AEROSPACE INFORMATION REPORT

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GAS ENERGY LIMITED STARTING SYSTEMS

1. PURPOSE AND SCOPE

This report presents information on gas energy limited starting systems which represent current state-of-the-art technology. The systems presented are those which utilize solid propellant cartridge gas, monopropellant hydrazine gas, compressed stored air, and cryogenic stored nitrogen. These gas energy limited starting systems have been utilized in various commerical and military aircraft, onboard Naval vessels, and at remote industrial sites. The information presented herein is intended to familarize the aerospace industry with the design, performance, capabilities, and limitations of these systems.

2. SYSTEMS DESCRIPTION

2.1 Solid Propellant Cartridge Gas

Solid propellant cartridges were first used for starting the reciprocating engines of World War II military fighter aircraft. A small cartridge, approximately the size of an 8-gauge shot gun shell, provided a short duration burst of energy sufficient to rotate the engine for a few revolutions. With the advent of the turbojet engine, a large increase in starting energy was required to rotate the engine for several thousand revolutions.

The British were the first to employ solid propellant cartridge starters for turbojet engines on the Hawker Sea Hawk and the English Electric Canberra. For these applications, the cartridge gas was expanded across a single stage turbine rotating the engine past the engine self-sustaining speed before the cartridge burned out. The first American cartridge starter was designed and developed for use on the Martin B-57, the American version of the Canberra. Cartridge starters were subsequently employed on numerous military aircraft including the F100, F101, F105, F111, F4C, B-52, KC-135, and GAM77.

The cartridge starter is a self-sufficient unit which allows aircraft to be dispersed to remote areas where ground support equipment is not available. The cartridge starter provides a quick simultaneous engine start capability for aircraft on alert status. Since no ground support equipment must be disconnected, the aircraft is ready for takeoff immediately after completion of the start cycle.

A disadvantage of cartridge start systems is the need for a special cartridge which results in a logistic and cost factor not present in most other types of start systems. To meet the self-sufficiency requirement, it is necessary to carry extra cartridges aboard the aircraft so that if the aircraft lands at a remote base, there will be cartridges available to return the aircraft to its home base.

Early cartridge starters were designed to operate with cartridge gas only. Current designs operate either with cartridge gas or low pressure bleed air and are referred to as cartridge/pneumatic starters. The combination starter does not have to be operated in the cartridge mode for all starts. Whenever ground support equipment is available the pneumatic mode can be utilized which extends the service life of the starter and reduces starting costs.

Starting a jet engine by direct impingement of high velocity cartridge gases on the jet engine turbine has been studied because of several advantages offered. An impingement start system could provide a significant weight savings by eliminating a starter turbine and gearbox. Impingement start systems have not been developed to date primarily due to the high temperature and corrosive properties of cartridge gas and their adverse effect on jet engine turbine blades.

2.1.1 Cartridge

A double base cartridge, designated the MC-1, was developed for the J65 engine starter on the Martin B-57. The MC-1 cartridge generated a heavy black smoke as the four-pound nitrocellulose-nitroglycerine propellant grain burned. In the mid 1950's, development of the MC-2 cartridge with a four-pound composite propellant grain was initiated. The MC-2 cartridge, which replaced the MC-1, incorporated ammonium nitrate as the main constituent and produced much less smoke. Production began in 1957 of the MXU-4/A cartridge. The MXU-4/A incorporated an eight-pound grain of ammonium nitrate and synthetic rubber and has sufficient energy to start the J52, J57, J75, J79, and TF33 engines. A product improvement version of the MXU-4/A in use today, is designated the MXU-4A/A. A four-pound cartridge, designated the MXU-129/A, is also available.

The basic components of a typical solid propellant cartridge shown on Figure 1, are the solid propellant charge or grain, an inhibitor, an igniter assembly, the cartrige case and a particle screen. The inhibitor, which is bonded, taped or dip-dried onto the propellant restricts the burning surface to achieve the desired burning characteristics. The particle screen restricts the passage of any pieces of unburned propellant from the cartridge case which could plug the turbine nozzles. The cartridge case is manufactured from a metallic or rubber material. A thin disc seal covering the particle screen prevents moisture from contacting the propellant and, hence, allows the cartridge to be stored in the starter cartridge breech in the "ready" position for a long duration. The seal ruptures and burns upon ignition of the cartridge. A circumferential seal around the outside of the cartridge case prevents hot cartridge gases from decomposing the cartridge case during a start cycle, thereby preventing a buildup of carbon on the breech walls. The seal also provides a gas tight connection at the starter breech parting line.

The igniter assembly is a pyrotechnic type consisting of an igniter case containing an igniter charge and an electrical wire surrounded by a small primer charge. The primer is heat sensitive igniting readily when the wire is supplied with an electrical current. The hot flame from the igniter charge ignites the cartridge grain.

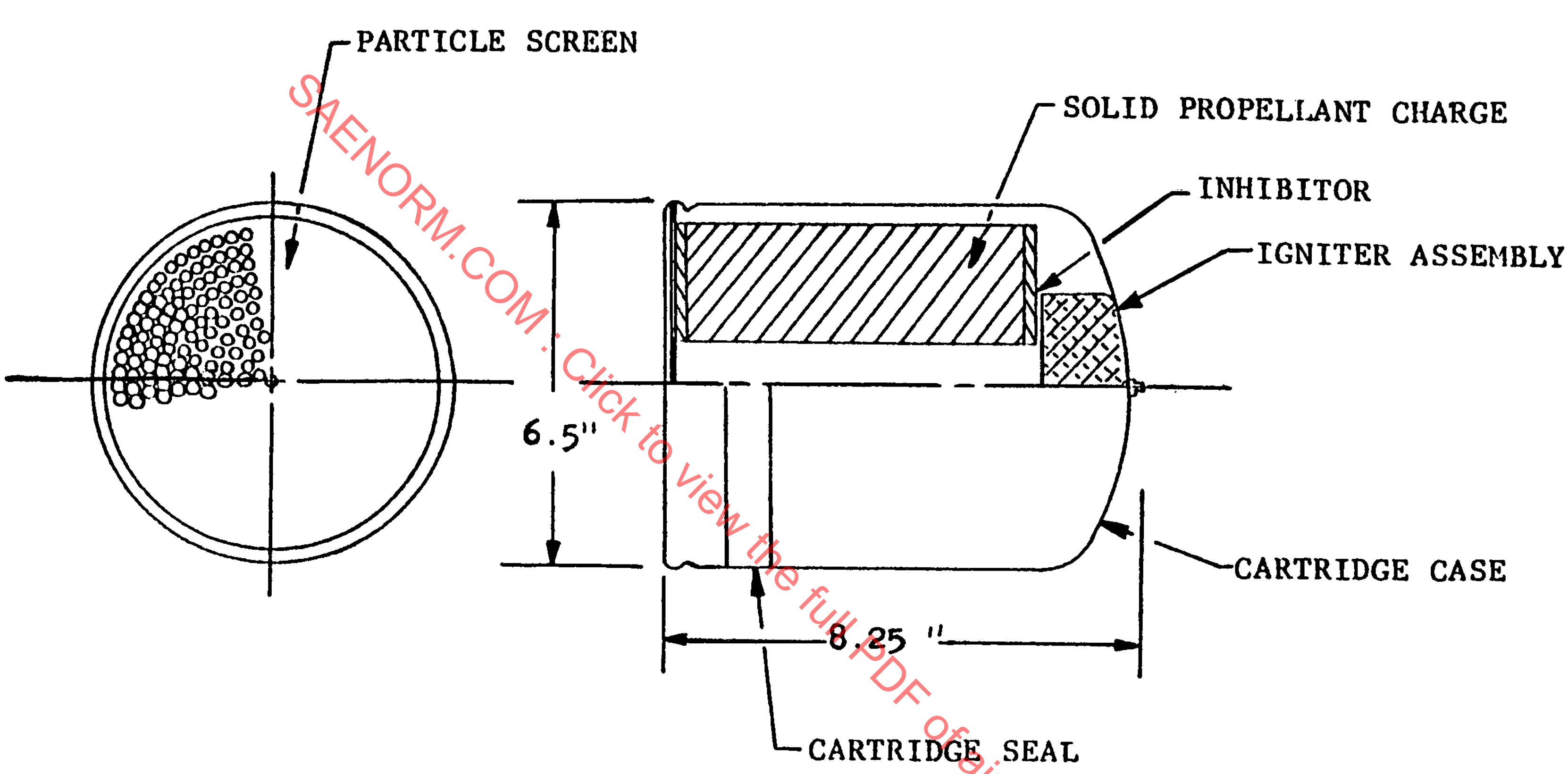


FIGURE 1

BASIC COMPONENTS
AIR FORCE TYPE MXU-4/A
STARTER CARTRIDGE

There are two major types of solid propellants. The first, often called composite propellants, has two constituents, a mixture of fuel and an oxidizer. The oxidizers of composite propellants usually consist of crystals of potassium, lithium, ammonium perchlorate or nitrate. A great variety of fuels are available including asphalt, rubber, synthetic resins and elastomers, which bind the finely ground oxidizer crystals in plastic-like cake form. The second type, called double base, uses fuels that are chemically bonded to the oxidizer material, that is the fuel and oxidizer are contained in the same molecule. Cordite and combinations of nitrated glycerin and nitrated cellulose are the most common examples of double base solid propellants. Double base propellants are not in use today primarily because of the heavy black smoke generated as the propellant burns.

In addition to the fuel and oxidizer, the propellant contains a small percentage of material to control the physical and chemical properties of the solid propellant. Typically, additives have been used for the following purposes:

- To accelerate or decelerate the burning rate.
- To increase chemical stability and increase storage life.
- To improve the fabrication properties of the propellant such as curing time and castability.
- To control radiation absorption properties of the burning propellant.
- To improve the propellant physical properties.
- To minimize sensitivity to ambient temperature.
- To minimize smoke.

There are a wide variety of propellants to select from, each with different properties. Some important propellant properties used to evaluate and compare solid propellants are:

- High release of chemical energy.
- Combustion products with a low molecular weight to provide high specific impulse.
- Long storage life.
- Smokeless, non-corrosive and non-toxic propellant gases.

- High density to permit small breech volume and low weight.
- Safe to manufacture and use.
- Good physical properties.
- Low cost.
- High auto-ignition temperature and impact sensitivity.
- Low sensitivity to ambient temperature.
- Suitable for case bonding and application of inhibitors.

Safety precautions must be observed in the operation, handling and storage of cartridges. The storage temperature range and storage life of the cartridge must be adhered to prevent the possibility of propellant deterioration. Temperature cycling can result in differential expansion and cracking of the grain. Any crack in the grain increases the burning area, and, therefore the mass flow which can lead to an explosion.

Today there are two sizes of cartridges qualified and available for use in the military inventory, the MXU-129/A with a four-pound grain, and the MXU-4A/A with an eight-pound grain. The starting energy requirements of many of the current operational aircraft engines are either too large or too small for the above cartridges. New cartridges for these applications would have to be developed.

2.1.2 <u>Performance Characteristics</u>

The burn rate (r), a major performance and design consideration, is the velocity at which the grain is consumed during operation. The burn rate is directly proportional to the cartridge operating or breech pressure (P_c) as follows:

$$r = aP_c^n$$

where a and n are constants. These constants which are different for each type of propellant can be obtained from cartridge ballistic characteristics published by various cartridge manufacturers. The constant a also varies with the initial propellant temperature, and thus the burning rate is a function of the grain soak temperature prior to combustion. The coefficient n is essentially independent of the initial grain temperature.

The burn characteristics of the cartridge propellants are such that they will burn approximately twice as fast with the cartridge at 160F than when the cartridge is at minus 65F. With a constant turbine nozzle area, the faster burn rate at 160F will increase the breech pressure, which in turn increases the burn rate of the grain until a stabilized pressure is attained. Therefore, on a hot day when the starting energy requirement for an engine start is the smallest, the energy available at the turbine is the greatest.

Some of the early cartridge starters utilized constant area nozzles, with the result that the starter torque on a hot day due to the higher flow rate and pressure was considerably higher than on a cold day. Current starter designs utilize a control valve which varies the effective nozzle area as a function of pressure. On a hot day, the nozzle area is increased to lower the pressure and burn rate, so that the difference in burn time between a cold and hot cartridge is greatly reduced.

The flow rate (w) of a cartridge grain is a function of exposed burning surface area (A_b), the density of the propellant (ρ_b), and the propellant linear burning rate (r), which is the velocity at which the propellant is consumed in a direction normal to the burning surface.

$$w = A_b r \rho_b$$

There are three types of variations of burning area with time, regressive, neutral and progressive. If the grain is so designed that the burning area and, therefore, the flow rate, increase with burning time, the grain has a progressive burning characteristic. The grain is regressive if the flow rate decreases with time and neutral if the flow rate remains constant with time. The MXU-129/A and MXU-4A/A cartridges have neutral grains.

The energy available from a cartridge can be calculated in terms of gas horsepower (GHP) as follows:

$$GHP = \frac{w\ H_{AD}}{33,000}$$

where,

w = Flow rate, lb/min

H_{AD} = Adiabatic head, ft

The adiabatic head can be expressed as follows:

$$H_{AD} = \frac{\gamma}{\gamma-1} RT \left[1 - \frac{1}{\left(\frac{P_c}{P_e}\right)^{\frac{\gamma-1}{\gamma}}} \right]$$

where,

γ = Specific heat ratio

R = Gas constant, ft-lb_f/lb_m-R

P_c = Breech pressure, psia

P_e = Nozzle exit pressure, psia

T = Cartridge gas flame temperature, R

The performance characteristics of a MXU-4A/A cartridge at 80F are:

P_c = 1000 psia

T = 2560R

γ = 1.27

R = 79.7 ft-lb_f/lb_m-R

w = 30.6 lb/min

Assuming an exhaust pressure of 14.7 psia, the adiabatic head (H_{AD}) and gas horsepower (GHP) are:

H_{AD} = 568,400 ft

GHP = 527.1 hp

The cartridge gas energy or gas horsepower is converted to shaft horsepower at the starter output pad by the starter turbine. Due to aerodynamic losses in the turbine stage and mechanical losses in the gearbox, only a percentage of the gas horsepower at the inlet is converted to useful work. The overall starter efficiency is the measure of the amount of shaft horsepower the starter will provide at the starter output shaft utilizing the available gas horsepower at the starter inlet.

The cartridge/pneumatic starter must be designed to operate as efficiently as possible with both high pressure, high temperature cartridge gas and low pressure, low temperature bleed air. An optimum turbine design for operation with low pressure bleed air would be a reaction type turbine with a converging nozzle cascade; whereas a turbine designed for maximum efficiency operating with cartridge gas would be an impulse type turbine with converging-diverging nozzles. A single turbine for both modes of operation, therefore, must be a compromise design based on the best efficiency for both energy sources.

The gear ratio selected for a cartridge/pneumatic starter is also a compromise between the best gear ratio for the cartridge mode and the pneumatic mode of operation. To obtain the correct torque/speed characteristics in one mode, it is necessary to have a gear ratio which is not optimum for the other mode.

The ignition characteristics of the cartridge are an important starter design consideration. The igniter pressure rise characteristics must be rapid enough, and the correct effective nozzle area must be selected, to ensure proper ignition at minus 65F. However, if the igniter pressure rise rate for a minus 65F cartridge is fast enough to achieve proper ignition, it is probable that a very rapid pressure rise will result with a 160F cartridge. A soft ignition transient is often required to protect the starter mechanical components from impact torque loads. This can be obtained by close control of the ignition characteristics or by utilizing a pressure modulating device.

2.1.3 Starter Description

A typical combination pneumatic/cartridge starter consists of a single stage impulse turbine, a gearbox to reduce the high speed of the turbine to a lower speed at the starter output shaft, a high pressure cartridge vessel or breech with ducting to the turbine nozzles, and controls to initiate, terminate and regulate the start cycle.

The breech consists of two halves, the breech and breech cap, which include a locking device for indexing and locking the breech. The locking device includes the contact for the electrical igniter circuit. To prevent an accidental firing of the igniter, the breech handle is designed so that the electrical circuit is not completed until the breech is locked.

Figure 2 shows a schematic of a combination cartridge/pneumatic starter. The energy from either the cartridge gas generator for a cartridge start or low pressure air from an APU or engine crossbleed for a pneumatic start is transferred to the appropriate nozzles. The same turbine, which is used for either mode of operation, converts the energy to shaft power.

Figure 3 shows a schematic of a cartridge/pneumatic starter where ambient air is induced through annular secondary nozzles. In the short tubular section downstream of the nozzles, the air and cartridge gases mix, and then the relatively cool cartridge gas-air mixture is then directed to the turbine wheel where it is expanded, and discharged through an exhaust plenum. The secondary nozzles are also used to direct air to the turbine to provide pneumatic engine starts.

Some cartridge/pneumatic starters utilize a speed limiting mechanism to terminate the start cycle when the proper engine assist speed is reached, and to prevent overspeed of the turbine wheel during an engine start or no-load. The speed limiting mechanism diverts the cartridge gas around the cartridge gas nozzles. Other cartridge/pneumatic starters employ a braking fan mounted directly to the turbine wheel via a common shaft as shown on Figure 2. By use of the aerodynamic brake, speed limiting is inherent to the turbine assembly and a safe maximum speed is assured for both cartridge and pneumatic modes.

A burst diaphragm or a pressure regulating valve protects the starter from overpressure due to an abnormal burning cartridge. In addition, the pressure regulating valve improves starter performance by providing optimum performance throughout all ambient temperature conditions.

The proper dissipation of cartridge starter exhaust gases is an important installation consideration. Due to the high temperature and velocity, and chemical composition of the cartridge exhaust gases, special installation precautions must be taken. An exhaust duct to an aircraft overboard port adequately sealed to prevent leakage of the cartridge gas within the engine nacelle is required. The duct must be properly oriented so that the gas does not impinge on the aircraft skin or external stores. The exhaust gas of current ammonium nitrate cartridges can produce corrosion on the aircraft not only during exposure to the high temperature gases, but from the residual exhaust particles remaining on the aircraft skin.

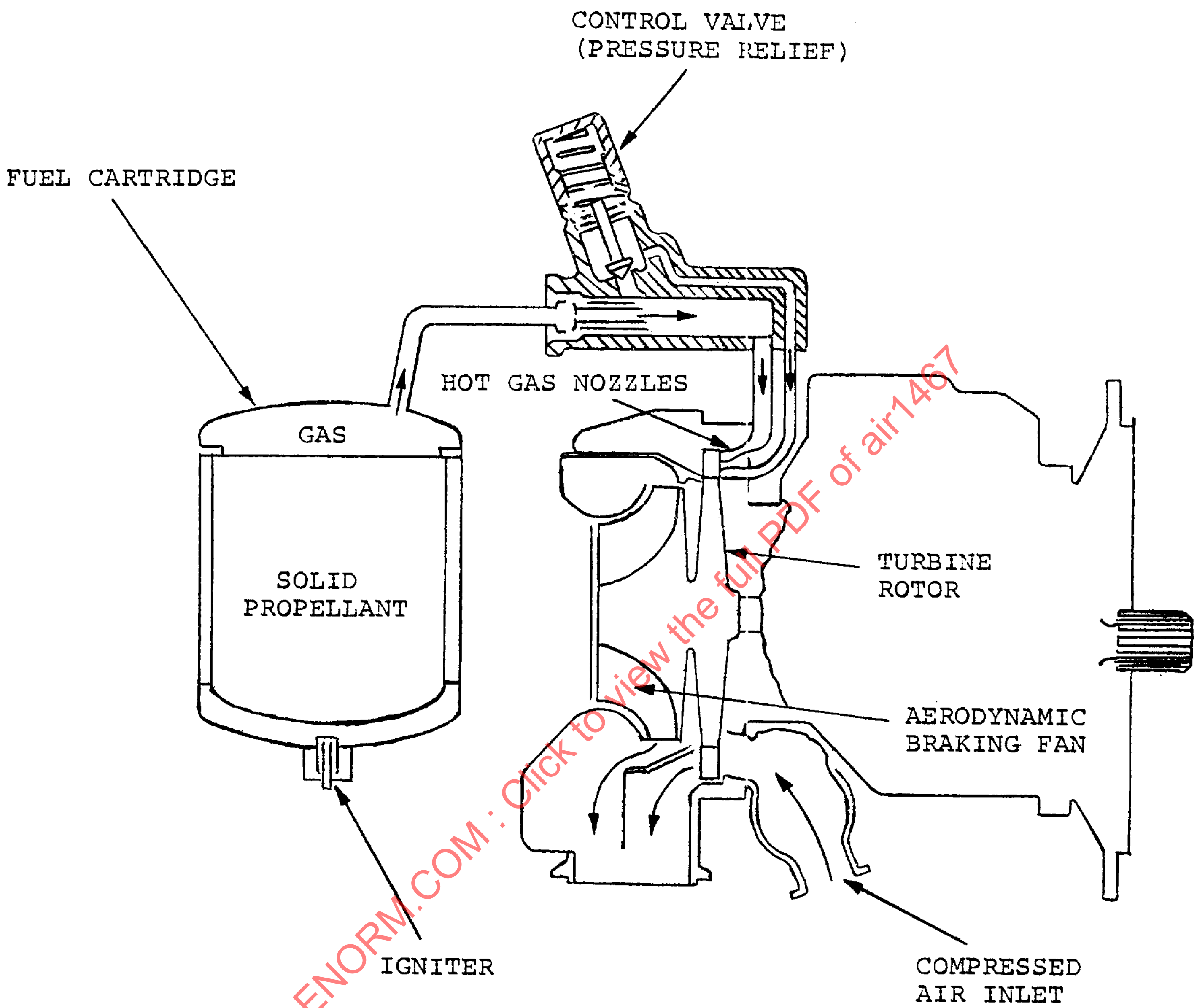


FIGURE 2

FLOW DIAGRAM
CARTRIDGE/PNEUMATIC STARTER

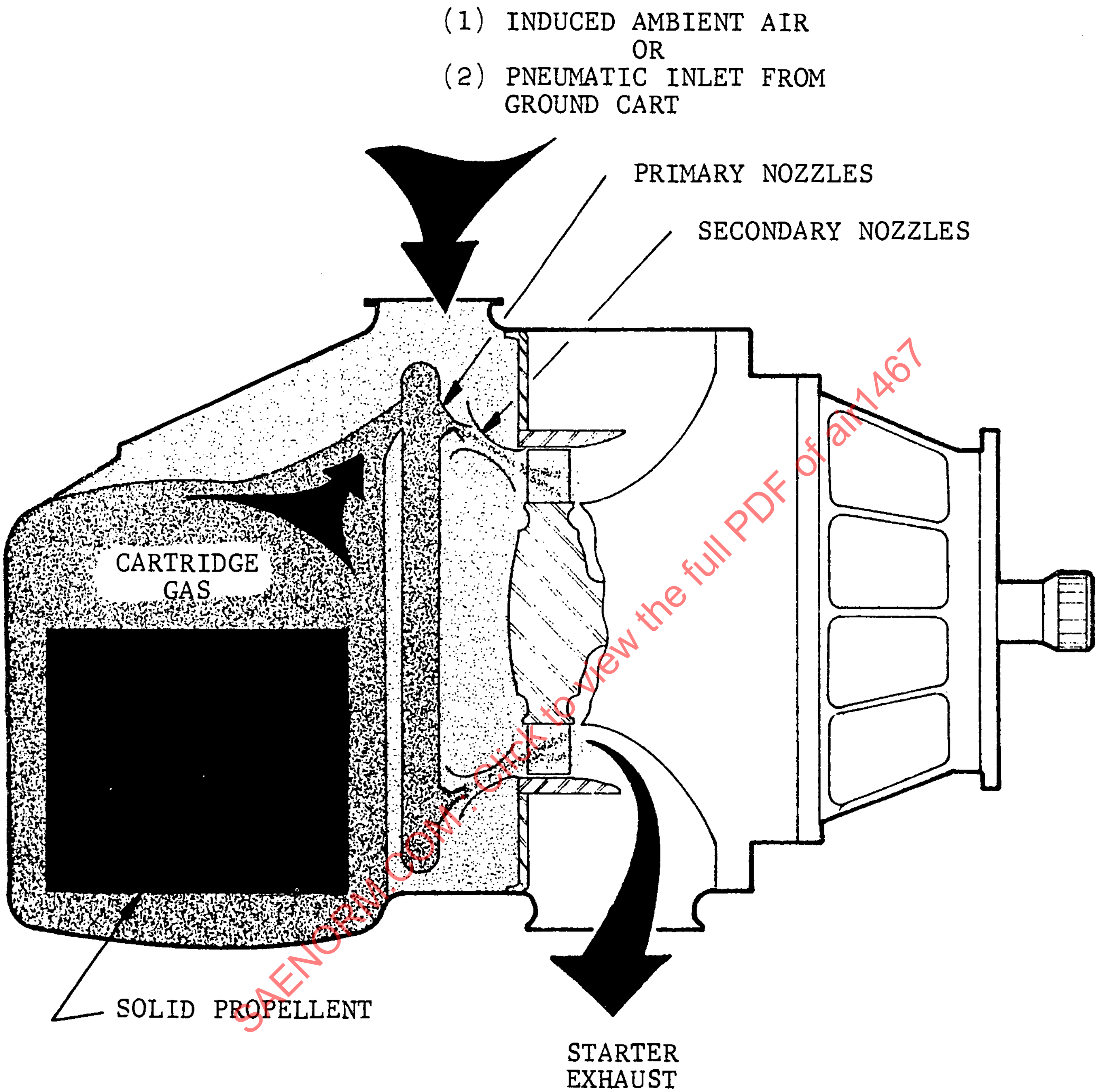


FIGURE 3

FLOW DIAGRAM
CARTRIDGE EJECTOR-PNEUMATIC STARTER

2.1.4 Applicable Specifications

MIL-S-27266	Starter, Engine, Cartridge and Pneumatic Shaft Drive, General Specification for
MIL-C-27505	Cartridge Engine Starter MXU-4A/A
MIL-C-27658	Cartridge Engine Starter MXU-129/A

Additional military and industrial specifications and standards applicable to cartridge starting systems are listed in Society of Automotive Engineers Aerospace Information Report AIR 1174.

2.2 Monopropellant Hydrazine Gas

The hot gas, produced by the decomposition of monopropellant hydrazine in a gas generator, can be used as the working fluid for generating shaft power in a turbine starting system. The gas, expanded through the turbine section of a starter for the desired period of time, produces the power for an engine start. The use of hydrazine, as the working fluid in a starting system, was first employed on the Grumman F-14B aircraft to provide inflight emergency engine starts in support of the flight test program. The multi-national MRCA Fighter aircraft employs a hydrazine power unit to provide emergency power to drive the aircraft accessories and provide engine starts.

The F-14B hydrazine emergency air start system, shown schematically on Figure 4, consists of a fuel supply system located in the aircraft radome and a gas generator and starter located in each engine nacelle. A nitrogen storage tank stores 1100 cubic inches of nitrogen at 3000 psig to pressurize the fuel system. A pressure regulator regulates the fuel tank pressure to approximately 300 psig. A 4200-cubic inch cylindrical fuel tank holds 155 pounds of the 70 percent hydrazine-30 percent water fuel mixture. The gas generator uses Shell 405 iridium catalyst to initiate the hydrazine decomposition and ammonia dissociation processes. The catalytic type decomposition chamber provides a multiple restart capability with maximum reliability.

The F-14B aircraft monopropellant hydrazine gas start system utilizes the existing pneumatic starters and starter valves, but does not compromise the primary pneumatic start mode using ground equipment. The system provides approximately 140 seconds of operation time, allowing for at least four normal engine starts. The system can also be used to motor the engine to drive the aircraft hydraulic pump at a speed which provides aircraft control capability, if required, prior to initiation of start-stop operation. In the event

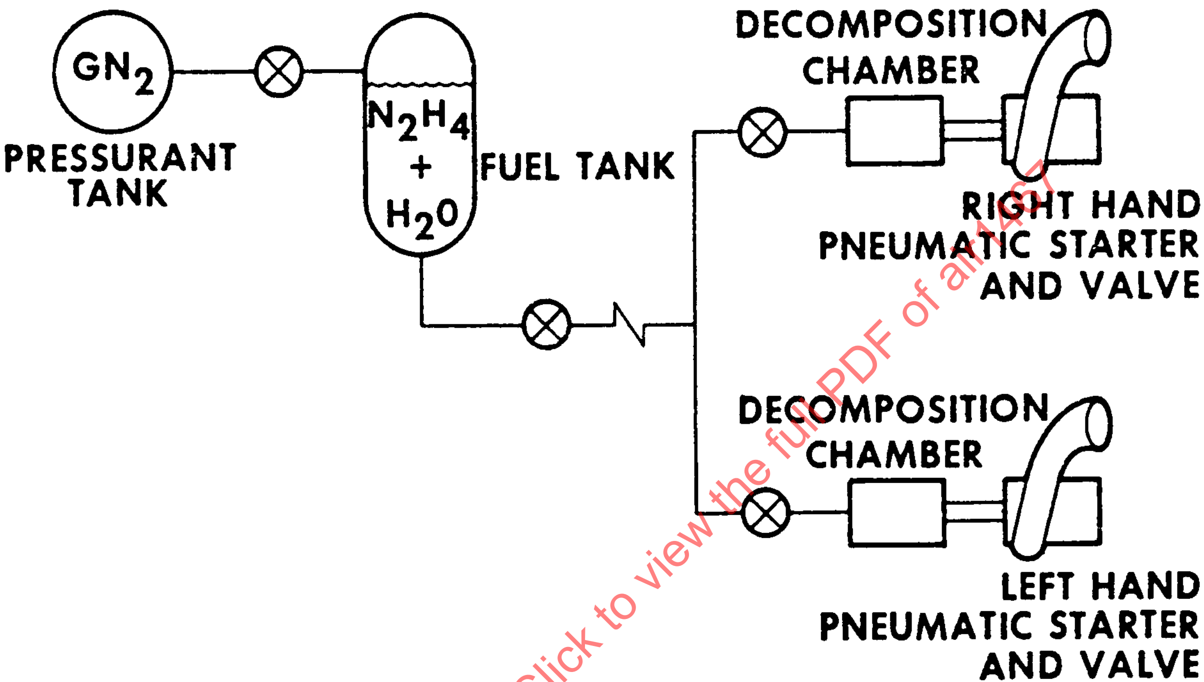


FIGURE 4

SCHEMATIC DIAGRAM OF F-14B
EMERGENCY AIR START SYSTEM

the system is actuated and a successful start is made, the flight test plan could be continued because of the multiple start capability. After inflight use, the system requires minimum purging and refurbishment for subsequent flight readiness. Turnaround time is approximately one-half to one hour.

The MCRA hydrazine power unit mounts on the aircraft accessory gearbox. The power unit drives the aircraft accessories prior to the initiation of the start cycle. The start cycle is initiated by filling a torque converter in the gearbox which connects the power unit to the engine. The system provides for operation of the aircraft accessories and two inflight engine starts.

The use of hydrazine start systems should find increasing applications in aircraft with reduced engine windmilling envelopes resulting from the design requirements of new high bypass ratio turbofan engines. The extreme flight maneuvers of fighter aircraft increase the possibility of an engine flame-out, and the windmill restart capability is marginal due to the reduced ram start envelope and increased drag of larger airframe accessories coupled to the accessory drive gearbox.

Hydrazine engine start systems are strong contenders for gas energy limited starting systems applications because of their simplicity, high power to weight ratio, installation flexibility and the desirable properties of hydrazine. Hydrazine can be easily stored in its liquid form without the necessity of employing low temperatures to maintain liquidity. In addition, hydrazine has a long shelf life and provides packaging flexibility, operation relatively independent of ambient conditions, exceptional cleanliness of combustion products, and relatively low vapor pressure and a high boiling point. Additives mixed with hydrazine can lower its freezing point to minus 65F and tailor the gas temperature for various start system applications.

2.2.1 Hydrazine

Hydrazine is a clear, colorless hydroscopic liquid with an ammonia like odor. Its density is approximately the same as water and it is miscible with water. In 100 percent concentrations, commonly referred to as "neat" or "anhydrous" hydrazine, the freezing point is 35.6F and its boiling point is 236.3F.

Hydrazine fuels are toxic and must be treated with due respect. Personnel health hazards can result if proper precautions and procedures are not followed when handling and servicing. The vapors are a strong irritant and may damage the eyes and cause respiratory tract irritation and systematic effects. If spilled on the skin or eyes, liquid hydrazine can cause severe local damage or burns and can cause dermatitis and other systematic effects.

Although these fuels are combustible and can undergo rapid decomposition when subjected to high temperatures or certain catalytic materials, they do not present any unusual explosion hazard. Rags, cotton waste, sawdust, or other materials of a large surface area that have absorbed hydrazine may eventually cause spontaneous ignition.

In storage, hydrazine fuels can react with moisture, rust (or other metal oxides), oxidizing agents and most organic substances; therefore, cleanliness is of utmost importance. The surfaces of compatible materials must be cleaned to the point where no reaction occurs, i.e. the surface must be "passive". In the system design, care must be exercised in selecting proper resistant and compatible materials to be used in contact with the fluid. Some materials generally found compatible with hydrazine fuels up to 160F are titanium, some types of stainless steels and aluminum, glass, teflon, ethylene propylene rubber, and polyethylene.

In spite of the hazards and conditions described herein, a properly designed hydrazine fueled system can be safely maintained by adequately trained personnel following prescribed procedures in any required operation. Hydrazine has long been used and recognized as a high energy rocket fuel, and more recently in various aircraft applications, and many good procedures for its utilization have been written. One of these documents is included in a section of the Chemical Rocket/Propellant Hazards Manual number AD870259, CPIA/194, Volume III.

Hydrazine has several advantages as an energy source. The absence of carbon in the compound leads to an exceptionally clean exhaust gas consisting of ammonia, nitrogen, hydrogen, and the addition of steam if a water blend fuel is used. The concentration of hydrogen and ammonia present in the exhaust must be considered in the safety aspect of the design.

Other advantages of hydrazine include its long term storage capability under normal storage temperature conditions and packaging flexibility. The fuel is also stable to friction and shock.

The monopropellant fuel provides high energy per pound of fuel (approximately 1500 btu per lb_m) with an adiabatic head almost twice that of compressed air at similar conditions of pressure and temperature.

Due to the relatively high freezing point, "neat" hydrazine is generally not used in turbine driven power and starting system applications. Additives such as water (H_2O), monomethyl hydrazine ($N_2H_3CH_3$), or hydrazine nitrate ($N_2H_5NO_3$), or ammonia can be added to improve or vary the properties of the mixture. A wide variety of hydrazine mixtures is thus obtained. Two important properties: 1) freezing point, and 2) working fluid temperature and composition, must be considered in selecting a hydrazine mixture for a start system. A low freezing point exposure to high altitude flight ambient temperatures, and the correct turbine inlet temperature insures the maximum performance compatible with the turbine mechanical design constraints.

The working fluid temperature must be compatible with the application and design requirements. The useful gas temperature range of hydrazine mixture can be varied from approximately 900F to 2700F by the addition of various additives. Control of the flow variables and the geometry of the gas generator provides another means of controlling the exhaust gas temperature and products.

Table 1 summarizes some of the properties and design data of some commercially available hydrazine based monofuel mixtures. Although neat hydrazine is not suitable for most starting system applications because of its relatively high freezing point, it provides a basis to compare other mixtures. The 68-percent mixture of hydrazine used on the F-14B emergency air start system has a relatively low freezing point and gas temperature range. The mixtures containing monomethyl hydrazine are not suitable with catalytic type gas generators since the carbon in the decomposition products will poison the catalyst.

None of the mixtures shown are shock sensitive in standard card gap or other sensitivity tests. Neat hydrazine is more prone to auto ignition than are hydrazine blends which contain water. The addition of monomethyl hydrazine to neat hydrazine also results in lower auto ignition temperatures. The various hydrazine blends vary considerably in stability and sensitivity. The appropriate safety codes should be referred to before selecting and handling a particular hydrazine blend.

2.2.2 Performance Characteristics

Hydrazine fuel may be considered to be decomposed in the gas generator according to the following consecutive reactions:

$$3N_2H_4 \xrightarrow[\text{cat}]{} 4NH_3 + N_2 + 144{,}300 \text{ Btu (pound-mole)}$$

$$4NH_3 \xrightarrow[\Delta\text{cat}]{} 2N_2 + 6H_2 - 79{,}200 \text{ Btu}$$

TABLE 1

HYDRAZINE-BASED MONOFUELS

Hydrazine, N_2H_4	100 percent	68 percent	63 percent	62 percent	58 percent	70 percent	26 percent	14 percent
Hydrazine Nitrate $N_2H_5NO_3$	-	-	10 percent	19 percent	25 percent	10 percent	19 percent	-
Monomethyl Hydrazine, $N_2H_3CH_3$	-	-	-	-	-	20 percent	55 percent	86 percent
Water, H_2O	-	32 percent	27 percent	19 percent	17 percent	-	-	-
Freezing Point, F	35.6	Minus 65	Minus 68	Minus 80	Minus 85	Minus 68	Minus 44	Minus 68
Specific Gravity (77F)	1.004	1.026	1.06	1.088	1.114	0.95	1.011	0.894
Useful Gas Temperature Range, R	2100 to 2600	1400 to 1600	1600 to 2000	1950 to 2450	2150 to 2600	1950	2000	1885
Auto Ignition Temperature, F	518	585	-	-	-	530	500	520
Boiling Point, F	238	248	237	-	-	200	207	194
Vapor Pressure (77F), psi	0.28	0.354	0.15	0.06	0.05	0.84	0.77	1.0
Flash Point, F	126	154	-	-	-	90	90	80
Card Gap Sensitivity	Neg	Neg	Neg	Neg	Neg	Neg	Neg	Neg

In the first reaction, hydrazine is decomposed catalytically into ammonia and nitrogen. In the second reaction, the ammonia formed is dissociated into nitrogen and hydrogen. This second step is endothermic and absorbs a portion of the heat generated during the first exothermic decomposition step. Basically, control of the flow variables and the geometry of the reaction chamber control the degree of completion of the second step of the reaction process. This provides the designer an additional means of controlling the exhaust gas temperature and products in addition to altering the fuel mixture composition by adding various additives.

Table 2 presents a comparison of the important performance parameters of the decomposition products of the monofuel mixtures previously described. The gas generator chamber temperature (T_c) shown are based on the percent dissociation of ammonia occurring in some typical gas generator designs. The mean molecular weight (M), and the ratio of specific heats (γ) correspond to the chamber temperature. The adiabatic head (H_{AD}) is for an assumed chamber pressure (P_c) of 100 psia and for a sea level expansion ratio of 6.8 to 1.

The adiabatic head is calculated from the following equation:

$$H_{AD} = \frac{\gamma}{\gamma-1} R T_c \left[1 - \frac{1}{\left(\frac{P_c}{P_e} \right)^{\frac{\gamma-1}{\gamma}}} \right]$$

where,

H_{AD} = Adiabatic head, ft

γ = Specific heat ratio

R = Gas constant, ft-lb_f/lb_m-R

T_c = Chamber temperature, R

P_c = Chamber pressure, psia

P_e = Nozzle exit pressure, psia

The gas horsepower (GHP) can then be calculated from the following equation:

$$GHP = \frac{w H_{AD}}{33,000}$$

where,

H_{AD} = Adiabatic head, ft

w = Mass flow, lb/min

TABLE 2

MONOFUEL PERFORMANCE COMPARISON

Monofuel	T_c (R)	R	γ	H_{AD}* (ft)
Neat Hydrazine	2160	117.9	1.275	400,000
68%H-32%W	1478	93.1	1.2584	218,000
63%H-10%HN-27%W	1730	99.7	1.272	271,000
62%H-19%HN-19%W	2130	99.0	1.261	334,000
58%H-25%HN-17%W	2240	101.6	1.267	359,000
70%H-10%HN-20%MMH	1950	118.8	1.35	350,000
26%H-19%HN-55%MMH	2000	114.5	1.2836	358,000
14%H-86%MMH	1885	112.0	1.2475	337,000

* Pressure ratio = 6.8:1 (100 psia at sea level)

H = hydrazine

HN = hydrazine nitrate

MMH = monomethyl hydrazine

W = water

The starter turbine converts the available gas horsepower or energy into useable shaft power. The turbine can be a single mode turbine designed to provide emergency engine starts only, or a dual mode turbine operating with hydrazine or low pressure bleed air to provide routine ground starts.

The efficient operation of the starter turbine is a necessity to minimize the required propellant weight and/or maximize system operational time. The turbine design must be carefully optimized for a complex mission profile to permit operation over a wide range of altitudes, inlet pressures and flow rates. Starter turbine design and gearbox gear ratio tradeoffs are necessary to establish the best design to meet the requirements of operation on two working fluids.

2.2.3 System Description

Starting systems utilizing stored monopropellant hydrazine and hydrazine mixtures consist of the following basic subsystems:

- Fuel Supply System
- Gas Generator
- Starter

Fuel Supply System

The purpose of the fuel supply system is to store and deliver a supply of liquid monofuel propellant to the gas generator at the proper time, in the desired quantity, and at the desired delivery pressure. The fuel supply system serves the fuel storage, fuel delivery, and fuel control functions of the power generation system. Proper overall system operation depends upon satisfactory and dependable performance of the fuel supply system.

Two basic monofuel supply approaches are most common. One involves use of direct monofuel supply from high-pressure tankage which is pressurized by an integral gas supply. The second involves use of monofuel pumps and low-pressure tankage. Selection of the optimum supply pressure level for both concepts involves tradeoffs performed at the system level for the application in consideration. A brief description of the two basic system approaches are summarized as follows:

a. Pressurized Systems - The essential components of a typical gas-pressurized propellant feed-system, shown schematically on Figure 5, are the high-pressure gas tank, gas control valve, pressure regulators, propellent tanks, propellant control valves, and feed lines to the decomposition chamber. Operation of the system is initiated when the gas control valve is opened, allowing compressed gas, usually nitrogen to flow through the pressure regulator into the propellant tank. When the propellant valve opens, the propellant is forced through a feed line to the decomposition chamber.

b. Pump-Fed Systems - The typical pump-fed monofuel supply system, shown schematically on Figure 6, is similar to the pressurized system except that with the low-pressure storage system, a pump is used to boost the monofuel pressure to the desired level. A reasonable estimate of the power required to drive the fuel pump is approximately two percent of the net turbine output power. The monofuel tank is pressurized sufficiently to provide positive delivery and the required pump inlet pressure under all acceleration conditions.

In both these systems, the monofuel can be supplied in sealed tanks to minimize ground servicing problems. The pump-fed system is lighter than the pressure-fed system when a large quantity of monofuel is carried to provide for long duration operation of the system. A weight, volume and cost tradeoff study is necessary to determine the best method for each application.

Gas Generator

The purpose of the gas generator is to decompose and provide a supply of gas to the turbine device in the quantity and at the pressure and temperature desired. Two basic types of gas generators are available, one using catalysts and the other depending upon thermal processes. Catalytic chambers cost more, but can be designed to operate for a large number of cycles without servicing, and do not require an external source of energy or a hypergolic reactant to obtain rapid, positive ignition. Thermal designs will either require refurbishment after use or will require electrical pre-heating before use. There are a large number of variants such as the specific flow arrangement, means of ignition, and types of injectors. Figure 7 presents diagrams of some typical catalytic and thermal designs.

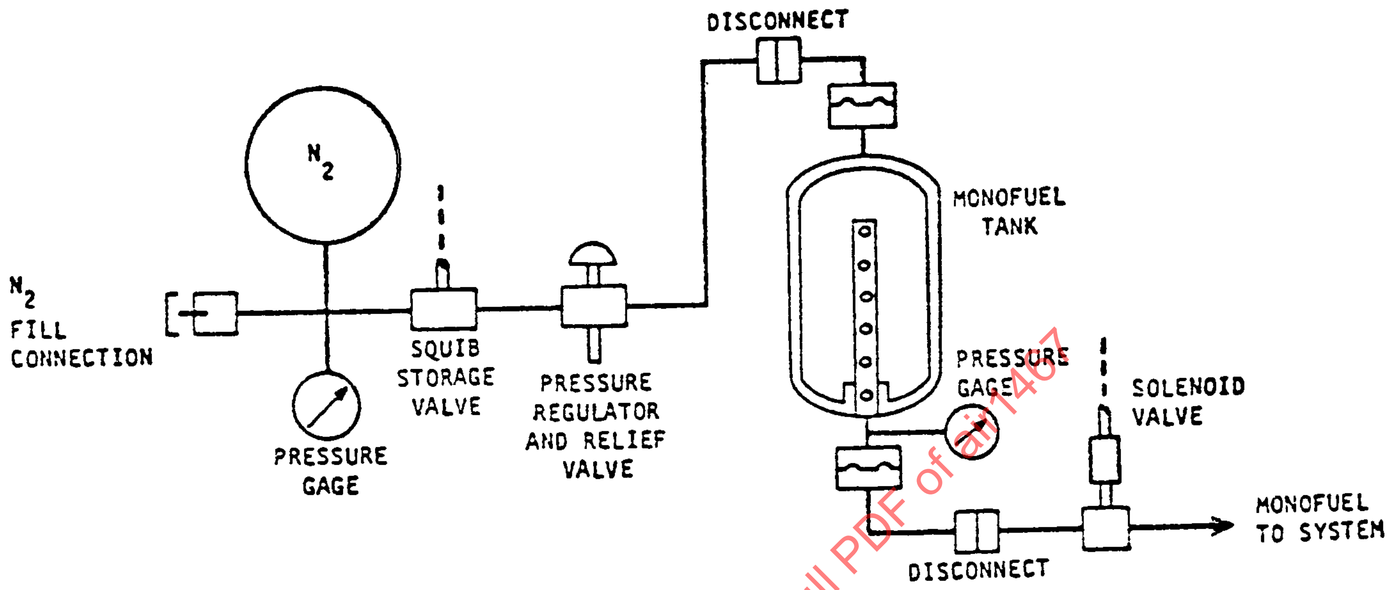


FIGURE 5

TYPICAL PRESSURIZED MONOFUEL SUPPLY SYSTEM
WITH HIGH PRESSURE GASEOUS NITROGEN PRESSURANT

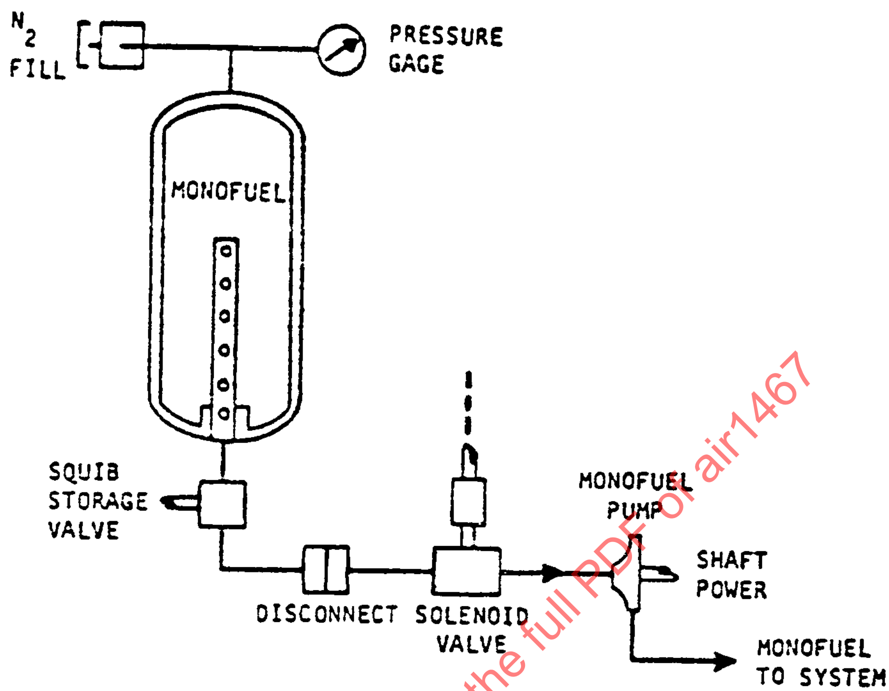


FIGURE 6

TYPICAL PUMP-FED MONOFUEL SUPPLY SYSTEM
WITH LOW PRESSURE FUEL STORAGE AND BOOST PUMP

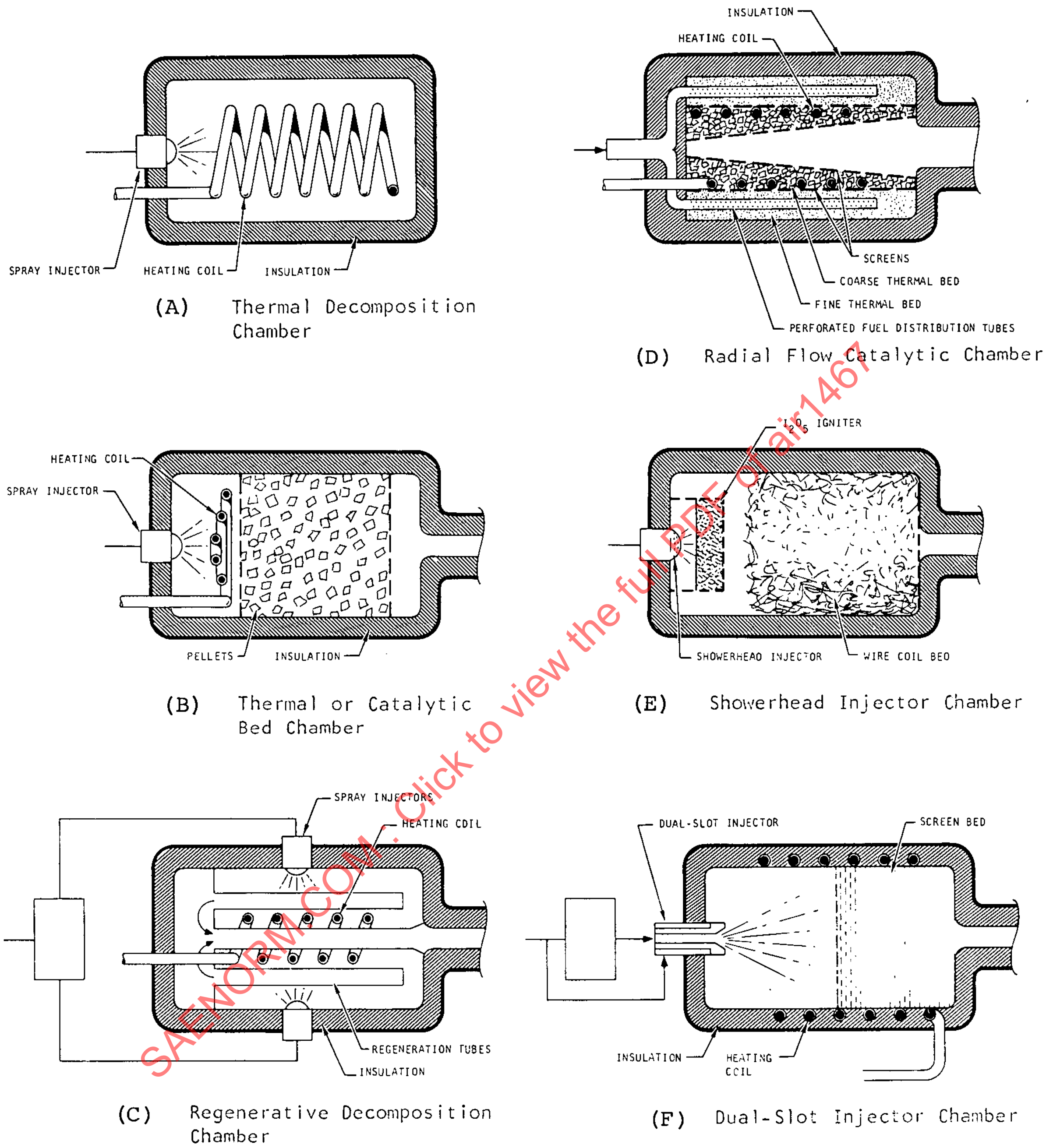


FIGURE 7

TYPICAL GAS GENERATOR CONFIGURATIONS

Hydrazine monofuel gas generators may be started by a variety of ways which include hypergolic solids and liquids, spontaneous catalysts, electrical heaters, and solid propellants. Usually, once the chamber has been fired it can be restarted within a certain period (up to approximately one hour, depending on the design) without additional energy input. A chamber employing a spontaneous catalyst can be restarted at any time.

The dimensions of the decomposition chamber are functions primarily of the fuel composition and fuel flow rate. Other variables affecting the chamber dimensions include the chamber ignition type, the injector type, the desired exit temperature, the operating pressure, and the materials of construction. Determination of the chamber dimensions requires a knowledge of the interdependence of these variables on the decomposition and dissociation processes occurring within the chamber.

Starter

The turbine starter can be designed to operate on hydrazine fuel only, or with hydrazine for inflight emergency starts, and with low pressure bleed air from ground support equipment for ground starting. The starter can also provide inflight emergency shaft power to produce electrical or hydraulic power by motoring the engine accessory drive gearbox.

Starter design tradeoffs are necessary to establish the best design to meet the requirements of operation on two working fluids and high efficiency on monofuel operation. Selection of the turbine design rotational speed, pitch line velocity, inlet pressure, inlet temperatures, and flow rates for both modes of operation are all influenced by these requirements as well as by cost, operating life, and reliability considerations. Furthermore, the starter design and performance will be a factor in all of the other system tradeoffs involving monofuel selection, gas generator design, and fuel supply design.

2.2.4 Applicable Specifications

MIL-P-26536	Propellant, Hydrazine

Additional military and industrial specifications and standards applicable to hydrazine starting systems are listed in Society of Automotive Engineers Aerospace Information Report AIR 1174.

2.3 Stored Gas

2.3.1 Compressed Stored Air System

2.3.1.1 System Description

A stored air starting system consists of the following basic elements:

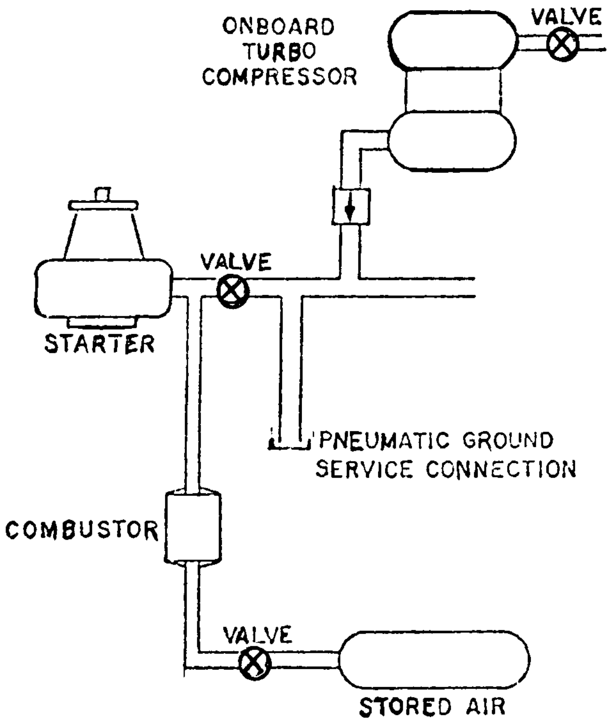
- Storage Tank
- Pressure Regulator and Shutoff Valve
- Combustor
- Turbine Starter
- Air Compressor
- Supply Lines, Safety Valve, and Control Elements

The pressurized air from the storage tank is converted to shaft power by the starter as the air expands through the starter turbine. A pressure regulator valve throttles the storage tank air to a lower pressure compatible with the starter turbine design pressure ratio. A jet fuel combustor is used with some stored air systems to increase the pneumatic energy and to reduce the required airflow and storage tank volume. Some systems incorporate a compressor to recharge the storage tanks when the air is depleted.

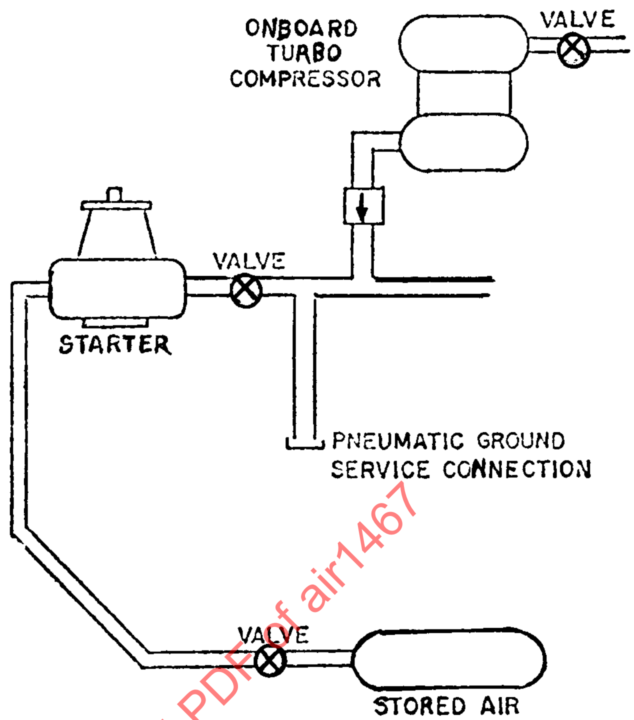
Steel or filament wound fiberglass tanks are used to store the high pressure air. The storage tank is designed in the shape of a sphere or cylinder depending on the envelope tolerances. The tank requires a wall thickness and weld efficiency sufficient to withstand an internal pressure of some multiple of operating pressure.

A fuel air combustor can be used to raise the temperature of the air and thus provide an engine start with a smaller storage tank or quantity of air. The higher the temperature that can be used, the less is the amount of air required to perform an engine start. The maximum temperature is determined by the required starter life. The optimum combustor temperature, therefore, is a compromise between starter life and air consumption.

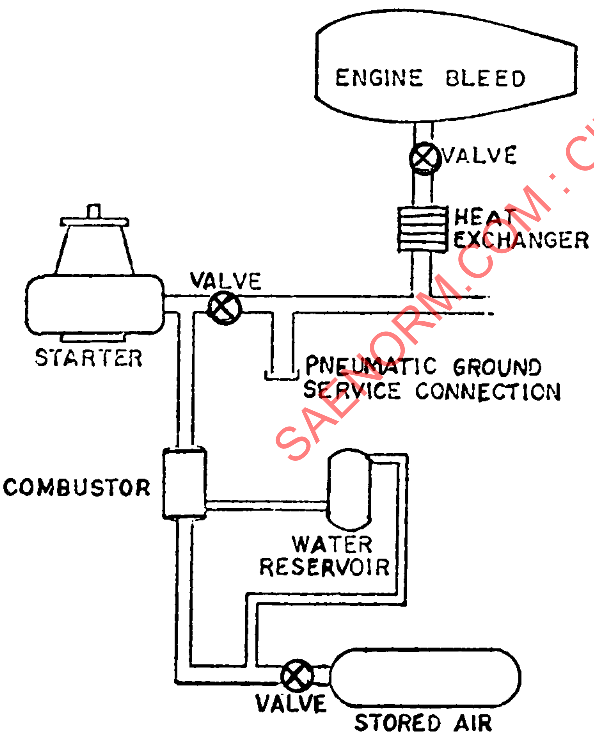
There are many stored air start systems in current use on commercial and military aircraft including the Boeing 707, 720B, and KC-135 the McDonnell Douglas DC8-62, the Lockheed Electra 188 and the General Dynamics F-102 and F-106 aircraft. The F102, F106, DC8-62, and KC-135 start systems utilize jet fuel combustors. Stored air start systems are also used for starting various industrial and marine gas turbines. Some typical stored air starting systems are shown on Figure 8.



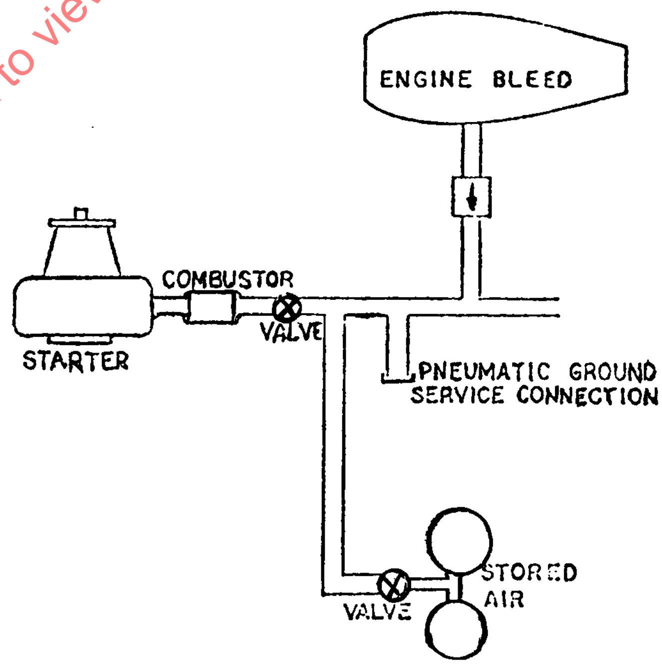
BOEING 707



BOEING 720B



MCDONNELL DOUGLAS DC-8



LOCKHEED ELECTRA 188

FIGURE 8

TYPICAL COMPRESSED STORED AIR START SYSTEMS

The Boeing 707 on-board system utilizes a 2-cubic foot cylindrical tank to store air at 3000 psig, which is enough air for a single start of the Pratt and Whitney JT3, JT3D, JT4, or Conway engines, using a cold gas starter. The initial 707 aircraft utilized a combustion starter which heated the air to 1000F, the temperature compatible with the low pressure turbine starter. The use of combustion or other means of heating the air upstream of the starter reduces the amount of air consumed. Both the cold gas and combustion starters could be alternately used with low pressure cross-bleed or ground cart air.

The Boeing 720B stored air start system utilizes a combination high and low pressure air turbine starter. The starter incorporates two sets of partial admission turbine nozzles. One set of converging nozzles is designed for operation with low pressure air and the other set of converging-diverging nozzles provides for operation with high pressure air. The turbine is optimized for operation with both high and low pressure air.

For the McDonnell-Douglas DC-8 on-board stored air system, the air was originally stored in the landing gear struts at 3000 psig. Flexible lines and swivel fittings allowed for movement of the landing gear. High pressure storage tanks are currently being used to store the compressed air. The pressure regulator and shutoff valve are mounted on the bulkhead, and the air is heated by stoiciometric combustion in a combustor mounted in the engine nacelle. Water/alcohol is used to cool the hot gas and add mass flow to the system. The end result is superheated steam at 750F which feeds the basic turbine starter. This system provides for two starts of the JT4 engine with a single filling of the 3000 cubic inch air reservoir. This starter can use either low pressure crossbleed or ground cart air.

The Lockheed Electra initially used a 1000F line combustor in conjunction with a 2-cubic foot, 3000 psig stored air system, to provide a single start of the Allison 501-D13 engine. The line combustor was also used during crossbleed or ground cart starting since the starter had been designed to minimize air consumption and provide a proper engine assist with the 1000F gas.

Some ground carts utilize a series of 3000 psig air tanks, an electric heater, and a pressure regulator to provide multiple pneumatic starts. For remotely located industrial engines, a large tank at pressures of 100 to 200 psig is used. Engine bleed air refills the tank. Emergency generators driven by a gas turbine engine onboard naval ships are started using a cold gas starter with a high pressure tank of air. A small diesel engine drives a compressor to pump up the tank to 3500 psig. This system can be energized and controlled with a hand valve and pressure gauge in the event of a normal control failure.

2.3.1.2 System Performance

The fundamental problem in designing a compressed stored air starting system is to determine the minimum tank volume required to perform an engine start. It is usually assumed that the storage tank is charged at standard day temperature (59F) and that the tank and air soaks and attains the ambient temperature at which the start cycle is performed. For a cold day start, the tank pressure and the energy available for a start is considerably lower than for a hot day. The storage tank is therefore sized to provide sufficient air to complete the engine start at the lowest design point ambient temperature.

The mass of the air required for an engine start cycle is:

$$M_{gas\ required} = M_{gas\ out} + M_{gas\ remaining}$$

Rearranging the equation the quantity of air consumed during the start is:

$$M_{gas\ required} - M_{gas\ remaining} = M_{gas\ out}$$

or

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

where

ρ_o = initial gas density

ρ_f = final gas density

V_t = required tank volume

The initial and final gas density is calculated from the following equation:

$$\rho = \frac{P}{ZRT}$$

where

P = tank air pressure

T = tank air temperature

R = is the gas (air) constant

Z = is the compressibility factor

The properties of air at high pressures deviate considerably from those based on the perfect-gas approximation as shown on Figure 9. The compressibility factor is used to calculate the density of air at high pressures.

The thermodynamic properties of air are shown on the temperature-entropy diagram presented as Figure 10. If the expansion process in the storage tank is assumed to be isentropic and the expansion of air across the regulating valve is a Joule-Thompson or throttling process, then the final tank pressure and temperature can be established. This is illustrated on Figure 10 where the initial pressure and temperature is given and the final starter inlet temperature is indicated for a valve regulation pressure of 150 psig. In actual practice the start cycle could continue after the valve goes off regulation.

Experiments have shown that the actual expansion process in the storage tank and supply line to the control valve is non-isentropic except for very short blowdown durations. However for the relatively long duration of an engine start cycle, there is considerable heat transfer to the air from the tank and supply line walls as the air discharges from the tank and through the supply line to the control valve. Therefore the final starter inlet temperature when the heat transfer effects are considered may be appreciably higher than for an isentropic blowdown. The deviation from isentropic expansion depends upon the duration of the tank blowdown, tank wall thickness, line length, line wall thickness, line diameter, etc.

An air storage tank that is sized assuming that the expansion process is isentropic will result in an oversized tank. If the storage tank size and weight is a critical design parameter the heat transfer effects would have to be considered during the tank expansion process in order to size the tank. The assumed Joule-Thompson expansion across the control valve is an adiabatic process. Since the expansion occurs over such a short length, the heat transfer effects can be ignored.

2.3.1.3 Applicable Specifications

MIL-STD-14/7F	Compressed Air Characteristics Supply Pressure and Hoses

Additional military and industrial specifications and standards applicable to pneumatic starting systems are listed in Society of Automotive Engineers Aerospace Information Report AIR 1174.