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GAS ENERGY LIMITED STARTING SYSTEMS

	PAGE
1. INTRODUCTION	3
2. SYSTEMS DESCRIPTION	3
2.1 Solid Propellant Cartridge Gas	3
2.1.1 Cartridge	4
2.1.2 Performance Characteristics	6
2.1.3 Starter Description	9
2.1.4 Applicable Specifications	12
2.2 Monopropellant Hydrazine Gas	12
2.2.1 Hydrazine	14
2.2.2 Performance Characteristics	16
2.2.3 System Description	20
2.2.4 Applicable Specifications	24
2.3 Bipropellant Gas	24
2.3.1 Performance Characteristics	25
2.3.2 System Description	26

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AIR1467

Rev.
A

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Page 2

	PAGE
2.4 Stored Gas	26
2.4.1 Compressed Stored Gas System	26
2.4.2 Stored Cryogenic Nitrogen	33
3. SYSTEM SELECTION	38
4. REFERENCES	40

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1. INTRODUCTION:

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, bipropellant gas, compressed stored gas, and cryogenic stored nitrogen. These gas energy limited starting systems have been utilized in various commercial and military aircraft, onboard naval vessels, and at remote industrial sites. The information presented herein is intended to familiarize the aerospace industry with the design, performance, capabilities, and limitations of these systems.

Methods of computing the energy available from each system are provided. The amount of energy required is a function of the drag and inertia characteristics of the engine to be started and the torque output, inertia, and efficiency of the starter which uses this energy. Guidance in this aspect may be obtained from the SAE AIR's listed as References 1 and 2.

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, 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.

2.1 Solid Propellant Cartridge Gas: (continued)

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.

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.

- 2.1.1 Cartridge: The basic components of a typical solid propellant cartridge shown on Fig. 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

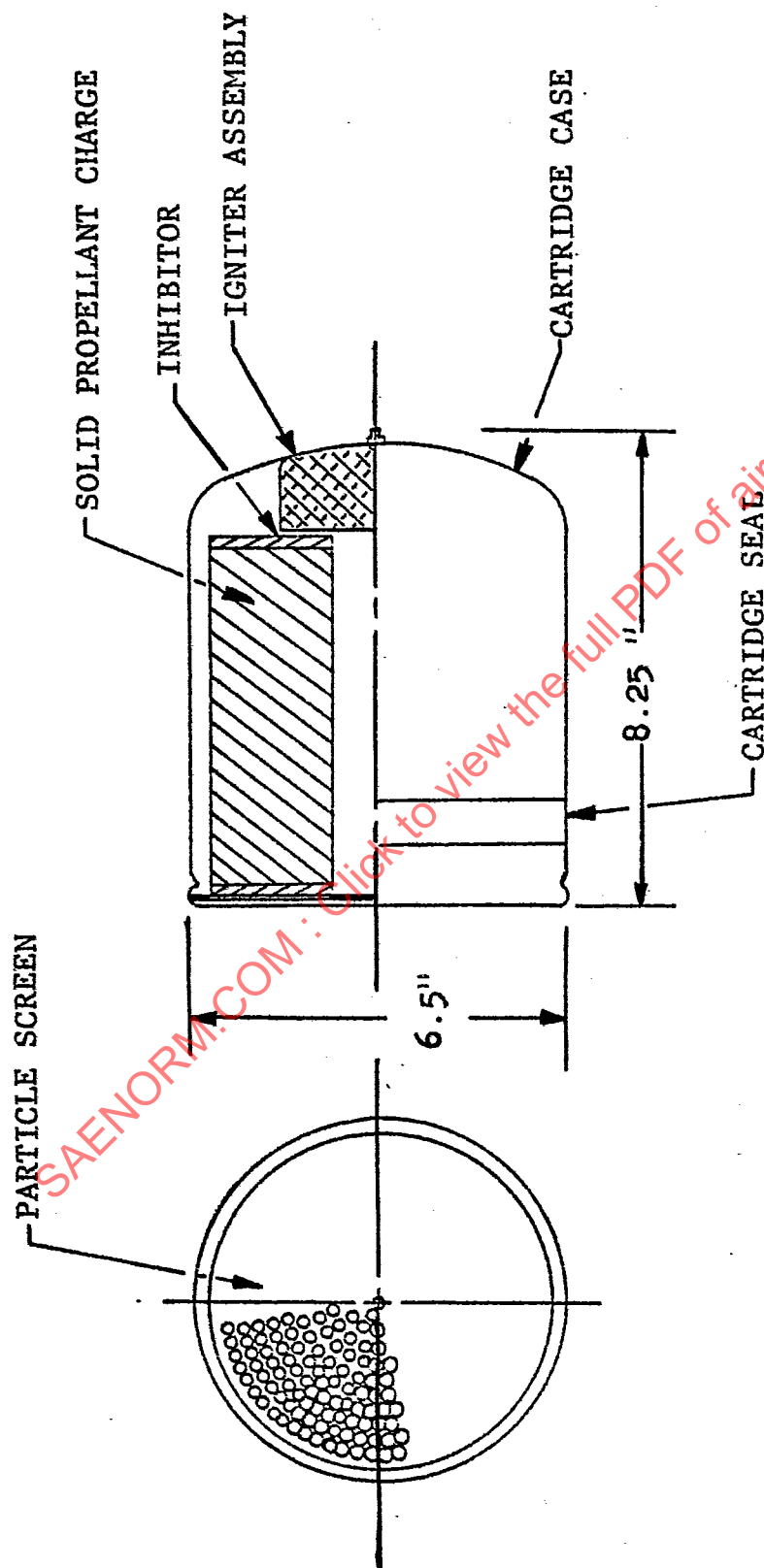


FIGURE 1 - Basic Components-Air Force Type MXU-4/A Starter Cartridge

2.1.1 Cartridge: (continued)

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.

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.

- 2.1.2 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.

2.1.2 Performance Characteristics: (continued)

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.

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)

2.1.2 Performance Characteristics: (continued)

P_e = Nozzle exit pressure, lbf/in² (absolute)

T = Cartridge gas flame temperature, °R

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

P_c = 1000 lbf/in² (absolute)

T = 2560°R

γ = 1.27

R = 79.7 ft-lbf/lbm-°R

w = 30.6 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 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.

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.

Fig. 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.

Fig. 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 Fig. 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.

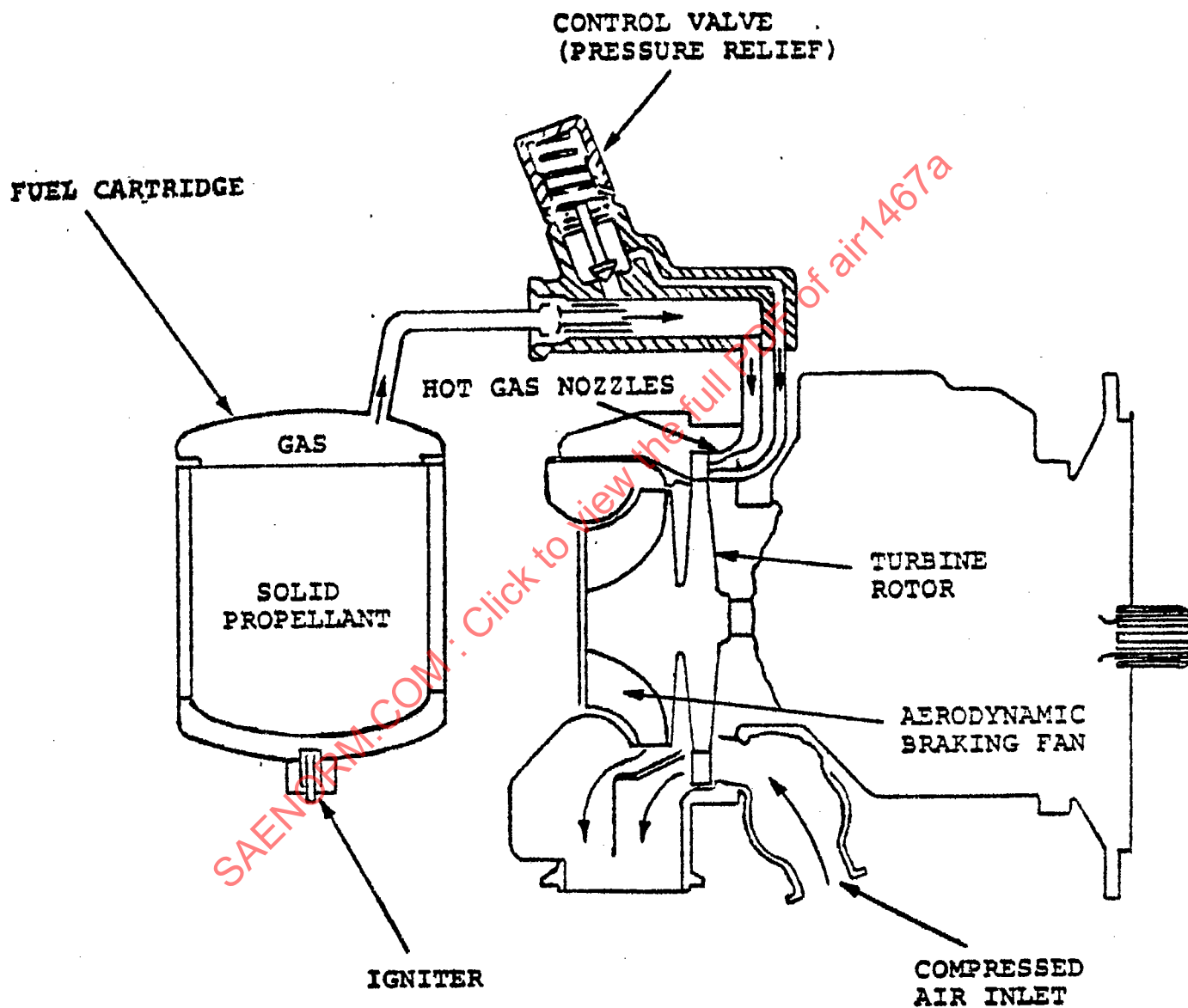


FIGURE 2 - Schematic Diagram Cartridge/Pneumatic Starter

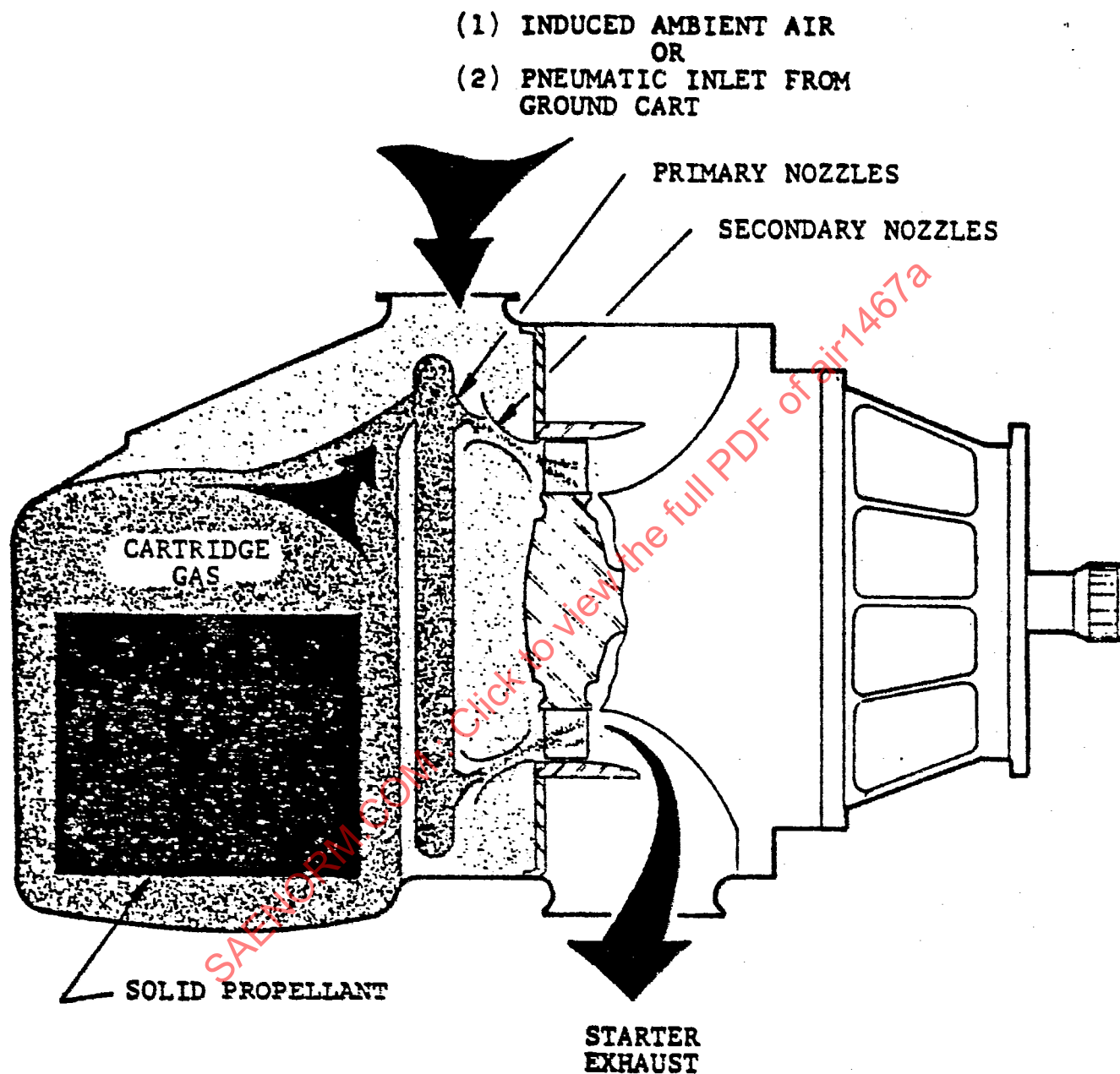


FIGURE 3 - Schematic Diagram Cartridge Ejector-Pneumatic Starter

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 SAE AIR1174.

2.2 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 (C_2H_4O), Otto Fuel II ($C_{2.75}H_{5.43}O_{3.05}N_{0.93}$), N-propyl nitrate ($C_3H_7NO_3$), 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 Fig. 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 in^3 of nitrogen at 3000 lbf/in^2 (gage) to pressurize the fuel system. A pressure regulator regulates the fuel tank pressure to approximately 300 lbf/in^2 (gage). A 4200 in^3 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.

2.2 Monopropellant Hydrazine Gas: (continued)

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.

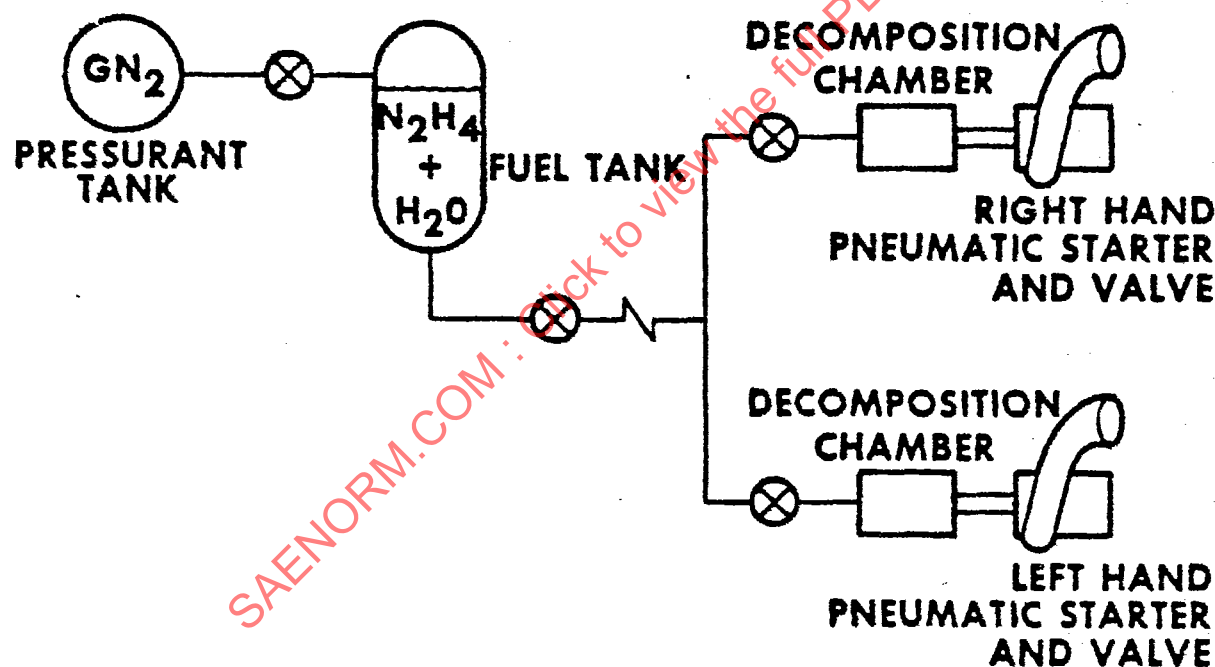


FIGURE 4 - Schematic Diagram of F-14B Emergency Air Start System

2.2 Monopropellant Hydrazine Gas: (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.

The use of hydrazine start systems is especially attractive for 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/reliability, 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 -65°F and tailor the gas temperature for various start system applications.

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

2.2.1 Hydrazine: (continued)

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 systemic effects. If spilled on the skin or eyes, liquid hydrazine can cause severe local damage or burns and can cause dermatitis and other systemic effects. Reference 9 provides an up-to-date perspective on hydrazine industrial hygiene.

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, that is, the surface must be "passive". In the system design, care must be exercised in selecting properly resistant and compatible materials to be used in contact with the fluid. Some materials generally found compatible with hydrazine fuels up to 160°F 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 Reference 10.

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 lbm) with an adiabatic head almost twice that of compressed air at similar conditions of pressure and temperature.

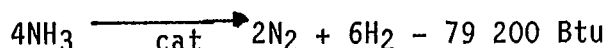
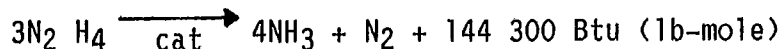
2.2.1 Hydrazine: (continued)

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 ($N_2H_3CH_3$), hydrazine nitrate ($N_2H_5NO_3$), or ammonia (NH_3) can be added to improve or vary the properties of the mixture. A wide variety of hydrazine mixtures is thus available. Two important properties must be considered in selecting a hydrazine mixture for a start system; 1) freezing point, and 2) working fluid temperature and composition. 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 a hydrazine mixture can be varied from approximately 900°F to 2700°F 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 I 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 mixtures containing monomethyl hydrazine are not suitable with catalytic type gas generators since the carbon in the decomposition products will poison the catalyst. The 70% mixture (30% water) is the choice in current systems.

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:

2.2.2 Performance Characteristics: (continued)

TABLE I - Hydrazine-Based Monofuels

Hydrazine, N_2H_4	100%	70%	63%	62%	58%	70%	26%	14%
Hydrazine Nitrate $N_2H_5NO_3$	0	0	10%	19%	25%	10%	19%	0
Monomethyl Hydrazine, $N_2H_3CH_3$	0	0	0	0	0	20%	55%	86%
Water, H_2O	0	30%	27%	19%	17%	0	0	0
Freezing Point, °F	35.6	-57	-68	-80	-85	-68	-44	-68
Specific Gravity (77°F)	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	NA	NA	NA	530	500	520
Boiling Point, °F	238	246	237	NA	NA	200	207	194
Vapor Pressure (77°F), psi	0.28	0.354	0.15	0.06	0.05	0.84	0.77	1.0
Flash Point, °F	126	154	NA	NA	NA	90	90	80
Card Gap Sensitivity	Neg	Neg	Neg	Neg	Neg	Neg	Neg	Neg

Note: NA = Not Available

2.2.2 Performance Characteristics: (continued)

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 II presents a comparison of the important performance parameters of the decomposition products of the monofuel mixtures previously described. The gas generator chamber temperatures (T) 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 lbf/in² (absolute) and for a sea level expansion ratio of 6.8 to 1.

The adiabatic head is calculated from the following equation:

$$H_{AD} = \frac{\gamma}{\gamma-1} RT_c \left\{ 1 - \frac{1}{\left(\frac{P_c}{P_e} \right)^{\frac{\gamma-1}{\gamma}}} \right\} \quad (\text{Eq 5})$$

where,

H_{AD} = Adiabatic head, ft

γ = Specific heat ratio

R = Gas constant, ft-lbf/lbm °R

T_c = Chamber temperature, °R

P_c = Chamber pressure, lbf/in² (absolute)

P_e = Nozzle exit pressure, lbf/in² (absolute)

The gas horsepower (GHP) can then be calculated from the following equation (Eq 3 repeated):

$$GHP = \frac{w H_{AD}}{33\,000} \quad (\text{Eq 6})$$

where,

H_{AD} = Adiabatic head, ft

w = Mass flow, lbm/min

2.2.2 Performance Characteristics: (continued)

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.

TABLE II - Monofuel Performance Comparison

Monofuel	T_c (R)	R	γ	H_{AD}^* (ft)
Neat Hydrazine	2160	117.9	1.275	400 000
70%H-30%W (H-70)	1650	86.8	1.230	231 000
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 lbf/in² (absolute) at sea level)

H = hydrazine

HN = hydrazine nitrate

MMH = monomethyl hydrazine

W = water

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

- a. Fuel Supply System
- b. Gas Generator
- c. Starter

2.2.3.1 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 either an integral or separate gas supply. The use of pressurizing gas stored integrally in the ullage volume of the fuel tank results in a simple, reliable system since the separate, high pressure gas tank, valve, and regulator are eliminated, but is best applied to designs requiring only a few pounds of fuel, due to the increased fuel tank weight resulting from the increased pressure and volume required to store adequate pressurant. The second approach 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 follows:

- a. Pressurized Systems: The essential components of a typical gas-pressurized propellant feed-system, shown schematically on Fig. 5, are the high-pressure gas tank, gas control valve, pressure regulator, propellant tank, propellant control valve, and feed line to the decomposition chamber. Positive expulsion may, or may not, be necessary. 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 Fig. 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 2% of the net turbine output power. The monofuel tank ullage is pre-pressurized sufficiently to provide positive delivery and the required pump inlet pressure under all acceleration conditions.

2.2.3.1 Fuel Supply System: (continued)

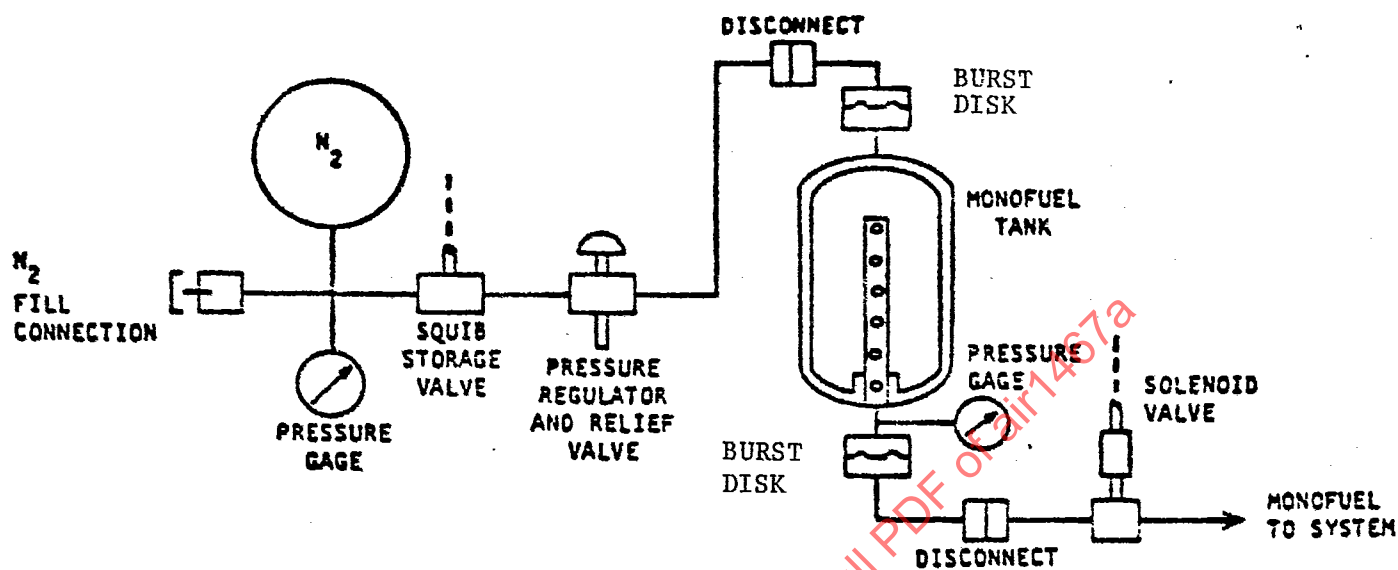


FIGURE 5 - Typical Pressurized Monofuel Supply System with High Pressure Gaseous Nitrogen Pressurant

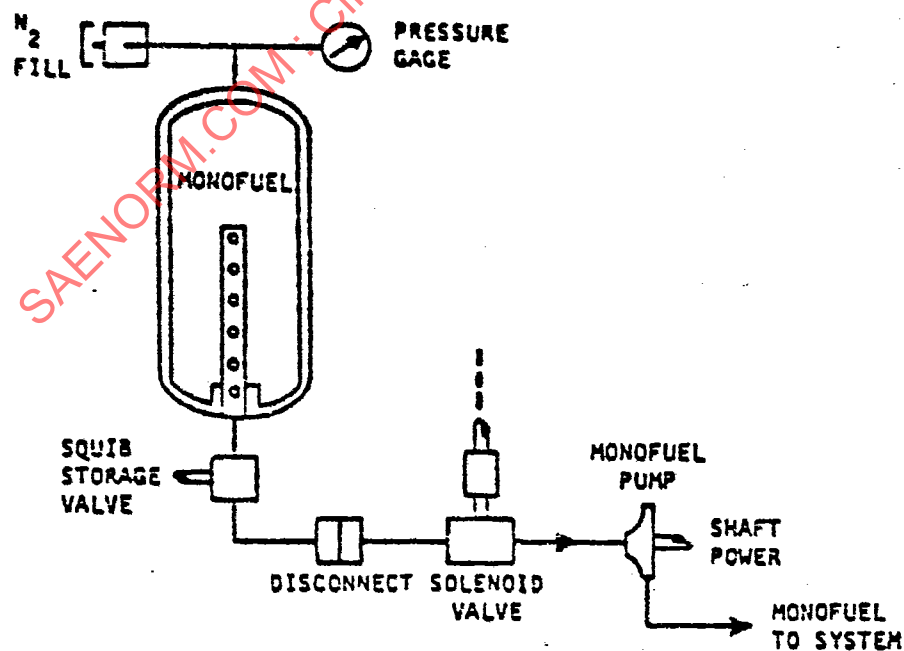


FIGURE 6 - Typical Pump-fed Monofuel Supply System with Low Pressure Fuel Storage and Boost Pump

2.2.3.1 Fuel Supply System: (continued)

In both these systems, the monofuel can be supplied in sealed tanks to minimize ground servicing problems. It is usually necessary to provide a means of gradual build-up of fuel pressure to the gas generator in order to avoid excessive impact torques during running engagements of the starter; this can be accomplished by stroking open either the pressurant or fuel control valves. 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 system for each application.

2.2.3.2 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. Historically, two basic types of gas generators are available, one using catalysts and the other depending upon thermal processes. Fig. 7 presents diagrams of some typical catalytic and thermal designs. Catalytic chambers, similar to Fig. 7B, D or F but without the heater, using Shell 405 catalyst are the almost universal choice (although they cost more), because they 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 (igniting upon contact) reaction to obtain rapid, positive ignition. Thermal designs will either require refurbishment after use or will require electrical pre-heating before use (since the advent of Shell 405 catalyst, thermal designs are seldom selected). There are a large number of variants such as the specific flow arrangement, means of ignition, and types of injectors. Fig. 7 presents diagrams of some typical catalytic and thermal designs.

Thermal hydrazine gas generators, Fig. 7A, C and E, may be started by a variety of ways which include hypergolic solids and liquids (such as iodine pentoxide, I_2O_5), 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.

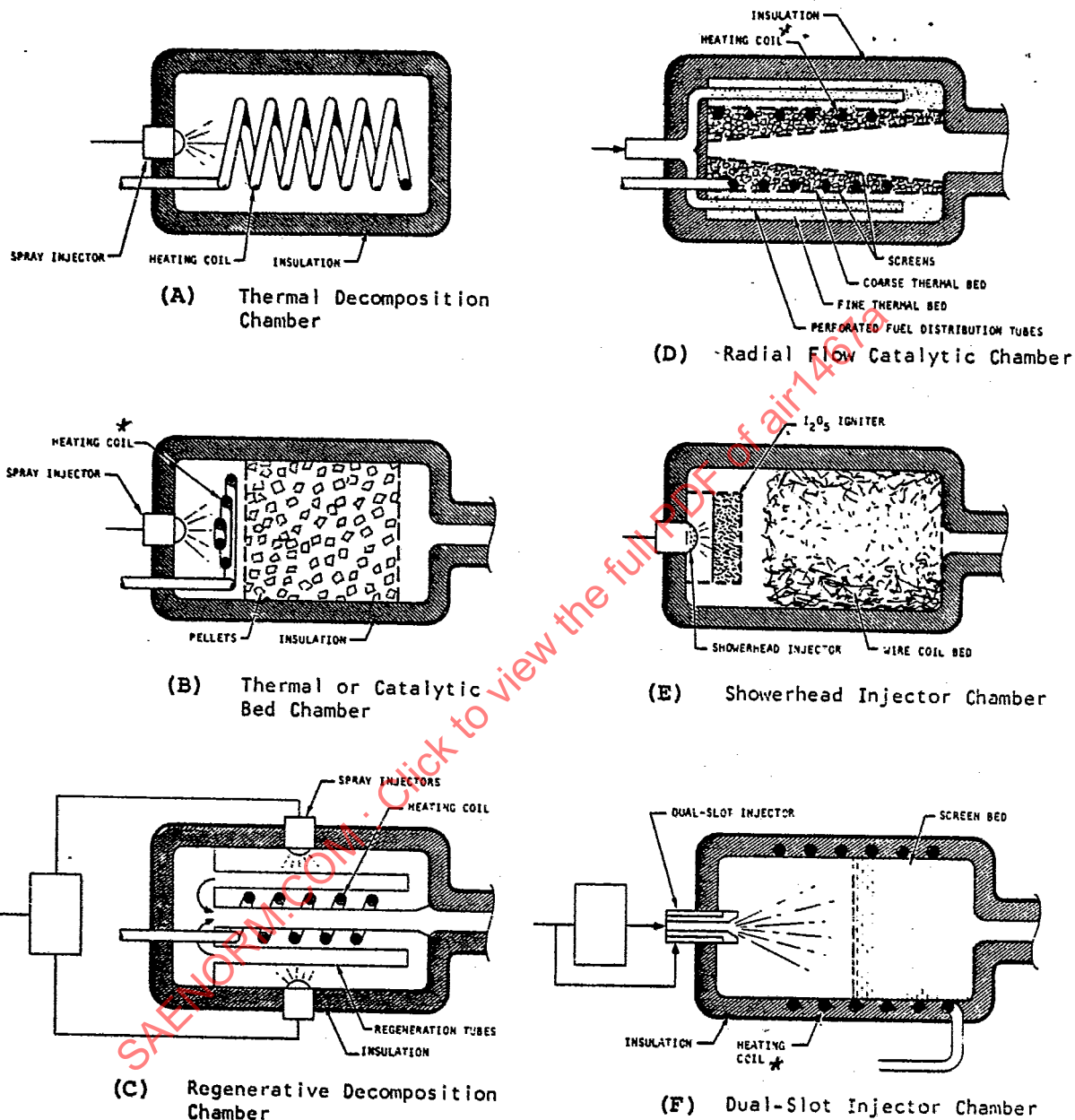


FIGURE 7 - Typical Gas Generator Configurations

Note: In (B), (D) and (F) above, Heating Coil is unnecessary if catalyst is spontaneous.

- 2.2.3.3 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.

Reference 4 describes a hot gas vane motor development program. The motor is designed to operate on hydrazine decomposition products, bipropellant, or solid propellant cartridge hot gas.

The precautions regarding ducting starter solid propellant cartridge exhaust gases overboard without bay leakage or external skin impingement/flow attachment also apply here due to both toxicity and corrosiveness.

2.2.4 Applicable Specifications:

MIL-P-26536 Propellant, Hydrazine

MIL-P-87930 Propellant, Hydrazine-Water

Additional military and industrial specifications and standards applicable to hydrazine starting systems are listed in SAE AIR1174.

- 2.3 Bipropellant Gas: By definition, a bipropellant gas system utilizes an oxidizer and fuel, reacted in a gas generator (that is, combustion chamber), to produce a hot gas energy supply. The system described in the next section under the heading of "Stored Gas", in which a jet fuel combustor is used to increase pneumatic energy, could as appropriately be incorporated under the present heading. The following are among the candidate oxidizer/fuel combinations which have been considered or used:

Liquid Oxygen/JP-4	Liquid Oxygen/Ammonia
Gaseous Oxygen/JP-4	Nitrous Oxide/JP-4
Liquid Air/JP-4	Hydrogen Peroxide/JP-4
Gaseous Air/JP-4	Nitrogen Tetroxide/JP-4
Gaseous Oxygen/Methanol*	Inhibited Red Fuming Nitric Acid/JP-4
Gaseous Oxygen/Ethylene Glycol*	

*Usually with water added to reduce both the freezing point and combustion temperature.

The combinations listed on the left have been found more acceptable from the viewpoint of safety and handling. All of these require ignition and must be operated off-stoichiometric mixture to avoid excessive temperatures (above 1800°F). The usual case is to run fuel-rich to minimize oxidizer storage requirements; however this can result in afterburning (torching), excessive smoke or coking of the combustor or both. One alternate approach burns air and JP-4 stoichiometrically and cools the exhaust products with added fuel, reportedly with minimal smoking. Another approach burns the same combination lean, also reportedly with minimal smoking. Alcohol with gaseous or liquid oxygen apparently does not smoke but will represent a two-fold logistics problem as fighter aircraft replace on-board liquid breathing oxygen with on-board oxygen generation. The trade-off between gaseous and cryogenic liquid storage is between simplicity, with long-term but bulky high pressure storage, and complex, cryogenic tankage, requiring frequent servicing, but much more compact.

- 2.3.1 Performance Characteristics: A recent SAE Paper, Reference 11, compares relative specific power (HP/PPM°R) of some of these systems with solid propellant cartridge and hydrazine, at the same pressure ratios as follows:

System	Relative Isentropic HP/PPM °R
Hydrazine	100
Cartridge (Ammonium Nitrate)	82
LOX/JP-4, GOX/JP-4	82
AIR/JP-4	47
GOX/Methanol	67

Specific power is an alternative form of the gas horsepower (GHP) and adiabatic head (H_{AD}) equations previously presented as measures of solid propellant and hydrazine monopropellant performance. This form permits comparison of the energy supplies independent of mass flow, W , and gas temperature, T :

$$\text{Specific Power} = \frac{GHP}{WT} = \frac{H_{AD}}{33\,000\,T} = \frac{\gamma}{\gamma-1} R \left[1 - \frac{1}{(PR)^{\frac{\gamma-1}{\gamma}}} \right] \quad (\text{Eq 7})$$

where,

γ = Specific Heat Ratio

R = Gas Constant, ft-lbf/lbm-°R

T = Gas Total Temperature, °R

PR = Gas Pressure Ratio (starter inlet to outlet)

- 2.3.2 System Description: The oxidizer and fuel supply systems are quite similar to the monofuel system shown on Fig. 5, with the addition of a second tank and split flow of the nitrogen gas line to pressurize both fuel and oxidizer tanks equally. Although JP-4 is convenient as a common fuel, a separate pressurized container is required to obtain the necessary pressure and for positive or extreme attitude expulsion. A variation incorporates a method of refilling the JP-4 tank from the main engine supply via a special fuel pump. For cryogenic liquids, helium pressurant gas results in significantly less weight than nitrogen.

The essentials of the combustor are the oxidizer/fuel injector, igniter (usually two for reliability), and the chamber, which is either air or fuel cooled. Injector design is critical and usually proprietary to individual vendors; operation off of stoichiometric mixture (for manageable temperatures) makes good ignition and mixing especially critical; also, poor injector spray patterns can result in hot or cold spots on the chamber wall which can lead to burn-through or coking. Much of the technology of LOX/hydrocarbon rocket engine gas generators is applicable.

The information regarding starter design presented for hydrazine monopropellant systems is equally applicable to bipropellant systems.

2.4 Stored Gas:

- 2.4.1 Compressed Stored Gas System: Compressed stored gas systems have been used extensively in the past for starting engines on both commercial and military aircraft. These included stored air systems on 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 utilized jet fuel combustors to increase energy. Stored air start systems are also used for starting various industrial and marine gas turbines.

With the advent of turbofan aircraft engines, which require more starting energy than turbojet engines, compressed stored gas systems could become excessively large and heavy; however, they merit serious consideration for starting jet fuel starters and auxiliary power units. Compressed stored gas systems are especially appropriate where starting the unit is required at low ambient temperature (-40°F and colder). In addition to providing excellent low temperature starting capability, these systems also provide high altitude APU start capability along with low weight and high reliability. Further, compressed gas starting systems are synergetic with OBIG (On Board Inert Gas) systems, since the two systems can share a common compressor and gas storage vessels. The primary drawback of compressed gas systems is the volume required; however, this is not a significant disadvantage at storage pressures of 3000 psi and higher. Reference 12 provides details and trade-offs on various alternative designs.

2.4.1.1 System Description: A stored gas starting system consists of the following basic elements (see Fig. 8):

- a. Storage Tank
- b. Pressure Regulator and Shutoff Valve
- c. Combustor (optional)
- d. Pneumatic Starter
- e. Air Compressor (optional)
- f. Supply Lines, Safety Valve, and Control Elements

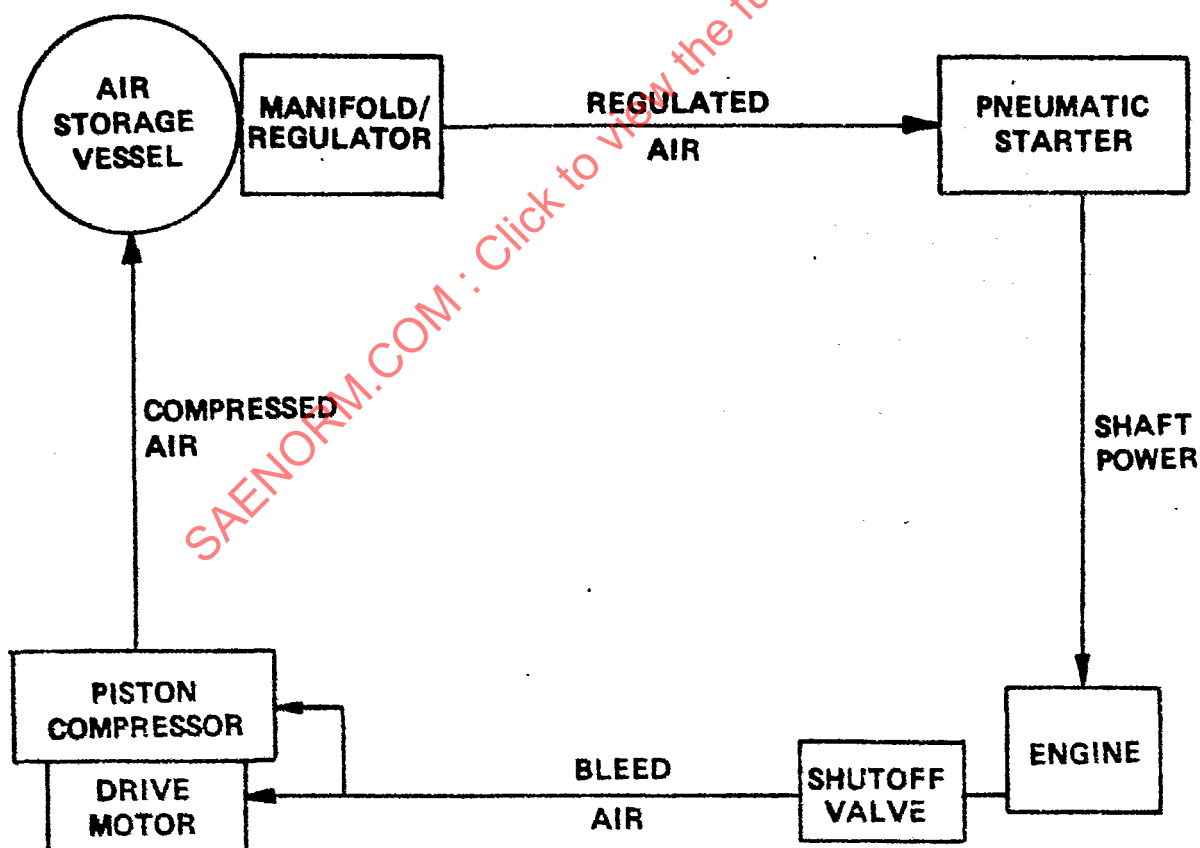


FIGURE 8 - Schematic Diagram of a Stored Gas Starting System

2.4.1.1 (Continued)

The pressurized gas (air or nitrogen) from the storage tank is converted to shaft power by the starter. A pressure regulator valve throttles the storage tank gas to a lower pressure compatible with the starter. Starters are either turbine or vane motors; direct impingement on the compressor or turbine wheel of the unit being started is also feasible, but at a cost of reduced efficiency. As with the systems previously described, the starter converts gas horsepower into useable shaft power; also, backup may be provided on the ground by start cart air and in-flight by cross-over engine bleed air. 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; the compressor may draw ambient air, or bleed air from the APU or the main engine.

Steel or filament wound tanks are used to store the high pressure gas. The storage tank is designed in the shape of a sphere or cylinder depending on the envelope. Tank capacity should provide sufficient stored gas for three start attempts (two with on-board compressor recharge); this will permit one failed attempt on the ground (two starts total) while preserving capability for at least one in-flight start.

- 2.4.1.2 System Performance: The fundamental task in designing a compressed stored gas 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 (59°F) and that the tank and gas attain 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 gas to complete the engine start at the lowest design point ambient temperature. The ideal energy available per start is given by the following equation:

$$E = \frac{V_T}{Z(\gamma-1)} (P_{T_i} - P_{T_f}) \quad (\text{Eq 8})$$

where,

E = Energy, ft-lbs

V_T = Volume of Tank, ft³

γ = Ratio of Specific Heats

Z = The Compressibility Factor at Initial Pressure

P_{T_i} = Initial Pressure in the Tank, lb/ft²

P_{T_f} = Final Pressure in the Tank, lb/ft²

2.4.1.2 (Continued)

For a one start system, the final pressure in the tank can be selected as the regulator pressure or the value at which the regulator ceases to hold design pressure. The energy available is set equal to the energy required, which is a function of starter and engine characteristics. As an approximation, the energy required per start can be assumed to be 1.25 times the engine kinetic energy at starter cutout divided by the system efficiency (η). System efficiencies typically range from 0.20 to 0.30.

$$E = 1.25 \text{ K.E.} / \eta \quad (\text{Eq 9})$$

The weight of gas in the tank can then be calculated from:

$$W = \frac{P_{T_i} V_T}{Z R T_{T_i}} \quad (\text{Eq 10})$$

where,

R = The Gas Constant, ft/ 12

T_{T_i} = Initial Tank (and gas) Temperature, °R

Iterative computations are required for multiple start systems. The properties of air and nitrogen at high pressures deviate considerably from those based on the perfect-gas approximation as shown by the compressibility factors provided on Figs. 9a and 9b.

The thermodynamic properties of air are shown on the temperature-entropy diagram presented as Fig. 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 Fig. 10 where the initial pressure and temperature are given and the final starter inlet temperature is indicated for a valve regulation pressure of 150 lbf/in² (gage). 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.

AIR1467

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Page 30

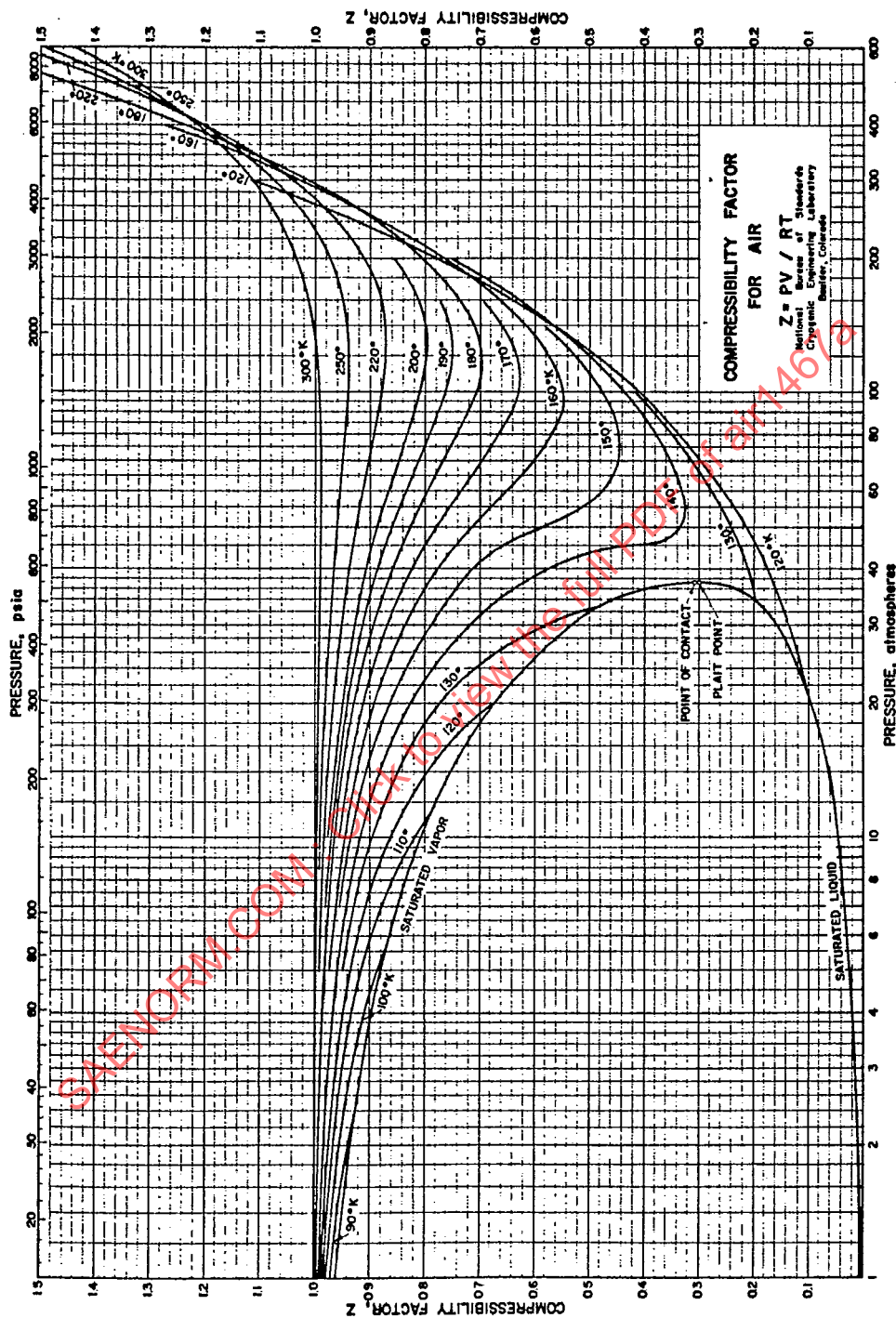


FIGURE 9a - Compressibility Factor for Air

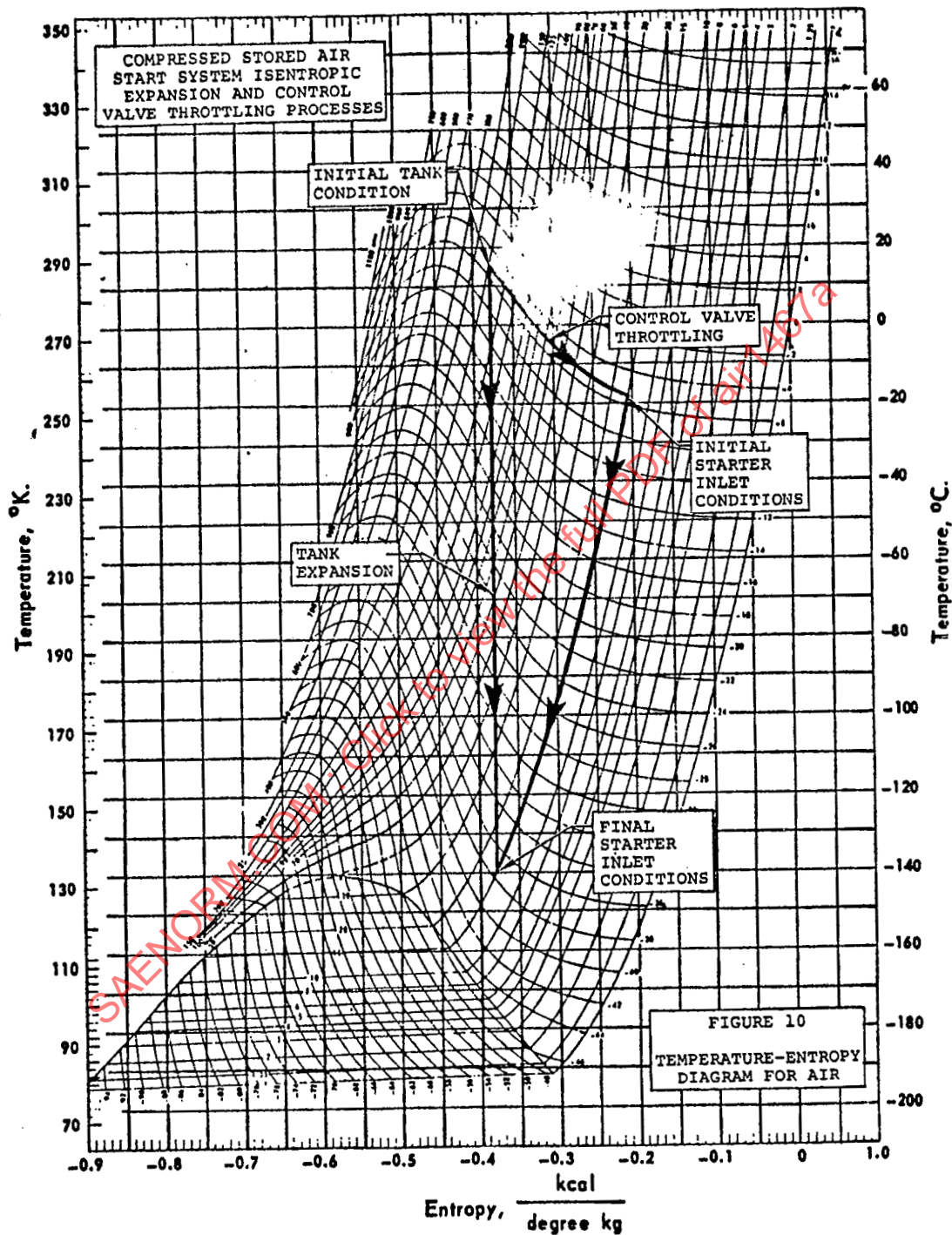


FIGURE 10 - Temperature-entropy Diagram for Air