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MODERN TECHNOLOGY SECONDARY POWER SYSTEMS FOR NEXT GENERATION MILITARY AIRCRAFT

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Abstract

The next generation of military aircraft will require significantly increased internal power capability, with high density packaging and integration of secondary power system elements. These aircraft will be self-sufficient for autonomous operation free of ground support equipment. This paper reviews the concepts and capabilities of modern technology secondary power systems and the application to meet the requirements for these aircraft. The secondary power system elements include the gas turbine auxiliary power unit, aircraft mounted accessory gearboxes, emergency power units, pumps, and pneumatic drives. Mechanical, pneumatic, electric and hybrid techniques to integrate the subsystem will be reviewed and evaluated. In addition, a technology assessment is presented for future gas turbine auxiliary power units.

Introduction

Aircraft secondary power systems (SPS) include the equipment required to provide ground power for main engine starting or motoring, hydraulic and electrical systems, environmental control systems, and checkout of in-flight emergency power systems. A self-sufficient air craft is one with an auxiliary power unit (APU) installed on-board to provide the power for these functions. This compares to an aircraft that requires ground support equipment to be connected for powering these systems on the ground.

The benefits of military aircraft with self-sufficiency have been verified by numerous studies and demonstrations.(1) The major benefits are as follows:

- Improved aircraft operations and maintenance
  - Increased efficiency in power generation
  - Flexibility in launching and maintenance
  - Operational readiness on short notice
  - Remote base operation
  - Reduced hazard of accidents using ground support equipment
  - Fewer personnel required for operation
- Life-cycle-cost of operations reduced
  - Less on-ground main engine operation, thus improving life and reducing fuel consumption
  - Reduced maintenance cost of an APU when compared with ground support equipment

The fact that almost all new military aircraft specifications, except for trainers, require on-board APUs verifies the operators' preference for aircraft self-sufficiency.

The intent of this paper is not to justify the use of an on-board APU in lieu of ground support equipment, but rather, the intent is to discuss various secondary power system design approaches with comparisons of the advantages and disadvantages of each. The systems discussed herein assume a twin-engine fighter or fighter/attack type aircraft. However, in general, these systems could be applied to single-engine aircraft (fighters) and to transport or strategic penetration type aircraft.

Projected APU technology improvements also are discussed.

Secondary Power System (SPS) Design Approaches

The typical SPS usually is identified by a power link between the APU and main engine starting device. Basic systems include:

- Pneumatic link - Compressed air is supplied from the APU to an air turbine starter/motor mounted on the accessory gearbox
- Mechanical link - Shaft power is directly transmitted to the main engine for starting via a clutch or hydrodynamic torque-converter coupling
- Electric link - Electrical power is supplied from an APU driven generator to an electric starter mounted on the accessory gearbox
- Hydraulic link - Hydraulic power is supplied from an APU driven pump to a hydraulic starter on the accessory gearbox
- Hybrid link - This concept identifies systems that comprise a combination of the above type systems; ie, one main engine may be mechanically started and the other pneumatically started

Pneumatic Link

The basic pneumatic link system is shown in Figure 1. As shown, the APU is remotely mounted from the main engine and accessory gearbox and is linked to these components via pneumatic ducting to an air turbine starter/motor (ATS/M). The ATS/M expands the compressed air supplied from the APU to provide shaft power for main engine starting and motoring, or to motor the gearbox for ground checkout of hydraulic and electrical systems.

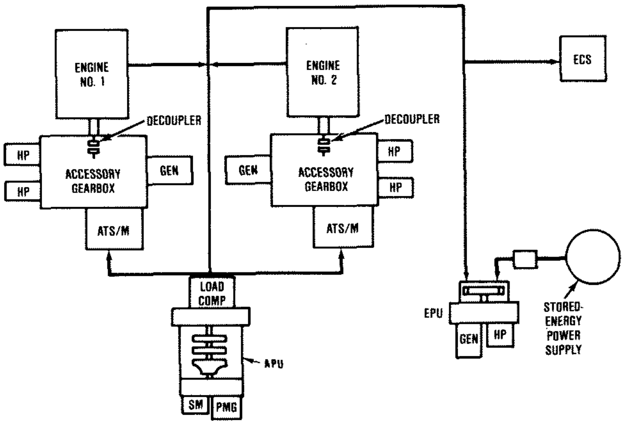

FIGURE 1. PNEUMATIC LINK SECONDARY POWER SYSTEM

In the main engine start mode, the power takeoff (PTO) shaft decoupler is engaged. With air supplied from the APU, the main engine is started by the ATS/M. The APU can be used to start both engines or (after one engine has been started) main engine bleed-air can be supplied to the opposite starter.

Ground checkout is performed by decoupling the accessory gearbox from the main engine and motoring the gearbox-mounted accessories with the ATS/M. Compressed air is supplied to the environmental control system (ECS) as well as the ATS/M.

A backup source of hydraulic and electrical power is available from the turbine-driven emergency power unit (EPU). This unit operates from main engine bleed air inflight or can be checked out on the ground using compressed air from the APU.

In the event of a dual-engine or accessory failure, a stored-energy power supply is used to drive the EPU turbine for emergency power. Candidate stored-energy power supply systems include mono-fuels such as a hydrazine/water mixture or bi-propellants such as jet fuel (from the aircraft's tanks) and an oxidizer (stored air or oxygen).(2)

Mechanical Link

The mechanical link system is schematically shown in Figure 2. For the twin-engine aircraft, the APU is located between the engines and coupled to the accessory gearboxes via accessory drive shafts. Decouplers are located between the APU (center) gearbox and accessory drive shafts to allow selection of right- or left-hand engines for engagement.

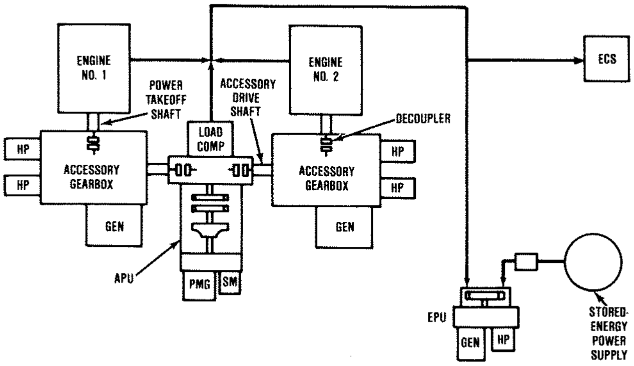

FIGURE 2. MECHANICAL LINK SECONDARY POWER SYSTEM

Main engine starting is accomplished with the PTO shaft decoupler engaged and the appropriate accessory drive shaft decoupler engaged. The APU mechanically drives the main engine to starter cutout speed if a free-turbine APU is used. Using a single-shaft (constant-speed) APU, a torque converter is normally used to convert constant speed APU power to variable speed for main engine starting.

Ground checkout of aircraft hydraulic and electrical systems is made with the PTO shaft disengaged from the main engine. This permits the APU to drive the accessory-gearbox-mounted pumps and generator. Simultaneously, compressed air can be supplied to the ECS from the load compressor mounted on the APU center gearbox.

EPU operation is the same as the pneumatic link system operation.

Electric Link

The electric link system is schematically shown in Figure 3. The APU, which drives a generator to supply electric power as well as compressed air for ECS and EPU checkout, is remotely mounted.

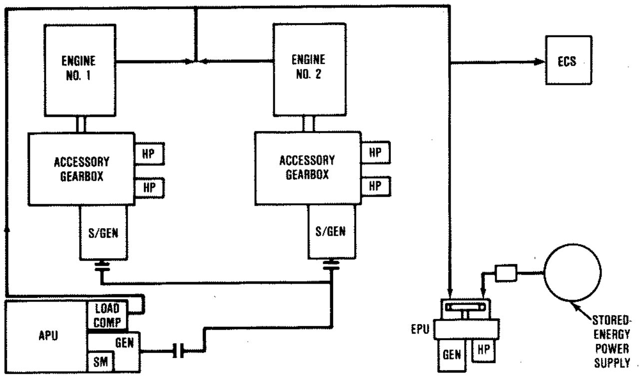

FIGURE 3. ELECTRICAL LINK SECONDARY POWER SYSTEM

The electric link system uses an integrated starter/generator that not only reduces the number of accessories, but also simplifies the accessory gearbox.

An optional arrangement using the electric link system is to use electric motors to drive the main hydraulic pumps (see Figure 4). This further simplifies the accessory gearbox and permits the hydraulic pumps to be remotely located. Ground checkout of electrical and hydraulic systems can be made without motoring the accessory gearbox; this eliminates the need for a PTO decoupler using the arrangement shown in Figure 4.

EPU checkout with the electric link is the same as described for the other systems.

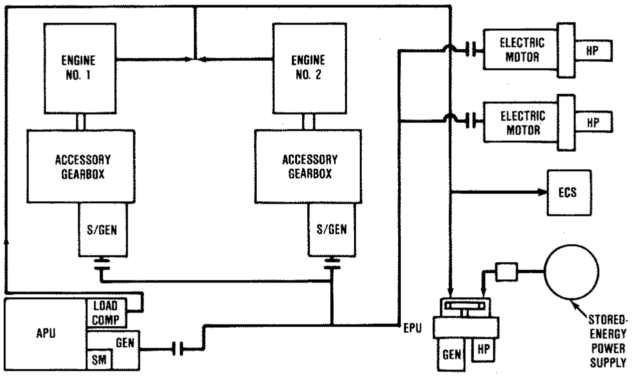

FIGURE 4. ELECTRICAL LINK SECONDARY POWER SYSTEM WITH REMOTE HYDRAULIC PUMPS

Hydraulic Link

The hydraulic link system is schematically shown in Figure 5. The hydraulic link is similar in operation to the pneumatic link system, shown in Figure 1, except that the APU drives a hydraulic pump for powering the hydraulic starter mounted to the accessory gearbox.

All operating modes are the same as described for the pneumatic link except that hydraulic power is used for main engine starting and ground checkout power for motoring the accessory gearbox.

Hybrid Link

An example of the hybrid link system using a combination mechanical and pneumatic link is illustrated in Figure 6.

The APU mechanically drives the left-hand accessory gearbox for engine starting and ground checkout power. Pneumatic power to the right-hand system is provided by the load compressor mounted to the left-hand accessory gearbox.

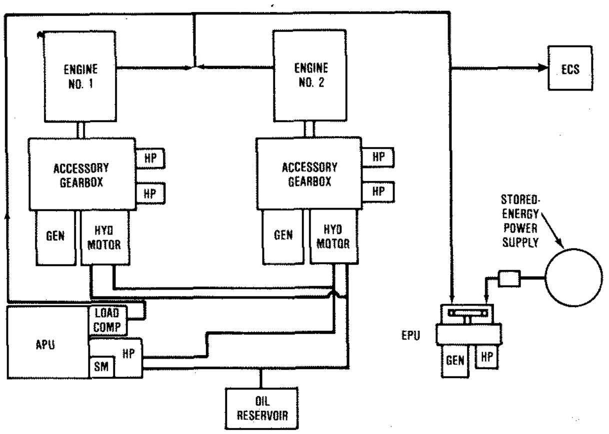

FIGURE 5. HYDRAULIC LINK SECONDARY POWER SYSTEM

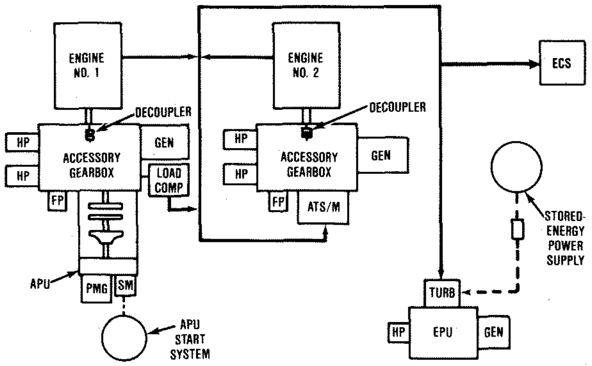

FIGURE 6. HYBRID MECHANICAL/PNEUMATIC LINKED SECONDARY POWER SYSTEM

ECS ground operation and EPU checkout are the same as described for the pneumatic link system.

Comparison of System Design Approaches

Each SPS concept described in the preceding paragraphs have basic advantages and disadvantages. This comparison is intended to serve only as a guide when considering a design approach for a new application. A quantitative comparison to evaluate weight, size, performance, reliability, maintainability, cost, etc. can only be conducted through detailed trade-off studies for a particular application.

A summary of the major advantages and disadvantages of each approach is provided in Table 1.

APU Technology Assessment

In the past, most military aircraft APUs were designed for simplicity to minimize cost and to be compatible with relatively low pressure ratio (less than 4) aircraft pneumatic systems. In addition, turbine wheel material technology for the small turbines of APUs have limited turbine inlet gas temperatures to less than 1750°F (954°C). Specific fuel consumption was not considered too important because the APU operating time was limited and fuel was readily available and not expensive.

The resulting typical APU design is a relatively simple unit, as illustrated in Figure 7, that uses a low pressure ratio centrifugal compressor, from which bleed-air can be extracted for main engine starting and ECS operation. Either a single-stage radial turbine or two-stage axial design can be matched for operation of this APU. Shaft power also is concurrently produced with the compressed air for driven accessories; ie, electrical generator or hydraulic pump.

For future airborne APUs, design improvements are required to meet increased demands such as:

- o APU operating time on the ground will be nearly equal to aircraft flight time to checkout aircraft systems, maintenance, and to provide power for environmental control of the crew, avionics, and weapons systems
- o Significant increases in cost and reduced availability of fuel require an improvement in specific fuel consumption (horsepower per pound per hour fuel flow)
- o To reduce aircraft installation penalties, an increase in APU power density (horsepower per cubic foot of volume) and specific weight (horsepower per pound of weight) are required
- o Improved reliability and reduced maintenance to allow autonomous operation from remote bases with a minimum of spare parts and personnel
- o Increased altitude start and operate capability (40,000 feet) to permit main engine restarts after a dual engine flameout

APU technology improvements must be directed at meeting these increased requirements. Candidate concepts are discussed in the following paragraphs.

To meet the requirements of reduced specific fuel consumption (SFC) and reduced size and weight, APU power sections will require higher cycle pressure ratios and increased turbine inlet temperatures. The improvement in SFC (lb/hp-hr) and increase in specific power (hp/lb-sec), with increased cycle pressure ratio, are shown in Figure 8. Since APU weight and size are influenced by the APU inlet airflow (lb/sec), maximizing the specific power is desired.

As shown in Figure 8, optimum specific power occurs at a cycle pressure ratio between 6 and 7. Advanced centrifugal compressor technology permits efficient operation of a single-stage compressor at this pressure ratio for minimum weight and complexity.

Future APUs will operate at higher turbine inlet temperatures. In the late 1980's a turbine inlet temperature of 2000°F (1093°C) will be possible using metallic super alloys for an uncooled turbine wheel and an air-cooled metallic nozzle. Thermal barrier coatings are required for the combustor for operation at this temperature. A hot section life in excess of 20,000 hours can be achieved at this rating, which is comparable to existing units that experience similar operating duty cycles.

APU turbine inlet temperatures up to 2500°F (1371°C) will be possible as soon as ceramic component research has been completed and subsequent development has demonstrated the durability of these components. Ceramic components are expected to be available for production applications in the early 1990's.

Use of high pressure ratio compressors for the APU power section requires the APU to drive a lower pressure ratio load compressor for an optimum match with an air cycle environmental control system. Load compressors directly driven at rotor speed already have been proven in several applications. Airflow control to the ECS or main engine starter is accomplished using variable inlet guide vanes at the load compressor entrance.

An example of an advanced technology APU using a high pressure ratio (7:1), power section compressor, cast super alloy turbine wheel, and low pressure ratio (3.5:1) load compressor, is shown in Figure 9. Fuel consumption at part-load (reduced load compressor airflow) is minimized using variable inlet guide vanes at the load compressor inlet for airflow control. The unit is

System Type	Advantages	Disadvantages
Pneumatic Link	o APU can be remotely located for flexibility in installation location and environment o System is compatible with widely used pneumatic start carts for backup main engine starting	o Low system efficiency resulting in relatively large APU power rating required o Routing of relatively large ducts in engine accessory bay
Mechanical Link	o High system efficiency results in relatively low APU power rating required	o Requires close APU coupling to main engines o Significant penalty for backup main engine start capability o Mechanical coupling equipment and controls tend to be complex
Electric Link	o APU can be remotely located for flexibility in installation location and environment o Offers increased system integration capability and simplification	o Relatively high-power starter/generator technology not proven o No backup main engine starting from standard ground carts
Hydraulic Link	o APU can be remotely located for flexibility in installation location and environment	o Power transfer hydraulic system tends to be complex o Backup starting from ground carts is difficult since aircraft hydraulic system must be penetrated
Hybrid Link	o Minimizes number of components in system	o Accessory gearbox commonality is difficult to maintain o Significant penalty for backup main engine starting

TABLE 1. SUMMARY COMPARISON OF SECONDARY POWER SYSTEM DESIGN APPROACHES

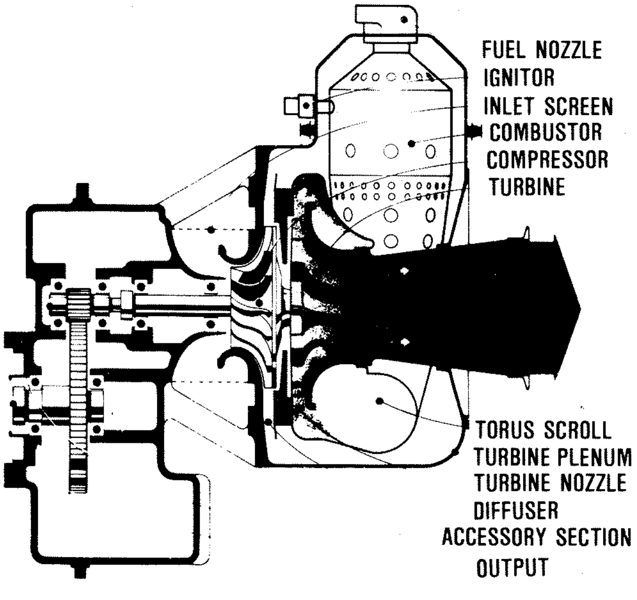

FIGURE 7. SIMPLE CYCLE GAS TURBINE AUXILIARY POWER UNIT

rated at approximately 500 equivalent shaft horsepower at sea level International Standard Atmosphere (ISA) conditions (59°F/15°C). APU characteristics are:

Cycle pressure ratio	6.7
Inlet airflow	4.1 lb/sec
Turbine inlet temperature	2000°F (1093°C)
Specific fuel consumption	0.59 lb/hp-hr
Basic unit dimensions	
Length	45 inches (114 cm)
Width	21 inches (53 cm)
Height	21 inches (53 cm)

APU weight will vary between 200 and 250 pounds (91 and 113 kg) depending on the specified accessory (generator drive) gearbox rating, containment, and controls.

Advanced digital electronic controllers will improve the reliability and availability of future APUs. In addition, APU starting at higher altitudes will be improved through increased flexibilty to monitor and control operating parameters with the digital controller. The digital controller also improves the capability for built-in-test of APU components and health monitoring. Digital controllers are currently in commercial airline service on APUs designed for the latest wide body aircraft and are expected to be in use in military aircraft in the near future.

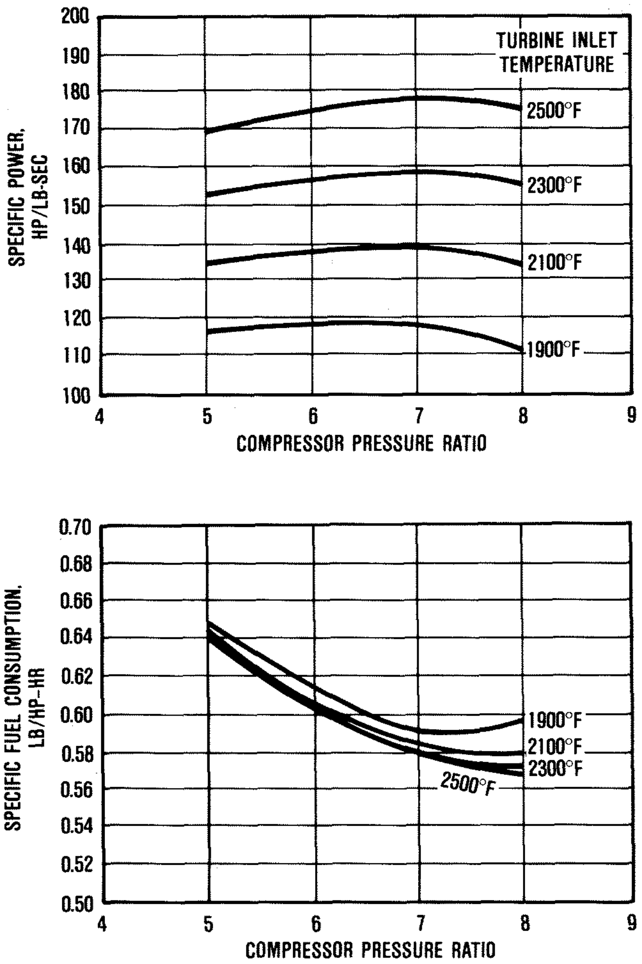

FIGURE 8. ADVANCED APU PARAMETRIC CYCLE ANALYSIS

Summary

The topics presented in this paper present only a brief overview of the expected requirements, system concepts, and APU technology assessment for future military applications. As shown, there are numerous trade-offs that must be conducted to evaluate a secondary power system for a particular application. A variety of system concepts can be used to integrate secondary power system functions. The nucleus of the power system, the gas turbine APU, is projected to offer significant future improvements including lower weight, size and fuel consumption, plus improved reliability. Maintenance improvements also are expected by using digital electronic controllers for built-in-test capability and health monitoring.

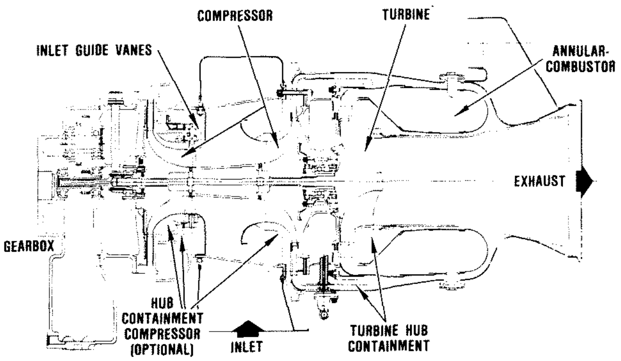

FIGURE 9. ADVANCED APU WITH SHAFT DRIVEN LOAD COMPRESSOR AND ACCESSORY GEARBOX

References

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2. Aircraft Super Integrated Power Unit, SAE Report 821461, October 1982, James A. Williams, Armando D. Lucci, and Buryl L. McFadden

Abbreviations and Acronyms

APU	-	Auxiliary Power Unit
ATS/M	-	Air Turbine Starter/Motor
°C	-	Degrees Centigrade
COMP	-	Compressor
cm	-	Centimeter
ECS	-	Environmental Control System
EPU	-	Emergency Power Unit
°F	-	Degrees Fahrenheit
FP	-	Fuel Pump
GEN	-	Generator
HP	-	Hydraulic Pump
hp	-	Horsepower
hr	-	Hour
HYD	-	Hydraulic
ISA	-	International Standard Atmosphere
kg	-	Kilogram
lb	-	Pound
NO.	-	Number
PMG	-	Permanent Magnet Generator
PTO	-	Power Takeoff
SAE	-	Society of Automotive Engineers
sec	-	Second
SFC	-	Specific Fuel Consumption
S/GEN	-	Starter/Generator
SM	-	Starter Motor
SPS	-	Secondary Power System
V/STOL	-	Vertical/Short Takeoff and Landing