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Aerospace Auxiliary Power Sources

RATIONALE

This document is in excellent shape to reflect most current characteristics of auxiliary power sources; there is no need for immediate revision or update.

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TABLE OF CONTENTS

1.	SCOPE.....	4
2.	REFERENCES.....	4
2.1	SAE Publications.....	4
2.2	U.S. Government Publications.....	4
2.3	ASTM Publications.....	4
2.4	DOT Publications.....	5
2.5	RTCA Publications.....	5
2.6	Acronyms and Abbreviations.....	5
3.	TYPES OF POWER SOURCES.....	6
4.	REQUIREMENTS FOR POWER SOURCES.....	7
4.1	General.....	7
4.2	Definition of Requirements.....	7
4.3	Power Source Selection.....	8
5.	SOLID PROPELLANTS.....	9
5.1	Description.....	9
5.2	Applications.....	9
5.3	Components.....	10
5.4	Advantages.....	13
5.5	Disadvantages.....	13
5.6	Developing Technology.....	14
6.	LIQUID PROPELLANTS.....	14
6.1	Description.....	14
6.2	Applications.....	14
6.3	Components.....	15
7.	HIGH PRESSURE STORED GAS SYSTEM.....	18
7.1	Description.....	18
7.2	Applications.....	18
7.3	Components.....	18
7.4	Sizing the Container.....	19
7.5	Advantages.....	22
7.6	Disadvantages.....	22

8.	ENGINE BLEED SYSTEMS	23
8.1	Description	23
8.2	Applications	24
8.3	Systems and Component Detail and Description (General)	24
9.	RAM AIR TURBINES	29
9.1	Description	29
9.2	Applications	29
9.3	Performance Characteristics	31
9.4	Advantages	35
9.5	Disadvantages	36
10.	BATTERIES	36
10.1	Description	36
10.2	Primary Batteries	36
10.3	Secondary Batteries	37
10.4	Common Battery Types	37
10.5	Application Terminology	37
10.6	Applications	38
10.7	Development Batteries	43
11.	FUEL CELLS	44
11.1	Description	44
11.2	Applications	45
11.3	Components	46
11.4	Advantages	46
11.5	Disadvantages	47
12.	SOLAR CELLS	47
12.1	Description	47
12.2	Applications	49
12.3	Components	49
12.4	Performance	49
12.5	Advantages	49
12.6	Disadvantages	49
13.	NUCLEAR POWER SYSTEMS	50
13.1	Description	50
13.2	Applications	50
13.3	Components	50
13.4	Advantages	52
13.5	Disadvantages	52
14.	GAS TURBINE AUXILIARY POWER UNITS (APUS)	53
14.1	Description	53
14.2	Applications	57
14.3	APU Installations	58
14.4	APU Performance	65
14.4.1	Uninstalled APU Performance	65
14.4.2	Ambient Pressure and Temperature	65
14.4.3	Exhaust Gas Back Pressure	69
14.4.4	Performance Correction Factors	69
14.4.5	APU In-Flight Performance	69
14.5	Advantages of an On-Board APU	69
14.6	Disadvantages of an On-Board APU	71
15.	FLYWHEELS	71
15.1	Description	71
15.2	Applications	72
15.3	Component Detail Design	74
16.	NOTES	85

FIGURE 1	REPRESENTATIVE TRACES OF STORED GAS TIME VERSUS PRESSURE DURING OPERATION.....	20
FIGURE 2	DENSITY OF NITROGEN VERSUS TEMPERATURE (AT VARIOUS PRESSURES IN PSIA)	21
FIGURE 3	ENGINE/SYSTEMS INTERFACES AND THEIR EFFECTS.....	24
FIGURE 4	BLEED STUDY OF THE JT9D-3A ENGINE, STANDARD DAY CONDITIONS	27
FIGURE 5	BLEED AIR CHARACTERISTICS OF THE JTD9D-3A ENGINE	28
FIGURE 6	SENSITIVITY CURVES FOR THE A1SA BPR-280024 ENGINE	30
FIGURE 7	GENERALIZED TURBINE POWER COEFFICIENT CHARACTERISTICS VERSUS N/V_0 FOR A FREESTREAM TURBINE.....	33
FIGURE 8	GENERALIZED TORQUE CHARACTERISTICS FOR HIGH- AND LOW-SOLIDITY TURBINES HAVING THE SAME BLADE SWEEP AREA AND SAME OPERATING AIRSPEED.....	35
FIGURE 9	ALKALINE FUEL CELL CONCEPT	46
FIGURE 10	TYPICAL AIRCRAFT PNEUMATIC SYSTEM.....	53
FIGURE 11	CROSS-SECTION OF AN INTEGRAL BLEED AIR APU	54
FIGURE 12	CROSS-SECTION OF A TWO-SPOOL APU	55
FIGURE 13	CROSS-SECTION OF A LOAD COMPRESSOR APU	55
FIGURE 14	CROSS-SECTION OF A SINGLE-SPOOL, SHAFT- ONLY- LOAD, APU	56
FIGURE 15	SECONDARY POWER SYSTEM FOR U.S. AIR FORCE B-1B	58
FIGURE 16	TYPICAL APU TAILCONE INSTALLATIONS	60
FIGURE 17	EXAMPLES OF MOUNTING ARRANGEMENTS	61
FIGURE 18	TYPICAL APU FUEL SUPPLY SYSTEM	62
FIGURE 19	TYPICAL APU CONTROL PANELS (DC-10).....	64
FIGURE 20	APU SIMPLIFIED CONTROL PANEL (B-767).....	64
FIGURE 21	TYPICAL SINGLE-SHAFT INTEGRAL-BLEED APU PERFORMANCE (MAXIMUM EGT CONDITION).....	66
FIGURE 22	TYPICAL TWO-SPOOL APU PERFORMANCE	67
FIGURE 23	TYPICAL PERFORMANCE FOR LOAD COMPRESSOR APU	68
FIGURE 24	TYPICAL CORRECTION FACTOR CURVES.....	70
FIGURE 25	TYPICAL STARTING AND OPERATING ENVELOPE WITH 100% RAM RECOVERY	71
FIGURE 26	COMPARATIVE PRACTICAL ENERGY STORAGE CAPABILITIES	73
FIGURE 27	COMPARATIVE POWER EXTRACTION CHARACTERISTICS AND EFFICIENCY	73
FIGURE 28	FLYWHEEL SHAPE FACTORS FOR VARIOUS GEOMETRIES	76
FIGURE 29	FLYWHEEL SPEED REDUCTION CHARACTERISTICS.....	78
FIGURE 30	SOLID UNIFORM STRESS DISK FLYWHEEL GEOMETRY OPTIMIZATION CHART	81
TABLE 1	TYPICAL SOLID PROPELLANTS FOR GAS GENERATORS	11
TABLE 2	MONOPROPELLANT CHARACTERISTICS.....	16
TABLE 3	TYPICAL BIPROPELLANT CHARACTERISTICS.....	17
TABLE 4	ADVANTAGES AND DISADVANTAGES OF BLEED AIR APPLICATION	23
TABLE 5	COMPUTATION OF POWER AVAILABILITY	25
TABLE 6	TYPICAL DATA FOR AIRCRAFT ENGINE JT3D-3B.....	26
TABLE 7	TURBINE POWER COEFFICIENTS	32
TABLE 8	COMMON BATTERY TYPES.....	37
TABLE 9	COMPARISON OF PRIMARY BATTERIES.....	39
TABLE 10	COMPARISON OF SECONDARY BATTERIES	42
TABLE 11	SUMMARY TABLE	44
TABLE 12	TYPES OF FUEL CELLS.....	45
TABLE 13	APU/AIRCRAFT INTERFACE CONSIDERATIONS.....	59
TABLE 14	FLYWHEEL MATERIAL PROPERTIES	74
TABLE 15	FLYWHEEL GEOMETRY FOR AN OPTIMIZED DISK	79

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 condensable 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, $\frac{\text{lbf} \cdot \text{s}}{\text{lbm}}$	180-195	170-200	200-215	180-190	180-190
Gas Temperature, °F (°C)	1800-2600 (980-1400)	1500-2200 (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 ₂ O, CO, CO ₂ , N ₂ , small quantities metal oxides	H ₂ , H ₂ O, CO, CO ₂ , CH ₄ , N ₂ , small quantities metal oxides	H ₂ , H ₂ O, CO, CO ₂ , CH ₄ , HCl, some solid carbon and metal compounds	CO, CO ₂ , H ₂ O, N ₂ , H ₂ , HCl, some solid carbon and metal oxides	CO, H ₂ , some solid carbon, KCl, and liquid KCl
Formula Density, $\frac{\text{lb}}{\text{in}^3}$ ($\frac{\text{kg}}{\text{dm}^3}$)	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 ($P \geq 10,000$).	Useful for flight control, piston actuation, small thrusters. Acidic exhaust (HCl + H ₂ O) 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 ($P \geq 10,000$ 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, Nitroguan- idine	Metal Oxides	Nitroguanidine, TAGN, HMX
Specific Impulse, lbf · s lbfm	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 ₂ O, HC ₁ , H ₂ , N ₂ , some solid carbon	CO, H ₂ , N ₂ , H ₂ O, CO ₂ , some solid carbon, especially at low T _F	CO, H ₂ , N ₂ , CO ₂ , H ₂ O, CH ₄ , some solid carbon	N ₂ (only gas), Balance filterable	CO, H ₂ , N ₂ , CO ₂ , H ₂ O
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 perform- ance 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. Considera- tions may range from stabilizer depletion with age, and low tempera- ture 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 rhenium.

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% N₂H₄ and 30% H₂O, 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

Chemical Formula	Ethylene Oxide C_2H_6O	N-Propyl Nitrate $C_3H_7NO_3$	Otto Fuel II Classified	Anhydrous Hydrazine N_2H_4	Alkylated Hydrazine Blends $CH_3N_2H_3$, N_2H_4	Typical Nitrate Hydrazine Blends $CH_3N_2H_3$, N_2H_4 , $N_2H_5NO_3$	Hydrogen Peroxide 90% 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% HF 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 ₂ H ₄ CO ₂ , O ₂ CO ₁ , H ₂	C, CO, H ₂ , N ₂ CO ₂ , CH ₄ H ₂ O	C, CO ₂ , C ₂ H ₆ CO, N ₂ H ₂ HCN, H ₂ O, NO	N ₂ , H ₂ , NH ₃	N ₂ , H ₂ , C, CH ₄	N ₂ , H ₂ , C, CH ₄ , H ₂ O Trace CO	H ₂ O, O ₂

TABLE 3 - TYPICAL BIPROPELLANT CHARACTERISTICS

TABLE 3A

Chemical Formula	Fuel Hydrogen		Fuel JP-4		Fuel Monomethyl Hydrazine		Oxidizer Oxygen		Oxidizer Nitrogen Tetroxide	
	H ₂	C _{9.86} H ₁₉	CH ₃ NH NH ₂	O ₂	N ₂ O 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, 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

Oxidizer/Fuel (O/F) Ratio (Weight) for 1800 °F (982 °C) Gas	H ₂ -O ₂		JP4-O ₂		MMN-N ₂ O ₄	
	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 x 10 ⁻⁶	3.1 x 10 ⁻⁶	1.60 x 10 ⁻⁵			

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 "O-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:

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

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:

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

or

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

where:

ρ_o = Initial container gas fill density (lb/in³) (kg/m³)

ρ_f = Final gas density (lb/in³) (kg/m³)

This simply states that the change in gas mass ($\Delta m \sim \text{lb or kg}$) within the container during the blowdown process is equal to the volume of gas in the container ($V_c \sim \text{in}^3 \text{ or m}^3$) times the change in container gas density ($\rho_o - \rho_f$).

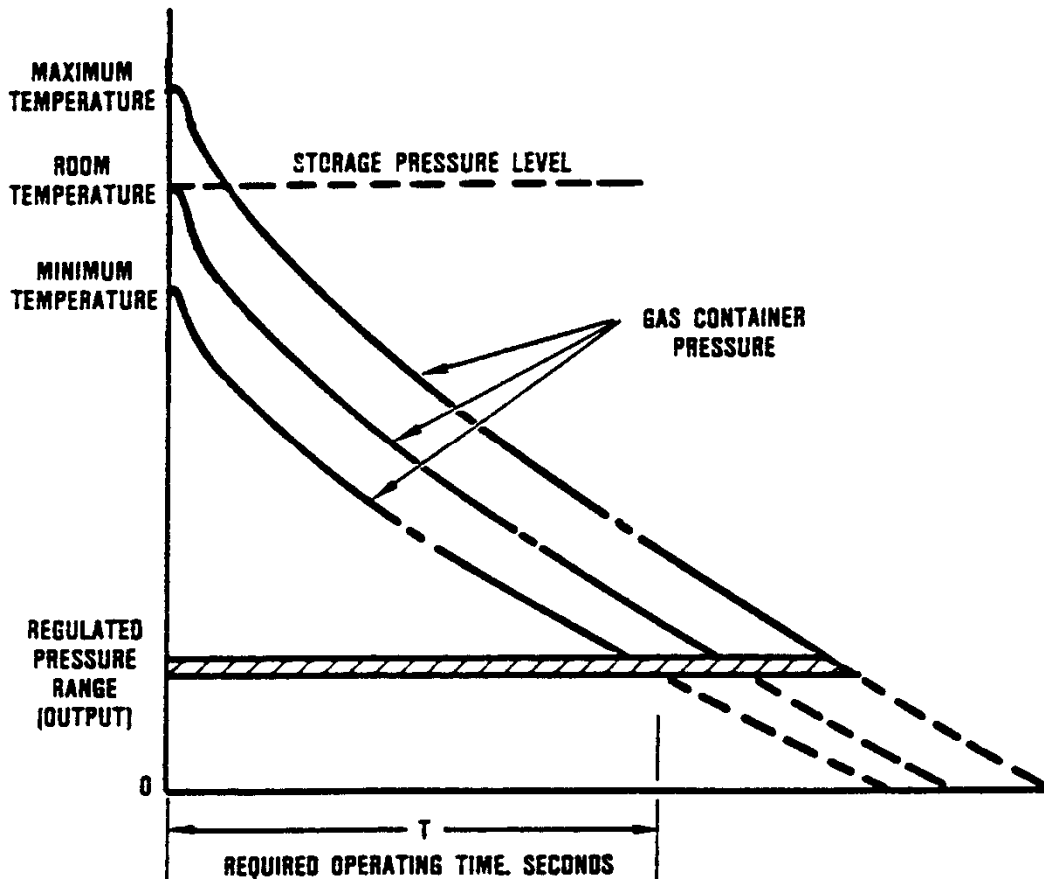


FIGURE 1 - REPRESENTATIVE TRACES OF STORED GAS TIME VERSUS PRESSURE DURING OPERATION

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_0) of 0.0167 lb/in³ (462.3 kg/m³) (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/in³ (108 kg/m³) (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/in³ (155 kg/m³) (Point D) and the average density (ρ_{avg}) of the gas discharged at 1000 psi (6895 kPa) during the process is 0.00475 lb/in³ (131.5 kg/m³) (Point E).

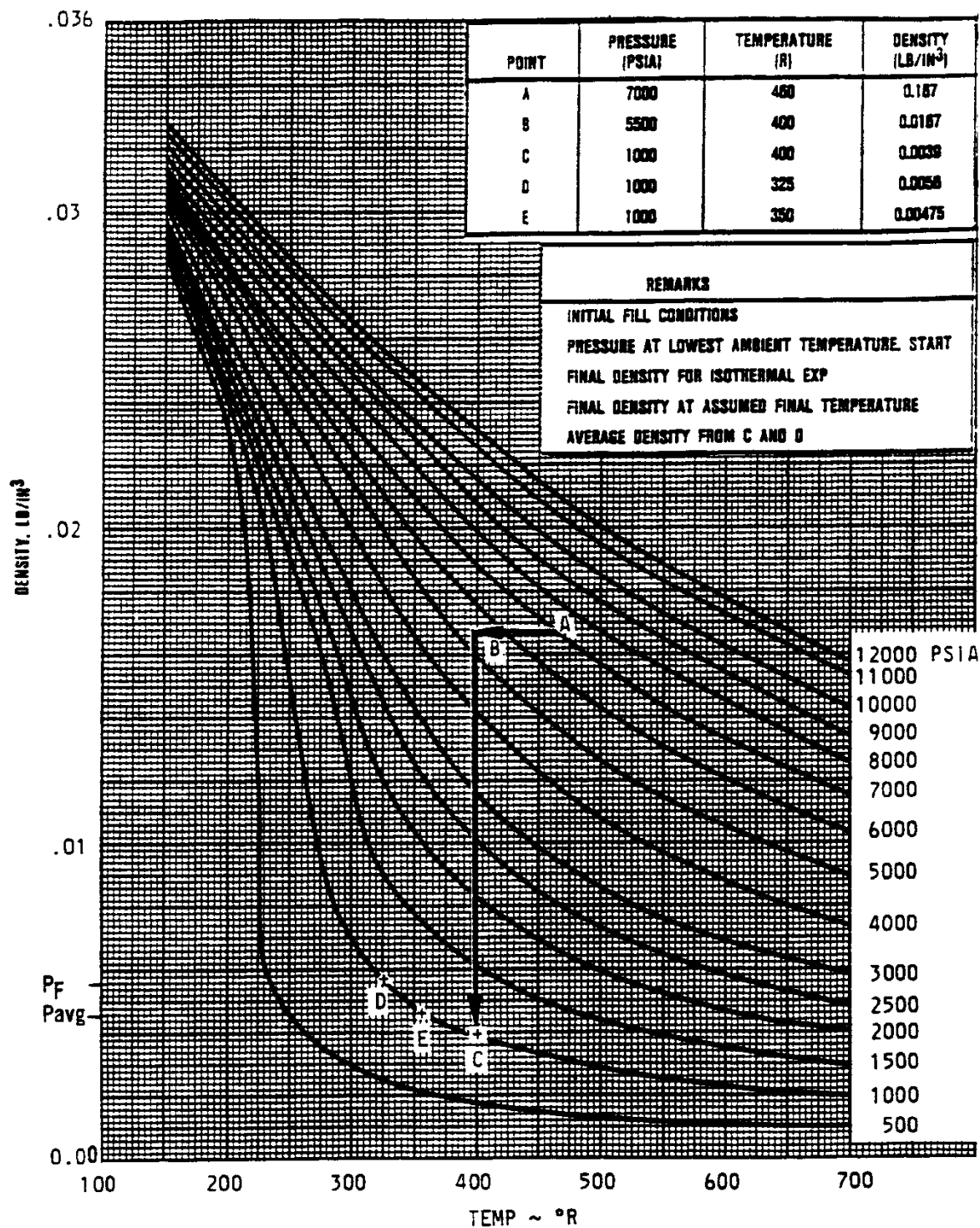


FIGURE 2 - DENSITY OF NITROGEN VERSUS TEMPERATURE
 (AT VARIOUS PRESSURES IN PSIA)

From Equation 2 is Equation 3:

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

Assume a flow rate of 10 in³/s (1639 x 10⁻⁷ m³/s) at 1000 psi (6895 kPa) (1639 x 10⁻⁶ m³/s) for 10 s was required (38 SDFM), then (see Equation 4),

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

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.

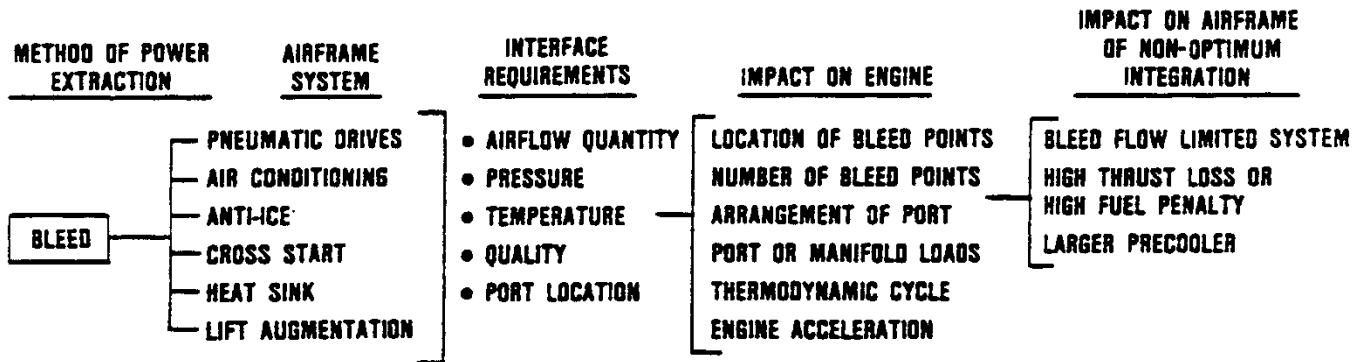


FIGURE 3 - ENGINE/SYSTEMS INTERFACES AND THEIR EFFECTS

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 ($S_i - S_o$) (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:

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

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

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

$$1 \text{ min} = 60 \text{ s}$$

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

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

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

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

$$P_{r_o} = \frac{P_{r_i}}{\text{TPR}}$$

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).