Electric Auxiliary Power Unit for Shuttle Evolution

Doug Meyer* and Kent Weber†
Sundstrand Aerospace, Rockford, Illinois 61125
and
Walter Scott‡
NASA Johnson Space Center, Houston, Texas 77058

The Space Shuttle Orbiter currently uses three hydrazine-fueled auxiliary power units (APUs) to provide hydraulic power for the vehicle aerodynamic surface controls, main engine thrust vector control, landing gear, steering, and brakes. Electric APUs have been proposed as possible replacements to the hydrazine APUs. Along with the potential advantages, this paper describes an electric APU configuration and addresses the technical issues and risks associated with the subsystem components. In addition, characteristics of an electric APU compared with the existing APU and the direction of future study with respect to the electric APU are suggested.

Introduction

THE three Orbiter auxiliary power units (APUs) and associated hydraulic systems (Fig. 1) provide critical flight control functions during the ascent, descent, and landing portions of a mission. Hydraulic power from the APUs is used to operate aerosurfaces, main engine thrust vector control, main engine valves, external tank umbilical, landing gear, brakes, and steering. During a typical mission, the APUs operate for approximately 90 min over a power range of 6–110 kW and from sea level to space altitudes.

The existing APU is a hydrazine-powered turbine that drives a hydraulic pump through a high-speed gearbox. A functional schematic of the APU is presented in Fig. 2. Figure 3 shows the APU configuration.

Monopropellant-grade hydrazine fuel is supplied to the inlet of the fuel pump. The fuel pump increases the pressure and supplies the gas generator (GG) through the gas generator valve module (GGVM). The GG catalytically decomposes the fuel into 927°C gas at a nominal 86.9-bar pressure. The hot gas is directed through a two-stage, supersonic re-entry turbine. Three redundant speed sensors are mounted at the turbine shaft and provide the electronic controller with speed signals. Once turbine operating speed is achieved, the electronic controller maintains a nominal turbine speed of 74,000 rpm by opening and closing the GGVM at predetermined speed levels, thereby maximizing low-power performance for minimum mission fuel consumption.

The power from the turbine shaft is transmitted to the hydraulic pump, fuel pump, and lube pump through the gearbox. The gearbox design features a lube system that functions in all attitudes and in zero gravity. More information can be found in Ref. 1.

Advances in battery, power, and motor technologies since the existing APU configuration was established for the Space Shuttle make an electric APU a possible alternative to the hydrazine APU. An electric APU offers potential improvements in the following areas: safety, reliability, system weight, vehicle turnaround, and operational costs.

Safety improvements can be realized with the elimination of hydrazine fuel and its associated hazards. Elimination of hydrazine fuel servicing may also reduce vehicle turnaround time and operational costs. System weight improvements are highly dependent on the power density of the selected electric energy source.

Electric Auxiliary Power Unit

Each electric APU subsystem would include an electrical power source, inverter, electric motor, gearbox, controller, and appropriate cooling system, as shown in Fig. 4. System output power would be sized to meet the specification requirements of the current APU. This entails 110-kW peak output and 15-kW continuous average output for a 90-min mission. Electric power is provided by a high-voltage dc source with nominal output of 270 Vdc. Total electrical energy of 35.3 kWh will be required per flight based on the mission duty cycle in Table 1 per the APU design specification.

The total energy requirement does take into account the overall efficiency for the electric APU, as shown in Fig. 5. A breakdown of the electric APU subsystem requirements is provided in Table 2.

Based on system requirements, the electric APU would be interchangeable with the hydrazine APU. No change to the hydraulic system would be required. Integration would be such as to minimize vehicle changes and provide maximum "transparency" to the crew.

Technical Issues

Electrical Energy Source

The electrical energy source comprises most of the weight of an electric APU and so offers the greatest potential for weight reduction.

Three kinds of electromechanical energy sources can be considered: primary battery, secondary battery, and fuel cell.

The primary battery is generally the lowest weight option, but has high turnaround cost because the batteries must be changed after every flight. Primary batteries typically have thermal management constraints due to their compact size and high power density. Flowing electrolyte is often considered as an approach to remove heat and maintain uniform temperatures within the cell stack. High-energy primary batteries also use very active metals, such as lithium or sodium, and thus have potential safety hazards. Although the common perception of a primary battery is a simple benign device such as a

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*Senior Program Engineer, Department 710E6, 4747 Harrison Avenue. Member AIAA.

†Advisory Engineer, Department 741F6, 4747 Harrison Avenue. Member AIAA.

‡APU Subsystem Program Manager, EP-2, 2101 NASA Road 1.

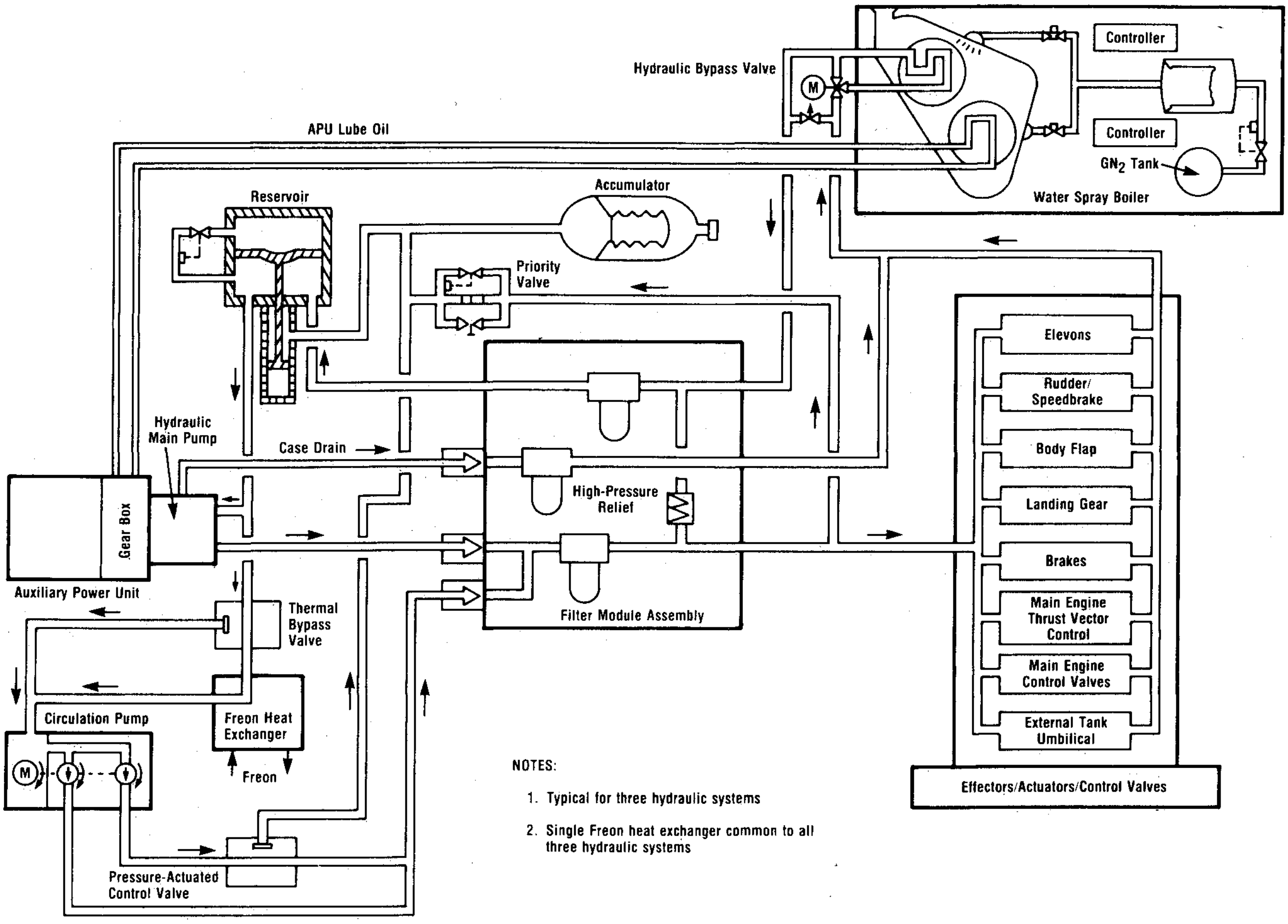

Fig. 1 Orbiter hydraulic system.

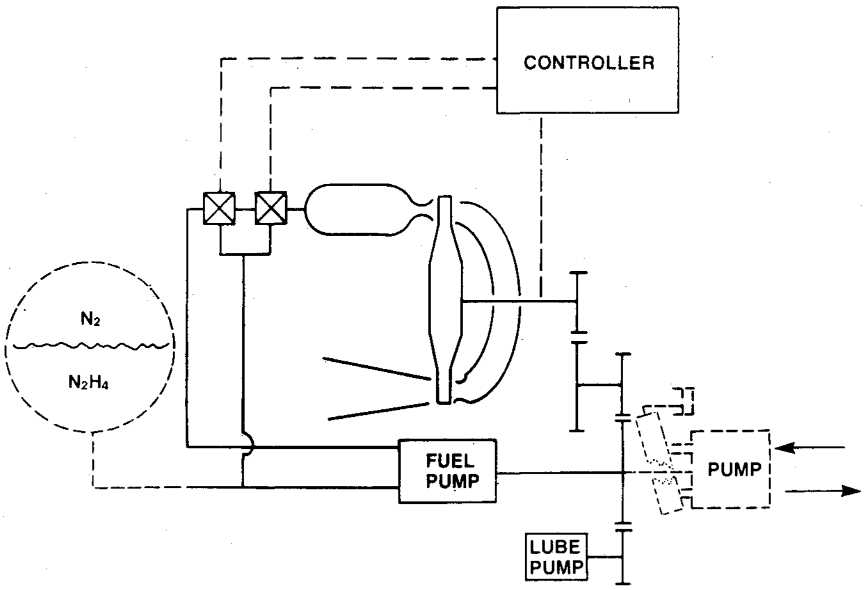

Fig. 2 Hydrazine auxiliary power unit system schematic.

flashlight battery, high-power density, large primary batteries typically consist of a large number of cells arranged in both parallel and series stacks, pumps and temperature control valves for either electrolyte or for cooling fluid circulation, thermal vents, safety neutralizing salts for vented electrolyte, fuses on each battery segment, and electronic monitoring and controls to avoid hazardous conditions such as overdischarge and hot spots.

Among the primary batteries, lithium electrochemical couples offer the highest energy density and have been developed actively over the past 10 years. Substantial progress has been made in low-rate, long-life small cells, to the point where they are now being mass-produced for consumer applications in cameras, watches, etc. Although high-rate lithium-thionyl chloride ($LiSOCl_2$) batteries show great theoretical promise, development during the same time period has not been nearly as rapid as for the low-rate chemistries.

High-discharge-rate cells require a large plate area, achieved by making stacks of many very thin plates. The large number of plates offer many opportunities for hot spots, shorting, and reverse-current damage. Although safety issues of large, high-rate lithium batteries are not yet resolved, the $LiSOCl_2$ battery is otherwise an excellent candidate for Space Shuttle electric APU application. The battery has demonstrated energy density in excess of 100 W · h/lb and specific power of 500 W/lb in small-scale tests. This yields a very light battery for electric APU use.

Secondary batteries are rechargeable and offer the great advantage of not requiring replacement after every mission. Six to ten recharge cycles are typical for highly stressed silver zinc cells, whereas 1000 recharge cycles are possible for advanced nickel-hydrogen (NiH_2) batteries, if they are discharged only partially and the discharge and charge rates are controlled carefully. Secondary batteries typically do not have the high-rate-discharge capability of primary batteries and, therefore, need to be oversized to supply peak loads. Although this rate limitation requires a much heavier battery than would otherwise be required, the larger size and lower average discharge rate that result obviate thermal management problems. The metals used (cadmium, silver, zinc, nickel) are much more benign than those used in high-rate primary batteries, so battery safety concerns are generally reduced.

Nickel-cadmium (NiCd) batteries have long been used in aircraft and spacecraft applications and have demonstrated long life at low energy density. More recent developments of the NiH_2 battery have shown improved life over the NiCd. Although individually pressured cell NiH_2 batteries are quite heavy, the pile-type batteries presently under development are expected to have an energy density of up to 40 W · h/lb in large sizes typical of the electric APU. NiH_2 batteries of this type would be 2.5 times the weight of $LiSOCl_2$, but would seldom, if ever, need replacement.

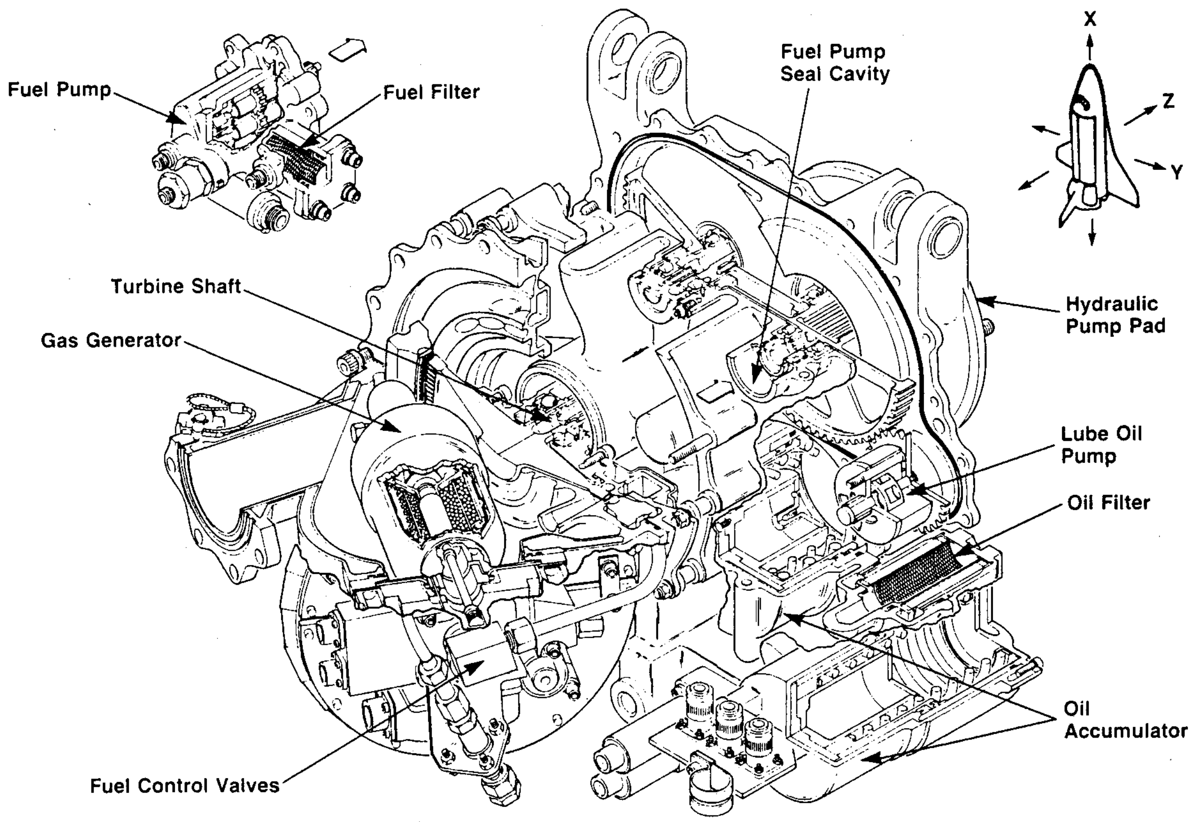

Fig. 3 Hydrazine auxiliary power unit.

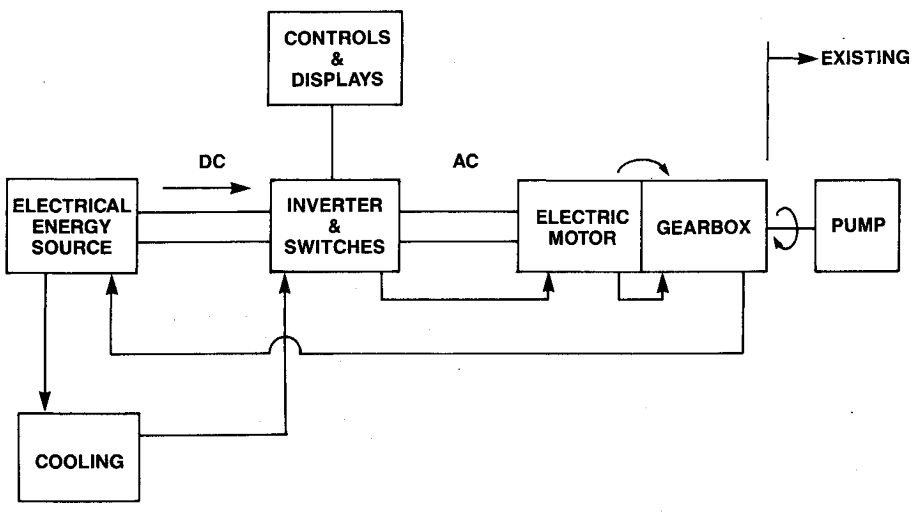

Fig. 4 Electric auxiliary power unit.

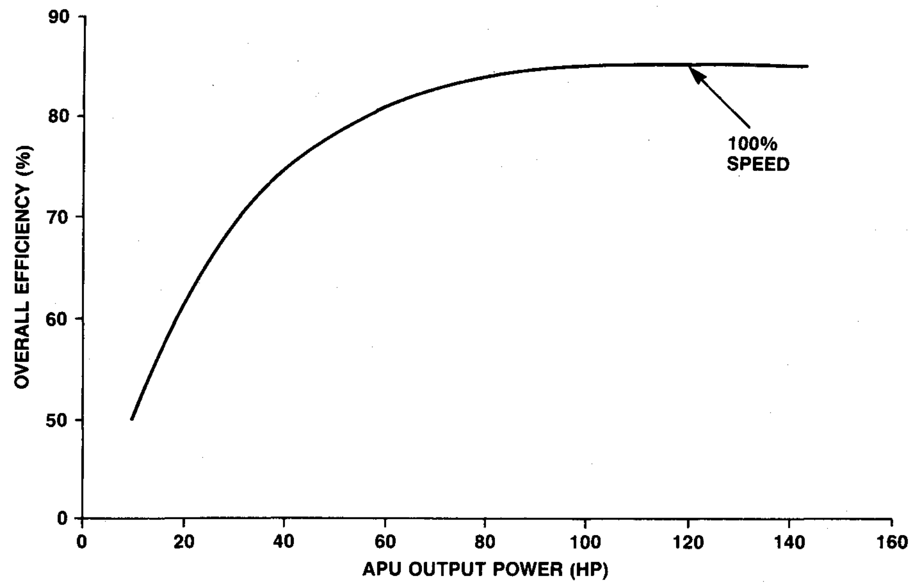

Fig. 5 Overall efficiency for electric APU (inverter/motor/gearbox).

Table 1 APU mission duty cycle

Condition	Time, s	Load kW	Load HP	Condition	Time, s	Load kW	Load HP
Ascent				Descent			
1	75	17	23	1	480	6	7.5
2	245	24	32.5	2	480	17	23.0
3	165	22	29	3	75	24	32.5
4	40	33	44	4	600	11	15
5	635	27	29	5	15	17	23
6	40		36.4	6	200	11	15
				7	5	24	32.5
Orbital checkout				8	250	11	15
1	55	17	23	9	10	33	44
2	10	94	126	10	250	11	15
3	55	17	23	11	5	21	28
				12	125	11	15
				13	5	17	23
				14	600	11	15
				15	5	29	39
				16	150	11	15
				17	10	27	36.4
				18	50	11	15
				19	10	29	39
				20	5	36	48
				21	5	67	90.5
				22	25	16	22
				23	260	11	15
				24	20	94	126
				25	60	13	18
				26	80	21	28
				27	300	11	15

Table 2 Electric APU subsystem requirements

Rated output	110 kW (148 HP) peak 15 kW (20 HP) continuous
Duty cycle	90 min
Energy source	270 Vdc 35.3 kWH
Thermal control	Inverter, motor, gearbox, energy source
Environment	Zero gravity and all-attitude sea level to space vacuum
Life	100 missions

Fuel cells are traditionally most applicable to low-rate, long-duration electrical loads. Recent developments in alkaline electrolyte, solid polymer, and monolithic solid oxide fuel cells promise energy densities in the same range as secondary batteries, and so advanced fuel cells could be considered for electric APU application. The advantage of fuel cells is that they could be integrated with the present fuel cell system on the Shuttle, providing both an energy source for the electric APU and greatly enhanced on-orbit electrical power. On the negative side is the need for greatly increased fuel cell cooling equipment, the general complexity of fuel cell systems, and the lack of fully developed technology at this time. Like the high-rate primary battery, fuel cells require high-temperature operations and have extensive pumps, valves, and controls.

Advanced alkaline electrolyte fuel cells are being developed for Strategic Defense Initiative applications. These fuel cells have energy density many times higher than present Space Shuttle fuel cells. Cell stack energy density of 80 W·h/lb has been quoted, but this ignores the fuel supply, temperature, and voltage management controls that can approach the cell stack in weight. Monolithic solid oxide fuel cells are being investigated that have even greater cell stack energy density than alkaline cells, but large modules have yet to be attempted. Even if only 40 W·h/lb system energy density can be achieved, the fuel cells will be weight-competitive with the NiH_2 battery, although the fuel cell system complexity will remain as a negative factor. With this energy density, the fuel cell system will be about 2.5 times as heavy as the $LiSOCl_2$ primary battery. The system can be "recharged" quickly by replenishing the hydrogen and oxygen tanks.

Electric Motor/Inverter

Both induction and brushless dc motors have been investigated to drive the electric APU hydraulic pump. Results of a comparative trade study of 110-kW peak-rated motors showed that the induction motor was slightly lighter. The induction motor is also more efficient, particularly at partial loads typical of the Shuttle APU duty cycle. Electronic controls and power switching are also somewhat simpler for the induction motor than for the brushless dc motor.

An induction motor/inverter package has been successfully developed for another application. The program goal was to produce a 262-kW motor/inverter package with a power density of 1.5 kW/lb, at least twice as high a power density as previous motors. The motor selected for this application is a counter-rotating induction motor with an integral speed-reducing gearbox. A block diagram of the motor/inverter is shown in Fig. 6. A photograph of the complete motor/gearbox/inverter package is displayed in Fig. 7. The motor efficiency is 91% and the inverter efficiency is 94%, for an overall efficiency of 86%. A power density of over 1.5 kW/lb was attained.

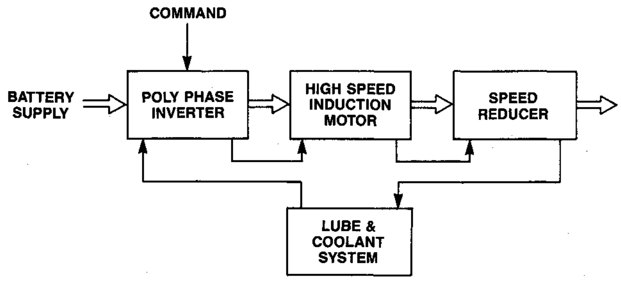

Fig. 6 Motor/inverter block diagram.

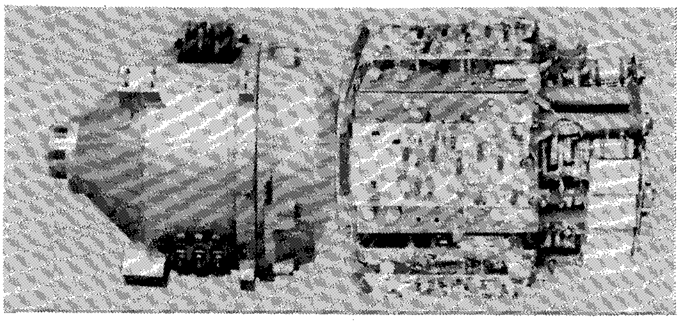

Fig. 7 The 262-kW (350-hp) motor system fits within a 81-cm (32-in.)-long 42-cm (16.5-in.)-diam envelope.

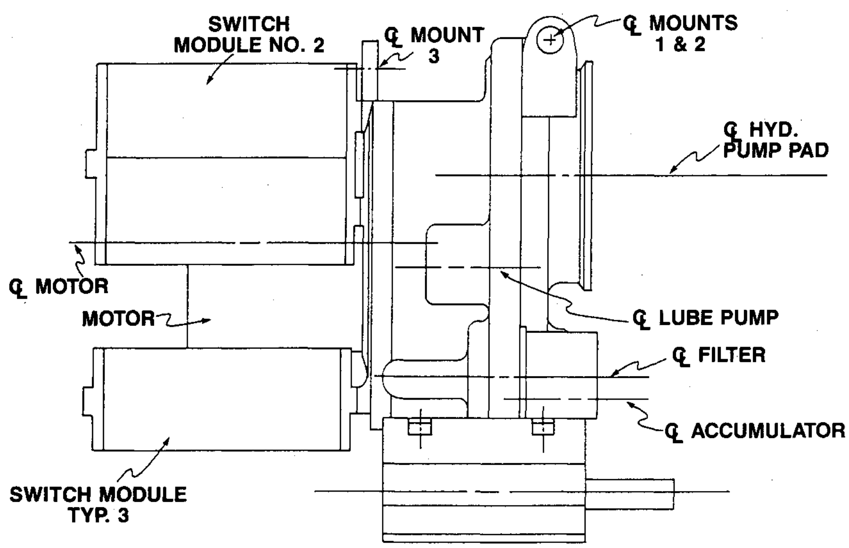

Fig. 8 Electric APU motor/inverter/gearbox.

The motor package includes cooling and lube pumps and variable-speed operation capability. Balanced torque, counter-rotating shaft output was provided for this application. The Space Shuttle electric APU motor does not require the complexity of counter-rotation or large-speed turndown ratio and thus can be expected to meet or exceed the 1.5 kW/lb achieved by the example motor/inverter package.

Cooling

The cooling system changes required to accommodate an electric APU are poorly defined, but are expected to require extensive changes to the present water boiler cooling system.

The motor/inverter package requires more cooling and a lower temperature coolant than the present water boiler provides. Energy source heat fluxes and cooling temperature requirements depend on the type of battery or fuel cell selected. One possible cooling system configuration would entail a completely new lower temperature ammonia boiler system to cool the inverter, motor, gearbox, and electrical energy source paralleled with the hydraulic system cooling requirements. Another possibility would be to retain the current water boiler to cool the motor, gearbox, and hydraulics, and then add a lower temperature ammonia boiler to cool the electronics.

Gearbox

The electric APU gearbox will be less complex than the present APU gearbox. The electric APU gearbox would have one power gear mesh instead of two, no fuel pump, no need for turbine thermal standoff isolation, and is generally smaller than the present APU gearbox. A 0-*g* all-attitude gearbox will be required. To meet this requirement, current APU gearbox technologies can be utilized. It uses close-conforming gearbox housing walls to gears, allowing the gears to act as scavenge pumps in all attitudes. The gearbox lube system also features piston accumulators that accommodate thermal expansion, regulate lube pressure, and act as a 0-*g* all-attitude lube reservoir. In addition, a nitrogen (GN_2) gearcase pressurization system is available in the event gearcase pressure is lost. Using these technologies, a gearbox for the electric APU is considered to be of low technical risk.

Figure 8 shows an outline sketch of a typical electric APU motor/inverter/gearbox package for a unit that directly replaces the present APU. The unit provides a peak power of 110 kW to the hydraulic pump and weighs 80 lb. Figure 9 shows an electric APU including just the motor and gearbox. In this version, the inverter is located near the battery. Here the electric APU is expected to weigh approximately 60 lb and the inverter 20 lb.

High-Voltage Requirements

A 270-Vdc electrical energy source has been proposed to reduce current and conductor weight, thereby preventing losses and penalties associated with lower voltages. As a result, special design considerations will be required. High-voltage hardware and cables will require shielding to protect them from natural and induced environments, and to preclude coupling into other low-voltage circuitry. Plasma interaction at low Earth orbit can cause arcs between exposed terminals at this voltage level.[2] Special packaging is required to prevent arcing and provide electromagnetic interference and radio frequency interference (EMI/RFI) protection. Added challenges lie in development of space-qualified high-voltage connectors, capacitors, contactors, and other hardware, along with minimizing the weight and volume of the subsystem hardware. The development and qualification of a 270-Vdc system for the electric APU represents a significant technical challenge.

Optimization Concepts

Several concepts have been studied to reduce the overall energy requirements of the electric APU, thus reducing the weight of the electrical power source. Foremost is a variable-pressure hydraulic pump operated at the lowest pump pressure consistent with flight-control demands, as shown in Fig. 10. A variable-pressure pump would reduce system losses caused by operation at constant pressure, which would also reduce the waste energy that must be actively cooled. Implementation requires addition of a variable-pressure servoregulator to the hydraulic pump, actuator brake changes to accommodate the lower hydraulic pressures, and an electronic controller with accompanying software.

Added enhancement could be realized with a variable-speed/pressure system. Again, the system would be operated at the lowest pressure and speed consistent with flight control demands. Variable speed allows electric APU operation at the highest system efficiency points. In addition, a low operating speed could be used on orbit for hydraulic oil circulation to prevent freezing, thereby allowing removal of the current circulation pumps.

These optimization concepts add complexity to the system with payback in system weight improvements. In addition, system interchangeability of the electric APU with the current APU is lost. Added study is required to assure that response of the aerosurfaces is not reduced.

Hydrazine vs Electric Auxiliary Power Units

Consideration of the electric APU as an alternative to the hydrazine APU is based on potential improvements in safety, reliability, system weight, vehicle turnaround, and operational costs. Only a preliminary assessment of the relative gains in these areas can be made at this time, due to the undefined state of the electric APU subsystem components. A comparative assessment needs to include planned improvements to the current APU, which will result with incorporation of the improved APU (IAPU) into the Orbiter fleet.[3]

Electric APU safety improvements primarily are due to elimination of hydrazine and its associated hazards. Potential APU hazards resulting from hot ignition sources and fragmentation from a wheel burst are also deleted. The electric APU does pose its own set of safety concerns associated with high-power density power conversion circuitry and the hazards of chemical power sources. In addition, if ammonia is selected for cooling, it will also require special handling procedures for servicing.

Reliability improvement is difficult to assess. An electrical subsystem should inherently be more reliable; however, the motor/inverter for the electric APU is very complex with a high part count. Development would be required to improve its reliability by reducing the part count and complexity. Electrical energy source selection will also affect the subsystem reliability, especially if a fuel cell system is selected with its added complexity. Reliability of the current APU will be enhanced with the IAPU. It should also be noted that the current system has operated successfully on all missions.

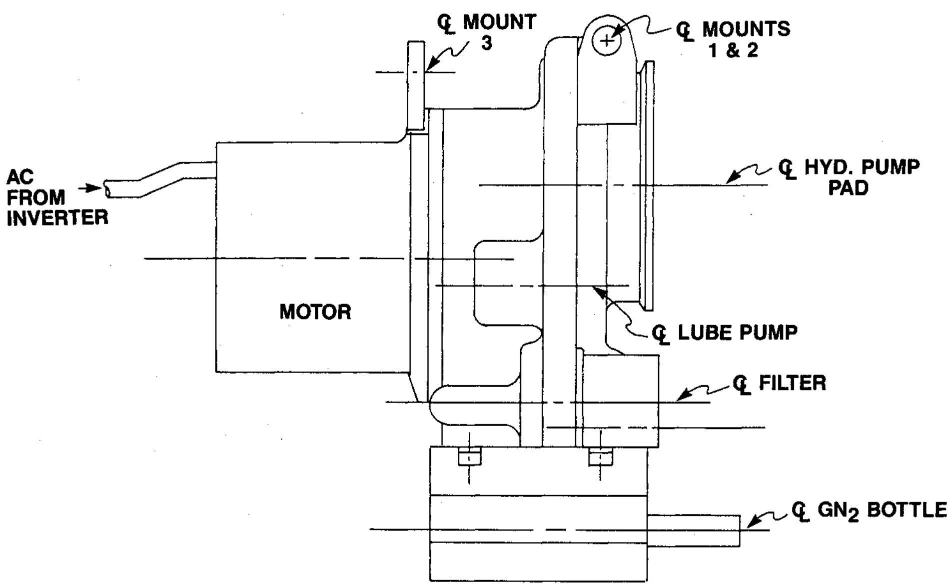

Fig. 9 Electric APU motor/gearbox.

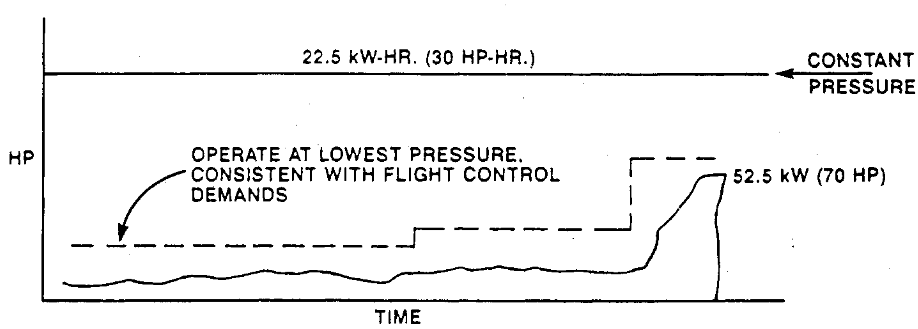

Fig. 10 Variable-pressure pump.

Table 3 Preliminary system weight comparison, lb

Hydrazine APU		Electric APU[a]				
			Weight, lb[b]			High power density fuel cell
Component	Weight, lb[b]	Component	NiH_2	$LiSOCl_2$	Alkaline fuel cell	
APU & controller	348	Electric APU	240	240	240	240
Fuel tank	500	Power source	2650	1100	2650	1325
N_2H_4	975	Cooling				
H_2O boiler	667	NH_3 boiler	450	450	450	450
H_2O	360	NH_3	850	850	850	850
GG cooler	30	Avionics	180	180	180	180
GG H_2O	9	Wiring, tubing, misc.	750	750	750	750
Exhaust duct	67					
Totals	2956		5120	3570	5120	3795

[a]Assumptions:
1. Power source
   NiH_2 @ 40 WH/lb → 150 W/lb
   $LiSOCL_2$ @ 100 WH/lb → 370 W/lb
   Alkaline fuel cell @ 40 WH/lb → 150 W/lb
   High power density fuel cell @ 80 WH/lb → 300 W/lb
2. Cooling
   Electric APUs 150,000 Btus
   Hydraulics 115,000 Btus
   80% energy source discharge efficiency

[b]Weights are totals for three APUs

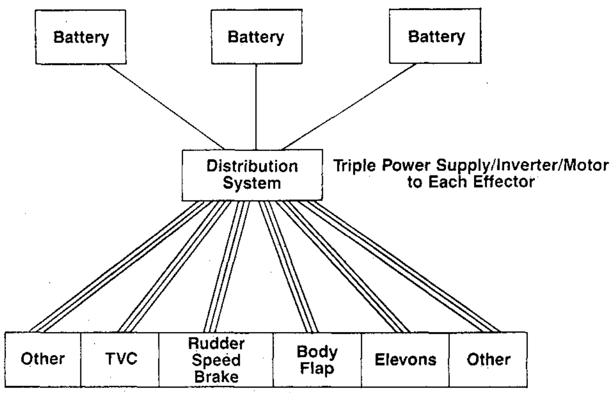

Fig. 11 All-electric Space Shuttle.

Electric APU system weight is highly driven by the electric energy source. Table 3 shows a system weight comparison for the hydrazine APU vs the electric APU with different electrical energy source selections. Weights are based on meeting the mission duty cycle power requirements as specified in the APU design specification. As can be seen, an electrical energy source with a very high-power density is required for the electric APU to be competitive based on weight.

Vehicle turnaround time and operational costs may be enhanced with the electric APU, particularly if rechargeable batteries or a fuel cell is selected. Although elimination of fuel, water, and lube oil service between missions is attractive, ammonia servicing and battery maintenance will be required. An electric APU will facilitate hydraulic system checkout for normal turnaround and reduce ground support equipment requirements. However, depending on electric energy source selection, either battery changeout, charging, or fuel cell servicing will be required.

In summary, the maintenance and servicing costs may be reduced if the very heavy fuel cells or rechargeable battery is selected. If the weight-competitive primary battery is selected, battery changeout after each flight may be no easier nor less hazardous than servicing the present APU. Overall, the most competitive electric APU system would have the highest technical risk in the development of a weight-competitive electrical energy source and reliability improvements of the motor/inverter.

The electric APU subsystem requires further definition, including selection of electrical energy source, motor and inverter, cooling systems, and power distribution requirements. Based on a selected electric APU subsystem, a trade study can be conducted to determine if the potential advantages of an electric APU over the current APU justifies further development.

All-Electric Vehicle

An all-electric vehicle using electromechanical actuators is an additional alternative to the hydrazine and electric APU and should also be considered in future studies. This modification, as shown in Fig. 11, would represent a radical change, as the hydraulic system is completely eliminated and replaced by direct electromechanical actuators. Significant weight savings is likely with an all-electric system, and reliability would be high, since each effector would have redundant motors and inverters. Turnaround and maintainability of the system would also be greatly enhanced. However, incorporation into the fleet will require significant development time and resources, thereby making this alternative more suitable for implementation on future Shuttle-derived vehicles.

Summary

Advances in battery, power, and motor technologies have made the electric auxiliary power unit (APU) a potential alternative to the hydrazine APU. Most of the electric APU's components can be readily developed. Challenges do remain in obtaining an electrical energy source with a suitable power density to make the electric APU competitive based on weight.

Preliminary tradeoffs indicate that, if a high-weight rechargeable energy source is selected, the electric APU offers advantages in safety and vehicle turnaround cost. A primary battery, weight-competitive with the present APU, is likely to have high development cost and may be no less hazardous than the hydrazine system it replaces. Further definition is required before a proper assessment can be made to determine if potential advantages warrant electric APU development.

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