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INTRODUCTION

The Space Shuttle Orbiter hydraulic subsystem provides fluid power to all parts of the Orbiter vehicle to drive the actuators which impart movement to flight control surfaces, landing gear, main engine gimbals and valves, and external tank umbilical retraction. The hydraulic subsystem consists of three independent fluid loops operating at a nominal pressure of 3000 psi, each powered by an Auxiliary Power Unit (APU) (1). The APU is a turbine-driven, hydrazine-fueled power unit which provides mechanical shaft power to a pump to pressurize the hydraulic system. The hydrazine fuel is stored in three tanks mounted in the aft section of the Orbiter together with the three APUs (Figure 1). The hydraulic subsystem reaches to all parts of the vehicle to the components which it powers (Figure 2). Figure 3 illustrates the hydraulic subsystem block diagram, and Figures 4 and 5 show the APU system with its major components, and a diagram of the water spray boiler system, respectively.

At the time of design selection for Orbiter subsystems in the early 1970s, an advanced concept of an "all-electric" Orbiter, or an electrically actuated flight vehicle, had been under consideration (2), but this concept was abandoned when it was judged that the technology of electrical actuation, also know as "fly-by-wire,"was not sufficiently mature to merit further consideration at that time.

Today, the state-of-the-art of "fly-by-wire" systems and their associated controls technology, as well as electrical power systems (e.g., batteries, fuel cells, etc.) is greatly advanced over that of two decades ago (3,4). For this reason an investigation was initiated by the Propulsion and Power Division, Power Branch, through the NASA Technology Bridging Program directed by Mr. Donald P. Brown of JSC (5), to perform trade studies of various energy storage and power source systems for electrically actuated space vehicles (launch vehicles, including the SRB and ALS/NLS systems, the Shuttle Orbiter, and Shuttle- derivative systems). This study is presently being conducted by Lamar University for the Power Branch (EP5) under the direction of Ms. Shannan Fisher. The Orbiter portion of the study assumes total electrical actuation for flight control surfaces, landing gear, etc.

Realistically, it may not be practical to replace an existing, flight-qualified, operational system which, though it is complex from an operational and ground-servicing standpoint, is well understood and functions in a predictable manner. For this reason it is anticipated that until such time as another Orbiter is built, an all-electric actuation (ELA) system will probably not be implemented, unless unforeseen difficulties are encountered with the present hydraulic system. At the same time, there is an acknowledged need for a system which, while leaving the present hydraulic system intact, would rid the vehicle and ground operations of the APUs and their troublesome hydrazine monopropellant. In other words, an alternate power source is needed to power the existing hydraulic system. This alternate design would not penetrate the present hydraulic system in any way, but would have its interface with this system at the hydraulic pump(s).

SCOPE OF THE INVESTIGATION

This investigation consists of a short-term feasibility study to determine whether or not an alternate electrical power source would trade favorably from a performance, reliability, safety, operational and weight standpoint in replacing the current APU subsystem with its attendant components (water spray boiler, hydrazine fuel and tanks, feed and vent lines, controls, etc.), operating under current flight rules (6). Results of this feasibility study are used to develop recommendations for the next step (e.g., to determine if such an alternate electrical power source would show an advantage given that the current operational flight mode of the system could be modified in such a way as not to constrain the operational capability and safety of the vehicle). However, this next step is not within the scope of this investigation. This study does not include a cost analysis, nor does it include investigation of the integration aspects involved in such a trade, except in a qualitative sense for the determination of concept feasibility.

APPROACH

Using flight data, test data, and design analysis for shaft horsepower delivered from APU startup through shutdown for nominal and worst-case Abort-Once-Around (AOA) missions, conceptual battery, fuel cell and inertial (flywheel) systems, with accumulators where applicable, were sized to compare with the present system, using current operational flight rules and procedures. Comparisons were then made with the present APU system with respect to weight, volume, performance, reliability, safety, and operational flexibility (both in flight and for ground servicing), with a qualitative assessment of integration impacts.

Recommendations were then made, relative to the most promising candidate replacement systems, for carrying this effort one step further, i.e., for (1) performing an analysis of current flight rules and procedures to identify those specific operational aspects of the current APU/Hydraulic system which are attributable to the design and operational characteristics of the APU subsystem proper; (2) conducting an investigation of how the current operational flight rules and procedures could be modified given an alternate power source, without sacrificing either safety or operational flexibility; and (3) reiterating the trade study performed in this proposed effort, using the most promising candidate system and the modified operational flight rules and procedures.

WORK PLAN AND SCHEDULE

This investigation was divided into the following tasks:

I. Analysis
II. Candidate System Sizing
III. System Comparisons to Current Baseline
IV. Recommendations
V. Documentation
IV. Presentation of Results
VII. Submission of Final Report

The schedule for the above tasks is shown in Figure 6.

ASSESSMENT OF APU-RELATED SYSTEM WEIGHTS

A system weight analysis was performed to determine all APU- related system weights (7) as a reference point for comparing the weights of other competing candidate systems. Rockwell International Corporation and NASA provided the data shown in Figure 7. This data indicates that for any three-equivalent-APU system to be competitive on a weight basis with the current Orbiter APU system, it must weigh less than approximately 2000 lb_m.

POWER PROFILE ANALYSIS

Using power profiles obtained from NASA (9), an analysis of these profiles was performed for all phases of the nominal and design reference missions, as well as the Abort-Once-Around (AOA) nominal and design profiles (Figures 8 through 17). The power levels shown are APU shaft output horsepower per unit, i.e., power at the hydraulic pump input of each system. Analysis of these profiles indicates that a "base" power level of 25-40 Hp per APU system is required to keep the hydraulic system pressurized at a nominal 3000 psia. Also, a "pulse" power delta- requirement (above the "base") up to 105 Hp per system is required. Thus the total power, "base" plus "pulse," in the worst case (entry phase of the design reference and the AOA design missions) is 145 Hp per system. The short-duration pulse loads occur for a period of 11 minutes from Mach 10 to Wheelstop.

A flight control simulation analysis was performed using a worst-case atmospheric model (30% turbulence), and this analysis indicated almost no hydraulic actuator activity for the six-minute period between Mach 10 and Mach 2.5, so that most of the actuator activity occurs in the last five minutes between Mach 2.5 and Wheelstop. Furthermore, during this period of time there are few transients, indicating a low duty cycle (less than 10%), with the duration of these transients always less than six seconds each, most transients being of one-to two-second duration. Highest activity was just prior to Wheelstop, and this period is still under investigation by NASA.

It was concluded from the power profile analysis that for system sizing from the standpoint of power level, the design reference mission profiles must be used, i.e., 40 Hp "base" per system, with pulse capabilities of 105 Hp for a total of 145 Hp maximum per system. For the pulses, a maximum 10% duty cycle was used with a maximum six-second pulse duration, and it was assumed that on-orbit checkout of the flight control system can be accomplished in a phased manner, e.g., 5 six-second increments, rather than by exercising all actuators simultaneously in one 30- second maneuver. "Base" load energy requirements at the hydraulic pump inlet are summarized by mission phase in Figure 18 for the design reference mission and the AOA "design" case, taking into account the various times in these missions when one, two or three hydraulic systems will be operating. In the figure, the total system energy for three systems depends not only on the number of systems operating, but also on whether or not they are independent systems, e.g., batteries, which are fully self- contained; or systems which derive their fuel or reactants from a common energy source, e.g., a cryogenic storage tank supplying several fuel cells. This analysis of system energy requirements led to the conclusion that the design reference mission, not the AOA case, sizes the system from an energy standpoint. Figure 19 shows the total energy values from the last two columns of Figure 18, converted from the hydraulic pump inlet to energy required at the power source, assuming an 89.5% motor/inverter/controller efficiency. An additional 2.5 kWh was added to the "base" requirements to accommodate the worst case energy of the short- duration pulse loads above the base. With "base" and "pulse" energy requirements established in this manner, total system requirements of 230.5 kWh for an "independent-system" configuration, and 186.5 kWh for a system which draws its reactants from a common source, were used in the remainder of this study.

IDENTIFICATION OF POWER CONVERSION OPTIONS

An initial field of power conversion options was next identified for "chemical-to-electrical" conversion ("base" and "pulse" systems) and "electrical-to-mechanical" conversion. "Base" power systems included primary and secondary batteries, existing and "modified" Orbiter fuel cells, and the High Power Density (HPD) fuel cell. "Pulse" systems included secondary batteries, inertial systems (flywheels), and a hydraulic accumulator. The HPD fuel cell needs no "pulse" system if it is sized to handle the transients imposed upon it. For converting the electrical power from the power source to mechanical torque at the hydraulic pump inlet, a brushless dc motor and an ac induction motor were investigated. Figure 20 shows the 26 system combinations initially identified for evaluation.

TECHNOLOGY ASSESSMENT

Technology assessments were conducted for batteries, flywheels, hydraulic accumulators and fuel cells with respect to safety, reliability, performance, maturity of the technology, system weight, operational requirements, and vehicle integration considerations. What follows is a summary of the technology assessments for each subsystem.

Motor/Inverter/Control Technology

As indicated in Figure 20, motor choices consisted of either brushless dc (pulse-modulated) or variable-field induction. The brushless dc motor does, of course, use an inverter, producing an ac waveform. It has a higher efficiency than the induction motor and consequently a somewhat lower weight. The induction motor, on the other hand, with an efficiency of only a few percentage points lower than the brushless dc motor, is rugged, reliable, and easily manufactured. Because it is somewhat less efficient, it is slightly heavier than the brushless dc motor.

A Sundstrand Corporation development program for a motor/inverter/controls package for a high-power electric propulsion drive is presently underway (11). It consists of a 300 kW Insulated Gate Bipolar Transistor (IGBT)-based inverter which drives a 350 Hp induction motor. The motor was developed by Sundstrand in the mid 1980's for the Naval Underwater System Center (NUSC). This motor, shown in Figure 21, represents state-of-the-art technology for this type of machine. Figures 22 and 23 illustrate one leg of a 300 kW inverter which is, in effect, a three-phase 100 kW inverter. This inverter is presently being tested by Sundstrand. Figure 24 shows a Sundstrand "universal" motor controller being used in the development program. This controller utilizes programmable Digital Signal Processor (DSP) technology. These photographs illustrate the fact that this technology allows very high-density inverter packaging. It is estimated that for this application such a package, sized for 145 Hp (108 kW) peak and 45 Hp (34 kW) average power, would weigh approximately 91 lb_m. The way these components would fit into an electric APU system is shown in Figure 25 (12). A conceptual electrical-to-mechanical conversion system using a variable-field induction motor is illustrated in Figure 26 (11), and data for the motor/inverter/controller package is included in Figure 27 (11). A motor/inverter/controller efficiency of 89.5% was assumed for this study.

Batteries

Batteries were considered for both "base" and "pulse" power requirements; however, for this application, "design" power requirements are so high that the weight of a single battery system which would supply both "base" and "pulse" loads would be prohibitive. Consequently, separate battery "base" and "pulse" systems will be required, i.e., a high-energy-density (and specific energy) battery for the "base" system, and a high-power-density battery for the "pulse" system.

Under a separate grant (NAG9-561), an assessment of battery technologies was performed which included the following battery types:

Lithium (Li-$SOCl_2$)
Silver-Zinc (Ag-Zn)
Zinc-Oxygen (Zn-O_2)
Nickel-Cadmium (Adv Ni-Cd)
Fiber-Nickel-cadmium (FNC)
Metal Hydride (Ni-MH)
Nickel-Hydrogen (CPV Ni-H_2)
Nickel-Iron (Ni-Fe)
Sodium-Sulfur (Na-S)
Lead-Acid (Bipolar Pb-PbO_2)

"Base" battery systems are sensitive to discharge rate, which is dictated by peak power and duration. The highest energy density batteries which can be sized for appropriate high-rate performance for this application are the lithium high-rate primary and the silver-zinc secondary.

The lithium thionyl chloride (Li-$SOCl_2$) primary battery has a high specific energy (up to 500 Wh/lb_m but more like 100 Wh/lb_m for this application), with a reasonable discharge rate capability and long shelf life. Its specific power ranges up to 40 W/lb_m, which is not as good as a silver-zinc battery. Because it is a primary battery, it is limited to one-time use. With higher cell voltage than most other batteries, it also has a long shelf life, i.e., leakage is not a problem. Use of the bipolar cell configuration lowers cell impedance, allowing current densities up to 200 mA/cm^2. Communication with one manufacturer (13) indicated major safety concerns associated with venting for this high-energy application. If venting occurs in a battery of this type, extremely dangerous toxic effluents would be produced. Concern was also expressed with regard to heat management problems due to the high impedance of this type of battery. Extremely high surface areas with thin plates would have to be used, driving the design in the wrong direction from a safety standpoint. A man-rated lithium battery this size has never been built, and although this technology is better than any other from the standpoints of specific energy, it is not known for its high-specific power capability. To eliminate its major potential problems (thermal runaway, venting, and possible explosion), the actual design would have to be so rugged that it would be heavier in the long run than current performance predictions would indicate, and most likely prohibitive for this application.

The silver-zinc (Ag-Zn) secondary (rechargeable) battery, with reasonable specific energy, has high-current performance which is inferior to the Ag-Zn primary, but it is adequate for this application. The Ag-Zn technology was used extensively in the Apollo program as a high-rate primary, and this technology has changed little since Apollo. Work on the bipolar design has resulted in a battery lower in weight and volume. Specific energy and power range from 5 to 35 Wh/lb_m and as high as 70 W/lb_m for a primary Ag-Zn battery for this application.

As a secondary battery with limited re-use, special separators are used which prolong its life and improve rechargeability, allowing on the order of ten deep discharges, or 500 shallow discharges. High-current performance of the secondary battery is inferior to the primary Ag-Zn. Development work on bipolar Ag-Zn secondaries has been underway at the Wright Patterson Air Force Base (WPAFB) in Ohio. Problems experienced in this program include cell leaks, shorting, recharging problems (venting), and high internal heat generation. Specific energy and power range from 5 to 35 Wh/lb_m and up to 55 W/lb_m for this application. Figure 28 shows a comparison of "best estimates" of specific energy for lithium primary and silver-zinc secondary batteries considered in this study for the "base" power system (14).

Specific battery technologies examined for "pulse" power system application included:

Rechargeable Silver-Zinc (R/C Ag-Zn)

Advanced Nickel-Cadmium (Adv Ni-Cd)

Fiber-Nickel-Cadmium (FNC)

Metal Hydride (Ni-MH)

Common-Pressure-Vessel (CPV) Bipolar Nickel-Hydrogen (Ni-H_2)

Nickel-Iron (Ni-Fe)

Sodium-Sulfur (Na-S)

Bipolar Lead-Acid (Pb-PbO_2)

Zinc-Bromine (Zn-Br)

Since the rechargeable Ag-Zn technology was discussed earlier for a "base" power system, it will not be discussed further except to point out that it can also be used as a "pulse" system if it is properly sized for high-rate performance.

The advanced nickel-cadmium (Ni-Cd) and closely related fiber-nickel-cadium (FNC) technologies were next investigated. An ongoing NASA program to develop a high-specific-power, high-specific-energy, low-temperature battery is in progress (15). With relatively high energy density, long cycle life, good deep-discharge tolerance, and a flat discharging profile, the Ni-Cd battery is rugged and maintenance-free, has the added advantage of having a known state of discharge, and it can be reconditioned to extend its life. Its disadvantages are: (1) it is not as good as the lead-acid or silver-zinc battery for high-rate operation; (2) it exhibits a "memory" effect, which is a tendency to adjust its electrical properties to a given duty cycle to which it has been subjected over an extended period of time; (3) carefully controlled charging is required to prevent thermal runaway; (4) cell quality and reliability are still major concerns; and (5) cadmium is considered to be a hazardous material (One solution to this problem would be to use the nickel-metal hydride cell, which has an energy density twice that of a Ni-Cd cell (16).) Although most of its experience base to date is found in aircraft operations, the new fiber-nickel-cadium technology is now being investigated with increased interest for electric vehicles (17).

The nickel-metal hydride (Ni-MH) battery, manufactured by Ovonics Battery Company (18), is similar in configuration to a Ni-Cd battery, but no cadmium is used in its construction. With specific power capability to 150 W/lb_m (estimated) and a specific energy of 30-40 Wh/lb_m, it is a sealed, low-cost battery capable of quick-recharge (1/32 the charge time of Pb-PbO_2). Its major disadvantage is that its development state is low, with manufacturability being a key issue.

Nickel-hydrogen (Ni-H_2) battery technology has seen considerable recent development effort by NASA (18) and WPAFB (19), although most experience to date has been with aircraft applications.. Work on demonstrating Ni-H_2 cell performance in pulse applications has also been done by the Air Force Phillips Laboratory (20). Advantages of this battery are its relatively high specific energy, long life cycle, good tolerance of over- discharge and reversal, and the fact that its state of charge is indicated by hydrogen pressure. Disadvantages are that it requires additional development for high-rate application, its characteristic of self-discharge proportional to hydrogen pressure, and the safety issues associated with the use of high- pressure hydrogen. Performance of a Ni-H_2 battery for this application would be in the specific energy range of 15-25 Wh/lb_m, with an estimated 50 W/lb_m specific power.

Nickel-iron batteries are currently under development through the Chrysler Electric Power Research Institute (EPRI) Program for Chrysler's TE Van Electric Vehicle (EV). Many technologists look to these batteries as the next viable step beyond Lead-acid batteries (21). A pilot production plant is planned for 1993 (500 Ni-Fe EV batteries per year). Nickel-Iron batteries have a higher specific energy (almost double Pb-PbO_2) and are long-lived and rugged. Its major disadvantages are its low development state and the fact that it cannot be sealed as are the sealed, maintenance-free lead-acid batteries, since it requires regular injection. Also, it needs a gas removal system for the hydrogen generated during the recharge process.

Also as part of the Advanced Battery Consortium, in addition to the Chrysler/EPRI and nickel-metal hydride efforts described above, the Ford Motor Company, in cooperation with Chloride Silent Power of the United Kingdom (CSP-UK), is developing the Sodium-Sulfur (Na-S) technology for EV application (21). Ford/CSP-UK will build a demonstration EV fleet (70-100 vehicles) using 40 kWh Na-S 336 v battery packs for a planned 30-month demonstration phase in the 75 Hp European Escort Van (22). The Na-S battery has also been considered as an advanced battery for space applications by the Hughes Aircraft Company (23). For the present application, a specific energy of 45 Wh/lb_m with a specific power of 65 W/lb_m were used. The Na-S battery has a high energy density and a reasonable power density, and is constructed of low-cost, commonly available materials using relatively simple processes. Its disadvantages are its low development state (It is further from commercial production than nickel-iron.); its high operating temperature (approximately 700^{o}F); need for an internal heater for maintaining battery temperature high enough to keep the electrolyte molten when the battery is not in use; and its short life (approximately 18 months based on a typical EV usage profile–no life projections have been made for the current application). Its high operating temperature poses safety problems with the potential for fire or explosion, as well as corrosion problems inside the cells. This operating temperature level also presents a packaging challenge, as the battery must be heavily encased for safety and ruggedness, and this could easily double its weight.

Serving as a standard for comparing various EV Battery candidates (24), the lead-acid (Pb-PbO_2) battery represents a well- established technology, particularly for high-rate applications. The USAF/Jet Propulsion Laboratories (JPL)/Johnson Controls, Inc. (JCI) is developing a sealed bipolar lead-acid battery for extended high-rate applications for the Strategic Defense Initiative Office (SDIO) (18). With varying pulse- duration capability (1-100 sec), a quasi-bipolar configuration is available now, but is expensive because it is fabricated manually. The true bipolar configuration will reduce the number of manufacturing steps by 85%, and will result in a 30% weight saving, since it replaces lead with plastic. As part of the U.S. Advanced Battery Consortium, another lead-acid development effort is underway for the GM Impact EV (18). Advantages of the lead- acid battery are its excellent high-rate performance, and very good test results to date. Its only disadvantage is its low specific energy (10 Wh/lb_m). High-rate performance is estimated at 75 W/lb_m for the electric APU application.

Another type of battery considered as a secondary battery for this application was the zinc-bromine (Zn-Br) battery (25). A close relative of the redox flow cell, reactants and reaction products are stored outside the cell. An aqueous zinc-bromide stream from each of two separate tanks is circulated, one for the anode and one for the cathode. System hardware consists of the cells, a pumping system and storage tank for the anolyte, a pumping system and storage tank for the catholyte, a storage system for free bromine with capability to transfer it to and from the cathode, and a heat exchanger for temperature control. Advantages of this battery type are its inherent chemical simplicity, ambient temperature operation (approximately 120°F), good energy density, low-cost materials of construction, and a bipolar design with a potential cost advantage. Disadvantages include dendrite formation at the zinc electrodes with resultant shorting, and poor efficiency (about 65%) due to corrosion at the zinc anode. A 20 kWh, 80 v zinc-bromine battery has been built for EV application by Exxon using 6 substacks of 52 bipolar cells connected in parallel. The prototype was cycled more than 100 times during its test program. It has a specific energy of 30 Wh/lb_m and a specific power of 30 W/lb_m. This performance was used for the electric APU application.

Inertial Systems (Flywheels)

Energy storage wheels, or flywheels, have been studied for many years for space applications, and significant technology advances in composite rotors, magnetic bearings, and motor/generator circuitry technology have been achieved in the last decade (26). A recent research effort by the SatCon Technology Corporation for dual-purpose attitude control and energy storage (27) appears promising, while another study by this same corporation was performed to size a small energy storage system for an electrochemical actuation application (28). Flywheel systems are particularly suitable for low-energy, high-power applications. A combined motor/generator unit using a 20 kHz ac system has been investigated and appears advantageous for this application (29). In this design, the flywheel rim is used as the rotor of the induction machine ("solid iron rotor" concept), and the design incorporates high-frequency ac control electronics (Figure 29). Another concept, by American Flywheel Systems (AFS), utilizes an advanced Fiberglass composite wheel (30). Designed for the GM Impact EV, it is estimated to provide five-to-six times the specific energy of the lead-acid battery. Recent solid state physics breakthroughs in superconductivity show promise of increasing system lifetime and efficiency even further, but this new technology is not considered to be of sufficient maturity for this application.

With high round-trip efficiency as an energy storage system (85%), an induction motor efficiency of 95%, and the use of recent advances in high-frequency ac control electronics, both the combined flywheel-motor/generator "solid iron motor" induction machine and the composite rotor show significant technology promise. With a direct interface to a high-frequency bus (20 kHz or greater), zero-current switching could be employed, resulting in lighter-weight components, and such a system would provide less distortion in wave-form synthesis, resulting in more efficient operation of electrical devices. The disadvantages of such a system are, first and foremost, its low state of system development. To the knowledge of these investigators, no system has ever been build for an application the size of the electric APU. For this application, relatively low system specific energy (10-20 Wh/lb_m) compared to other systems is expected, with a high specific power range (500-1000 W/lb_m).

Hydraulic Accumulators

The APU power profile has requirements for steady state power (tens of minutes) as well as very short-duration (6 seconds or less), high-magnitude (105 hp) pulses. Since the pulse power requirements are several times the steady state requirement, options of devices with high specific power but perhaps lower specific energy should be included in optimizing a power source for the APU. One such device is the hydraulic accumulator.

In the present application, the hydraulic accumulator has a number of beneficial features. The peak power demanded of the system is in the form of hydraulic demand and therefore the accumulator directly supplies the energy required, rather than converting to and from some other form. In addition, accumulators have been in use in the aerospace industry for some time, and therefore require only engineering and no development.

In meeting a peak power requirement, there are two basic approaches: one is to supply all pulse power required without intermediate recharging; and the other is to supply only part of the requirement and then recharge the system. Hydraulic accumulators have such low specific energy that recharging after every pulse must be considered. Fig. A1 in

Appendix A shows that the steady state power required must be increased from P_{ss} to P_{max} to recharge the accumulator in the non-pulse part of the duty cycle. The magnitude of this increase is quite sensitive to the duty cycle, as shown in Fig. A2. Further, it is sensitive to the relative magnitudes of P_{ss} and P_{peak}. The values taken from the APU power profile are: peak power, 145 hp.; steady state power, 40 hp.; and duty cycle, 10%. Appendix A also details the feasibility design of a spherically shaped, carbon steel accumulator pressurized with gaseous nitrogen as a "pulse" power, or load-leveling, system for this application. The design used the criteria in the paragraph above and carried pulse width time, t_p, as a variable. The accumulator designed for this application has a volume of 5.7 ft^3 and a mass of 167 lb_m. About half the mass of the accumulator is due to the nitrogen, with the other half split between the shell and the hydraulic oil, as shown in Figure A4. The location of the accumulator in the APU hydraulic system is shown in Figure A3. The resulting specific power and specific energy are 470 W/lb_m and 1.5 Wh/lb_m, respectively.

SUMMARY OF DEDICATED "PULSE" POWER SYSTEMS

For the systems discussed earlier, optimized specific energy and power comparisons of dedicated "pulse" power systems for this application are shown in Figures 30 and 31, respectively. A qualitative assessment of the technology readiness state of each system is also included. Figure 32 consists of a combined specific power and energy plot taken from a battery and fuel cell handbook (25) which includes several of the battery types considered in this study, as well as some which are not applicable to the present study. The purpose of this plot is to show that, for the system discussed earlier, only the hydraulic accumulator and the flywheel can compete from a specific power standpoint with the present APU system. These two systems, however, have a much lower specific energy capability, which is not as important as specific power for this high-power, low- energy "pulse" application. Because of this, batteries would probably not be selected as a "pulse" power source. The selection, then, between a hydraulic accumulator and a flywheel would then be according to its technology readiness state. The HPD-FCP and current FCP points on the plot will be discussed in the report section on fuel cells. Table 1 gives an overall figure of merit for applicability of the "pulse" systems discussed to this point for the APU application. This figure of merit is subjective and is driven primarily by the assessed technology readiness state, beginning with the Orbiter APU itself as the best all-around system from both a performance and technology standpoint. The hydraulic accumulator is next, since it too is flight technology, and because of its high specific power. Although the flywheel has the highest specific power next to the APU, it was ranked 7th due to its low state of system-level technology at these power and energy levels. The best two "pulse" battery systems were judged to be the bipolar rechargeable silver-zinc battery and the bipolar lead-acid battery, again not because of their performance alone, but also due to their technology readiness state. Other battery types had high specific power, but their technology readiness state was judged to be lower than these two.

In summary, there are many secondary (rechargeable) battery technologies available for this application, with specific energy and power values ranging from 10-55 Wh/lb_m and 50-150 W/lb_m, respectively. The more readily available (better developed) technologies are heavier (e.g., lead-acid), whereas the systems with the lightest "potential" system weight and highest performance are the least developed. Flywheels have low specific energy (10-20 Wh/lb_m) with competitive specific power (500-1000 W/lb_m), but their state of system development is extremely low for this size. Hydraulic accumulators are well-developed and highly reliable, are extremely weight-sensitive to duty cycle and duration of pulse loads, and are practical for this application provided their operational duty cycle is below 20% with pulse durations below 6 seconds. They are "flight-technology-ready" and would require only engineering design, and because of this and their high specific power they are considered to be the best dedicated "pulse" system when used with an appropriate "base" system.

FUEL CELLS

Because of the nature of the fuel cell, viz., its capability to act as both a "base" and a "pulse" system, it is treated separately in this section of the report.

Fuel cells were considered in this investigation because of their high power and energy density and their excellent specific power and energy, coupled with their benign effluents and advanced development state due to use in the Apollo and Shuttle programs and in subsequent technology development programs.

The Orbiter Fuel Cell Power plant (FCP), with a specific energy of greater than 1000 Wh/lb_m and specific power over 50 W/lb_m steady state and 100 W/lb_m transient for this application, has demonstrated excellent performance and reliability. With 46 missions and more than 27,000 hours of operation to its credit, this FCP is qualified for 2400 hours (10-12 missions). Twenty- one (21) powerplants are currently in active service, with 12 installed in Orbiter vehicles while the remaining units are undergoing maintenance and overhaul procedures. This powerplant has a wet weight of 281 lb_m (Figure 33) with a steady state power output of 15 kW, and up to 25-30 kW for several seconds.

Since the principal limitation to producing higher power levels with an Orbiter FCP is its accessory section (The stack can handle transients well, although use of Orbiter FCPs for this application would severely limit cell section life.), the concept of a "modified" Orbiter FCP was investigated. With accessory section components sized for 20 kW steady state, a possible course of action would be to increase coolant system sizing (pumps, lines, heat exchangers) for increased heat transport capability, increase reactant line sizing, and increase the size of the wiring harness if necessary. The estimated weight of an Orbiter FCP modified in this manner would be approximately 310 lb_m.

Another alternative is the High-Power-Density (HPD) FCP (31). This approach, based on a technology advancement and demonstration program by the SDIO, was initiated in the 1980s with the goals of a power density increase of 10 to 15 times that of the Orbiter FCP, with a corresponding reduction in cell mass and no sacrifice of efficiency. To do this, operation at high temperature (300^{o}F compared to the Orbiter's 180^{o}F) and pressure (200 psia compared to the Orbiter's 60 psia) was necessary. Also, new cell materials and an improved cell structure were required to withstand the corrosive oxidizing cell environment. And finally, a new electrode microstructure capable of the mass transport required for high current densities was necessary.

This technology program culminated in a four-cell stack demonstration test at the International Fuel Cell (IFC) Division plant of the United Technologies Corporation (UTC). Power levels equivalent to 12 times Orbiter levels were imposed on this stack for 7 or 8 15-minute cycles, during which time the stack was pulsed to 40-50 kW equivalent power levels for short times (minutes). Weight density comparison of the HPD cell stack with the Orbiter stack indicates 12 lb_m/kW for the HPD technology compared with 1.2 lb_m/kW for the Orbiter stack. For Orbiter application, the HPD fuel cell would increase useful FCP life from 2400 hr to 10,000 hr. If it is assumed that use of these fuel cells in the APU application would derate their life by a factor of 10, then use of the Orbiter FCP could be expected to provide 240 hr compared to 1000 hr for the HPD FCP. The current APU has a useful life under 30 hr. As an aside, Figure 34 shows what an HPD FCP would weigh if it were sized as an Orbiter power plant. This represents approximately a 50% reduction in FCP wet weight for this technology. Figures 35 and 36 show cell performance and degradation, respectively, for the HPD technology compared to that of the Orbiter cell.

To size a HPD FCP for this application, two power levels were considered (Figure 37) (32). Figure 38 compares Orbiter, Modified Orbiter, and HPD FCP weights (for both HPD sizing levels), and shows the transient capability of each power plant. Figure 39 shows a power density comparison for the various components of these same powerplants.

Three fuel cell options are available for this application. If it is desired to use Orbiter FCPs, an additional "pulse" power system would be required because of the 15-20 kW steady-state capability of the Orbiter FCP. Additionally, it cannot be utilized "as is," since a prohibitive number of FCPs would be required to sustain the "base" load per APU. Two FCPs would produce 40 kW steady state at beginning-of-life (BOL), and only 30 kW steady state at end-of-life (EOL), resulting in the fact that 3 FCPs per APU would be required for this option. The Orbiter FCP option would be extremely life-limited for this application, and is not recommended by the manufacturer.

A "modified" Orbiter FCP, on the other hand, would produce 20 kW steady state from BOL to EOL since its stack already possesses the 20 kW capability, but this option would nevertheless still require 2 FCPs per APU, plus an accompanying "pulse" power system. Aside from other considerations, this option would certainly not be attractive from the standpoint of system volume.

The HPD FCP on the other hand, sized for either 60 or 80 kW steady state, would be capable of performing this task with a single FCP per APU. This power plant would run at the 34 kW steady state maximum "base" load (40 Hp at the hydraulic pump inlet), but it must be designed for at least 60 kW steady state to provide adequate current-carrying capacity at 120 kW (145 Hp at the hydraulic pump inlet). Additionally, the HPD FCP with a "dual mode" control system would enhance total Orbiter operational capability and vehicle reliability. This concept would permit the use of a common FCP for both EPS and APU applications, resulting in longer life for EPS use and adequate power for hydraulic system operation. This system, known informally as the "two-speed" fuel cell, could operate at two temperature and pressure settings (180°F and 60 psia for low power, or EPS, use; and 300°F and 200 psia for high power, or APU, use).

MASS OPTIMIZATION ANALYSIS

Since a large number of candidate systems were considered, along with several constraints relating to the power and energy to be supplied, the selected approach was to optimize the system about the expected operating point utilizing a linear programming method to minimize system mass.

Candidate systems for "base" power include two types of rechargeable silver-zinc batteries, one sized for a 1 hr discharge rate and the other for a 2.5 hr rate, due to the nature of APU use on the vehicle. A lithium-thionyl chloride battery with a 2.5 hr discharge rate was also considered. Fuel cell options included the existing Orbiter FCP, a Modified Orbiter FCP, and the HPD FCP. For the "pulse" power systems, the rechargeable silver-zinc battery, the flywheel, and the hydraulic accumulator were used. An ac induction motor/inverter was selected based on the Sundstrand development work to date. Obviously a power source with both high specific energy and high specific power would be desirable such as is the case with the present APU gas turbine. Since there are no systems with as high values for these two parameters as the APU gas turbine, a combination of systems taken from the above candidates was considered. Appendix B documents the approach taken here which consists of: expressing the power requirements in terms of a 1.0 hour and a 2.5 hour steady state power; providing for a pulse- type power source such as an accumulator, and providing for a fuel cell power source. While the linear programming approach would permit all candidate systems to be simultaneously optimized, a systematic combination of logical components was used to both gain insight into the effects of each type system, and to insure that the operating point used for linearization was consistent with the calculated results.

First, systems were grouped logically into those with a high state of development and those that would require substantial development. The types of systems considered in the first group were batteries, accumulators, and the Orbiter fuel cell and modifications to this FCP. The second group included HPD FCPs and flywheels. Figure 40 shows the initial power conversion options for the mass optimization study.

During the course of the optimization process it was discovered that the use of modified Orbiter FCPs for "base" power did not produce results significantly different from those of the Orbiter FCP. Also, while flywheels for "pulse" power offer an advantage in "stored energy" over the hydraulic accumulator, since the flywheel is considered "new technology" for purposes of this investigation, it is compared only in conjunction with HPD FCPs, and the optimization analysis confirmed that no pulse power system is needed with the HPD FCD if it is properly sized. Consequently, the modified Orbiter FCP and flywheels were dropped from further consideration. This reduced the total number of system options to the five shown in the Figure 41. Although the best "usual" battery is the silver-zinc, the lithium battery represents a better but substantially more hazardous alternative. Figure 42 lists the calculated results with several alternatives which would involve judgment decisions. However, the best of these alternatives involves doubling the system mass (over the existing APU system), tripling the system volume, and increasing the system first cost by an order of magnitude. On the positive side, the hydrazine associated with the APU could be removed and an additional 90 kW of on-orbit power could be supplied. The cost/benefit ratio appears to be beneficial. Note that for fuel cell combinations, two cases were analyzed: new consumables tankage with required consumables (use of partially filled tanks, which adds mission capability); and use of onboard Orbiter consumables, which results in a reduction in mission time. System weights accounted for in the analysis include vehicle-integration hardware, tankage and reactants, motor/inverter/controls, additional required cooling, and additional avionics. Supplementary weights data for Orbiter systems (33) are given in Tables 2 through 5.

Figure 43 lists the calculated results for the HPD FCP system sub-options. There are two benefits of the HPD FCP that make this technology competitive with the APU gas turbine for this application. The first is much higher specific power, and the second is the ability to support pulse power requirements of up to twice its steady-state power rating. There are a number of issues to be considered in the possible substitution of HPD FCPs for gas turbines for this application. The HPD FCPs are an approximate trade for gas turbines on a mass basis. Potential negative factors are the uncertainty in the technology projections made by the manufacturer, the increase in system volume, and the increase in system first cost. Potential positive factors include: removal of APU hydrazine, more reliable operation, provision of 180-240 kW of additional on-orbit power, possible removal of the EPS FCPs, and additional safety by adding the capability to switch HPD FCP power from a failed hydraulic system to another system.

Figure 44 shows all calculated results in graphical form. In addition, Appendix B examines the combination of flywheels with Orbiter FCPs. About 200 lb_m out of 4500 lb_m can be saved by substituting flywheels for accumulators. The uncertainty in the state of technology, the potential hazard, and the relatively small gain all suggest that flywheels are not a significant factor in the APU application.

CONCLUSIONS

The APU gas turbine can be replaced by an "existing technology" combination of Orbiter FCPs, batteries, and accumulators at a mass penalty of 2000-3000 lb_m, a volume penalty of about 3 and an increase in first cost of about an order of magnitude. This system would have the benefits of removal of APU hydrazine, additional on-orbit power of 90 kW, and in some configurations, additional hydrogen and oxygen tankage.

An "advanced technology" alternative consisting of HPD FCPs would trade about evenly on mass but with increases in system volume and cost. This system would have benefits of removal of APU hydrazine, additional on-orbit power of 180-240 kW, increased system life, the possible removal of EPS FCPs, and increased safety due to the ability to switch power from failed hydraulic systems.

RECOMMENDATIONS

More detailed power profile analysis should be continued for the high activity period between Mach 2.5 and Wheelstop in order to assure that the duration and duty cycle of hydraulic system transients are within the range of the values assumed in this study (6 sec and 10%). Should any system changes be contemplated, system engineering analysis should be continued to assure that target objectives remain feasible during development and subsequent testing. NASA should also conduct inhouse testing to provide independent verification of prototype hardware performance both at the component and system levels. Test data analysis should parallel this effort to keep the development program on track. Development should constantly look ahead to possible evolution toward an electric APU.

If an "existing technology" alternative is chosen, extensive testing of PP708 should be conducted both in transient and steady state to determine the bounds of the operating envelope, at the expense of shorter life (but still at system life greater than the present gas turbine). Electric power switching among hydraulic systems should be considered to increase system safety.

Should an "advanced technology" alternative be decided upon (HPD FCPs), an early exploratory series of cell tests should be undertaken to verify the manufacturer's claims, which are critical to the viability of this option. Additional component and system tests should follow in a phased manner to assure that any development program stays on target. Development tests should include final stage integrated systems tests including FCPs, motor/inverter packages, and as much of the hydraulic system as possible in the test configuration. The part of the hydraulic system not included should be properly simulated both for steady state and transient performance. The tendency for hydraulic resonance is high, potentially affecting both the power source performance and flight control stability. Should removal of the EPS FCPs be considered in favor of a common APU/EPS FCP, it may be desirable to include an accumulator to greatly diminish transient hydraulic loads which could cause electrical supply transients. Electrical power switching should also be considered to increase system safety.

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APU/Hydraulic/Water Spray Boiler Equipment Location Within Orbiter Aft Compartment

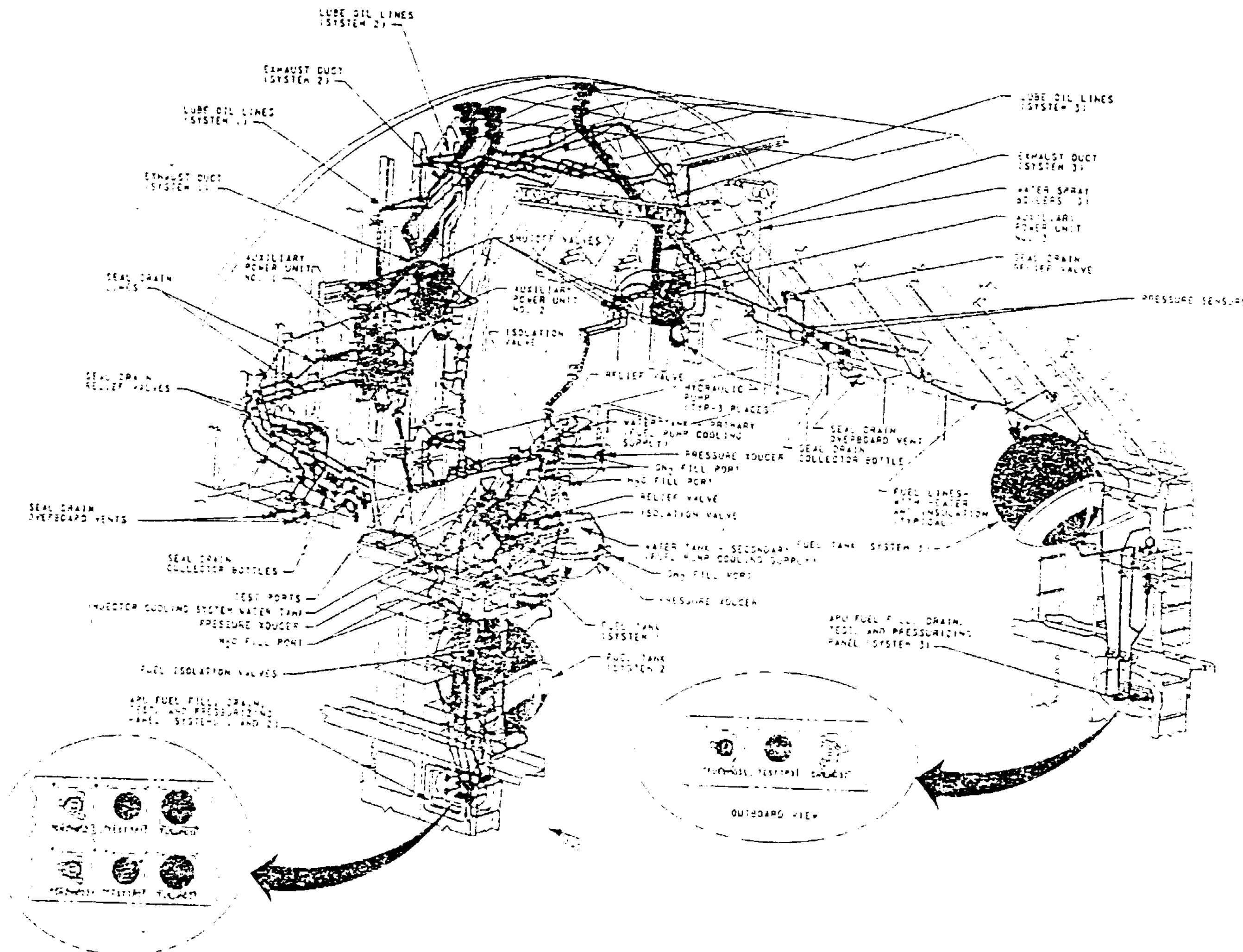


Figure 1

Orbiter Hydraulic Subsystem Elements

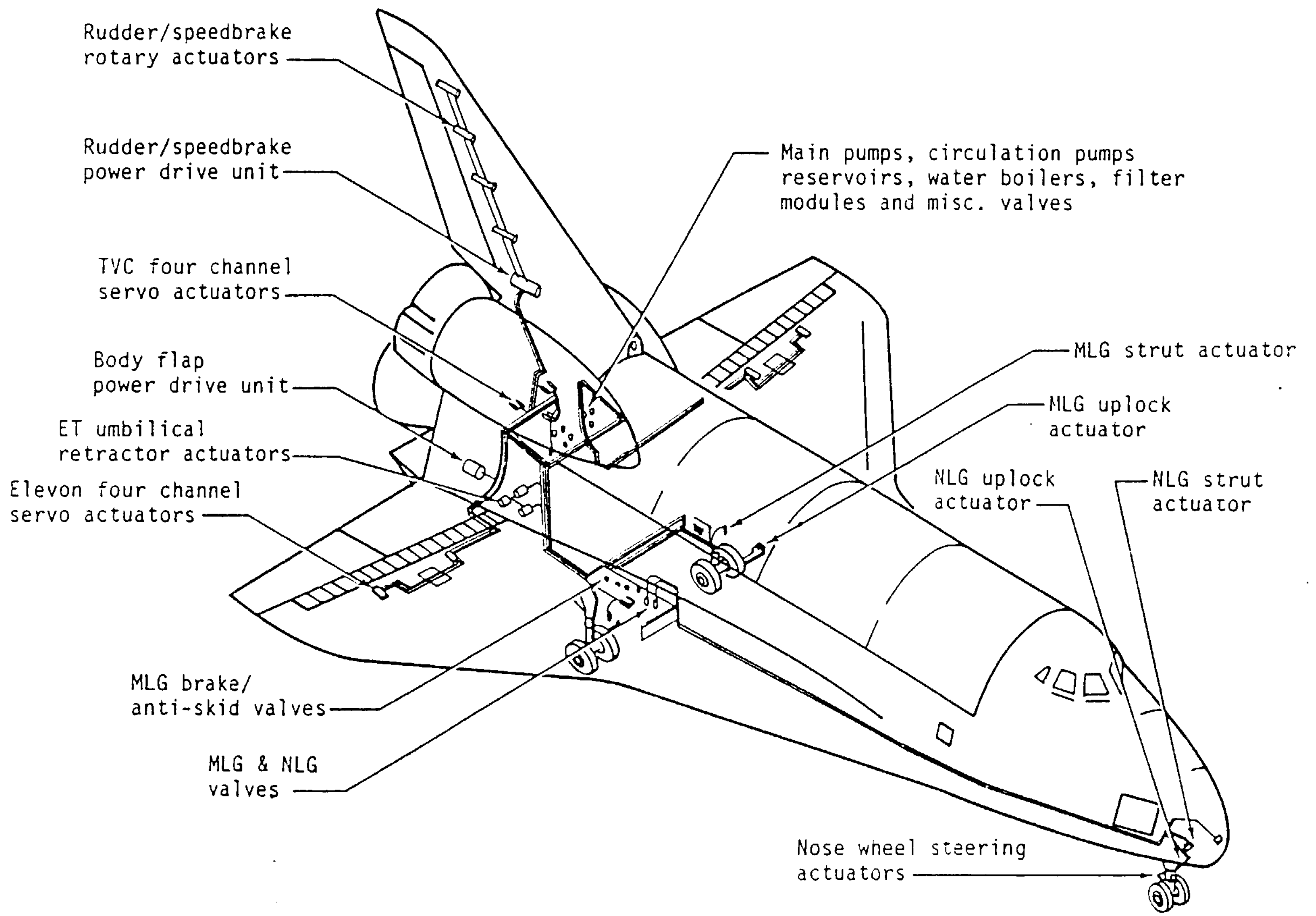


Figure 2

Hydraulic Subsystem Block Diagram

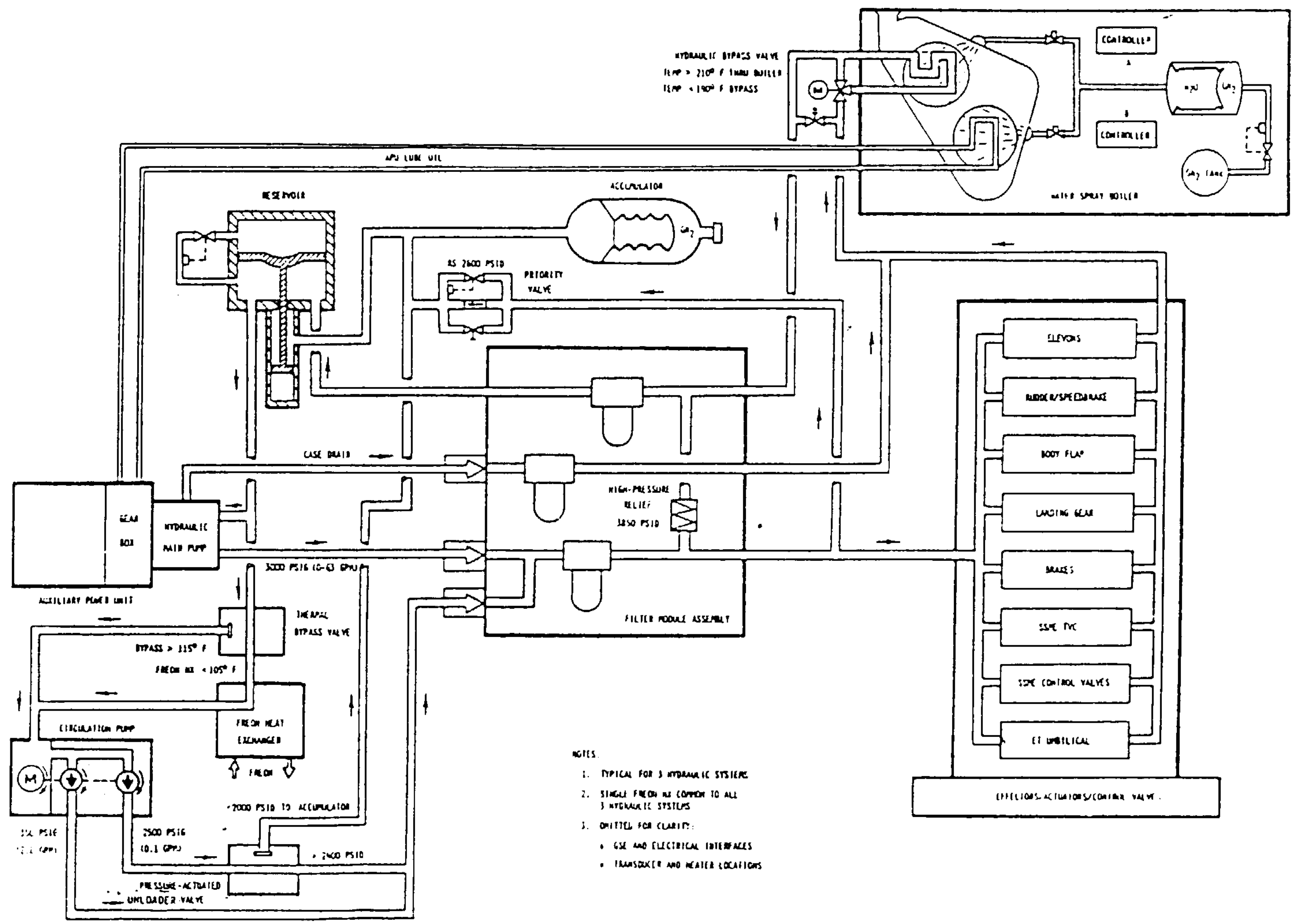
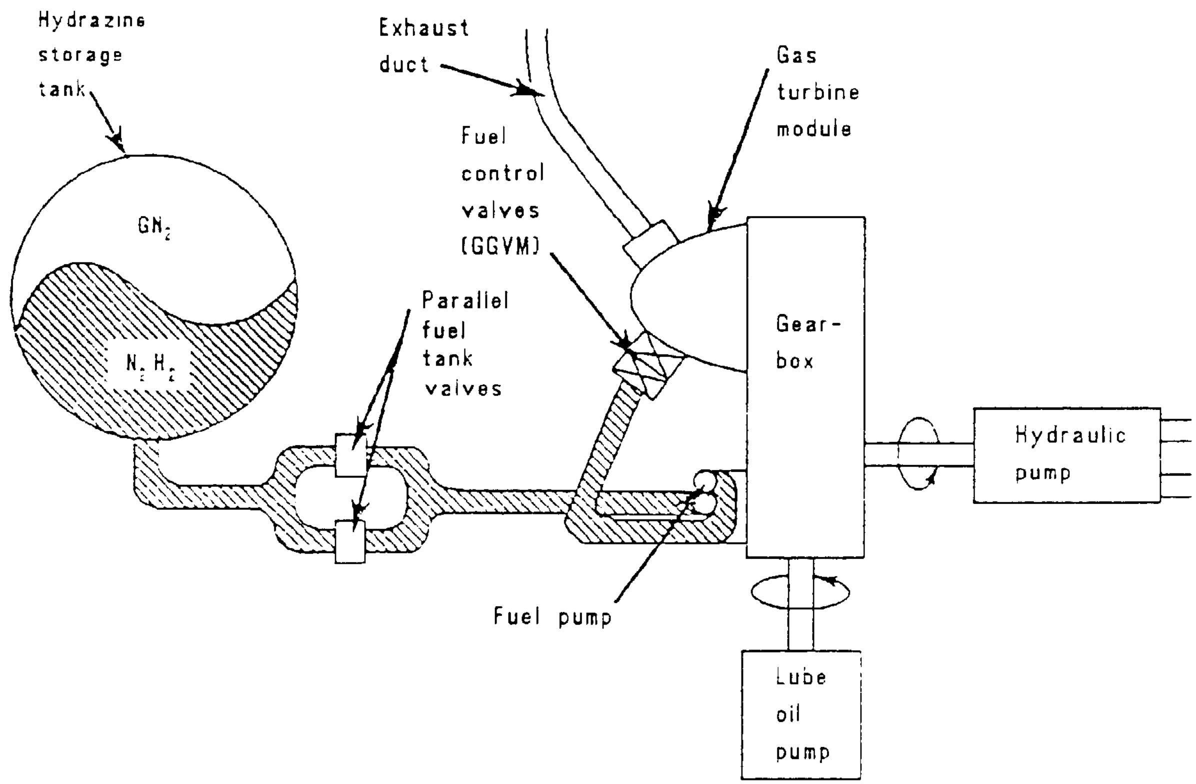


Figure 3

APU System

Major Components of the APU System :



- Fuel Tank
- Fuel Tank Valves
- Fuel Pump
- Fuel Control Valves
- Gas Generator and Turbine
- Lubricating Oil System
- Electronic Controller
- Fuel Pump/Fuel Valve
- Cooling System
- Injector Cooling System
- Heaters

Figure 4

Water Spray Boiler System

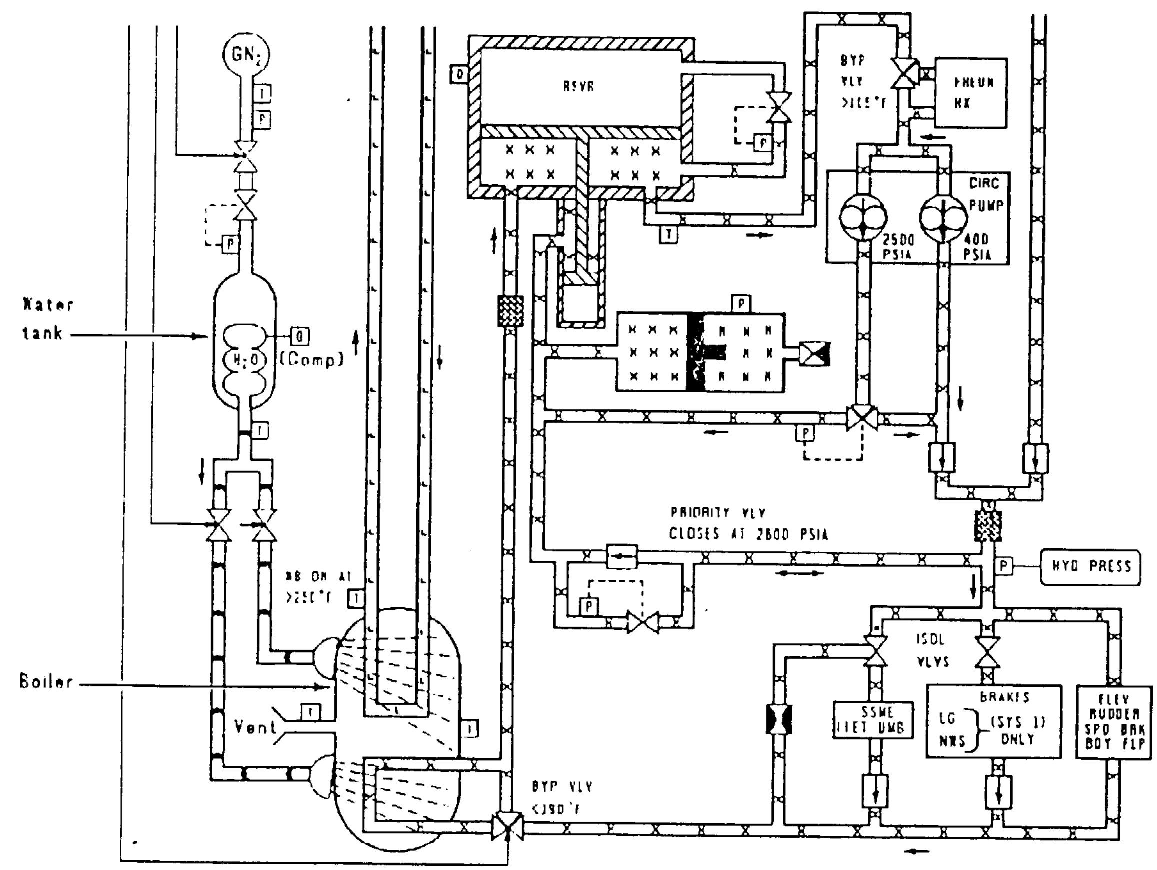


Figure 5

SCHEDULE

Investigation of Alternate Power Source for Space Shuttle Orbiter Hydraulic System

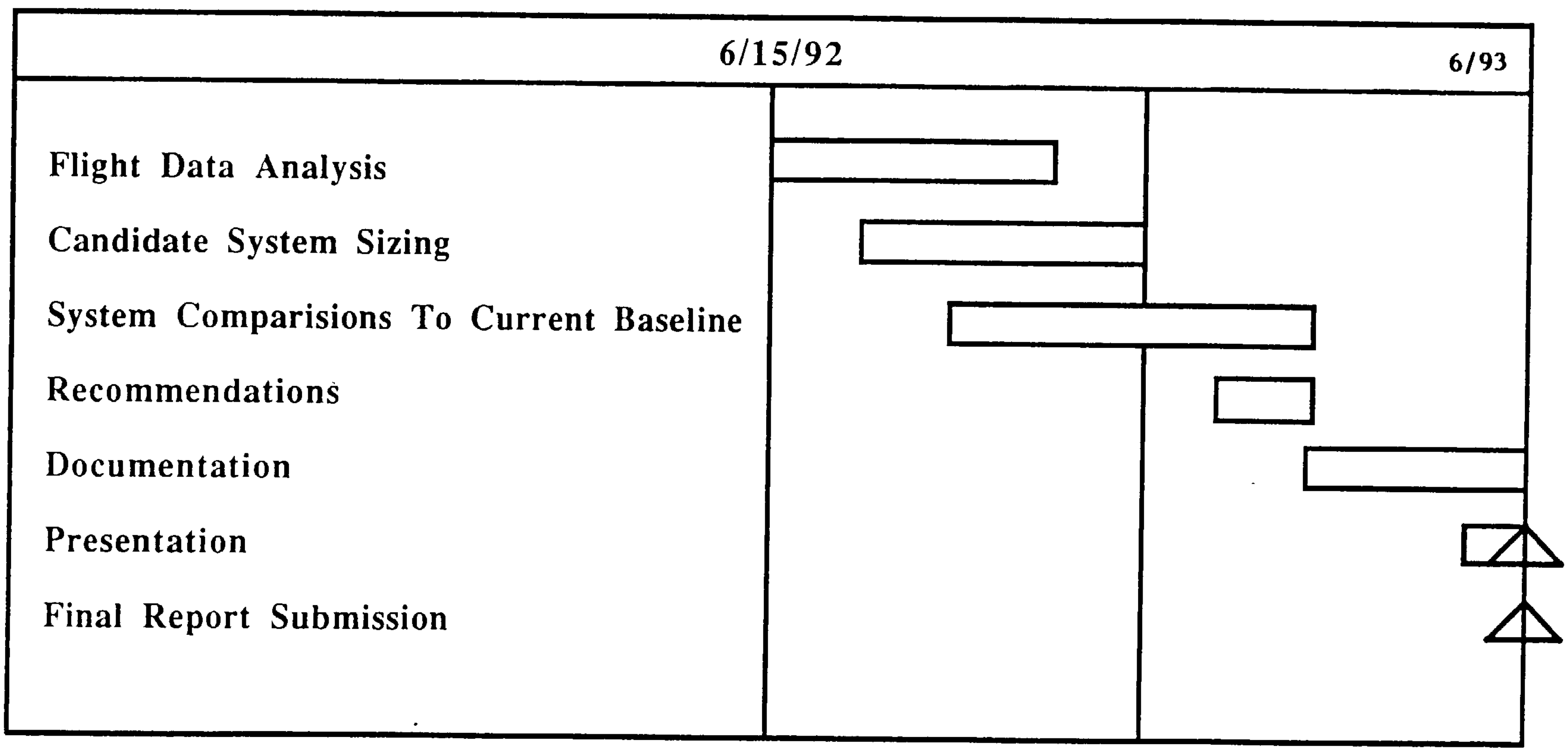


Figure 6

APU-Related System Weights (3 systen

APU, Controllers, Insulation, Drain Plumbing, Support	366
Fuel Tanks, Heaters, Insulation, Plumbing, Valves, Supports	325
Lube Oil Coolant Loop(Plumbing, Insulation, Supports)	46
APU Exhaust System (Ducts, Insulation, Supports)	82
APU Water System(Tanks, Plumbing, Insulation, Supports)	93
Instrumentation Sensors	8
Total Inert Weight	920
APU Fluids (Fuel, Lube Oil)	1000
Total System Wet Weight	1920

Source : Rockwell International RI-1549, Response D/280, July 1991

Figure 7

Normal Mission Profile

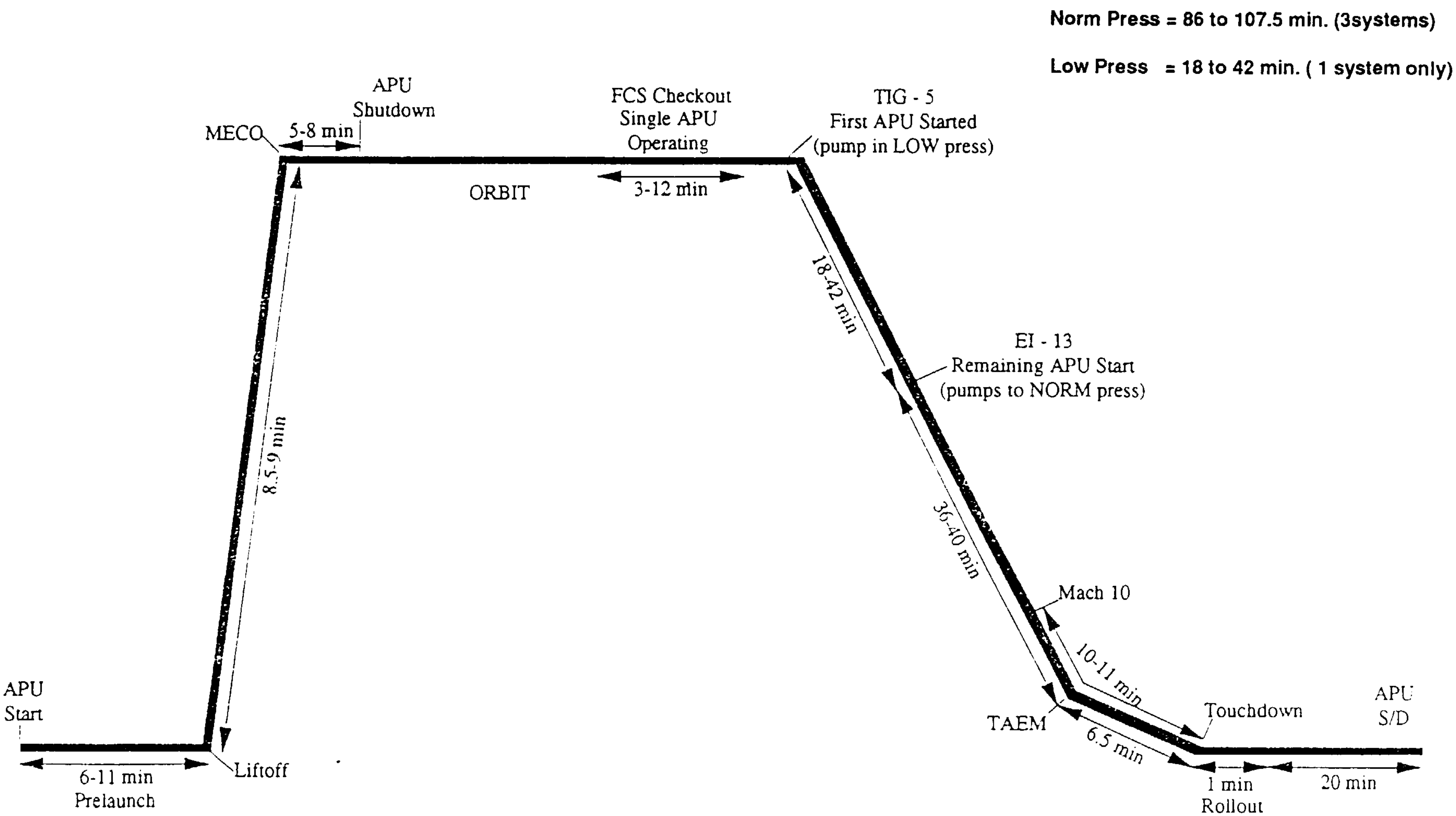


Figure 8

Hydraulic Power vs Time
Ascent Case (nominal mission)

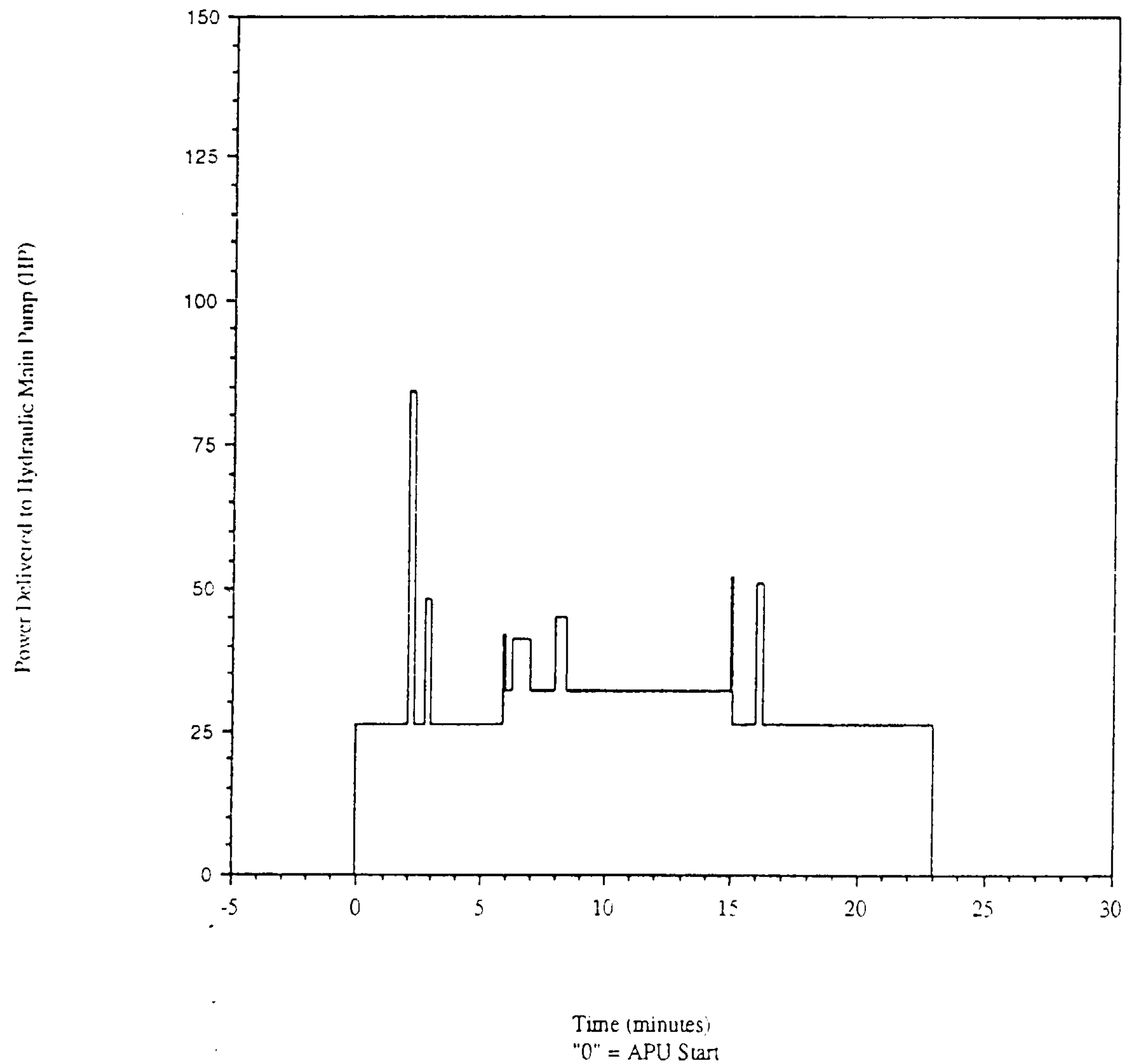


Figure 9

Hydraulic Power vs Time
FCS Checkout Case (nominal mission)

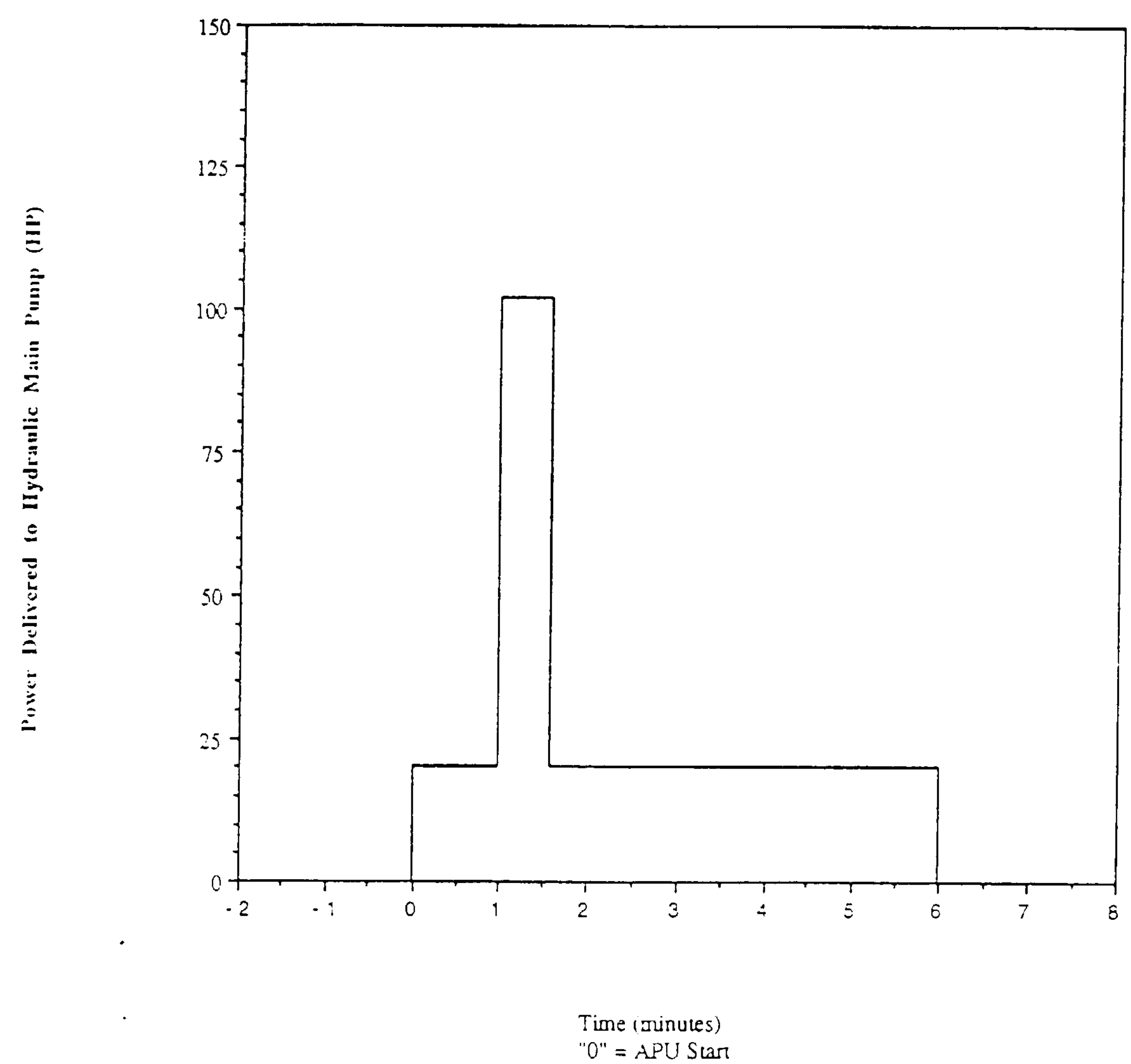


Figure 10

Hydraulic Power vs Time
Entry Case (nominal mission)

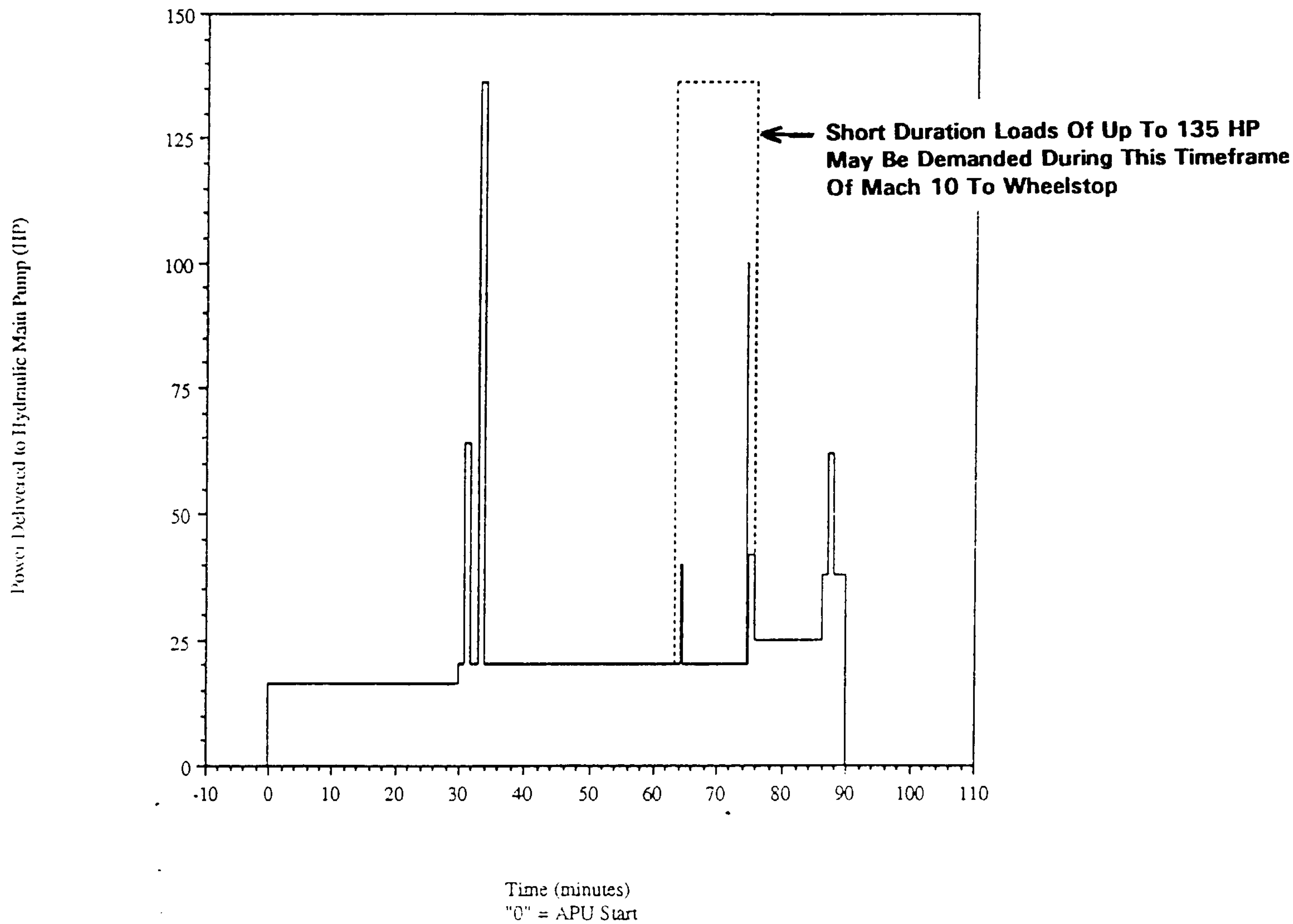


Figure 11

Hydraulic Power vs Time
Ascent Case (design mission)

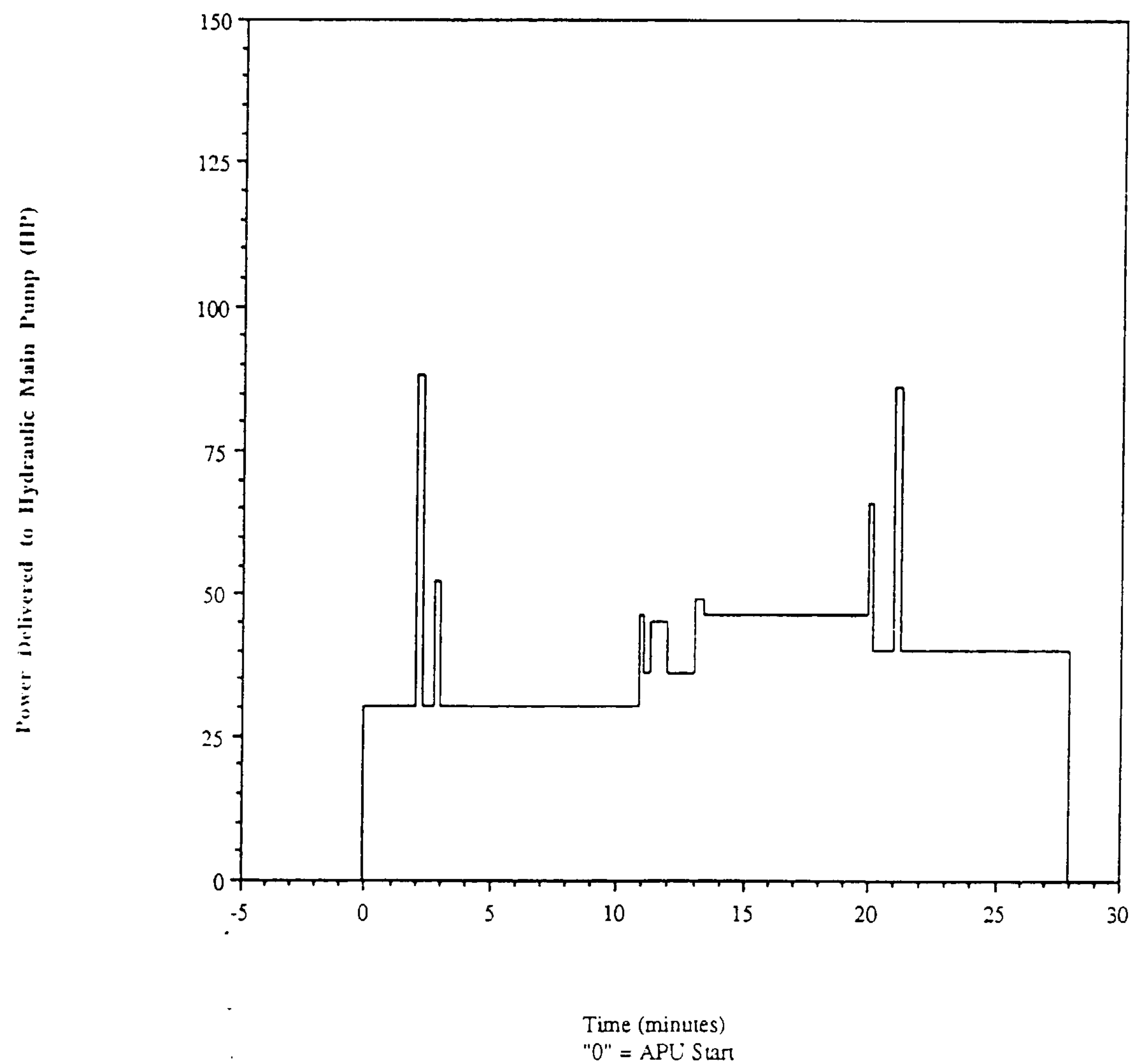


Figure 12

Hydraulic Power vs Time
FCS Checkout Case (design mission)

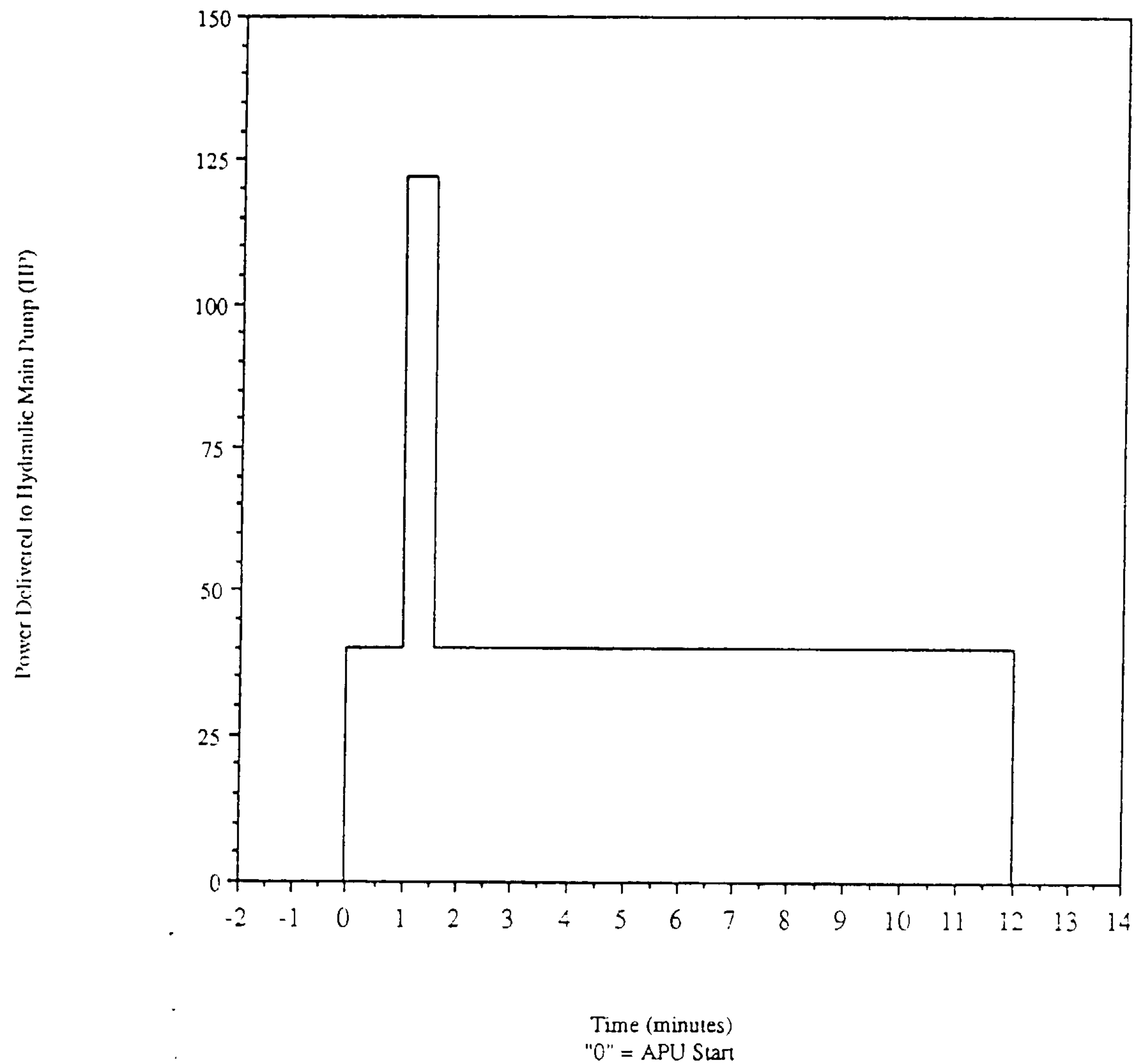


Figure 13

Hydraulic Power vs Time
Entry Case (design mission)

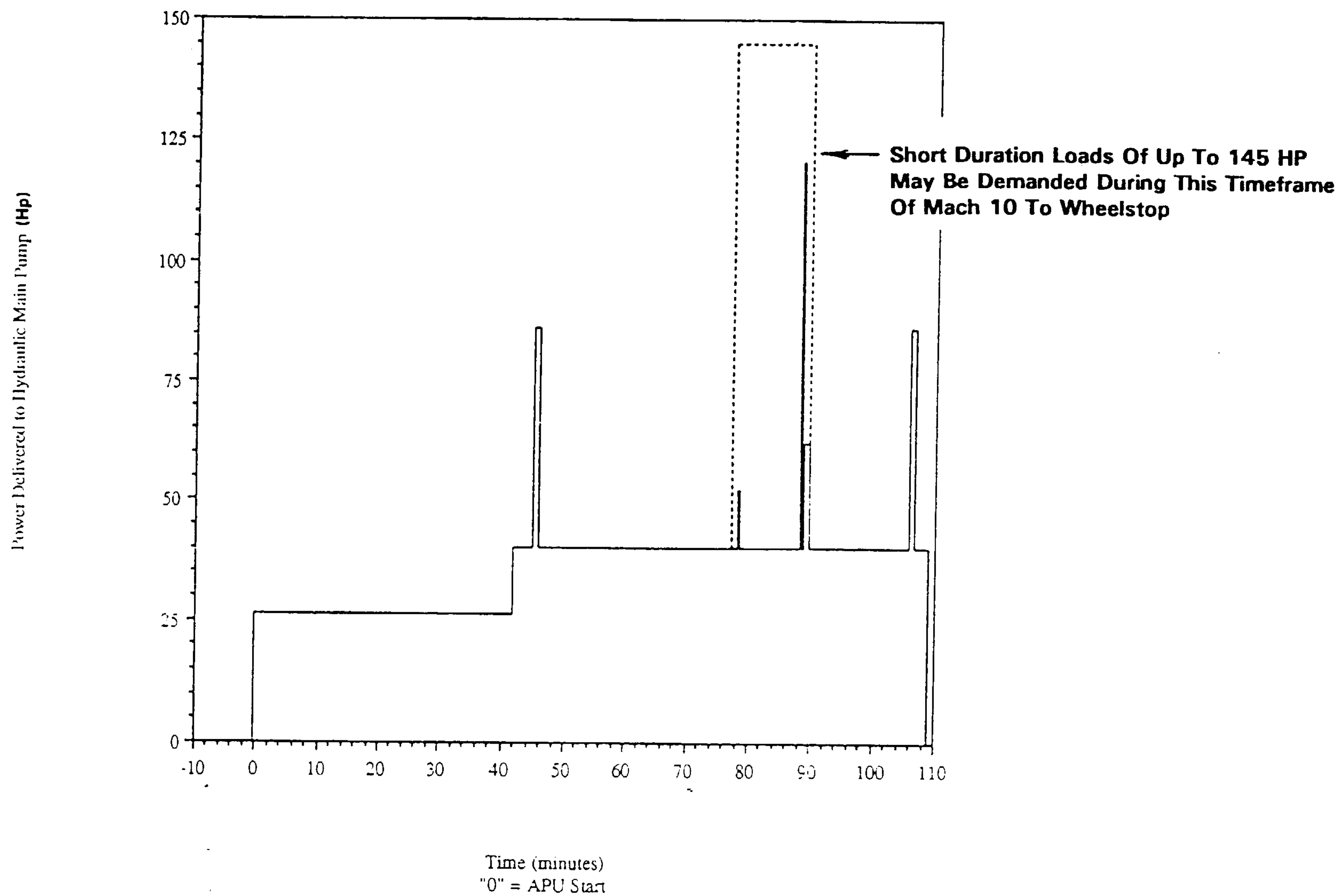


Figure 14

AOA Abort Profile

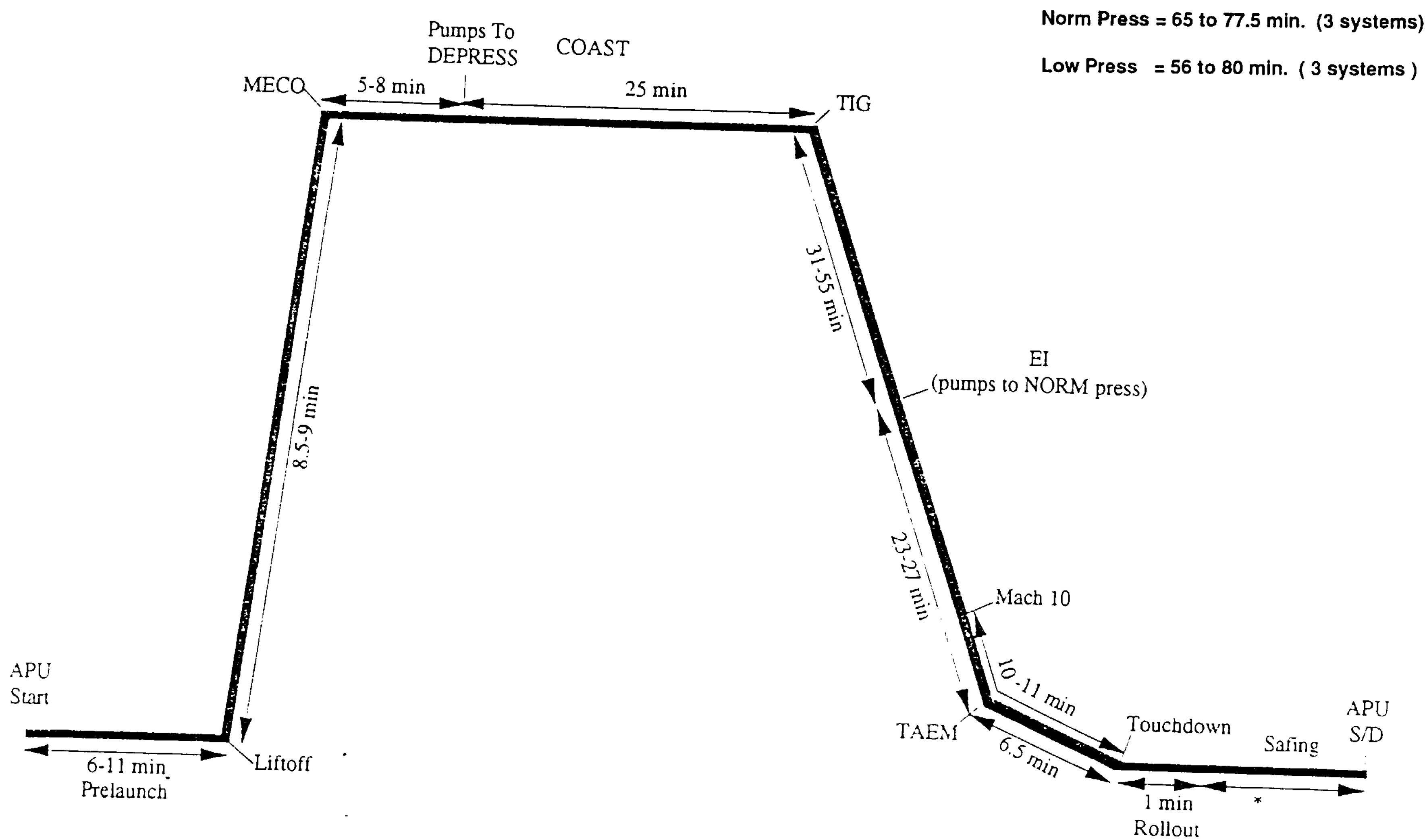


Figure 15

Hydraulic Power vs Time
Abort-Once-Around Case (nominal abort mission)

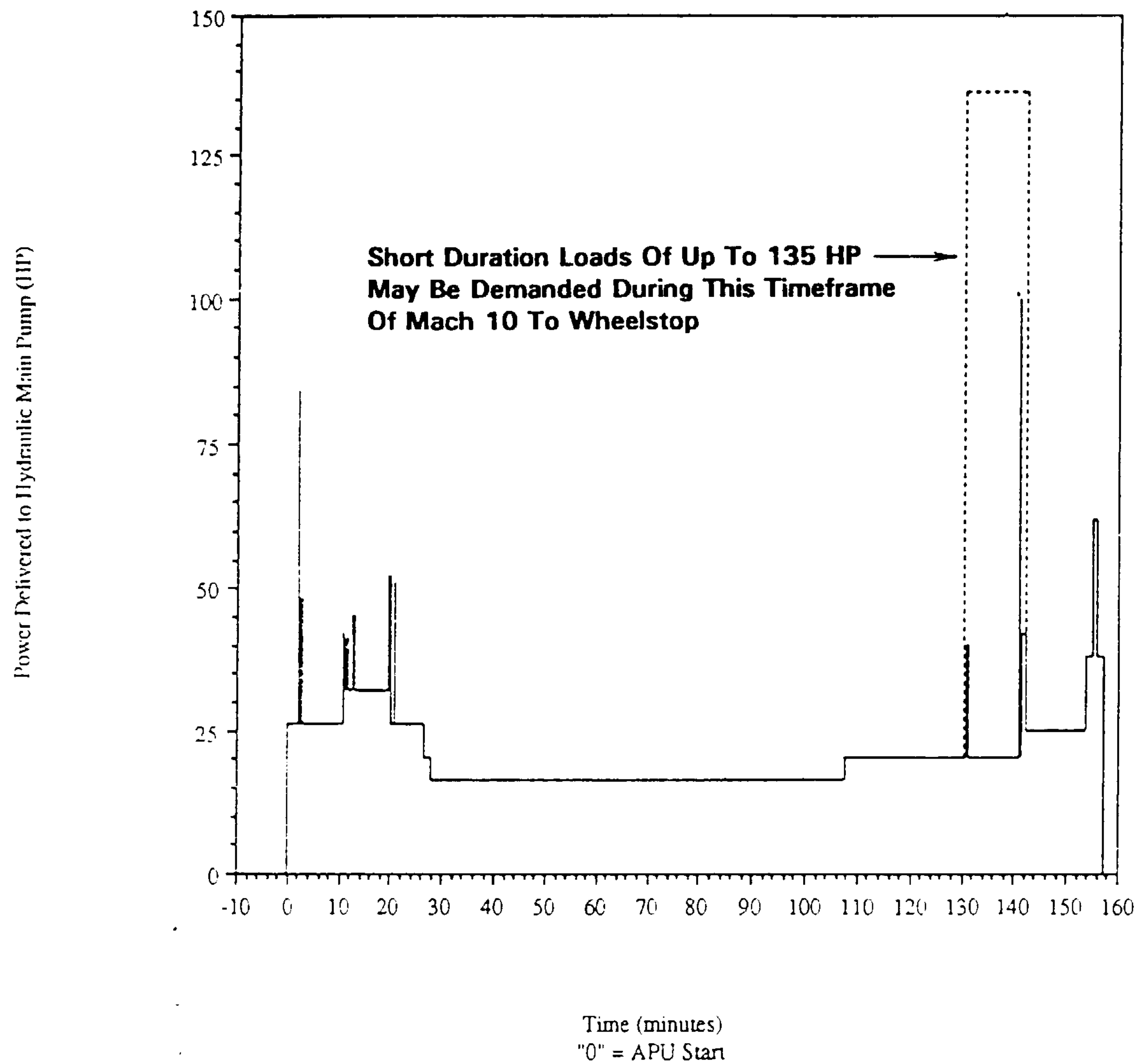


Figure 16

Hydraulic Power vs Time
Abort-Once-Around Case (design mission)

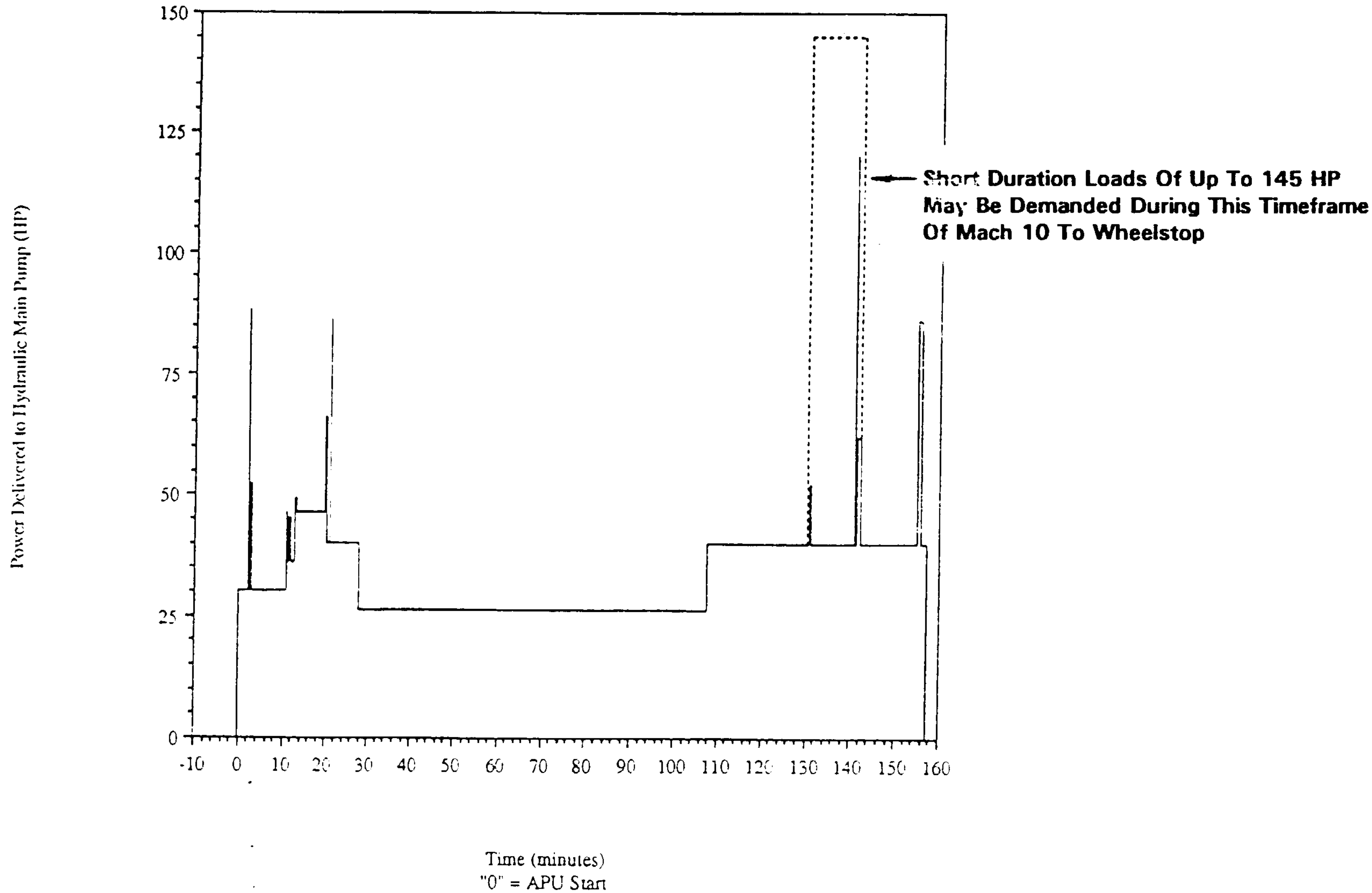


Figure 17

"Base" Energy Requirements at Hydraulic Pump Inlet

"Design " Case

Mission Phase	Time(min.)	HP/System	Number of Systems		Total Energy(KWh) - 3 systems	
			Independent Systems	Common Energy Source	Independent Systems	Common Energy Source
Ascent (3 systems)	28	40	3	3	42	42
FCS Checkout (1 system)	12	40	3	1	18	6
Pre-Entry (1 system)	42	27	3	1	42	14
Entry (3 sytems)	68	40	3	3	102	102
Total	150				204	170

AOA Case— "Nominal" Mission(1) : 156 min. at 19.9 Hp avg. = 38.5 KWh X 3 systems = 116 KWh
"Design" Mission(2) : 156 min. at 32.6 Hp avg. = 63.2 Kwh X 2 systems = 126 Kwh

Conclusion : "Design" case , not AOA, sizes the power system from an energy standpoint

(1) 3 operating hydraulic systems
(2) 2 operating hydraulic systems

Figure 18

"Base" Energy Requirements at Power Source (kW)*

"DESIGN" CASE

Mission Phase	Time (min.)	Total Energy (kWh)	
		Independent Systems	Common Energy Source(Reactants)
Ascent	28	47	47
FCS Checkout	12	20	7
Pre-Entry	42	47	16
Entry	68	114	114
Total	150	228	184

Note : For total ("Base" + "Pulse") energy requirements for system sizing, add 2.5 kWh max. to above, i.e., Independent Base/Pulse System = 230.5 KWh Base, with Common Energy Source = 186.5 KWh

* Assume Average Electric Motor Conversion, Conditioning and Controller Losses = 10.5 %

Figure 19

Power Conversion Options

Chemical-to-Electrical

"Base "

- Primary Battery
- Secondary Battery
- Fuel Cell (Existing Orbiter)
- Fuel Cell (Orbiter Modified)
- Fuel Cell (High Power Density)

"Pulse"

- Secondary Battery
- Inertial System
- Hydraulic Accumulator
- Handled by Fuel Cell

Electrical-to-Mechanical

- Brushless DC Motor
- AC Induction Motor

26 systems options

Figure 20

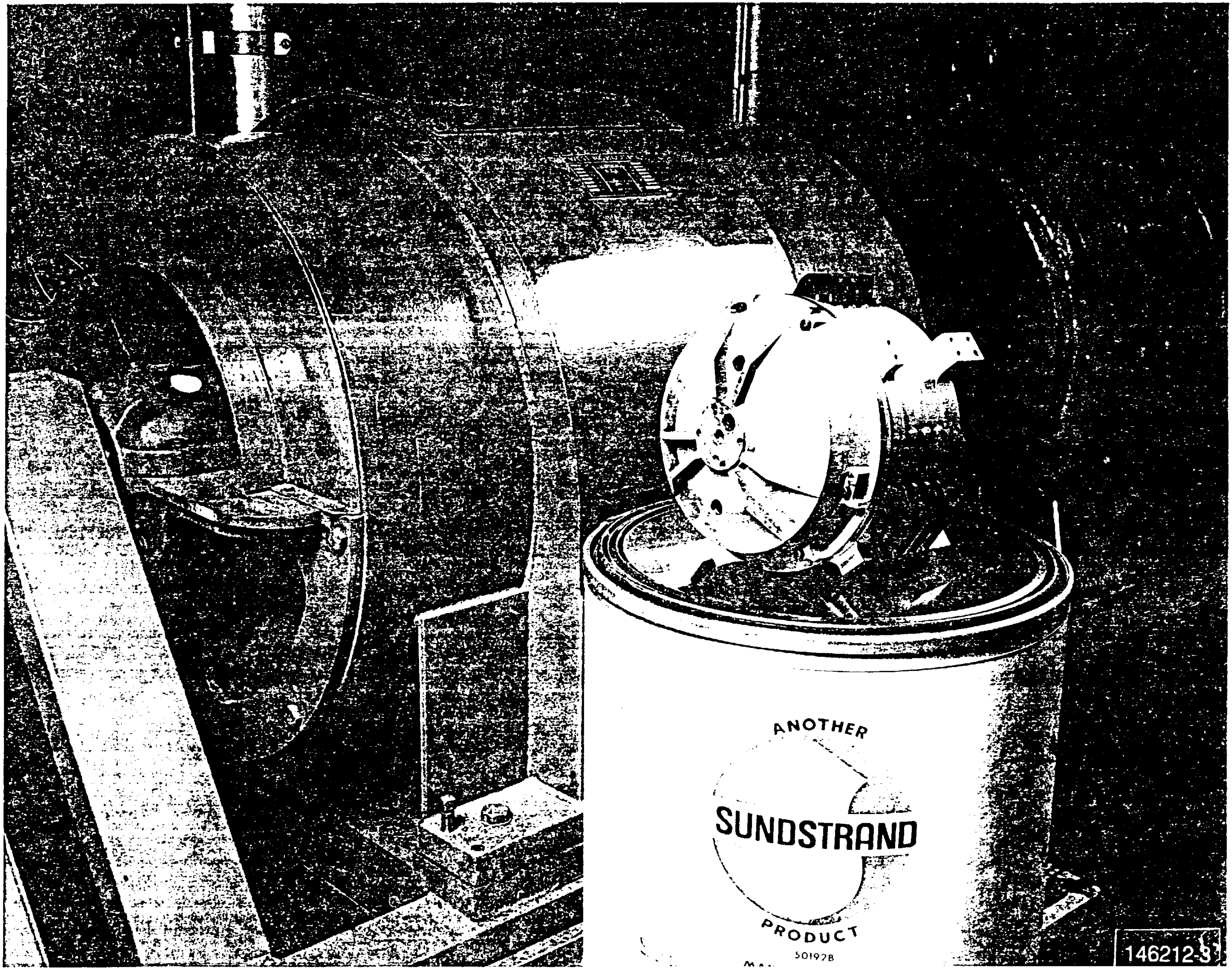


Figure 21 250 HP Induction Motor/Gearbox, shown next to 250 HP Industrial Motor

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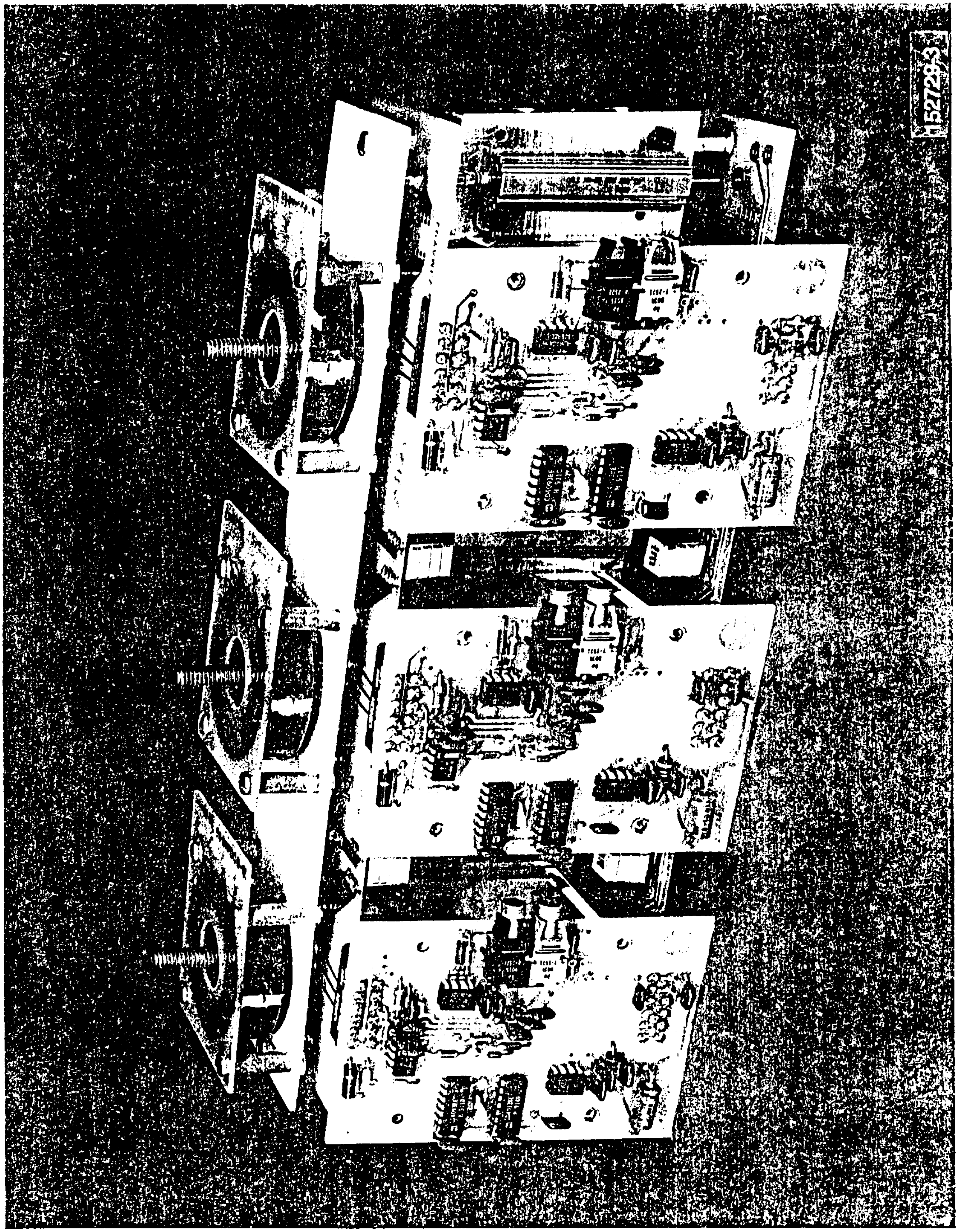

Figure 23 100 KW Inverter (one third of planned 300 KW inverter)

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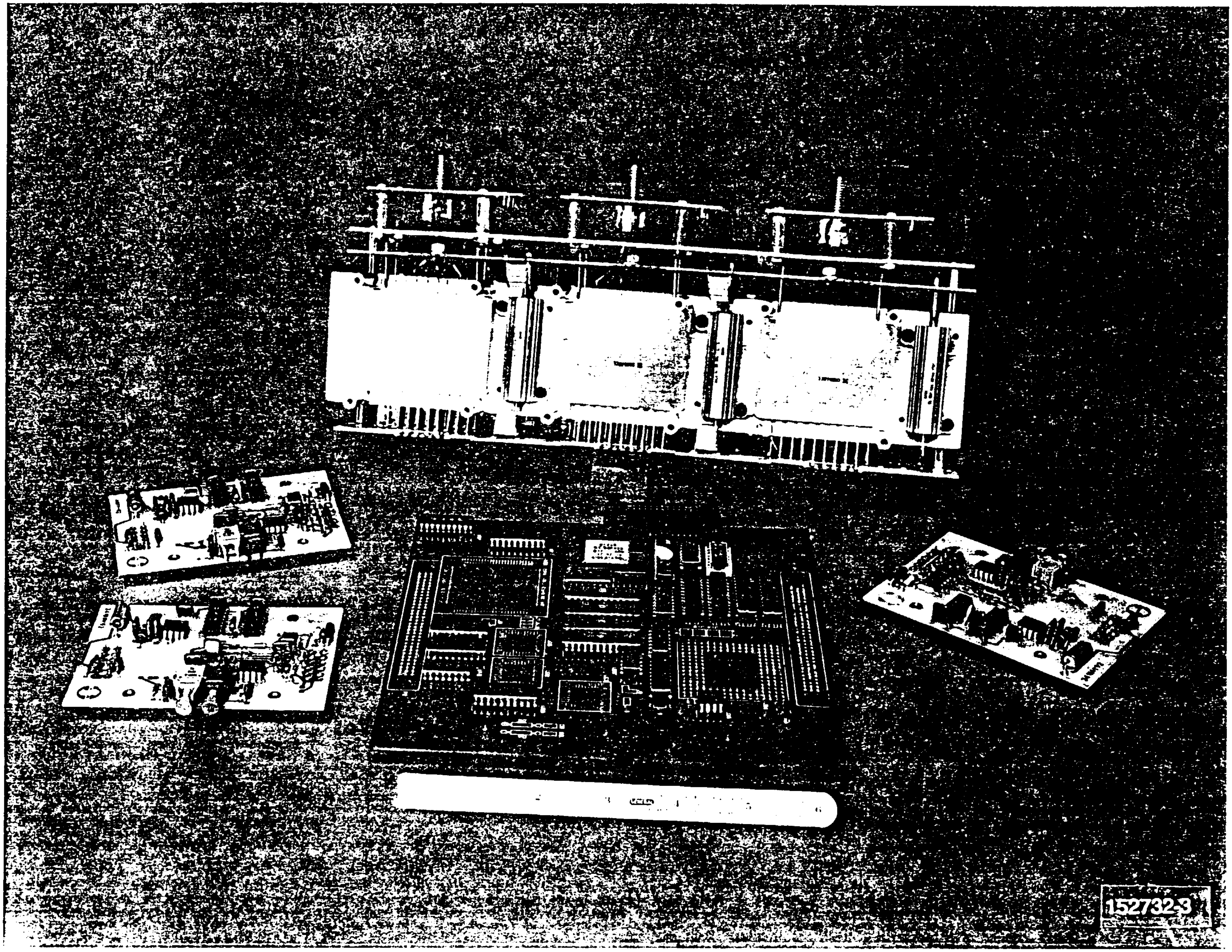

Figure 23 100 KW Inverter (gate drives removed on one side) and programmable controller

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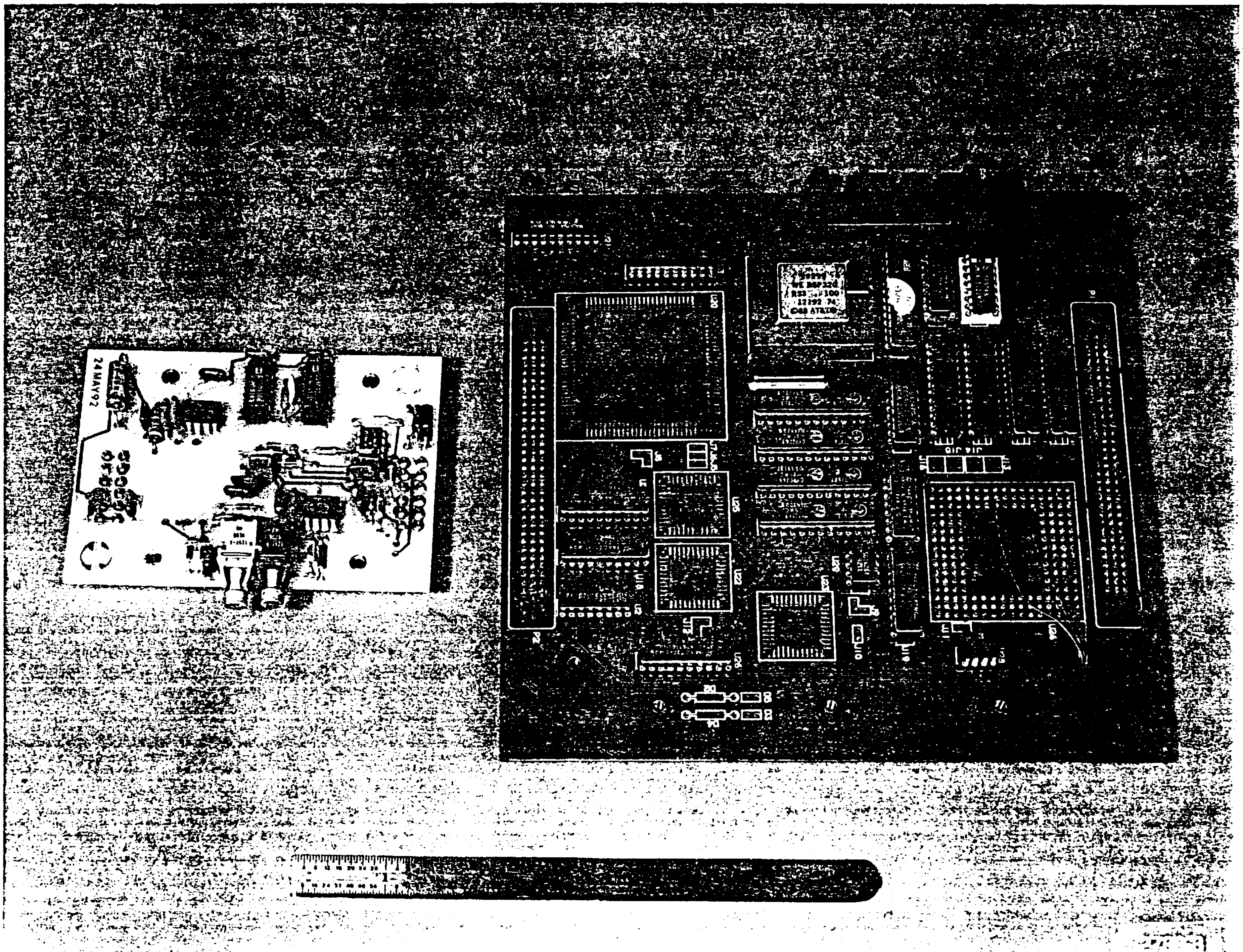

Figure 24 Programmable Controller and Gate Drive Circuit

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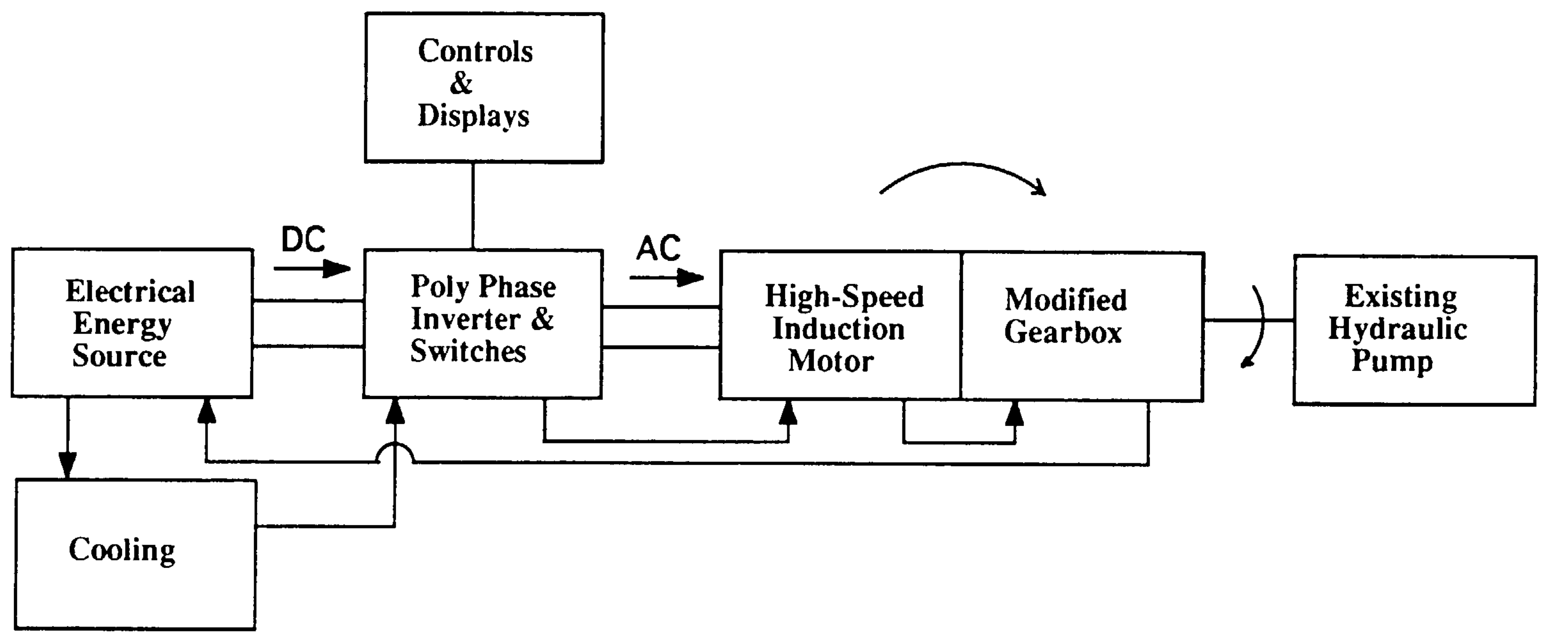
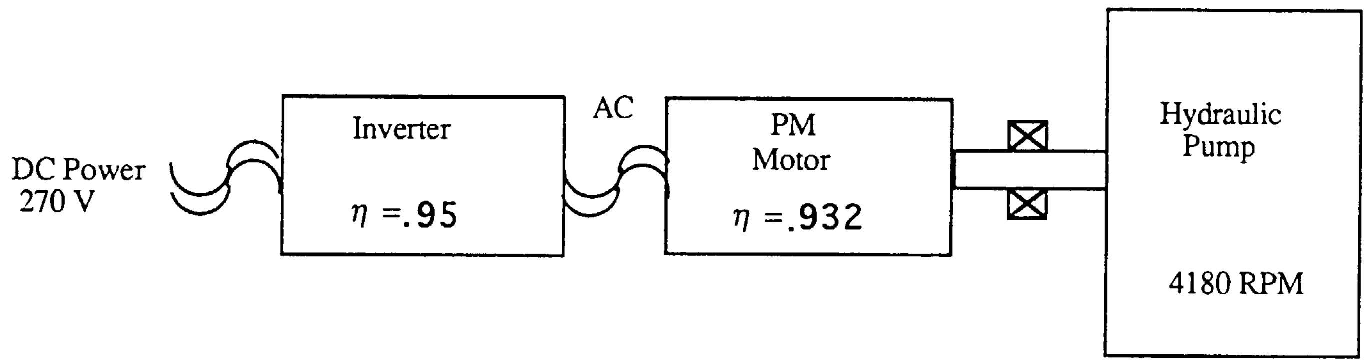
Electric APU Components*



*Source : Meyer, D. , Weber, K. and Scott, W. , "Electric Auxiliary Power Unit for Shuttle Evolution," Journal of Propulsion and Power, Vol.8, No.1, January-February 1992, pp. 233-239

Figure 25

Conceptual Electrical-To-Mechanical Conversion System (Variable-Field Induction)*



Peak Power (Hp/kW)	167.5/125.0	→	159.1/118.7	→	148.0/110.4
Cycle Avg. (Hp/kW)	50.9/38.0	→	48.4/36.1	→	45.0/33.6

*Source : Sundstrand Corporation

Figure 26

Motor/Inverter/Controller System Data

System Data	
Weight (total, excluding mounts)	91 lb
Efficiency	88.5%
Cycle life	20 cycles min
Startup time	210 msec (unloaded)/900 msec (loaded)
Motor Data	
Weight:	
Electromagnetic	43 lb
Housing and bearings	19 lb
Efficiency	93.2% at 72 hp rated speed
Type	12-pole permanent magnet brushless dc
Materials:	
Magnets	Samarium cobalt
Windings (insulation)	
Conductor covering	Polyimide enamel
Ground insulation	Polyamide/polyimide composite
Impregnation	Polyimide varnish
Armature	50% cobalt/iron laminated magnetic core
Inverter/Controller Data	
Weight	29 lb
Efficiency	95% at 72 hp, rated speed
Switches	3 transistors, 6 diodes per switch; hermetically sealed APT transistors
Control method	Pulse-width modulated (PWM), vector control, resolver feedback
Cooling method	Passive, beryllium heat sink

Source: Sundstrand Corporation

Figure 27

Energy Density of "Base" Battery Systems

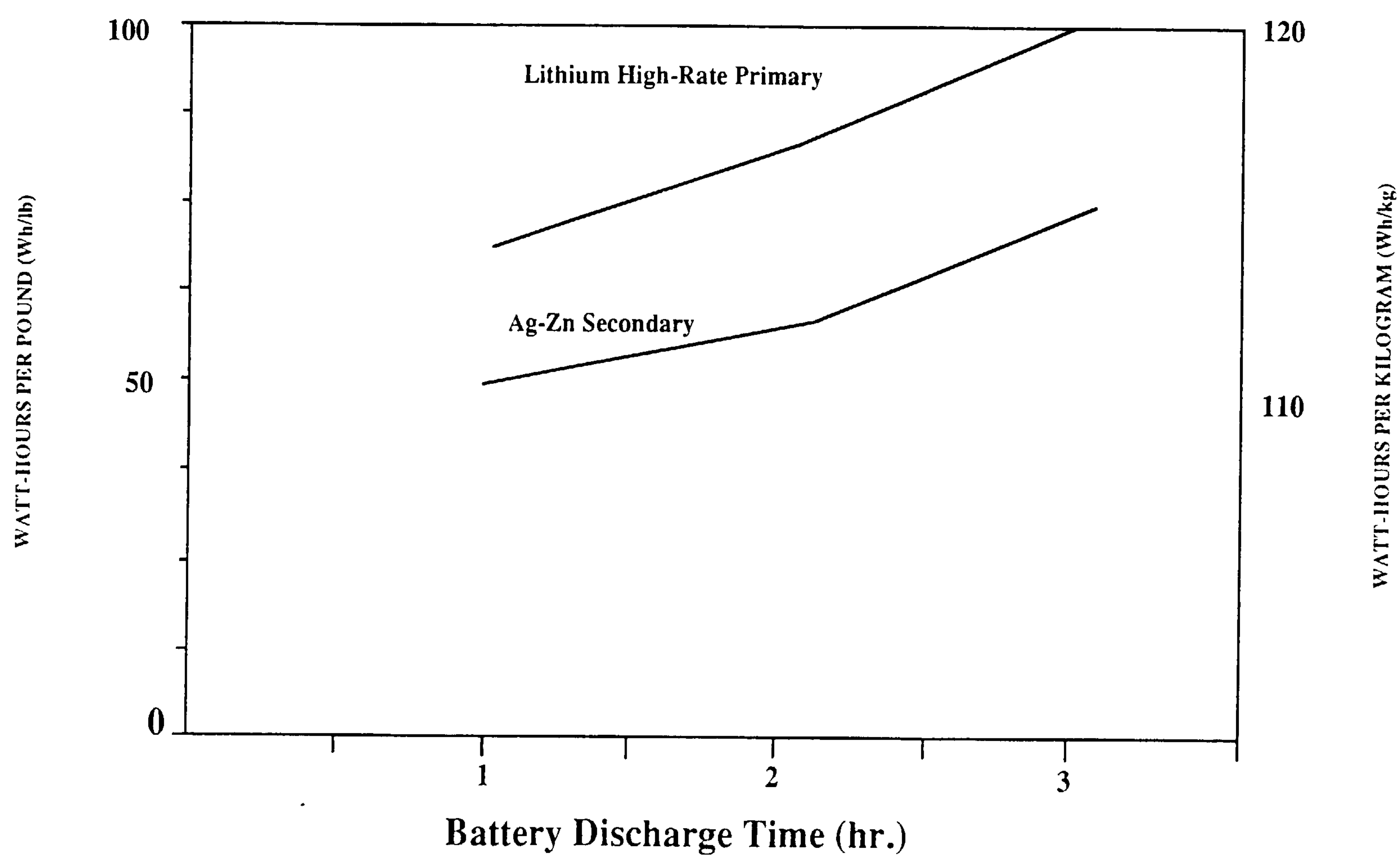
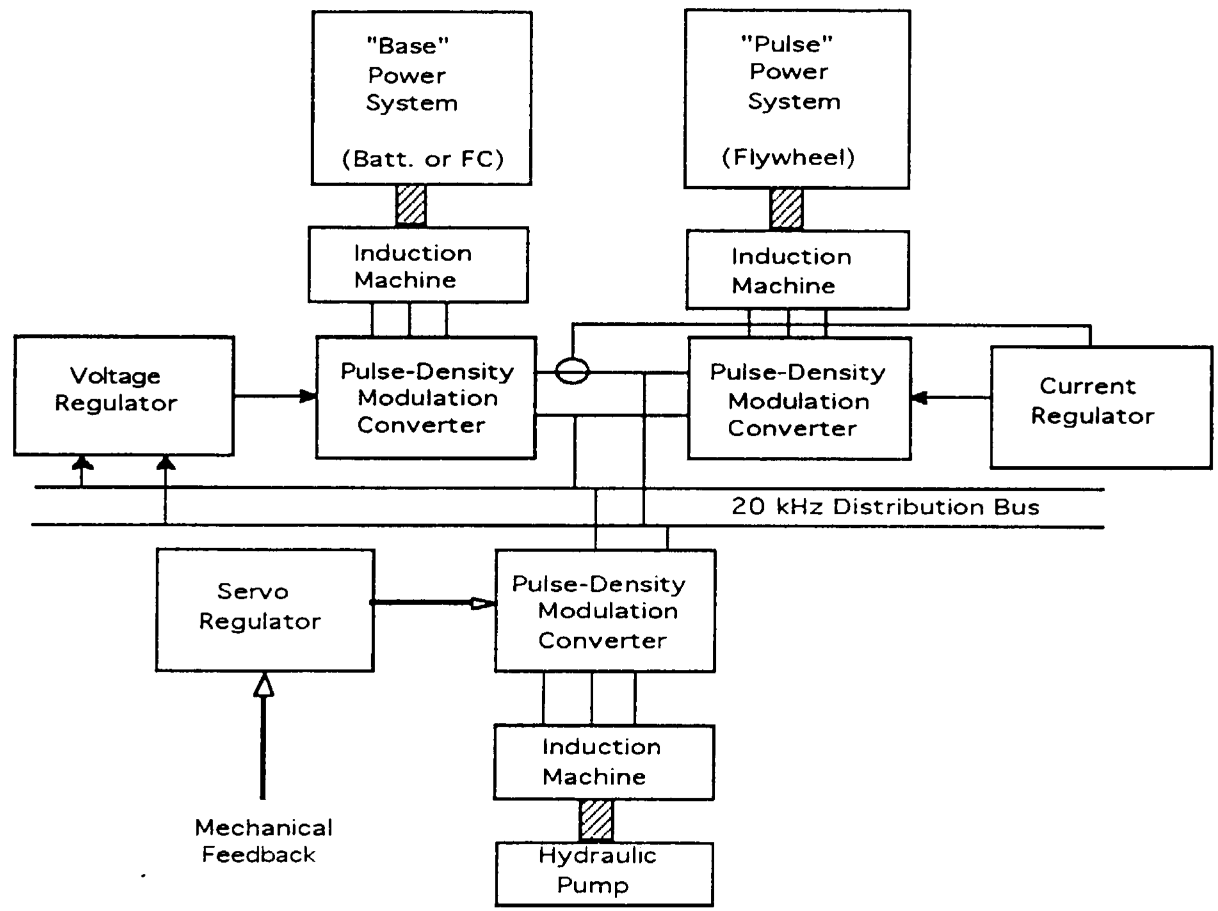


Figure 28

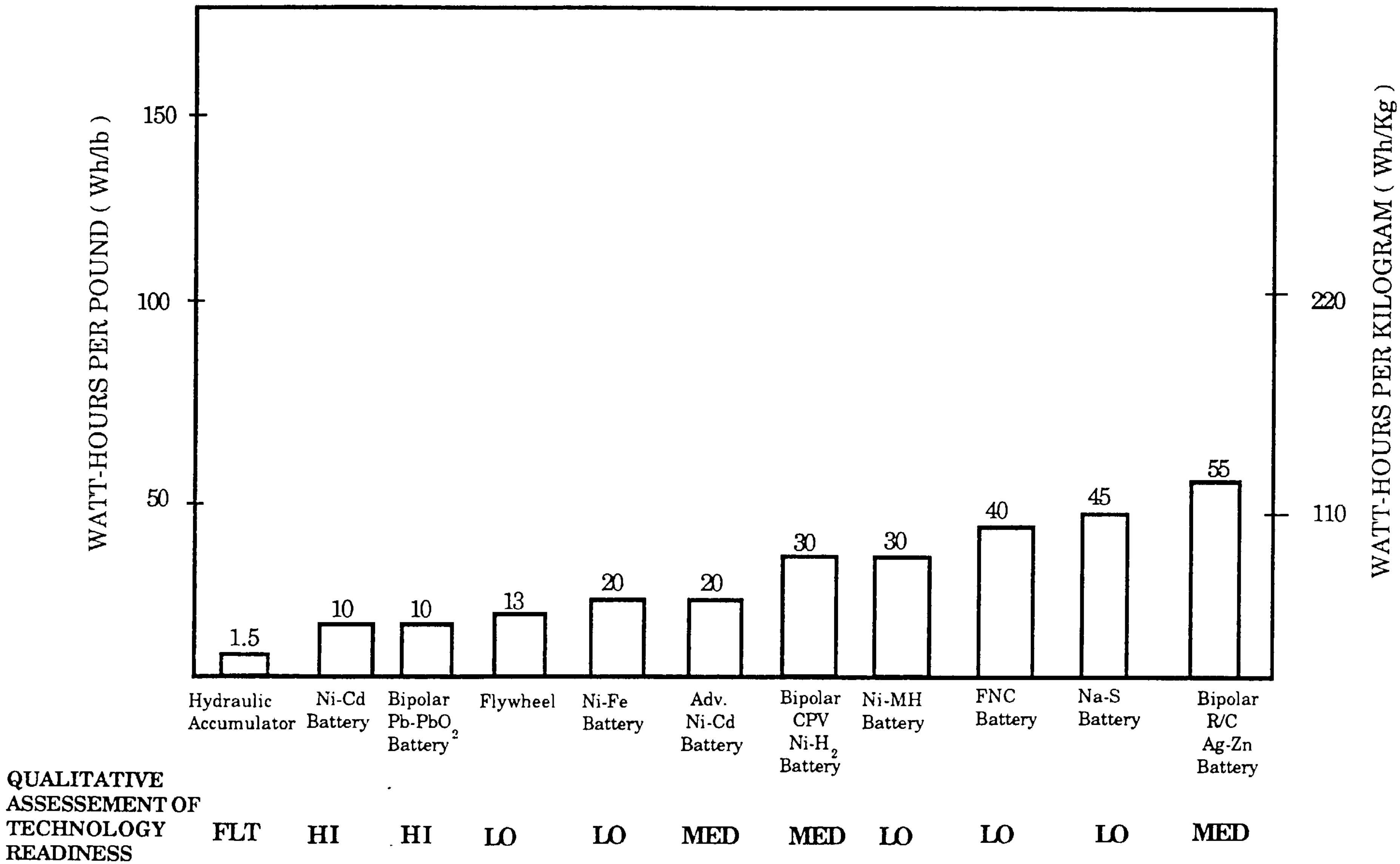
Conceptual Flywheel System Configuration



Source : SatCon Technology Corporation(modified)

Figure 29

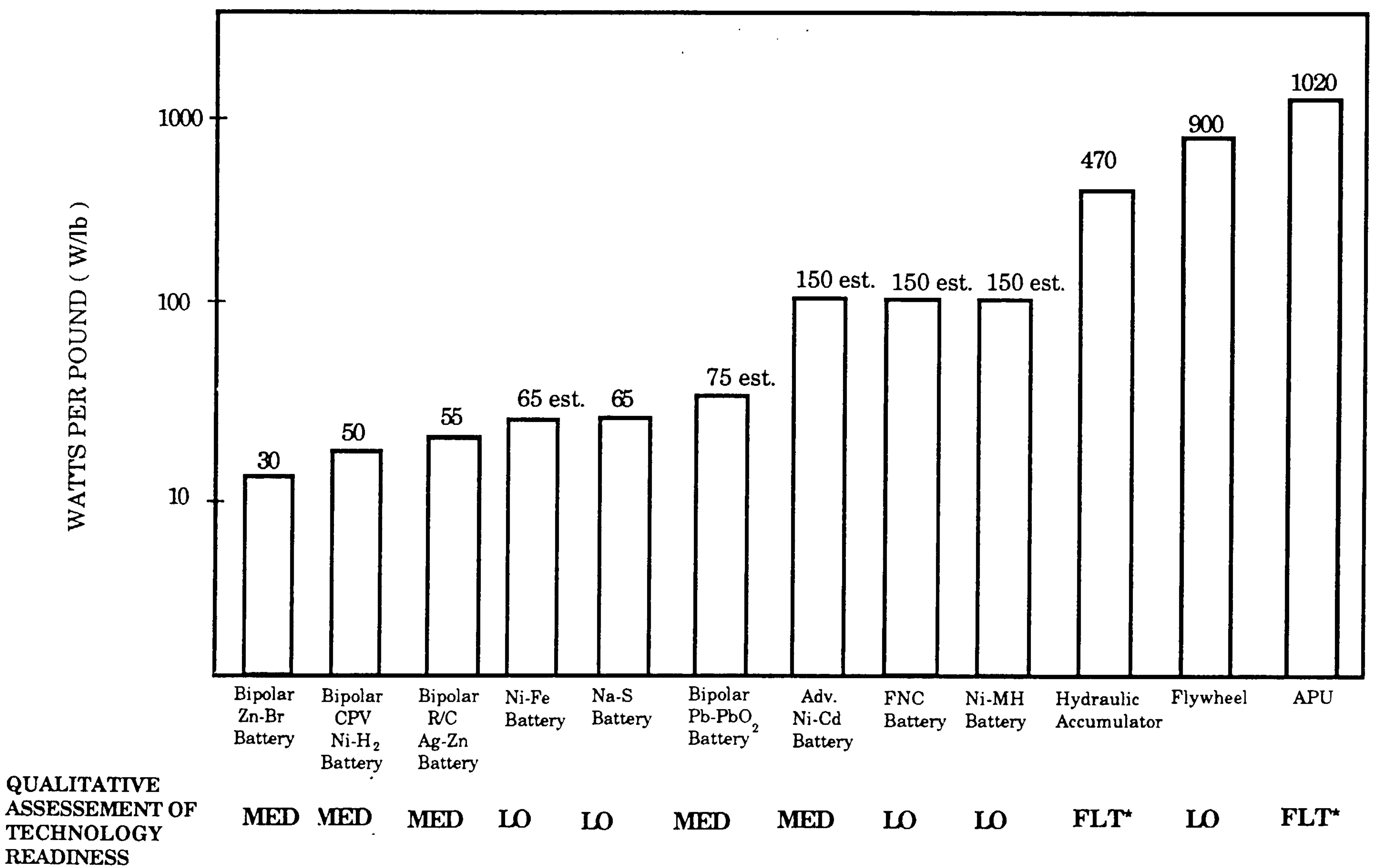
Optimized Specific Energy Comparision of Dedicated "Pulse" Power Systems for APU Application



Note : APU Specific Energy ~ 600 Wh/lb

Figure 30

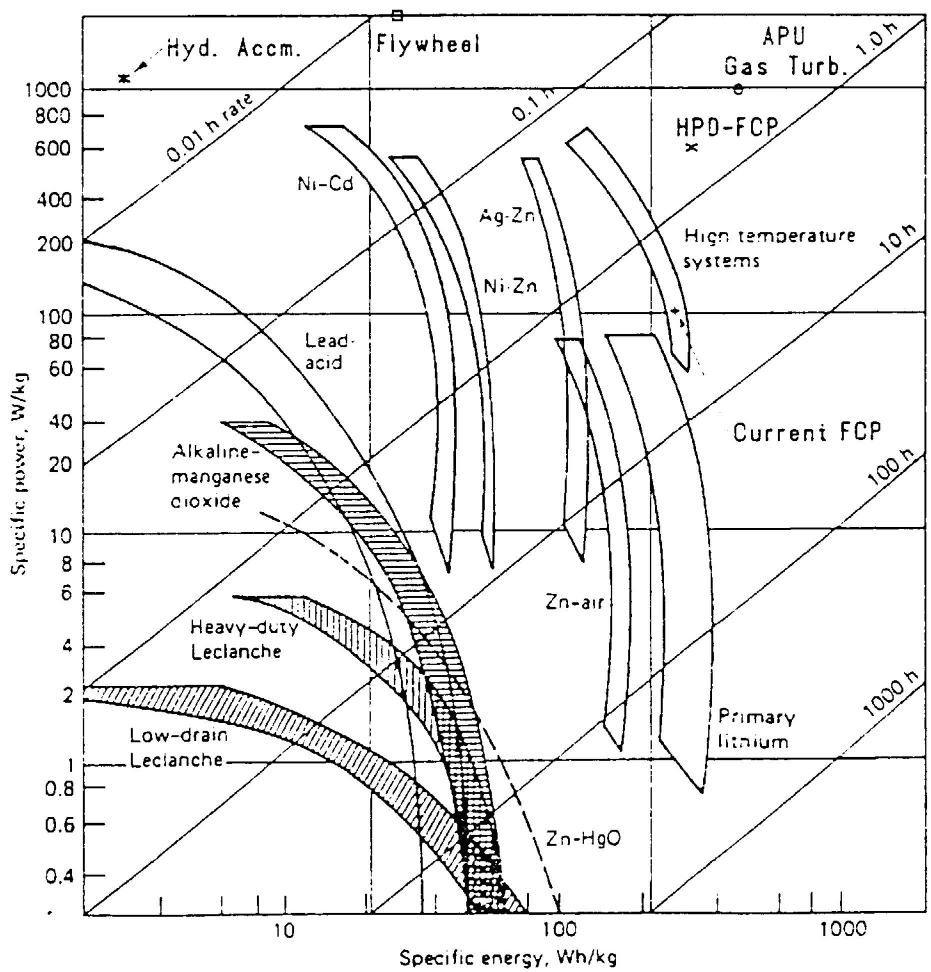
Optimized Specific Power Comparision of Dedicated "Pulse" Power Systems for APU Application



*Flight technology

Figure 31

Specific Power and Energy Diagram



Source : Linden, David, Handbook of Batteries and Fuel Cells

Figure 32

Current Orbiter FCP

Cell Stack	12 lb/kW x 15 kW	=	180 lb
Accessory Section	4.1 lb/kW x 20 kW	=	82
Coolant		=	19
Total FCP Weight (Wet)		=	281 lb

Capability : 15 kW Steady State
30 kW Transient

Figure 33

"Orbiter-Equivalent" HPD FCP*

Cell Stack	2 lb/kW x 15 kW	=	30 lb
End plates, etc.		=	15
Accessory Section	4.1 lb/kW x 20 kW	=	82
Coolant		=	19
Total FCP Weight (Wet)		=	146 lb

* 15 kW steady state, 30 kW for several seconds

Figure 34

High-Power-Density Cell Performance

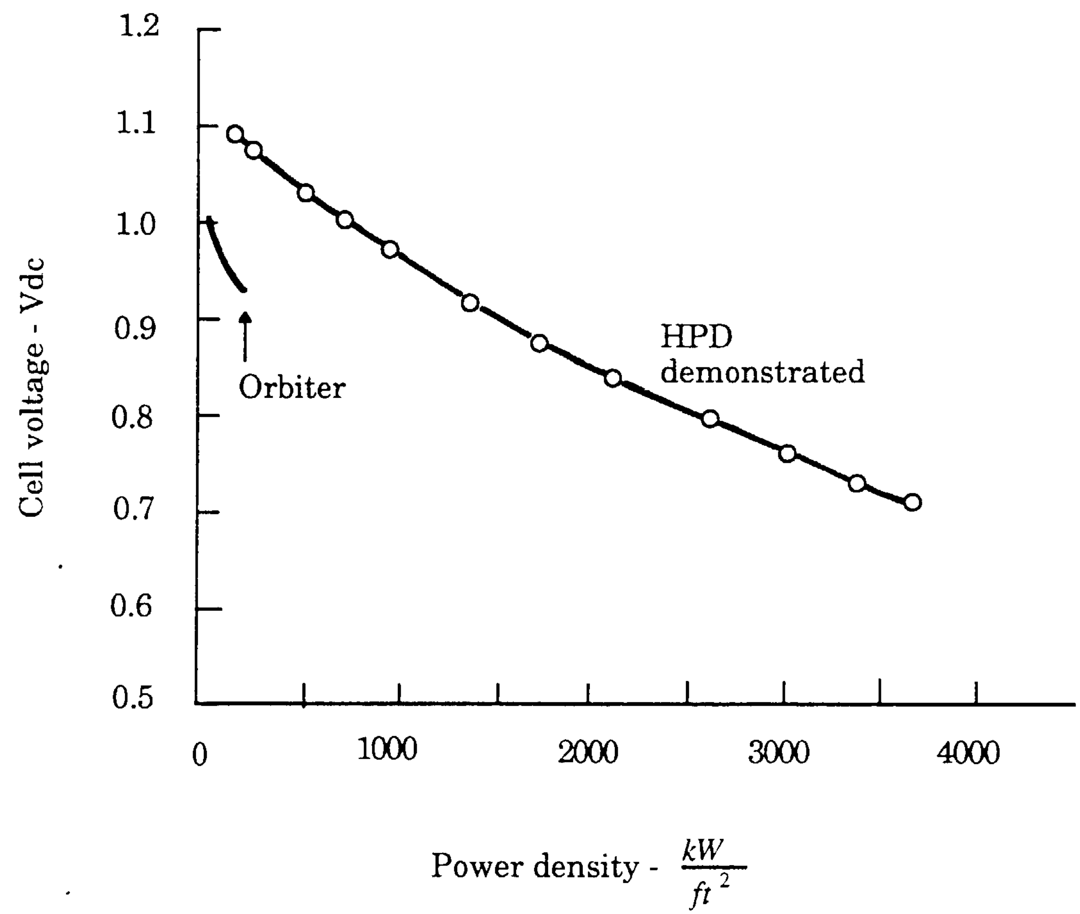


Figure 35

HPD Cell Performance Degradation

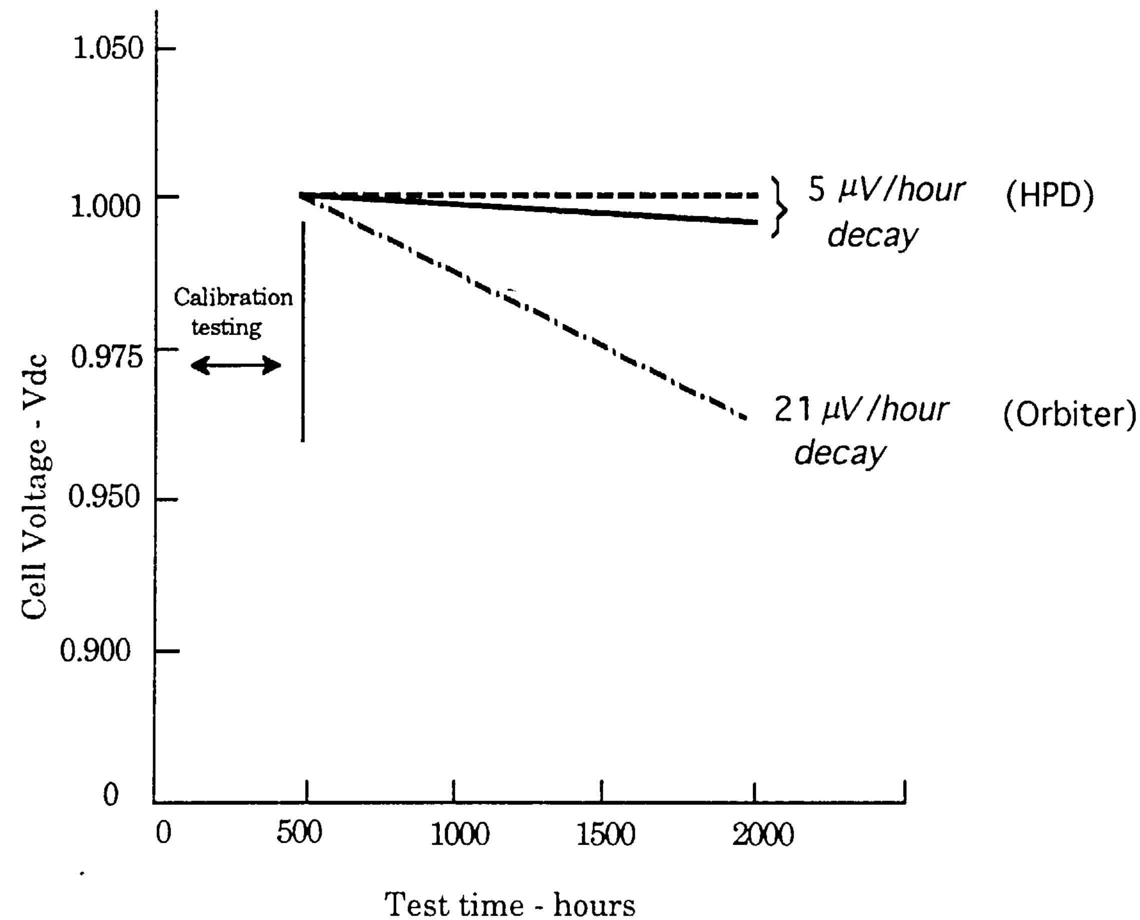


Figure 36

HPD FCP for APU Application

		MAX	MIN
Cell Stack[(1)]	$2\frac{lb}{kW} \times \left\{\begin{matrix} 80kW\,SS\ \max \\ 60kW\,SS\ \min \end{matrix}\right\}$	= 160	120
End plates, etc.		= 20	20
Accessory Section[(2)]	$(4.1\frac{lb}{kW} \times 20kW) \times \left\{\begin{matrix} (\frac{80}{20})^{0.6} \times 80kW \\ (\frac{60}{20})^{0.6} \times 60kW \end{matrix}\right\}$	= 184	159
Coolant		= 25	23
Total FCP Weight		389 lb max 80 kW SS 150 kW Trans.	322 lb min 60 kW SS 120 kW Trans.

(1) Demonstrated 1 lb/kW
(2) No optimization. Could be improved with,e.g, lighter motors, common motor drive for two pumps, etc.

Figure 37

Comparison of Orbiter and HPD FCP Weight

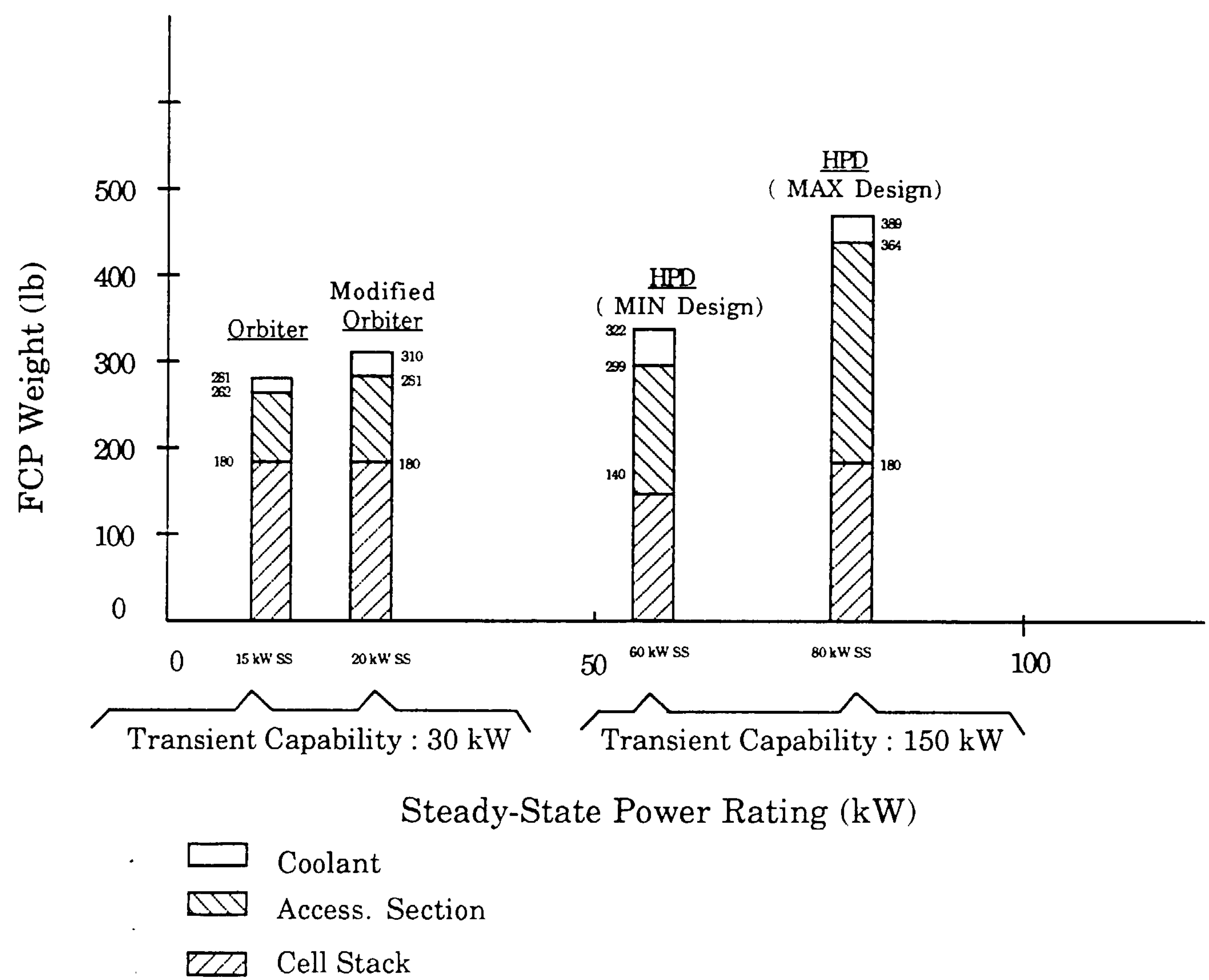


Figure 38

Power Density Comparison
Orbiter, Modified Orbiter, HPD-FCP

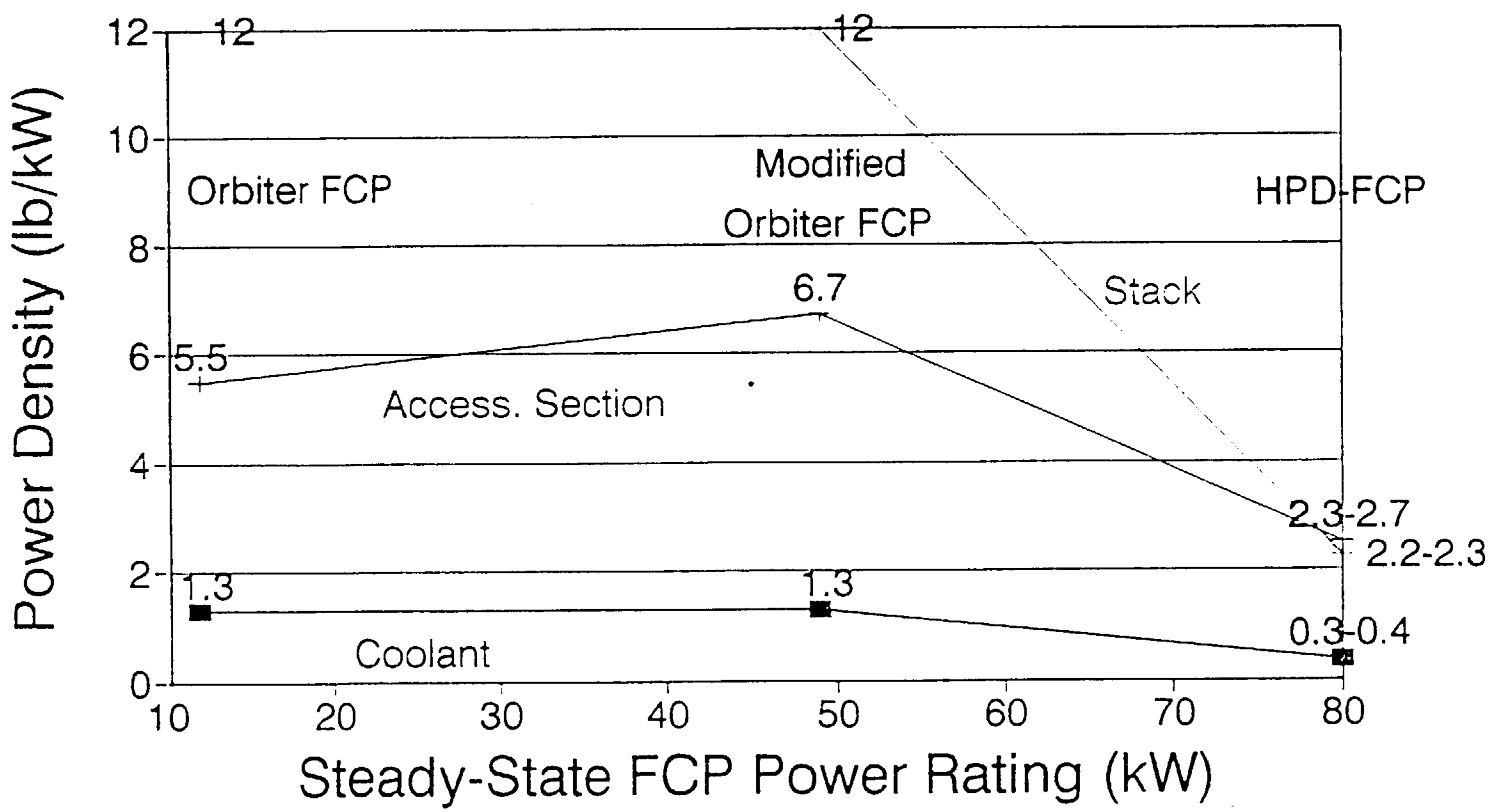


Figure 39

Initial Power Conversion Options for Mass Optimization Study

	Chemical-to-Electrical: "Base"	Chemical-to-Electrical: "Pulse"	Electrical-to-Mechanical
"Existing" Technology	R/C Ag-Zn 1 hr Battery R/C Ag-Zn 2.5 hr Battery Li Primary 2.5 hr Battery Existing Orbiter FCP Modified Orbiter FCP	Hydraulic Accumulator	
"New" Technology	HPD FCP	Hydraulic Accumulator Flywheels No "pulse" system(1)	AC Induction Motor/Inverter

8 subsystem options, with tankage variations(2)

(1)HPD FCP sized to handle all "Pulse" power requirements as well as "Base" load
(2)Fuel cells only

Figure 40

Final Power Conversion Options for Mass Optimization Study

	Chemical-to-Electrical: "Base"	Chemical-to-Electrical: "Pulse"	Electrical-to-Mechanical
"Existing" Technology	R/C Ag-Zn 1 hr Battery R/C Ag-Zn 2.5 hr Battery Li Primary 2.5 hr Battery Existing Orbiter FCP	Hydraulic Accumulator	
"New" Technology	HPD FCP	No "pulse" system(1)	AC Induction Motor/Generator

5 systems options, with tankage variations(2)

(1)HPD FCP sized to handle all "Pulse" power requiremants as well as "Base" load
(2)Fuel cells only

Figure 41

System Weight Comparisons (lb) - <u>Existing Technology</u>
(Results of Mass Optimization Analysis)

Definition of Listed Cases

Case	Description
2FCA	2 FCPs, new consumables tankage, with consumables
2FCB	2 FCPs, use existing consumables
1FCA	1 FCP, new consumables tankage, with consumables
1FCB	1 FCP, use existing consumables
BtA	All Ag-Zn Batteries and accumulator
BtB	Ag-Zn, 1 hr. disch. and Lithium, 2.5 hr. disch.

Existing Technology Summary for 3 APUs

Component	3FCA*	3FCB*	2FCA	2FCB	1FCA	1FCB	BtA	BtB
Fuel Cell	2529	2529	1686	1686	843	843	0	0
H_2 and O_2 Tanks	662	0	662	0	662	0	0	0
Consumables	182	0	182	0	91	0	0	0
Integr. Hardware	835	835	556	556	278	278	0	0
Ag-Zn 1 hr. Batt.	0	0	711	711	1215	1215	1661	1215
Ag-Zn 2.5 hr.	0	0	0	0	514	514	1834	0
Lithium 2.5 hr.	0	0	0	0	0	0	0	1719
Batt. Intg. Hdw.	0	0	142	142	346	346	699	759
Accumulator	501	501	501	501	501	501	449	501
Electric Motor	180	180	180	180	180	180	180	180
Inverter	60	60	60	60	60	60	60	60
Add. Cooling	273	273	273	273	273	273	273	273
Avionics	180	180	180	180	180	180	180	180
Total	5402	4558	5133	4289	5143	4390	5336	4887

*Not optimized

Figure 42

System Weight Comparisons (lb) - New Technology
(Results of Mass Optimization Analysis)

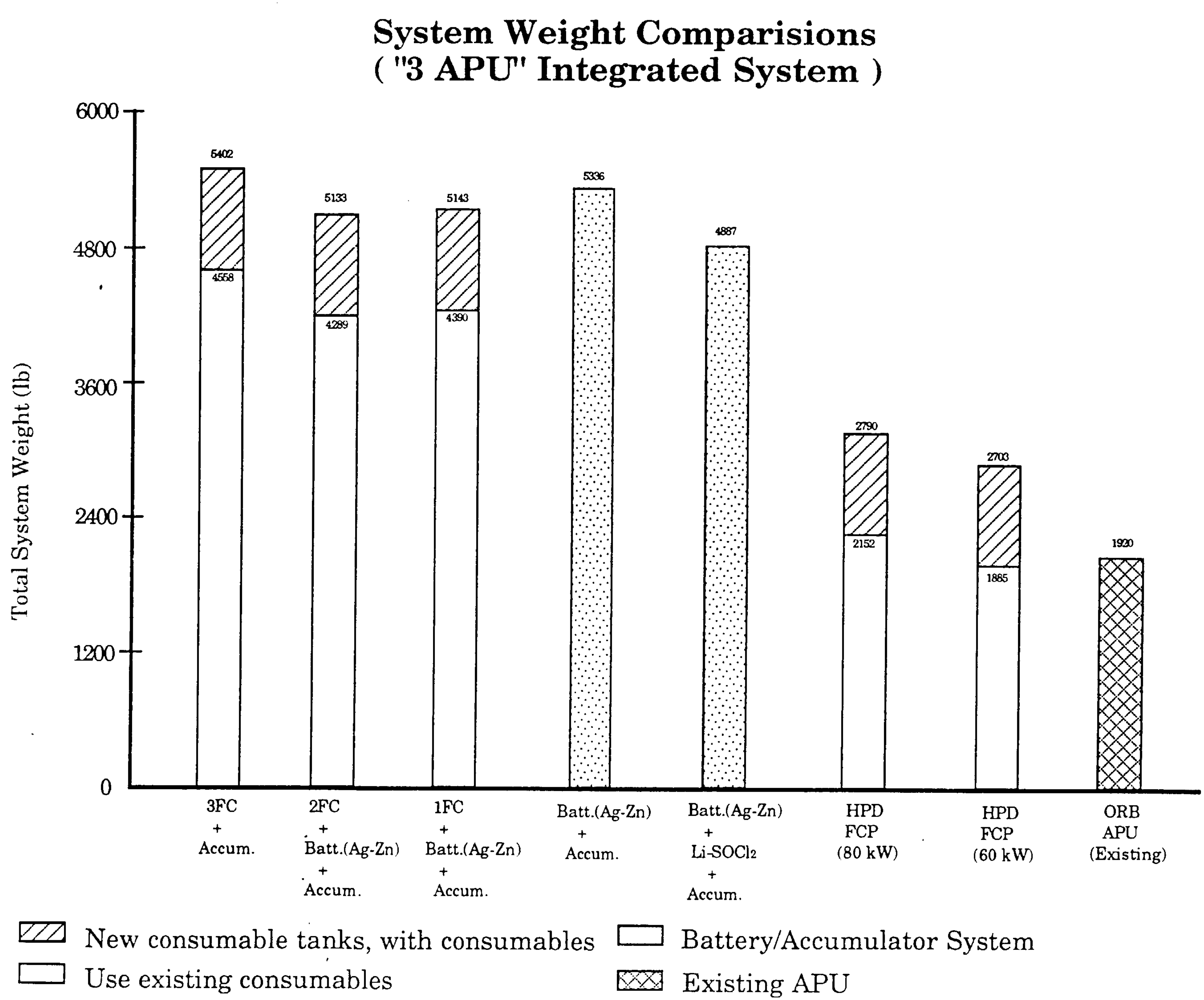
Definition of New Technology Cases

Case	Description
80A	80 kW HD-FCP, new tankage, with consumables
80B	80 kW HD-FCP, prorated tankage, with consumables
80C	80 kW HD-FCP, use existing consumables
60A	60 kW HD-FCP, new tankage, with consumables
60B	60 kW HD-FCP, prorated tankage, with consumables
60C	60 kW HD-FCP, use existing consumables

New Technology Summary for 3 APUs

Component	80A	80B	80C	60A	60B	60C
HPD-Fuel Cell	1167	1167	1167	966	966	966
H_2 and O_2 Tanks	662	122	0	662	122	0
Consumables	156	156	0	156	156	0
Integr. Hardware	385	385	385	319	319	319
Electric Motor	180	180	180	180	180	180
Inverter	60	60	60	60	60	60
Add. Cooling	273	273	273	273	273	273
Avionics	180	180	180	180	180	180
Total	2970	2430	2152	2703	2163	1885

Figure 43



System Weight Comparisions
("3 APU" Integrated System)
Total System Weight (lb)
6000
4800
3600
2400
1200
0
5402
4558
5133
4289
5143
4390
5336
4887
2790
2152
2703
1865
1920
3FC + Accum.
2FC + Batt.(Ag-Zn) + Accum.
1FC + Batt.(Ag-Zn) + Accum.
Batt.(Ag-Zn) + Accum.
Batt.(Ag-Zn) + Li-SOCl2 + Accum.
HPD FCP (80 kW)
HPD FCP (60 kW)
ORB APU (Existing)
New consumable tanks, with consumables
Use existing consumables
Battery/Accumulator System
Existing APU

Figure 44

Comparision of Energy Density, Power Density and State of Technology "Readiness" for "Pulse" Power Source

Type	Specific Energy (Wh/lb)	Specific Power (W/lb)	Technology "Readiness"	Overall Figure of Merit for APU Application
Orbiter APU	250	1100	FLT	1
Hydraulic Accumulator	1.5	600	FLT	2
BP R/C Ag-Zn	55	55	HI	3
Bipolar $Pb\text{-}PbO_2$	10	75 (est.)	MED	4
Adv. Ni-Cd	20	150 (est.)	MED	5
BP CPV $Ni\text{-}H_2$	30	50	MED	6
BP Zn-Br	30	30	MED	7
Flywheel	13	900	LO	8
FNC	40	150 (est.)	LO	9
Ni-MH	30	150 (est.)	LO	10
Na-S	45	65	LO	11
Ni-Fe	20	65 (est.)	LO	12

Table 1

Orbiter Fuel Cell System Weight Breakdown (lb)[1]

FCP[2]	3 @ 264	792.0 lb.
Relief, Vent and Purge Plumbing		9.2
Product Water Plumbing		22.1
Product Water Valve		2.3
Fuel Cell Coolant (FC40)		87.6
Fuel Cell Coolant Plumbing		26.5
Fuel Cell Coolant Filters		1.2
Supports		46.7
Installation		61.2
TOTAL (3 ORBITER FCPs)		1048.8 lb

350 lb/FCP Integrated Into vehicle[3]

1. Source of data: Rockwell International "Control Book of Mass Properties," OV-102
2. With improved H_2 pump
3. Represents 25% integration penalty over FCP Wet Weight

Table 2

Oxygen System Weight Breakdown, lb[1]

Tank Assembly, PRSA[2] (3 oxygen tanks)	632.9 lb
Fill and Drain Plumbing	14.6
Fill and Drain Disconnects	4.2
Fill and Drain Insulation	11.7
Relief, Vent and Purge Plumbing	28.1
Relief, Vent and Purge Valves	12.8
Relief, Vent and Purge Disconnects	2.8
Relief, Vent and Purge Insulation	67.9
Relief, Vent and Purge Panel	9.2
Supply Plumbing	24.3
Supply Valves	20.9
Supply Filters	1.8
Supply Disconnects	0.9
Supply Insulation	22.1
Supply Panel	5.4
Supports	38.4
Installation	120.9
TOTAL (3 O_2 TANK SETS)	1018.9 lb

1. Source of Data : Rockwell International "Control Book of Mass Properties," OV-102
2. PRSA $\equiv$ Power Reactant Storage Assembly

Table 3

Hydrogen System Weight Breakdown, lb[1]

Tank Assembly, PRSA[2] (3 hydrogen tanks)	659.9 lb
Fill and Drain Plumbing	16.4
Fill and Drain Disconnects	4.2
Fill and Drain Insulation	10.7
Relief, Vent and Purge Plumbing	27.3
Relief, Vent and Purge Valves	10.8
Relief, Vent and Purge Disconnects	2.8
Relief, Vent and Purge Insulation	17.0
Relief, Vent and Purge Panel	9.6
Supply Plumbing	24.6
Supply Valves	16.3
Supply Filters	1.8
Supply Disconnects	0.8
Supply Insulation	16.0
Supply Panel	5.9
Supports	38.0
Installation	105.2
TOTAL (3 H_2 TANK SETS)	967.3 lb

1. Source of Data : Rockwell International "Control Book of Mass Properties," OV-102
2. PRSA ≡ Power Reactant Storage Assembly

Table 4

Available Fuel Cell Reactants[1]

EPS H_2		92 lb	$\left.\begin{matrix}\\ \\ \end{matrix}\right\}$ 761 lb reactant per tank set
Total O_2	781		
ECLSS O_2	-112		
EPS O_2		669 lb	
"Loaded" Energy	$\frac{761\ lb \cdot rctnt}{0.81\ lb/kWh} =$	939 kWh	
"Usable" Energy		840 kWh [2]	
Reserve		99 kWh	

Usable reactants per tank tank set = 840 kWh x 0.81 lb/kWh = 680.4 lb

Usable H_2 = 680.4/9 = 75.6 lb H_2 per tank

Usable O_2 = 680.4 - 75.6 = 604.8 lb O_2 per tank

(1)Single PRSA tank set
(2)Defined by flight rules

Table 5

APPENDIX A

Hydraulic Power Averaging with an Accumulator

Nomenclature

d - duty cycle

f - fraction of power supplied by the accumulator

k - specific heat ratio - c_p/c_v

p - pressure in psi

P - power in horsepower

Q - Volume in ft^3

r - radius of equivalent spherical accumulator in ft

t - time in seconds

v - specific volume ft^3/lb_m

V - Volume ft^3

ϵ - recharge efficiency

ξ - efficiency of the hydraulic pump

Superscripts

$\cdot$ - time rate of change

Subscripts

$_i$ - pertaining to pulse interval

$_{N_2}$ - pertaining to the gaseous nitrogen

$_{oil}$ - pertaining to the hydraulic oil in the accumulator

$_p$ - pertaining to pulse width

$_{sh}$ - pertaining to the accumulator shell

$_{ss}$ - pertaining to steady state operation

$_{tot}$ - pertaining to the total

$_1$ - pertaining to the nitrogen at full pressure - 3000 psi

$_2$ - pertaining to the nitrogen at expanded pressure - 2600 psi

Introduction

The desire to remove hydrazine from the Space Shuttle has caused a careful reexamination of the operational requirements imposed on the APUs. Flight test data now indicates that the peak hydraulic power requirement is 145 horsepower over a six second period with a maximum duty cycle of 10% . This contrasts with the APU capability to supply 145 horsepower continuously.

Power Averaging

One method of supplying the hydraulic power required is to augment a steady power source with an energy storage device which would supply the short peak power demands and then recharge during the lower power demand during the "steady state operation." Fig. A1 indicates such a power requirement as a function of time with P_p representing the maximum power required, P_{ss} representing the steady state power required, t_p the pulse time and t_i the balance of the interval time before the duty cycle repeats. The duty cycle, d, is then given by:

$$d = \frac{t_p}{t_p + t_i}$$

or

$$\frac{t_p}{t_i} = \frac{d}{1-d}. \tag{1}$$

If a power source of constant output, P_{max}, is to supply the energy shown in Fig. A1 then the energy extracted during the period t_p must be equal to the energy stored during the period t_i. If the fraction of the energy input to the storage device to the energy actually stored is ϵ, then the following relation results.

$$\epsilon(P_{max} - P_{ss})t_i = (P_p - P_{max})t_p \tag{2}$$

Substituting Eq. (1) into Eq.(2) and rearranging, an expression for P_{max} is obtained.

$$P_{max} = \left(\frac{P_{ss} + \frac{P_p d}{\epsilon(1-d)}}{1 + \frac{d}{\epsilon(1-d)}} \right) \tag{3}$$

Fig. A2 is a plot of P_{max} as a function of duty cycle, d, for values of ϵ of 1.0, 0.9, and 0.2 with $P_{ss} = 40hp$ and $P_p = 145hp$.

Accumulators as Energy Storage Devices

One method of storing the excess energy during the period t_i is to design an accumulator, as shown in Fig. A3, with sufficient volume to supply the peaking power during the period t_p. Assuming a hydraulic system pressure drop of 3000 psi at the peak power requirement of 145 hp and a hydaulic pump efficiency of ξ the hydraulic system volume flow rate is determined from the following energy balance.

$$P_p\xi = 145\xi hp = \dot{Q}\Delta p = \dot{Q}(3000\frac{lb_f}{in^2})(144\frac{in^2}{ft^2})(\frac{hpsec}{550ftlb_f})$$

From test data for the hydraulic pump a reasonable estimate of ξ is 0.875 which gives a hydraulic system flow rate of:

$$\dot{Q} = 0.1615 \quad \frac{ft^3}{sec} = 72.50 \quad \frac{gal}{min} \tag{4}$$

The portion of this flow rate from the accumulator taken from Fig. A2 taken at a duty cycle of 0.1 and a recharge efficiency of 90% is;

$$\dot{Q}_{oil} = \frac{0.1615(P_p - P_{max})}{P_p} = 0.1041\frac{ft^3}{sec}.$$

Assuming an allowable pressure variation of 2600 to 3000 psi in the hydraulic system, an isentropic expansion of gaseous nitrogen in the accumulator and a constant hydraulic flow rate of $0.1041 ft^3/sec$ during the peak power demand an expression for the accumulator volume can be developed as shown.

$$p_1 v_1^k = p_2 v_2^k$$

$$\frac{p_1}{p_2} = \frac{3000}{2600} = 1.1538 = \left(\frac{v_2}{v_1}\right)^{1.4}$$

$$v_2 = 1.1076 v_1 \quad ft^3/lb_m$$

Since the mass of gaseous nitrogen is constant, an expression for the volumes may be obtained.

$$V_2 = 1.1076 V_1 \quad ft^3 \tag{5}$$

However,

$$\Delta V = \int \dot{Q} dt \approx \dot{Q} t_p \quad ft^3 \tag{6}$$

which is the volume flow rate out of the accumulator (assumed approximately constant) during the peak power period, t_p. Eq. (6) then can be expanded to give,

$$V_2 - V_1 = \dot{Q}_{oil} t_p = 0.1041 t_p \quad ft^3$$

and Eq. (5) also gives an expression for $V_2 - V_1$.

$$V_2 - V_1 = 0.1076 V_1 = 0.1041 t_p \quad ft^3$$

$$V_1 = 0.9675 t_p \quad ft^3$$

The total accumulator volume is the the sum of the gaseous nitrogen volume and the oil volume.

$$V_{tot} = V_{oil} + V_{N_2} = (0.1041 + 0.9675) t_p = 1.0716 t_p \quad ft^3$$

An expression for the accumulator radius is obtained by assuming a spherical shape.

$$\frac{4\pi r^3}{3} = V_{tot} = 1.0716 t_p \quad ft^3$$

$$r = 0.6348 t_p^{\frac{1}{3}} \quad ft \tag{7}$$

Letting the wall thickness be δ and the working tensile stress in the accumulator walls be 30 Ksi an expression relating the radius and wall thickness is given as:

$$A \Delta p = \sigma 2 \pi r$$

$$\pi r^2 (3000)(144) = 30000 \delta 2 \pi r (12)$$

or using Eq. (7)

$$\delta = 0.06r = 0.03809t_p^{\frac{1}{3}} \quad inches.$$

The weight of the accumulator shell is then:

$$W_{sh} = 4\pi r^2 \frac{\delta}{12}(492) \quad lb_f$$

$$W_{sh} = \frac{0.4030t_p^{\frac{2}{3}}(4\pi)(492)(.03809t_p^{\frac{1}{3}})}{12} \quad lb_f$$

$$W_{sh} = 7.909t_p \quad lb_f.$$

The weights of gaseous nitrogen, the hydraulic oil and the total weight are respectively:

$$W_{N_2} = \frac{(3000)(144)}{(55.18)(530)}(0.9675t_p) = 14.291t_p \quad lb_f$$

$$W_{oil} = (52)(0.1041)t_p = 5.413t_p \quad lb_f$$

$$W_{tot} = 27.613t_p \quad lb_f$$

Fig. A4 shows the weights of these accumulator components as a function of pulse width for this case. Also shown are the maximum power required of the source and the accumulator volume.

The resulting accumulator would weigh 165.7 lb_f and have a volume of 5.719 ft^3. During this maneuvering phase of re-entry the power source would have to supply 51.5 hp to the hydraulic pump.

Figure A1. Pulse Power Level Superimposed on a Base Level

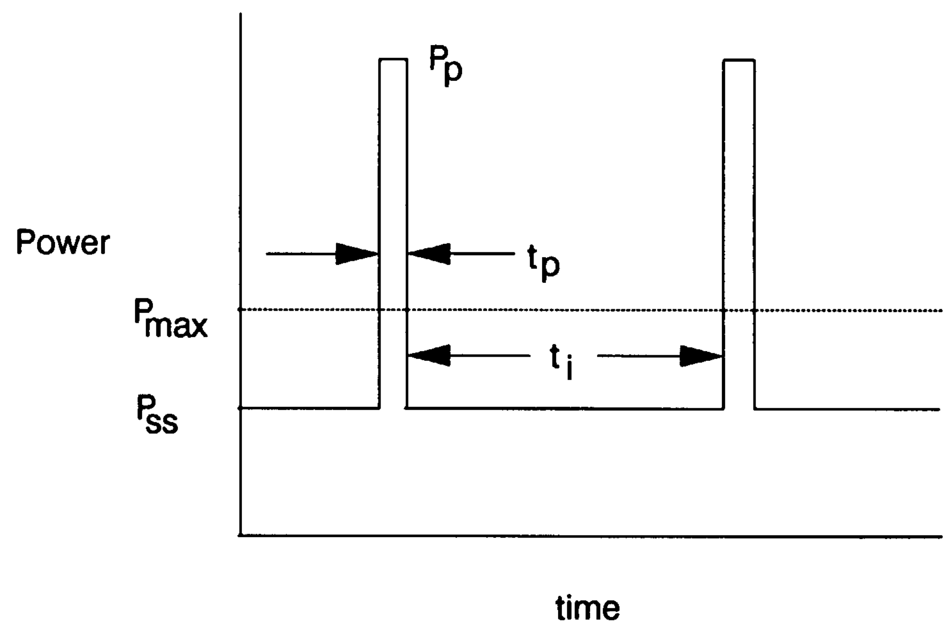
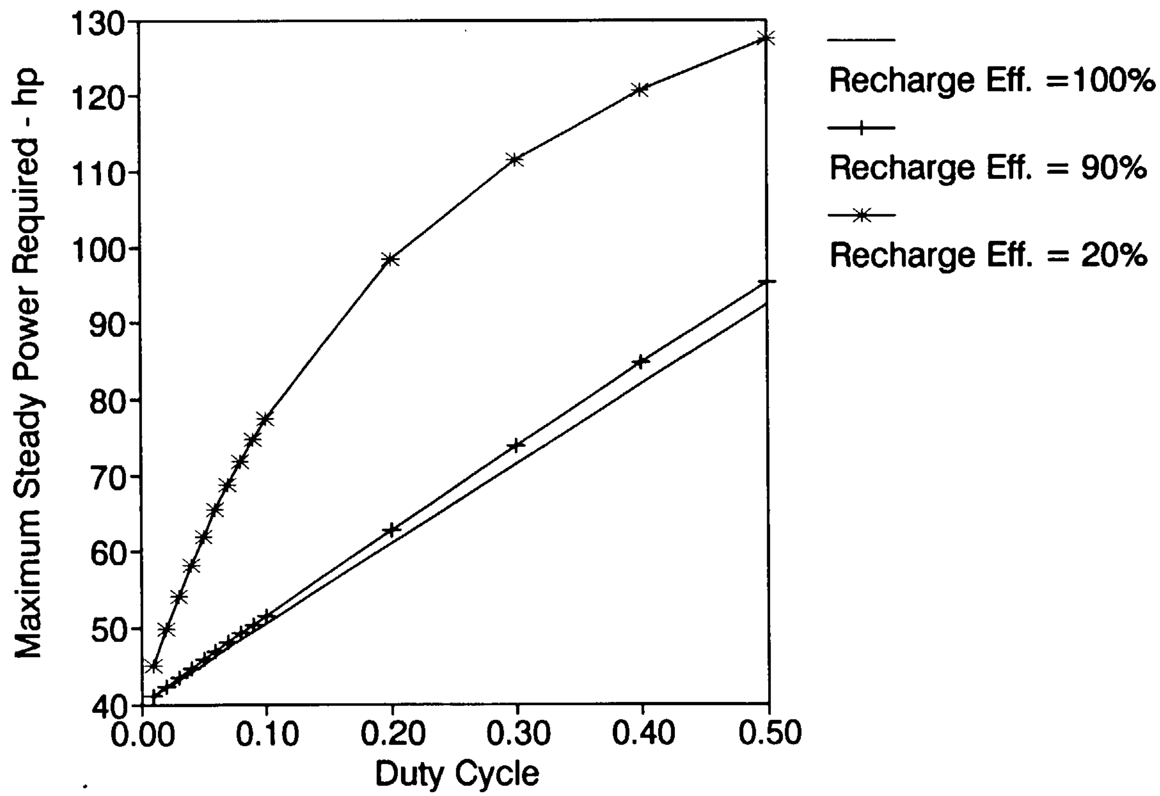


Figure A2. Maximum Power Required vs. Duty Cycle, Pss=40 hp, Pp=145 hp



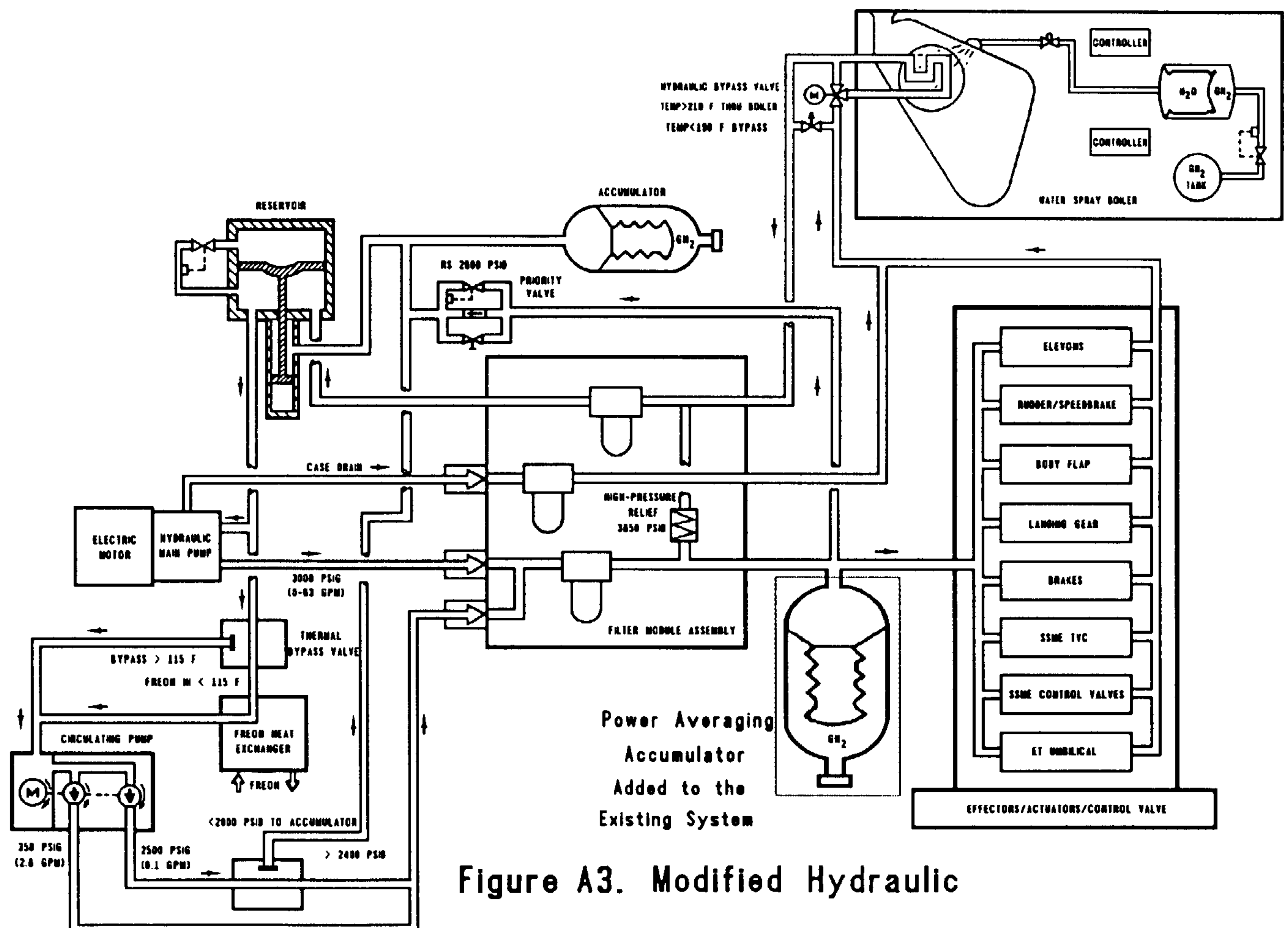
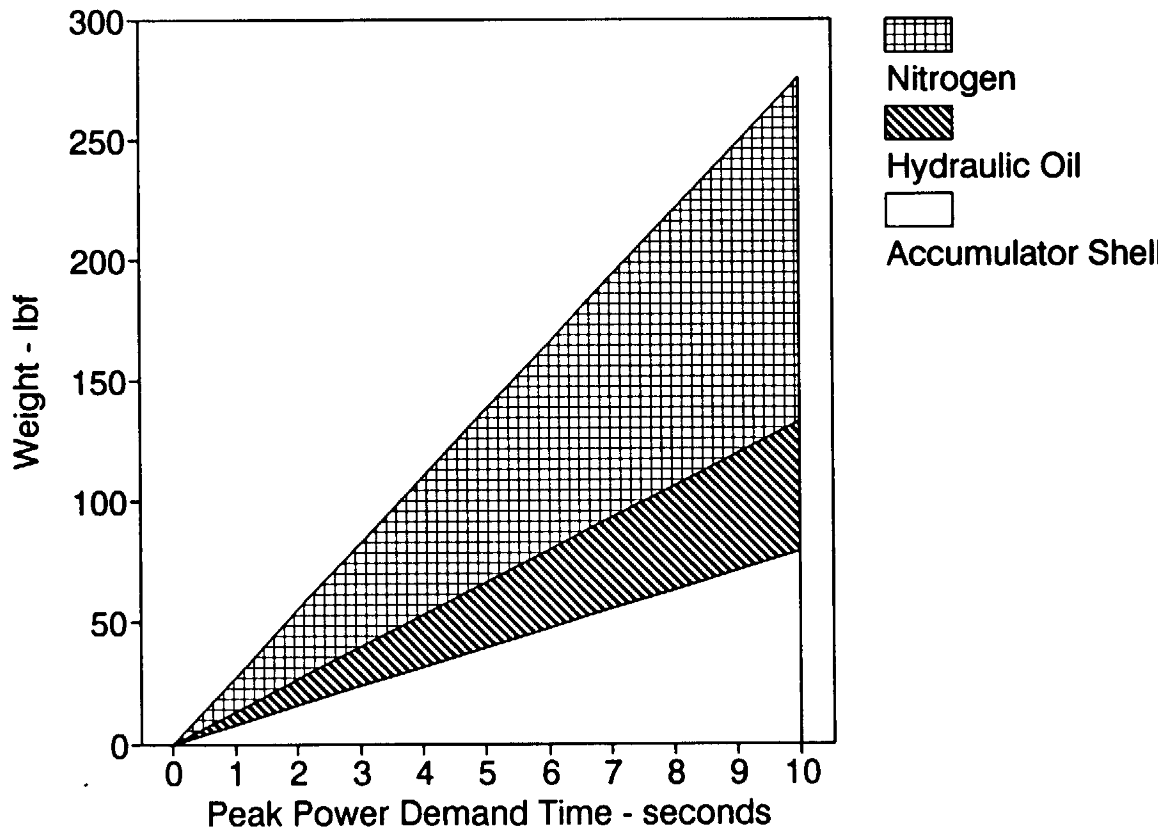


Figure A3. Modified Hydraulic Subsystem Block Diagram

Figure A4. Accumulator Component Weight vs. Pulse Width for a duty cycle of 0.1



APPENDIX B

Concept Feasibility Analysis of APU Alternate Power Source

Nomenclature

E - specific energy - energy per unit mass

m - mass

P - specific power - power per unit mass

ϕ - objective function

Subscripts

$_{acm}$ - pertaining to the hydraulic accumulator

$_{b1}$ - pertaining to a battery with a 1 hour discharge rate

$_{b2.5}$ - pertaining to a battery with a 2.5 hour discharge rate

$_{fc}$ - pertaining to a fuel cell

Introduction

The most promising alternatives to the gas turbine as an APU power source are batteries, fuel cells, and a reduction of the pulse power requirements imposed on the APU with either a hydraulic accumulator or a flywheel system. In order to systematically examine these alternatives and seek an optimized design alternative, the specific power and energy of each alternative must first be determined and then a methodology for optimizing the design developed.

Specific Power and Energy

The specific power, P, is defined as the power per unit mass while the specific energy, E, is defined as the energy per unit mass. The specific power of the current fuel cell powerplant (FCP) is calculated based on a maximum output power of 15 Kw, a mass (including coolant) of 281 lb_m, consumables for 37.5 Kwh of 30.38 lb_m (37.5 Kwh is the electrical equivalent of the product of APU horsepower at the hydraulic pump input shaft and 2.5 hours, the total APU on time), and an allowance for tankage, and other integration hardware. The current FCP specific power is therefore,

$$P_{fc} = \frac{15,000}{[281 + 0.33(281) + 110.33 + 30.38]} = 29.16 \ \frac{w}{lb_m} = 64.15 \ \frac{w}{Kg}.$$

The specific energy is then calculated from the previously mentioned energy and masses.

$$E_{fc} = \frac{37,500}{491.83} = 72.89 \ \frac{wh}{lb_m} = 160.37 \ \frac{wh}{Kg}$$

The specific power and energy are actually variables since the addition of consumables would provide significantly greater energy with a relatively small additional weight. The values chosen reflect the design energy profile and must be re-examined when a design alternative is selected to assure that the assumptions are consistent with the designed service.

The power of the hydraulic accumulator, which has a mass of 167 lb_m for the designed service, is taken as the pulse power requirement satisfied by the accumulator, which is (145-51.5) hp = 93.5 hp. However, this is hydraulic power which will be compared to electrical power. The hydraulic power must then be divided by the power conditioning system efficiency, 0.895, to obtain the electric power equivalent.

$$P_{acm} = \frac{(93.5)(746)}{(0.895)(167)} = 466.67 \ \frac{w}{lb_m} = 1026.68 \ \frac{w}{Kg}$$

The energy supplied by the accumulator is extremely small, consisting of the 93.5 hp supplied for 6 seconds. The specific energy is then given below.

$$E_{acm} = \frac{(93.5)(746)(6)}{(167)(3600)} = 0.7 \ \frac{wh}{lb_m} = 1.5 \ \frac{wh}{lb_m}$$

Fig. 1, taken from the *Handbook of Batteries and Fuel Cells*, Edited by David Linden, McGraw Hill Book Company, New York, 1985, shows the specific power plotted as a function of specific energy for a number of batteries, the current FCP, the hydraulic accumulator, the high-power-density fuel cell powerplant (HPD FCP), and the present APU gas turbine. Table B.1 below lists the specific power and energy for a number of these batteries with an addition of 20% to the mass for installation hardware and integration into the vehicle. The lithium battery has 30% added since additional venting is anticipated, and toxic effluents must be contained.

Table B.1 Battery Specific Power and Energy

	Battery Only		Battery Installed	
Type of Battery	P	E	P	E
	$\frac{w}{lb_m}$	$\frac{wh}{lb_m}$	$\frac{w}{lb_m}$	$\frac{wh}{lb_m}$
Ag-Zn, 1 hr.	54.54	54.54	45.45	45.45
Ag-Zn, 2.5 hr.	34.09	55.45	28.41	46.21
Li, 2.5 hr.	36.36	102.73	27.97	78.67

Design Methodology

Although there are a large number of constraints imposed on the APU, the major power and energy requirements will be used initially and other constraints examined later. The power required of the APU can be idealized as a constant 25 hydraulic hp required for a period of 1.5 hours and 40 hydraulic hp required for 1 hour with 105 hydraulic hp pulses superimposed on this 40 hp base. These pulses have a maximum duration of 6 seconds and a maximum duty cycle of 10%. The maximum power required is then 105+40=145 hydraulic hp which taken back to the terminals of the electrical source is 120,860 watts. The total energy required from a mission profile analysis is 64,200 watt hours. Since there are two distinct time periods, batteries with a 1 hour discharge time and a 2.5 hour discharge time will be included. The following set of constraints may then be developed.

Total Power Required

$$m_{acm}P_{acm} + m_{b1}P_{b1} + m_{b2.5}P_{b2.5} + m_{fc}P_{fc} \geq 120,860 \ w$$

Total Energy Required

$$m_{acm}E_{acm} + m_{b1}E_{b1} + m_{b2.5}E_{b2.5} + m_{fc}E_{fc} \geq 64,200 \ wh$$

Time Integral of Power (Energy)

$$m_{b1}P_{b1} + 2.5m_{b2.5}P_{b2.5} + 2.5m_{fc}P_{fc} \geq 64,200 \ wh$$

Power Required During the 1.5 hour Period

$$m_{b2.5}P_{b2.5} + m_{fc}P_{fc} \geq 20,838 \ w$$

Constraints on Masses

$$0 \leq m_{acm} \leq 167 \ lb_m$$

$$0 \leq m_{b1} \leq 5,000 \ lb_m$$

$$0 \leq m_{b2.5} \leq 5,000 \ lb_m$$

$$0 \leq m_{fc} \leq 5,000 \ lb_m$$

Objective Function (Total Mass)

$$m_{fc} + m_{b1} + m_{b2.5} + m_{fc} = \phi \ lb_m$$

The constraints and objective function described above obviously constitute a simple linear programming problem, with provision for two battery discharge rates.

Existing Technology

Using parameters characteristic of silver-zinc batteries and the current fuel cell, the equations above were transformed into the set below.

$$466.7m_{acm} + 45.45m_{b1} + 28.41m_{b2.5} + 29.16m_{fc} \geq 120,860 \ w \tag{1}$$

$$0.7m_{acm} + 45.45m_{b1} + 46.21m_{b2.5} + 72.89m_{fc} \geq 64,200 \ wh \tag{2}$$

$$2.5(30.50)m_{fc} + 45.45m_{b1} + 2.5(28.41)m_{b2.5} \geq 64,200 \ wh \tag{3}$$

$$30.50m_{fc} + 28.41m_{b2.5} \geq 20,838 \ w \tag{4}$$

$$0 \leq m_{acm} \leq 167 \ lb_m \tag{5}$$

$$0 \leq m_{b1} \leq 5,000 \ lb_m \tag{6}$$

$$0 \leq m_{b2.5} \leq 5,000 \ lb_m \tag{7}$$

$$0 \leq m_{fc} \leq 5,000 \ lb_m \tag{8}$$

$$m_{fc} + m_{b1} + m_{b2.5} + m_{fc} = \phi \ lb_m \tag{9}$$

The solution is then as given below.

$$m_{acm} = 167 \ lb_m, \quad m_{b1} = 486.0 \ lb_m, \quad m_{b2.5} = 0 \ lb_m, \quad m_{fc} = 714.6 \ lb_m$$

$$Total\ Mass = 1367.6 \ lb_m$$

One practical objection to this solution is that the existing fuel cells are already designed with a total mass including consumables and tankage of 514.44 lb_m. If the solution above is modified by changing the lower limit of Eq. (8) to 1028.88 lb_m, the mass of two FCPs, the following solution is obtained.

$$m_{acm} = 167 \ lb_m, \quad m_{b1} = 284.4 \ lb_m, \quad m_{b2.5} = 0 \ lb_m, \quad m_{fc} = 1028.9 \ lb_m$$

$$Total\ Mass = 1480.3 \ lb_m$$

This solution is consistent with the initial assumption that the mass of a set of consumables tankage would be distributed among six FCPs (two per APU).

If a solution is generated for one fuel cell the result is:

$$m_{acm} = 167 \ lb_m, \quad m_{b1} = 486.0 \ lb_m, \quad m_{b2.5} = 205.4 \ lb_m, \quad m_{fc} = 514.4 \ lb_m$$

$$Total\ Mass = 1372.8 \ lb_m$$

The specific power and energy on which these calculations are based on the assumption that the mass of one set of H_2 and O_2 tankage is to be shared by six FCPs instead of three. Therefore, 110.33 lb_m must be added to the total above for a comparable total mass of 1483.1 lb_m. If the specific power and energy of the fuel cell are adjusted to reflect the distribution of tank mass among three FCPs instead of six (24.01 and 60.02 respectively), a new solution is obtained.

$$m_{acm} = 149.6 \ lb_m, \quad m_{b1} = 664.5 \ lb_m, \quad m_{b2.5} = 733.5 \ lb_m, \quad m_{fc} = 0 \ lb_m$$

$$Total\ Mass = 1547.6\ lb_m$$

Another consideration is the use of higher specific energy lithium batteries. With the specific power and energy replacing those of silver-zinc for the 2.5 hour discharge rate battery the following solution is obtained.

$$m_{acm} = 167\ lb_m, \quad m_{b1} = 486.0\ lb_m, \quad m_{b2.5} = 745.0\ lb_m, \quad m_{fc} = 0\ lb_m$$

$$Total\ Mass = 1398\ lb_m$$

The actual optimum solution is then for silver-zinc batteries to provide the high power required during the 1 hour period and lithium primary batteries to provide the base load. Since the electric motor (60 lb_m), inverter (20 lb_m), addtional system cooling (91 lb_m), and avionics (60 lb_m) must be added to any of the systems above, the masses have not been included in the optimization process. The optimum practical solution is 1398 in batteries and accumulator plus 231 or 1629 lb_m which for three APUs is 4887 lb_m.

This solution is over twice the mass of the existing gas turbine and three times the volume. The justification for any such modifications would have to be based on a suboptimal two FCP solution and the benefits of an additional 90 Kw of on orbit power and the fact that a set of consumables tankage was added with an 681 lb_m capacity when only 182 lb_m of the capacity is used. This solution would, however, have the additional disadvantage of being an order of magnitude more costly than the present gas turbine system.

Summary of Existing Technology

Tables B.2-3 below summarize the set of solutions above with a slight variation related to the source of the consumables. Consumables for the fuel cells have been sized for the maximum output of the FCPs for 2.5 hours even though this amount of energy exceeds the total design energy requirement.

While these tables indicate a mixture of sub-system types, system integration issues were not addressed. For example, in case BtA batteries of two discharge rates were selected. Systems to effectively parallel these batteries were not examined since the total system does not appear to be attractive.

Table B.2 Definition of Listed Cases

Case	Description
2FCA	2 FCPs, new consumables tankage, with consumables
2FCB	2 FCPs, use existing consumables
1FCA	1 FCP, new consumables tankage, with consumables
1FCB	1 FCP, use existing consumables
BtA	All Ag-Zn Batteries and accumulator
BtB	Ag-Zn, 1 hr. disch. and Lithium, 2.5 hr. disch.

Table B.3 Existing Technology Summary for 3 APUs

Component	2FCA	2FCB	1FCA	1FCB	BtA	BtB
Fuel Cell	1686	1686	843	843	0	0
H_2 and O_2 Tanks	662	0	662	0	0	0
Consumables	182	0	91	0	0	0
Integr. Hardware	556	556	278	278	0	0
Ag-Zn 1 hr. Batt.	711	711	1215	1215	1661	1215
Ag-Zn 2.5 hr.	0	0	514	514	1834	0
Lithium 2.5 hr.	0	0	0	0	0	1719
Batt. Intg. Hdw.	142	142	346	346	699	759
Accumulator	501	501	501	501	449	501
Electric Motor	180	180	180	180	180	180
Inverter	60	60	60	60	60	60
Add. Cooling	273	273	273	273	273	273
Avionics	180	180	180	180	180	180
Total	5133	4289	5143	4390	5336	4887

New Technology

80 Kw High Power Density Fuel Cell

The specific power and energy of an 80 Kw high power density fuel cell are estimated to be;

$$P_{fc} = \frac{120,860}{[(1.33)(389) + 220.67 + 52]} = 152.98 \ \frac{w}{lb_m} = 336.56 \ \frac{w}{Kg}$$

and

$$E_{fc} = \frac{64,200}{790.04} = 81.26 \ \frac{wh}{lb_m} = 178.78 \ \frac{wh}{Kg}$$

respectively. The specific power is based on the vendor's estimates and assertion that the new technology fuel cell will handle power pulses of two times the nominal rating. With these parameters substituted into Eqs. (1-4) the following solution is obtained.

$$m_{acm} = 0 \ lb_m, \quad m_{b1} = 0 \ lb_m, \quad m_{b2.5} = 0 \ lb_m, \quad m_{fc} = 790.04 \ lb_m$$

$$Total\ Mass = 790.04 \ lb_m$$

Again the electric motor, inverter, extra cooling, and avionics must be added for a total mass of 990 lb_m. This solution has the same potential advantage as the two current FCP solution, an additional set of consumable tanks has been added with only 52 lb_m out of a capacity of 681 lb_m and additional 240 Kw of electric power is available while on orbit.

60 Kw High Power Density Fuel Cell

The specific power and energy of an 60 Kw high power density fuel cell are estimated to be;

$$P_{fc} = \frac{120,860}{[(1.33)(322) + 220.67 + 52]} = 172.43 \ \frac{w}{lb_m} = 379.34 \ \frac{w}{Kg}$$

and

$$E_{fc} = \frac{64,200}{700.93} = 91.59 \ \frac{wh}{lb_m} = 201.50 \ \frac{wh}{Kg}$$

respectively. Again, the specific power is based on the vendor's estimates and assertion that the new technology fuel cell will handle power pulses of 2.5 times the nominal rating. With these parameters substituted into Eqs. (1-4) the following solution is obtained.

$$m_{acm} = 0 \ lb_m, \quad m_{b1} = 0 \ lb_m, \quad m_{b2.5} = 0 \ lb_m, \quad m_{fc} = 700.93 \ lb_m$$

$$Total\ Mass = 700.93 \ lb_m$$

Again the electric motor, inverter, extra cooling, and avionics must be added for a total mass of 901 lb_m.

Flywheels

The specific power and energy of a theoretical flywheel designed for 0.069 Kwh are 909 w/lb_m and 13 wh/lb_m respectively. When these values were used in an optimization process such as that above, the optimum solution was still the all-HPD-FCP. When the values were used with the FCPs, the following 3 APU mass decreases were obtained: Case 2FCA - 201 lb_M, Case 1FCA - 140 lb_m, Case BtA - 278 lb_m, and Case BtB - 150 lb_m.

Summary of New Technology

A summary of the new technology solutions above, and modifications which relate to consumables and tankage, are shown in the Tables B.4-5 below. Essentially there are three cases for each solution which include; (A) a new set of existing type H_2 and O_2 tanks with just the 156 lb_m load of reactants required for the APU mission, (B) a prorated mass to account for newly designed tanks and the reactant load, (C) no new tankage mass or reactant mass, which assumes that the reactants would be taken from the reactant load already aboard the Orbiter.

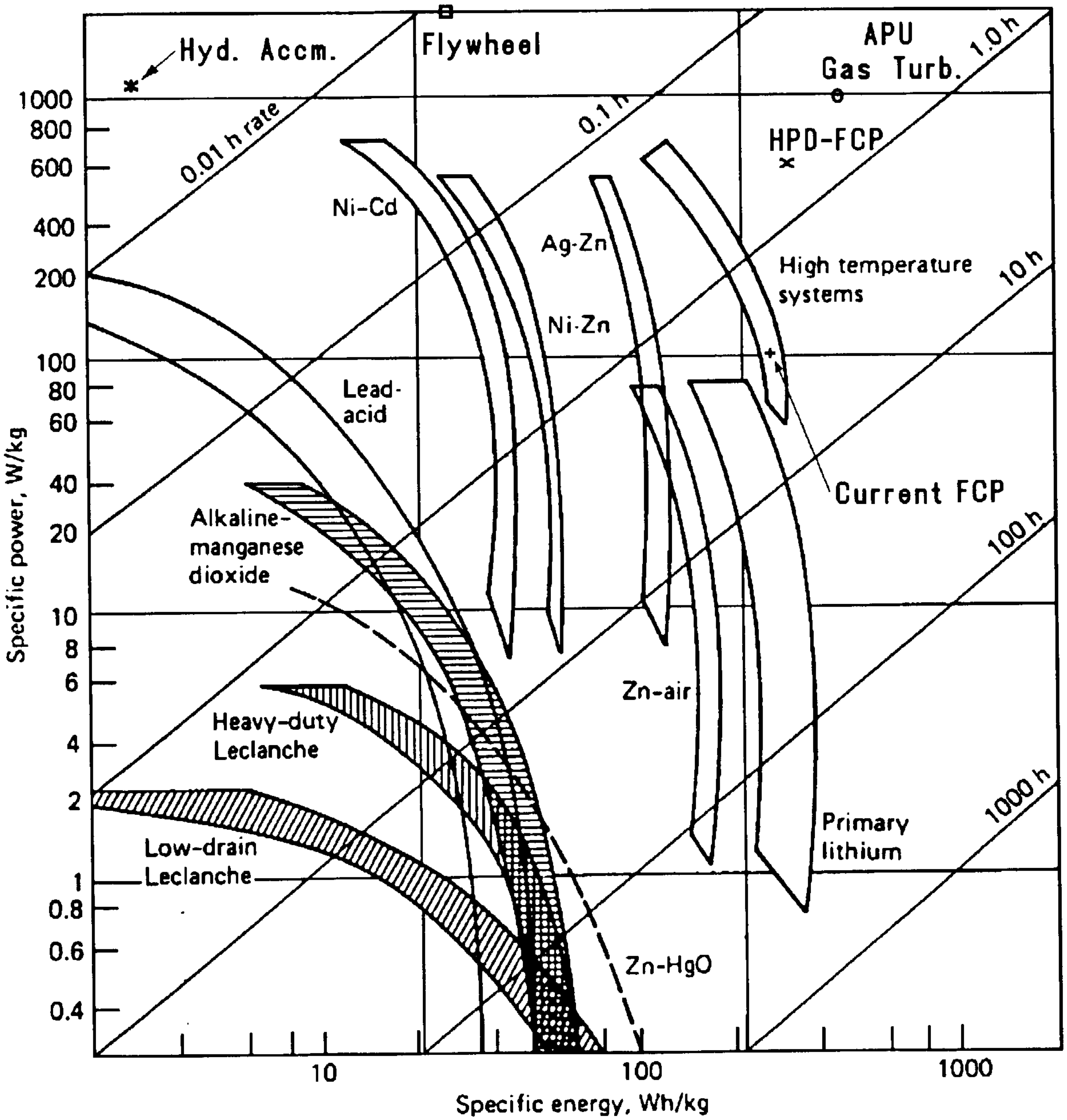
Table B.4 Definition of New Technology Cases

Case	Description
80A	80 Kw HD-FCP, new tankage, with consumables
80B	80 Kw HD-FCP, prorated tankage, with consumables
80C	80 Kw HD-FCP, use existing consumables
60A	60 Kw HD-FCP, new tankage, with consumables
60B	60 Kw HD-FCP, prorated tankage, with consumables
60C	60 Kw HD-FCP, use existing consumables

Table B.5 New Technology Summary for 3 APUs

Component	80A	80B	80C	60A	60B	60C
HPD-Fuel Cell	1167	1167	1167	966	966	966
H_2 and O_2 Tanks	662	122	0	662	122	0
Consumables	156	156	0	156	156	0
Integr. Hardware	385	385	385	319	319	319
Electric Motor	180	180	180	180	180	180
Inverter	60	60	60	60	60	60
Add. Cooling	273	273	273	273	273	273
Avionics	180	180	180	180	180	180
Total	2970	2430	2152	2703	2163	1885

Figure B1. Specific Power and Energy Diagram



Source of battery data: Linden, David, Handbook of Batteries and Fuel Cells