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Gas Energy Limited Starting Systems

FOREWORD

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1. SCOPE:

This SAE Aerospace Information Report (AIR) presents information on gas energy limited propulsion engine starting systems employed in commercial and military applications and remote industrial sites. The types of systems discussed utilize solid propellant cartridge gas, monopropellant hydrazine gas, bipropellant gas, compressed stored gas, and cryogenic stored nitrogen. Presented information conveys design features, performance capabilities and system limitations with methods of computing results.

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3. SYSTEMS DESCRIPTION:

3.1 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, F106, F111, F4C, B-52, KC-135, GAM77, and A3D.

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. Later designs operated either with cartridge gas or low pressure bleed air and are referred to as air turbine cartridge 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 to extend the service life of the starter and reduce starting costs.

3.1 (Continued):

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, for large engines, 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.

Vane motors have also been used to convert cartridge gas energy to rotational power. Reference 3 describes an application to starting diesel engines; the approach has also been applied to gas turbines.

The Air Force has funded development of a hot gas vane motor suitable in size to start jet fuel starters or APUs and capable of operation on gases generated by solid or liquid propellants (Reference 4).

Disadvantages of solid propellant cartridge systems, which have resulted in no recent aircraft applications, are limited selection of existing cartridges, excessive smoke, excessive deposits (necessitating frequent cleaning of the starter hardware), and poor resistance to temperature cycling. The latter can result in cracking of the propellant grain which leads to overpressurization or explosions or both. To sum up, future applications are most likely to be based on new propellant formulations tailored to the application. Applications are likely to be limited to starting jet fuel starters, auxiliary propulsion units and small un-manned aircraft engines. A potential user would do well to contact the agencies referenced herein prior to conducting extensive design studies; it is to be expected that on-going effort by Cartridge Manufacturers will reduce some of the disadvantages.

- 3.1.1 Cartridge: 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 cartridge 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.

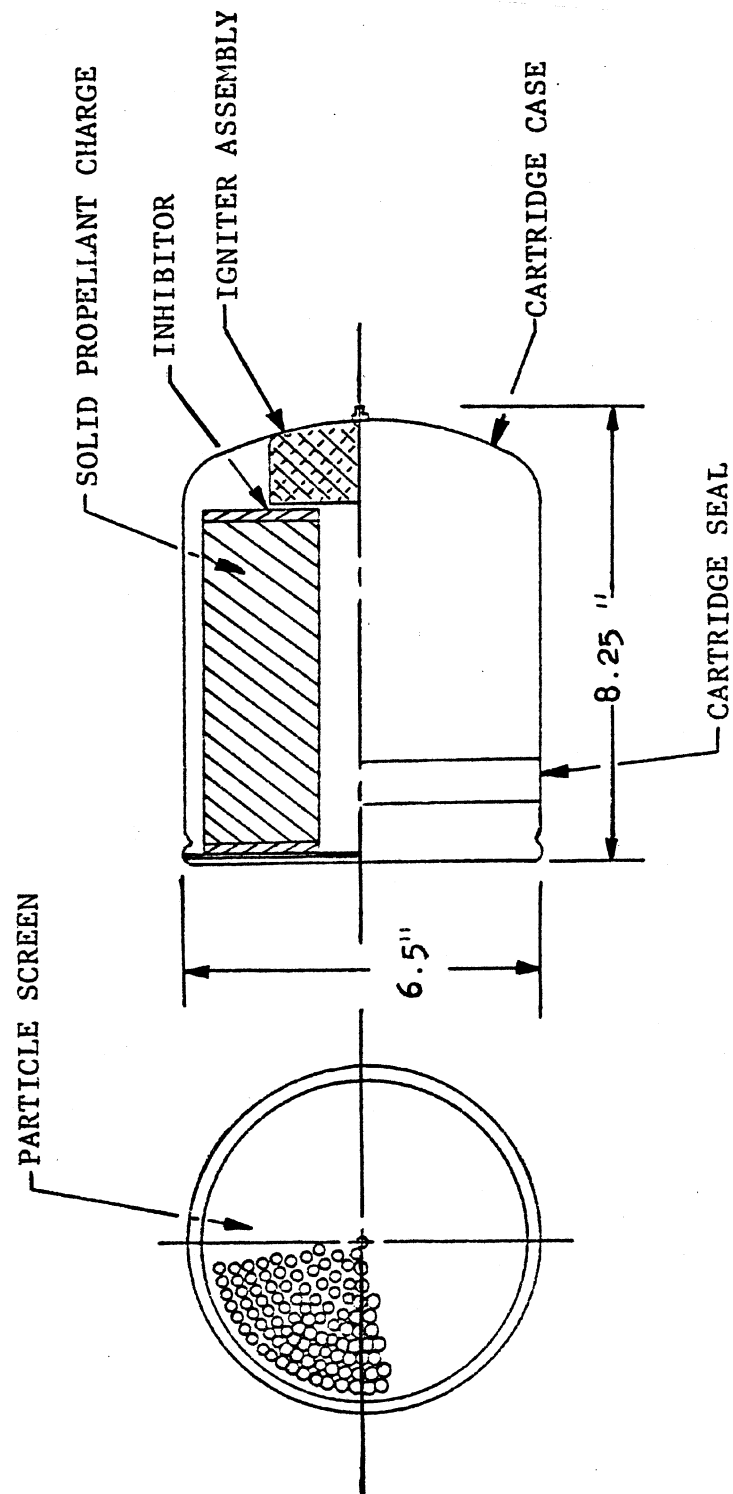


FIGURE 1 - Basic Components-Air Force Type MXU-4/A Starter Cartridge

3.1.1 (Continued):

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, 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 overpressurization of the starter breech or an explosion or both.

Existing qualified cartridges in the military inventory are the 4 lb grain MXU-129/A and the 8 lb grain MXU-4A/A; a smaller cartridge, designated the CJU-2/B by the Navy, is used to start an engine on an unmanned vehicle (Reference 5). The Naval Ordnance Station, Indian Head, MD, has been working to remedy the other listed disadvantages as have the Air Force Rocket Propulsion Lab, Edwards AFB, CA, and the cartridge vendors.

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. A possible candidate for small engines is the cartridge developed for automobile airbag passive restraint systems.

- 3.1.2 Performance Characteristics: The linear 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:

$$r = aP_c^n \quad (\text{Eq. 1})$$

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 burn characteristics of the cartridge propellants are such that they will burn approximately twice as fast with the cartridge at 160 °F than when the cartridge is at -65 °F. With a constant turbine nozzle area, the faster burn rate at 160 °F 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. Later starter designs utilized 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.

3.1.2 (Continued):

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.

$$w = A_b r \rho_b \quad (\text{Eq. 2})$$

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:

$$\text{GHP} = \frac{w H_{AD}}{33\,000} \quad (\text{Eq. 3})$$

where,

w = Flow rate, lbm/min
 H_{AD} = Adiabatic head, ft

The adiabatic head can be expressed as follows:

$$H_{AD} = \frac{\gamma}{\gamma - 1} RT \left[1 - \left(\frac{P_c}{P_e} \right)^{\frac{\gamma - 1}{\gamma}} \right] \quad (\text{Eq. 4})$$

where,

γ = Specific heat ratio
 R = Gas constant, ft-lbf/lbm-°R
 P_c = Breech pressure, lbf/in² (absolute)
 P_e = Nozzle exit pressure, lbf/in² (absolute)
 T = Cartridge gas flame temperature, °R

3.1.2 (Continued):

For example, the performance characteristics of a MXU-4A/A cartridge at 80 °F are:

$$P_c = 1000 \text{ lbf/in}^2 \text{ (absolute)}$$

$$T = 2560 \text{ }^\circ\text{R}$$

$$\gamma = 1.27$$

$$R = 79.7 \text{ ft-lbf/lbm-}^\circ\text{R}$$

$$w = 30.6 \text{ lb/min}$$

Assuming an exhaust pressure of 14.7 lbf/in² (absolute), the adiabatic head (H_{AD}) and gas horsepower (GHP) are:

$$H_{AD} = 568\,400 \text{ ft}$$

$$\text{GHP} = 527.1 \text{ hp}$$

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.

- 3.1.3 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.

3.1.3 (Continued):

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 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 abnormally 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. Both the exhaust gas and residual particles from current ammonium nitrate cartridges can produce corrosion on the aircraft.

3.1.4 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 SAE AIR1174.

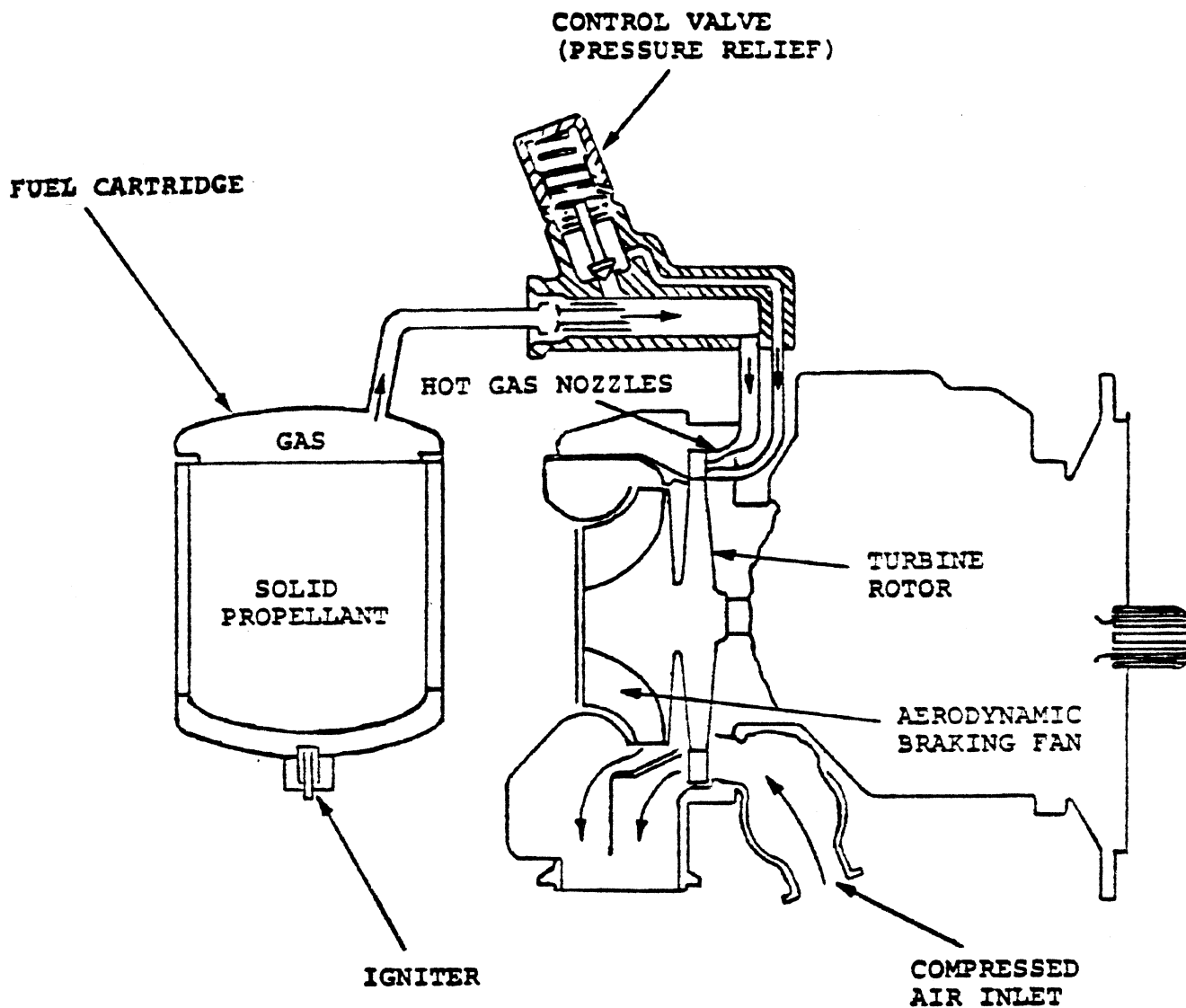


FIGURE 2 - Schematic Diagram Cartridge/Pneumatic Starter

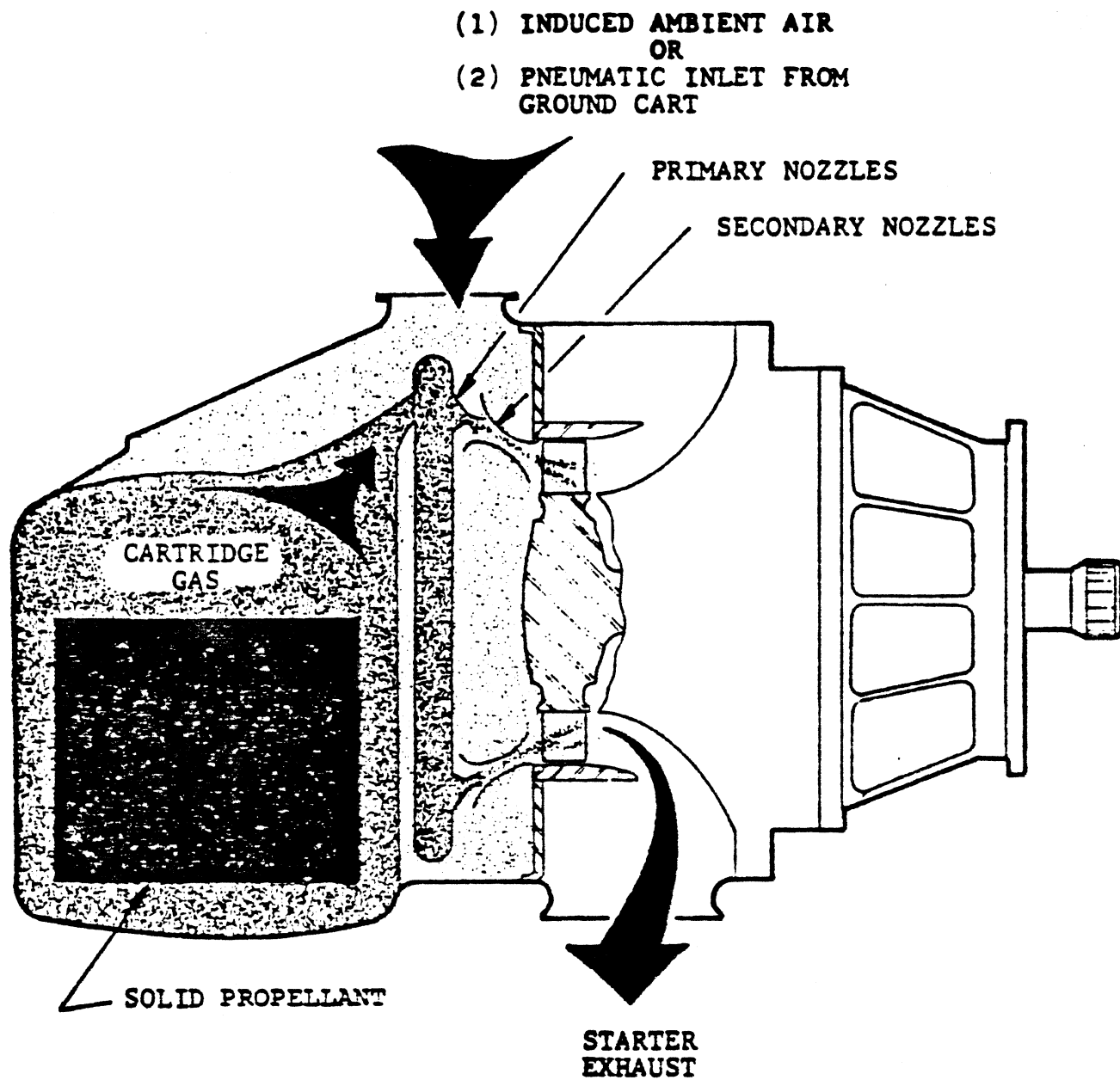


FIGURE 3 - Schematic Diagram Cartridge Ejector-Pneumatic Starter

3.2 Monopropellant Hydrazine Gas:

When considering a monopropellant gas energy system for starting, hydrazine (N_2H_4) is usually the fuel of choice. Other candidates include: hydrogen peroxide (H_2O_2), ethylene oxide ($\text{C}_2\text{H}_4\text{O}$), Otto Fuel II ($\text{C}_{2.75}\text{H}_{5.43}\text{O}_{3.05}\text{N}_{0.93}$), N-propyl nitrate ($\text{C}_3\text{H}_7\text{NO}_3$), and nitrous oxide (N_2O). All are toxic to some degree, most provide gases at temperatures that exceed turbine material limits, some present storage problems, and some are difficult to react and have dirty gas products. Although hydrazine is as toxic as any of the choices, its properties meet all other requirements for a good monopropellant fuel; perhaps the most stellar property is its ability to decompose instantaneously and smoothly in the presence of Shell 405 catalyst. This patented catalyst, consisting of iridium deposited on a substrate of alumina - usually in coarse, granular form, initiates the hydrazine decomposition and ammonia dissociation processes. Hydrazine has been a mainstay of the space program, both for derivative-fueled bipropellant booster rockets and reaction control jets, and most recently, as the fuel for the space shuttle auxiliary power unit. In manned aircraft, hydrazine systems have been used as the energy source for both emergency power units (F-16, F-17, X-29, Toronado) and starters (F-14A&B, Toronado, and F-20). Reference 6 provides a summary of experience. The hot gas, produced by the decomposition of monopropellant hydrazine in a gas generator, provides 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 F-14 system, shown schematically on Figure 4, represents a typical design. The design 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 in³ of nitrogen at 3000 lbf/in² (gage) to pressurize the fuel system. A pressure regulator regulates the fuel tank pressure to approximately 300 lbf/in² (gage). A 4200 in³ cylindrical fuel tank holds 155 lb of the 70% hydrazine-30% water fuel mixture. The gas generator uses Shell 405 catalyst. 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 s 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 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. Reference 7 provides a discussion of design, safety and maintainability aspects.

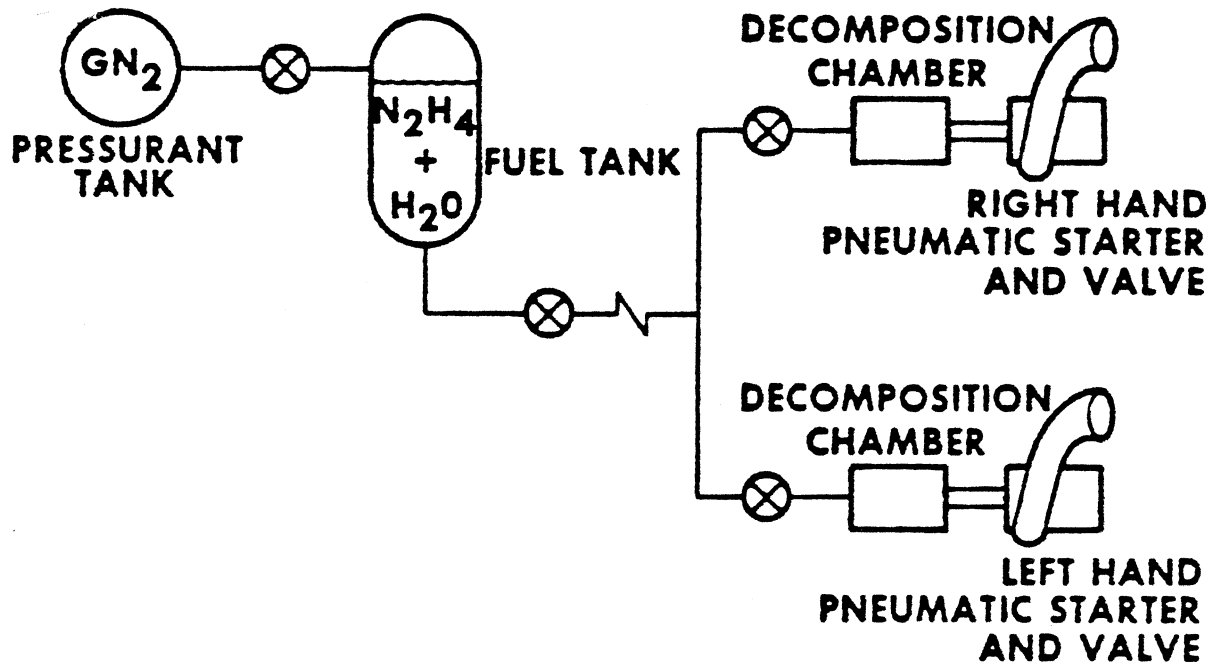


FIGURE 4 - Schematic Diagram of F-14B Emergency Air Start System

3.2 (Continued):

The Toronado 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 F-20 hydrazine starting system, described in Reference 8, is similar to the F-14B. In the normal ground start mode, pneumatic energy from a ground cart is provided to an air turbine starter (ATS) which cranks the engine through an airframe-mounted accessory gearbox; for emergency ground (scramble) and in-flight assisted starts, energy is provided to the same turbine by hydrazine decomposition gases at a temperature of 1100 °F and a pressure of 57 lbf/in² (absolute). The 715 in³ sealed cartridge of hydrazine is installed in the belly of the aircraft via drip-proof quick disconnects. An advantage of hydrazine systems over solid propellants is that the gas temperature is amenable to typical ATS wheel materials and pressure more nearly matches ground cart output, thus requiring no special provisions in design of the ATS.

While not used for starting, the F-16 aircraft makes use of a hydrazine-fueled emergency power unit which has set the precedent and safe operating procedures for hydrazine on fully deployed, manned aircraft.