SAE Aerospace
An SAE International Group

AEROSPACE INFORMATION REPORT

SAE AIR1343 | REV. B

Issued 1981-11
Revised 1992-03
Reaffirmed 2007-11
Stabilized 2013-06

Superseding AIR1343A

Liquid Propellant Gas Generation Systems

RATIONALE

This document has been determined to contain basic and stable technology which is not dynamic in nature.

STABILIZED NOTICE

This document has been declared "Stabilized" by the A-6C6 Power Sources Committee, and will no longer be subjected to periodic reviews for currency. Users are responsible for verifying references and continued suitability of technical requirements. Newer technology may exist.

TO PLACE A DOCUMENT ORDER: **Tel: 877-606-7323 (inside USA and Canada)**
Tel: +1 724-776-4970 (outside USA)
Fax: 724-776-0790
Email: CustomerService@sae.org
SAE WEB ADDRESS: **http://www.sae.org**

SAE values your input. To provide feedback on this Technical Report, please visit
http://www.sae.org/technical/standards/AIR1343B

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

1. SCOPE:

This information report presents a preliminary discussion of liquid propellant gas generation (LPGG) systems. A LPGG system, as used herein, is defined as a system which stores a liquid propellant and, on command, discharges and converts the liquid propellant to a gas. The LPGG system can interface with a gas-to-mechanical energy conversion device to make up an auxiliary power system. Figure 1 shows a block diagram of LPGG system components which include a propellant tank, propellant expulsion system, propellant control and a decomposition (or combustion) chamber.

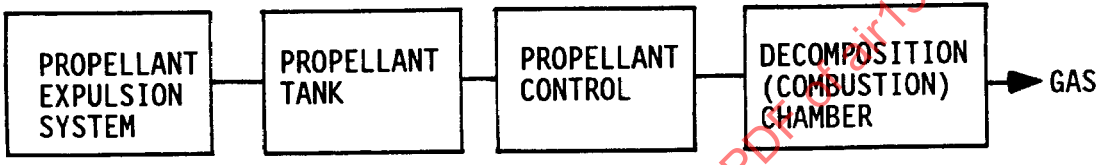

FIGURE 1 - LPGG System Block Diagram

The purpose of this report is to provide general information on the variety of components and system arrangements which can be considered in LPGG design, summarize advantages and disadvantages of various approaches and provide basic sizing methods suitable for initial tradeoff purposes.

2. REFERENCES:

2.1 Compatibility of Hydrazine Blend Fuels in metal containers at elevated temperatures - CPIA Publication 160, December 1957

2.2 Thermal Stability of Mixed Hydrazine Fuels, CPIA Publication 160, December 1957

2.3 MHF-5 Storage Data - USAF Propellant Handbooks Hydrazine Fuels Vol. I AFRPL-TR-69-149, March 1970

2.4 “Hydrogen Peroxide Handbook” AFRPL-TR-67-144, July, 1967 Rocketdyne, a Division of North American Aviation Inc., Canoga Park, California
Air Force Rocket Propulsion Laboratory
Edwards Air Force Base, California

2.5 “USAF Propellant Handbooks Hydrazine Fuels” Volume I, March 1970 Contract No. F04611-69-C-0005
Bell Aerospace Company
Division of Textron, Buffalo, N.Y.
Air Force Rocket Propulsion Laboratory
Edwards Air Force Base, California

2.6 “Compatibility of Rocket Propellants with Materials of Construction”
Defense Metals Information Center
Battelle Memorial Institute
Columbus 1, Ohio
OTSPB161215
September 15, 1960 DMIC Memorandum 65

2.7 “The Handling and Storage of Liquid Propellants”
March 1961
Office of the Director of Defense Research & Engineering
Washington 25, D.C. Department of Defense

2.8 “Hydrazine Handling Manual” AF/SSD-TR-61-7 R-3134 and

2.9 “Mechanical System Design - Criteria Manual for Hydrazine” AF/SSD-TR-61-6 R-3130
Rocketdyne, a Division of North American Aviation, Inc.
Canoga Park, California
Contract AF 33(616)-6939
September 1961
Rocket Test Annex
Space Systems Command
Edwards Air Force Base, California

2.10 “Research on Hydrazine Decomposition”
AFRPL-TR-67-219 July 1967
Rocketdyne - A Division of North American, Inc.
Canoga Park, California
Air Force Rocket Propulsion Laboratory
Research and Technology Division
Edwards Air Force Base, California

2.11 “The Decomposition of Hydrazine on the Shell 405 Catalyst”
AIAA Paper No. 70-606
C.F. Sayer
Rocket Propulsion Establishment
Westcott, Aylesbury, Buckinghamshire, England

2.12 “A Survey of the Compatibility of Various Materials with Hydrazine and Mixtures of Hydrazine, Hydrazine Nitrate, and Water” Memorandum No. 20-152
Donald H. Lee Jet Propulsion Laboratory
December 22, 1957 Pasadena, California

2.13 Chemical Rocket/Propellant Hazards
Volume III - Liquid Propellant Handling, Storage and Transportation
AD870259
CPIA/194

2.14 “Code of Federal Regulations, Department of Transportation, Title 49”
General Service Administration
National Archives and Records Service
Federal Register Division
(For sale by Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402)

2.15 Investigation of Space Storable Propellant Acquisition
Devices, Volume I Evaluation October 1970
Volume II Design and Analysis December 1970
MCR-70-171 Martin Marietta, Denver Division, Denver, Colorado
NASA Contract NAS7-754

2.16 Aerospace Tanks
Characteristics of Existing Propellant Tanks and Pressure Vessels for Spacecraft Application
Volume I & II
Prepared for NASA Contract NAS7-388
January 1969
IIT Research Institute
Chicago, Illinois

2.17 “Gas Generator Design Handbook”
Volume I
SAE A6B Fluid Power Sources Subcommittee
A6 Aerospace Fluid Power and Control Technologies 1968

2.18 “Subcritical, Controlled-Ullage, Cryogenic Tankage Concept”
Clifford N. Hall, Sunstrand Aviation, Rockford, Illinois. ARS Space Power Systems Conference, Santa Monica, California. Pre Print 2513-62 September 1962.

2.19 Aerospace Tanks
Characteristics of Existing Propellant Tanks and Pressure Vessels for Spacecraft Application
Volume I & II
Prepared for NASA Contract NAS7-388
January 1969
IIT Research Institute
Chicago, Illinois

2.20 Rocket Research Corp., Redmond, Washington
“Development of Design and Scaling Criteria for Monopropellant Hydrazine Reactors Employing Shell 405 Spontaneous Catalyst”
RRF-66-R-76-Vol. II
NASA Contract NAS7-372
January 18, 1967

2.21 “Liquid Propellant Gas Generators”
National Aeronautics and Space Administration
NASA SP-8081
March 1972

3. SYSTEM CONSIDERATIONS:

Liquid propellant gas generator (LPGG) systems are suitable for a wide variety of auxiliary power supply applications, particularly those requiring a variable duty cycle, long duration and/or reuse. Through use of liquid flow control devices (on-off or proportional valves) power output of the LPGG can be varied over a wide range resulting in efficient usage of propellant. This load-following capability is a primary advantage of LPGG systems.

Alternates to LPGG systems are discussed in AIR744. This report presents a summary of equipment used and the experience gained with various types of power sources for use in auxiliary power systems for aerospace applications.

The following types of auxiliary power systems are typically powered with LPGG systems.

a. Turbine machinery supplying electrical, hydraulic, pneumatic and/or shaft power.
b. Positive displacement engines supplying electrical, hydraulic, pneumatic and/or shaft power.
c. High pressure warm gas sources supplying a variety of piston type actuators for rocket engine thrust vector control or aerodynamic control surface positioning.
d. High pressure warm gas sources for pressurization of rocket engines propellant tank.
e. Power source for driving propellant feed pumps for the vehicle’s main propulsion engines.
f. Attitude reaction controls.
g. Warm gas source for fluidic devices and fluidic computation systems.

The way the LPGG will be used in the system and the characteristics of the particular system will impact the LPGG design. The following variables should be defined and considered in the design:

a. Duration of active life
b. Duty cycle
c. Storage life
d. Power level
e. Type of power (pressure-flow, electrical, moment, etc.)
f. Power density
g. Environment (temperature, space, nuclear, etc.)
h. Check-out requirements
i. Response (activation time and operating dynamics)
j. Safety
k. Cost
l. Reliability
m. Interfaces and limitations
n. Maximum exhaust gas temperature
o. Exhaust gas composition constraints

4. LIQUID PROPELLANTS:

4.1 Monopropellants:

A monopropellant is a liquid capable of undergoing an exothermic reaction (decomposition), releasing energy in the form of hot gases. This reaction can be initiated by the application of heat or contact with a catalytic or hyperbolic substance.

Monopropellants have the advantage of controllability and packaging flexibility when compared to solid propellants, and lack of complexity when compared to bipropellant systems. A number of monopropellants have been developed, and are available to meet a variety of specific system requirements. Hydrogen peroxide, Otto fuel, ethylene oxide, and various hydrazine blends are well known and a wealth of engineering data is available. Specific system and operational requirements dictate the choice of the particular monopropellant. For example, a requirement for extended sealed storage life could remove hydrogen peroxide from consideration since hydrogen peroxide slowly decomposes. On the other hand, where fuel is being consumed over an extended period of time, as in a satellite application, hydrogen peroxide has demonstrated reliable operation in a sealed system for a period of more than three years. A low temperature operating requirement may also eliminate some of the hydrazine blends and Otto Fuel.

See Table 1 for properties of various monopropellants. Additional information on monopropellants can be obtained from the references listed in the final section of this standard.

Hydrazine and hydrazine blend monopropellants have received considerable attention in recent years due to their storability, high energy release cleanliness of exhaust, and moderate cost; however, the possible toxicity of liquid hydrazine is a potential problem.

TABLE 1 - Monopropellant Characteristics
Viscosity, 77 °F (25 °C)

	Ethylene Oxide	N-Propyl Nitrate	Otto Fuel II	Anhydrous Hydrazine	Typical Alkylated Hydrazine Blends	Typical Nitrated Hydrazine Blends	Hydrogen Peroxide 90%
Chemical Formula	C_2H_6O	$C_3H_7NO_3$	Classified	N_2H_4	$CH_3N_2H_3$, N_2H_4	$CH_3N_2H_3$, N_2H_4, $N_2H_5NO_3$	H_2O_2
Specific Gravity 77 °F (25 °C)	0.870	1.050	1.234	1.004	0.900	0.950	1.380
Viscosity, 77 °F (25 °C), cs	0.24	0.65	3.80	0.905	1.10	1.70	1.05
Freezing Pt., °F (°C)	-171 (-113)	-150 (100)	-24.8 (31.5)	34.7 (1.5)	-68 (-54)	-68 (-54)	12 (-11)
Vapor Pressure, 77 °F, psia (25 °C, kPa)	26 (179)	0.510 (3.52)	.002 (.014)	0.278 (1.92)	0.90 (6.21)	0.84 (5.79)	0.10 (.69)
Flash Pt., °F (°C)	<0 (-18)	65 (18)	235 (113)	126 (52)	80 (26)	85 (29)	>230 (110)
Gas Hp. h/lb. (kJ h/kg)	.248 (147)	.293 (173)	.337 (200)	.375 (50% NH_3 Disso.) (222)	.312 (185)	.341 (202)	.137 (81)
Avg. Mole. Weight	20.7	16.8	21.7	13.8	12.8	13.0	22.1
Gas Temp., °F (°C)	1740 (949)	2190 (1199)	2150 (1176)	1800 (982)	1340 (726)	1500 (815)	1380 (748)
Material Compatibility	Very Good	Good	Very Good	Good	Good	Good	Poor
Storability	Very Good	Good	Very good	Good	Good	Good	Poor
Fire Hazard	High	Medium	Very Low	Low	Low	Low	Med./Low
Toxicity	Low	Low	Very Low	Medium	Medium	Medium	Low
Decomposition Products	C, CH_4, $C_2H_4CO_2$, O_2 CO, H_2	C, CO, H_2, N_2CO_2, CH_4 H_2O	C, CO_2, C_2H_6CO, N_2 H_2 CHN, H_2O, NO	N_2, H_2NH_3	N_2, H_2, C, CH_4	N_2, H_2, C, CH_4, H_2O Trace CO	H_2O, O_2
Comments	High Carbon Content in Exhaust	Exhibits Dieseling Tendency	Exhibits Dieseling Tendency	High Freezing Point	High Carbon Content in Exhaust	Nitrates Decrease Storability at high temperatures	Requires Venting with limited storability

4.1 (Continued):

Anhydrous hydrazine (N_2H_4) is a commonly used monopropellant in aerospace applications. This monopropellant exemplifies all of the advantages listed in the above paragraph, and in addition it is readily decomposed upon contact with a spontaneous catalyst such as Shell 405. The major restriction to use of anhydrous hydrazine is its freezing point of approximately 34 °F (1 °C).

The environmental requirements in many applications, therefore, eliminate the use of anhydrous hydrazine. To meet these requirements, a freezing point depressant is added to the hydrazine. These depressants include water, monomethyl hydrazine and hydrazine nitrate. Typical fuels with depressed freezing points, which contain these additives are Mixed Hydrazine Fuels (MHF) such as MHF-3, MHF-5 and Monopropellant Gas Generator Propellants (MGGP) such as MGGP-1, and hydrazine-water mixtures. The freezing point of hydrazine can be depressed to near -65 °F (-54 °C) by the addition of approximately 30% water. Figure 2 shows the freezing point as a function of water content. Hydrazine energy content decreases with water addition. As an example, a 70% hydrazine, 30% water blend has less than 65% of the available energy (BTU/lb) (J/kg) of undiluted anhydrous hydrazine. Table 2 shows constituents of various hydrazine blends with depressed freezing points and Table 3 shows their physical and chemical properties.

MHF-3 and MHF-5 both contain monomethyl hydrazine, a carbon containing compound. These carbon containing compounds normally cannot be used with catalytic decomposition systems since the catalyst surface quickly becomes coated with carbon and is rendered useless for further reactivity with incoming propellant. MGGP-1 and hydrazine-water mixtures can be used with catalytic decomposition chambers. All of the above mentioned fuels can be used in a thermal type chamber.

Storability, energy content, material compatibility, and safety become the parameters used in selecting a fuel for a particular application. The Monopropellant blends which contain either hydrazine nitrate or hydrazine azide exhibit high energy levels and good reactivity, however, they have limited storage capability at elevated temperatures, as determined by measuring pressure rise in a sealed propellant tank. Pressure rise rates of the nitrate and azide blends are high compared to monomethylhydrazine blends such as MHF-3 or water-hydrazine blends. MHF-5 is a high nitrate content blend and MGGP-1 and 70/20/10 are moderate nitrate content blends.

As a general guideline for this document, "long-term storage" is measured in years. Typical monopropellant and pressurization system tankage storage requirement for aircraft emergency power units is three years. Reference to "short-term storage" generally relates to months. Short-term storage capability is adequate for many launch and space vehicle applications where propellant loading is done just before launch and tank storage time requirements during the mission are short.

Most of the published data of propellant capability for long-term storage are in the 100 to 165 °F (38 to 74 °C) range. Decomposition of mixed hydrazine fuels is temperature dependent. The higher the temperature, the higher the rate of fuel decomposition. Also, it has been shown that the mixed hydrazine fuels do not attain a constant slope for pressure rise rate until approximately 60 days.

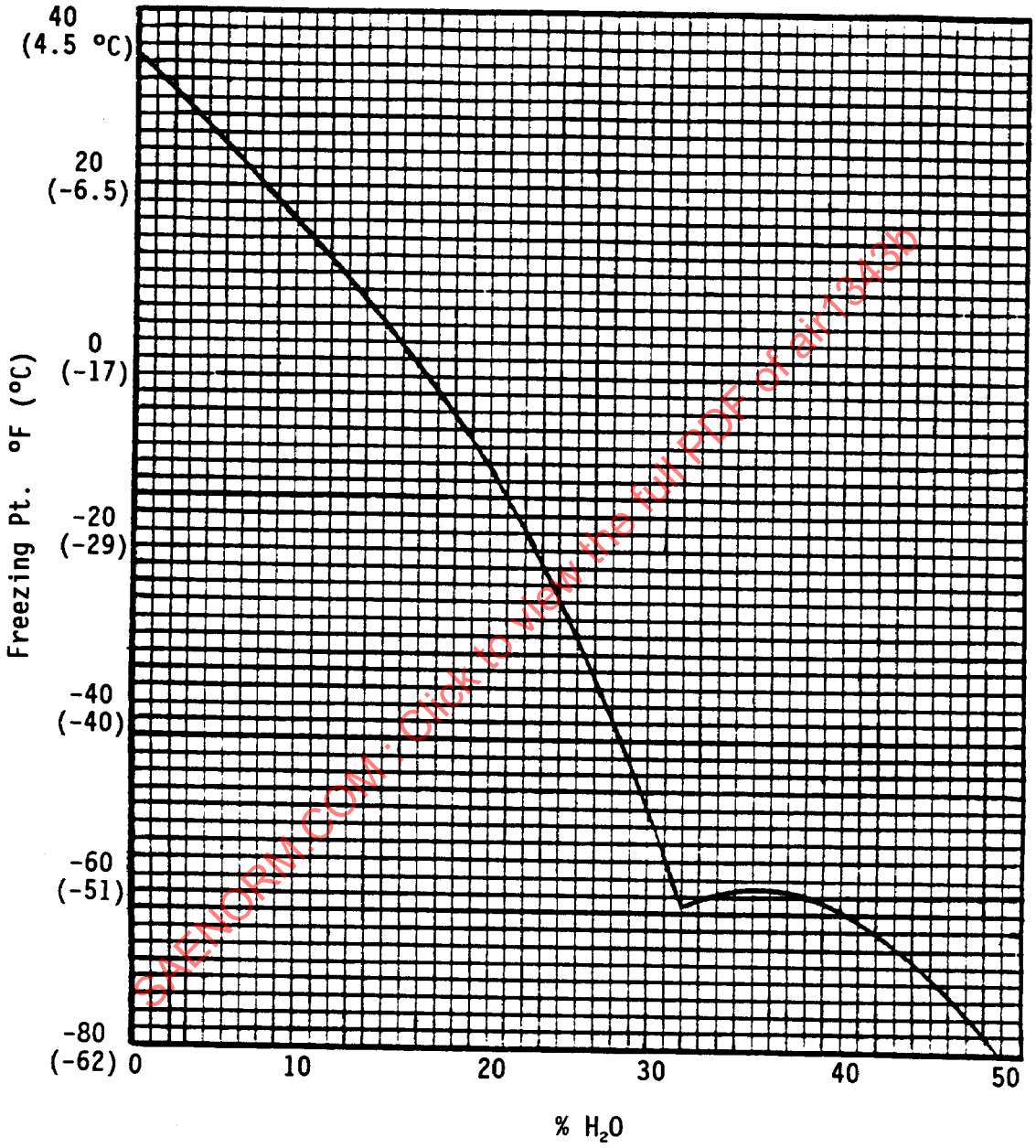

FIGURE 2 - Freezing Point Versus Percent H_2O in N_2H_4/H_2O Blend

TABLE 2 - Constituents of Hydrazine Blends With Depressed Freezing Points

Fuel	Hydrazine N_2H_4	Water H_2O	Hydrazine Nitrate $N_2H_4HNO_3$	Monomethyl Hydrazine MMH
Hydrazine	X			
MHF-3	X			X
70-20-10	X		X	X
MGGP-1	X	X	X	
N_2H_4/H_2O	X	X		

TABLE 3 - Physical and Chemical Properties of Hydrazine Monopropellants

Percent H_2O	Hydrazine 0	Hydrazine 10	Hydrazine 20	Hydrazine 30	70-20-10	MHF-3	MHF-5	MGGP-1
Freezing Point								
°F	34.7	14	-12	-58	-68	-68	-44	-68
(°C)	(1.5)	(-10)	(-11)	(-54)	(-54)	(-54)	(-42)	(-54)
Boiling Point								
°F	238	243	247	248	200	194	207	237.1
(°C)	(114)	(117)	(119)	(120)	(93)	(90)	(97)	(114)
SP Gravity at 77 °F (25 °C)	1.004	1.01	1.02	1.026	.95	.894	1.011	1.06
Vapor Pressure								
psia at 77 °F	.28	0.308	0.33	.354	0.84	1.0	0.77	0.15
(kPa at 25 °C)	(1.93)	(2.12)	(2.28)	(2.44)	(5.79)	(6.90)	(5.31)	(1.03)
Viscosity (CS) at 77 °F (25 °C)	0.9	1.1	1.5	1.65	1.32	1.0	1.9	1.9
0 °F (-17 °C)	--	--	5.2	5.5	5.0	3.0	7.0	7.4
-40 °F (-40 °C)	--	--	--	18.0	13.6	9.0	30.0	25.0
-64 °F (-53 °C)	--	--	--	32.5	68	29	100.0	90.0
Ignition Temp.								
°F	518	--	--	--	530	520	500	--
(°C)	(270)				(276)	(271)	(260)	
Flashpoint								
°F	126	134	143	154	90	80	90	--
(°C)	(52)	(57)	(62)	(68)	(32)	(27)	(32)	

4.1 (Continued):

Reports have been published (2.1 and 2.2) on storage tests of mixed hydrazine fuels at temperatures of 100 to 160 °F (38 to 74 °C) in laboratory and field experiments while in contact with various tankage materials. MHF-3 was shown to be storable for three years or more in 1100, 2024, and 6061 aluminum, 304 stainless and Ti-6Al-4V alloys, although analysis of the fuel blends, prior to and after storage, ascertained that some fuel decomposition occurred in all storage containers.

Figure 3 shows elevated temperature long-term storage data for MHF-3 and 70-20-10. Five year storage appears practical with either of these fuels. Storage data on MHF-5 and MGGP-1 are also shown.

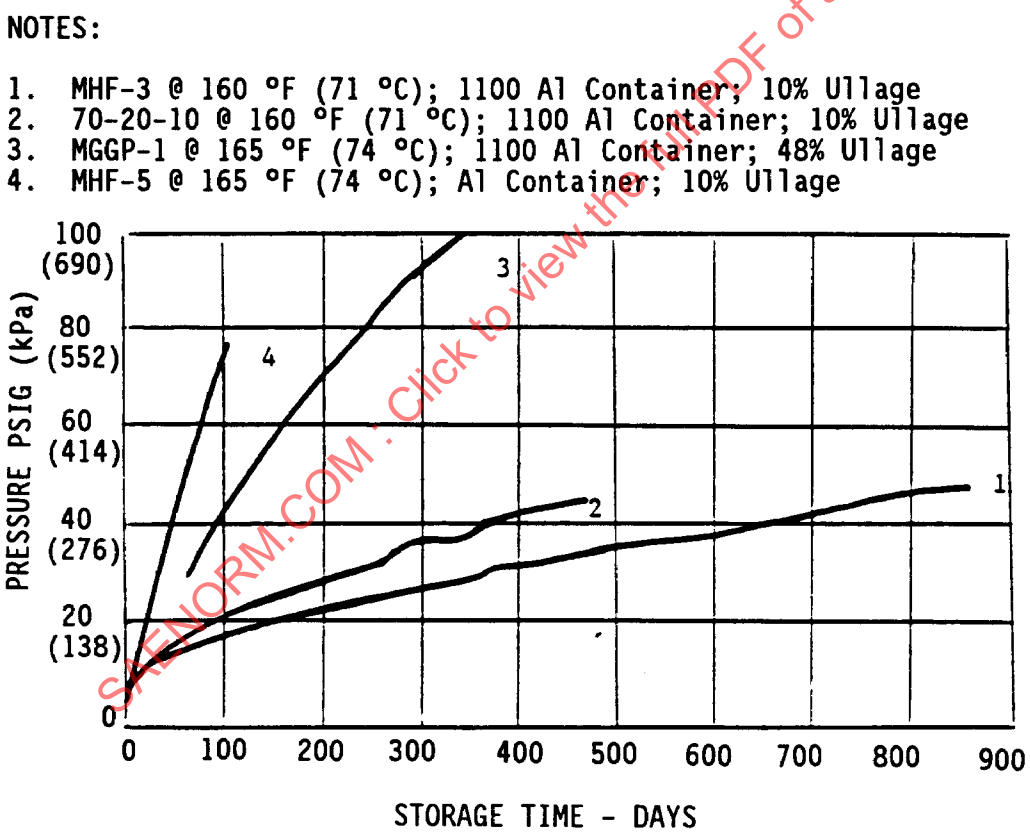

FIGURE 3 - Storage Data on Hydrazine Blends

4.2 Bipropellants:

A bipropellant system uses a fuel and an oxidizer, which when mixed, undergo an exothermic reaction (combustion), releasing energy in the form of hot gases. Ignition of the fuel and oxidizer mixture can be hyperbolic (spontaneous combustion upon contact), catalytic or promoted through application of a heat source.

Bipropellants used in auxiliary power systems are normally the same as those used by the vehicle's main propulsion or attitude control systems. The performance potential of bipropellants is generally higher than that of monopropellants; but, gas temperatures at the peak performance mixture ratio are much too high for conventional power conversion equipment. For this reason, fuel-rich mixtures are generally used. A vast amount of engineering data is readily available on bipropellant characteristics and specific design requirements. Table 4 illustrates physical and energy characteristics for a few typical propellants. Additional information on bipropellants can be obtained from the references listed in the final section of this standard.

4.3 Safety and Handling:

The safety and handling requirements for the various fuels, oxidizers and monopropellants must be considered and these requirements are an important part of any tradeoff study for system selection. Tables 1 and 4 include basic handling and storage information. Each of the candidate fuels, oxidizers and monopropellants have unique flammability, explosive hazard and toxicity characteristics which must be understood and considered in the selection process. A good reference document for safety and handling information is 2.13. The volume includes descriptions of properties, hazards, safety measures, materials and equipment for transfer and storage, main storage and ready storage, systems and equipment cleaning, transfer operations, transportation, emergency procedures and disposal. This document can be obtained from the Chemical Propulsion Information Agency (CPIA), John Hopkins University/APL, 11100 John Hopkins Road, Laurel, Maryland 20810.

In addition, the Department of Transportation of the U.S. Government has detailed extensive regulations related to hazardous materials. These regulations are published in the "Code of Federal Regulations 49, Transportation" in two volumes; parts 1 to 99 and parts 100 to 199. These regulations cover the propellant and pressure containers. The volumes are obtainable through the Superintendent of Documents, Washington, D.C.

5. PROPELLANT TANKS:

The propellant tank provides two functions: storage of the LPGG propellant and fuel expulsion during LPGG operation. The storage function necessitates use of tankage materials that are compatible with the LPGG propellant for a duration required by the specific application. The expulsion function is provided with either a positive expulsion device, or by direct propellant pressurization.

TABLE 4 - Typical Bipropellant Characteristics

	Fuel Hydrogen	Fuel JP-4	Fuel Monomethyl Hydrazine	Oxidizer Oxygen	Oxidizer Nitrogen Tetroxide
Chemical Formula	H_2	$C_{9.66}H_{19}$	CH_3NHNH_2	O_2	N_2O_4
Specific Gravity	0.071 @ -423 °F (liquid) (-253 °C)	0.0747-0.825 @ 60 °F (15 °C)	0.878 @ 68 °F (20 °C)	1.14 @ -297 °F (liquid) (-183 °C)	1.44 @ 68 °F (20 °C)
Freezing Pt.	-434 °F (-259 °C)	-76 °F (-60 °C)	-63 °F (-53 °C)	-363 °F (-219 °C)	11 °F (-12 °C)
Boiling Pt.	-423 °F (-259 °C)	270-470 °F (132-243 °C)	187 °F (86 °C)	-297 °F (-183 °C)	70 °F (21 °C)
Vapor Pressure	33.9 psia @ -417 °F (-249 °C)	7.2 psia @ 160 °F (71 °C)	8.8 psia @ 160 °F (71 °C)	37 psia @ 280 °F (138 °C)	111 psia @ 160 °F (71 °C)
Stability	Good	Good	Good	Good	Dissociation is a function of temp., but is reversible
Shock Resistance	Insensitive	Insensitive	Insensitive	Insensitive	Insensitive
Storage Life	Cryogenic Fluid	Good-similar to gasoline	Good	Cryogenic Fluid	Good when dry/1/
Compatibility, Handling and Storage	Satisfactory with austenitic S.S., aluminum & copper. PTFE & Kel-F for limited use. Flammable in air mixtures.	Store in steel tanks. Protect from sun. Attacks rubber, paints & plastics. Vapor explosive.	Store in stainless steel drums or tanks. Protest from contaminants. Hygroscopic. Low flash point.	May cause spontaneous ignition with combustibles, shock sensitive combinations with certain oxidizable materials.	Satisfactory with steels, aluminum, nickel alloys, PTFE, Kel-F and neoprene. Store in sealed mild steel tanks.
		H_2 - O_2	JP4-O_2		MMH-N_2O_4
O/F Ratio (Weight) for 1800 °F (982 °C) Gas		0.95	0.56		0.23
GHP-H/lb Energy/lb @ Indicated O/F 77 °F (25 °C) Supply Temp.		50/1 Pressure Ratio 1.80	0.234	0.383	

/1/ Leak will combine with ambient moisture producing corrosive nitric acid which will etch back or leak and degrade container integrity.

5. (Continued):

In applications with all attitude, zero "g", or severe vibration and shock requirements, some type of positive expulsion device may be required. Capillary and surface tension devices are often used in zero "g" space applications. In applications with limited duration and no requirement for all attitude or zero "g" operation, a positive expulsion device may not be required; but provision must be made to insure that some propellant is retained at the tank outlet at all times. If gravity can be relied upon to position the propellant at the tank outlet, direct gas pressurization of the propellant can be used and no expulsion device is required.

5.1 Positive Expulsion Devices:

Several types of positive expulsion devices have been developed, including bladders, bellows, and pistons.

In the bladder type tank, propellant is stored inside a metallic or elastomeric bag which is in turn supported by the tank shell. Pressurization gas is supplied to the space between the bladder and wall, causing the bladder to collapse and expulse the propellant. A perforated standpipe or propellant exit port cover may be used to prevent the bladder from covering the exit port before all the propellant is expelled.

5.1.1 Elastomeric Bladders: Elastomeric bladders have been built and used for storage of propellants. Materials considered compatible for hydrazine and hydrazine blends include Teflon, Butyl, Polyethylene and Ethylene Propylene. Storage time requirements usually determine how the bladder will be used in the tank design. For example, for long-term (3 year) storage in aircraft applications the bladder is typically protected and fuel contact occurs only during the expulsion cycle. For short-term storage requirements of some space vehicles, fuel contact may be allowed at all times.

5.1.2 Metallic Bladders: Several types of metallic bladders have been built and tested. They consist generally of a thin aluminum bladder with provision to prevent crimping as the bladder is collapsed.

These aluminum tanks are not reuseable. If reuse is required, the cost of system operation becomes considerably higher. Long-term propellant storage is the primary advantage of these tanks.

5.1.3 Bellows Tanks: A metal bellows is another type of propellant expulsion device. To obtain good expulsion efficiency, the bellows are usually of an edge welded construction. The bellows must have a wide range of expansion and contraction to minimize the "dead" volume and is thus limited in number of cycles.

Formed bellows tend to have lower expulsion efficiencies and higher spring rates than edge welded bellows. At best, bellows tanks have a space utilization efficiency of about 75%. The fuel tank outside dimensions are thus larger than for other types of tanks and the weight is greater. Prevention of bellows cocking or jamming requires guiding with an additional size and weight penalty.

5.1.3 (Continued):

Bellows tanks are reusable, making them attractive from a system cost standpoint when reuse is required.

5.1.4 Piston Tanks: Piston expulsion systems can be used with high volumetric efficiency if the tank has a high length-to-diameter ratio. The piston volume is then small compared to the tank volume. Piston tanks can be made to be reusable.

Piston length to diameter ratios of about two-thirds are usually satisfactory to prevent piston cocking. The tank must be held to fairly close tolerances on the inside diameter and roundness must be maintained.

6. PROPELLANT EXPULSION SYSTEMS:

A number of methods have been used for expelling propellant from its tank and pressurizing it to the level required in the decomposition/combustion chamber. Following is a list of six propellant expulsion systems and a discussion of advantages and disadvantages of each:

a. Stored pressurized gas - N_2, He, CO_2
b. Propellant pump used to pressurize propellant
c. Solid propellant (or catalytic hydrazine pressurization) gas used to pressurize propellant tank
d. Differential area piston used in propellant tank with boot strap gas from gas generator
e. Cryogenic propellant storage
f. Hyperbolic propellant injection

6.1 Stored Pressurized Gas System:

A block diagram of a typical stored pressurized gas system is shown in Figure 4. High pressure stored gas is released by the gas valve and a regulator maintains low pressure to the propellant tank.

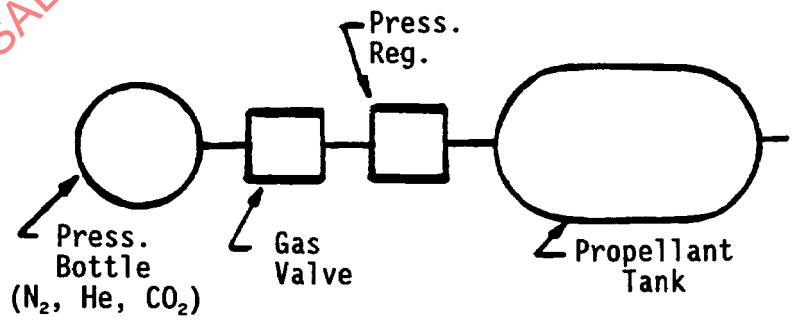

FIGURE 4 - Pressurized Propellant Expulsion System Block Diagram

6.1 (Continued):

Systems can be considered where no pressure regulator is used and the gas may be stored separately as shown in Figure 4 or in an appropriately sized ullage volume in the propellant tank. Primary advantage is system simplicity and disadvantages are variable propellant pressure and greater overall system volume.

6.1.1 Pressurization Gas: The pressurization source in this system is usually a high pressure (3000 psi) gas bottle. When a limited environmental temperature range is expected it is possible to use CO_2 or one of the Freons as a pressurant. These gases have their critical points at low temperatures and can thus be stored as high density liquids and used as low density gases. With a wide environmental temperature range, however, this storage volume advantage is lost and nitrogen is usually used as a pressurant.

Nitrogen is readily available, inert to propellants and their exhaust products, and has proven storability. Thus nitrogen can also be used as a purge gas (if required) and is not harmful to decomposition (combustion) chamber components since N_2 is a normal constituent in the exhaust of many propellants.

Another commonly used pressurant is helium. Helium is more limited in availability than nitrogen. The thermodynamic advantages of helium can result in reduced weight and space.

Many propellants will absorb a finite amount of pressurant gas, including nitrogen. Therefore tank lock-up pressure may decay over a period of time even though system leakage is proven to be negligible. Therefore the solubility of the pressurant gas in the propellant should be determined if a long-term pressurized state is required (8 h or more).

6.1.2 Pressurant Storage Bottle: Pressurant storage bottles can either be hermetically sealed for long-term storage or can be fitted with a pressure checking port and refill fittings. The increased maintenance cost of the refillable system is compensated for by the reduced storage and refurbishment cost if the system is reused.

Bottle materials can be metallic, steel or titanium, or fiberglass wound. Titanium bottles are lighter weight than steel, however more expensive to fabricate. Fiberglass wound bottles generally are as light or lighter than titanium, however, gas loss by permeability is significantly higher and strength is lost gradually with pressure cycling (reuse or temperature cycling). The use of liners, such as aluminum, helps to reduce gas loss by permeability.

6.1.3 Pressurization Gas Valve: When long-term storage is required, a squib actuated gas release valve is normally used. It is important that the valve has a very low leak rate, both to prevent loss of pressurant to the atmosphere and to prevent leakage to the propellant system. Even a small leak to the propellant tank would pressurize the tank, possibly initiating propellant expulsion. The valve must also respond rapidly to achieve rapid system initiation and must be highly reliable.

Squib valves use an explosive primer charge to force a ram through a hermetic seal, opening the valve passage. These valves have high reliability and can be provided with dual igniter wire circuits if complete electrical signal redundancy is required.

If intermittent operation is required a solenoid gas valve can be used for short duration opening of the pressurant bottle.

A vent system should be incorporated to prevent propellant tank pressurization in the event of leakage from either the diaphragm or solenoid type valve.

6.1.4 Pressurant Regulator: A pressure regulator is needed in this system to maintain a constant regulated gas pressure to the propellant tank as the storage pressure varies (due to use or temperature changes). In most systems it is desirable to predetermine the propellant pressure for propellant control purposes and to ensure proper decomposition/combustion operation. It is desirable to design the regulator so that failures occur in the closed position, thereby protecting the propellant tank from overpressurization. If the regulator can fail open a relief valve should be considered to protect against over pressurization.

6.1.5 Advantages and Disadvantages:

a. Advantages

(1) Simple, reliable, inexpensive

b. Disadvantages

(1) Heavy for systems requiring large propellant quantities or when high gas generator pressures are required (high gas generator pressure is needed to obtain stable decomposition with some monopropellants)
(2) Propellant tank is exposed to high pressure gas
(3) Low volumetric efficiency because of the volume occupied by the "inert" gas bottle

6.2 Propellant Pump:

If the LPGG has a long duty cycle and medium to high power output, weight and volume trade offs usually indicate a pump fed system is superior to a pressure fed system. The gas pressurant supply is minimized, or eliminated, in the pump pressurization system and a weight savings results. Pump inlet pressure can be supplied with an external gas pressurant (Figure 5(A)) or through use of a bootstrap system as in Figure 5(B).

The selection of the specific pump system depends upon several factors which must be carefully considered for each particular design. Primary among these factors are: rotational speed of the available power, pressure rise, weight and cost.

6.2.1 Positive Displacement Propellant Pump: The positive displacement piston pump is the most efficient of all pumps with typical volumetric efficiencies running above 90%. It is, however, usually larger, heavier, more costly and must be operated at relatively low (≈10KRPM) input speed. A primary advantage of the positive displacement pump is the ease with which a large pressure rise may be achieved in a single stage, Δp's of 5000 psi (34 500 kPa) are common. There are several positive displacement pump designs which include internal means to control flow, these include variable displacement, variable porting arrangements, and internal bypass.

Care must be exercised in selecting materials of construction in these pumps, historically the piston rings have been the most critical element because of the tendency for erosion and corrosion with the low lubricity high reactivity of some propellants.

Gear pump designs with by-pass provisions offer a reliable, lightweight, low cost pumping system for low lubricity fluids at some sacrifice in efficiency.

6.2.2 Hydrodynamic Fuel Pump: To avoid the problems of metal to metal contact of the positive displacement pump, a hydrodynamic pump can be used. Dynamic pumps are usually used for low pressures and high flows, conditions associated with high specific speed. For low specific speeds (low flow and high pressure) multistage centrifugal pumps are often used. In the case of high speed turbo-pumps where multiple discs and seals become a problem due to the high rotative speed, a single stage centrifugal pump can be used, although its efficiency is low. Care must be taken to avoid excessive heating of the propellant due to pump inefficiency or localized hot spots.

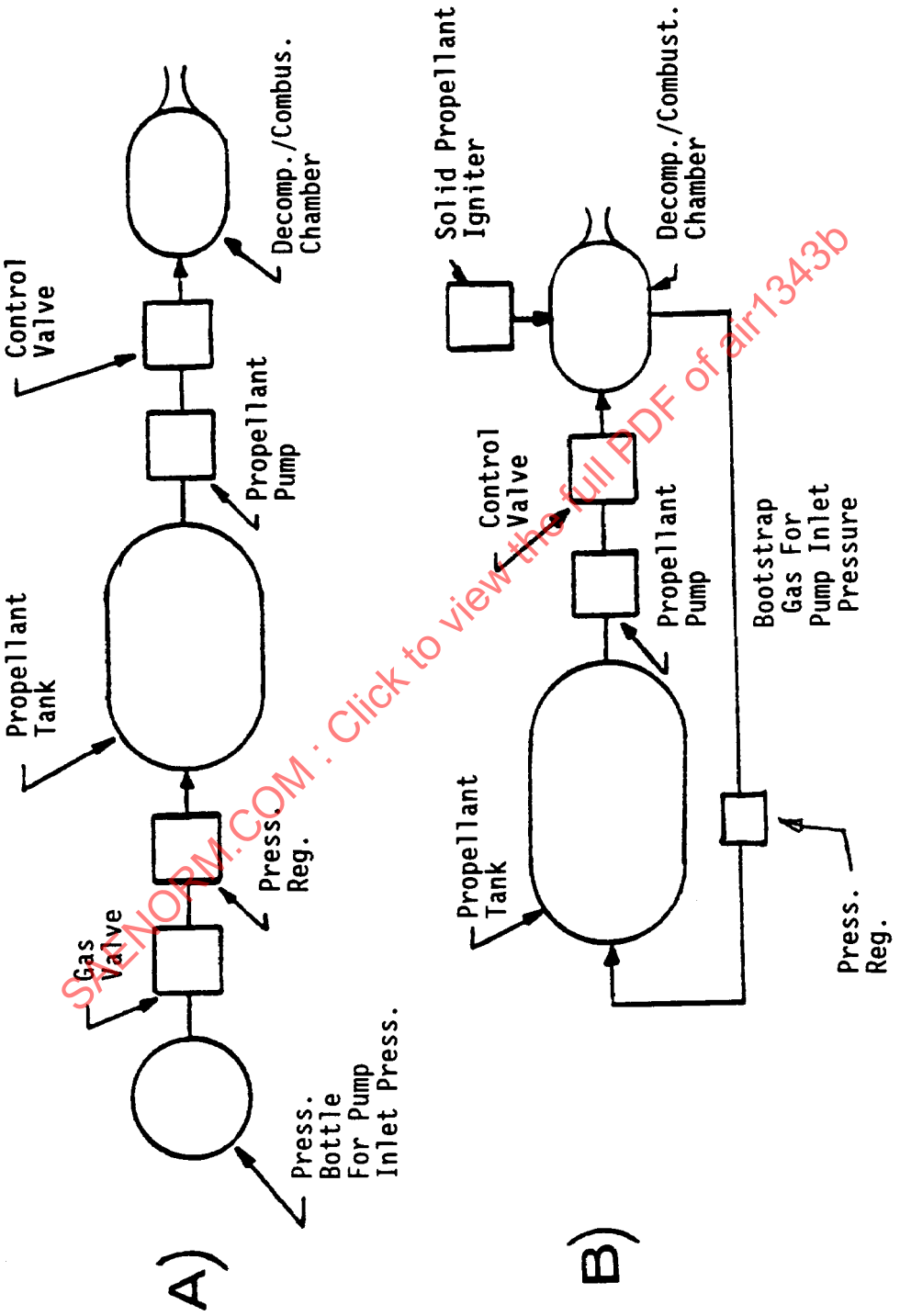

FIGURE 5 - Pumped Propellant System

6.2.3 Advantages and Disadvantages of Pumps:

a. Advantages

(1) Eliminates or minimizes auxiliary tank pressurization system
(2) Propellant tank exposed only to low pressure gas required to provide the pump a net positive suction head
(3) Low weight system particularly in applications requiring high propellant volumes
(4) Pump pressure can be varied through mission profile
(5) Pump pressure can provide a pressure/speed control signal
(6) Advantageous when high pressure propellants are required at the decomposition/ combustion chamber.

b. Disadvantages

(1) Pump requires driving source i.e., pad on APU gearbox, electric motor, etc.
(2) Pump may add significant cost to system depending on propellant and pump type selected
(3) More complex system than stored gas pressurization
(4) Presents possible seal problem at pump - drive source interface
(5) Pump adds heat to propellant
(6) Power required to drive pump may be prohibitive in low power applications

6.3 Solid Propellant Gas Pressurization:

The use of a solid propellant gas generator for tank pressurization is a third method of liquid propellant expulsion. Figure 6 shows a schematic of such a system. The solid propellant provides more pressurant per pound than a cold gas, however, it is less adaptable to variable load profiles.

More detailed discussion on solid propellant systems can be found in 2.1.

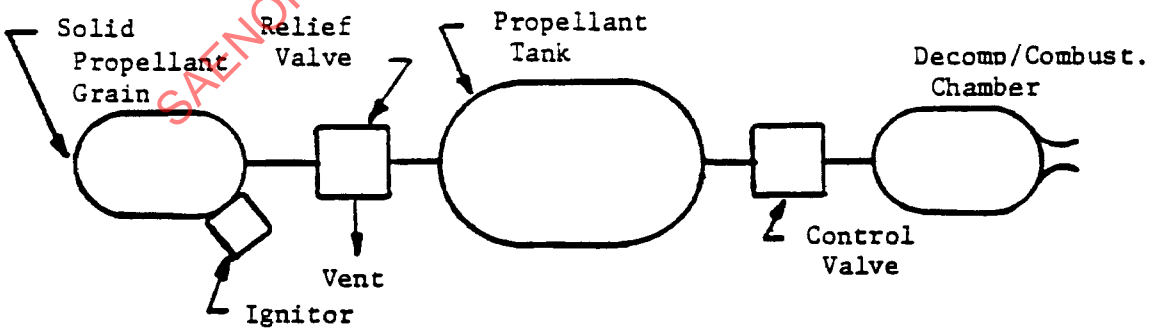

FIGURE 6 - Solid Propellant Expulsion System

6.3.1 Advantages and Disadvantages of Solid Propellant Pressurization:

a. Advantages

(1) Solid propellant has greater energy density than pressurized cold gas possibly resulting in lighter expulsion system particularly if high propellant pressures are required.

b. Disadvantages

(1) Propellant tank is exposed to high pressure hot gas
(2) Propellant may be exposed to hot gas
(3) Hot gas relief valve is required to maintain constant tank pressure
(4) Solid propellant burn cannot be easily regulated to match load profile therefore gas must be dumped during low load demands
(5) Tank must be well insulated so that gas temperature (and pressure) does not drop significantly due to heat loss.

6.4 Differential Area Piston Fuel Tank Gas Generator System:

Systems using a monopropellant gas generator for fuel tank expulsion have been developed to provide a variable demand source of gas. This type of system should be lighter than a solid propellant gas generator expulsion system which has difficulty in regulating gas generation to meet a variable load profile.

A monopropellant gas generator concept developed for tank expulsion purposes consists of a differential area piston and an integral decomposition chamber. The differential piston provides pressure amplification required to feed the monopropellant to the decomposition chamber during operation. Decomposition gas pressure acting on the gas side of the piston develops a force which is transmitted to the monopropellant across a smaller piston area, thus amplifying the monopropellant pressure. Once the cycle is initiated, a self-sustaining bootstrap pressurization system results. Initial system pressurization and initiation of monopropellant decomposition may be provided either by an external source of pressurized cold gas or by a self-contained pyrotechnic igniter cartridge. Gases from either source act upon the differential area piston, initiating operation.

This system was originally developed as a pressurization system for liquid propellant rocket engines on tactical missiles. However, it can be applied to other applications requiring a variable source of warm gas, such as turbine APU's and actuation systems. A cross-section schematic of the differential area piston system is shown in Figure 7.

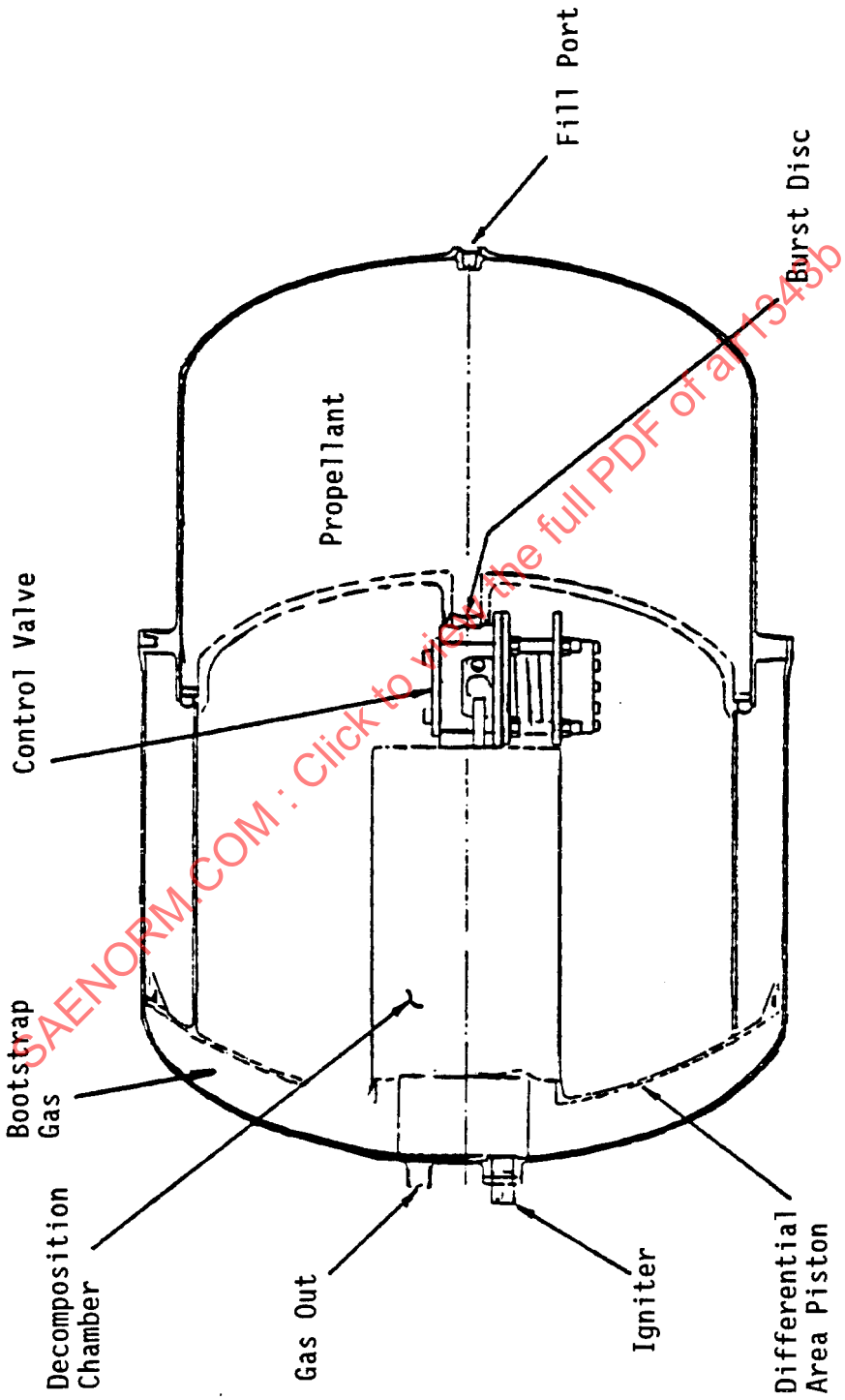

FIGURE 7 - Variable Demand Prepackaged Gas Generator

6.4.1 Advantages and Disadvantages: a.Advantages

(1) Eliminates fuel pump or auxiliary tank pressurization system except for initiation
(2) Provides variable supply of gas pressurant and therefore should be lighter than a solid propellant pressurization system
(3) Compact, self-contained total gas generation system

b. Disadvantages

(1) Differential area piston adds weight and volume to propellant tank
(2) Propellant tank is exposed to high pressure hot gas
(3) More complex than auxiliary cold gas pressurization system
(4) Less flexible choice of tank positive expulsion device

6.5 Cryogenic Storage:

Cryogenic propellants are stored either in a supercritical state or a subcritical state. In supercritical storage the propellant is above the critical pressure and a homogeneous fluid can be withdrawn at a fixed high pressure by the addition of heat to the tank. Figure 8 shows a schematic of this system.

In subcritical storage the propellant is a liquid and vapor mixture below the critical temperature and pressure. Vapor is withdrawn at low pressure or liquid is expelled with external pressurization. If high pressure is required, a vapor compressor or liquid pump can be used.

The primary problem with the subcritical system is operation in a zero gravity atmosphere. Since the propellant is present in both vapor and liquid phases, the availability of the desired phase at all times is questionable. To solve this problem, some type of liquid/vapor separator must be incorporated. Figure 9 shows a schematic of a subcritical storage system.

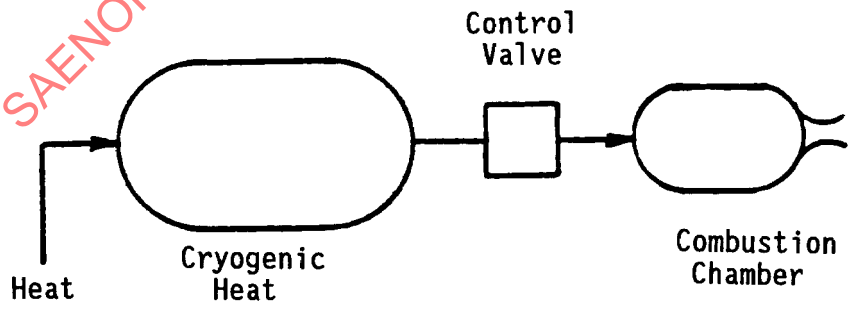

FIGURE 8 - Supercritical Storage System

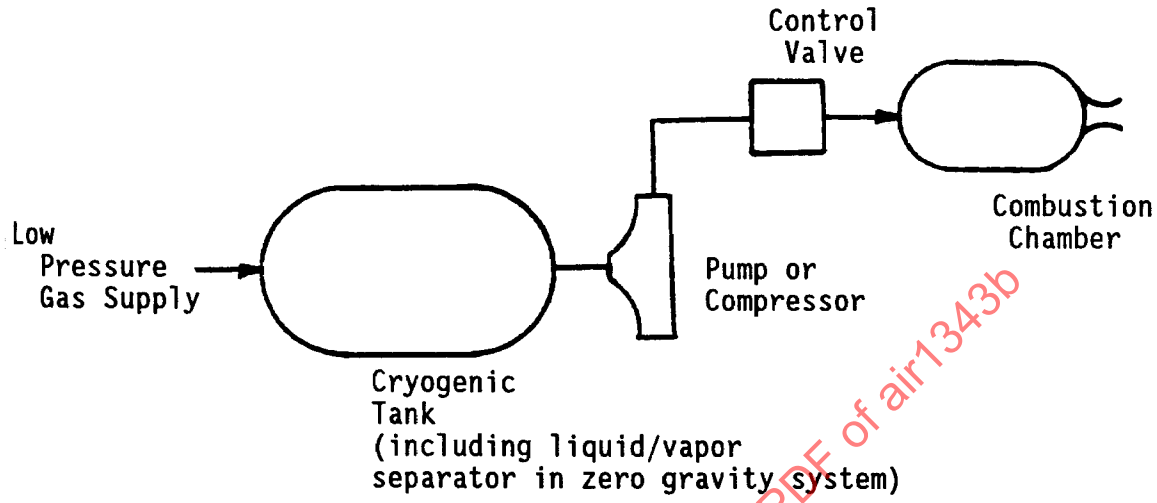

FIGURE 9 - Subcritical Storage System

6.5 (Continued):

The supercritical tank, while not having liquid/vapor separation problem in zero gravity is normally heavier than the subcritical one since tank pressure is higher. The subcritical system, however, does require use of compressors or pumps to obtain comparable pressures. The supercritical system has the following disadvantages:

a. Propellant properties continually change as the tank is emptied
b. Approximately 10% of the initial propellant weight cannot be expelled from the tank resulting in a weight penalty

Cryogenic storage system venting losses are a disadvantage that must be considered. Sophisticated design and installation of insulation and structural supports to minimize heat leak are major cost factors in cryogenic tankage. Care should be exercised relative to cryogenic feed lines in that heat input may flash the liquid in the small diameter (relatively) lines causing flow interruptions. Precooling and/or bleed-in feed lines may be required.

6.6 Hyperbolic Propellant Injection:

A typical system is shown in Figure 10.

Two varieties of systems are possible. One injects reagent (i.e., oxidizer) onto the liquid (fuel) surface with combustion taking place in the tank ullage. The resultant gaseous products are relatively hot, and of large volume, so a small amount of reagent can produce a lot of pressurization. However, a long launch delay results in pressurization sag due to cooling. The second scheme injects reagent below the liquid surface, with combustion taking place within the liquid (fuel) bulk. Combustion products are cooled and condensibles are extracted such that only stable gases (N_2, CO_2, CO, etc.) bubble into the tank ullage. Tank walls remain cool and ullage pressure is stable over long periods (say 8 h). However subsurface injection requires more reagent to achieve the same pressure as surface injection. Fuel heating when the tank is nearly empty can be a problem.

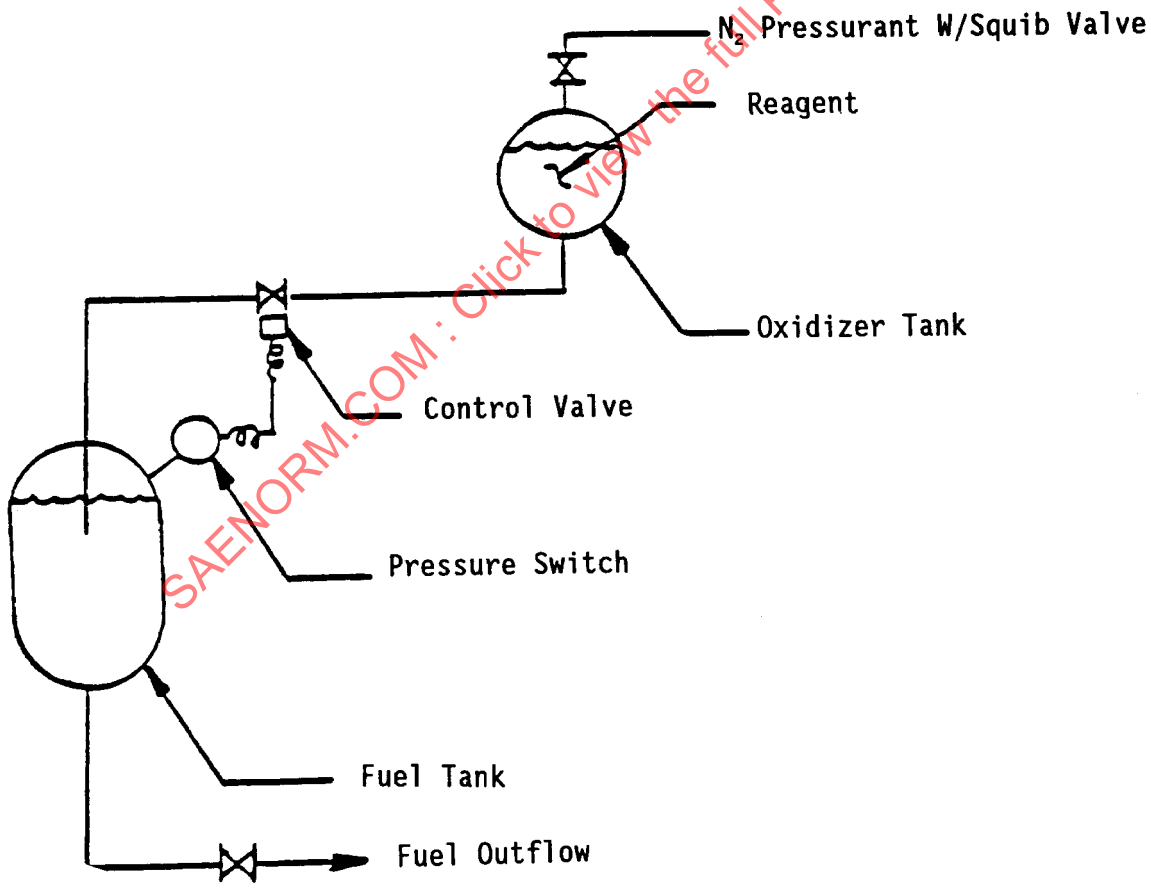

FIGURE 10 - Hyperbolic Propellant Injection System

6.6.1 Advantages of hyperbolic propellant injection (HPI) are as follows:

a. A large amount of pressurant can be carried in a relatively small volume (liquid versus gaseous state).

b. Rapid, controllable and stable pressurization can be achieved for a quick launch or rapid activation main system.

c. During storage, the tankage is at low pressure throughout system if a pyrotechnic gas generator is used to drive the reagent bottle.

d. Potential high pressure leakage of gas pressurants is eliminated. Long-term storage of rapidly deployable system becomes feasible.

6.6.2 Disadvantages of HPI are as follows:

a. A malfunction can cause an explosion.
b. Combustion process may induce high frequency dynamic response in tankage.
c. Surface injection may lead to local structural hot spots.
d. High fuel temperature at the end of a mission.
e. High pressure tankage as compared to pumped systems.

7. PROPELLANT CONTROLS:

A primary advantage of a liquid over a solid propellant gas generator is the ability to control propellant flow as desired. Typical auxiliary power requirements have variable profiles with power turn-down ratios as high as 10:1. The use of a system in which propellant flow follows a variable power profile can result in a significant reduction in propellant consumption.

There are two basic methods to control propellant flow.

a. Pressure modulated control
b. Pulse modulated (bang-bang) control

Figure 11 shows theoretical flow and speed profiles for a turbine driven hydraulic power unit with the two types of controls.

7.1 Pressure Modulated Control:

With a pressure modulating control, propellant is continuously being throttled to provide the variable flow required throughout the load profile. When flow is throttled, pressure is reduced proportionately. Available energy of the propellant is a function of pressure ratio across the gas generator nozzle. Pressure is decreased along with flow when throttling occurs resulting in energy being reduced more than proportionately to the flow reduction. Therefore, specific propellant consumption (pound propellant per HP H output) (kg propellant per J output) increases as flow is throttled.

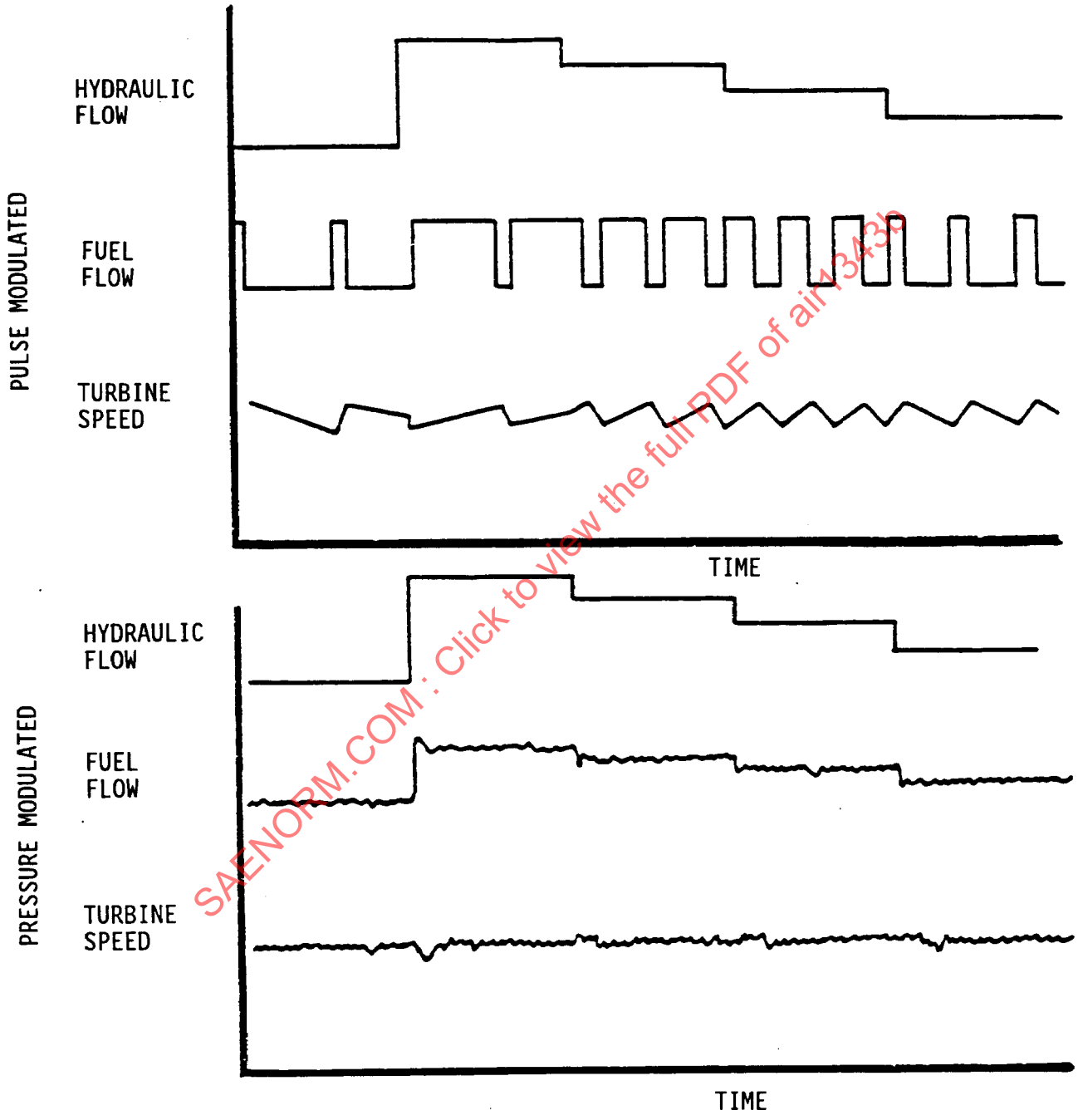

FIGURE 11 - Speed Control Systems Pulse and Pressure Modulated

7.2 Pulse Modulated Control:

With a pulse modulated control, the specific propellant consumption theoretically remains constant across the total load profile. With this type of control, propellant is pulsed either totally on or off. Gas generator pressure is therefore (theoretically) at rated pressure with an "on" pulse or at exhaust pressure with an "off" pulse. The method of control with a pulse modulated system is to vary the pulse length as a function of load. With rated load, the "on" pulse is long and "off" pulse short. The opposite is the case for low part loads.

Actual performance achieved with a pulse modulated control is always below theoretical, however, it can approach theoretical under ideal conditions. A square wave pressure pulse is required to achieve good performance. This requires the ignition delay to be very low. If a large chamber is required, an accumulator effect will result.

Consideration must be given to the dynamic structural response of the system induced by a bang-bang system and to any catastrophic potential due to a bang-bang system hung in the "on" position. Suitable control element redundancies may be required.

8. DECOMPOSITION (COMBUSTION) CHAMBER AND INITIATION SYSTEM:

The following sections describe the two basic types of chambers which are the monopropellant decomposition chamber and the bi-propellant combustion chamber.

NASA document SP8081, "Liquid Propellant Gas Generators", covers a review of the state-of-the-art and design recommendations for large units in the 1.6 (.73) to 170 (77) lb/s (kg/s) flow range.

8.1 Monopropellant Decomposition Chamber:

There are two basic types of monopropellant decomposition chambers:

a. Catalytic
b. Thermal

The catalytic chambers are particularly useful in applications requiring multi-start capability.

To obtain high initiation energies an auxiliary energy source such as a solid grain propellant or a hyperbolic reaction of monopropellant with an oxidizer may be employed. Since these energy levels might deteriorate the catalyst bed, the auxiliary starting procedures are usually used in conjunction with a thermal type decomposition chamber, i.e., a chamber where decomposition is maintained by the exchange of heat between hot decomposition products and incoming propellant.

Limitations of a catalyst system are life and propellant selection. Catalyst material tends to physically break up in use, thus increasing pressure drop across the bed and reducing reactivity. Catalysts are often hydroscopic and need to be protected from moisture.

8.1 (Continued):

The choice of propellant that can be successfully used with a catalyst is also limited. No satisfactory catalyst, for example, exists for monopropellants that have free carbon in their decomposition products.

8.1.1 Solid Propellant Initiators (See Figure 12): Solid propellant grains may be used as monopropellant initiators. They respond very rapidly, releasing a quantity of warm gas which can be used to heat the decomposition chamber and increase the rate of gas flow. A wide range of reliable propellant formulations permit the designer to tailor the temperature, pressure, and burn time as required for reliable and rapid starts. The start grain may be packaged with its ignition squib in a separate hermetically sealed chamber, or placed in the main decomposition chamber for single start systems.

Decomposition chamber pressure during the start grain burn is usually higher than during normal running. Fuel is thus prevented from entering the decomposition chamber until the grain burning is nearly complete and the pressure in the chamber drops below that in the fuel line. Since the grain energy varies depending on ambient soak temperature, a wide band of initial energy level must be accepted.

8.1.2 Hyperbolic Start Systems: A hyperbolic start system uses the spontaneous reaction of the monopropellant with an oxidizer to initiate decomposition. The initial reaction is much hotter (approximately 6000 °R if stoichiometric) than the decomposition process so excess energy is available to warm the chamber.

After the initial start, decomposition is maintained by thermal energy storage in the chamber.

Limited amount of oxidizer in presence of large amount of fuel will tend to burn fuel rich, which reduces the combustion temperature.

8.1.2.1 Solid Oxidizer: Iodic acid (HIO_3) and iodine pentoxide (I_2O_5) are typical solid oxidizers. They have been used to initiate decomposition on a wide range of hydrazine blend monopropellants. The oxidizer is usually stored in a small recess inside the decomposition chamber. For long-term storage requirements, the oxidizer is sealed in place by a Mylar film to protect it from gradual contamination from the atmosphere. Figure 13 shows a sketch of a typical solid oxidizer chamber. Fuel is sprayed directly on the oxidizer to initiate combustion. Chamber pressure is low during this initial fuel entry period so fuel nozzle pressure drop is high and fuel flow is greater than normal. As the fuel ignites, chamber pressure rises rapidly.

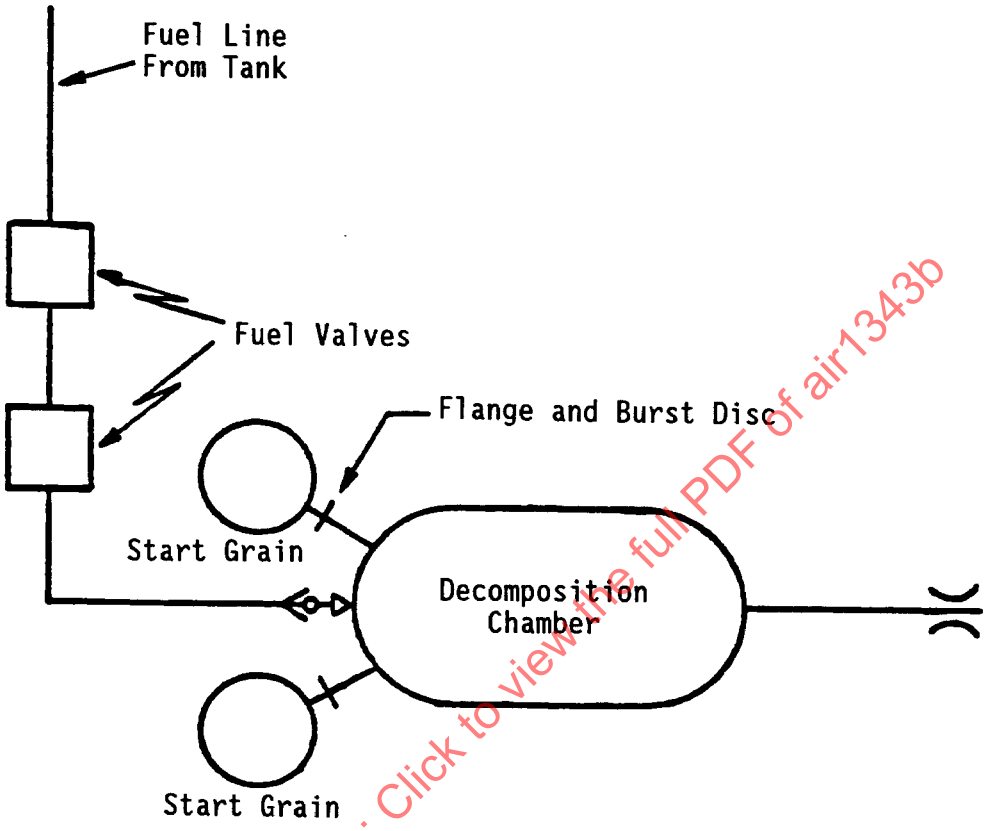

FIGURE 12 - Solid Propellant Dual Start System

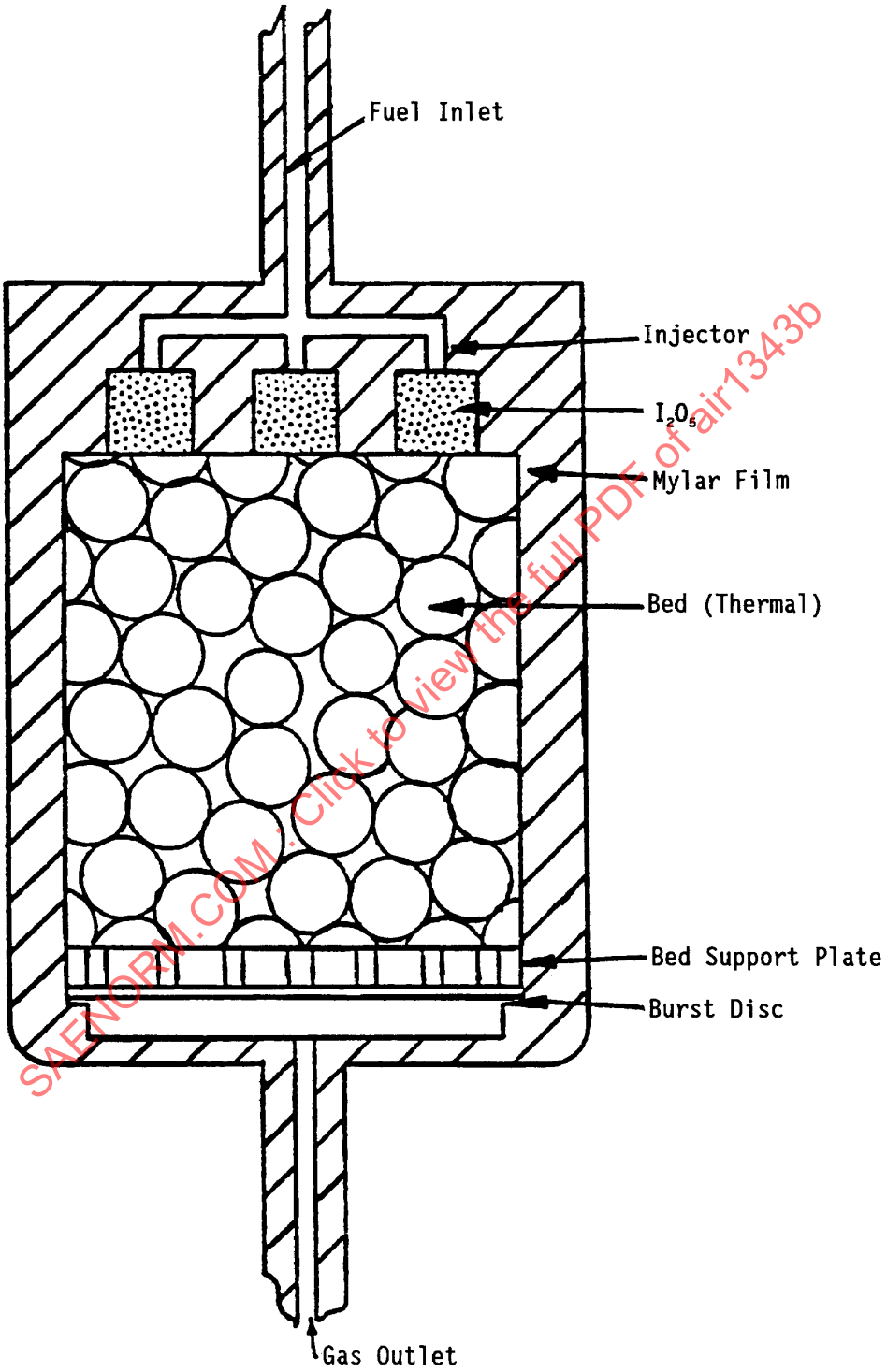

FIGURE 13 - Solid Oxidizer Decomposition Chamber

8.1.2.2 Liquid Oxidizers: Liquid oxidizers such as nitrogen tetroxide (N_2O_4) and inhibited red fuming nitric acid (IFRNA) can also be used to initiate monopropellant decomposition. The liquids have the advantage of being usable for multiple starts since they can be stored outside the decomposition chamber and injected as required. Figure 14 shows several schemes which can be used to provide metered charges of a liquid oxidizer for single and multiple start systems.

8.1.2.3 Hyperbolic Start Summary: Hyperbolic agents give reliable fuel initiation. Solid oxidizers, while quite storable and easy to package are only usable for a single start unless dual chambers are used. Liquid oxidizers require additional system complexity, however, they do have multistart capability. This complexity is a result of the need for injection of a metered amount (enough to insure initiation but not enough to overheat the components).

Unlike a start grain system, the hyperbolic start system has limited excess energy during the start.

Longer start times for hyperbolic systems must usually be accepted.

8.1.3 Thermal Start Systems: All chambers, other than catalytic, are thermal chambers in the sense that fuel decomposition is sustained by thermal energy stored and transferred within the chamber. Thermal start systems require a means of maintaining the chamber, or a portion of the internal surface, at a temperature high enough to initiate combustion. Fuel temperatures of between 500 °F (260 °C) and 700 °F (371 °C) are sufficient to ignite most monopropellants.

Chamber temperature can be maintained by insulating a chamber which has been heated by previous fuel decomposition, by heat input from an electric heating element or other heat source, and by combination of these effects. Well insulated chambers should be able to hold sufficient heat to provide restart a few minutes after shut down.

8.1.4 Catalytic Initiators: Catalytic decomposition chambers have a major advantage of offering multiple starts without addition of multiple initiating devices.

The catalyst material is deposited on an open pore bed to maximize the surface area for fuel reaction. Many configurations of catalytic chambers have been built and operated successfully.

Catalysts are available only for the noncarbon containing fuels and catalyst beds are subject to degradation with repeated use.

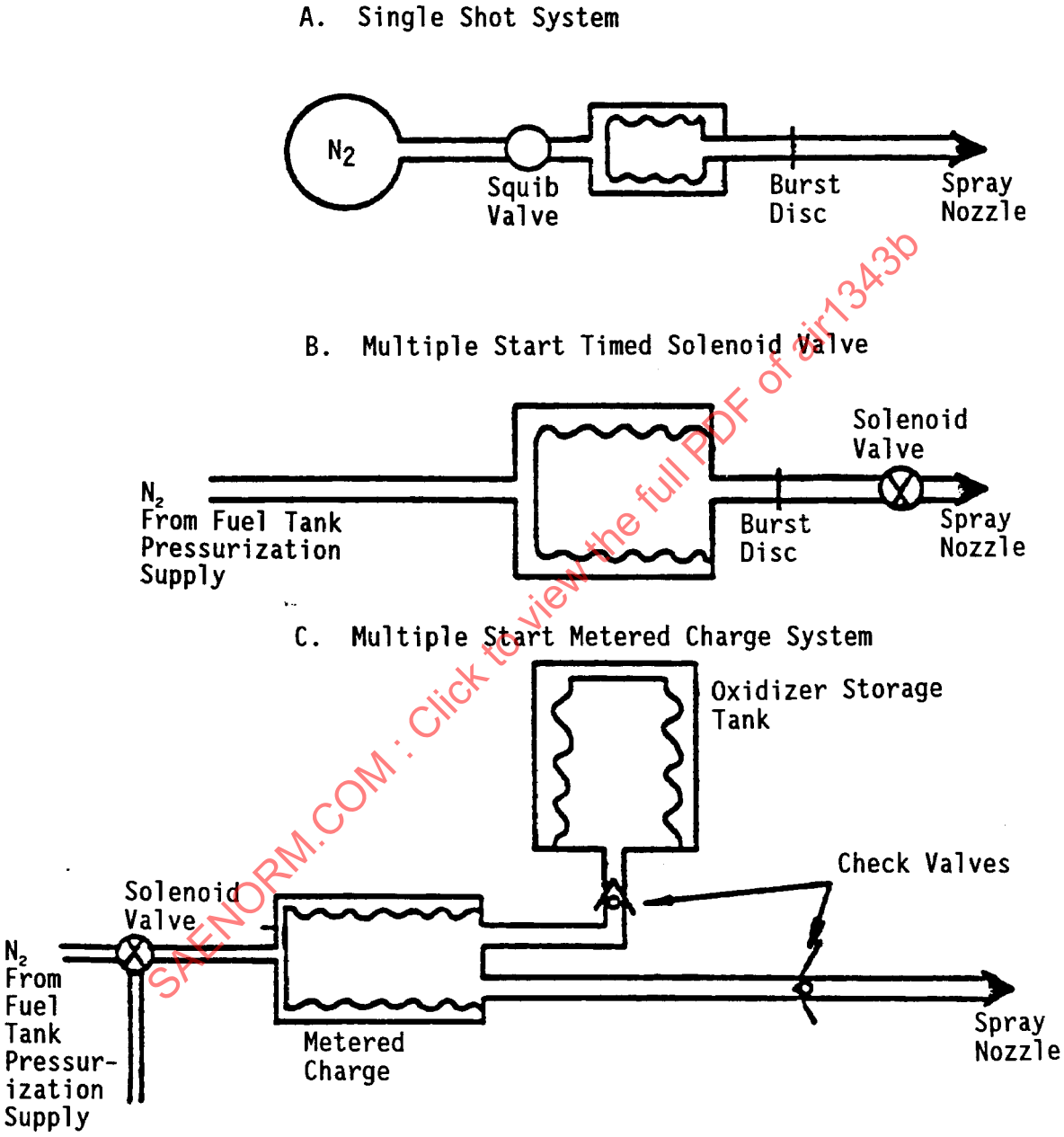

FIGURE 14 - Liquid Oxidizer Injection Systems

8.2 Bipropellant Combustion Chamber:

The design of a bipropellant combustor is dependent upon method of initiation - hyperbolic, spark or catalytic.

Many bipropellants are hyperbolic (fuel ignites spontaneously upon contact with oxidizer), including such common bipropellants as MMH and N_2O_4. Bipropellants such as H_2 and O_2 are not hyperbolic and must be ignited either with a spark or through use of a catalyst.

Bipropellants have had considerable usage in rocket engines and thruster applications in which fuel/oxidizer ratios are near stoichiometric. The resultant high combustion temperatures are normally not compatible with gas-to-mechanical conversion devices (turbines) used in auxiliary power systems. Therefore, when bipropellants have been used as power sources for auxiliary power systems, provisions have been made either to reduce the gas temperature or to keep the energy conversion device cool. Gas temperature is normally reduced by operating at a fuel-rich propellant mixture. This often negates the bipropellants energy/density advantage over a monopropellant resulting in selection of a monopropellant system due to greater system simplicity.

A notable exception to the correlation between bipropellant gas temperature drop (with off-stoichiometric mixtures) and loss in available energy is found in the hydrogen/oxygen system. When operated fuel-rich to produce 1800 °F (982 °C) gases, this system still produces available energy fairly close to the stoichiometric value. In fact it may be noted that peak impulse does not occur with stoichiometric combustion but with a fuel-rich mixture producing a chamber temperature in the 4000 °F (2204 °C) range.

8.2.1 Hyperbolic Combustion: The function of a hyperbolic combustor is to bring together the fuel and oxidizer in a manner that results in stable combustion with gas temperature maintained at a level desired. A number of injection methods have been used in bipropellant combustors. These include stream impingement, conical injection and shower head injection. Common problems of bipropellant injection include localized hot streaking due to improper fuel/oxidizer mixture and pressure spiking due to reaction delays. Fuel injection normally leads or lags oxidizer injection a few milliseconds to minimize pressure spiking or possible detonation.

8.2.2 Spark Ignition: Spark ignited bipropellant combustors are similar to hyperbolic combustors except that a spark is required to ignite the fuel and oxidizer mixture. If operation is continuous, an ignition spark only is required and combustion will become self-sustaining. If a pulse type propellant control is used, a spark must be applied for each pulse. This is more difficult than the continuous operation approach in that proper lead (or lag) times of fuel (or oxidizer) entry must occur for each pulse along with proper timing of the spark.

9. SIZING METHODS:

9.1 Propellant Consumption:

Propellant consumption for a specific LPGG application is determined as follows:

a. Determine pertinent application parameters (environment, initiation requirements, storage, etc.) so that propellant selection can be made.

b. Select pressure ratio between the decomposition (combustion) chamber and exhaust. Chamber pressure is a function of propellant selected, expulsion method with optimum pressure being a total system weight trade-off. Exhaust pressure is a function of altitude and duct sizing.

c. Identify LPGG load profile in terms of gas horsepower.

Having identified gas horsepower requirements, propellant flow ($\dot{W}$) can be determined for the selected propellant and pressure ratio as follows in Equation 1:

a. American Standard:

$$\dot{W} = \frac{550\ (\text{ft lb}_f/\text{HP s}) \times \text{GHP}}{H\ (\text{ft lb}_f/\text{lb}_m)}\ (\text{lb}_m/\text{s}) \qquad \text{(Eq. 1)}$$

where:

W = Propellant flow (lb_m/s)
H = Available Head of selected propellant (ft lb_f/lb_m)
GHP = Required gas horsepower

b. Metric:

$$\dot{W} = \frac{746\ (\text{J/W.s}) \times \text{R.E.}}{H\ (\text{J/kg})} = (\text{kg/s}) \qquad \text{(Eq. 2)}$$

where:

W = Propellant flow (kg/s)
H = Available head of selected propellant (J/kg)
R.E. = Required energy (watts)

9.1 (Continued):

Head is a function of propellant thermodynamic properties and pressure ratio as follows:

$$H = T_o \times C_p \times Y \times J \ (\text{ft lb}_f/\text{lb}_m) \ (\text{J/kg}) \qquad \text{(Eq. 3)}$$

where:

T_o = Chamber exit temperature (°R) (K)
C_p = Specific heat at constant pressure

$$\frac{(\text{BTU})}{\text{lb}_m\,°\text{F}}\left(\frac{\text{CAL}}{\text{kg}\,°\text{C}}\right)$$

$$= \frac{R}{J}\left(\frac{K}{K\text{-}1}\right)$$

R = Gas Constant

$$= \frac{1544}{M}\ (\text{ft-lb})\left[\frac{2903}{M}\ (\text{J})\right]$$

M = Molecular Weight of Gas
K = Specific heat ratio
J = 778 ft lb_f/BTU [1898 J/CAL]

$$Y = 1 - \frac{1}{P_R^{\frac{\kappa\text{-}1}{\kappa}}}$$

P_R = Pressure Ratio

9.1.1 Specific Propellant Consumption (SPC): Specific propellant consumption is frequently used to define propellant consumption in lb_m/hp hr of useful mechanical output. It is a function of head and engine efficiency and can be determined as follows:

a. American Standard:

$$SPC = \frac{550\ (\text{ft lb}_f/\text{HP s}) \times 3600\ (\text{s/h})}{H\ (\text{ft lb}_f/\text{lb}_m) \times \text{engine efficiency}}\ (\text{lb}_m(/\text{hp} \cdot \text{h}) \qquad \text{(Eq. 4)}$$

$$SPC = \frac{746\ (\text{J/W s}) \times 3600/\text{s/h})}{H\ (\text{J/kg}) \times \text{engine efficiency}} = (\text{kg/w} \cdot \text{h}) \qquad \text{(Eq. 5)}$$

9.1.2 Part Load Propellant Consumption: To determine total propellant consumption for a given load profile, part load propellant consumption must be calculated. This is not as straightforward as the full load calculation. Method of propellant flow control (pulse modulated or pressure modulated) requires different approaches.

9.1.3 Specific Impulse (I_{SP}): Another common method of measuring propellant energy is specific impulse. Written in terms of Head,

$$I_{SP} = \left(\frac{2H}{gM}\right)^{1/2} (s\ lb_f/lb_m)\ (s\ kg/kg) \qquad \text{(Eq. 6)}$$

To determine propellant flow for an application requiring thrust, the following equation can be used.

$$\dot{W} = \frac{\text{Thrust } (lb_f)}{I_{SP}}\ (lb_m/s)\ (kg/s) \qquad \text{(Eq. 7)}$$

9.1.4 Characteristic Exhaust Velocity (C*): Another measure of available propellant energy is the characteristic exhaust velocity:

$$C^* = \frac{(g\ KRT_o)^{1/2}}{K\left[\left(\frac{2}{K+1}\right)^{\frac{K+1}{K-1}}\right]^{1/2}}\ (ft/s)\ (m/s) \qquad \text{(Eq. 8)}$$

To determine propellant flow from a known C* the following equation can be used.

$$\dot{W} = \frac{P_c \times A_t \times g}{C^*}\ (lb_m/s)\ (kg/s) \qquad \text{(Eq. 9)}$$

where:

P_c = Chamber pressure (lb_f/in^2) (kPa)
A_t = Nozzle throat area (in^2) (m^2)
g = 32.2 $\frac{lb_m ft}{lb_f s^2}$ (9.8 m/s^2)

9.2 Propellant Tank Sizing:

Tank weights vary considerably as a function of expulsion device and specific requirements such as pressure indicators, etc. For preliminary estimates, however, the following conventional container sizing methods can be used.

9.2.1 Spherical Tank: First, total propellant required for the application's load profile is determined. Additional propellant weight must then be added due to inability of the expulsion device to remove all propellant from the tank. Total propellant volume is calculated as

$$\text{Propellant Volume} = \frac{\text{Propellant Expelled Wt. + Residual}}{\text{Propellant Density } (\rho)} \quad \text{(Eq. 10)}$$

Additional tank volume must be included for tank ullage and for space required by the expulsion device. Ullage volume of 5 to 10% is commonly used to allow for thermal expansion and to provide space for gases evolved from the propellant due to decomposition. Propellants do tend to decompose at a slow rate in storage resulting in a slow pressure rise in the tank.

$$\text{Since volume (V) of a sphere} = 4/3\pi r^3 \quad \text{(Eq. 11)}$$

$$\text{radius (r)} = \left(\frac{3}{4}\ \frac{V}{\pi}\right)^{1/3}$$

$$\text{or diameter (D)} = \left(\frac{6V}{\pi}\right)^{1/3}$$

A thin-wall cylinder has a wall thickness such that the assumption of constant stress across the wall results in negligible error. Cylinders having internal-diameter-to-thickness (D/t) ratios greater than 10 are usually considered thin-walled. Equilibrium equations reveal the circumferential, or hoop, stress to be S = PD/2t under an internal pressure P. If the cylinder is closed at the ends, as in a propellant tank, a longitudinal stress of PD/4t is developed. The tensile stress developed in a thin hollow sphere subjected to internal pressure is also PD/4t.

$$\text{So, Strength of sphere (S)} = \frac{PD}{4t}\ \text{(psi) (kPa)} \quad \text{(Eq. 12)}$$

where:

P = Required Burst Pressure (psi) (kPa)
t = Wall thickness (in) (m)

Having selected a tank material, the material tensile strength together with the required tank burst pressure determines required wall thickness

$$t = \frac{PD}{4s}\ \text{(in) (m)} \quad \text{(Eq. 13)}$$

In estimating minimum wall thickness it should be noted that requirements relative to proof and burst pressure frequently both need to be examined to determine which will govern design - these criteria are sometimes not balanced with respect to particular materials.