AEROSPACE INFORMATION REPORT	AIR744™	REV. C
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Aerospace Auxiliary Power Sources

RATIONALE

AIR744C has been reaffirmed to comply with the SAE five-year review policy.

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1. SCOPE

This SAE Aerospace Information Report (AIR) is a review of the general characteristics of power sources that may be used to provide secondary, auxiliary, or emergency power for use in aircraft, space vehicles, missiles, remotely piloted vehicles, air cushion vehicles, surface effect ships, or other vehicles in which aerospace technology is used.

The information contained herein is intended for use in the selection of the power source most appropriate to the needs of a particular vehicle or system. The information may also be used in the preparation of a power source specification.

Considerations for use in making a trade study and an evaluation of the several power sources are included. More detailed information relating to specific power sources is available in other SAE Aerospace Information Reports or in Aerospace Recommended Practices.

2. REFERENCES

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

ARP699 High Temperature Pneumatic Duct Systems for Aircraft

AIR1168/1 Thermodynamics of Incompressible and Compressible Fluid Flow

AIR1343 Liquid Propellant Gas Generation Systems

J1775 Bleed-Air Pneumatic Systems for Gas Turbine Equipped Marine and Amphibious Craft

2.2 U.S. Government Publications

Available from the Document Automation and Production Service (DAPS), Building 4/D, 700 Robbins Avenue, Philadelphia, PA 19111-5094, Tel: 215-697-6257, http://assist.daps.dla.mil/quicksearch/.

MIL-STD-810 Environmental Engineering Considerations and Laboratory Tests

MIL-DTL-5624 Turbine Fuels, Aviation Grades, JP4-JP5

MIL-PRF-7808 Lubricating Oil, Aircraft Turbine Engine, Synthetic Base

MIL-PRF-23699 Lubricating Oil, Aircraft Turbine Engine, Synthetic Base, NATO Code Number 0-156 Reviewer: 68 AR AV GS SH

2.3 ASTM Publications

Available from ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959, Tel: 610-832-9585, www.astm.org.

ASTM D1655 Standard Specification for Aviation Turbine Fuels

ASTM D910 Standard Specification for Aviation Gasolines

2.4 DOT Publications

Available from DOT, 400 7th Street SW, Washington, DC 20024.

DOT 3HT

DOT Code of Federal Regulations (Title 49) Transportation 49 Parts 400 to 99, Revised as of October 1, 1992

2.5 RTCA Publications

Available from RTCA, Incorporated, 1828 L Street, NW, Suite 805, Washington D.C. 20036, Tel: 202-833-9339, Fax: 202-833-9434, www.rtca.org.

RTCA DO-311 Minimum Operational Performance Standards for Rechargeable Lithium Battery Systems

RTCA DO-254 Design Assurance Guidance for Airborne Electronic Hardware

RTCA DO-178B Software Considerations in Airborne Systems and Equipment Certification

2.6 Acronyms and Abbreviations

AC	Alternating Current
ADG	Accessory Drive Gearbox
AIR	Aerospace Information Report
ALSEP	Apollo Lunar Surface Experiment Package
AM	Air Mass
APU	Auxiliary Power Unit
ARP	Aerospace Recommended Practice
ATS	Air Turbine Starter
ATSCV	Air Turbine Starter Control Valve
AU	Astronomical Unit
CRT	Cathode Ray Tube
DC	Direct Current
DOT	Department of Transportation
EBW	Exploding Bridgewire
ECA	Electronic Control Assembly
ECU	Electronic Control Unit
EGT	Exhaust Gas Temperature
FAA	Federal Aviation Administration
HP	Hydraulic Pump

HS	Hydraulic Starter
IDG	Integrated Drive Generator
MCT	Maximum Continuous Rating
MTBF	Mean Time Between Failures
NRC	Nuclear Regulatory Commission
O/F	Oxidizer to Fuel Ratio
PMG	Permanent Magnet Generator
SNAP	Space Nuclear Auxiliary Power
SPS	Secondary Power System
TBI	Thru-Bulkhead Initiator
TC	Torque Converter
TSFC	Thrust Specific Fuel Consumption

3. TYPES OF POWER SOURCES

The more prominent types of auxiliary power sources are described. These power sources provide energy in the form of gas or airflow at various pressures and temperatures or as mechanical or electrical energy. Energy conversion equipment may be required to convert the energy to the form desired, i.e., to shaft, electric, hydraulic, or pneumatic power.

These power sources are:

a. Solid propellant gas generators that produce hot gas

b. Liquid propellant gas generators that produce hot gas

c. Noncirculating or blowdown systems that provide gas from a stored high-pressure fluid

d. Engine bleed systems that provide high-pressure air

e. Ram air turbines that generate mechanical power to drive generators or pumps

f. Primary and secondary batteries

g. Fuel cells that produce electrical power

h. Solar cells that convert incident sunlight into electrical power

i. Nuclear (usually radioisotope fueled) thermoelectric power sources

j. Auxiliary gas turbine engines for bleed air and/or mechanical power

k. Stored mechanical energy (flywheel)

4. REQUIREMENTS FOR POWER SOURCES

4.1 General

An auxiliary power source may be required to:

a. Provide continuous power to a system, auxiliary system, or subsystem

b. Provide power in response to system needs

c. Provide power in the event of malfunction or failure of a primary power source

An auxiliary power source may not be required to meet, in full, the specification requirements for the primary power source, i.e., limited duty.

A malfunction of an auxiliary power source when used in a manned vehicle, other than when used in place of a failed primary source, shall not cause a catastrophic failure of the parent vehicle.

4.2 Definition of Requirements

At a minimum, a clear definition of the following requirements should be made:

a. Functional Requirements: A description of primary and secondary (if any) functional requirements should be made.

b. Type: Type, energy-level duration, and quality of power required; such as hydraulic, pneumatic, electrical, mechanical, actuation, or force (thrust) should be described.

c. Duty Cycle: Operational requirements should be described, including those for ground checkout prior to and following the mission as well as those for the complete mission. Also to be included are: overload requirements and quality of power; operational requirements for a single mission or for successive missions extending over a period of time; system prefunction testing requirements, i.e., solid propellant gas generator lot sample destruct tests; and unattended standby time.

d. Response Time: Power source response time should be described with respect to actuation, activation signal or command, or changing loads.

e. Environment: Operational and nonoperational power source requirements should be described during and/or after exposure to the following environmental conditions:

   1. Pressure
   2. Acceleration
   3. Temperature
   4. Contaminants
   5. Ambient gases
   6. Foreign objects
   7. Ambient liquids
   8. Corrosion/erosion
   9. Vibration
   10. Radiation
   11. Shock

The effect of an extended time period in the environment on standby status should be considered. The requirements of MIL-STD-810 should apply.

4.3 Power Source Selection

In making a tradeoff study of candidate power sources, the systems approach is suggested. Considerations to be made regarding use of candidate power sources may include those listed below:

a. Cost: Cost considerations may include:

   1. Unit cost

   2. System cost

   3. Nonrecurring cost

   4. Development cost

   5. Cost per unit of output or performance

   6. Life cycle cost

b. Weight: Weight considerations may include:

   1. Weight per unit of output

   2. System weight

c. Installation: Packaging of shaping of system to fit available envelope should be considered, as should any requirements for protective zones, shielding, servicing, and mounting provisions.

d. Availability: Availability considerations may include:

   1. Off-the-shelf

   2. Development time

   3. Lead time

   4. Single or multiple sources

e. Complexity: Complexity considerations may include any special equipment requirements.

f. Reliability and Safety: Reliability and safety considerations may include the following:

   1. Failure and removal rates and impact on life cycle costs

   2. Safety effects of loss of power and consequent need for redundancy

   3. Failure modes and consequent hazard to the vehicle

g. Serviceability: Serviceability considerations may include:

   1. Equipment needed

   2. Potential hazards to personnel or equipment (product liability)

   3. Personnel training

h. Maintainability: Maintainability considerations may include:

1. Periodic inspections
2. System checkout
3. Field maintenance
4. Specialized personnel and equipment

i. Life Expectancy: Life expectancy considerations may include:

1. Anticipated operating life
2. Anticipated number of cycles
3. MTBF
4. Anticipated storage life

j. Manufacturers Warranties

k. Special Considerations

l. Performance: Effects on the vehicle regarding performance, including operating cost, effectiveness, etc., may be considered.

m. Compatibility: Compatibility with other equipment, i.e., interfacing of emergency/normal/standby system, may be considered.

n. Growth Factors

o. Survivability

5. SOLID PROPELLANTS

5.1 Description

A solid propellant gas generator consists of three basic components: a self-sustaining combustible solid mixture called the propellant; an initiator to start the combustion reaction upon command; and a chamber to house the above components and to serve as a confining pressure vessel during combustion. Combustion gases are generated at a rate determined by the ballistic properties of the propellant, the geometry and temperature of the propellant grain, and output load or size of orifice through which the generated gases are flowing.

5.2 Applications

Solid propellant gas generators are suitable for a wide range of applications requiring the delivery of a preprogrammed level of power for a relatively short duration. Generated gases may be used to power turbines that drive alternators, pumps, hydraulic systems, or direct mechanical drive systems; may drive linear and rotary actuators, either singly or in combinations; or may provide supplemental gas pressurization for hydraulic accumulators or for expelling liquids from tankage. In addition, the hot combustion gases may be used directly for reaction jet control; directly or in combination with coolant devices for inflation of nonrigid structures such as air bags, bladder actuators, and inflatable airfoils; or in combination with water or auxiliary gas-producing chemicals in pop-up expulsion or flotation systems.

Historically, solid propellant gas generator burn times have ranged from less than 1 s to more than 1000 s, with most applications requiring between 10 and 60 s of power. Conventional solid propellant gas generators are considered "one-shot" devices because the propellant charge normally remains burning until consumed, though many systems may be reloaded with a replaceable cartridge for repeated use. Gas generator weights may range from a fraction of a pound to large units of several hundred pounds. Operating pressures range from a low of about 200 psi (1400 kPa) to above 15 000 psi (103 000 kPa), with most systems operating in the 1000 to 2000 psi (7000 to 14 000 kPa) range.

5.3 Components

The components required for a solid propellant gas generator are described below:

a. Propellants: Solid propellants are mixtures of chemicals that when cast, pressed, or extruded into a specific mechanical geometry will burn with predictable performance. The most common types of gas generator solid propellants are:

    1. Composites consisting of an oxidizer and a fuel binder that react with each other

    2. Multibases that contain one or more highly reactive oxygenated chemical components

    Propellants normally contain small amounts of additives that serve to control the burn rate, temperature sensitivity, and pressure exponent; improve mechanical properties; stabilize aging characteristics; and cool the combustion gases.

    Table 1 presents typical properties for several major families of gas generator solid propellants. Selection of a propellant for a specific application depends on a careful evaluation of numerous factors, including exhaust gas composition and temperature; ballistic properties, particularly burn rate, which directly affects the required physical envelope; mechanical properties to survive the dynamic environments; sufficient shelf life; the capability for stable operation at the required pressure; and cost. Applications incorporating the use of control valving or turbine wheels require special attention to assure that the exhaust gas is sufficiently clean or free of products that may be corrosive, erosive, reactive, or condensible since these may impair system performance. Other applications, such as driving closed actuators, are more tolerant of exhaust gas products. Some specialized applications such as the automotive air bag and certain inflatables require the generation of essentially nontoxic gases because of human factors.

b. Ignition Systems: Ignition systems for solid propellant gas generators typically consist of two major components:

    1. An initiator

    2. Some supplemental ignition boost material to initially pressurize the unit and sustain combustion until the main solid propellant grain has reached stable combustion.

TABLE 1 - TYPICAL SOLID PROPELLANTS FOR GAS GENERATORS

Propellant Type	Hydrocarbon Binder/AN (Rubber/AN)	Oxygenated Binder/AN (Plastic/AN)	Hydrocarbon Binder/AP	Oxygenated Binder/AP	Hydrocarbon Binder/KP
Typical Binders	Isoprene, PBAA, CTPB HTPB, Butadiene-Methyl Vinyl Pyridine	Epoxide, Cellulose Acetate, Polyacrylate, Polyester	PBAA, CTPB, PBAN, HTPB, PVC, CTBN	Polyacrylate, Polyester	PBAN, HTPB, PVC
Oxidizer(s)	Ammonium Nitrate	Ammonium Nitrate	Ammonium Perchlorate	Ammonium Perchlorate	Potassium Perchlorate
Specific Impulse, $\frac{lbf \cdot s}{lbm}$	180-195	170-200	200-215	180-190	180-190
Gas Temperature, °F (°C)	1800-2600 (980-1400)	1600-2200 (870-1200)	1800-3000 (980-1600)	1800-2300 (980-1300)	2400-3000 (1300-1600)
Average Gas Molecular Weight	19-20	19-23	18-21	21-23	26-28
Typical Exhaust Products	H_2, H_2O, CO, CO_2, N_2, small quantities metal oxides	H_2, H_2O, CO, CO_2, CH_4, N_2, small quantities metal oxides	H_2, H_2O, CO, CO_2, CH_4, HCl, some solid carbon and metal compounds	CO, CO_2, H_2O, N_2, H_2, HCl, some solid carbon and metal oxides	CO, H_2, some solid carbon, KCl, and liquid KCl
Formula Density, lb/in^3 (kg/dm^3)	0.052-0.055 (1.44-1.52)	0.054-0.056 (1.50-1.55)	0.053-0.056 (1.47-1.55)	0.057-0.060 (1.58-1.66)	0.056-0.063 (1.550-1.744)
Burning Rate Range, in/s at 1000 psia (m/s at 6895 kPa)	0.05-0.21 (0.0013-0.0053)	0.025-0.15 (0.00063-0.0038)	0.2-1.5 (0.005-0.038)	0.06-0.7 (0.0015-0.018)	0.6-0.8 (0.015-0.020)
Hazards Classification	Class C (1.4) or Flammable Solid	Class C (1.4) or Flammable Solid	Class B (1.3)	Class B (1.3)	Class B (1.3)
Remarks	Most widely used for engine starter cartridges. Also used for power and flight control. Moisture barriers and/or hermetic seals generally required.	Widely used for power and flight control actuators. Moisture barriers and/or hermetic seals required. Some rigid binder systems capable of very high pressure operation (P ≥ 10 000).	Useful for flight control, piston actuation, small thrusters. Acidic exhaust (HCl + H_2O) and soot may be important considerations.	Useful for starter grains, small thrusters, limited turbine power, and tank pressurization. Acidic exhaust and aging properties under high humidity, high temperature conditions are potential concern.	Useful for high pressure operation (P ≥ 10 000 psia). Has seen service for high pressure actuator systems. Condensable KCl and high pressure exponent are concerns.

TABLE 1 - (CONTINUED)

Propellant Type	Oxygenated Binder/ Organic Oxidizer	Hydrocarbon Binder/ Energetic Oxidizer	Oxygenated Binder/ Energetic Oxidizer	Inorganic Generant	Multibase (Single, Double, and Triple Base)
Typical Binders	Polyester	HTPB, CTPB	Polyether, Polyester with and without nitrate esters	Sodium Azide	Nitrocellulose, Nitroglycerin, Polyether/nitrate ester
Oxidizer(s)	Dihydroxy Glyoxime Ammonium Perchlorate	RDX, HMX	RDX, HMX, Nitroguanidine	Metal Oxides	Nitroguanidine, TAGN, HMX
Specific Impulse, $\frac{lbf \cdot s}{lbm}$	180-190	205-225	180-220	110-145	180-205
Gas Temperature, °F (°C)	1800-2300 (980-1300)	2200-3000 (1200-1600)	1800-3000 (980-1600)	1800-2100 (980-1100)	2000-3000 (1100-1600)
Average Gas Molecular Weight	20-21	19-21	19-21	28	20-22
Typical Exhaust Products	CO, CO_2, H_2O, HC1, H_2, N_2, some solid carbon	CO, H_2, N_2, H_2O, CO_2, some solid carbon, especially at low T_F	CO, H_2, N_2, CO_2, H_2O, CH_4, some solid carbon	N_2 (only gas), Balance filterable	CO, H_2, N_2, CO_2, H_2O
Formula Density, lb/in^3 (kg/dm^3)	0.056-0.06 (1.55-1.66)	0.050-0.059 (1.38-1.63)	0.055-0.059 (1.52-1.63)	0.085-0.090 (2.35-2.49)	0.055-0.058 (1.52-1.60)
Burning Rate Range, in/s at 1000 psia (m/s at 7000 kPa)	0.06-0.35 (0.0015-0.0089)	0.06-0.15 (0.0015-0.0038)	0.05-0.15 (0.0013-0.0038)	0.7-1.7 (0.018-0.043)	0.10-0.50 (0.003-0.013)
Hazards Classification	Class B (1.3) to Class C (1.4), Flammable Solid	Class A (1.1)	Class B (1.3) to Class A (1.1)	Class C (1.4)	Class B (1.3) to Class A (1.1)
Remarks	Used for a variety of applications and capable of operations to pressures in excess of 10 000 psi (70 000 kPa). Possible concern for effect of long-term humidity and high temperatures on polyester binder.	Used for high performance systems when hazards classification may be acceptable. Low T_F systems may be very sooty.	Usable in wide variety of pressurization, thrusting, power, and special high performance applications. Hazards classification and polyester moisture sensitivity may be considerations.	Nontoxic gas for specialized applications. Low specific impulse. High burn rates/rapid pressurization at low temperature.	Usable in wide range of applications. Considerations may range from stabilizer depletion with age, and low temperature embrittlement.

The ignition system may be inside the gas generator housing or, less frequently, in a separate chamber that is either external or integral to the main chamber, with hot ignition gases directed onto the surface of the main propellant grain. When the ignition system operates within an independent pressure vessel it is sometimes called a "pyrogen" igniter. Pyrogen igniters normally add complexity and increased cost but may offer improved ignition properties (i.e., faster, more reproducible) with less ignition material to contaminate exhaust gases. An initiator is most frequently an electroexplosive device, sometimes referred to as a squib, in which applied electric current heats a thin wire and ignites a small charge of sensitive pyrotechnic material to produce a hot gas capable of igniting adjacent propellant materials. Some specialized gas generators utilize more complex initiators, such as EBW devices for increased electrical safety or TBIs activated via a detonation transfer line in lieu of an electrical input. Alternative nonelectrical initiation systems, such as mechanically activated percussion primers, are also utilized.

Ignition boost materials are generally small quantities of higher temperature solid propellants that are more readily ignited than typical gas generator propellants. Depending upon the output characteristics of the initiator, intermediary ignition materials such as high temperature metal-oxidant mixtures in powder, granular, or pellet form may also be used. Examples of these materials are boron-potassium nitrate and magnesium PTFE mixtures. Design of the ignition system should be the responsibility of the gas generator developer as it requires close tailoring in order to achieve reliable ignition over the service temperature range with a minimum of overpressure and detrimental high temperature exhaust products.

c. Combustion Chamber: Combustion of the solid propellant takes place within the same chamber or housing in which the propellant is stored and occurs simultaneously on all noninhibited surfaces of the propellant grain. There are two basic approaches to gas generator chambers:

1. Integral

2. Cartridge-loaded

Integral gas generators are normally "one-shot" units in which the case is a pressure vessel designed to withstand operating pressures, as well as provide sealing, insulation, and associated mechanical functions.

Cartridge-loaded gas generators are reusable devices in which the solid propellant grain and ignition systems are located in an expendable lightweight shell, normally of metal, which serves as an environmental seal and facilitates handling. The cartridge is then installed within a high strength breach that serves as the pressure vessel. Such breech-loaded units can normally be reloaded and activated numerous times between major refurbishment. The cartridge-loaded approach is used primarily for turbine starter systems such as that used on the U.S. Air Force B-52 and other military jet-engine aircraft.

5.4 Advantages

Solid propellant gas generators offer a compact, simple, efficient, reliable, and generally low-cost method to store energy as a source of power. Contrasted to other approaches such as stored-gas, liquid propellant systems, and batteries, solid propellant systems have demonstrated the capability for long storage life with no need for maintenance and minimal routine inspection.

5.5 Disadvantages

Solid propellants operate at elevated temperatures and deliver energy at a preprogrammed, normally constant rate and are considered one-shot devices. The high temperature gas requires that downstream components such as tubing, valving, turbines, etc., be capable of withstanding these high temperatures.

Solid propellant burn rate, and thus the resultant unit mass flow rate, is temperature related. Therefore, unit operating pressure and burn time will vary over the environmental temperature range. This would have little impact on a closed system or gas generator designed to operate under a closely controlled temperature environment, as in a missile silo. However, for systems operating over a wider temperature range such as -65 to 160 °F (18 to 71 °C), some degree of extra propellant/unit weight may be required to meet all requirements over the temperature range. This may be handled several ways:

a. Design the unit to meet the minimum required burn time at the upper temperature limit and the minimum pressure/mass flow at the lower temperature limit

b. Design the unit to meet the minimum burn time at the upper temperature limit and dump the excess through a relief valve

c. Add the complexity of a temperature compensated constant mass flow valve and allow the operating pressure to shift.

Progress has been made toward developing more sophisticated solid propellant gas generator systems that vary the operating pressure to control the mass flow in order to more closely meet precise system demands. Such systems provide "energy management" for more efficient utilization of on-board propellant and, when designed to a valid duty cycle, offer significant improvements in performance at a reduction of unit size and weight. Such systems are achieved only at a significant increase in unit complexity and cost. Most solid propellant gas generator systems, therefore, continue to be of a constant or preprogrammed maximum power output, with excess power dumped through relief/diverter valves or otherwise dissipated as heat.

5.6 Developing Technology

Recent work on solid propellants for thruster power is in the 3500 to 4000 °F range with both AN and AP propellants with ISPV up to 240. These propellants require the use of carbon-carbon or very high temperature materials such as tungsten or raenium.

6. LIQUID PROPELLANTS

6.1 Description

A liquid propellant auxiliary power system consists of:

a. Propellant

b. Propellant tankage

c. Propellant expulsion system and flow control devices

d. Combustion or decomposition chamber (gas generator)

In support of these components is an instrumentation system plus safety elements. The system can use a monopropellant, a bipropellant (a propellant plus oxidizer), or a propellant that uses ambient air as an oxidizer. AIR1343 provides a good composite of typical system components.

6.2 Applications

Liquid propellant systems are generally applied to situations that require propellant flows to be varied over wide ranges and often shut off and restarted. The hot gases from the combustion or decomposition chamber can be passed through a nozzle to provide reaction thrust, to either a linear or rotary actuator, or to an engine that provides shaft power by use of a reaction turbine or positive displacement expander. The final use of the generated shaft power will dictate control accuracy and response requirements.

6.3 Components

The components of a liquid propellant auxiliary power system are described below:

a. Propellants:

1. Monopropellants: A liquid monopropellant is defined as a fluid capable of undergoing an exothermic reaction, releasing energy in the form of hot gases, without the addition of an oxidizer. This reaction can be initiated by the application of heat or through contact with a catalyst or hypergolic substance. The reaction is usually sustained by self-generated heat.

   Numerous monopropellants have been developed and are available. Hydrogen peroxide, Otto fuel, ethylene oxide, and various blends of hydrazine are typical examples. Each fuel has unique characteristics. For example, a requirement for extended storage life could remove hydrogen peroxide from consideration, since hydrogen peroxide slowly decomposes. A low-temperature operating requirement may also eliminate some of the hydrazine blends and Otto fuel. A clean exhaust requirement can eliminate all the fuels containing carbon. A low toxicity has been one of the major objectives in the development of Otto fuel. A selected group of monopropellants is listed in Table 2. Other monopropellants and variations of the listed group are possible. For example, a mixture of 68% anhydrous hydrazine and water yields a monopropellant that has a freezing point below -62 °F (-52.8 °C). This mixture removes the high freezing point disadvantage of anhydrous hydrazine (70% N_2H_4 and 30% H_2O, the freezing point is -56 (F).

2. Bipropellants: A bipropellant system uses an oxidizer to react with the fuel in a reaction chamber. A source of ignition is usually required to initiate the reaction, which is sustained by self-generated heat. The temperature of the product gases is dependent on the fuel/oxidizer mixture ratio. Stoichiometric mixtures normally yield excessive temperatures for use in power conversion engines. Therefore, fuel- or oxidizer-rich mixtures are usually used. Table 3 illustrates the typical physical and energy characteristics for a few selected bipropellants.

b. Tankage: The tankage configuration is set by the quantity and types of propellant required, envelope available, storage requirements, and expulsion method. Spherical, toroidal, and cylindrical shapes have been used. Requirements for positive expulsion under zero or randomly applied g-loads are met with the use of diaphragms, bladders, pistons, bellows, or capillary action devices. Materials of construction vary to meet chemical compatibility considerations. Weight of tankage is important and is dictated by the materials required and the strength capability specified as related to the tank normal operating pressure.

c. Flow Control: One of the major benefits of liquid propellants over solid propellants is that propellant flow rates can be controlled by simple liquid throttling valves upstream of the decomposition chamber/combustor.

   Fuel delivery can be provided by a tank expulsion system or by a fuel pump. The fuel pump approach is more complicated but often lighter. Expulsion gases can be provided by a regulated cold gas supply or by a bootstrap differential area piston tank using gases from the decomposition chamber/combustor.

   The ease of multiple restarts is related to the ignition system. Fuels which are hypergolic, catalytically decomposed, or spark ignited are easier to restart than those requiring thermal ignitors or injected chemicals to achieve ignition.

d. Decomposition/Combustion Chamber:

1. Decomposition Chamber: A decomposition chamber is used with monopropellants. This chamber contains catalyst, hypergols, thermal beds, or combinations of these to achieve the desired operation. A spontaneous catalyst is one that causes the monopropellant to decompose upon contact. Large surface areas per unit volume allow extensive contact between the monopropellant and catalyst. The temperature of the fuel often affects the ability of the monopropellant to decompose; therefore, thermal bed chambers require careful design to assure stable decomposition. Hypergolic initiation systems require a sustaining catalyst or thermal bed. The propellant flow rate range or "turndown ratio" required of the power plant control system is very important in the design of the chamber. Also, dissociation of the gas products takes place in the chamber and will have an effect upon the outlet temperature. The thermal design of the chamber should minimize heat soak back to the propellant inlet lines.

TABLE 2 - MONOPROPELLANT CHARACTERISTICS

	Ethylene Oxide	N-Propyl Nitrate	Otto Fuel II	Anhydrous Hydrazine	Typical Alkylated Hydrazine Blends	Typical Nitrated Hydrazine Blends	Hydrogen Peroxide 90%
Chemical Formula	C_2H_6O	$C_3H_7NO_3$	Classified	N_2H_4	$CH_3N_2H_3$, N_2H_4	$CH_3N_2H_3$, N_2H_4, $N_2H_5NO_3$	H_2O_2
Special Gravity, 77 °F (25 °C)	0.870	1.050	1.234	1.004	0.900	0.950	1.380
Kinematic Viscosity at 77 °F (25 °C), CS	0.24	0.65	3.80	0.905	1.10	1.70	1.05
Freezing Point, °F (°C)	-171 (-113)	-150 (-101)	-24.9 (-32)	34 (1.1)	-68 (-56)	-68 (-56)	31 (-0.6)
Vapor Pressure, 77 °F (25 °C) lb/in^2 (kPa)	26 (180)	0.511 (3.52)	0.0020 (0.014)	0.278 (1.92)	0.901 (6.21)	0.840 (5.79)	0.0999 (0.689)
Flash Point, °F (°C)	0 (-17.8)	64.9 (18.3)	235 (113)	126 (52.2)	80.1 (26.7)	84.9 (29.4)	230 (110)
Gas Energy, Joule/kg x 10^{-6}	1.47	1.73	1.99	2.22 (50% HH_3 Disso)	1.85	2.02	0.81
Average Molecular Weight	20.7	16.8	21.7	13.8	12.8	13.0	22.1
Gas Temperature, °F (°C)	1740 (949)	1251 (677)	2151 (1177)	1800 (982)	1341 (727)	1501 (816)	1380 (749)
Material Compatibility	Very Good	Good	Very Good	Good	Good	Good	Poor
Storability	Very Good	Good	Very Good	Good	Good	Good	Poor
Fire Hazard	High	Medium	Very Low	Low	Low	Low	Med/Low
Toxicity	Low	Low	Very Low	Medium	Medium	Medium	Low
Decomposition Products	C, CH_4, $C_2H_4CO_2$, O_2 CO, H_2	C, CO, H_2, N_2 CO_2, CH_4 H_2O	C, CO_2, C_2H_6 CO, N_2 H_2 HCN, H_2O, NO	N_2, H_2, NH_3	N_2, H_2, C, CH_4	N_2, H_2, C, CH_4, H_2O Trace CO	H_2O, O_2

TABLE 3 - TYPICAL BIPROPELLANT CHARACTERISTICS

TABLE 3A

	Fuel Hydrogen	Fuel JP-4	Fuel Monomethyl Hydrazine	Oxidizer Oxygen	Oxidizer Nitrogen Tetroxide
Chemical Formula	H_2	$C_{9.66}H_{19}$	CH_3NHNH_2	O_2	N_2O_4
Specific Gravity	0.071 at -423 °F (-253 °C) (liquid)	0.747 to 0.825 at 61 °F (16 °C)	0.878 at 68 °F (20 °C)	1.14 at -297 °F (-183 °C) (liquid)	1.44 at 68 °F (20 °C)
Freezing Point, °F (°C)	-434 (-259)	-76 (-60)	-63 (-53)	-362 (-219)	10 (-12)
Boiling Point, °F (°C)	-423 (-253)	270-469 (132-243)	187 (86)	-297 (-183)	70 (21)
Vapor Pressure, lb/in^2 at degrees F (kPa at degrees C)	33.9 lb/in^2 at 480 °F (234 kPa at -249 °C)	7.3 lb/in^2 at 160 °F (50 kPa at 71 °C)	8.8 lb/in^2 at 160 °F (61 kPa at 71 °C)	37 lb/in^2 at -279 °F (255 kPa at -173 °C)	111 lb/in^2 at 160 °F (765 kPa at 71 °C)
Stability	Good	Good	Good	Good	Disassociation is a function of temperature but is reversible
Shock Resistance	Insensitive	Insensitive	Insensitive	Insensitive	Insensitive
Storage Life	Cryogenic Fluid	Good - similar to gasoline	Good	Cryogenic Fluid	Good when dry
Compatibility, Handling, and Storage	Satisfactory with austenitic S.S., aluminum, and copper. PTFE and Kel-F for limited use. Flammable in air mixtures.	Store in steel tanks. Protect from sun. Attacks rubber, paints, and plastics. Vapor explosive.	Store in stainless steel drums or tanks. Protect from contaminants. Hygroscopic. Low flash point.	May cause spontaneous ignition with combustibles, shock sensitive combinations with certain oxidizable materials.	Satisfactory with steels, aluminum, nickel alloys, tetrafluoroethylene, Kel-F, and neoprene. Store in sealed mild steel tanks.

TABLE 3B

	H_2-O_2	JP4-O_2	MMN-N_2O_4
Oxidizer/Fuel (O/F) Ratio (Weight) for 1800 °F (982 °C) Gas	0.95	0.56	0.27
Gas Energy Joule/kg at Indicated O/F 50/1 Pressure Ratio 77 °F (25 °C) Supply Temperature	6.39×10^{-6}	3.1×10^{-6}	1.60×10^{-6}

2. Combustion Chamber: A combustion chamber is used with bipropellant systems in which both a fuel and an oxidizer are injected into the chamber. Flow controls to maintain proper mixture proportions are required. Mixture ratios, either fuel rich or lean from stoichiometric, are adjusted to control gas outlet temperature. Dissociation also occurs in bipropellant systems and must be considered when performance values are determined. Fuel injector, ignitor, and combustion chamber designs are all interrelated to assure start-up and controlled stable operation. Thermal protection and heat dissipation must be provided to prevent deterioration of the combustor and its components.

7. HIGH PRESSURE STORED GAS SYSTEM

7.1 Description

A high pressure stored gas power source system consists of four elements:

a. The fluid medium or gas

b. A container

c. An actuator to open the container upon command

d. A pressure reducer that reduces the container gas pressure to the required system discharge level

Simple systems may operate without the use of a pressure reducer, thereby providing unregulated output.

7.2 Applications

The power source may be used to drive linear and rotary pneumatic actuators or turbo alternators and to power various reaction thrusters. The reduced pressure may be used as the expulsion force for a liquid accumulator, the driving force for a free piston HP, or the supply pressure for other applications. Stored gas systems are also used in emergency applications as quick opening devices or inflation devices and as the power source for steering short-duration tactical weapons.

Usually the most economical designs provide low regulated operating pressures since the amount of available power from the container is set by the regulated pressure level.

7.3 Components

The components required for a high pressure stored gas system are described below:

a. Fluid Medium: The fluid medium or gas used for most applications is either air, helium, or nitrogen. Helium is especially attractive for cold gas operation and checkout of warm gas driven turbine systems because turbine performance on room temperature helium approaches that achieved on warm gas propellants. This is true because the thermodynamic properties of helium permit operation at weight flows and nozzle spouting velocities similar to those for typical warm gas systems. Helium also offers the advantages of better low temperature characteristics and smaller valve sizing. Nitrogen is usually easier to seal than helium and is less expensive. Dichlorodifluoromethane gas has been used in a few applications and compressed air/oxygen systems are used in aircraft applications.

b. Container: The container used to store the gas at high pressure (3000 to 10 000 psi) (2000 to 70 000 kPa) is usually made of steel, although filament-wound fiberglass has been used in some applications. The container may be designed in the shape of a sphere, cylinder, helix, or toroid depending upon envelope allowances. Spheres and cylinders are usually the most economical. Generally, the end closure or diaphragm is either welded in place or sealed through the use of a metal gasket.

c. Actuator: The actuator consists of a "one-shot" device that ruptures the container diaphragm upon command. The command is usually an electrical signal that powers a pyrotechnic or mechanically operated ram. In some applications, shaped charges are used to rupture the diaphragm. The actuator must have sufficient power to rupture the pressurized diaphragm in a short period of time (usually in the order of milliseconds) and assure the minimum flow area required for output demands.

d. Pressure Reducer: The pressure reducer is usually a pressure regulator that maintains a virtually constant supply gage pressure to the system over the range of system flow rate demand and from the maximum bottle pressure to the minimum usable bottle pressure. Since the minimum usable bottle pressure is the required system operating pressure plus the pressure drop across the reducer, an important design consideration is the minimum reducer pressure drop at maximum flow demand. In some systems, a small operational range beyond this ideal minimum can be accepted with some performance degradation.

   Another critical design point in the reducer area is its capability to withstand the initial surge of inlet pressure that is ported directly from the container. This requires close attention to "0-ring" clearance design. Reducers usually consist of a spring-loaded valve and may be designed with single or double sensing areas and with or without integral relief valves. The double sensing area allows for greater reduced pressure accuracy and the relief valve ports excessive regulated pressure surges overboard.

7.4 Sizing the Container

The fundamental problem in sizing the internal volume of a gas storage container is determining the minimum mass of gas required to complete the prescribed duty cycle. This can be simply stated as shown in Equation 1:

$$M_{gas}\ \text{required} = M_{gas}\ \text{Out} + M_{gas}\ \text{remaining} \quad \text{(Eq. 1)}$$

The mass of the gas remaining is defined as that which is in the container when the minimum specified design pressure is reached and is, therefore, unavailable to do useful work. As is shown in the representative blowdown curve in Figure 1, the gas in the container is only useful down to the regulated output pressure level. In addition, Figure 1 shows that the container must be sized for the lowest operating temperature conditions and stressed to meet the highest operating temperature conditions.

The sizing requirements then are based on the minimum operating pressure and temperature and on the operating time and flow rate.

Equation 1 can be rewritten as shown in Equation 2:

$$M_{gas}\ \text{required} - M_{gas}\ \text{remaining} = M_{gas}\ \text{Out} \quad \text{(Eq. 2)}$$

or

$$\Delta M_{gas} = V_c\,(\rho_o - \rho_f)$$

where:

ρ_o = Initial container gas fill density (lb/in^3) (kg/m^3)

ρ_f = Final gas density (lb/in^3) (kg/m^3)

This simply states that the change in gas mass (Δm ~ lb or kg) within the container during the blowdown process is equal to the volume of gas in the container (V_c ~ in^3 or m^3) times the change in container gas density (ρ_o - ρ_f).

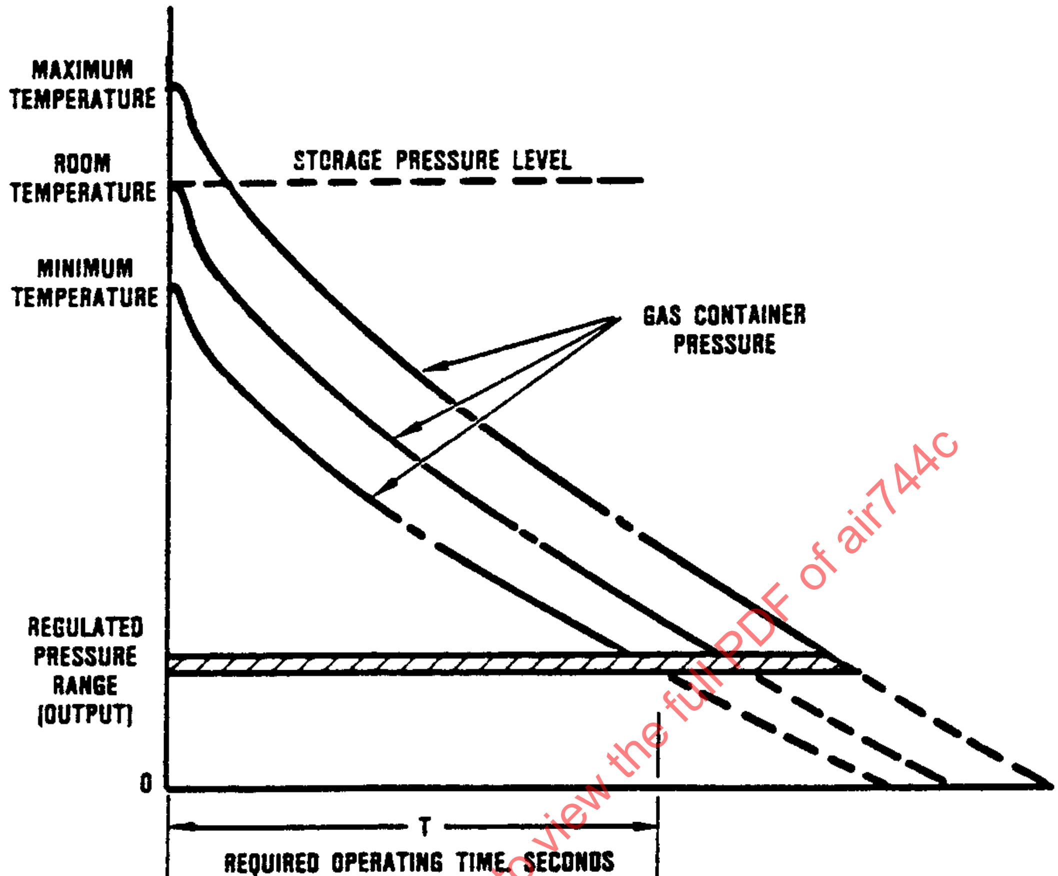

FIGURE 1 - REPRESENTATIVE TRACES OF STORED GAS TIME VERSUS PRESSURE DURING OPERATION

The gas density during the blowdown process is usually taken as the average density (ρ_{avg}) at regulated output pressure from time zero to the end of the required operating time.

Using Figure 2 as an example, it can be seen that a container filled to 7000 psi (48 000 kPa) at 460R (256K) will have a density (ρ_o) of 0.0167 lb/in^3 (462.3 kg/m^3) (point A on curve).

If the lowest ambient temperature operating condition is 400R (222K), then the starting pressure of the gas will be 5500 psi (38 000 kPa) (Point B). If the blowdown process then takes place at a regulated discharge pressure of 1000 psi (6895 kPa), then the final density (ρ_f) on an isothermal expansion basis would be 0.0039 lb/in^3 (108 kg/m^3) (Point C). Since the gas blow-down does involve a combination of cooling due to expansion and heating due to heat transfer effects, the true final density of the gas lies somewhere to the left of the 400R (222K) point on the 1000 psi (6895 kPa) line. Assume that the final temperature of the gas is 325R (181K), then the true final density (ρ_f) is 0.0056 lb/in^3 (155 kg/m^3) (Point D) and the average density (ρ_{avg}) of the gas discharged at 1000 psi (6895 kPa) during the process is 0.00475 lb/in^3 (131.5 kg/m^3) (Point E).

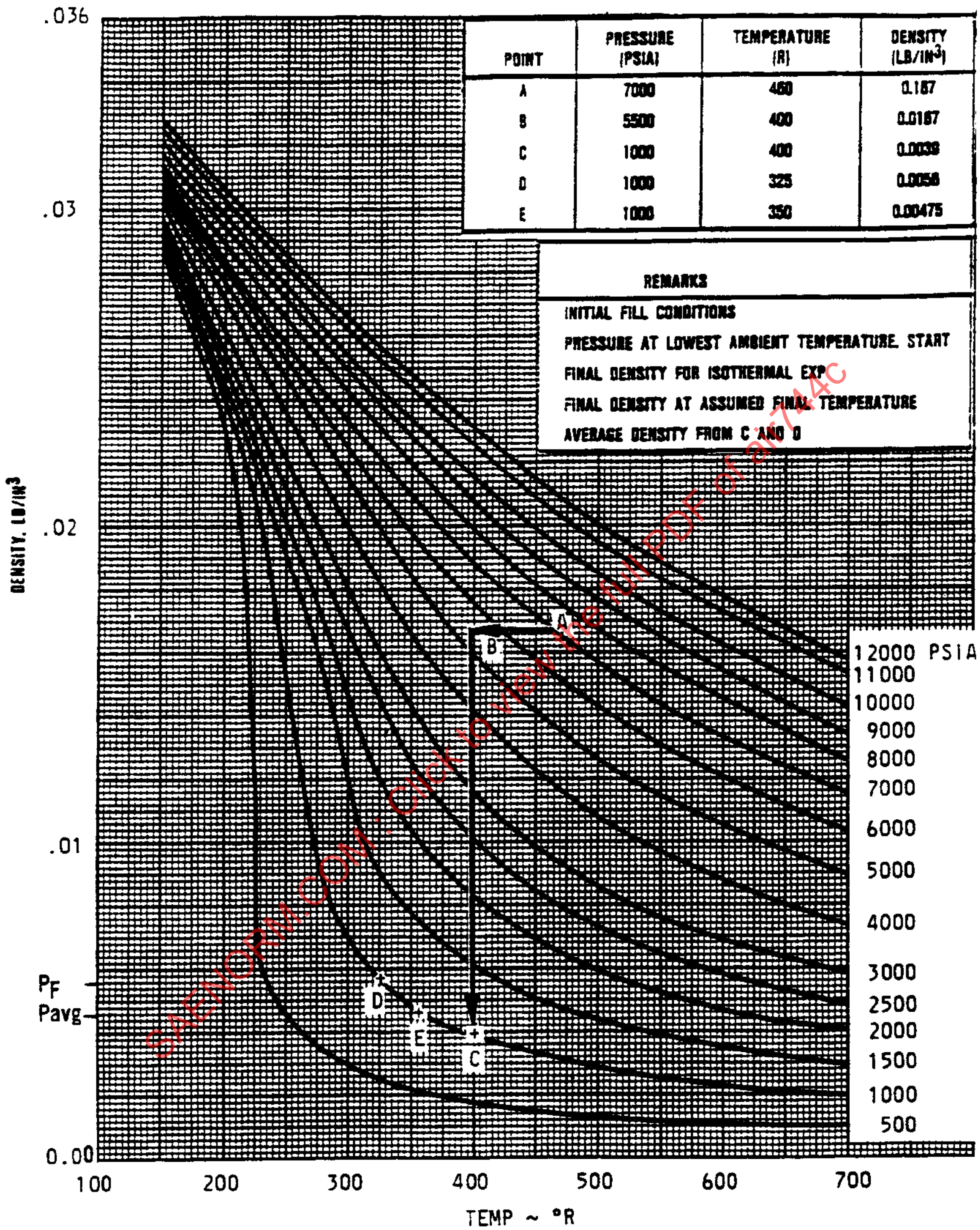

FIGURE 2 - DENSITY OF NITROGEN VERSUS TEMPERATURE
(AT VARIOUS PRESSURES IN PSIA)

From Equation 2 is Equation 3:

$$V_c = \frac{\Delta M_{gas}}{\rho_o - \rho_f} \qquad \text{(Eq. 3)}$$

Assume a flow rate of 10 in^3/s (1639 x 10^{-7} m^3/s) at 1000 psi (6895 kPa) (1639 x 10^{-6}m^3/s) for 10 s was required (38 SDFM), then (see Equation 4),

$$\begin{aligned} V_c &= \frac{(10)(10)\ \rho_{avg}}{(\rho_o - \rho_f)} \\ &= \frac{(100)(0.00475)}{(0.0167 - 0.0056)} = \frac{0.475}{0.0111} = 42.79 \\ V_c &= 43 \text{ in}^3 \end{aligned} \qquad \text{(Eq. 4)}$$

Container designs require a wall thickness and weld efficiency sufficient to withstand an internal pressurization of some multiple of charge pressure. Charged gas containers that will be transported must also comply with Department of Transportation (DOT) requirements as specified in the Code of Federal Regulations, Title 49. The requirements include design, material, testing, marking, and inspection details. Also, containers must pass a fire test without bursting. DOT design testing and inspection requirements are markedly different for flight weight containers that are refillable or nonrefillable. In general, common requirements are that AISI4130 material must be used and proof and burst tests must be performed. Specifications for refillable containers (such as DOT 3HT) require that the cylinders be seamless and be able to pass a cycling test. All DOT requirements are waived if containers are shipped uncharged or under a U.S. Government bill of lading.

7.5 Advantages

High reliability in both duty cycle requirements and storage are the main advantages. Actual data on 7000 psi (48 000 kPa) helium and nitrogen charged containers has verified storage times in excess of 8 years. Compared to other types, the reliability advantages of stored gas power sources are obvious when considering that there is usually one moving part (that moves only once) in the actuator and one moving part in the reducer. Also, once the container has been designed to accommodate the amount of gas necessary for the lowest operating temperature, duration time problems are minimal. Cleanliness is another advantage and simplicity of design offers cost competitiveness for many applications. The tactical weapons application "round-of-ammunition" concept is achieved through the ability to store the required gas in a sealed container that has no moving parts or elastomers. During system storage periods, the container can be weighed to verify retention of stored gas.

7.6 Disadvantages

Since all of the system power is stored within the container and the specific power of cold gas systems is relatively low, problems may arise in providing the required container envelope in restricted designs.

Precautions must be taken in the handling and storage of high pressure gas containers. One potential improvement that requires further development is that of heat addition. Since the blowdown process in the gas bottle causes cooling of the gas and a loss of efficiency, further work is required to prove heat addition without overheating which might cause an explosion. It is also possible that some heat transfer will occur from the hardware in the system (container, lines, and components) which are at ambient temperature and the cold gas inside. If a simple, economical means could be used to add heat to the containers during the blowdown process, then more power would be available for useful work.

8. ENGINE BLEED SYSTEMS

8.1 Description

Engine bleed air is usually extracted from two available stages. The use of three or more stages to minimize engine bleed air penalty is impractical due to inherent engine design characteristics. Bleed air is normally defined as "high pressure" air extracted from the compressor section of a turbine engine. The term "high pressure" embraces compressor and bleed systems used for engine starting, auxiliary power, anti-icing, air-conditioning, and other services. Pressures may range to 200 psig (1380 kPa) and 1150 °F (621 °C) in present-day aircraft. SAE Aerospace Applied Thermodynamics Manual is an excellent guide for turbines and air distribution.

a. Engine Design Parameters/Philosophy: The basic engine is designed for no utility bleed and industry practice is to design the compressor with a specified degree of margin. The engine is then uprated for operation with no bleed or extraction; hence, there may be no apparent engine weight savings if the bleed requirement is equal to the uprating. To extract bleed air from an engine it is necessary to install manifolds and open passages to the specific compressor stages required. The basic engine is designed with baseline manifolding for both strength and potential surge bleeding. The weight required to add normal bleed components is, therefore minimal (e.g., 5 to 10 lb (2.25 to 4.5 kg)). However, adding a bleed system can have a significant impact on aircraft weight (Reference Table 4).

TABLE 4 - ADVANTAGES AND DISADVANTAGES OF BLEED AIR APPLICATION

Advantages	Disadvantages
The accessory can be mounted remotely from the engine compartment.	Lower efficiencies than competitive power extraction methods (shaft drives).
Bleed air can be cross-utilized in case of engine failure.	Control problems including slow response during sudden load requirements.
Limited accessory power can be generated during an "engine out" windmilling condition.	Can have an engine-component mismatch.
Intermittent operation with shutoff valves controlling duty cycle.	Overall fuel consumption will usually be higher than shaft drive systems.
Air-turbine exhaust may be used for other purposes.	Ducting requires considerable volume for installation.
	High temperature air can create problems due to leakage.
	System weight is generally higher.
	Total bleed available is limited and many other systems will compete for this air; therefore, practical applications may be limited to very small power requirements or emergency systems, or intermittent operation.

Adjacent compressor stages are difficult to bleed because of the physical requirement for separate external manifolds. Engine length could be extended to provide the required space, but this would result in a significant weight penalty.

Some stages are essentially buried and would be extremely difficult to bleed. This would include stages adjacent to the last fan stage and those stages under the variable geometry (stator) controls. Any consideration of these stages would result in weight penalties.

b. Engine/System Interface Considerations: The engine design and installation can impose several constraints on power derived from bleed gas extraction. Factors such as bleed port locations, duty cycle requirements, envelope restraints, and engine output should be considered in the design selection phase for comparison to other available power extraction methods. Figure 3 illustrates engine/systems interface requirements and their impact on an engine.

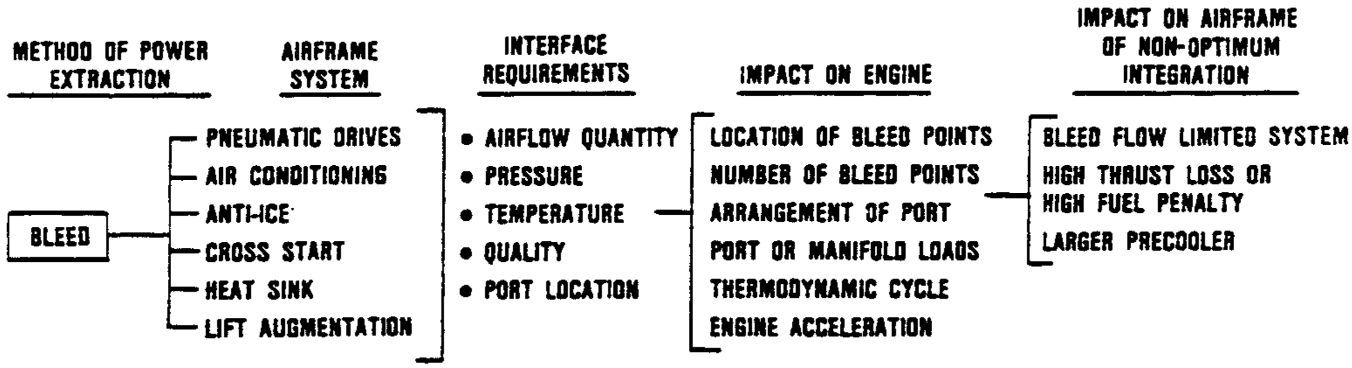

FIGURE 3 - ENGINE/SYSTEMS INTERFACES AND THEIR EFFECTS

8.2 Applications

In general, bleed air utilization is suitable for application wherever auxiliary power is required. Present bleed air applications include engine starting, thrust reversers, cabin air source, cabin air-conditioning, equipment cooling, engine and airframe ice protection, powered doors and stairs, leading and trailing edge actuators, lift devices, air motor/ turbines, and thrust vectoring.

System operation and sizing is dependent upon power level availability throughout the aircraft's flight envelope and the design of the specific subsystem to satisfactorily perform the required functions. Bleed air can be used to furnish power to any subsystem that can be powered by an accessory transmission system (shaft power extraction), electric motors, or hydraulics.

A limiting factor in bleed air application (pneumatic turbine application) is that efficiency can be lower than that of a direct "hard" driven accessory transmission system. However, where energy requirements are small and intermittent, this disadvantage can be negligible. Other uses including direct pressure flow energy convertors must be assessed against competing power extraction on an overall system efficiency basis. (See Table 4 for application information.) Also reference SAE J1775.

8.3 Systems and Component Detail and Description (General)

Bleed air is extracted from the selected compressor stage(s) by a suitable duct affixed to a plenum at this stage. The quantity of air that can be bled is limited by engine operating restrictions generally to values between 1 to 8% of total engine inlet airflow. In high capacity bleed systems, it is advisable to provide a flow limiting device or choke at or near the bleed ports to prevent excessive bleeding in case of control malfunction or duct damage. In addition, check valves should be installed at each engine (multiengine system) to prevent reverse flow of air into an inoperative engine. Isolation valves and temperature sensors may be installed in air ducts for detecting and control of systems in case of leakage. Duct velocities (air) should be kept below 0.25 Mach number in order to prevent excessive pressure losses.

Bleed air ducts should be well insulated to obtain optimum efficiency and to protect adjacent aircraft structure. Provisions for thermal expansion of bleed air ducts is mandatory and can be accomplished by inserting bends in strategic locations to obtain a structurally stable system. Flexible bellows, swivels, or gimbals can also be used to allow for duct expansion in case of space limitations. Trade studies including duct air velocities, insulation, and weight should be performed. ARP699 and AIR1168 should be consulted for details.

a. Power Availability: A method for computing the availability of power (horsepower) is presented in Table 5 to furnish a guide or baseline in assessing bleed air utilization from a typical engine. This method establishes the theoretical horsepower as a function of altitude and Mach number relative to temperature, pressure, mass flow, and enthalpy. The total available airflow can be used for environmental control system assessment, while the head drop is used for design of turbines motors. Other areas of investigation should include appraisal of various Mach numbers to include:

TABLE 5 - COMPUTATION OF POWER AVAILABILITY

1. Steady state flow
2. Isentropic expansion (S_i-S_σ) (not realized even on a variable area stator machine)
3. No change in potential energy
4. Inlet velocity, disregarded (assumed to be zero) since no information given
5. Exit properties of the air are in equilibrium with the surroundings
6. Disregarded magnetic, electrical, and surface effects
7. Chemical equilibrium:

Equation (1): Available horsepower = $W = \frac{60\ \Delta\ W_T}{42.4}$

W_T = airflow = $\frac{lbm}{s}$

1 HP = 42.4 $\frac{Btu}{min}$

1 min = 60 s

Equation (2): Auxiliary Turbine Pressure Ratio = TPR = $\frac{\text{Bleed Air Pressure}}{\text{Atmospheric Pressure}}$ (Absolute)

T_i - Find in air tables (inlet air temperature) - °R (Keenan & Kaye)

h_i - Find from air tables at T_i (inlet enthalpy - $\frac{Btu}{lb - mass}$)

P_{r_i} - Note at T_2 condition (inlet relative pressure ratio) = P_{r_i}

P_{r_o} - $\frac{P_{r_i}}{TPR}$

P_{r_o} - Find this value then note h_o (exit relative pressure ratio)

Find: $\Delta h = \Delta$ (negative change in enthalpy)

Substitute values for final HP into Equation (1)

1. The highest and lowest temperature and pressure encountered in the flight regime

2. Thrust and fuel penalties for bleed extraction at takeoff and cruise, respectively

Table 6 and Figure 4 provide typical data to be used for establishing engine bleed air energy levels.

b. Bleed Air Characteristics: Figure 5 provides typical bleed air pressure, temperature, and flow characteristics available from a JT9D-3A engine. Also shown are effects of Mach number and altitude on the parameters. Of primary airflow, 13% was available for bleed air extraction up to 40% MCT and 5% was available at higher thrust conditions. Pressure and temperature data are plotted for high and low pressure bleed ports of the engine, as well as the combined bleed flow from both ports.

To determine the application potential, energy availability must be determined throughout the duty cycle of the secondary power element to assure power extraction/utilization compatibility. This can be accomplished by obtaining data like that in Figure 5 from the engine manufacturer and deriving a power level curve throughout the aircraft mission. Additional design evaluation is required to assess the effects of air bleed extraction on engine operation (thrust, match, and TSFC).

TABLE 6 - TYPICAL DATA FOR AIRCRAFT ENGINE JT3D-3B

Maximum Altitude, ft	T_2 Temperature In, °R	P_1 Pressure In, psi	W_T Flow In, lbm/s	h_2 Enthalpy In, Btu/lbm	P_{r1} Pressure Ratio In, psi/psi	P_{re} Pressure Ratio In, psi/psi	P_e Pressure Out, psi	h_e Enthalpy Out, Btu/lbm	Δj Enthalpy, Btu/lbm	W Power Available, hp
High Pressure	High Pressure	JT3D-3B	JT3D-3B	Standard Day	Standard Day	5.5% Bleed Idle to MCT	5.5% Bleed Idle to MCT	5.5% Bleed Idle to MCT	5.5% Bleed Idle to MCT	5.5% Bleed Idle to MCT
5 000	1120	150	9.6	271.03	18.604	1.522	12.23	132.66	138.37	1878
15 000	1072	106	8.0	258.97	15.842	1.240	8.296	124.99	133.98	1515
25 000	1030	75	6.2	248.45	13.692	0.995	5.452	117.32	131.13	1151
35 000	980	57	4.4	236.02	11.430	0.693	3.4585	105.83	130.19	810
Low Pressure	Low Pressure	12th JT3D-3B	12th JT3D-3B	Standard Day	Standard Day	2% Bleed	2% Bleed	2% Bleed	2% Bleed	2% Bleed
5 000	940	75	3.6	226.11	9.834	1.604	12.23	134.58	91.53	467
15 000	900	60	2.9	216.26	8.411	1.163	8.296	122.70	93.56	384
25 000	870	45	2.2	208.90	7.450	0.903	5.452	114.15	74.75	295
35 000	850	32	1.5	204.01	6.8560	0.741	3.4585	107.80	96.21	204
Low Pressure	Low Pressure	9th JT3D-3B	9th JT3D-3B	Standard Day	Standard Day	2% Bleed	2% Bleed	2% Bleed	2% Bleed	2% Bleed
5 000	803	35	3.6	192.54	5.600	1.96	12.23	142.60	49.94	253
15 000	780	27	2.9	186.94	5.051	1.552	8.296	133.25	53.69	221
25 000	740	20	2.2	177.23	4.193	1.145	5.452	122.11	55.12	171.5
35 000	705	15	1.5	168.77	3.533	0.814	3.4585	110.80	57.97	123

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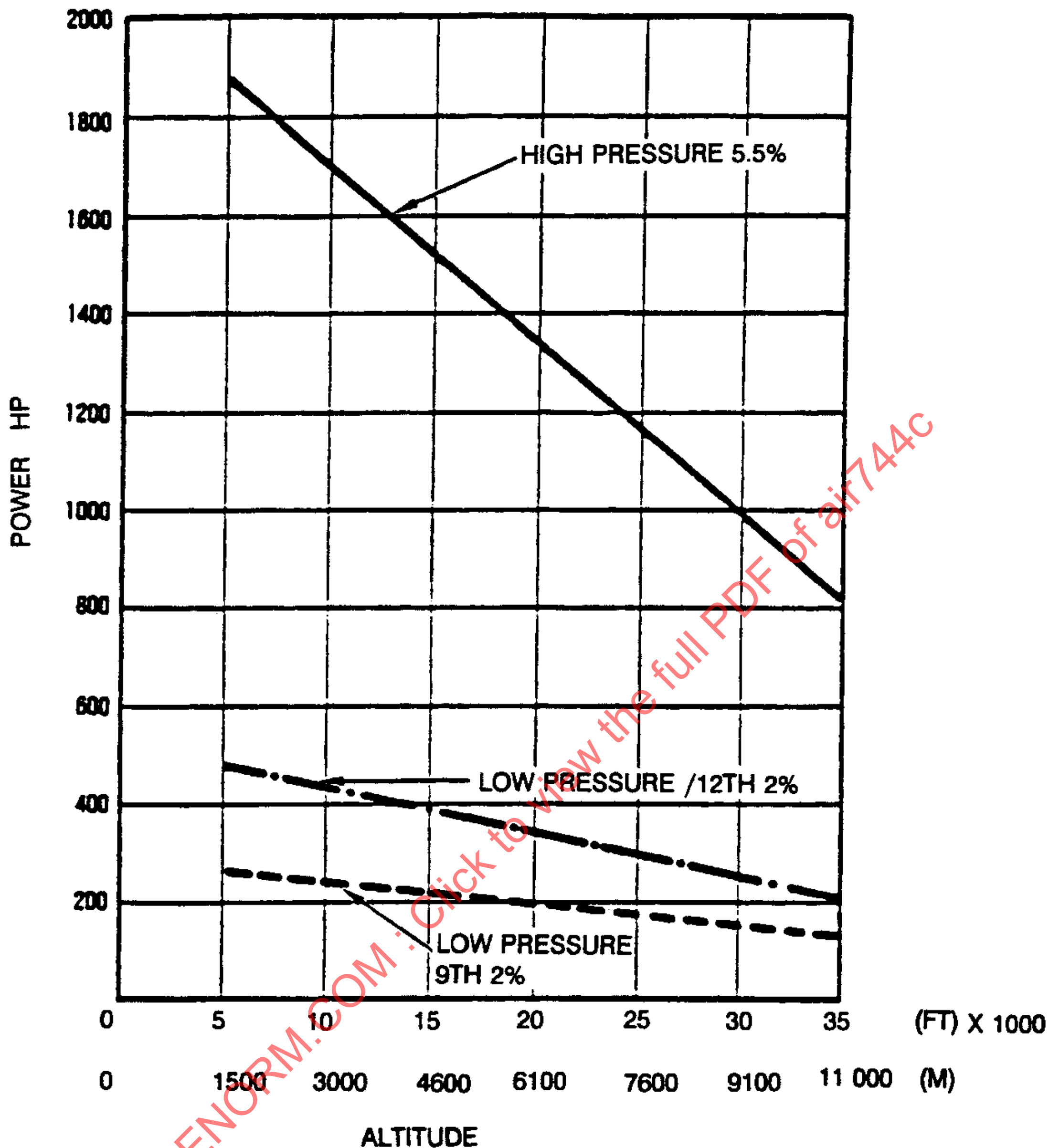


FIGURE 4 - BLEED STUDY OF THE JT9D-3A ENGINE,
STANDARD DAY CONDITIONS

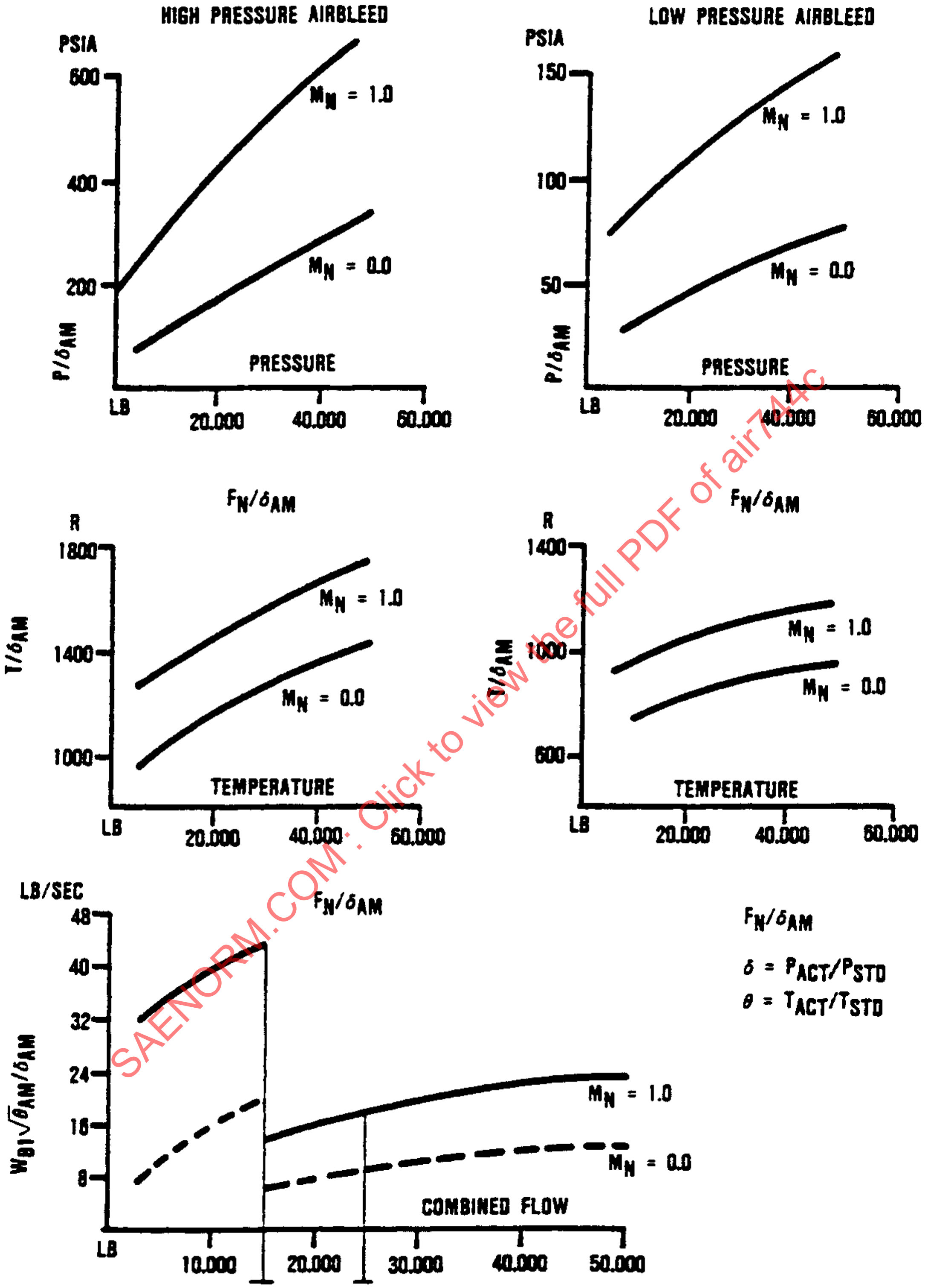


FIGURE 5 - BLEED AIR CHARACTERISTICS OF THE JTD9D-3A ENGINE

c. Engine Performance Consideration: The effect of air bleed on engine thrust during various conditions must be evaluated. This includes power extracted versus thrust losses to evaluate system efficiency. Conditions to be evaluated include takeoff, climb, cruise, descent, and landing. The same investigation must be conducted relative to specific fuel consumption versus extracted power for the same flight conditions. The current trend is to reduce engine noise by increasing engine bypass ratios (i.e., ratio of fan airflow to the primary gas generator airflow). This can effectively reduce engine efficiency (increasing the percent loss) and results in engine sensitivity to power extraction as a function of bypass ratio. Figure 6 illustrates typical changes in thrust and specific fuel consumption as the bypass ratio increases. This must be evaluated and included in the overall application for air bleed extraction. AIR1168, Part 31, should be consulted.

d. Alternative Pneumatic Pressure Sources: As engine performance demands increase, the power extraction from the compressor has become a major consideration as the performance and fuel consumption. The recent trend is to add more pneumatic accessories which can compound the problem. The use of a turbo supercharger (compressor driven by a power takeoff, (PTO)) on a high bypass fan engine could be a less expensive and more efficient way to provide high pressure air. The use of a high pressure pneumatic compressor driven by an AC motor could also be a consideration depending on the volume required.

9. RAM AIR TURBINES

9.1 Description

A ram air turbine is an aerodynamic device that extracts energy from the relative airstream produced by forward vehicle flight. The power derived is used to drive emergency or auxiliary equipment. Ram air turbines may be driven by airstreams ducted into vehicles, but the majority are stowed within the vehicle and deployed when needed directly into the external airstream. In these cases the RAT system will need ancillary equipment such as an uplock, deployment actuator and means of retracting the equipment into the vehicle after deployment. External mounting of ram air turbines is usually in the nose or aft end of a streamlined body or on struts on a vehicle lateral surface.

A typical ram air turbine consists of two or more airfoil-shaped blades attached to and rotating about a central hub, much like a propeller. Airflow passing through the turbine in a direction parallel to the axis of rotation reacts with the airfoils, generating blade forces that result in the development of torque and power. Most ram air turbines also contain governor systems to maintain rotational speeds within predetermined limits while output requirements and flight conditions vary over a wide range.

Ram air turbines are reliable when operated within their design flight envelopes and are lightweight sources of shaft power, with outputs from about 0.4 hp/lb to more than 3 hp/lb, depending on design flight speed.

9.2 Applications

Ram air turbines can be used in any application where it is useful to extract shaft power from the airstream. Systems typically provide shaft power to pneumatic, hydraulic, or electrical components and have been used on aircraft, missiles, external pod systems, tow targets, and target drones. Ram air turbines have been built in a wide range of ratings and sizes. The smallest systems supply less than 1 W output signal for instrumentation equipment, while the higher rated systems provide as much as 100 hp (75 kW). Units have been produced with blade tip diameters up to 64 in (163 cm). Flight envelope speed requirements range from approximately 70 knots (130 km/h) to Mach 2.2. Altitude requirements range from sea level to approximately 70 000 ft (20 000 m).

The ram air turbine mechanical design, size, and operating characteristics required for a specific application depend on all of the following items, which should be determined in advance of design or selection:

a. Flight envelope: airspeed and altitude range

b. Temperature range: cold, standard, or hot day

c. Installation aerodynamic interference: free stream interference including pitch and yaw effects

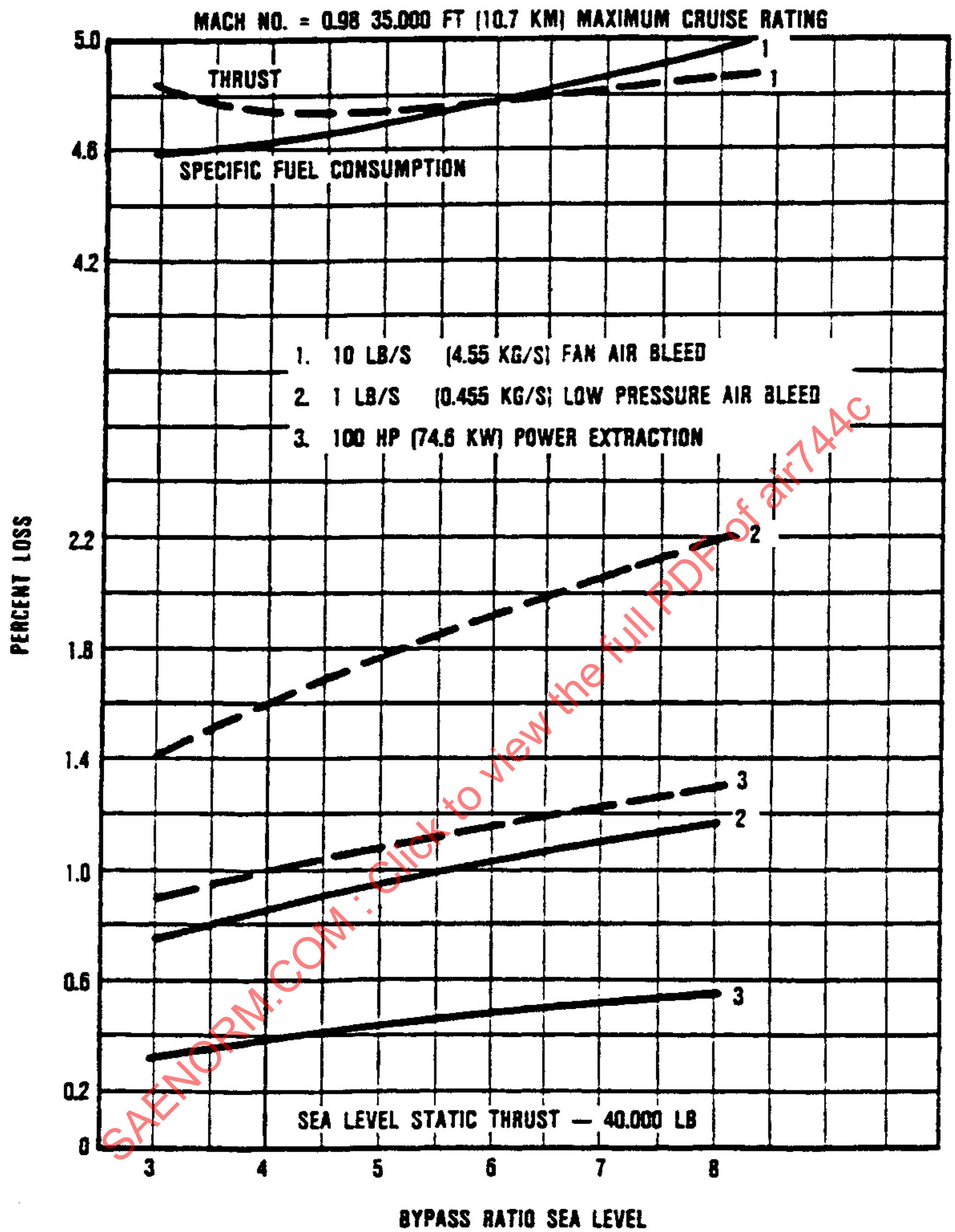


FIGURE 6 - SENSITIVITY CURVES FOR THE A1SA BPR-280024 ENGINE

d. Drag requirements

e. Load characteristics: power requirements and applicable airspeeds

f. Start-up torque and acceleration time requirements with applicable airspeeds

g. Speed control: steady state and transient requirements

h. Installation envelope

i. Ejection system and door attachment/loads

j. Structural requirements: Mount stiffness and adequacy to meet maximum load conditions

k. Checkout requirement and methods

l. Life and reliability requirements

m. Effects of handling, icing, volcanic ash, stability, weight, and the environment

n. Compatibility of ancillary equipment, pumps, valves, generator, controls, etc.

p. Retraction loads for deployable systems

q. Vehicle maneuver loads

r. Door size and aerodynamic loads for deployable RAT systems

s. Deployment times for deployable RAT systems

Maximum flight limit capability of the turbine system is usually the adverse effect of high temperatures on the driven components and/or adverse in-flow angles (pitch and yaw) that induce, at high airspeed, significant alternating bending moments in the blade section. These structural requirements must be accounted for in the design.

9.3 Performance Characteristics

The performance of a ram air turbine in a free airstream is a function of airstream conditions, turbine blade size and aerodynamic design, and governor characteristics. Additionally, installation effects often significantly modify the airstream, degrading performance.

The maximum theoretical energy that can be extracted from the airstream is 59.2% for an unshrouded machine and 38.49% for a ducted unit without diffusion. Diffusion will increase the ducted unit performance but normally will not increase it above free stream unit performance when both systems have the same maximum diameters, i.e., free stream turbine diameter equals maximum diffuser diameter.

Due to losses, turbine output power of an unshrouded turbine in practice is approximately 70% of these theoretical values at the design point and considerably less at off-design conditions. Sometimes a design may be compromised to provide best performance at two design points by designing for some intermediate condition. This usually occurs at low airspeeds and the problem quickly disappears for small increases in airspeed because of the increased energy available to the turbine.

A power coefficient is employed in computing ram air turbine performance capability. The maximum theoretical value of this component for free stream, unshrouded turbines is $\Omega_i = 0.296$.

The power coefficient is defined as:

$$\Omega = \frac{hp \times 550}{\rho \times A \times V_o^3} \left(= \frac{kw \times 1000}{\rho \times A \times V_o^3} \right) \quad \text{(Eq. 5)}$$

where:

hp = Horsepower output (kw_i = ideal kilowatt output)

Ω = Power coefficient

ρ = Density of air, slugs per ft^3 (kg/m^3) (0.002378 $slug/ft^3$ [1.225571 kg/m^3] for standard conditions, sea level)

A = Blade swept area, ft^2 (m^2)

V_o = True airspeed, ft/s (m/s)

The shaft horsepower attainable from a free stream ram air turbine is therefore:

$$hp = \frac{\Omega \times A \times \rho \times V_o^3}{550} \left(kw = \frac{\Omega \times A \times \rho \times V_o^3}{1000} \right) \quad \text{(Eq. 6)}$$

Several items will affect the actual value of the power coefficient, such as hub size, blade aerodynamics, turbine diameter, afterbody effects, installation effects, angle of attack, turbine rpm, altitude, and airspeed. Various data from past units show a general trend of obtainable design point power coefficient values as follows (note in Table 7 that these values apply to the turbine and do not account for the efficiency of the driven components):

TABLE 7 – TURBINE POWER COEFFICIENTS

Turbine Diameter ft	Turbine Diameter m	Ω Power Coefficient Sea Level, Free Airstream, Standard Conditions	Ω Power Coefficient Installation Effects, etc. Reduction
1.0	0.3	0.16	0.11-0.14
1.5	0.46	0.21	0.17-0.19
2.0	0.61	0.23	0.18-0.21
2.5	0.76	0.25	0.20-0.23

The power coefficient of equation 5 represents the design point condition only. A characteristic curve for a given ram air turbine is shown in Figure 7 for the power coefficient versus N/V_o (where N is the turbine rpm and V_o is true air velocity in knots).

The fine pitch blade angle is generally the blade angle that will obtain the highest value of Ω. The blade solidity is chosen so that the curve peaks just to the left of the design N/V. When evaluating ram air turbine performance at other points in the flight envelope, it becomes necessary to calculate the new N/V_o and required value of Ω. From Figure 7, it is obvious that velocity (airspeed) has the greatest effect on the power output of the turbine. As V_o increases, the value of N/V_o decreases, and the turbine blades must be positioned at coarser blade angles, as shown. The attainable power coefficient decreases, but output power increases rapidly, anyway, due to the V_o^3 dependence of the airstream power. As long as the turbine operates to the right of the peak and below the power coefficient line, the turbine will deliver power and will not stall.

Previous discussion has related turbine aerodynamic effectiveness to the ability to extract a percentage of the ideal free stream energy. Turbine system efficiency is the ratio of output shaft power to input power (power required to move the system through the airstream). Turbine input power is drag (lb [kg]) x velocity (ft/s [m/s]). The lowest drag configuration is not the same as the unit that has the highest power coefficient, Ω, for its given diameter. The drag improvement that might be experienced by a larger diameter turbine, providing the same power (reduced Ω is in practice relatively small. As a result, design emphasis is on the smallest blade diameter for envelope, weight and structural considerations.

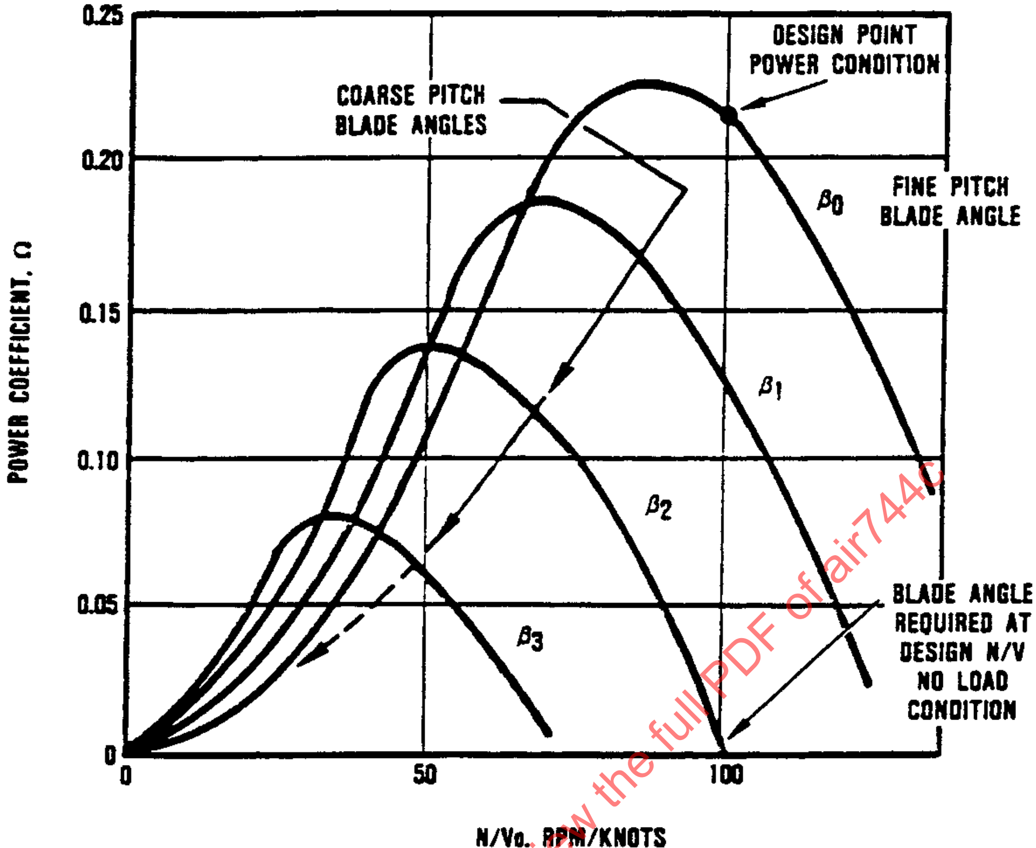


FIGURE 7 - GENERALIZED TURBINE POWER COEFFICIENT CHARACTERISTICS VERSUS N/V_O FOR A FREESTREAM TURBINE

Ram air turbines utilize aerodynamically designed blades for efficient extraction of power from the airstream, converting airstream energy to rotary speed and torque. The torque-speed characteristics can be selected by the blade design, the number of blades, blade chord, length, angle, and airspeed/altitude design point.

Solidity (defined as the total blade area of all the blades divided by the rotor swept area) is established by the condition in the flight envelope at which maximum turbine power extraction efficiency is desired. The aerodynamic theory of ram air turbines requires that, as the design airspeed increases, the solidity must increase for the same turbine rotational speed. For instance, a turbine designed for 12 000 rpm and 120 knots (222 km/h) true airspeed may have two blades with rather short average chords. Another design, for 200 knots (370 km/h) true airspeed and 12 000 rpm, will require either additional blades or increases in the blade chord of a two-blade design. In general, it is preferred to increase the number of blades and maintain a high airfoil aspect ratio except in the case of deployable ram air turbines when a two bladed design can be deployed through a smaller opening than a multi-bladed machine.. Increased solidity is also required if the design rotational speed is reduced at the same airspeed.

An important effect that must be taken into consideration in certain designs is the effect of high altitude flight. As altitude increases, temperature and sonic velocity decrease. In the case of high blade tip velocities, the airfoil may reach transonic speeds at the minimum aircraft velocity at the altitude condition. The effect is reduced airfoil lift and increased drag, resulting in degraded performance. Reductions in power coefficients of approximately 25% may be encountered. These Mach number effects become noticeable with blade tip speeds over approximately 700 ft/s (213.4 m/s). The effects are minimized through the use of high speed airfoil sections or maintaining a tip speed below the critical speed.

Nearly all current day ram air turbines include proportional governing mechanisms to maintain turbine shaft speed, and therefore, component stresses due to centrifugal force, within acceptable ranges. A mechanical governor with proportional governing can be designed simpler and more reliable than the integral hydraulic type. The design of the governor depends upon the range of flight speeds in the design flight envelope and upon the speed control accuracy required by the driven component. Although governor performance is often specified in terms of steady-state characteristics, transient response and stability characteristics must be considered and specified for transient loads over the entire flight envelope.

The most common governor systems operate on the principle of positioning the blade to provide the lift necessary to maintain specified rotational speed. This arrangement provides the least drag by extracting only the airstream energy required to support the load.

Governor types employed are:

a. Fully mechanical, variable pitch blades

b. Mechanically sensed and hydraulically controlled variable pitch blades

c. Electrically sensed and hydraulically controlled variable pitch blades

d. Fully mechanical, fixed blades, variable inlet guide vanes

e. Fully mechanical, fixed blades, variable exit area

The most common governor types are mechanically or hydraulically actuated variable pitch blades. Most simple machines will provide ±15% of nominal shaft rotational speed control. This control is normally adequate for hydraulic pump drives or equivalent systems.

Speed control accuracy of ±5% of nominal shaft is normally required for AC electric drives providing relatively constant frequency limits of 380 to 420 Hz. However, more recently variable frequency systems allow a wider governing range.Tighter control is accomplished using increased energy governor systems having a higher level of sophistication. Systems have demonstrated ±1.0% shaft speed control. Very close speed control can produce instability and care must be exercised in the design to provide stability margin and transient characteristics compatible with application requirements.

Installation effects are probably the most serious cause of ram air turbine performance degradation. In determining power coefficients, turbines are generally wind tunnel tested in a free airstream with no installation effects. The turbine experiences uniform airflow, producing constant velocity across the face of the disk. Airflow disturbances by the installation will degrade performance and must be accounted for by increased performance margin when sizing the turbine. The turbine should be installed in a location where the free stream is least affected by the aircraft.

Installation conditions to be considered may include:

a. Inlet airflow and afterbody disturbance of landing gear, flaps, dive brakes, air scoops, and mounting struts

b. Boundary layer effects

c. Performance effects due to yaw/pitch

d. Door and compartment effects on emergency systems

Performance degradation due to combinations of pitch and yaw result when the flow into the turbine is nonparallel to the turbine center of rotation. At the landing condition, high pitch angles are normally encountered. Power output degradation due to the combined pitch-yaw angle varies approximately as the third power of the cosine.

Free stream performance is attained in pod-nose-mounted systems where installation effects are minimal.

Ram air turbine starting characteristics are determined by the turbine torque developed at below rated shaft rotational speeds, the tare losses within the drivetrain, and the resistive torque of the driven component.

Figure 8 shows turbine torque characteristics as a function of shaft rotational speed for two turbines of high and low solidity. The airspeed and blade swept area are the same for both machines.

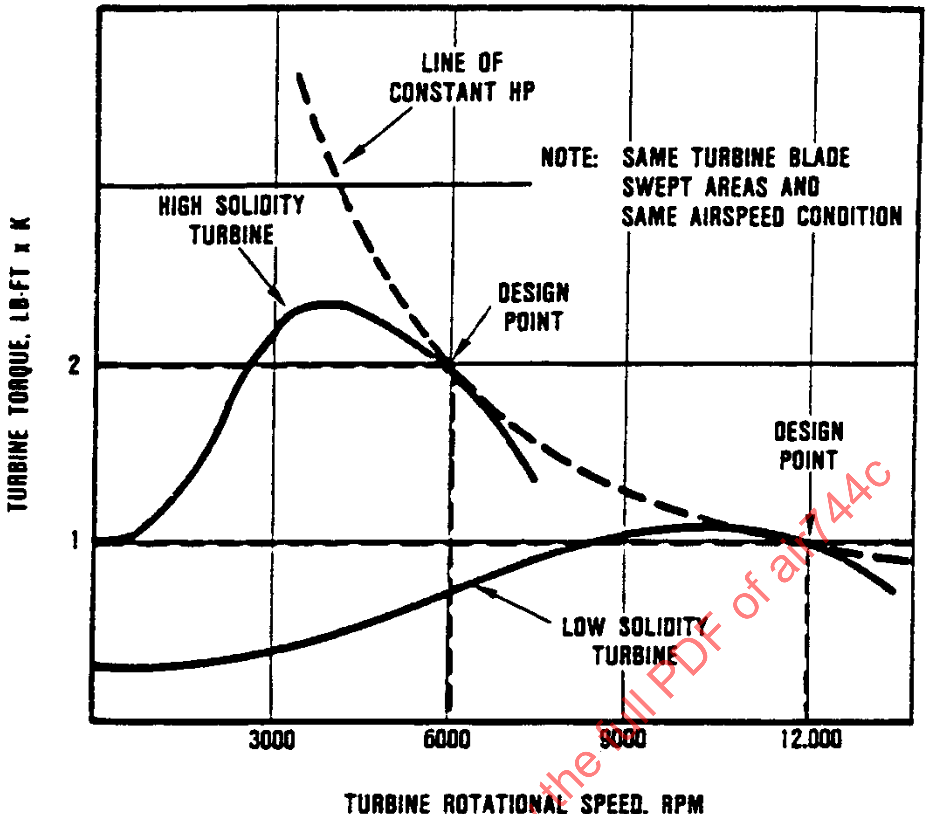


FIGURE 8 - GENERALIZED TORQUE CHARACTERISTICS FOR HIGH- AND LOW-SOLIDITY TURBINES HAVING THE SAME BLADE SWEPT AREA AND SAME OPERATING AIRSPEED

The low-solidity turbine "power" peaks at approximately 12 000 rpm and has relatively low starting torque characteristics. The high-solidity turbine "power" peaks at approximately 6000 rpm and has relatively high starting torque characteristics. The low-solidity turbine is theoretically more efficient than a high-solidity machine. However, in practice this is not always the case because of blade tip losses, Mach number effects, etc.

Rapid acceleration requirements are normally associated with emergency power systems in which "on-line" power is required in the shortest possible time. In addition, these emergency systems often incorporate hydraulic or other components that have inherently high starting torque requirements. This is particularly true of hydraulic components at low temperature conditions. To improve turbine acceleration characteristics, unloading devices are often employed in combination with the driven equipment. Hydraulic components may also include provisions for warm bleed oil circulation from the aircraft main system to eliminate cold oil starting. For electrical systems, start up management is performed by the control unit commanding the line contactor open until the turbine has come up to the necessary speed.

The concern for low starting torque characteristics is primarily limited to low flight speed conditions. Turbine torque improves quickly for small increases with airspeed and varies approximately with V_o^2.

9.4 Advantages

Ram air turbines are best suited to applications in which sources of self-contained power are needed for extended periods of time. Ram air turbines are relatively lightweight and may be operated intermittently or continuously and at random load cycles. When properly matched to airstream conditions, the ram air turbine will be a reliable source of auxiliary or emergency power.

9.5 Disadvantages

Ram air turbines cannot, from the standpoint of energy conversion, be as efficient as obtaining power directly from an engine accessory pad. High power requirements at very low airspeeds may require an unacceptable turbine blade diameter. Ram air turbines cannot deliver significant power during aircraft stall or spin conditions.

Since checkout equipment to air drive the ram air turbine in the field is large, complex, noisy, and costly, the requirement for such checkouts can be eliminated by establishing confidence through periodic flight test deployments, or the checkout requirement may be met by defining other means to drive the turbine or by periodically backdriving the ram air turbine on the ground.

10. BATTERIES

10.1 Description

Batteries are DC electrical potential devices that provide electrical discharge rates to power any electrical power consuming device within specified voltage limits for durations on the order of seconds to hours.

Two basic types of batteries are used in auxiliary power systems: primary types, which are one-shot batteries and cannot be used more than once, and secondary units, which are capable of repeated charge-discharge cycles.

10.2 Primary Batteries

Primary batteries are further subdivided according to the manner in which electrolyte is retained during periods of nonoperation. They may be classified as reserve or nonreserve primary batteries as follows:

a. Reserve Primary Batteries: In reserve primary batteries, the electrolyte is stored in a compartment usually attached to the battery but forming a separate container, so that the cell stack is stored dry. A pyrotechnic valve is often used to permit remote activation of the battery. The reserve electrolyte system offers extremely long shelf life in the preactivated condition but adds the complexity of the activation system and the extra volume required for electrolyte storage.

b. Nonreserve Primary Batteries: In nonreserve primary batteries, the electrolyte is not stored in a separate container but is located between the positive and negative plates. According to the state of the electrolyte, they may be classified as dry cell batteries, wet cell batteries, or thermal batteries.

    1. Dry Cell Batteries: Batteries in which the electrolyte is immobilized by absorption into a gel or compounded into a paste form are called "dry" cell batteries. The use of a paste form of electrolyte or gels to immobilize the electrolyte provides handling convenience and is, therefore, commonly applied to primary batteries.

    2. Wet Cell Batteries: Batteries that are stored with a liquid electrolyte in the cells are called "wet" cell batteries. Prefilling of the battery with electrolyte so that the battery can be stored wet has advantages both in reducing the storage volume of the battery and in instantly available power output. In some cases, particularly with the newer high rate batteries, wet storage promotes undesirable chemical reaction in the cell stack during storage, thus reducing battery power or life.

    3. Thermal Batteries: In a thermal battery, the electrolyte is solid, nonconductive, and electrically inert during storage. The battery is activated by igniting pyrotechnic paper or heat pellets within the cells, causing the electrolyte to melt and become electrically conductive.

10.3 Secondary Batteries

Secondary batteries are also subdivided according to the manner in which electrolyte is retained within the battery cells. As with primary batteries, secondary batteries may be "dry" cell or "wet" cell batteries. In addition, because some types of secondary batteries (such as silver-zinc) have a relatively short "wet-stand" life, some secondary batteries are stored without electrolyte. The electrolyte is added prior to anticipated use.

10.4 Common Battery Types

There are many parameters used to categorize batteries. Examples of major categories are: primary versus secondary, reserve versus active, high versus low power density, high versus low energy density, and storage life. A general listing of battery types and characteristics is given in Table 8. It will be observed that some battery types or systems can exist in several different forms. For example, Zn/AgO can be designed and used as a secondary battery, a high energy density primary battery, or a very high power reserve battery. It should also be noted that the ranges of energy density, shelf life, etc., are sometimes very large for a given system.

TABLE 8 - COMMON BATTERY TYPES

System	Primary/Secondary	Active/Reserve	Wh/Kg	Self Disch. (wet)
Li/CFx	Primary	Active/Reserve	700	2%/yr
Li/MnO2	Primary	Active	250	3%/yr
Li/SOC2	Primary	Active/Reserve	450	2%/yr
Li/SO2	Primary	Active	280	2%/yr
Zn/C	Primary	Active	75	15%/yr
Zn/AgO	Primary/Secondary	Active/Reserve	220	10%/yr
Zn/MnO2	Primary/Secondary	Active	95	8%/yr
Zn/HgO	Primary	Active	100	4%/yr
Zn/NiOOH	Secondary	Active	60	10%/mo
Pb/PbO2	Secondary	Active	30	5%/mo
Cd/HgO	Primary	Active	50	3%/yr
Cd/NiOOH	Secondary	Active	44	5 to 20%/mo
He/NiOOH	Secondary	Active	28	25%/mo
H2/NiOOH	Secondary	Active	55	60%/mo
Ca/CaCro4	Primary	Reserve	6	no
LiM/FeS2	Primary	Reserve	25	no

10.5 Application Terminology

In determining the suitability of a type of battery for a given application, a number of characteristics must be considered. Among the most important factors are:

a. Energy Density: An important factor to consider is the amount of energy that can be packaged within the weight or volume constraints of a given application. Energy density may be expressed in terms of energy per unit mass (W-h/lb, W-h/kg), or in terms of energy per unit volume (W-h/cm^3, W-h/in^3).

b. Current Density: Current density is the current per unit area at which a given battery type can satisfactorily operate. Current density is expressed in units of amp/in^2 and amp/cm^2. Current density should be considered from the standpoint of transient current density and average current density.

   When transient loads are encountered, such as in motor start-up or other momentary high current loads, transient current density should be considered. When the load is relatively constant, average current density is important.

   Batteries with higher current density capabilities will require smaller plate areas and hence reduced cross section.

   Generally speaking, the reliability of a battery in a given application will increase if the current density is in the lower range for a given type of battery.

c. Voltage Regulation: Voltage regulation is the behavior of the output voltage of the battery under its intended load. Depending on the type of battery, output voltage may be relatively flat and constant over most of its discharge life, or it may be a steadily declining characteristic. In addition, depending on the type of battery, it may be smooth in nature or may be noisy at times, having voltage transients. The characteristics of the output voltage should be compared with the voltage requirements of the load being powered.

d. Internal Resistance Characteristics: Internal resistance of a battery causes the output voltage of a battery under a given load to be less than its no-load voltage. Depending on the type of battery, internal resistance can be relatively large or relatively small. In applications of widely varying load currents, a battery with a low internal resistance is desirable to minimize the voltage change. The behavior of internal resistance with discharge time should also be considered, since some batteries exhibit a flat internal resistance, while other batteries exhibit significant internal resistance change during discharge.

e. Aging Characteristics: Batteries exhibit varying degrees of capacity degradation with age and/or storage temperature. If the battery being utilized in a given application exhibits aging degradation, it must be sized so that the battery has adequate capacity to perform its function at the end of its planned calendar life. Environmental storage conditions also need to be carefully specified if a battery is subject to degradation with temperature.

f. Charge-Discharge Capability (Secondary Batteries): Secondary batteries may be recharged to or close to the rated capacity. The charge-discharge cycle capability is dependent upon a number of conditions such as the type of electrochemical system, depth of discharge, recharge rate, and temperature. The number of cycles can vary from several to many thousands. Self- or internal discharge is a common characteristic of secondary batteries and varies with the electrochemical composition and temperature. As the temperature increases, the self-discharge rate is accelerated. Lead-acid battery capacity is rapidly decreased if, for example, the battery is allowed to self-discharge frequently or to remain in a discharged condition. A nickel-cadmium battery, however, can remain discharged indefinitely although it will self-discharge at a similar rate.

g. Environmental Capability: Environmental conditions can influence battery selection. In the case of batteries with liquid electrolyte, the minimum operating temperature may be limited by electrolyte viscosity considerations (reserve primary batteries) or by the freezing point of the electrolyte. In other cases, electrochemical activity decreases at low temperature which may decrease the operating life of a battery or may suppress output voltage. Batteries susceptible to these conditions may still be usable, but heaters may be required to condition them.

h. Operating Life: Some types of primary batteries can be activated under severe shock and acceleration environments and in any orientation, while certain types of primary reserve batteries must be activated at rest and in a specific orientation. Consequently, dynamic environment and orientation during activation should be considered. Since dynamic environment can also influence battery operating life, the dynamic environment during discharge should also be considered in selecting a battery.

10.6 Applications

Batteries may further be classified by cell type and are discussed below:

a. Primary Cells: The primary or "one-shot" cell is so called because the chemical reaction that releases the electrical power is not practically reversible. Primary batteries can have substantially higher energy density than secondary batteries but are often less attractive for secondary power sources than rechargeable batteries because they are partially depleted during repeated checkout of the secondary power devices.

The types of primary batteries that are available and presently in production for auxiliary power systems are the mercury cell, the water activated silver chloride cell, the silver-zinc cell, and thermal batteries. Characteristics of various primary batteries are summarized in Table 9.

TABLE 9 - COMPARISON OF PRIMARY BATTERIES

	Battery Type Mercury	Battery Type Seawater Silver Chloride	Battery Type Silver Zinc	Battery Type Calcium Thermal	Battery Type Lithium Thermal
Energy Density					
W-h/lb	50	47	50-70[1], 20-30[2]	1.0-11	8-35
W-h/in^3	5.0	5.0	4.8[1], 1.5-2.0[2]	0.2-1.0	0.76-3.85
Derate factor for reliable operation				2X	1.2-2X
Current Density					
Normal Discharge (mA/cm^2)			78	50-150	150-800[5]
Transient Pulse (mA/cm^2)			930	500-1500	10 000-18 000[5]
Internal Resistance (ohm-in^2/cell)			0.001 ohm/cell[3] 0.004 ohm/cell[4]	0.3-0.5	0.005-0.060
Shelf Life (Years;% Loss)			5;25%, 30;40%	15;0% and 25;10%	15;0% and 25;10%
Voltage Regulation (1=Excellent, 4=Poor)			1	4 ± 1/2	2 ± 1/2
Operating Life			seconds-days	minutes (0.5 s-15 min)	15 min[5] (0.5 s->60 min)
Relative Cost			3X	1X	1X
Operating Temperature Range			-54 to +70 °C Heaters required below +50 °C	100 °C between -200 and +200 °C. No heaters required	Up to 150 °C between -200 °C and +200 °C[5]. No heaters required.

[1] Manually activated primary
[2] Remote activated primary
[3] Minutes run time at ≤0.5 A/in^2 current density
[4] Hours run time at ≤0.5 A/in^2 current density
[5] High currents, long lives, and wide temperature ranges reduce effective energy densities

1. Mercury Cell: The mercury cell was developed during World War II. The cathode consists of mercuric oxide to which electrolytic manganese dioxide is added. The anode is of pressed amalgamated zinc particles and the electrolyte is a concentrated solution of potassium hydroxide saturated with zincate. The cell container is usually made of steel.

   This cell provides high discharge rates, up to 30 W-h/lb, close voltage regulation, and good performance at high temperatures. These batteries are mainly used for communications and airborne telemetry systems in which the main requirements are minimum size and weight, long total life, good charge retention, convenient recyclability, and good voltage regulation.

2. Silver Chloride Cell: The water-activated silver chloride cell was also perfected during World War II. This battery cell contains silver chloride and magnesium electrodes. The battery cells can be stored dry in an active condition in hermetically sealed containers and have the advantage of an electrolyte that need not be transported with the battery. The rugged construction of these batteries enables them to operate continuously after air-to-sea impacts from 50 000 ft and under the flow of sea water at various pressures and depths. These cells are available in sizes from 0.2 A hours to more than 100 A-hour capacities. These batteries can be activated at temperatures ranging from +28 to 90 °F (-2 to 32 °C). At low temperatures, the starting voltage and current capacity will be lower than the rated values but, because of internal heating during discharge, the voltage and current rise.

   These batteries can be activated in less than 10 s. These units have found wide application in air-sea rescue equipment and in torpedoes.

3. Silver Zinc Cell: The primary silver zinc battery is a reserve electrolyte, remotely activated, primary battery that provides high output per unit weight and volume and has a very long shelf life at room ambient storage due to the use of a reserve electrolyte system. The battery has a high energy density unless stored at high temperatures.

   Shelf life at higher storage temperatures is limited due to degradation of the positive (silver) plate, which can be compensated for by capacity overdesign. The silver plates are unstable at temperatures above 120 °F (49 °C). When the temperature is exceeded, the silver slowly decomposes from the peroxide to the oxide state with a resultant theoretical reduction of capacity up to 50%. Based on historical data, actual loss ranges from 30 to 40%. The reserve electrolyte system precludes battery checkout prior to actuation.

4. Thermal Batteries: Thermal batteries are nonreserve primary batteries. They are capable of an extremely long storage life under a wide range of storage temperatures due to the inert state of the electrolyte. Several combinations of anode/electrolyte/cathode are possible. Among the most widely used are:

   (a) $Ca/LiCl\text{-}KC_1/CaCr0_4$

   (b) $Li/LiC_1\text{-}KC_1/FeSx$

   (c) $Li\text{-}A_1/LiC_1\text{-}KC_1/FeSz$

   The calcium anode system was most widely used in the past. Newer batteries incorporate the lithium anode systems, which exhibit significant advantages over the calcium system in several key areas such as energy density, internal resistance, and voltage regulations.

   Among the advantages of thermal batteries are:

   (a) Wide operating temperature range

   (b) Storage life

   (c) Ruggedness

   (d) Position insensitivity

   Among the limitations are:

   (a) Voltage regulation

   (b) Discharge time

   (c) High surface temperature during discharge

   Thermal batteries are typically cylindrical in shape, although some with other shapes have been developed.

b. Secondary Cells: The secondary cell was initially the most extensively used battery in missile applications. The reliability of this battery is high when adequate quality control is exercised in its manufacture and the relatively simple maintenance procedures are followed prior to use.

   The secondary cell, as received from the manufacturer, does not contain electrolyte. The electrolyte is shipped in separate containers and must be added to the individual cells when received at the user's facility. The individual cells must be allowed to stand for a period of time and then charged to maximum voltage level. The batteries may be stored prior to charging in the wet condition for several years. Standard charging methods can be used to place the cells in service. The "ready" life of the cells in the missile is a minimum of several years if kept on a continuous float charge and if excessive low or high temperatures are not encountered. In order to obtain the full output capacity within the required voltage limits below 32 °F (0 °C), heat must be applied to the cells from an external source. This is usually accomplished by providing electrical heater wires within the battery package.

The individual cells are placed in series to obtain a battery. Nominal battery voltage for missile application is 28 V, although batteries with a voltage output of 28 to 117 V DC have been used. The current capacity of each cell ranges between 2 and 300 A. When higher current output is required, two or more batteries are placed in parallel. When batteries are placed in parallel, diode protection circuitry is required to prevent one battery from discharging into another. Since discharging batteries generate explosive gases, the diode circuitry is essential to prevent disastrous explosions that are capable of destroying the battery.

The secondary types available are the lead-acid cell, the nickel-iron cell, the nickel cadmium cell, the silver cadmium cell, and the silver zinc cell. Many other types of cells are available but, since only high discharge type cells are considered, the chemical types listed are the most applicable for aerospace uses. Characteristics of secondary batteries are summarized in Table 10.

1. Lead-Acid Cell: The lead-acid battery has its major use in aircraft systems to supply engine starter and accessory power. The nominal voltage level is 24 V. These batteries have the capability of 10 W-h/lb. These batteries are used where space and weight are not critical and are the least expensive of all the secondary type batteries.

2. Nickel-Iron Cell: The nickel-iron battery has the same uses and the same approximate watt-hour capacity as the lead-acid battery. Its main advantage is that it can withstand many more charge-discharge cycles. These batteries have been known to have a life expectancy of more than 2500 charge-discharge cycles.

3. Nickel Cadmium Cell: The nickel cadmium secondary battery is widely used because of its capability of being charged and discharged up to approximately 1000 cycles. Charge-discharge cycling capability is of importance during the early phases of a missile development program since it allows battery replacement to be held to a minimum during the considerable time that may be spent in testing the missile and its components on the ground. The nickel cadmium battery can be charged more rapidly over a wider temperature range than any other battery.

4. Silver Cadmium Cell: The silver cadmium secondary battery is normally used in aircraft power systems having a 24 to 28 V output. A battery with a capacity of 20 A hours would yield a power density of 25 W-h/lb. When used in this capacity, the unit has a capability of approximately 200 charge-recharge cycles.

5. Silver-Zinc Cell: The zinc silver oxide secondary battery has seen limited missile use. Although the output per unit weight and volume of this battery is the highest of any battery presently available (its watt-hour per pound capacity is approximately five times that of the sintered plate nickel cadmium battery, and it occupies only about one-third as much space), its sensitivity to charging abuses, shorter life, and greater maintenance requirement make it less desirable for many applications. Also, the change in voltage that occurs when load is first applied is more pronounced in this battery than in other types. The reliability of this battery is high if the special maintenance procedures required are followed.

   Silver-zinc secondary batteries have been used almost exclusively in all manned space flight and satellite launch applications because of their high energy efficiency and high reliability. Also many thousands have been used for field radio pack batteries because of their energy efficiency and high cycle recharge capability.

   Because of the relatively short wet stand life of the silver-zinc oxide secondary battery, it is normally shipped in the dry condition. A storage life of several years can be expected if stored dry, provided temperatures in excess of 90 °F (32 °C) are not encountered for an appreciable period of time.

   Typically the major cost driver of a silver-zinc battery of any significant size is the silver, which is recoverable at the end of the battery useful life.

TABLE 10 - COMPARISON OF SECONDARY BATTERIES

	Lead-Acid	Nickel-Iron	Nickel Cadmium	Silver Cadmium	Silver-Zinc
Energy Density					
W-h/lb	12	13	12	32	59
W-h/in^3	1.0	0.7	1.1	4.4	3.5
Current Density					
Normal Discharge (W/cm^2)					39
Transient Pulse (mA/cm^2)					155
Internal Resistance (ohm-10^2/cell)					
Charge-discharge Capability			Upward of 400 000 for small (approximately 10%) discharges; approximately 3000 for discharge of 90 to 95%.	7000 cycles at discharge rate and 50% capacity, 500 cycles at high discharge rate and to 50% capacity.	80 cycles at low discharge rate and to 50% capacity. 5 cycles at high discharge rate and to 50% capacity.
Shelf Life (Years; percent loss)					5;0%[1]
Voltage Regulation (1 = Excellent 4 = Poor)					1
Operating Life					1 year maximum
Relative Cost					3X
Operating Temperature			Optimum temperature 80 °F (27 °C). Energy level approximately 20% reduced at 0 °F (-18 °C). Energy level approximately 35% reduced at -65 °F (-54 °C).	Optimum temperature 100 °F (38 °C). Energy level approximately 30% reduced at +10 °F (-12 °C). Upper limit = 160 °F (71 °C).	Optimum temperature 80 °F (27 °C). Energy level approximately 40% reduced at 10 °F (-12 °C). Upper limit = 160 °F (71 °C).

[1] Batteries are normally stored at low temperature prior to activation and use.

10.7 Development Batteries

At the present time, two major categories of high power batteries are under development and are beginning to be produced in sufficient quantities and power levels to be considered for aerospace applications. The batteries are available as primary or secondary units. The units use zinc air or oxygen and lithium in chemical reactions to produce electrical power. These batteries are discussed in detail.

a. Zinc Air-Oxygen Batteries: Zinc air-oxygen batteries do not consist of simple cells but have a bicell. The bicell consists of two cathodes connected in parallel and supported by a frame that together form a container for the electrolyte. The anode, enclosed in separator paper, is inserted between the cathodes. The battery is then built up of the required number of cells in series and parallel for the particular application. The battery unique characteristics of high specific power, good low temperature performance, and quick, simple mechanical recharging make it especially suited for unattended military and space applications. These batteries do require an external supply of oxygen, which may be carried in a high pressure storage bottle and attached to the battery if very high discharge rates are required. When low discharge rates are anticipated, ambient air can be used to supply oxygen to the battery. No venting is necessary when the battery is operating on a pure oxygen supply and the batteries can be completely sealed. The energy density of these batteries is predicted to be approximately 30 W-h/lb at high discharge rates.

b. Lithium Primary Batteries: Several types of lithium primary battery systems are in use today. These are lithium sulphur dioxide ($LiS0_2$) and lithium thionyl chloride ($LiSOC1_2$); many others are in the research and development stage. The major size categories are AAA size cells to DD size cells. One high drain application has been developed for the Minuteman silo standby power application. The batteries that have been developed and evaluated show power density capabilities of 175 to 225 W-h/lb and 12.5 to 15.5 W-h/in^3. These capabilities have been verified in low drain applications. The present development of lithium anode batteries is pointed toward the automotive industry, which many battery manufacturers feel is the greatest market if and when they obtain a rechargeable battery design. Some manufacturers are studying battery designs that will be capable of supplying high current for 1 to 20 min, but high development costs are slowing these programs. The advantages of a lithium anode battery are high energy densities and extremely good operation at low temperatures. The disadvantages of lithium anode batteries are:

1. Anode passivation when stored at temperatures slightly above ambient
2. Thermal runaway and resulting explosion safety
3. Disposition of material from depleted batteries

c. Lithium-Ion Batteries: There are several variations of the type of secondary battery commonly referred to as Lithium-Ion. The major differences between these batteries types are related to the chemistry and cell design characteristics. Notably, lithium-cobalt oxide ($LiCoO_2$) was one of the first chemistry combinations commercialized. This chemistry variation offered the promise of much higher specific energy than other dominant chemistries, and the electronics industry quickly adopted this chemistry as the new standard for cell-phones and laptop computers. In the years that have followed, many other chemistry variations, such as lithium-manganese spinel ($LiMn_2O_4$), lithium-nickel-cobalt-aluminum oxide ($LiNiCoAlO_2$), lithium-iron phosphate ($LiFePO_4$), and others have followed. The typical per-cell voltage of the majority of these chemistries is 4.0 VDC fully charged and 3.6 VDC nominal (under load), enabling the battery designer to achieve a 28 VDC aircraft battery design with 7 cells instead of the typical 20 cell design of Ni-Cd. The exception to this $LiFePO_4$ which is typically 3.5 VDC fully charged and 3.3 VDC nominal per cell. Many of these chemistries can be found in both cylindrical and prismatic cell designs, with features that offer distinct application advantages. Consequently, there is no single chemistry that is the best for all applications.

The table below gives a basic comparison of the chemistries;

TABLE 11 - SUMMARY TABLE

Cathode	Specific Energy, Wh/Kg	Specific Power	Safety	Life	Cost
$LiNiCoAlO_2$ (NCA)	**High** 120 - 150	**Excellent**	**Fair-Good** Dependent on cell construction	**Excellent**	**High**
$LiFePO_4$	**Medium** 50 - 110	**Very Good**	**Very Good** In small cell designs. (Still uses flammable electrolyte and carbon negative)	**Good** at room temperature, **Poor** at high temperature (<6 months @ 60°C)	**Low-Medium**
$LiCoO_2$	**High** 100 - 130	**Good**	**Challenging**	**Medium**	**High**
$LiMn_2O_4$	**Low** 40 - 85	**Excellent**	**Good**, except in very large cells	**Acceptable** at room temp., **poor** at high temp	**Medium**

Battery designers have made great improvement in these products over recent years, expanding the operating temperatures from the limited range of 15 °C to 40 °C of a few years ago to the current range of -40 °C to 71 °C and beyond. These advances have opened up a variety of applications including aerospace.

Application experience from recent years has revealed the need for very closely controlled charging and cell balancing, to prevent undesirable thermal events, and in spite of claims to the contrary, the vast majority of the Li-Ion chemistries currently offered must include these electronic controls in the interest of application safety. To illustrate the seriousness of this point, the FAA has issued Special Conditions papers for the application of Rechargeable Lithium Batteries in Aerospace applications. Subsequently, the RTCA has drafted DO-311, Minimum Operating Performance Standards for these batteries.

A new facet to be dealt with by suppliers of rechargeable lithium aerospace batteries is the requirement for significant testing of the onboard electronics to RTCA/DO-254, and the design of embedded software to the requirements of RTCA/DO-178.

The advantage of these new battery systems comes in the form of completely integrated battery / charger systems in a single Line Replaceable Unit, with enhanced capabilities to communicate with aircraft systems and provide a wider range of diagnostic data. Additionally, potential weight and space savings may be realized, dependent upon the airframe system design requirements.

11. FUEL CELLS

11.1 Description

Fuel cells are devices that convert chemical energy directly into electrical energy. When supplied with fuel and oxidant (usually hydrogen and oxygen either in pure form or dilute, such as reformed hydrocarbons or air), the fuel cell produces electrical power and, as byproducts, pure water and waste heat. Instead of the chemical to heat to electricity conversion processes required by conventional engines, fuel cells convert the hydrogen and oxygen reactants directly into electricity. Because of this, fuel cell efficiency is relatively high (in the order of 60 to 70% cell efficiency), which results in low reactant consumption. On reformed hydrocarbons and air, a 50 to 60% efficiency is achievable. Fuel cell power systems can provide energy densities up to about 1000 W-h/lb. The space shuttle orbiter system is 500 to 600 W-h/lb.

Fuel cell types are based on:

a. Type of electrolyte used (base, acid, etc.)

b. Type of fuel and oxidant used

c. Fuel cell system design (a function of application requirements and manufacturer preference)

Fuel cell systems can be built in sizes ranging from a few watts to hundreds of kilowatts to meet the needs of different applications. (For types of fuel cells, see Table 12.)

TABLE 12 - TYPES OF FUEL CELLS

Technology	Maturity	Applications	H_2 Source	O_2 Source	Temperature	Status
Alkaline (AFC)	Present	Space Shuttle Orbiter	Onboard H_2	Onboard O_2	80 °C	Operational
Alkaline (AFC)	Development	Future Space Missions	Onboard H_2	Onboard O_2	120 °C	In development
Polymer Electrolyte (PEMFC)	Present	Aerospace, hydrospace, terrestrial, transportation, batteries	Onboard H_2, reformed hydrocarbons, MeOH	Onboard O_2, air	80 °C	In development
Phosphoric Acid (PAFC)	Present	Terrestrial	Reformed hydrocarbons	Air	190 °C	Commercial
Phosphoric Acid (PAFC)	Development	Transportation	Reformed hydrocarbons	Air	210 °C	In development
Molten Carbonate (MCFC)	Present	Terrestrial	Reformed hydrocarbons	Air	600 °C	Early development
Solid Oxide (SOFC)	Present	Terrestrial, possible space	Reformed hydrocarbons, pure H_2	Air, O_2	1000 °C	Very early development

11.2 Applications

Fuel cells can be used to supply electric power for space, undersea, and terrestrial applications. Both hydrogen-oxygen and hydrazinehydrogen peroxide fuel cells have been used in experimental undersea applications, however, further development is needed.

The Gemini spacecraft used two polymer electrolyte fuel cell modules rated at 1 kW each, however, these were severely limited by available membrane technology. The Apollo missions were powered by three 1.4 kW power plants based on medium temperature alkaline electrolyte, however, temperature induced corrosion limited useful life to 300 h. Space shuttles orbiter carry three low temperature alkaline electrolyte power plants capable of 16 kW each. All of the above fuel cells operate at the nominal 28 V used by space systems.

Larger fuel cell power plants have also been developed and used by the U.S. Navy for undersea applications. The Deep Quest submersible used low temperature alkaline 120 V power plants rated at 30 kW. Development is currently underway for polymer electrolyte fuel cells which can directly oxidize methanol (without reforming); these are of interest due to high volumetric energy density of methanol compared to hydrogen.

11.3 Components

A fuel cell power plant (module) consists of a power section and an accessory section. The power section is made up of individual fuel cells stacked in series or series parallel to provide the desired system output voltage (multiple stacks may be used). Each cell consists of two electrodes separated by an electrolyte-containing matrix or membrane (Figure 9). Hydrogen and oxygen (the most common reactants used), each supplied to the proper electrode, combine in an electrochemical reaction to produce electric power, water, and waste heat. The power plant's accessory section provides subsystems for controlling:

a. Supply of reactants

b. Removal of product water

c. Removal of waste heat

d. Power conditioning (if needed)

There are a wide variety of feasible methods for providing these subsystem functions. The methods employed are determined by the type of application for which the system is designed.

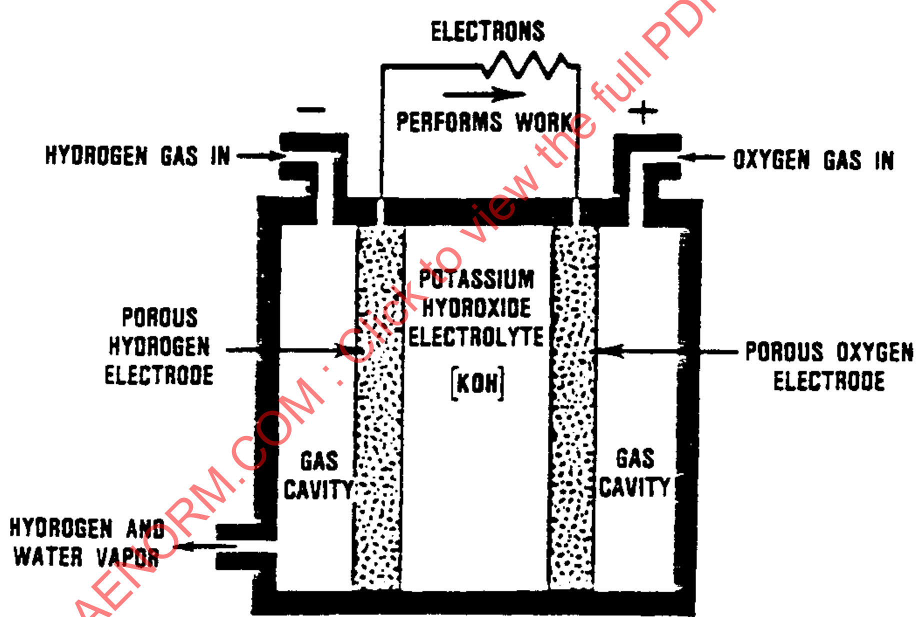


FIGURE 9 - ALKALILNE FUEL CELL CONCEPT

11.4 Advantages

Fuel cell power plant specific weight (lb/kW) has been reduced from as high as 180 lb/kW for the early Apollo power plants to a present capability of about 16 lb/kW for orbiter power plants. Recent development programs have achieved levels of 1.0 lb/kW. Lifetime has been increased from a few hundred hours in early 1960 to about 2500 h (1983) with a design goal of 10 000 h for next generation systems, with some test cells indicating a capability for 20 000 h or more. Other advantages of fuel cell power plants are:

a. Compact Size: Present hydrogen-oxygen fuel cells occupy approximately 0.4 ft^3/kW.

b. Wide Power Range: Fuel cells have excellent overload capability. They can supply power at several times their design rating for spike loads. Voltage response is nearly instantaneous and smooth without voltage dips or overshoots.

c. High Efficiency Over Wide Power Range: Fuel cells maintain their high efficiency and, hence, low reactant consumption over the full range of output from part load to overload.

d. Long Life: Fuel cell systems have operating lifetimes between 2000 and 3000 h before major maintenance is required.

e. Automatic Operation: Fuel cell systems start and stop by remote push-button control.

f. Silent Operations: The fuel cell's static energy conversion results in extremely quiet operation.

g. Low Waste Heat Rejection: The fuel cell's high efficiency means only small amounts of waste heat must be rejected; hence, heat rejection systems are compact and lightweight.

h. Potable Water: Water by-product produced by the H_2/O_2 fuel cell reaction is completely potable.

i. By-Products: Clean by-products result from cell reaction process.

11.5 Disadvantages

The disadvantages of fuel cell power plants are:

a. Start-up time to full output power operation in the order of 15 min at current technology

b. Size limitation and the present high cost of reactants and modules

12. SOLAR CELLS

12.1 Description

Solar cells are constructed from semiconductor materials. In metals, the resistivity is inversely proportional to the number of free electrons available for the conduction of an electric current. Those materials with resistivities of less than 10^{-3} Ω-cm that conduct electricity well are classified as metals. Those elements whose resistivities are in excess of 10^{12} Ω-cm are classified as insulators. Those whose resistivities are in between are classified as semiconductors. Common semiconductors are germanium, silicon, cadmium, etc. Thus, some of the common solar cell materials are silicon and cadmium sulfide (CdS). The use of gallium arsenide (GaAs) in solar cells is under development.

A solar cell operates because of the effect of radiant energy upon a semiconductor device containing a +positive - negative (P-N) junction. The first effect of the radiant energy is to cause an increase of the conductivity of the material near the junction area due to the release of electrons; the second is the creation of electron-hole pairs. Some of these freed electrons and holes will migrate to the vicinity of the junction. If they reach the junction area, the built-in electronic field will separate them and a voltage will be generated between the P region and the N region. If an external load is connected between the P region and the N region, current will flow through this load and power will be generated. A solar cell has the capability of generating a set voltage and a current proportional to the amount of light that is absorbed by the cell. Thus, a solar cell has the same properties as a battery cell. The cells can be connected in series/parallel combinations to form an array that can have multiple current and voltage ratings depending upon the desires of the user.

Solar cells are typically rated for illumination normal to the front surface and at air mass equals zero (AM0) for space application or AM equals one (AM1) for terrestrial application at sea level and standard altitude both at 82 °F (28 °C) temperature. One AM is the amount of atmosphere that sunlight passes through before striking the earth when the sunlight hits the atmosphere normal to the earth's surface. A typical aerospace silicon cell, 0.8 in x 1.6 in (2 cm x 4 cm), will generate 0.15 A at 0.47 V at AM1, 82 °F (28 °C). A typical 3 in (7.6 cm) diameter terrestrial silicon cell will generate 1.25 A at 0.43 V at AM1, 82 °F (28 °C). At AM0, the above 0.8 in x 1.6 in (2 cm x 4 cm) silicon cell will produce 0.26 A at 0.47 V.

A typical 3 in x 3 in (7.6 cm x 7.6 cm) CdS thin film solar cell generates about 0.80 A at 0.35 V in full sunlight at normal temperature. The output of the cell changes with the impedance of the external load. As the load impedance is increased, the power output reaches a maximum at a value that matches the internal impedance of the cell and then falls off. This is the same principle for the maximum power transfer of any generator and load.

The output of a solar cell is more conventionally shown by the current-voltage relationship, or IV characteristics. Maximum power is characterized by the point on the IV characteristic curve at which the area of the rectangle drawn between the curve and the axes is at a maximum. Impedance then is that voltage, V_{mp}, divided by that current value, I_{mp}.

Output of the solar cell is reduced as the temperature of the cell is increased. Voltage decreases almost linearly with increasing temperature over a wide range, whereas current is affected only slightly. The use of thin film solar cells on high-altitude balloons is especially favorable in this respect because the very low ambient temperatures in the upper atmosphere offset the temperature rise resulting from absorption of sunlight. Temperatures of panels of thin film solar cells on high-altitude balloons are generally in the range of 32 to 77 °F (0 to 25 °C). Temperatures of space panels in the sun near the earth are generally in the range of 113 to 140 °F (45 to 60 °C).

The output of a solar cell increases as the intensity of the incident illumination increases. Most of the change is in current output, as voltage generally saturates at relatively low light levels. Here again, the high-altitude balloon application favors the solar cell, as light intensity increases appreciably with altitude. Also, there is less probability of clouds completely obscuring the sun as altitude increases. Where increased cell temperature accompanies increased illumination intensity, a maximum cell power point will be reached after which temperature effects on cell power override increased illumination effects. This is a consideration in the application of light-concentrating mirrors to get more power from solar cells, as well as in the design of passive or active cooling of solar cells.

If a number of cells are connected in series, the voltage output of the resulting array will be approximately equal to the sum of the voltages of the individual cells, while the current output will be about the same as the current of a single cell. On the other hand, if a number of cells are connected in parallel, with all positive leads connected to one bus and all negative leads to another bus, then the voltage output of the array will be the voltage of a single cell, while the current will be approximately equal to the sum of the currents of all the individual cells. In principle, this is the same as interconnecting any group of batteries or other generators. Thus, larger power ratings can be achieved by interconnecting sufficient numbers of cells in various series/parallel combinations.

Single crystal silicon solar cells can be built in various sizes to adjust the number of cells in a given area that can be placed in series and thereby provide higher or lower voltage, and higher or lower current, per series string. Thin film solar cells can be made in smaller sizes, or larger cells can be cut into narrower strips. The standardization of solar cell sizes is sought, however, to reduce cost.

Arrays for balloon applications are designed to operate in a horizontal plane, either on top of the balloon or, more usually, on top of a gondola or other panel suspended below a balloon. Thus, the panels receive light energy dependent on the sun-angle at any particular time. Since the output of a solar cell follows the cosine law, at low angles of illumination the output is greatly reduced. Arrays for space applications are supported on lightweight rigid panel structures that are either mounted on the body of the satellite or deployed following orbit attainment. Array average power in the sun is increased by the use of sun tracking capability in one axis for deployed arrays; two-axis tracking capability maximizes the array average power output. Further array weight reduction is obtained with flexible plastic film substrates replacing the rigid panel substrates.

Improvements in silicon solar cell design have increased cell efficiency while making cells thinner and lighter. High-efficiency cells for space can be made with 15% efficiency compared to the 10 or 11% maximum efficiency of a few years ago. Metal solar cell electrical interconnects are bonded to metallized contacts on the solar cells. The bonding methods used are typically soldering and parallel gap electric resistance welding. Conductive adhesives, thermocompression bonding, and ultrasonic bonding techniques have also been developed.

12.2 Applications

Solar cells have been used in high-altitude balloons and in earth satellites. In the latter application, they are used with secondary batteries to supply the required average power in the sun and in earth eclipse periods, as well as power peaks. Solar cells are used as detectors in solar tracker units to point solar arrays and other instruments. Solar cell arrays have been used for power in space probes to within 0.3 AU of the sun and out to Mars (1.5 AU from the sun).

12.3 Components

Solar cells for space application are constructed of silicon material. Thickness varies between 5 to 12 mils, with new developments down to 2 mils. Silicon cell sizes are usually 0.8 in x 0.8 in, 0.8 in x 1.6 in, and 0.6 in x 2.4 in (2 cm x 2 cm, 2 cm x 4 cm, and 2 cm x 6 cm) depending on application. Arrays are fabricated by bonding the interconnected cells in the proper series/parallel combination to a structural backing such as aluminum (Al) honeycomb panels, with Al or composite face sheets, or thin (0.5- to 2-mil thick) plastic film, or a heavy fabric. The cell interconnect metals usually used are Kovar, silver, copper, and silver-plated molybdenum.

High-altitude balloons have employed thin film CdS solar cells and GaAs cells are being developed for space applications in which their higher temperature capability will allow the use of sun concentrators to increase power output.

12.4 Performance

The solar constant is measured at 110 to 120 mW/cm^2 at altitudes between 40 000 and 70 000 ft (12 000 and 21 000 m) and at 135.6 mW/cm^2 in space at the earth's distance from the sun (1 AU). The efficiency of the solar cells at 1 AU and at operating temperature is about 10%. The specific power is about 15 W/lb for rigid substrate designs and 20 W/lb for flexible substrate designs, under normal illumination. The power/area ratio is 10 W/ft^2. Thus a 1 kW solar array will have a surface area of 100 ft^2 (9.3 m^2) and weigh between 50 to 70 lb (23 to 32 kg). Array designs are being developed to provide 30 to 90 W/lb for future application.

12.5 Advantages

Solar cells:

a. Are high reliability static convertors that provide high specific power in arrays (30 w/lb)

b. Can be mounted to conform to an available flat area envelope

c. Can be used as an automatic battery charger when a battery is used to power a device during times of no sunlight; the battery can then be charged during daylight

d. Of long duration performance will last indefinitely unless mechanically damaged by external means

e. Can be used as sun sensors for solar tracking and for space orientation

f. Can be compactly stored for launch and later deployment

12.6 Disadvantages

Solar cells:

a. Require sunlight to operate and, therefore, do not operate during periods of darkness or cloud cover

b. Are expensive at the present time because of limited production

c. In large exposed array area require the deployment of solar cell panels in space applications

d. Are degraded by space radiation, as are panel thermal-optical properties; temperature cycling eventually damages the cell interconnecting system

13. NUCLEAR POWER SYSTEMS

13.1 Description

There are two basic types of nuclear auxiliary power systems. One type is powered by radioisotopes, and the other type by a nuclear reactor. They differ only in the heat power source, with power conversion subsystems and power regulation subsystems being similar for both types of nuclear auxiliary power sources. The heat power conversion to electrical power is accomplished using thermoelectric, thermionic, or dynamic power conversion devices. Only the radioisotope thermoelectric generators have seen practical application. Considerable development effort has been accomplished on all the concepts, and the dynamic power conversion systems utilizing turboalternators may see application in the near future because of their relatively high power conversion efficiency. At all times, a tradeoff must be made against solar cells for low power applications.

13.2 Applications

Some of the applications for the two basic types of nuclear auxiliary power systems are:

a. Radioisotope Power Systems: There have been several SNAP systems developed since 1957. Many have not been carried any further than advanced development. The primary applications have been to earth satellites and lunar experiment power packages. Two SNAP 39 systems have been successfully launched by the U.S. Navy on Transit 4A. The power units were designed to operate for 5 years with a power output of 2.7 W. These satellites were launched in 1961, and telemetry is still being received from one unit.

   Two SNAP 9A systems were successfully launched in 1963 aboard a U.S. Navy navigational satellite. One was still operating in 1970. This power system was designed to operate for 6 years with a power output of 25 W.

   Another development is the SNAP 19. This is used to augment the solar array and batteries on the Nimbus B spacecraft. It has a 2 year design life at 50 W power.

   The SNAP 27 is a 56 W radioisotope thermoelectric generator designed for the Apollo program to power the Apollo Lunar Surface Experiment Package (ALSEP). It was designed for a 1 year life. It is unique in that fueling was accomplished concurrently with deployment of the experiment on the lunar surface.

   All of the aforementioned SNAP systems utilize plutonium-238 as the radioisotope fuel.

b. Nuclear Reactor Power Systems: There are two SNAP programs that represent the state-of-the-art in nuclear reactor powered space power systems.

   The SNAP 8 Experimental Reactor operated from May 1963 through April 1968 and demonstrated:

   1. Capability of sustained powered operation

   2. Static and dynamic stability

   3. Stable operation during rapid power level changes

   The reactor operated at 1300 °F (700 °C) and the maximum power generated was 600 kW (570 Btu/s), with a total power output of 5 100 000 kW-h (18 000 000 Mj).

   The SNAP 10-A is a flight-test reactor operating at 1000 °F (500 °C) that has been successfully operated in space. It demonstrated a capability of producing 500 W (370 ft-lb/s) of electrical power but failed after 43 days in space.

13.3 Components

The components that make up these nuclear auxiliary power systems are detailed below:

a. Radioisotope Power Systems: A typical radio isotope power system includes three major subsystems, which are:

1. A radioisotope heat source

2. A power conversion subsystem

3. A space heat power radiator

A power flattening dissipation device is used only when the mission duration is a substantial fraction of the radioisotope half-life, to assure a reasonably constant power output over the entire mission. In this case, an appreciable part of the available power must be rejected to the environment during the early part of the system life. There are many radioisotopes that can be used. The selection is based on required mission life and application limitations.

The power from a radioisotope appears as the motion of emitted alpha and beta particles and/or as the power of gamma photons. The slowing down and/or absorption of these radiations causes an increase in the temperature of the surrounding properly selected material. The shielding of the nuclear particles and the electromagnetic radiation from the surrounding environment, including biological entities, is related to the relative proportion of the aforementioned radiations, which vary in different radioisotopes. One of the most commonly used radioisotopes is plutonium-238.

Plutonium-238 has a half-life of 87.4 years and has been used in all space power generators flown to date. It is used because it does not require a great deal of shielding, even in manned applications, and it has a long half-life.

Thermoelectric systems utilize the same principle for producing an electric current as the common thermocouple. They are operated with temperatures up to 1800 °F (1000 °C) and have an overall efficiency of 3 to 8%. Current specific powers of approximately 1 W/lb are being achieved at low power levels, with a slight increase when operating at several hundreds of watts.

The thermionic system utilizes the radioisotope to heat a refractory metal emitter to a temperature varying from 2500 to 3400 °F (1400 to 1900 °C), causing an electric current of several amperes per unit area to leave the surface. The electrons travel across a small cesium-vapor-filled gap to a cooler 1200 °F (650 °C) collector. The cesium serves to form positive ions to neutralize the space charge, which would otherwise obstruct electron flow. Thermionic systems have an overall efficiency of 8 to 15%.

The dynamic energy conversion systems have seen two implementations, the Rankine cycle and the Brayton cycle. The Rankine cycle involves use of a turboalternator powered from vapor produced by heating a fluid such as mercury, rubidium, byphenyl, or a freon compound. A closed-loop system incorporates a condensor for conditioning the liquid prior to reheat.

The Brayton cycle is similar, only in this system a gas is used as the working fluid. Typical gases are argon, neon, krypton, helium, xenon, or mixtures of inert gases. Cold gas is compressed and passed through a regenerator, where it is preheated by gas from the turbine exhaust. The gas is then heated and expanded through the turbine, which drives the compressor and the alternator.

The dynamic energy conversion systems have an overall cycle efficiency of 20 to 25% and, thus, have considerable advantage over the radioisotope thermoelectric generator. However, realization of their potential must await considerable development to resolve fuel containment and safety problems.

b. Nuclear Reactor Power Systems: A typical nuclear reactor power system incorporates two heat transfer loops. The primary loop transfers heat to the power conversion subsystem, where thermal energy is converted to electrical energy. Any unused thermal energy is transferred via an auxiliary heat transfer loop to a space radiator. In the compact reactor systems, the primary loop utilizes liquid metals (such as lithium or sodium) pumped by electromagnetic or centrifugal pumps. In systems utilizing dynamic energy conversion, the auxiliary heat transfer fluids can be the conversion cycle working fluids (possibly NaK).

The compact nuclear reactors used in auxiliary power sources consist of a quantity of fissionable material in a geometry capable of sustaining a neutron chain reaction. The quantity of fissionable material required is determined principally by minimum critical mass and heat transfer design. The quantity of fissionable material is not strongly dependent on the chosen power level but rather on reactor lifetime, which puts limits on burnup. Reactor cost, therefore, does not vary appreciably with power level change.

The design of a nuclear reactor consists of an assembly of special materials that, if arranged in the proper geometry and composition, are capable of sustaining a controlled fission chain reaction. The key materials in a SNAP reactor are fully enriched U-235 fuel, a zirconium hydride neutron moderator, Hastelloy fuel cladding, beryllium neutron reflectors, a lithium hydride shield, stainless steel structure, and liquid metal heat transfer fluid. Advanced reactor designs could incorporate UO_2 or UN fuels with MoRe or ASTAR-811C cladding (with a tungsten liner).

The nuclear reactor auxiliary power source is in a technology development stage. Indications are that a usable life of 5 years is possible. A design limit on minimum power output is apparent, and the nuclear reactor power source will find application where 80 kW or greater of electrical power are required. The power conversion subsystem and the space radiator subsystem are similar in concept to those used for the radioisotope power systems, except that sterling cycle power systems may also be attractive. These reactor space power systems are currently being investigated in the Tri-Agency SP-100 program. A goal of this program is to produce a 100-kW reactor space power system with an overall weight of 6614 lb (3000 kg).

13.4 Advantages

The advantages of the two systems are:

a. Radioisotope Power System: The radioisotope power systems offer a reliable, self-sufficient space power source. They incorporate minimum moving parts, have long usable life without maintenance, and provide design flexibility because physical orientation in the vehicle is not critical to operation.

b. Nuclear Reactor Power Systems: The nuclear reactor can be designed, fabricated, and checked out without radioactive buildup, thus allowing convenient handling prior to activation. The fuel consumption is negligible, and power can be accurately modulated to demand.

13.5 Disadvantages

The disadvantages of the two systems are:

a. Radioisotope Power Systems: The radioisotope power system is an exponentially decaying source, resulting in a nonconstant power source unless a variable heat rejection system is incorporated to compensate, or "power flatten." This introduces complexity.

   The commonly used plutonium-238 has a half-life of 87.4 years, which is desirable. It is, however, an alpha emitter producing significant quantities of helium gas, which must be vented or contained within a fuel container that is built to withstand the pressure buildup.

   Current projected costs of $300 to $500/g of encapsulated fuel means that the cost of fuel normally equals the cost of the remainder of the system. The thermionic power conversion system shows potential for substantial improvement in efficiency. However, the high operating temperatures have posed serious material selection and safety problems.

   The availability of fuel is not certain. The only current source is the NRC. Future needs may require developing additional sources.

   The utilization schedule must be closely controlled for maximum life. Commitment of a power system requirement demands close scheduling of actual power source buildup.

b. Nuclear Reactor Power Systems: The materials of construction are expensive and the mechanism is complex. The development of high temperature reactors may be required (up to 1500K [2700R]). The reactor produces radioactive materials that require complex shielding. Disposal of the hot reactor after useful life could be a problem.

14. GAS TURBINE AUXILIARY POWER UNITS (APUS)

14.1 Description

A gas turbine APU is a continuous combustion open Brayton power cycle machine that provides power to aircraft equipment, both on the ground and in-flight, independent of the main engines.

Power produced by an APU is in the form of shaft and/or pneumatic output. Shaft power is used to drive electrical generators, HPs, and other aircraft equipment requiring constant-speed operation. Pneumatic power is used for main engine starting, cabin air-conditioning and pressurization, airframe deicing, operation of compartment cooling ejectors, air turbine motors, or other pneumatically driven components. A typical aircraft pneumatic system, which incorporates an APU, is illustrated in Figure 10.

APUs are categorized into four basic types depending on the mechanical configuration of the machine:

a. Single-spool integral-bleed APU

b. Two-spool integral bleed APU

c. Load compressor APU

d. Single-spool,shaft-only-load, APU

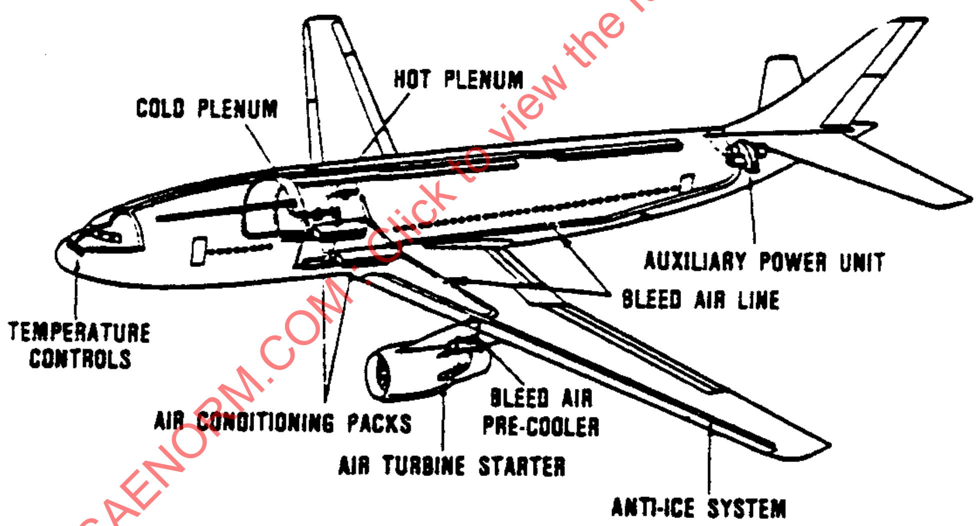


FIGURE 10 - TYPICAL AIRCRAFT PNEUMATIC SYSTEM

Cross sections of these APUs are illustrated in Figures 11, 12, 13 and 14 to show the differences in component arrangement and construction. Each APU type can be further subdivided into the following major assemblies or components:

a. Power section

b. Accessory gearbox

c. Control and accessories

d. Load compressor (load compressor APUs only)

The power section drives the accessory gearbox and any aircraft accessory equipment. Clean, high-pressure air also can be bled from the power section compressor of an integral-bleed APU to supply the aircraft pneumatic system.

The power section comprises:

a. One or more compressor stages, either axial or centrifugal

b. A high heat release fuel/air combustor

c. One or more turbine stages, either axial or radial

The combination of a compressor and a turbine into a single rotating group is referred to as a spool. One or more spools may comprise the power section, as in the two-spool integral bleed APU shown in Figure 12.

The accessory gearbox includes integral output pads for mounting driven equipment (i.e., electrical generators and HPs) as well as the necessary electrical, fuel, and lubrication components. Output pads for driven equipment typically operate at 6000, 8000, or 12 000 rpm.

The controls and accessories necessary for starting, operation, and shutdown of the APU include the fuel control, bleed air load control valve, lubrication pumps, and temperature, pressure, and rotational speed sensors. Additionally, some APU applications employ air/oil coolers and cooling fans, PMGs, surge valves for protection of the power section compressor during transient load or high altitude operation, and an ECU.

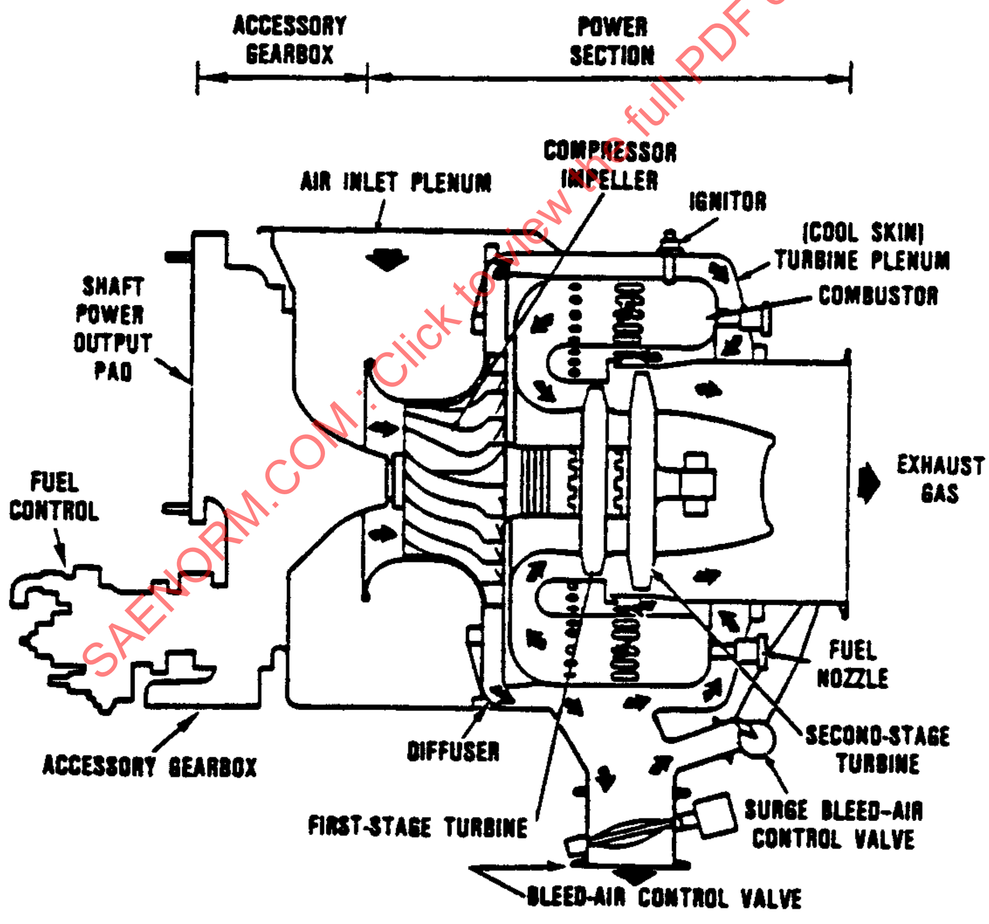


FIGURE 11 - CROSS-SECTION OF AN INTEGRAL BLEED AIR APU

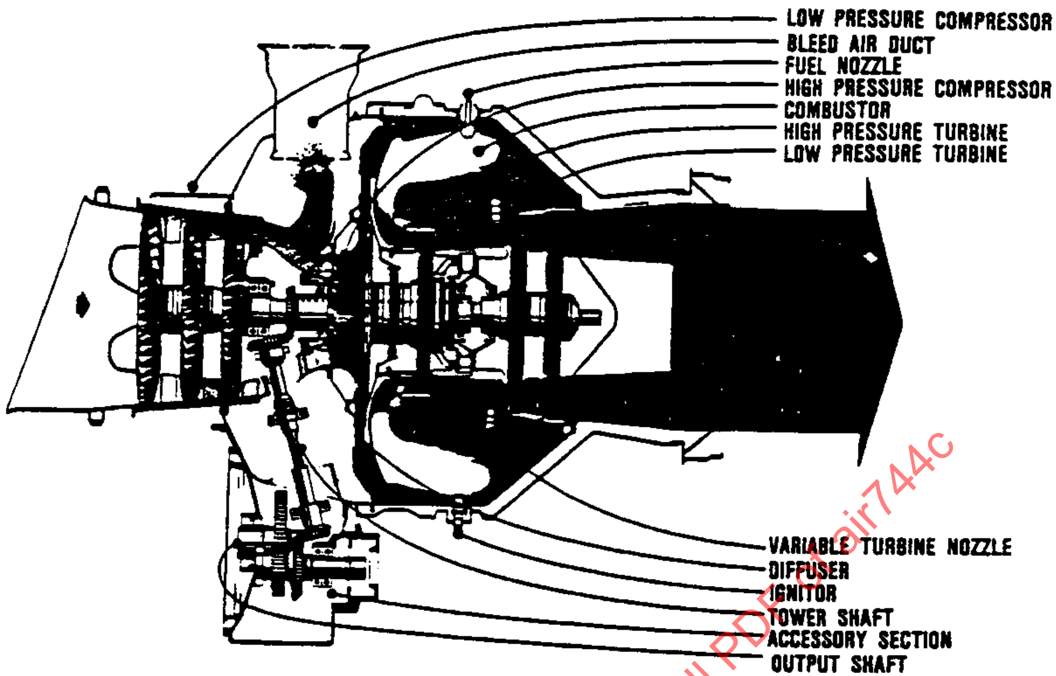


FIGURE 12 - CROSS-SECTIOIN OF A TWO-SPOOL APU

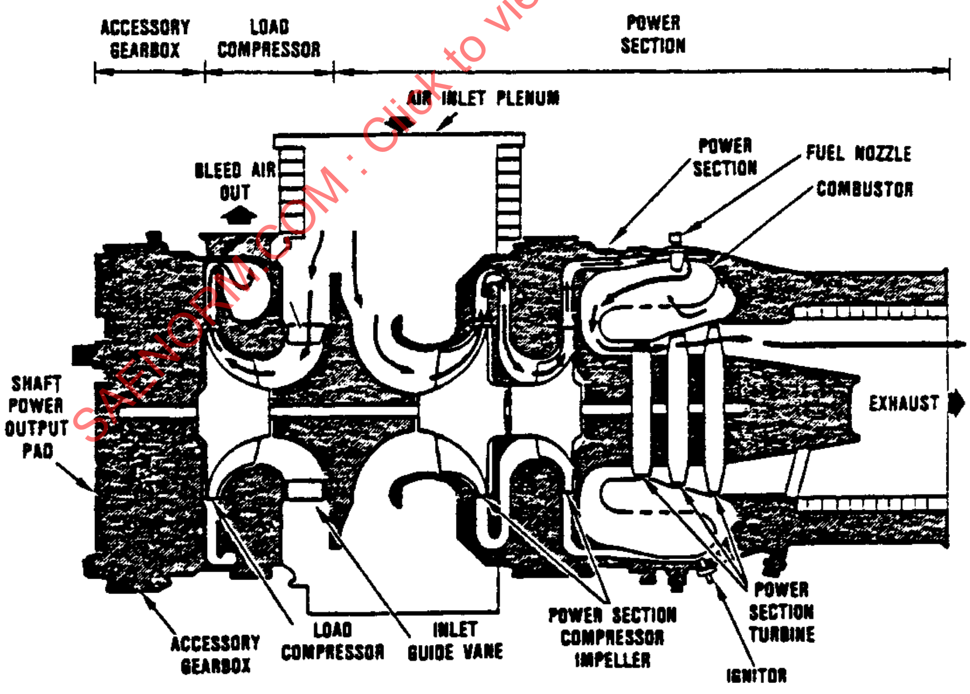


FIGURE 13 - CROSS-SECTION OF A LOAD COMPRESSOR APU

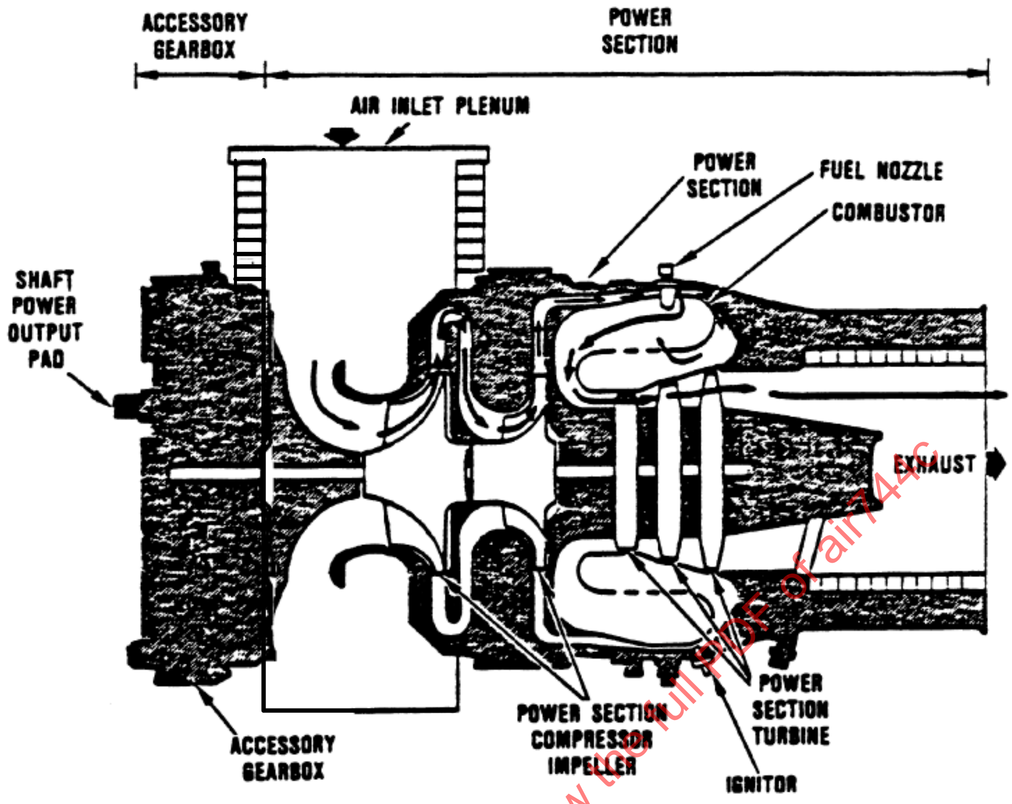


FIGURE 14 - Cross-Section of a Single-Spool, Shaft- Only- Load, APU

Unique to the load compressor APU is a driven load compressor assembly that supplies bleed air to the aircraft pneumatic system. Shaft power produced by the APU power section is used to drive the load compressor.

A description of the three basic types of APUs follows:

a. Integral Bleed: The cross section of an integral bleed APU is shown in Figure 10. In this example, the single-shaft constant speed power section includes a low-pressure ratio single-stage centrifugal compressor, a reverse-flow annular combustor, and a two-stage axial turbine. The APU operates at a low cycle pressure ratio (P/P = 3 to 4) for compatibility of the APU bleed air with the aircraft relatively low-pressure pneumatic system.

   Pneumatic power output of the APU is regulated by a bleed air load control valve. Under combined shaft and pneumatic load conditions, the load control valve will modulate to limit the quantity of bleed air delivered and prevent an excessive load from being placed on the APU.

b. Two-Spool Integral Bleed APU: The construction of a two-spool integral bleed APU is shown in Figure 12. The two rotating spools are mounted concentrically on separate bearings. The high-pressure spool operates at a fixed rotational speed (N_2), while the low-pressure spool operates over a controlled speed (N_1) range.

   In this example, the high-pressure spool has a single-stage centrifugal compressor driven by a single-stage axial flow turbine. Constant frequency power generated by the high-pressure spool is transferred through a tower shaft to drive the accessory gearbox and aircraft accessory equipment. The three-stage axial flow compressor of the low-pressure spool is driven by a two-stage axial flow turbine. Low pressure bleed air is extracted from the APU through bleed ports located between the last stage of the low-pressure compressor and the inlet to the high-pressure compressor. The quantity and pressure of the bleed air is varied by increasing or decreasing the rotational speed (N_1) of the low pressure spool. Speed of the low pressure spool (N_1) is controlled by the variable flow feature of the low pressure turbine nozzle, which limits the energy developed by the low pressure turbine.

c. Load Compressor APUs: The load compressor APU shown in Figure 13 comprises a constant speed, single-shaft power section driving a single-stage centrifugal load compressor and accessory gearbox. This APU configuration differs from an integral bleed APU because pressurized bleed air is supplied by the driven load compressor and not by the power section. Since the APU power section does not provide low pressure bleed air, the power section cycle pressure ratio can be increased to take advantage of higher turbine inlet temperatures for more fuel efficient operation.

   Control of the bleed airflow from the load compressor is accomplished using variable position inlet guide vanes at the load compressor inlet. The position of the inlet guide vanes is controlled by an ECU that receives information on bleed air demand from flow sensors located at the bleed air discharge port. At part-load conditions (reduced bleed airflow demand), fuel consumption is minimized by partially closing the load compressor inlet guide vanes, thereby reducing the shaft load on the power section.

   Excess shaft power developed by the power section, which is not absorbed by the driven load compressor, is used to drive the accessory gearbox and aircraft accessory equipment.

d. Single-spool, shaft- only- load, APU: The Single-spool, shaft- only- load, APU shown in Figure 14 comprises of a single rotating shaft power section driving a load (electrical, hydraulic, etc) directly or through an accessory. The power-head section compressor(s) pressure ratio need not be limited to 3- 4 to match the aircraft's air cycle environmental control system. The compressor pressure ratio may be higher to achieve the best balance between cycle efficiency, mechanical simplicity, noise, emission and manufacturing cost.

14.2 Applications

Gas turbine APUs are used on commercial and military aircraft as an efficient source of mechanical and pneumatic secondary power. Secondary power is defined as the power not associated with the propulsion of the aircraft. Aircraft equipped with an on-board APU are termed "self-sufficient" because these aircraft can operate worldwide without ground support equipment at each destination. An APU also minimizes main engine operating time and fuel consumption, resulting in lower aircraft operating costs.

Typically, APUs are used during aircraft ground operations to generate electrical power for avionics, cabin lighting, and other auxiliary loads, and to provide compressed bleed air for main engine starting and cabin air-conditioning. In flight, the APU may serve as a source of emergency electrical or hydraulic power in the event of a main engine or auxiliary equipment malfunction. Additionally, APU bleed air can be used in flight for cabin pressurization and main engine starting assist.

APUs are available in a wide range of size and power ratings. An APU used in small business aircraft can supply 10 hp (7 kW) and 12.6 lb/min (5.7 kg/min) of bleed air[1] and weighs only 60 lb (27 kg). The largest APU currently produced, which is used in the Boeing 747 and E-4 aircraft, delivers 65 hp (48 kW) and 507 lb/min[1] (230 kg/min) of bleed air and has a dry weight of 579 lb (263 kg).

SPSs for tactical and strategic military aircraft must be optimized for weight, volume, and performance. Optimization of the SPS is achieved by integrating the power-producing components (i.e., main engines and APU) with the power distribution system to minimize power transfer losses.

Figure 15 shows an example of the highly integrated SPS design used on the U.S. Air Force B-1B aircraft. The primary functions of this system are to provide aircraft self-sufficiency for ground checkout, alert readiness, and main engine starting. Each B-1B includes two SPS units (Figure 15), one in each of the two dual-engine nacelles. The APU can selectively power each of the two accessory drive gearboxes (ADGs). During ground checkout, the right ADG is mechanically driven by the APU for electrical and hydraulic power. The left ADG is pneumatically driven by an ATS for starting the left main engine. Once the four main engines have been started, each ADG is driven by a main engine via a power takeoff (PTO) shaft, and the APUs are disengaged from the respective right hand ADGs by clutches. APU bleed air also is used during ground systems checkout for cabin and avionics heating or cooling.

[1] Performance for uninstalled APU at sea level, 100 °F (38 °C) conditions.

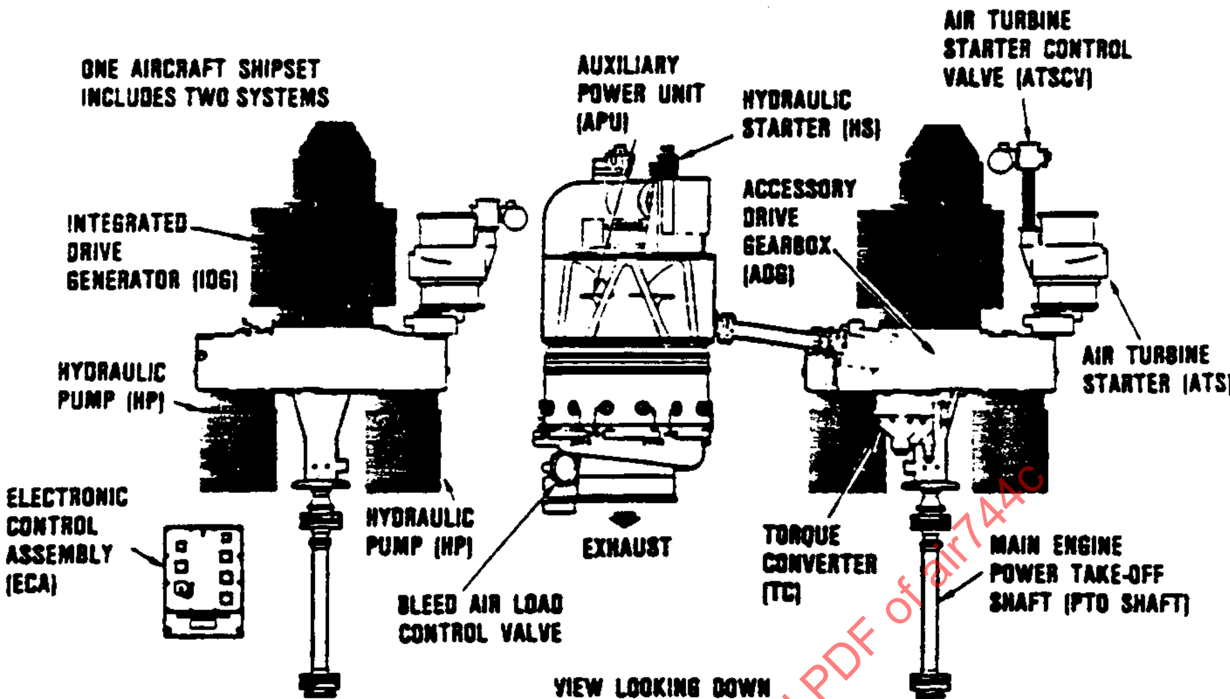


FIGURE 15 - SECONDARY POWER SYSTEM FOR U.S. AIR FORCE B-1B

14.3 APU Installations

Proper design of the APU installation will afford greater dividends to the aircraft operator in the form of better operation and performance, improved reliability, reduced maintenance, and longer service life.

The design of an aircraft APU installation occasionally suffers because of the tendency to regard the APU as just another accessory, whereas in fact, it is one more gas turbine engine on the aircraft and should be treated as such. Current APUs are state-of-the-art gas turbine engines with all of the characteristics, requirements, and complexities of main propulsion engines. Sometimes, design of an APU installation is more difficult than that of the main engines. Reasons for this include such items as increased complexities in the associated systems resulting from APU location within the fuselage, and remote location of fuel and electrical sources.

Numerous considerations of interfacing between the APU and aircraft must be carefully analyzed for the design of a successful APU installation. Table 13 lists the interface considerations applicable to most APU installations, and a brief discussion of some important items is provided in the following paragraphs.

TABLE 13 - APU/AIRCRAFT INTERFACE CONSIDERATIONS

APU Location
Compartment Design
Accessibility and Maintainability
Air Inlet and Exhaust Port Locations
APU Mounting
APU Fuel Supply System
APU Lubrication System
Electrical Power Generation and Distribution
Safety
Pneumatic System Compatibility
APU Starting
APU Performance
Weight
Accessory Equipment Requirements
Cockpit Instrumentation
Fire Detection and Extinguishing
Acoustics
Ecology

a. APU Location: APUs have been installed in a variety of locations on different aircraft depending on the intended use, including:

1. Tailcone
2. Wheel wells or wheel sponsons
3. Engine nacelles
4. Cargo bays
5. Wing roots
6. External enclosures
7. Other fuselage locations

Many significant factors must be considered in selection of the APU installation location, and even the final choice will usually involve some degree of compromise.

Every effort should be made to avoid locating the APU in close proximity to critical aircraft systems such as fuel tanks, oxygen systems, primary flight controls, hydraulic systems, and fire extinguishing systems, as well as passengers and crew. In addition to potential fire hazards, the possibility of destructive mechanical failures within the compartment should be considered.

Most APU installations are located in the fuselage in an unpressurized area (Figure 16).

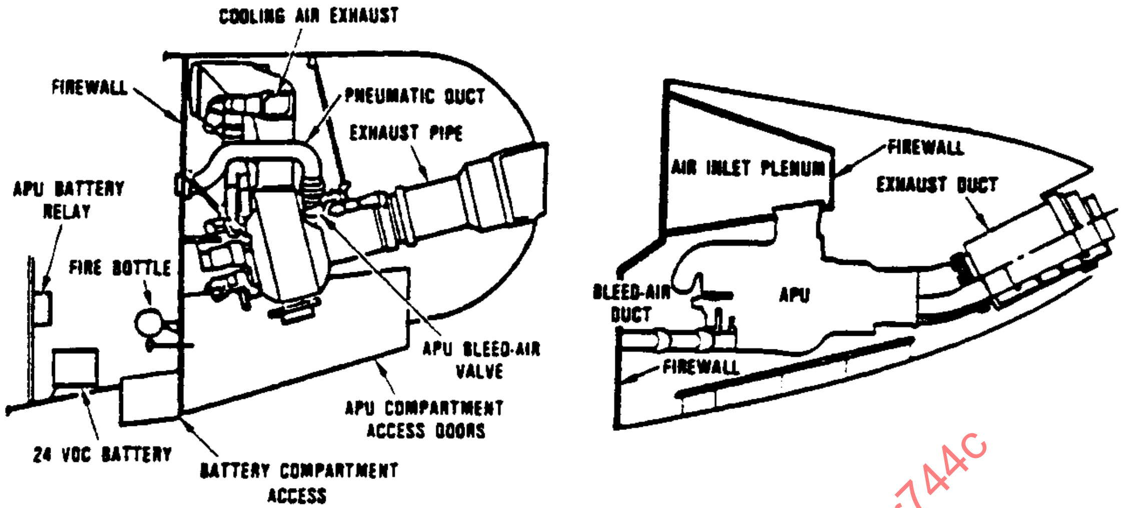


FIGURE 16 - TYPICAL APU TAILCONE INSTALLATIONS

b. Air Inlet and Exhaust Port Locations: The air inlet and exhaust ports should be separated by as much distance as reasonably possible, or separated by some existing barrier on the aircraft, to preclude ingestion of hot APU exhaust gases into the air inlet. The location of the inlet also should minimize the possibility of ingestion of foreign objects and fluids such as airplane washing solvents. The least favorable inlet location is well aft on the bottom surface of the fuselage where water, mud, ice, and other runway debris may be thrown up by the tires or thrust reversers, or sucked into the inlet during maximum rotation of the aircraft through takeoff.

For acoustic reasons, the APU inlet and exhaust discharge typically are directed upward to minimize noise exposure to passengers and ground crew.

Another factor that must be considered is in-flight pressure differential between the APU inlet and exhaust ports. The air inlet should be located in a region of pressure slightly higher than at the exhaust outlet (positive ΔP). The opposite condition (negative ΔP) will decrease APU performance and make in-flight starting difficult or impossible. When the APU is not operating in-flight, a negative DP can produce reverse windmilling, which is damaging to the APU if the installation is not provided with a suitable inlet or exhaust door.

c. APU Compartment Design: The APU compartment, like the main engine nacelles, is designated a fire zone by the FAA. The APU compartment or enclosure must be fireproof and must include appropriate isolation devices (i.e., fire wall fuel shutoff valves) and a fire detection/extinguishing system. Materials considered suitable for fire wall construction are stainless steel at least 0.015 in (0.38 mm) thick or titanium 0.020 in (0.51 mm) thick. The fire wall should not be stressed with air loads or loads from mounted equipment such that early failure could occur due to loss of strength, even though flame penetration may not be imminent.

d. APU Mounting: Aircraft structure in the immediate vicinity of the APU must be suitable for attaching the APU mounting system. The structure also must be adequate to resist loads from the mount system throughout all flight and APU operating conditions.

The APU mounting system may either be statically determinate or redundant. A statically determinate system has six stable restraints and may utilize either resilient or rigid suspension mounting. A redundant system is one having more than six stable restraints and only resilient mounts. Examples of APU mounting arrangements are shown in Figure 17.

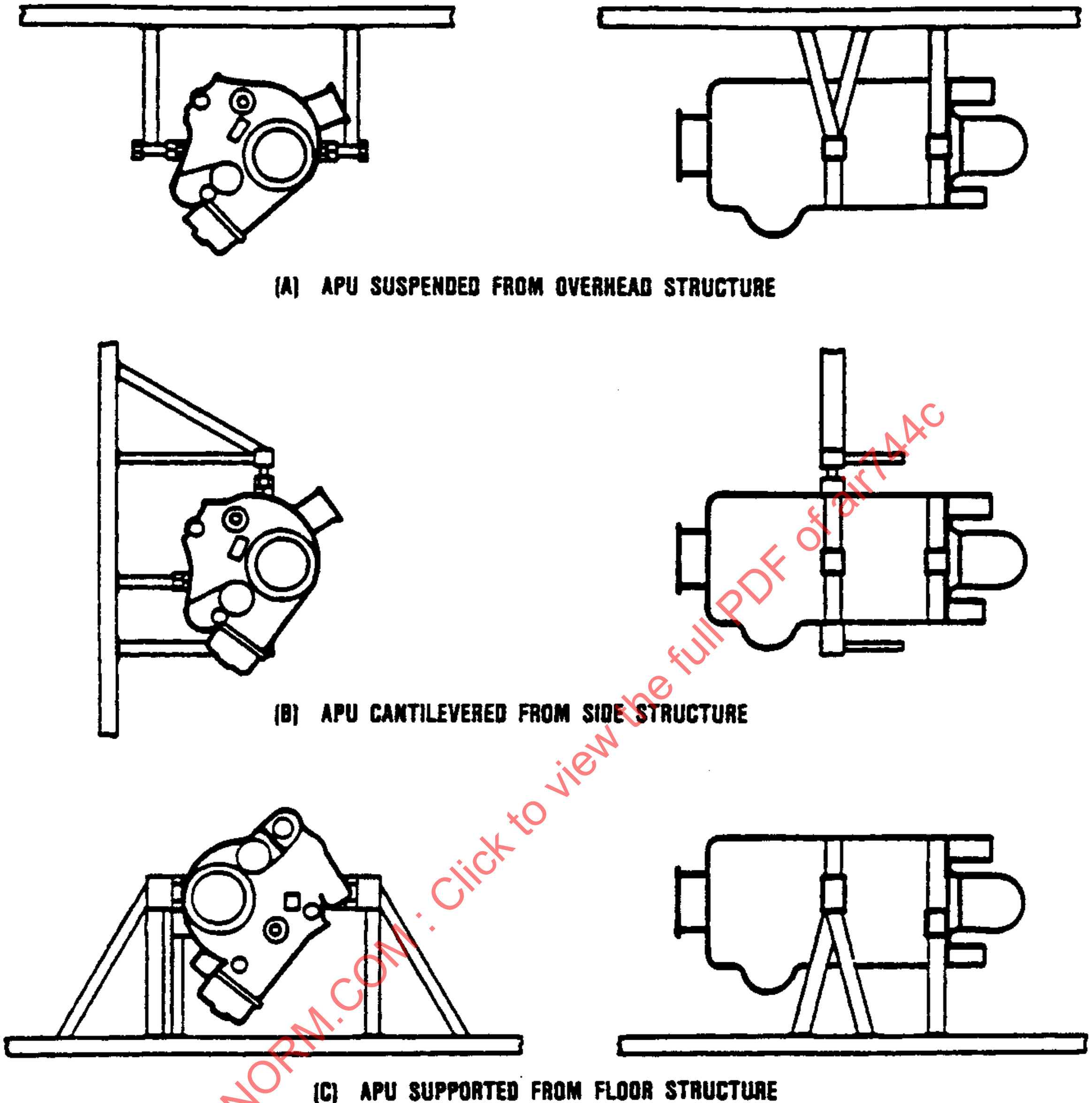


FIGURE 17 - EXAMPLES OF MOUNTING ARRANGEMENTS

e. Fuel Supply System: Filtered fuel should be supplied to the APU free of vapor and at sufficient pressure to assure proper performance from sea level to operating altitudes over the required range of fuel temperatures.

A typical APU fuel supply system is shown in Figure 18. The aircraft portion of the fuel system includes a DC boost pump with pressure regulating valve, a bypass check valve, a solenoid-operated shutoff valve incorporating a thermal relief feature, and a fuel filter with bypass. The APU includes a fuel inlet port, fuel control seal cavity drain port, and turbine plenum drain. The boost pump should have a maximum capacity 30% greater than APU maximum fuel requirements. The fuel supply system should maintain a positive head of fuel at the APU fuel inlet port, even when the boost pump is not operating.

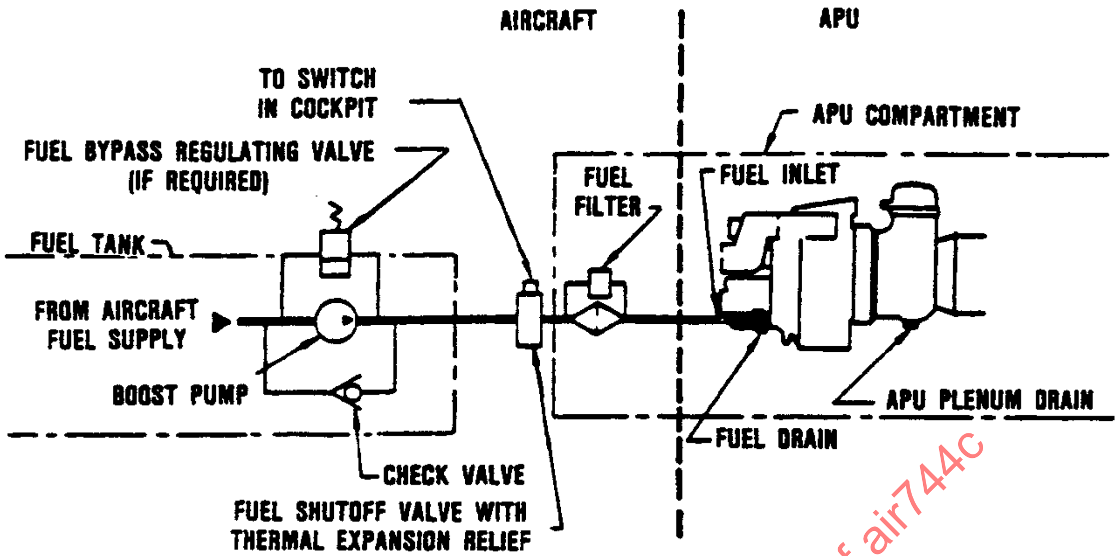


FIGURE 18 - TYPICAL APU FUEL SUPPLY SYSTEM

APUs can operate on the same fuels as the main engines:

1. MIL-T-5624 (Grade JP-4 and JP-5)

2. ASTM D 1655 (Types Jet A, B, and A-1)

   Aviation gasoline per MIL-G-5572 may be used for short durations as an emergency fuel.

   Typically, the maximum fuel temperature limit is 135 °F (57 °C), while the lower fuel temperature limit is restricted to an equivalent viscosity no lower than 12 cst.

f. Lubrication System: APUs are designed to use synthetic oils, per MIL-L-7808 or MIL-L-23699. No changes in lubricants or additives are required throughout the entire operating range. With few exceptions, the same lubricant used in the main engines can be used in the APU. A list of approved lubricants is published by the APU manufacturer.

The lubrication system is a positive-pressure type that provides lubrication for the gears and bearings within the gas turbine and accessory drives. The oil system usually consists of an oil pump, oil sump or tank, oil cooler, pressure regulating valve, oil filter, associated plumbing, and various oil jets within the gas turbine. Some APUs also incorporate the lubrication and oil cooling system for an aircraft-furnished oil-cooled generator.

Aircraft connections to the APU lubrication system typically include:

1. Pressure sensor

2. Temperature sensor

3. Reservoir/sump drains

4. Reservoir scupper drain (if used)

5. Oil filter ΔP (if used)

6. Oil level sensor (if used)

7. Chip detector sensor (if used)

g. Electrical System: Most APUs utilize a DC electrical system. However, in installations that use hydraulic APU starting without an on-board battery, the APU incorporates a PMG that supplies AC electrical power. The AC power is rectified to DC power for the APU DC electrical system.

The APU electrical components consist of solenoids, switches, sensors, and a capacitive discharge ignition unit. The amount of power required depends on the combination of devices needed for starting and loading the APU.

h. Bleed-Air System: The bleed-air ducting should be compatible with the bleed air temperature, pressure, and flow from the APU and should be fabricated of fireproof materials. Duct sizing should not create undue pressure losses that would degrade the performance of the aircraft pneumatic system.

i. APU Control Panels: The extent of control panel functions and displays widely varies depending on installation requirements. Typical APU control panels for the cockpit and remote ground operation are shown in Figure 19. At a minimum, the cockpit control panel should include:

1. Master switch
2. Start/stop switch
3. EGT indicator
4. APU speed (rpm) indicator
5. Indication of any fault protection device operation
6. Bleed-air selector switch
7. Switches for selecting operation of any accessory loads such as an alternator, HP, and battery charging
8. Fire warning indicator and extinguishing agent discharge controls

On many modern aircraft, APU monitoring such as speed and temperature indications have been integrated into the aircraft CRT displays. The CRT display can be programmed to come up only if specified Limits are exceeded, thereby considerably reducing the complexity of the APU control panel and also reducing the workload on the pilots. This simplified APU control panel is illustrated in Figure 20.

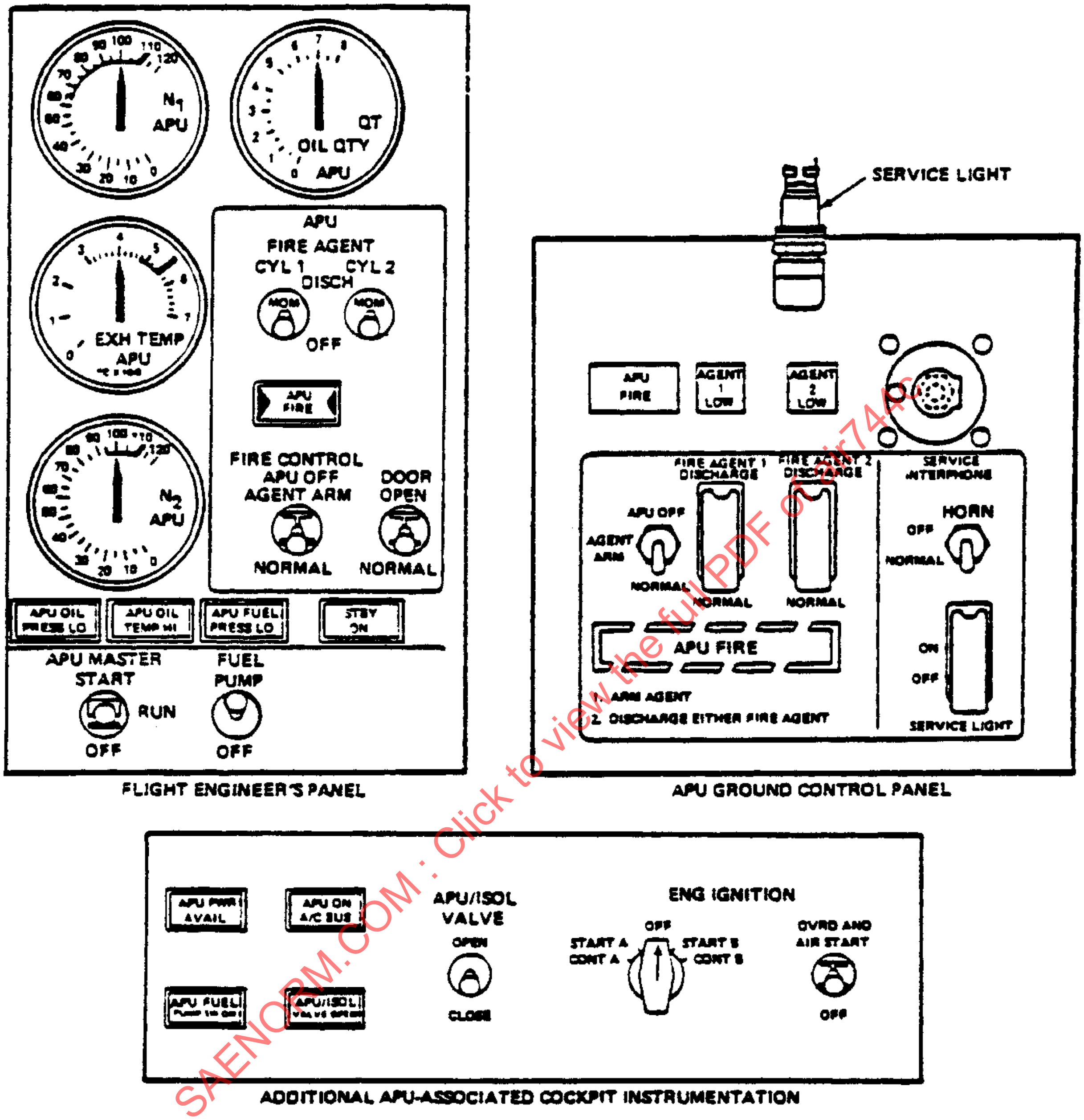


FIGURE 19 - TYPICAL APU CONTROL PANELS (DC-10)

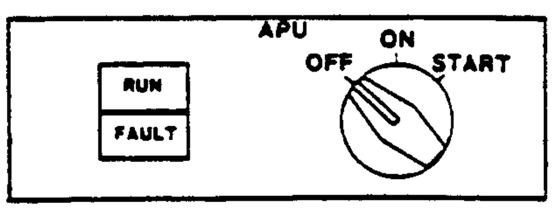


FIGURE 20 - APU SIMPLIFIED CONTROL PANEL (B-767)

14.4 APU Performance

The purpose of this section is to describe typical APU performance characteristics and the effects of APU installation and aircraft flight conditions on APU performance. Topics covered include:

a. Uninstalled APU performance

b. Ambient pressure and temperature

c. Exhaust gas back pressure

d. Performance correction factors

e. APU in-flight performance

14.4.1 Uninstalled APU Performance

Generalized performance characteristics for an uninstalled[2] constant speed, single-shaft integral-bleed gas turbine APU are shown as a function of inlet air temperature and pressure conditions in Figure 20. The performance shown is at the maximum EGT condition. APU bleed airflow, bleed air pressure, and fuel consumption can be delta (δ)-corrected to estimate performance up to a pressure altitude of 15 000 ft (4572 m), where δ is defined as shown in Equation 7:

$$\delta = \frac{\text{APU Inlet Total Air Pressure, psia}}{\text{14.696 psia}} \qquad \text{(Eq. 7)}$$

Uninstalled performance for a two-spool APU (Figure 21) also varies as a function of low-pressure spool speed (N_1). High-pressure spool speed (N_2) is held constant to supply accessory shaft power to drive a constant-frequency 400 Hz electrical generator.

Uninstalled performance for a constant-speed, single-shaft load compressor APU is shown in Figure 22. The APU matches the bleed air demand by varying the position of the load compressor inlet guide vanes.

14.4.2 Ambient Pressure and Temperature

As indicated by Figures 20, 21, and 22, APU bleed air performance is affected by ambient pressure and temperature. Additionally, the amount of output shaft power produced also is affected by ambient pressure and temperature. The general characteristics of ambient conditions on maximum APU performance (i.e., maximum EGT) are:

a. For constant output shaft power, the maximum bleed airflow, W_B, and bleed air pressure, P_B, decrease with increased altitude (decreased ambient pressure).

b. For constant output shaft power, the maximum bleed airflow, W_B, and bleed air pressure, P_B, decrease with increased ambient temperature.

c. For constant ambient pressure and temperature conditions, bleed airflow, W_B, decreases and bleed air pressure, P_B, increases with increased output shaft power (integral-bleed APUs only)

d. At no-bleed conditions, the maximum output shaft power produced decreases with increased altitude (decreased ambient pressure)

e. At no-bleed conditions, the maximum output shaft power produced decreases with increased ambient temperature

[2] Uninstalled APU performance refers to the basic APU without inlet air pressure losses, exhaust gas back pressure, or inlet air heating effects.

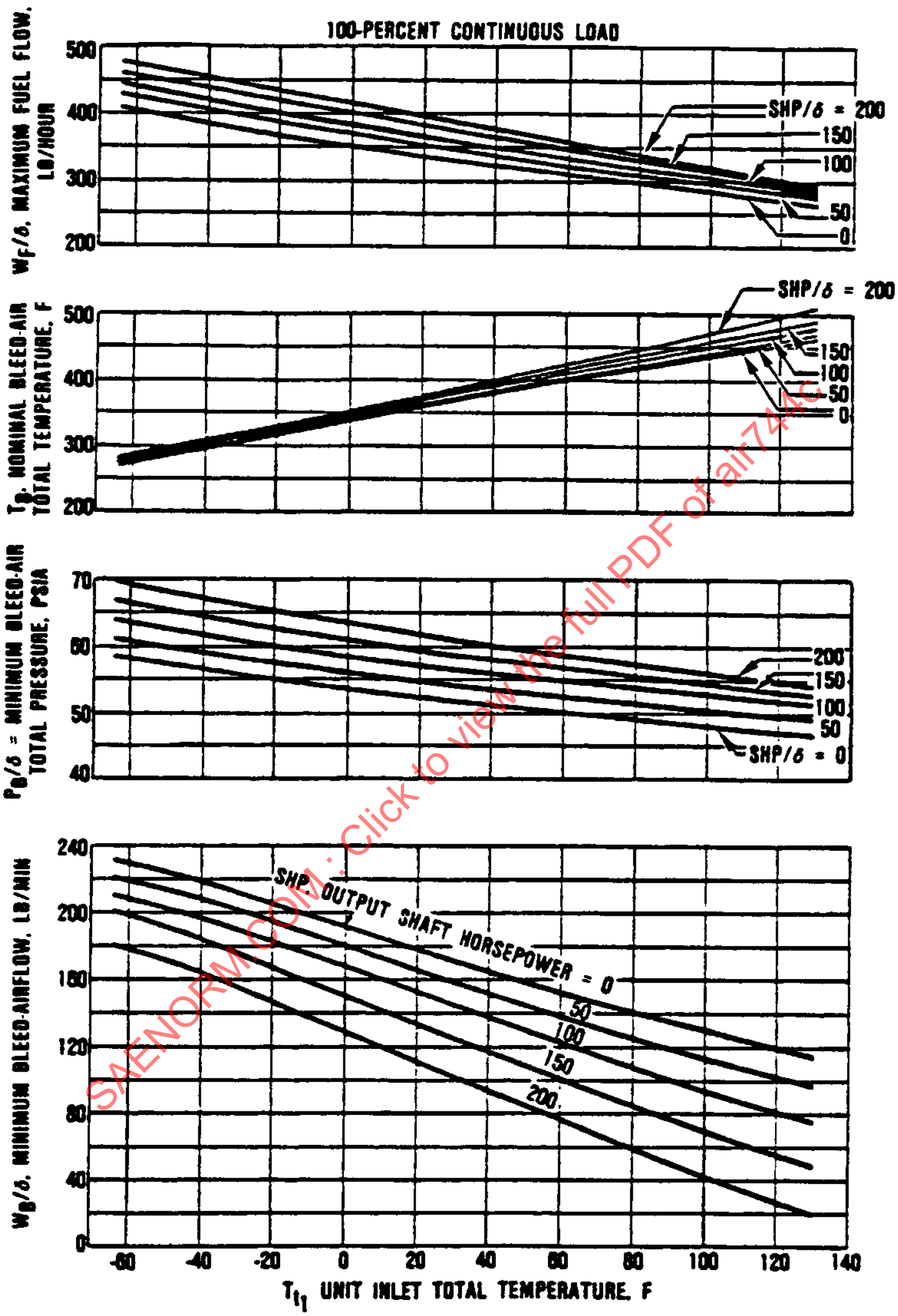
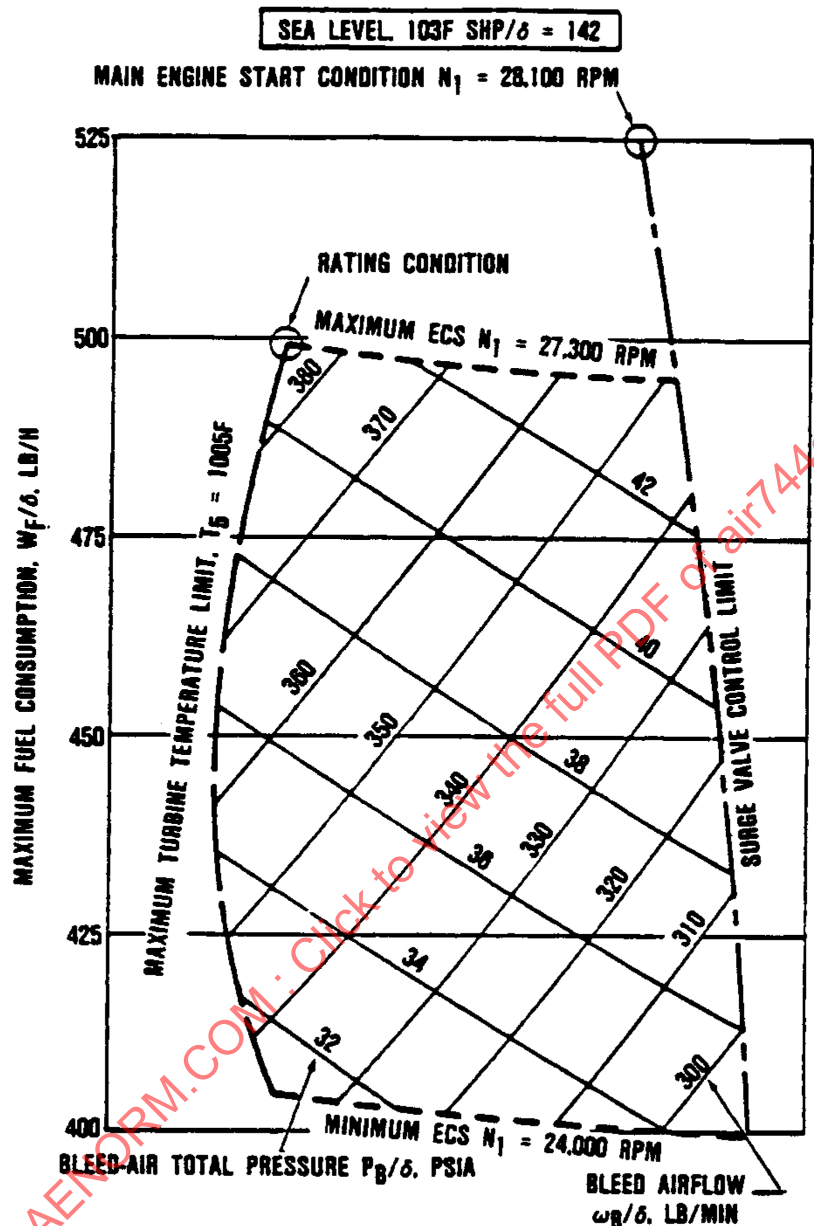


FIGURE 21 - TYPICAL SINGLE-SHAFT INTEGRAL-BLEED APU PERFORMANCE
(MAXIMUM EGT CONDITION)



NOTE:

SL IDLE RATING: T_{T_1} = 103F

N_1 = 17,800 RPM

SHAFT HP = 142, FUEL FLOW = 294 LB/H

SHAFT HP = 0, FUEL FLOW = 221 LB/H

FIGURE 22 - TYPICAL TWO-SPOOL APU PERFORMANCE

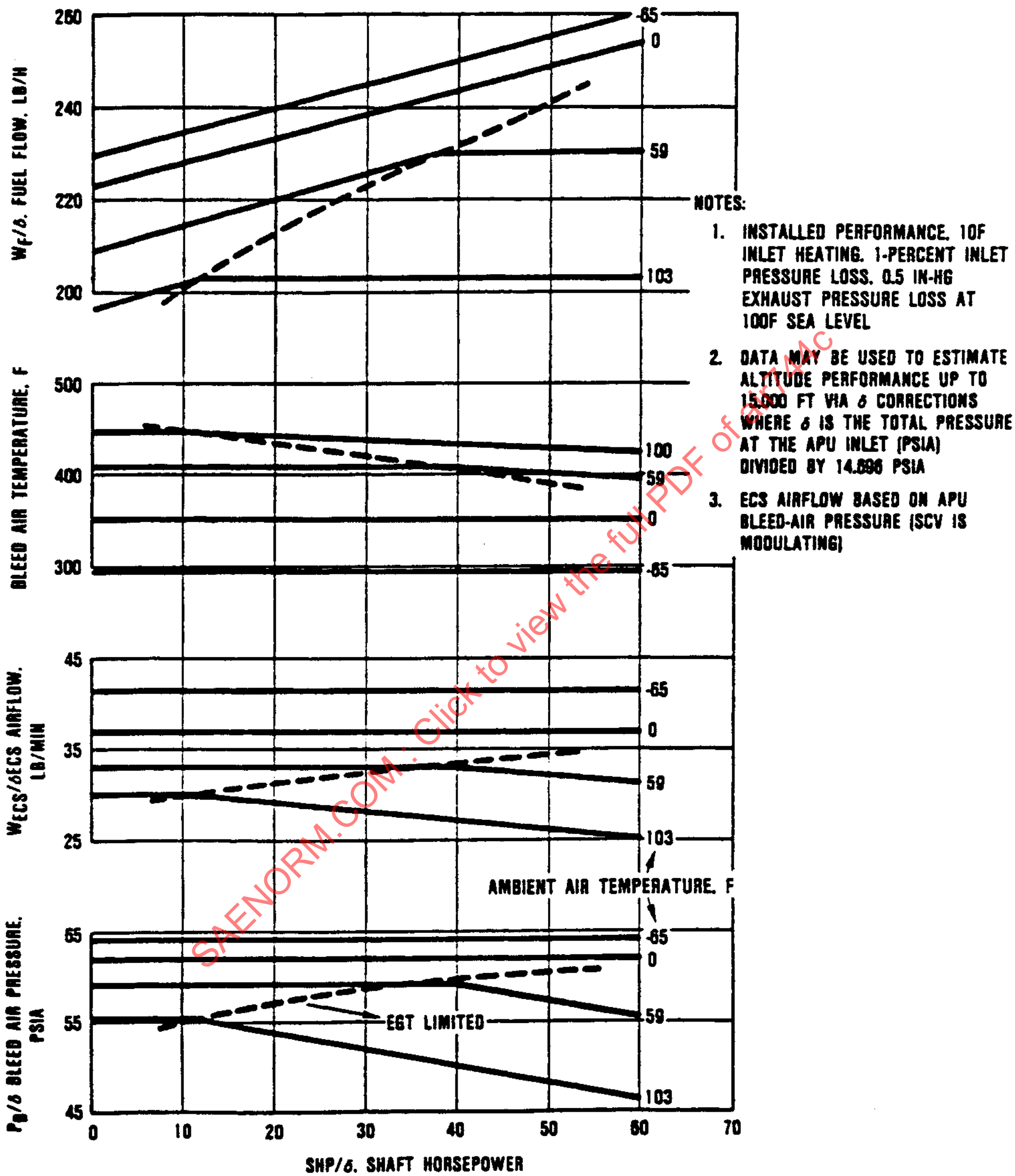


FIGURE 23 - TYPICAL PERFORMANCE FOR LOAD COMPRESSOR APU