commands to provide a wider range of adjustment with more precise control. Motor torque remains relatively constant because suction pressure varies as long as the condensing temperature remains constant (Reference 1. This implies that reducing the cooling load will not result in reducing the input power unless other variables are changed at the same time. Newer units introduced variable speed operation which results in a more effective and efficient operation than on/off cycling of the compressor. Reducing the speed lowers the cooling produced as well as the amount of power required. Low temperature protection is typically provided by condenser air flow control or by passing hot gas from the compressor discharge back into the evaporator section. It should be apparent that control of the system is critical for practical use of the system and requires substantial development. This is particularly true for shaft-driven systems because speed control is much more difficult to achieve.

One consideration is the choice of refrigerant. Current legislation banning Chlorofluorocarbons (such as R-12) has basically limited any future systems to R-134a. If centrifugal compressors are developed, finding a suitable refrigerant for these systems could be a significant part of the development effort.

Based on the above discussion, reciprocating compressors are the obvious short-term solution as long as high rotational speeds or speed reduction devices are not required for shaft coupling. Additional development of scroll and rotary vane compressors may result in lighter, more reliable systems. The optimal integration of a system for producing power and cooling might consist of a monoblock assembly containing engine components, compressor components, all necessary bearings and seals, and one common shaft. Development of such a unit includes any required development in the compressor components.

REFERENCE

1. ASHRAE, 1988 Equipment Handbook, p. 12.14.

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