SPARTON
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(2)

7097-0001-1192

ENERGY SOURCE STUDY TECHNICAL REPORT

FOR

DEPLOYABLE ACOUSTIC PROJECTOR SYSTEM (DAPS)

Contract N62190-88-M-0755

23 December 1988

Submitted To

Naval Research Laboratory - USRD
Orlando, Florida

Prepared By

ASW TECHNICAL CENTER

Sparton Defense Electronics
Sparton Corporation
Jackson, Michigan

Submit in accordance with the requirements of item 0001 of the subject contract

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
29 Dec 88

3. REPORT TYPE AND DATES COVERED
Final

4. TITLE AND SUBTITLE
Energy Source Study Technical Report for Deployable Acoustic Projector System (DAPS)

5. FUNDING NUMBERS
C:N62190-88-M-0755

6. AUTHOR(S)

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
ASW Technical Center
Sparton Defense Electronics
Sparton Corporation
Jackson, Michigan

8. PERFORMING ORGANIZATION REPORT NUMBER
7097-0001-1192

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Naval Research Laboratory
Underwater Sound Reference Detachment
P.O. Box 568337
Orlando, FL 32856-8337

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Potential energy sources and energy conversion mehtods for the Deplorable Acoustic Projector Systems (DAPS) were studied. Various battery systems, including primary, secondary, and reserve cells, were considered, and the use of nontraditional power sources such as fuel cells and internal combustion engines were explored. Energy conversion methods (direct versus load leveling) were compared on the basis of total size and weight. Direct energy conversion was viewed as an energy source (battery) supplying power to the load (projector) at peak pulse levels through a dc-to-ac inverter. Indirect conversion was viewed as a mechanical means (flywheel) to store energy between pulses to reduce the peak drain on the battery, fuel cell, or other energy supply. Factors considered were peak drive levels, total stored energy requirement, size, weight, system reliability, initial cost, and long-term operating cost. The best choices for energy sources appear to be the non-traditional fuel cell or the internal combustion engine, in conjunction with mechanical energy storage to load leveling.

14. SUBJECT TERMS
Deployable Acoustic Projector System (DAPS), power supplies batteries(electrical), fuel cells, internal combustion engines, energy conversion

15. NUMBER OF PAGES
42

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

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SECTION 1
SUMMARY

A study of potential energy sources and energy conversion methods for the Deployable Acoustic Projector System (DAPS) has been conducted. Various battery systems, including primary, secondary, and reserve cells, were considered and the use of nontraditional power sources such as fuel cells and internal combustion engines were explored.

Energy conversion methods (direct versus load leveling) were compared on the basis of total size and weight. Direct energy conversion for the purpose of this study was viewed as an energy source (battery) supplying power to the load (projector) at peak pulse levels through a dc-to-ac inverter. For the purpose of this study, indirect conversion is viewed as a mechanical means (flywheel) to store energy between pulses to reduce the peak drain on the battery, fuel cell, or other energy supply.

The peak drive levels to the acoustic projector are defined in the DAPS energy study statement of work as 100 kW for 10-second pulses, or 400 kW for 2-second pulses. The total stored energy requirement is given as 132 kWh.

The projected weight for the different energy sources varied from 550 pounds for an internal-combustion-engine/flywheel-energy-storage system to 3313 pounds for a silver-zinc secondary-battery/direct-energy-conversion system. Volume projections varied from 14 cubic feet for a fuel cell source to 43 cubic feet for a direct energy inversion, lithium-sulfur dioxide, primary battery system. In addition to size and weight, other factors considered were system reliability, initial cost, and long-term operating cost.

When all factors are considered, the best choices for energy sources appear to be the non-traditional fuel cell or the internal combustion engine, in conjunction with mechanical energy storage for load leveling.

SECTION 2
STATEMENT OF WORK

The Deployable Acoustic Projector System (DAPS) is a high acoustic energy source that can be deployed in various geographic areas of the ocean. The program is sponsored by PMW-180 at SPAWARS with the cognizant laboratory being NUSC, New London.

Preliminary investigations by NUSC identified several risk areas in this program; two of them are the transducers (projectors) and the power sources. NUSC, New London, through NRL, Orlando, issued a contract to Sparton Defense Electronics for the investigation of various power sources that can be utilized in the DAPS program. Subsequent study and this final report are a compilation of the investigation of various types of energy sources as they would apply to the DAPS program.

The statement of work (SOW) for this contract requires Sparton to investigate and to document in a technical report for the feasibility of providing a 132-kWh source and a means of converting this dc energy into an ac signal (inverter) for driving the projector. In addition to the capacity requirements, this report addresses a peak power rate of 100 kW for 10 seconds or 400 kW for 2 seconds.

The SOW requires Sparton to perform a tradeoff analysis of the energy source in terms of cost/energy density, replacement cost, MTBF, linearity, recovery time between pulses, recharging cost (if required), and viability of technology. In the analysis of the energy source, Sparton has made a minimal number of assumptions to assist in the study of those energy sources that would be suited to the operation of the DAPS. Those assumptions are:

(1) The 100 kW for 10 seconds is the important peak power requirement. This is based upon the total energy to be supplied during the pulse being greater than the 400 kW for 2 seconds.

(2) The volume allowed for the energy source is 20 cubic feet, based upon the volume of an S-3, bomb-bay-launched large weapon being 29 cubic feet with 9 cubic feet allocated to the electronics and projector system. The weight allowed is 3000

pounds. This assumption is flexible but is based upon a 4000-pound maximum limit for the DAPS.

(3) The inverter study requirement is for a means to convert the energy source output into projector drive and not into line-type ac power (440-V/3-phase).

The technical portion of the report is written in two sections; section 3 discusses the energy source and section 4 the inverter. In section 4, the various energy systems are discussed. The energy system studied represents various families of energy technology: primary types (alkaline (MnO_2), lithium), reserve (lithium and aluminum), secondary (lead-acid, NiCd), thermal, and fuel cell. A table is included that summarizes the energy systems by theoretical watts per kilogram and per liter, practical watts per kilogram and per liter, and the required weight and volume to meet the 132-kWh requirement of the SOW. The difference between theoretical and practical sizes is discussed. Additional discussions cover cost factors between existing battery technology and those technologies that have commercial application but have not been developed, operational safety of the commercial energy sources, peak power loading/level loading with an energy storage system, and exotic energy sources on the horizon that have not been tested and measured in enough depth to determine their feasibility and safety.

Sparton's recommendations for the best candidates are presented in section 7.

SECTION 3
ENERGY SOURCES

In a pulsed system such as DAPS, the energy source can be designed for either high power density (capable of providing the peak pulse levels directly from the supply) or using some form of load leveling (interpulse energy storage). Load leveling will reduce the peak power requirement, allowing the use of a moderate or low-power-density source. The DAPS pulse duty cycle of one 10-second pulse every 15 minutes (approximately 1%) is in a range that does not strongly favor one approach over the other. In this DAPS energy source study, both approaches were considered in terms of total system weight, size, and cost.

The energy sources that were evaluated include primary, secondary, and reserve batteries. Other energy sources considered are chemical fuel cells and an energy conversion system utilizing an internal combustion engine.

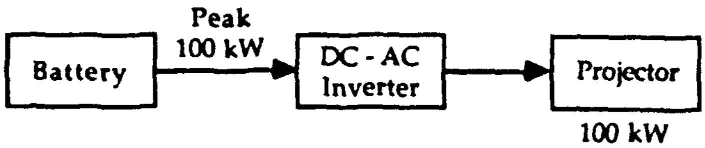
3.1 DAPS ENERGY/POWER REQUIREMENT

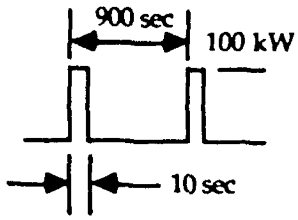
The DAPS energy source requirements are specified by the NUSC specification P-2132/8167-591 (Critical Item Development Specification for a Deployable Acoustic Projector System DAPS) and the NRL statement of work for this study as follows:

Total (deliverable) stored energy	132 kWh
Peak power (2-second pulse duration)	400 kW
Peak power (10-second pulse duration)	100 kW
Pulse interval	900 seconds

Based on the 132-kWh energy storage and the 100-kW and 400-kW peak power requirements, four possible power supply concepts, using direct and indirect power conversion are:

(1) direct conversion, 100 kW (figure 3-1),
(2) direct conversion, 400 kW (figure 3-2),
(3) indirect conversion, 100 kW (figure 3-3), and
(4) indirect conversion, 400 kW (figure 3-4).





Ave = 1.11 kilowatts
Life = 119 hours
Total = 132 kilowatt-hours

(pulse) $E = 100\text{ kW} \times \frac{10\text{ sec}}{3600\text{ sec}} = 0.277\text{ kWh}$

$$N = \frac{132\text{ kWh}}{0.277\text{ kWh per pulse}} = 476\text{ pulses (10 sec)}$$

$$\text{duty cycle} = \frac{10\text{ sec}}{900\text{ sec}} = 0.011$$

$$\text{power average} = 100\text{ kW} \times 0.011 = 1.11\text{ kW}$$

$$\text{life} = \frac{476\text{ pulses}}{4\text{ pulses per hr}} = 119\text{ hr}$$

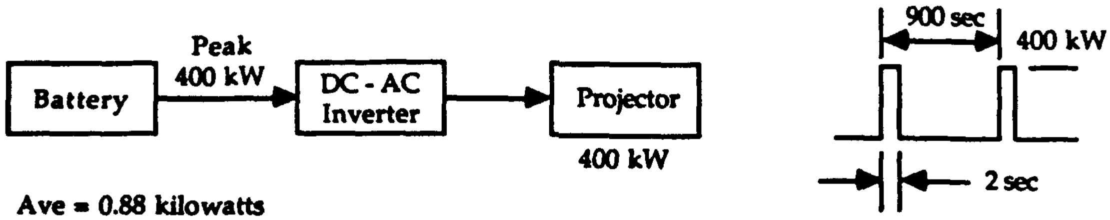
$$\text{pulse life} = 10\text{ sec} \times 470\text{ pulses} = 1.32\text{ hr}$$

$$\text{transmitter peak power} = 100\text{ kW}$$

$$\text{battery peak power} = 100\text{ kW}$$

$$\text{battery average} = 1.11\text{ kW}$$

Figure 3-1. Direct Conversion, dc-ac Inverter, 100-kW Pulse



Ave = 0.88 kilowatts
Life = 149 hours
Total = 132 kilowatt-hours

(pulse) $$E = 400\ \text{kW} \times \frac{2\ \text{sec}}{3600\ \text{sec}} = 0.222\ \text{kWh}$$

$$N = \frac{132\ \text{kWh}}{0.222\ \text{kWh per pulse}} = 595\ \text{pulses (2 sec)}$$

$$\text{duty cycle} = \frac{2\ \text{sec}}{900\ \text{sec}} = 0.00222$$

$$\text{power average} = 400\ \text{kW} \times 0.00222 = 0.888\ \text{kW}$$

$$\text{life} = \frac{595\ \text{pulses}}{4\ \text{pulses per hr}} = 148.75\ \text{hr (6.2 days)}$$

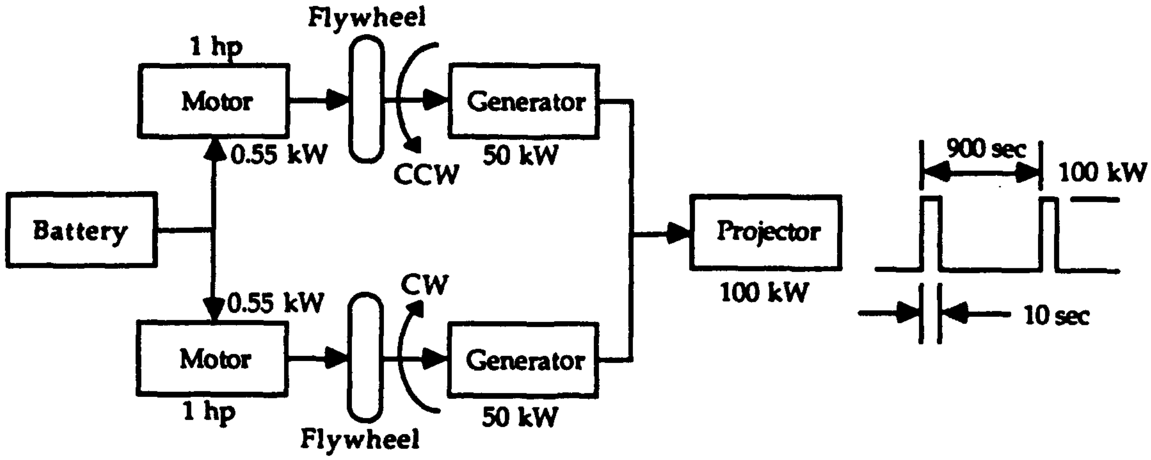
$$\text{pulse life} = 10\ \text{sec} \times 470\ \text{pulses} = 0.33\ \text{hr}$$

$$\text{transmitter peak power} = 400\ \text{kW}$$

$$\text{battery peak power} = 400\ \text{kW}$$

$$\text{battery average} = 0.888\ \text{kW}$$

Figure 3-2. Direct Conversion, dc-ac Inverter, 400-kW Pulse



Ave = 1.11 kilowatts
Life = 119 hours
Total = 132 kilowatt-hours

(pulse) $$E = 100\ \text{kW} \times \frac{10\ \text{sec}}{3600\ \text{sec}} = 0.277\ \text{kWh}$$

$$N = \frac{132\ \text{kWh}}{0.277\ \text{kWh per pulse}} = 476\ \text{pulses (10-second duration)}$$

$$\text{duty cycle} = \frac{10\ \text{sec}}{900\ \text{sec}} = 0.011$$

$$\text{power average} = 100\ \text{kW} \times 0.011 = 1.11\ \text{kW}$$

$$\text{life} = \frac{476\ \text{pulses}}{4\ \text{pulses per hr}} = 119\ \text{hr (5 days)}$$

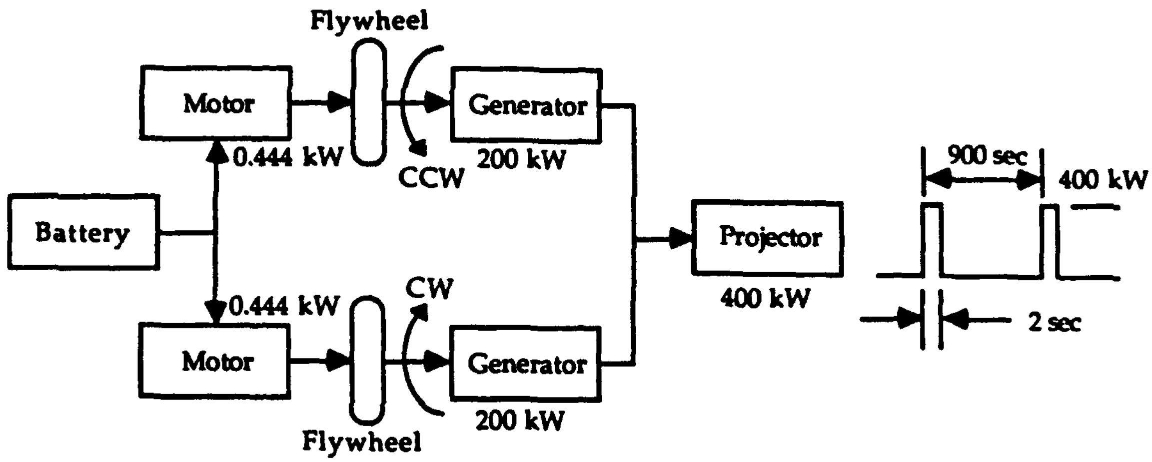
$$\text{pulse life} = 10\ \text{sec} \times 470\ \text{pulses} = 1.32\ \text{hr}$$

transmitter peak power = 100 kW

battery peak power = = 2.22 kW

battery average = 1.11 kW

Figure 3-3. Indirect Conversion, Generator/Flywheel, 100-kW Pulse



Ave = 0.888 kilowatts
Life = 149 hours
Total = 132 kilowatt-hours

(pulse) $E = 400\text{ kW} \times \frac{2\text{ sec}}{3600\text{ sec}} = 0.222\text{ kWh}$

$N = \frac{132\text{ kWh}}{0.222\text{ kWh per pulse}} = 595\text{ pulses (2 sec)}$

$\text{duty cycle} = \frac{2\text{ sec}}{900\text{ sec}} = 0.00222$

$\text{power average} = 400\text{ kW} \times 0.00222 = 0.888\text{ kW}$

$\text{life} = \frac{595\text{ pulses}}{4\text{ pulses per hr}} = 148.75\text{ hr (6.2 days)}$

pulse life = 10 sec × 470 pulses = 0.33 hr

transmitter peak power = 400 kW

battery peak power = 1.776 kW

battery average = 0.888 kW

Figure 3-4. Indirect Conversion, Generator/Flywheel, 400-kW Pulse

3.2 BATTERY SYSTEMS

Batteries can be divided into three general categories: primary, secondary, and reserve.

Primary batteries are fabricated of consumable electrode materials that involve a non-reversible chemical reaction. These are intended for one-time operation and cannot be recharged.

Secondary batteries are designed for reversible electrochemical reaction processes that allow recharging of the battery. In this type of battery, the anodic materials change in chemical structure but are not consumed in the discharge process.

Reserve batteries can be of the primary or the secondary type, but the electrode and the electrolyte are separated until the battery is activated. This method allows for a long storage life.

One type of a reserve battery that does not physically separate the electrolyte and the electrode is the thermal battery. This type of battery involves operation at high temperatures, which converts solid electrolyte materials to a molten form. Activation is accomplished with a pyrotechnic heater. The thermal battery is a one-time high power density type of battery with a very short life.

Another high-temperature, solid-electrolyte battery having the characteristics of both reserve and secondary batteries is the sulfur-sodium storage cell. This battery type has a solid electrolyte and liquid electrode materials. The sulfur-sodium cell exhibits both high energy and high power densities.

The physically separate storage of the electrolyte in low-temperature reserve cells removes the requirement for low leakage to achieve acceptable shelf life. This process allows the cell to be designed for greater power density or otherwise conflicting requirements.

3.2.1 Energy/Power Characteristics

Battery performance generally is specified in terms of energy density and power density. The two factors are related in terms of the discharge rate. This is a consequence of the battery internal resistance that dictates the internal losses as a function of current drain.

The energy density or specific energy measured in watt-hours/kilogram is a measure of the available energy of a battery at a given current drain. The power density or specific power measured as watts/kilogram is a measure of the instantaneous power available at the same drain rate.

If the specific energy is plotted as a function of specific power, a characteristic curve of battery performance is generated. Characteristic curves for various battery types are shown in figure 3-5. It is apparent from figure 3-5 that the highest energy density is achieved with the smallest power drain for all battery types shown. High internal loss and associated low ene density at high current drains are indicated for alkaline batteries. In general, the greater slope, the higher the internal losses for each battery type.

Based on a 3000-pound weight limit for the DAPS battery complement, the dashed line AA (figure 3-5) represents the minimum acceptable energy density that will provide the required 132 kWh of energy storage. This is approximately 96 Wh/kg, if 100% efficiency for the energy conversion system is assumed.

The dashed line BB (figure 3-5) represents the lower limit for the power density for direct conversion at 100 kW per pulse. This is equal to 73 W/kg, again assuming 100% efficiency. The power density for indirect conversion using energy storage is by comparison 0.80 W/kg.

The energy data for the various battery types throughout this report and specifically in figure 3-5 and table 3-1 are not taken from a single source, but are compiled from the sources listed in the bibliography. The cost data, table 3-6, were taken from David Linden, *Handbook of Batteries and Fuel Cells* (see bibliography).

3.2.2 Primary Batteries

Table 3-1 compares the theoretical and practical energy densities for the five most commonly used primary battery types in terms of watt-hours/kilogram. The energy density in terms of watt-hours/liter is given to compare the volume requirements.

The energy density values shown in table 3-1 are based upon a 119-hour current drain. To realize these values, the DAPS energy system would require some form of load leveling to provide a constant power drain for the 119-hour life of the system.

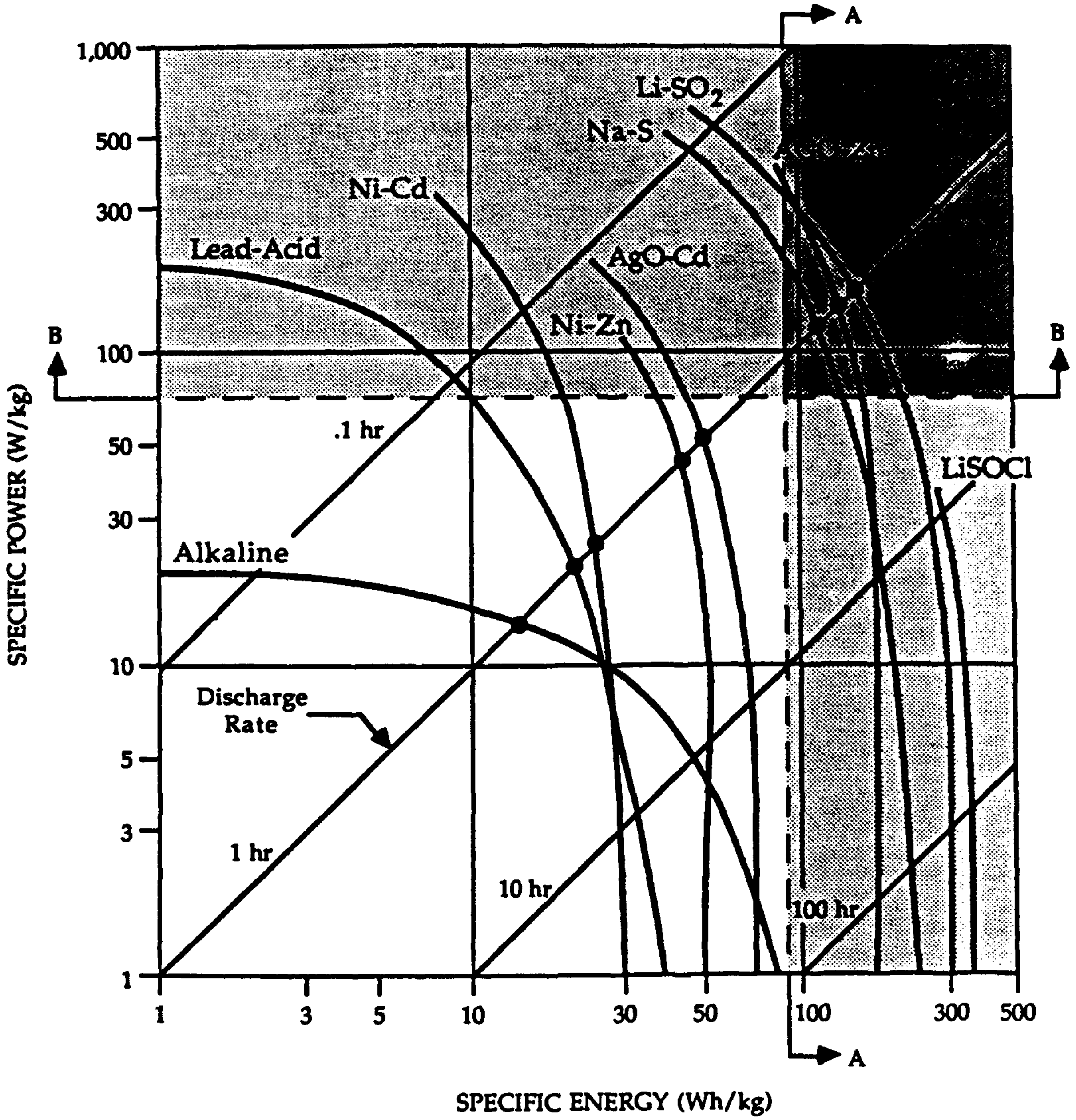


Figure 3-5. Power Characteristics of Battery Systems

Table 3-1. Energy Capacity
119-Hour Discharge Rate

Battery System		Capacity - 119-Hour Rate: Theoretical (Wh/kg)	Theoretical (Wh/lb)	Practical (Wh/kg)	Practical (Wh/lb)	Practical (Wh/l)	Practical (Wh/ft^3)
Primary							
Lithium-sulfur dioxide	Li/SO_2	1175	533	300	136	425	12,040
Lithium-thionyl chloride	$Li/SOCl_2$	N/A	N/A	340	154	675	19,122
Manganese dioxide, alkaline	Zn/MnO_2	350	159	90	41	200	5,666
Mercuric oxide	Zn/HgO	250	113	100	45	320	9,065
Silver oxide	$ZnAg_2O$	290	132	130	59	515	14,589
Secondary							
Sealed lead-acid	Pb/PbO_2	250	113	35	16	80	2,266
Nickel-cadmium	$Cd/NiOH_2$	240	109	35	16	80	2,266
Silver-zinc	Zn/AgO	500	227	180	82	490	13,881
Silver-cadmium	Cd/AgO	318	144	80	36	165	4,674
Sulfur-sodium	Na/S	790	358	190	86	285	8,074
Reserve							
Lithium-thionyl chloride[1]	$Li/SOCl_2$	1470	667	165	75	245	6,941
Lithium-silver oxide[1]	Li/AgO	1370	621	200	91	290	8,215
Aluminium-silver oxide[1]	Al/AgO	1040	472	170	77	250	7,082
Fuel cell, alkaline	H-O/HOH	N/A	N/A	660	299	933	26,431
Hydrocarbon (internal combustion engine)	--		N/A	2234	1013	1084	30,708

In general, primary batteries provide the highest energy density of the various battery types considered, but they also have the lowest power density.

All of the types listed, except the alkaline battery, meet the DAPS energy source weight and volume requirement. The figures shown in table 3-1 are based upon operating temperature in excess of 20°C and would require derating for actual operating temperatures.

The mercuric oxide battery probably would be ruled out on the basis of low-temperature performance. The silver oxide battery is available only in small (button) sizes. The lithium batteries in D-size or larger cells will provide in excess of 3000 Wh/kg of energy storage.

[1]Discharged at 0.10/hour rate (no other data available).

The lithium-thionyl chloride batteries have the highest energy density in terms of weight and volume, followed by the lithium-sulfur dioxide. On the basis of the 132-kWh energy requirement, the cell count using Li/SO_2 D cells will exceed 5000 if load leveling is used and will exceed 9000 if direct conversion is used. Because of the number of cells required, the use of lithium cells presents a safety hazard.

The mean time between failures (MTBF) for a lithium-battery-based energy source would be 2469 hours. This MTBF is based upon a failure rate of 4.5×10^{-8} cells per hour as listed in the ERAPS DAU battery specification.

3.2.3 Secondary Batteries

The five most commonly used and readily available secondary batteries are listed in table 3-1. Lead acid and nickel-cadmium batteries are similar in energy and power density, but both fare poorly in comparison to primary lithium batteries. The energy density at 35 Wh/kg is only 10% of the lithium capability and only 15% in terms of energy per unit volume. The silver-cadmium battery at 80 Wh/kg is better, but falls short of the 96-Wh/kg minimum requirement.

The silver-zinc storage battery appears to meet both size and weight requirements. The energy density of 180 Wh/kg is well above the minimum 96-Wh/kg requirement, while the energy/volume ratio of 490 Wh/l surpasses lithium-sulfur dioxide primary cells.

Sulfur-sodium storage cells are still largely in the developmental stage. These cells offer an energy density comparable to silver-zinc but at a much lower cost. The sulfur-sodium cell is considered to be a future energy source for electric traction vehicles. The sulfur-sodium cell is not a viable candidate for the DAPS requirement because the cell has not reached commercial production status.

3.2.4 Reserve Batteries

The reserve battery offers two unique advantages over primary and secondary battery systems:

(1) greater safety during storage and deployment and
(2) a potentially very high power density.

The safety concern for high-energy systems is a serious problem. The reserve electrolyte system of activating a battery essentially reduces the hazards of primary battery systems before deployment.

The higher power density attainable with reserve batteries (where storage life is not dependent upon internal cell leakage) allows for the design of a battery capable of extremely high current drains. This type of battery would allow direct energy conversion without the need for load leveling.

Three examples of a high power density reserve system are shown in table 3-1. These are the lithium-thionyl chloride, lithium-silver oxide, and the aluminum-silver oxide battery system, developed by SAFT for the MK-50 ALWT requirement. These batteries demonstrated an energy density of up to 200 Wh/kg and a power density over 2000 W/kg.

3.2.5 Fuel Cell

Listed among the reserve batteries in table 3-1 is a fuel cell. This particular fuel cell is an alkaline (hydroxide) unit similar to the one currently used in the space shuttle. The fuels used are gaseous hydrogen and oxygen. The energy storage density is high, 660 Wh/kg and 933 Wh/l.

The fuel cell generally is designed for a moderate power density and is best used in conjunction with a load leveling system.

3.2.6 Internal Combustion Engine

No other energy source can compete in terms of volume efficiency with the internal combustion engine. The engine listed in figure 3-1 is a small four-horsepower, four-cycle unit that can be designed to operate from gasoline or propane or any other appropriate fuel source.

The energy density, including the weight of the engine and fuel for a 119-hour operation, is 2234 Wh/kg or 1085 Wh/l. This is by far the highest energy density available for any type of energy source, but it must be offset by the weight of the additional equipment needed to convert the energy into electrical form. The size and weight advantage is compromised further by the need to operate the engine near the surface (snorkel operation) and to transmit power down a cable to the subsurface unit. However, the advantages of low cost, high reliability, and overall safety make this energy source very attractive.

3.2.7 Size and Weight - 119-Hour Discharge Rate

Estimates of the size and weight of the various energy sources is provided in table 3-2, based upon a 119-hour discharge rate. The lithium-thionyl chloride battery provides both the lowest weight and the smallest size of the primary cells. The 854-pound weight estimate is well below the 3000-pound upper limit, while the projected volume of 6.9 ft^3 is well below the 20-ft^3 allowance. These values are followed closely by the size and weight estimates for lithium-sulfur dioxide battery.

Of the currently available secondary, or storage, batteries only the silver-zinc battery meets the weight and volume restrictions. At 1613 pounds and 9.5 ft^3, the silver-zinc battery is a

Table 3-2. Size and Weight Estimates
119-Hour Discharge Rate

Battery System		Size and Weight To Meet 132-kWh Requirement: Weight (lb)	Volume (ft^3)
Primary			
Lithium-sulfur dioxide	Li/SO_2	968	11.0
Lithium-thionyl chloride	$Li/SOCl_2$	854	6.9
Manganese dioxide, alkaline	Zn/MnO_2	3226	23.3
Mercuric oxide	Zn/HgO	2904	14.6
Silver oxide	Zn/Ag_2O	2234	9.1
Secondary			
Sealed lead-acid	Pb/PbO_2	8297	58.3
Nickel-cadmium	$Cd/NiOH_2$	8297	58.3
Silver-zinc	Zn/AgO	1613	9.5
Silver-cadmium	Cd/AgO	3630	28.3
Sulfur-sodium	Na/S	1508	9.1
Reserve			
Lithium-thionyl chloride[1]	Li/SOCl2	1760	19.0
Lithium-silver oxide[1]	Li/AgO	1708	16.4
Aluminum-silver oxide[1]	Al/AgO	1416	18.6
Fuel cell	H-O/AgO	441	5.0
Hydrocarbon (internal combustion engine)		130	4.3

[1]Discharged at 0.10/hour rate (no other data available).

reasonably good choice for an indirect conversion system. The silver-zinc cells have a long and proven record for high reliability and performance.

The reserve batteries listed are designed for high-current, short-life application and probably would not meet the 119-hour life requirement because of internal leakage while activated.

The fuel cell at 441 pounds and 5.0 ft^3 volume is a clear winner among chemical energy sources for low-drain systems. As with other indirect conversion systems, the weight of the energy storage and load leveling component must be included.

Of all systems considered, the internal combustion engine, at 130 pounds and 4.3 ft^3 volume, is the lightest and smallest energy source available. Here again, considerable weight must be added to convert the mechanical energy to a usable form.

3.2.8 Energy Capacity – 1.32-Hour Discharge Rate

The 1.32-hour discharge rate is based upon direct conversion of energy at 100-kW peak pulse levels such that the cumulative drain on the battery is 132 kWh; a total of 475 pulses of 10-second duration is assumed to equal a 100-kW discharge of 1.32-hour duration. The capacity of the various energy sources at the 1.32-hour discharge rate is given in table 3-3. In addition to the capacity in terms of energy density, the power density of the batteries (i.e., W/kg and W/l) is provided.

To meet the direct conversion energy and power density requirement, the battery characteristic must exceed the limits AA and BB (dashed lines) shown in figure 3-5. The minimum energy and power densities required are 96 Wh/kg and 73 W/kg, respectively.

Only three battery types (shown in the upper right corner of figure 3-5) meet these requirements:

(1) silver-zinc (secondary),
(2) sulfur-sodium (secondary), and
(3) lithium-sulfur dioxide (primary).

Table 3-3. Energy Capacity
1.32-Hour Discharge Rate

Battery System		Capacity – 1.32-Hour Rate: Energy Density Wh/kg	Wh/lb	W/l	W/ft³	Power Density Wh/kg	Wh/lb	W/l	W/ft³
Primary									
Lithium-sulfur dioxide	Li/SO_2	176	80	250	7,082	133	60	188	5,326
Lithium-thionyl chloride	$Li/SOCl_2$	NA	NA	NA	NA	NA	NA	NA	NA
Manganese dioxide, alkaline	Zn/MnO_2	15	7	34	963	11	5	26	737
Mercuric oxide	Zn/HgO	11	5	35	992	8	4	27	765
Silver oxide	Zn/Ag_2O	121	55	478	13,541	91	44	361	10,227
Secondary									
Sealed lead acid	Pb/PbO_2	22	10	50	1,416	17	8	37	1,048
Nickel-cadmium	$Cd/NiOH_2$	27	12	63	1,785	21	10	47	1,331
Silver-zinc	Zn/AgO	154	70	419	11,870	116	53	316	8,952
Silver-cadmium	Cd/AgO	60	27	124	3,513	46	21	94	2,663
Sulfur-sodium	Na/S	132	60	198	5,609	100	45	149	4,221
Reserve									
Lithium-thionyl chloride[1]	Li/SOCl2	165	75	245	6,941	1650	748	245	6,941
Lithium-silver oxide[1]	Li/AgO	170	77	290	8,215	2035	923	290	8,215
Aluminum-silver oxide[1]	Al/AgO	205	93	250	7,082	1690	767	250	7,082

The reserve batteries shown have the potential to meet the energy and power density requirements, but they will not meet the 119-hour life without a redesign to reduce internal leakage while activated.

3.2.9 Size and Weight – 1.32-Hour Discharge Rate

The size and weight of the lithium-sulfur dioxide battery, while still within limits, is nearly double compared to the 119-hour values. The weight as shown in table 3-4 is up to 1650 pounds compared to 968 for the 119-hour rate. The size shows an increase from 11.0 to 18.7 ft^3.

[1] Discharged at 0.10/hour rate (no other data available).

Table 3-4. Size and Weight
1.32-Hour Discharge Rate

Battery System		Direct Conversion (1.32 Hour) Size and Weight To Meet 132-kWh Requirement Weight (lb)	Volume (ft^3)
Primary			
Lithium-sulfur dioxide	Li/SO_2	1,650	18.7
Lithium-thionyl chloride	$Li/SOCl_2$	NA	NA
Manganese dioxide, alkaline	Zn/MnO_2	19,360	137.0
Mercuric oxide	Zn/HgO	26,400	133.0
Silver oxide	Zn/Ag_2O	2,400	9.75
Secondary			
Sealed lead-acid	Pb/PbO_2	13,200	93.0
Nickel-cadmium	$Cd/NiOH_2$	10,750	74.0
Silver-zinc	Zn/AgO	1,885	11.1
Silver-cadmium	Cd/AgO	4,840	37.6
Sulfur-sodium	Na/S	2,200	23.5
Reserve			
Lithium-thionyl chloride[1]	Li/SOCl2	1,760	19.0
Lithium-silver oxide[1]	Li/AgO	1,708	16.0
Aluminum-silver oxide[1]	Al/AgO	1,416	19.0

The silver-zinc battery shows a much smaller increase in both size and weight (approximately 15%). However, the silver-zinc battery has a considerable size advantage, 11.1 ft^3 compared to 18.7 ft^3 required for lithium-sulfur dioxide. The sulfur-sodium battery is a weak third and is out of specification in terms of volume (23.5 ft^3).

3.2.10 Linearity Characteristics

The discharge profile is affected by operating load and temperature. In general, a flat profile is preferred to avoid undesired voltage regulation with attendant losses, or variations in delivered load power. The discharge profiles and the power densities of the various battery systems are compared in table 3-5.

[1]Discharged at 0.10/hour rate (no other data available).

Table 3-5. Linearity Characteristics

Battery System		Linearity: Discharge Profile	Linearity: Power Density
Primary			
Lithium-sulfur dioxide	Li/SO_2	very flat	high
Lithium-thionyl chloride	$Li/SOCl_2$	flat	moderate
Manganese dioxide, alkaline	Zn/MnO_2	moderate slope	low
Mercuric oxide	Zn/HgO	flat	low
Silver oxide	Zn/Ag_2O	flat	high
Secondary			
Sealed lead-acid	Pb/PbO_2	flat	high
Nickel-cadmium	$Cd/NiOH_2$	very flat	high
Silver-zinc	Zn/AgO	double plateau	high
Silver-cadmium	Cd/AgO	double plateau	moderate
Sulfur-sodium	Na/S	flat	high
Reserve			
Lithium-thionyl chloride	Li/SOCl2	moderate slope	very high
Lithium-silver oxide	Li/AgO	moderate slope	very high
Aluminum-silver oxide	Al/AgO	moderate slope	very high
Fuel cell	H-O/HOH	flat	moderate
Hydrocarbon (internal combustion engine)		flat	low

Silver-zinc and silver-cadmium batteries have a double plateau charge/discharge characteristics, which result in a discrete step in the voltage discharge profile. This is a result of a change in the chemical reaction in the middle of a cycle.

3.2.11 Cost Comparison

Table 3-6 provides a cursory look at the energy source costs in terms of dollars/kWh. Table 3-6 compares the costs based upon various chemistries that are indicative of the total supply cost. The energy cost figures are used to estimate the cost of a 132-kWh energy source in terms of initial and replacement cost, but they do not reflect the savings resulting from recharging of secondary battery systems. Cost for reserve cells is not available because of the special (noncommercial) designs (and unique cost) for every battery system.

Table 3-6. Cost Comparison

Battery System		Energy Cost (dollars/kWh)	Battery Replacement (Total System) (dollars/132 kWh)
Primary			
Lithium-sulfur dioxide	Li/SO_2	\$ 250.0	\$ 33,000
Lithium-thionyl chloride	$Li/SOCl_2$	\$ 250.0	\$ 33,000
Manganese dioxide, alkaline	Zn/MnO_2	\$ 70.0	\$ 9,200
Mercuric oxide	Zn/HgO	\$ 450.0	\$ 59,000
Silver oxide	Zn/Ag_2O	\$4000.0	\$528,000
Secondary			
Sealed lead-acid	Pb/PbO_2	\$ 50.0	\$ 6,600
Nickel-cadmium	$Cd/NiOH_2$	\$1000.0	\$132,000
Silver-zinc	Zn/AgO	\$1150.0	\$152,000
Silver-cadmium	Cd/AgO	\$1500.0	\$198,000
Sulfur-sodium	Na/S	NA	NA
Reserve			
Lithium-thionyl chloride[1]	Li/SOCl2	NA	NA
Lithium-silver oxide[1]	Li/AgO	NA	NA
Aluminum-silver oxide[1]	Al/AgO	NA	NA
Fuel cell	H-O/HOH	NA	NA
Hydrocarbon (internal combustion engine)	--	\$ 1.65	\$ 18 (propane)

[1]Discharged at 0.10/hour rate (no other data available).

SECTION 4
ENERGY INVERSION TECHNIQUES

To convert the source energy to a form suitable for driving a high-power acoustic projector, several inversion techniques were considered. The energy sources consisted of primary and secondary batteries, a fuel cell, and an internal combustion engine.

The energy inverters included a solid-state dc/ac inverter, motor generator, flywheel, and a variable-speed, constant-frequency (VSCF) aircraft generator. Energy conversion was accomplished in both direct and stored form using mechanism storage.

4.1 INVERTER METHOD A

Method A shown in figure 4-1 utilizes a lithium-sulfur dioxide primary battery as the energy source. Direct energy conversion is used with a solid-state inverter to convert the battery voltage to a sonic frequency drive for the transducer array.

Energy is drawn from the battery in 100-kW, 10-second pulses at 15-minute intervals. The inverter weight and volume characteristics are based upon commercial equipment operating at similar power and frequency values. The inverter weight scaling factor was 70 W/lb.

Energy Source	Power Converter	Load
PRIMARY BATTERY ⇨	SOLID STATE INVERTER ⇨	TRANSDUCER ARRAY
Type = Lithium (Li/SO_2) w = 1650 lb Vol = 18.7 ft^3 No. Cells = 8860 D size Drain = 100 kW	P_0 = 100 kW w = 1428 lb Vol = 24 ft^3 t = 10 s	SL = 241 dB/µPa (eff) DI = 10 dB t = 10 s

Total Weight: 3078 lb
Total Volume: 43 ft^3

Figure 4-1. Inverter Method A

Examples of commercial grade dc-ac static inverter systems shown in EEM 88, 89[1] provide an insight to the size and weight requirements for direct conversion energy systems, methods A and B. Based upon the power/weight ratios of the units shown (i.e., 10 W/lb to 100 W/lb), an optimistic value of 70 W/lb was used to predict the weight of the inverters used in methods A and B.

The power source of method 1 weighs 3078 pounds and has a volume of 43 ft^3. The weight and volume are divided evenly between the battery and the inverter.

4.2 INVERTER METHOD B

Method B is identical to method A except a secondary type of battery (silver-zinc) is used in place of the primary battery. This results in a slight increase in total weight and a small drop in total volume. The total weight of the power source is 3313 pounds and the volume is 35.1 ft^3 (figure 4-2).

4.3 INVERTER METHOD C

Method C is an energy storage system utilizing a flywheel for load leveling. The energy source is a primary battery (lithium-sulfur dioxide) operated at a low level (figure 4-3).

The battery power is used to drive a 2-horsepower electric motor, which in turn is used to drive a 200-pound flywheel at a high speed (10,000 rpm). The flywheel is coupled directly to a VSCF (variable speed constant frequency) generator that supplies 100 kW, 10-second sonar frequency pulses to the transducer array. The method 3 power source weighs 1378 pounds and has a volume of 20 ft^3. This is an appreciable saving in size and weight compared to the direct inversion method.

Calculations in support of the flywheel energy support system are given in appendix A. An example of an aircraft VSCF generator design is given in the *Handbook for Electrical Engineers*.[2] Table 21-4 of the *Handbook* lists the characteristics of typical aircraft generators in terms of kilovolt-ampere rating, size, weight, and other pertinent parameters. This table

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[1] *Electronics Engineers Master Catalog*, volume D, *Power Sources, Instrumentation, Computer Products, and Equipment*, 31st edition.

[2] *Handbook for Electrical Engineers*, 10th edition, Fink and Carroll, McGraw-Hill, 1968, p. 21-9, 21-10.

Energy Source	Power Converter	Load
SECONDARY BATTERY	SOLID STATE INVERTER	TRANSDUCER ARRAY
Type = Silver-Zinc w = 1885 lb Vol = 11.1 ft^3 Drain = 100 kW	P_o = 100 kW w = 1428 lb Vol = 24 ft^3 t = 10 s	SL = 241 dB/µPa (eff) DI = 6 dB t = 10 s

Total Weight: 3313 lb

Total Volume: 35.1 ft^3

Figure 4-2. Inverter Method B

Energy Source	Power Converter	Energy Storage	Driver	Load
PRIMARY BATTERY	ELECTRIC MOTOR	FLYWHEEL STORAGE	VSCF GENERATOR	TRANSDUCER ARRAY
Type = Lithium (Li/SO_2) w = 968 lb Vol = 11 ft^3 No. Cells = 5200 D size Drain = 1100 watts	P_o = 2 hp w = 10 lb Vol = 0.5 ft^3	E = 896 Wh ΔE = 277 Wh w = 200 lb Vol = 0.5 ft^3 ω_1 = 10,000 rpm ω_2 = 8,300 rpm	P_o = 100 kW t = 10 s w = 200 lb Vol = 8.0 ft^3	SL = 241 dB/µPa (eff) DI = 10 dB t = 10 s

Total Weight: 1378 lb

Total Volume: 20 ft^3

Figure 4-3. Inverter Method C

was used in the estimates of size and weight for the DAPS energy source using stored mechanical energy such as in inverter methods C, D, E, and F. Figure 21-5 of the *Handbook* is a block diagram of a VSCF generator system used to generate a discrete frequency output voltage with a variable armature speed.

4.4 INVERTER METHOD D

Method D is identical to method C with a secondary (silver-zinc) battery substituted for the lithium primary battery. The weight is considerably higher (2023 pounds compared to 1378 pounds), and there is a slight reduction in volume (18.5 ft^3 compared to 20.0 ft^3) (figure 4-4).

4.5 INVERTER METHOD E

Method E substitutes a fuel cell for the battery as an energy source. Otherwise, the system is identical to method C and method D. With a total fuel cell weight (including fuel for 119 hours of operation) of 341 pounds, the total system weight is reduced to 851 pounds. The volume is reduced to 14 ft^3 (figure 4-5).

4.6 INVERTER METHOD F

Method F is a totally unique system using an internal combustion engine as an energy source. The system can be designed to operate from gasoline or propane, but it requires an air intake. Consequently, operation near the surface is required (snorkel breather). Since power must be transmitted down the signal/suspension cable to the lower unit, an additional motor-generator set is required. The total fuel weight for 119 hours of operation is 110 pounds.

Even with the additional power conversion functions, the total system weight is less than for the other inversion methods. The total power source weight is estimated at 550 pounds, with a volume of 13.8 ft^3 (figure 4-6). Calculations in support of these estimates are given in appendix B.

Energy Source	Power Converter	Energy Storage	Driver	Load
SECONDARY BATTERY ⇨	ELECTRIC MOTOR ⇨	FLYWHEEL STORAGE ⇨	VSCF GENERATOR ⇨	TRANSDUCER ARRAY
Type = Silver-Zinc w = 1613 lb Vol = 9.5 ft^3 Drain = 1100 watts	P_o = 2 hp w = 10 lb Vol = 0.5 ft^3	E = 896 Wh ΔE = 277 Wh w = 200 lb Vol = 0.5 ft^3	P_o = 100 kW t = 10 s w = 200 lb Vol =8.0 ft^3	SL = 241 dB/μPa (eff) DI = 10 dB t = 10 s

Total Weight: 2023 lb

Total Volume: 18.5 ft^3

Figure 4-4. Inverter Method D

Energy Source	Power Converter	Energy Storage	Driver	Load
FUEL CELL ⇨	ELECTRIC MOTOR ⇨	FLYWHEEL ⇨	VSCF GENERATOR ⇨	TRANSDUCER ARRAY
Type = Alkaline H-O/KOH w = 341 lb w enclosure = 100 lb Vol = 5 ft^3 Drain = 1100 watts	P_o = 2 hp w = 10 lb Vol = 0.5 ft^3	E = 896 Wh ΔE = 277 Wh w = 200 lb Vol = 0.5 ft^3 ω_1 = 10,000 rpm ω_2 = 8,300 rpm	P_o = 100 kW t = 10 s w = 200 lb Vol =8.0 ft^3	SL = 241 dB/μPa (eff) DI = 10 dB t = 10 s

Total Weight: 851 lb

Total Volume: 14 ft^3

Figure 4-5. Inverter Method E

Energy Source	Energy Converter	Energy Converter	Power Converter	Energy Storage	Driver	Load
GASOLINE PROPANE ⇨	INTERNAL COMBUSTION ENGINE ⇨	GENERATOR DC ⇨	MOTOR DC ⇨	FLYWHEEL ⇨	VSCF GENERATOR ⇨	TRANSDUCER ARRAY
w = 110 lb Vol = 2.3 ft^3	P_o = 2 hp w = 20 lb Vol = 2.0 ft^3	P_o = 2 kW w = 10 lb Vol = 0.5 ft^3	P_o = 2 hp w = 10 lb Vol = 0.5 ft^3	E = 896 Wh ΔE = 277 Wh w = 200 lb Vol = 0.5 ft^3	P_o = 100 kW t = 10 s w = 200 lb Vol =8.0 ft^3	SL = 241 dB/μPa (eff) DI = 10 dB t = 10 s

Total Weight: 550 lb

Total Volume: 13.8 ft^3

SECTION 5
STOWAGE AND DEPLOYMENT

The deployed configurations for each of the inverter methods are shown in figures 5-1, 5-2, and 5-3.

Figure 5-1, for inverter methods A and B using direct inversion, requires the energy source (batteries) to be located near the transducer to avoid large cable losses.

The energy source for inverter methods C, D, and E shown in figure 5-2 can be located in either the upper or lower units. Locating the source at the surface allows simpler repair, replacement or recharging of the batteries, or replenishment of the fuel supply for the fuel cell.

The stowage and deployment configuration for the internal combustion engine (figure 5-3) requires the engine to be near the air supply. Thus, the engine and fuel tank are located in the surface unit. A generator located in the surface unit converts the mechanical power to electrical for transmission down the power/signal cable. The low-level power (1100 watts) transmitted down the cable is used to drive a motor flywheel energy storage system, coupled to a VSCF generator. The VSCF generator in turn supplies the high-level sonar frequency pulses to the transducer array.

The losses in the power cable will be minimal. For example, 1100 watts of power transmitted down the cable to a depth of 500 feet, using number 10 conductor, at an RMS current of 5 amperes will result in a loss of only 60 watts.

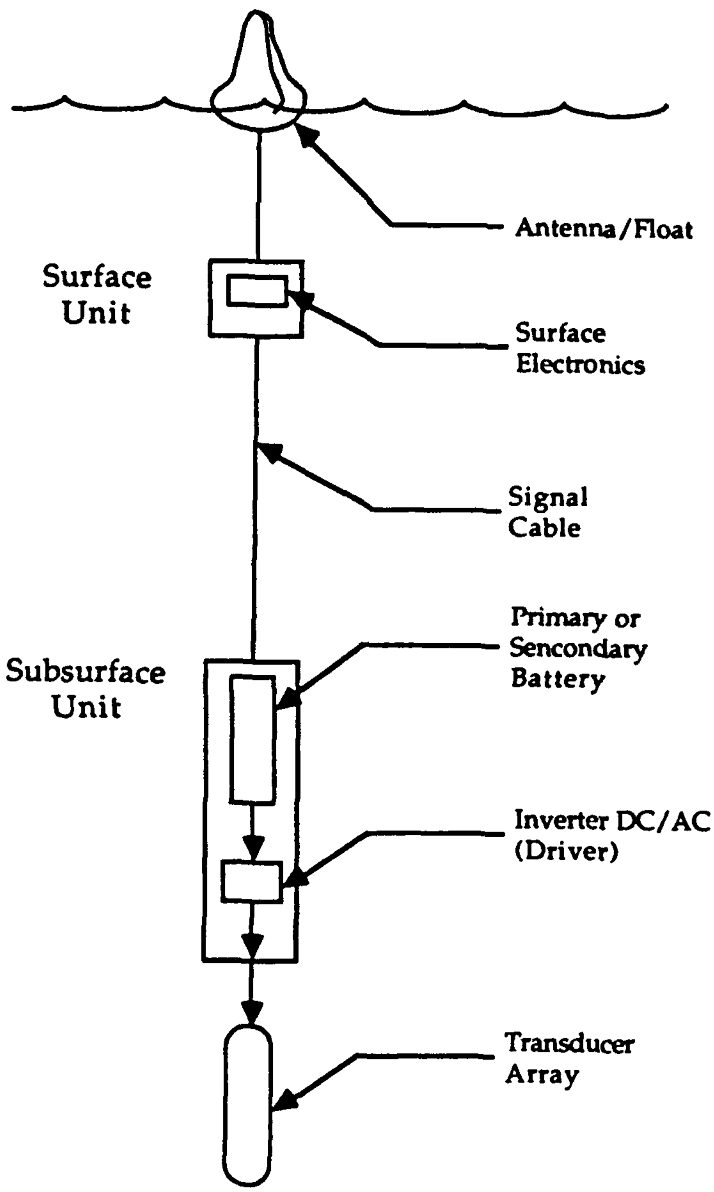

Figure 5-1. Stowage and Deployment Inverter Methods A and B, Direct Inversion

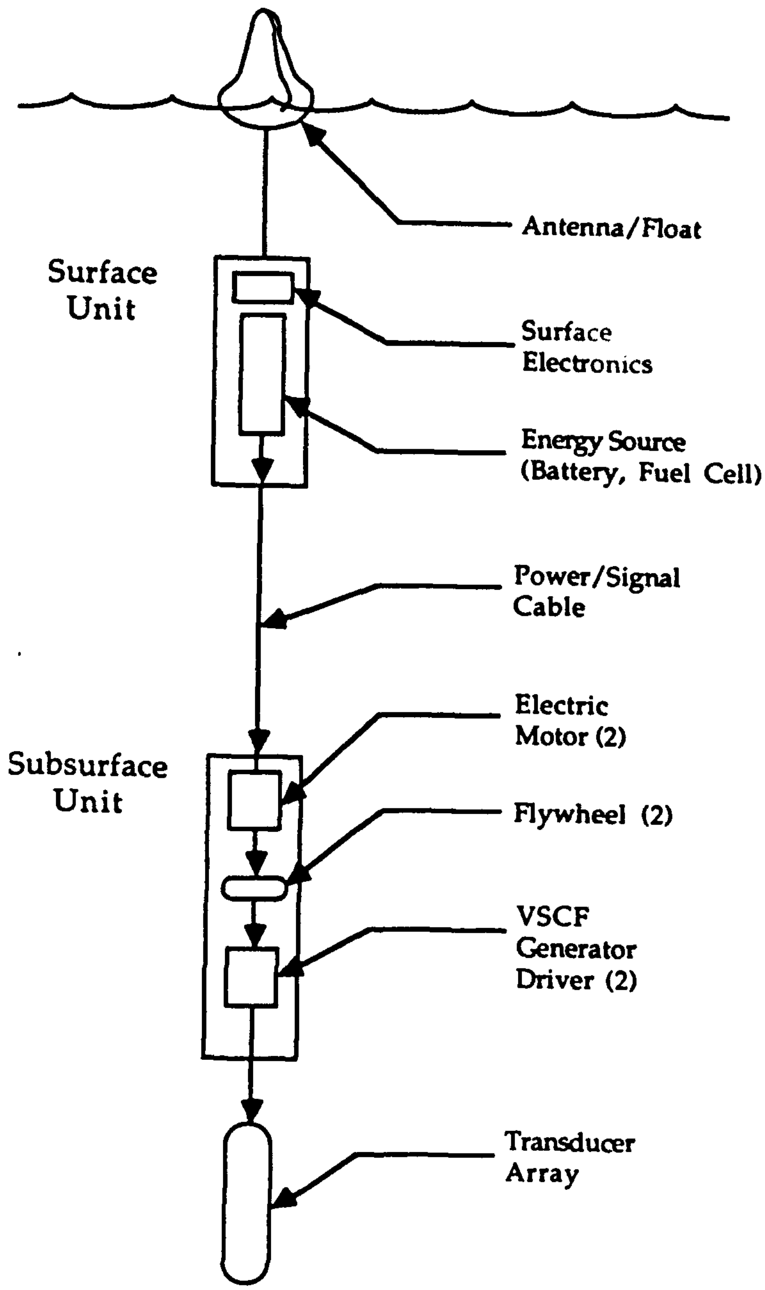

Figure 5-2. Stowage and Deployment Inverter Methods C, D, and E, Load Leveling

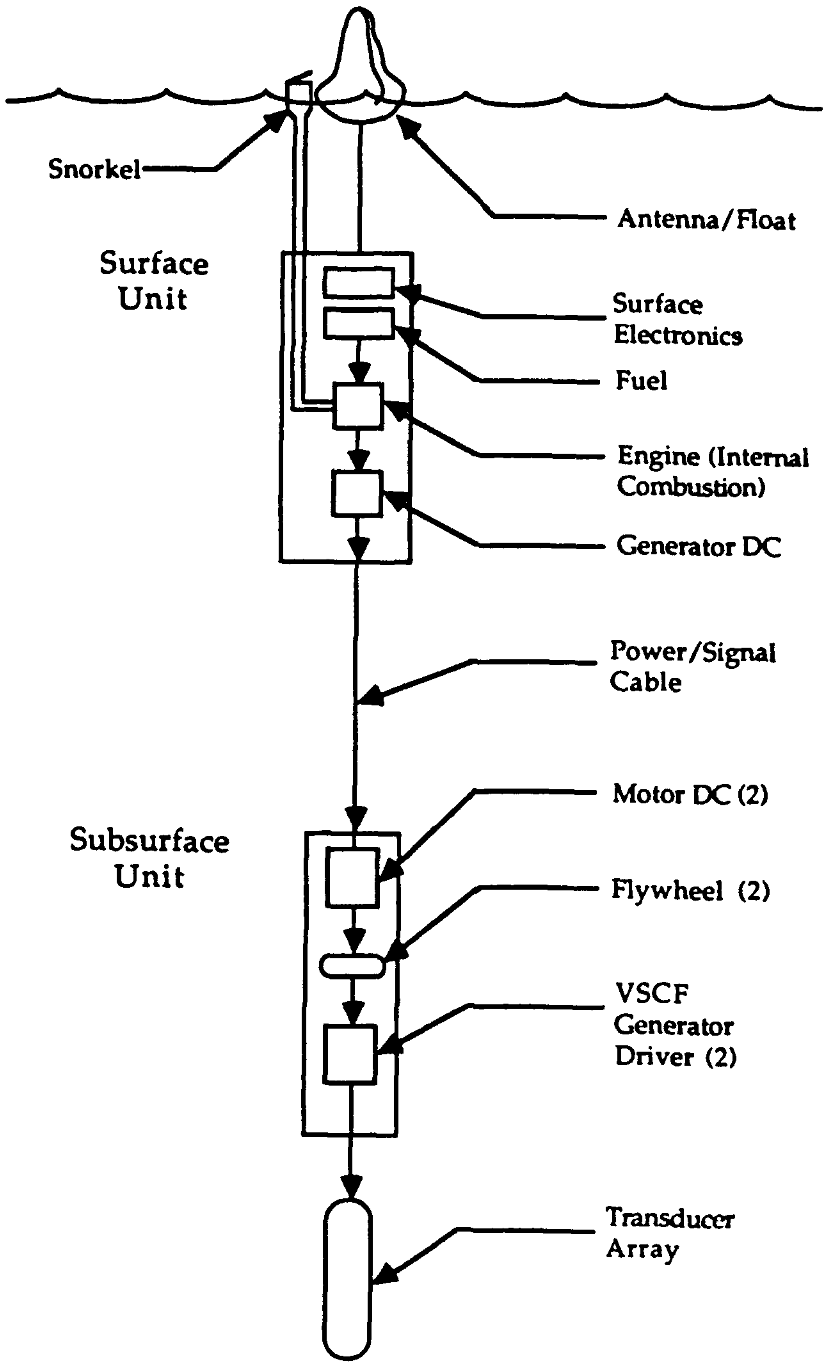

Figure 5-3. Stowage and Deployment Inverter Method F, Internal Combustion Engine

SECTION 6

ADVANCED POWER SOURCES

Sparton chose not to include advanced power sources in this study, since those considered applicable are still in early phases of development and not yet commercially available. These advanced power sources are, however, worthy of future consideration, because of their potentially high energy densities and small volume. These sources may prove themselves with low operating costs and reduced maintenance requirements. Future consideration of these concepts will likely be made after comprehensive test and evaluation on the commercial market.

6.1 ALUMINUM AIR

There are several advantages associated with use of an aluminum air power source:

(1) it has high theoretical energy density (8.135 Wh/kg) with 300 Wh/kg achievable at this time,

(2) it is lightweight,

(3) it uses widely available nonhazardous materials, and

(4) it is safe to operate.

Because the cathode is air, the bulk of the power source volume would be taken by the anode. This gives much greater capacity than would be available with power sources containing both active electrodes.

Although aluminum air at first glance may not seem like a new power source technology, use of aluminum air in underwater applications is. This is because there is no direct efficient means of supplying air/oxygen to the underwater source. However, a new artificial gill technology is evolving, which holds promise of making underwater aluminum air power source applications feasible.

This new artificial gill technology is being developed by Aquanautics, a California firm, and has been funded by DARPA. In fact, DARPA has awarded Aquanautics a $1.2 million extension to continue this effort through FY-88. A small 15-watt fuel cell system (aluminum air) having a 3-day life has been demonstrated. Aquanautics intends to develop a 300-watt power source using the DARPA funds.

The artificial gill has three subsystems: a matrix of hollow fiber membranes through which oxygen diffuses, an oxygen-binding carrier fluid, and a chamber used to separate oxygen electrochemically. This system emulates the function of hemoglobin in the human blood.

6.2 NUCLEAR

Another potential power source that is not necessarily new but has a new twist is nuclear. Periferal Systems, Inc., of Portland, Oregon, announced in *Design News*, September 1988, that a new nuclear battery (Nucell) is under development that converts nuclear energy directly into electric energy rather than the traditional method of conversion of heat energy into electrical energy. This new technology yields an increase of 100,000 times over conventional methods.

The new system uses nuclear waste products (strontium-90), which are enhanced for this purpose. Strontium-90 has an upper yield of 7500 watts per gram. A Nucell the size of a soup can would be able to produce 75 watts and a wastebasket size would be able to produce 50 kW. Half-life of strontium is 28 years.

Nucell has no moving parts and will be able to produce power for years. There is no concern over radiation since the alpha particles can be contained by a piece of paper and the beta particles can be contained by 0.03 inch of aluminum. Research and development cost of this battery is likely to exceed $5 million.

Both of these power sources, when fully developed, have the potential capability of supplying the energy needs of DAPS as well as other devices requiring large power demands. One of the greatest difficulties in meeting high pulse power demands such as required in DAPS is developing a power source that can meet required high current densities without resulting in gross overcapacity. Minimum material thicknesses plus large electrode surface areas usually will result in an overcapacity condition and prevent achievement of the smallest package design.

SECTION 7
RECOMMENDATIONS

To determine the most suitable energy source for the DAPS concept, the six energy inversion methods described in section 4 were ranked on the basis of five physical and operational parameters:

(1) weight,
(2) size,
(3) reliability,
(4) procurement cost, and
(5) operating cost (10 missions).

The rankings are given in table 7-1 on the basis of 1 to 6, where 1 is the best choice for a given characteristic.

The battery-powered systems using direct energy conversion are clearly the poorest choices in nearly all categories. The lithium-powered systems using indirect conversion are acceptable but suffer from poor reliability and high extended operating cost. Silver-zinc batteries incur a large weight penalty plus a high initial cost using the indirect conversion system.

The fuel cell is a good choice but will have a high development cost. The internal combustion engine appears to be the best overall selection, but there is little experimental data to support this choice. However, since the internal combustion engine, combined with the suggested flywheel energy storage technique, is based upon proven technology, the development risk is quite low.

On the basis of the results of this study, Sparton recommends the internal combustion engine system be pursued as the energy source portion of the DAPS. Should factors not considered within this study make this system unusable, the fuel cell energy source with load leveling is our recommendation.

Sparton further recommends that additional research and/or preliminary development effort related to nontraditional power sources and fuel cells be conducted. This effort should be carried out in parallel with a program to modify existing VSCF generator equipment to include additional initial energy storage.

Table 7-1. Energy Source Ranking

Inverter Reference Method	Energy Source	Inversion	Weight*	Size*	Reliability*	Initial Cost*	10-Mission Operating Cost*	Total Points†
A	Primary-lithium	Direct	6	6	6	3	6	27
B	Secondary-Zn/AgO	Direct	5	5	4	5	4	23
C	Primary-lithium	Indirect	3	4	5	2	5	19
D	Secondary-Zn/AgO	Indirect	4	3	3	4	3	17
E	Fuel cell	Indirect	2	2	1	6	2	13
F	Gas engine	Indirect	1	1	2	1	1	6

*1 is best, 6 is worst.

†Lowest total is best.

APPENDIX A

FLYWHEEL ENERGY STORAGE

The energy stored in a flywheel is proportional to its mass, its radius (effective), and its rotational speed. When energy is transferred into or out of the flywheel, the rotational speed must change. The following derivation calculates the resulting change in rotational speed for a 100-kW, 10-second pulse and a 400-kW, 2-second pulse. This change in speed can be used to select the proper variable-speed, constant-frequency (VSCF) generator for this system.

100-kW Pulse
(figure A-1)

Assume the following:

$$\begin{aligned}
\text{flywheel weight} &= w &&= 100\ \text{lb} \\
\text{radius} &= r &&= 10\ \text{in.} \\
r\ (\text{effective}) &= r_e &&= 9\ \text{in.} = 0.75\ \text{ft} \\
\text{rotational speed} &= \omega_1 &&= 10{,}000\ \text{rpm} = 1047\ \text{rad/s}
\end{aligned}$$

The moment of inertia (I) is the mass (m) times the square of the effective radius for a flywheel system. Mass is the weight divided by the gravitational constant. Therefore:

$$\begin{aligned}
I = m(r_e)^2 = (w/g)(r_e)^2 &= [100\ \text{lb}\ (32\ \text{ft/s}^2)]\ [0.75\ \text{ft}]^2 \\
&= 1.75\ \text{ft-lb-s}^2
\end{aligned}$$

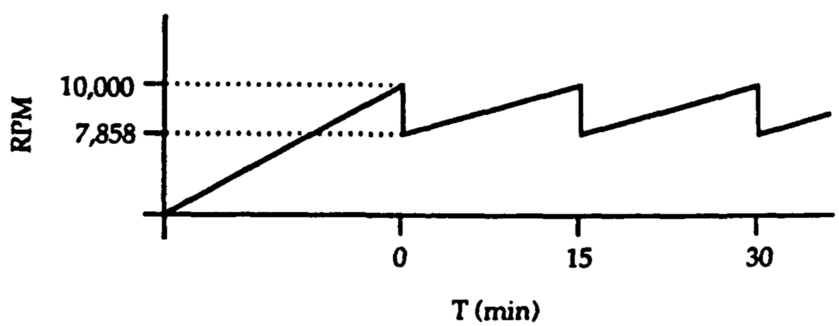

Figure A-1. 100-kW Pulse rpm Profile

The kinetic energy (KE) contained in the system is one-half the moment of inertia times the rotational speed squared. Therefore,

$$KE = (1/2)\, I\, (\omega)^2 = (1/2)(1.76 \text{ ft-lb-s}^2)(1047 \text{ rad/s})^2$$
$$= 964{,}663.9 \text{ ft-lb}$$

The system Sparton has proposed uses two counter rotating flywheels; therefore, the 100-kW pulse can be split equally for each flywheel. The 50-kW pulse with a 10-second duration can be converted to joules (energy) by multiplying the two factors. The joules are converted to foot-pounds by the conversion factor 0.7376. Therefore, the change in kinetic energy of the flywheel system (ΔKE) is:

$$\Delta KE = (50 \text{ kW})(10 \text{ s})(0.7376 \text{ ft-lb/W-s})$$
$$= 3.69 \times 10^5 \text{ ft-lb}$$

The difference between the starting kinetic energy and the change in kinetic energy determines the final kinetic energy KE_2 in the system at the end of the pulse:

$$KE_2 = KE - \Delta KE = 9.65 \times 10^6 \text{ ft-lb} - 3.69 \times 10^5 \text{ ft-lb}$$
$$= 5.96 \times 10^5 \text{ ft-lb}$$

From this number, the rotational speed of the flywheel at the end of the pulse (ω_2) can be calculated from earlier formulas. Therefore:

$$\omega_2 = \sqrt{(2)(KE_2)/I} = \sqrt{(2)(5.96 \times 10^5 \text{ ft-lb}/(1.76 \text{ ft-lb-s}^2)}$$
$$= 822.96 \text{ rad/s}$$
$$= 7858.69 \text{ rpm}$$

Likewise, the 400-kW, 2-second pulse can be substituted into the analysis and the final rotational speed can be calculated. Only the calculations are presented for this pulse.

400-kW Pulse
(figure A-2)

$$\Delta KE = (200\ kW)(2\ s)(0.7376\ ft\text{-}lb/W\text{-}s) = 2.95 \times 10^5\ ft\text{-}lb$$

$$KE_2 = KE - \Delta KE = 9.65 \times 10^5\ ft\text{-}lb - 2.95 \times 10^5\ ft\text{-}lb = 6.7 \times 10^5\ ft\text{-}lb$$

$$\omega_2 = \sqrt{(2)(KE_2)/I} = \sqrt{(2)(6.7 \times 10^5\ ft\text{-}lb/(1.76\ ft\text{-}lb\text{-}s^2)} = 872.56\ rad/s = 8332.35\ rpm$$

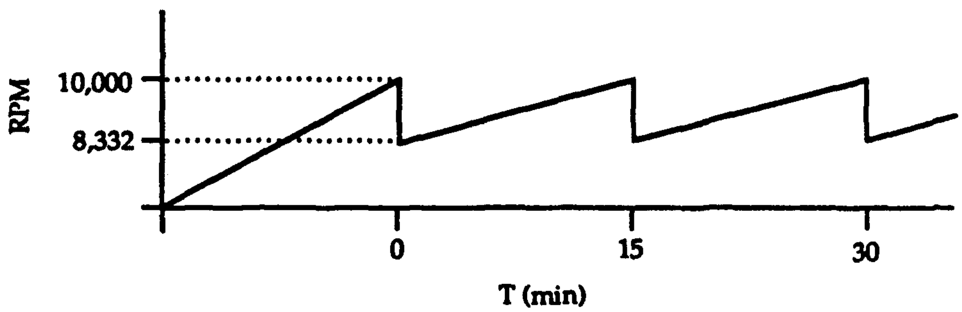

Figure A-2. 400-kW Pulses upon Profile

APPENDIX B
ENERGY STUDY

The size and weight estimates for inverter method F (internal combustion engine) are based upon an engine efficiency of 20%. The energy content of the fuel (regular gasoline) is taken as 125,000 Btu/gal. The conversion factor for British thermal units to kilowatt-hours is:

$$\text{kWh} = 3413 \text{ Btu}$$

The conversion from gallons to pounds is:

$$1 \text{ gallon} = 6.09 \text{ pounds}$$

The energy output then is equal to:

$$E = 0.20 \times 125{,}000 \frac{\text{Btu}}{\text{gal}} \times \frac{1}{6.09} \frac{\text{gal}}{\text{lb}} \times \frac{1}{3413} \frac{\text{kWh}}{\text{Btu}}$$

$$= 1.2 \frac{\text{kWh}}{\text{lb}}$$

For a total energy storage requirement of 132 kWh, the weight of fuel required is:

$$W = 132 \text{ kWh}/1.2 \text{ kWh/lb} = 110 \text{ lb}$$

With an additional 20 lb for the internal conbustion engine, the energy capacity as stated in table 3-1 becomes:

$$E = \frac{132 \text{ kWh} \times 2.2 \frac{\text{lb}}{\text{kg}}}{110 \text{ lb} + 20 \text{ lb}} = 2234 \text{ Wh/kg}$$

The volume of fuel is:

$$V = \frac{110 \text{ lb}}{6.09 \text{ lb/gal}} = 18 \text{ gallons } (2.3 \text{ ft}^3)$$

and the volume of the engine is taken as 2.0 ft^3.

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